Assessment of Fault Ride Through Capability of Wind Generation System with a Doubly-Fed Induction Generator

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I declare that this document is an original work of my own authorship and that it fulfills all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.
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Abstract

Recently, it has become mandatory that wind turbines remain connected to the grid in the occurrence of a voltage dip. Indeed, it is required by regulatory entities and, therefore, by the transmission system operator, that these systems must have the fault ride through (FRT) capability, as a possible disconnection could lead to a cascading effect due to the lack of voltage. Besides, they must guarantee the injection of reactive power to the grid for specific profiles of voltage sags, also according to current standards.

The purpose of this work is to evaluate the FRT capability of a wind turbine equipped with a doubly-fed induction generator and a back-to-back power converter. This equipment allows the speed control of the wind turbine shaft and guarantees the Maximum Power Point Tracking (MPPT). It is installed alongside a common DC-link not only for energy storage but also to decouple the control of both AC/DC and DC/AC power converters. An active crowbar, connected in series with the machine rotor and triggered when the DC-link voltage exceeds a defined threshold, ensures the FRT capability.

The simulation model allows the study of its operating limits under a symmetrical voltage dip with a depth of 80% for 500 ms and a total duration of 2 s. The FRT capability is corroborated, as the crowbar is activated to protect the turbine equipment. During this event, the priority is no longer the MPPT, it is the injection of reactive power to help supporting the grid voltage.

Keywords: Wind Turbine; Doubly-Fed Induction Generator; Back-to-Back Converter; Voltage Dip; Fault Ride Through Capability; Maximum Power Point Tracker
Resumo

Atualmente é obrigatório que as turbinas eólicas se mantenham ligadas à rede aquando da ocorrência de uma cava de tensão. De facto, é requisito das entidades reguladoras e do gestor da rede de transporte que os sistemas eólicos tenham capacidade de “Fault Ride Through” (FRT), pois uma eventual desconexão poderia causar perturbações em cascata na rede, devido à falta de tensão. Além disso, deverão garantir o suporte de potência reactiva para determinados perfis de cavas, também de acordo com as normas em vigor.

Neste trabalho pretende avaliar-se a capacidade de FRT de uma turbina eólica incorporada com uma máquina de indução duplamente alimentada e um conversor AC/DC - DC/AC. Este conversor permite controlar a velocidade do eixo da turbina e garantir o seguimento do ponto de máxima potência (MPPT). É instalado com um andar DC intermédio não só para o armazenamento de energia como também para facilidade de controlo dos conversores AC/DC e DC/AC. A capacidade de FRT é assegurada por um crowbar ligado em série com o rotor da máquina, activado quando a tensão no andar DC excede um determinado limite de segurança.

O modelo simulado permite estudar o comportamento em caso de cava simétrica, com profundidade de 80% durante 500 ms e duração total de 2 s. A capacidade de FRT é corroborada, pois o crowbar é ativado corretamente para proteger o equipamento. Durante a cava, o suporte de potência reactiva à rede para auxiliar a elevar a tensão passa a ser prioridade, em detrimento do MPPT.

**Palavras-chave:** Turbina Eólica; Máquina de Indução Duplamente Alimentada; Conversor Back-to-Back; Cavas de Tensão; Capacidade de Fault Ride Through; Seguidor de Potência Máxima
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<table>
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<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>AC</td>
<td>Alternating Current</td>
</tr>
<tr>
<td>AC/AC</td>
<td>Alternating Current to Alternating Current Conversion</td>
</tr>
<tr>
<td>AC/DC</td>
<td>Alternating Current to Direct Current Conversion</td>
</tr>
<tr>
<td>ASG</td>
<td>Adjustable Speed Generator</td>
</tr>
<tr>
<td>DC</td>
<td>Direct Current</td>
</tr>
<tr>
<td>DC/AC</td>
<td>Direct Current to Alternating Current Conversion</td>
</tr>
<tr>
<td>DFIG</td>
<td>Doubly-Fed Induction Generator</td>
</tr>
<tr>
<td>DGEG</td>
<td>Direção Geral de Energia e Geologia</td>
</tr>
<tr>
<td>DVR</td>
<td>Dynamic Voltage Restorer</td>
</tr>
<tr>
<td>ERSE</td>
<td>Entidade Reguladora dos Serviços Energéticos</td>
</tr>
<tr>
<td>FACTS</td>
<td>Flexible AC Transmission System</td>
</tr>
<tr>
<td>GSC</td>
<td>Grid Side Converter</td>
</tr>
<tr>
<td>IGBT</td>
<td>Insulated Gate Bipolar Transistor</td>
</tr>
<tr>
<td>LVRT</td>
<td>Low Voltage Ride Through</td>
</tr>
<tr>
<td>MC</td>
<td>Matrix Converter</td>
</tr>
<tr>
<td>MPP</td>
<td>Maximum Power Point</td>
</tr>
<tr>
<td>MPPT</td>
<td>Maximum Power Point Tracking</td>
</tr>
<tr>
<td>PCC</td>
<td>Point of Common Coupling</td>
</tr>
<tr>
<td>PI</td>
<td>Proportional Integral</td>
</tr>
<tr>
<td>PV</td>
<td>Photovoltaic</td>
</tr>
<tr>
<td>RPM</td>
<td>Rotations per Minute</td>
</tr>
<tr>
<td>RSC</td>
<td>Rotor Side Converter</td>
</tr>
<tr>
<td>STATCOM</td>
<td>Static Synchronous Compensator</td>
</tr>
<tr>
<td>VSC</td>
<td>Voltage Source Converter</td>
</tr>
</tbody>
</table>
List of Symbols

A  Area swept by the rotor blades
C  Concordia transformation matrix
\( C_p \)  Wind turbine power coefficient
\( C_{pm} \)  Wind turbine power coefficient
\( E_{cin} \)  Kinetic energy
G  Gearbox gain
\( I \)  Currents matrix in stator and rotor windings
\( i_{rd}, i_{rq} \)  Rotor currents in dq coordinates
\( i_{rdq_{\text{ref}}} \)  Reference rotor currents in dq coordinates
\( i_{sd}, i_{sq} \)  Stator currents in dq coordinates
\( J_{\text{total}} \)  Total moment of inertia
\( K_d \)  Friction coefficient
\( K_i \)  Integral gain
\( K_p \)  Proportional gain
\( L \)  Matrix of the DFIG inductance coefficients
\( L_r \)  Matrix of the DFIG rotor self-inductance coefficients
\( L_r \)  Rotor self-inductance coefficient
\( L_s \)  Matrix of the DFIG stator self-inductance coefficients
\( L_s \)  Stator self-inductance coefficient
m  Mass of the air flow
M  Stator and rotor mutual inductance
\( M_r \)  Matrix of the rotor mutual inductance coefficients
\( M_r \)  Rotor mutual inductance
\( M_s \)  Matrix of the stator mutual inductance coefficients
\( M_s \)  Stator mutual inductance
\( n_{pp} \)  Pair of poles of the DFIG
\( P \)  Park transformation matrix
\( P_{av} \)  Wind power available in the area swept by the rotor blades
\( P_e \)  Electrical power extracted from the wind
\( P_m \)  Mechanical power extracted from the wind
\( Q_s \)  Stator reactive power
\( T \)  Blondel-Park transformation matrix
\( T_c \)  Load torque
\[ T_{em} \] Electromagnetic torque

\[ T_g \] Mechanical torque extracted from the generator

\[ T_m \] Mechanical torque extracted from the turbine rotor

\[ R \] Radius of the wind turbine

\[ R_m \] Matrix of both stator and rotor windings resistance

\[ R_m \] Resistor of DFIG stator and rotor

\[ r_r \] Rotor resistance

\[ r_s \] Stator resistance

\[ u \] Wind speed

\[ U_{DC} \] DC-link voltage

\[ u_{dq, grid} \] Grid voltage in dq-coordinates

\[ u_{max} \] Cut-out speed of the turbine

\[ u_N \] Rated output speed of the turbine

\[ u_o \] Cut-in speed of the turbine

\[ u_{rd}, u_{rq} \] Rotor voltage in dq coordinates

\[ u_{sd}, u_{sq} \] Stator voltage in dq coordinates

\[ V \] Matrix of DFIG stator and rotor voltages

\[ V_{AB} \] Line-to-line output voltage between leg A and B of a converter

\[ V_{BC} \] Line-to-line output voltage between leg B and C of a converter

\[ V_{CA} \] Line-to-line output voltage between leg C and A of a converter

\[ V_{\alpha}, V_{\beta} \] Converter output voltage in \( \alpha\beta \) coordinates

\[ V_{ef} \] RMS value of the grid voltage

\[ W_m^c \] Magnetic co-energy

\[ X \] Matrix of the generator linkage fluxes and currents

\[ \phi \] Grid phase

\[ \beta \] Pitch angle of a rotor blade

\[ \lambda \] Tip Speed Ratio

\[ \lambda_i \] Auxiliary variable

\[ \gamma_k \] Semiconductor state function (\( k = A, B, C \))

\[ \rho \] Air density

\[ \omega \] Grid angular frequency

\[ \omega_{dq} \] Angular speed of dq reference frame

\[ \omega_m \] Angular speed of the generator shaft

\[ \omega_m, \text{ref} \] Reference angular speed of the generator shaft

\[ \omega_r \] Angular speed of the DFIG rotor
\( \omega_T \) Angular speed of the turbine shaft

\( \omega_s \) Angular speed of the DFIG stator

\( \omega_{\text{Topt}} \) Optimum angular speed of the turbine shaft

\( \Psi \) Vector of DFIG stator and rotor fluxes

\( \Psi_{rd}, \Psi_{rq} \) Rotor flux in dq coordinates

\( \Psi_{sd}, \Psi_{sq} \) Stator flux in dq coordinates

\( \Theta \) Rotor angular position

\( \Phi \) Displacement between \( \alpha\beta \) and dq reference frames
1. Introduction

The aim of this chapter is to set a brief context of this work, as well as the motivation that led to its development. In addition, the main objectives of the work are presented, and the thesis organization is outlined.

1.1. Context and Motivation

While there may be agreement that it is necessary to decarbonise the energy system, there is not a specific way to achieve this: the solutions to be used in one country may not necessarily apply in other countries. Views are subjective and influenced by different regional perspectives, by the current stage of development within a region and by the part of the energy sector being discussed [1]. In 2016, some factors directly influenced several developments and ongoing trends on renewable energy, such as low global fossil fuel prices, huge price declines of several renewable energy technologies (especially solar PV and wind power) and a continued increase related to energy storage. As of 2016, modern renewables (excluding traditional use of biomass) provided an estimated 10.4% of global final energy consumption [1]. Of this total share, the greatest portion was renewable electricity with 5.4%, most of which was generated by hydropower (3.7%), as shown in Figure 1.1.

For many countries, wind power has become a pillar in their strategies to phase out fossil and nuclear energy. Almost 55 GW of wind power capacity was installed in 2016, bringing the global total to almost 487.28 GW. In the end of the 2017, the installed capacity grew 10.6% to a total of 539.12 GW [2]. Figure 1.2 represents the evolution of the annual installed wind power capacity and the cumulative capacity, since 2001.
The total installed capacity of 539.12 GW corresponds to almost a quarter of the total renewable power capacity. In fact, and according to Figure 1.3, wind power has a total share of 24.55% in 2017, corresponding to 5.6% of global electricity production by the end of 2017 [1].
In December of 2017, China was the largest regional market with 19.66 GW of installed capacity, representing 37% of the total wind power capacity in that year [3]. Therefore, from Figure 1.4 it is possible to conclude that China retains its lead for the cumulative installed capacity, followed distantly by the United States and Germany.

![TOP 10 CUMULATIVE CAPACITY DEC 2017](image)

Figure 1.4 - Cumulative wind power capacity in 2017, top 10 countries [3]

Portugal had 5.09 GW of wind power installed capacity by the end of 2017, which corresponds to a share of 38% of the renewable installed capacity (and 25.7% of the total installed capacity in the country). Relatively to the production of the national electrical system, wind power comes in with 56.6% of the renewable energy production and 22% of the global production in that year [4].

The first wind turbines had a rated output power of 200 kW. These systems used a simple squirrel-cage induction generator connected to a three-phase power grid. In this solution, the rotational speed of the generator and its frequency were fixed. Thus, the wind-speed fluctuations were directly reflected as mechanical-torque fluctuations, mirroring current oscillations of the generator [5]. Besides, their performance was limited in terms of extracted power: incapable of operating in their maximum efficiency, a lot of the available wind power was wasted.
The aim of wind turbine systems development is to continuously increase the output power, not only onshore but especially on offshore applications [6]. In fact, the installation of wind turbines has grown at a fast pace over the last two decades, expecting to surpass 760 GW by 2020 [3]. In 2015, the average rating of wind turbines installed in Europe was 2.7 MW for onshore and 4.2 MW for offshore, having now cutting-edge 8 MW wind turbines [5]. These modern high-power systems allow an adjustable speed operation and extraction of the maximum power provided by the wind. To achieve that, the system requires a power conditioning circuit capable of converting variable voltages and frequencies of the generator (as its RPM change) into a fixed frequency and output voltage compliant with the grid [7]. This conversion is accomplished by two different ways:

- Direct conversion with a single AC/AC stage for energy processing. In this case there is no energy storage level;
- Indirect conversion, where the first stage is an AC/DC conversion and the second stage is a DC/AC conversion. Between both levels, there is a common DC-link with a capacitor.

There are implementations with an adjustable speed generator (ASG) connected to the grid through a power converter connected directly in line to transform variable frequency AC power into fixed frequency AC power. AC/AC direct transformation of Figure 1.5 (a) can be obtained through a matrix converter (MC) with a bi-directional single-stage converter, able to supply output voltages with variable frequency. Its significant size and weight reductions due to the absence of any large energy storage elements, such as DC-link capacitors, offers the potential for higher robustness and reliability [8].

![Figure 1.5](image)

(a) Direct-in-line topologies for energy conversion: (a) direct AC/AC conversion with a MC; (b) indirect AC/AC conversion via an AC/DC - DC/AC converter with a common DC-link

Usually, an AC/DC - DC/AC converter (indirect conversion of Figure 1.5 (b)) can also be installed directly in line with the ASG. This converter has a rated power equal to the wind turbine, as it processes all the system power, and its efficiency plays an important role in the global operation efficiency. Filters applied are also rated to full power, making their design difficult and expensive [6].

The prevention of most disadvantages referring ASG based on direct-in-line converter leads to an alternative concept, analyzed in this work: a doubly-fed induction generator (DFIG) with an AC/DC -
DC/AC converter (back-to-back converter) based on insulated gate bipolar transistors (IGBT) connected to the rotor windings (Figure 1.6). In this configuration, the stator windings of the DFIG are directly connected to the power grid. The decoupling capacitor in the common DC-link is an energy storage element that provides the energy buffer required between the generator and the grid [7]. Moreover, it offers an independent control capability for both Rotor Side Converter (RSC) and Grid Side Converter (GSC).

![Wind Turbine with a DFIG connected to a back-to-back converter](image)

Figure 1.6 - Wind Turbine with a DFIG connected to a back-to-back converter

One main advantage is the fact that both converters need only to be rated to handle a fraction of the total power – the rotor power – typically about 20-30% of the total system power, thus reducing their cost. Therefore, the losses in both power electronic converters can also be reduced, compared to the previous system, where the converter handles the entire power [7]. Bidirectional power flow is also achievable, providing sub-synchronous and sup-synchronous operation, depending on the wind speed. However, the existence of a heavy and bulky DC-link capacitor increases global costs and reduces the global lifetime of the system [9].

With an increasing penetration of wind power in electrical power systems, grid operators have modified grid codes to guarantee the reliable operation of the electrical system [10]. Therefore, it is indispensable to study the behavior of wind farms in the presence of disturbances in the network, particularly for voltages dips. A voltage dip is known as a sudden voltage reduction in one or more than one phases. According to Standard EN50160, this drop occurs in a range of 10% to 90% of the rated or declared voltage, by a period between 10 ms and 60 s. In Figure 1.7 is represented the voltage sag that wind generation systems have to support, according to the Portuguese grid operator requirements.
Faults in electrical power systems mostly occur due to natural phenomena such as lightning, storms and in a smaller extent to birds and technical reasons.

In three-phase power systems there are four different types of short-circuit faults: single-phase-to-ground (1Ø), two-phase-to-ground (2Ø), three-phase-to-ground (3Ø) and phase-to-phase (ØØ). Fault types 1Ø, 2Ø and ØØ result in asymmetrical voltage dips, where the voltage magnitude of the three phases is not the same (and/or the phase difference between successive phases is not 120º) [12].

It is therefore worldwide recognized that to enable large-scale application of wind energy without compromising system stability, the turbines should stay connected to the grid in case of a failure. This behavior is called “Low Voltage Ride Through” (LVRT). Additionally, as in conventional power plants, they should supply active and reactive power for frequency and voltage support immediately after the fault has been cleared, which is generally within a fraction of a second [13]. In Portugal, the curve requested for the reactive power supply is defined by ERSE (Entidade Reguladora dos Serviços Energéticos) and DGEG (Direcção Geral de Energia e Geologia) regulations.

Wind farms using squirrel cage induction generators directly connected to the network usually are disconnected from the power system during a grid fault, as they have neither direct nor speed control of the torque [14]. On the other hand, despite being widely used all over the world, the DFIG configuration is very sensitive to grid disturbances, particularly to voltage dips, since the stator terminals are directly connected to the grid. An abrupt voltage drop can result in overvoltages or overcurrents in the rotor windings and common DC-link, which may destroy the rotor-side converter (in case of no protection measures are taken) [15].

A variable speed turbine requires power electronic converters as an interface in the connection to the grid. In the event of grid disturbances, FACTS (Flexible AC Transmission Systems), can control the active and/or reactive power at the point of common coupling with the network. To compensate
voltage dips with a specific profile, the most commonly used FACTS are mainly the STATCOM (Static Synchronous Compensator) and the DVR (Dynamic Voltage Restorer) [16].

The STATCOM is a power electronic based device, connected to the power system through a filter in a shunt connection and, usually, a coupling transformer. Regarding voltage dips, it injects a compensating current that does not depend on the voltage level of the connecting point [14].

The operation principle of a DVR is to inject a voltage that, summed with the grid voltage, mitigates the dip to maintain the load supply voltage at its rated value. Normally, stored energy by batteries or capacitors is used to supply the delivered power [17].

The implementation of the LVRT ability adopted in this work refers to a protection scheme called crowbar, an alternative to the power electronic referred above. This hardware is based on a crowbar resistor, an IGBT switch and a three-phase diode rectifier, as shown in Figure 1.8. With this configuration, the RSC is disconnected from the rotor and its over-currents will flow through a by-pass established by the crowbar protection. The occurrence of a voltage dip triggers the IGBT switch, creating this supplementary path.

![Figure 1.8 - Wind turbine equipped with an active crowbar](image)

**1.2. Objectives**

The primary goal of this thesis is to evaluate the LVRT capability of a wind generation system equipped with a DFIG. In this topology, the stator of the generator is directly connected to the grid. The rotor is connected to the grid through two Voltage Sorce Converters (VSCs) in a back-to-back arrangement.

For specific voltage dips the system must stay connected to the grid and guarantee the reactive power support, according to system operators’ legislation. For the wind turbine to stay connected to the grid without exceeding the system ratings during faults, an active crowbar protection is implemented. The behavior of the wind turbine under these circumstances is analyzed, as well as the operation limit the system can abide.
1.3. Thesis Outline

This thesis is organized in six chapters.

In the first chapter is presented the context of the thesis, its objectives, as well as its organization.

Chapter 2 introduces the wind turbine components, and its model based on power equations and the MPPT analysis. Furthermore, the detailed model of the DFIG used in this work is also presented.

The third chapter presents the VSCs in a back-to-back arrangement. For both RSC and GSC the state-space vector representation is presented and their contribution to the system is explained.

In chapter 4, the controllers for the whole system are designed. The Field Orientation Control (FOC) is used in the DFIG in order to control both torque (active power) and reactive power and a speed controller is used to guarantee the MPPT. Moreover, non-linear current controllers are designed for the RSC and GSC, and a linear controller is designed for the DC-link voltage. Finally, to guarantee the system operation under a voltage dip in the grid, new controllers are designed.

In Chapter 5, simulations in a normal operation are reported, regarding several important variables and measures. For a voltage dip operation both results with and without the crowbar protection are presented and compared.

The sixth chapter includes the conclusions of the developed dissertation and suggestions for future work.
2. Wind turbine

The worldwide concern about the increasing concentration of atmospheric gases (produced by the burn of fossil fuel in conventional electricity generation systems) has resulted in the growth of interest in technologies for generation of renewable electrical energy [18]. Therefore, with such a trend towards the diversification of the energy market, wind power is one of the most sustainable and promising renewable energy resources [19].

Wind turbines convert wind kinetic energy of the air flow into mechanical energy and finally into electrical energy. The mechanical energy available is converted into electrical energy through a synchronous or asynchronous generator. Nowadays, wind turbines energy systems are mostly based on doubly-fed induction generators, an asynchronous generator, as this configuration allows the use of converters directly connected to the rotor of the induction machine. In fact, the rotor only processes 20-30% of the system rated power, which enables a significant reduction of power converters size and cost, comparing to full rated power converter systems [18].

2.1. Wind turbine components

A single wind turbine is primarily constituted by a rotor, a nacelle (mainly with a gearbox and a generator) and a tower, as shown in Figure 2.1.

![Figure 2.1 - General configuration of a wind turbine](image)
• **Rotor:**

The rotor blades’ performance is based on the technology implemented on airplanes wings. Even though airplane wings are designed to operate in traction, rotor blades are designed to perform in rotation [20]. These components convert the kinetic energy from the wind into mechanical energy available in the generator shaft.

There are two possible arrangements for the position of the rotor relatively to the tower:

- Upwind: the rotor is allocated upstream in order to avoid the wind shade behind the tower. This possibility is used by most part of wind turbines;
- Downwind: the rotor is installed downstream from the tower, enabling an auto-alignment regarding the wind direction. This configuration has been discontinued as the tower disrupts the wind flow before it reaches the rotor blades.

One main characteristic of the rotor blades is to limit the available power to avoid damaging the wind turbine. This control is achieved by using different technologies [21]:

- Pitching mechanism: variation of the blade angle to control the rotor torque and power from the wind side, and at the same time provide power and speed limitation at high wind velocities;
- Stall mechanism: rigid blade position to provide air flow break-off after a certain wind speed in order to provide aerodynamic loss.

• **Nacelle**

The nacelle is the cabin where the main shaft, brake, gearbox, generator, yaw mechanism, hydraulics system and other equipments are located [20].

The main shaft operates at low rotational speed and transfers the wind turbine torque to the gearbox. With this equipment, it is possible to couple the low-speed shaft of the turbine (Figure 2.1) to the required rotational speed of the generator, in order to produce electricity.

The brake system is triggered in the occurrence of a failure in the aerodynamic brake mechanism (related to the rotor blades’ angle). It is also used at the time of maintenance.

It is vital for the wind turbine to be aligned to the wind direction in order to extract the maximum power available. This feature is granted to the yaw mechanism.

• **Tower**

The tower supports the nacelle and elevates the rotor to a height where the wind speed is higher and less unsettling than the speed at ground level. Most manufacturers use tubular towers, built with steel and cement. This type of infrastructure is safer for maintenance, as it provides an interior staircase for accessing the nacelle [20].
2.2. Wind Power

The available kinetic energy of the wind, $E_{cin}$, depends on the air volume moving across the blades area at uniform and constant speed, $u$ (m/s).

$$E_{cin} = \frac{1}{2} m u^2$$  \hspace{1cm} (2.1)

The mass of air available per second depends on the wind speed, $u$ (m/s), the area swept by the wind turbine, $A$ (m$^2$), and the air density, $\rho$ (kg/m$^3$), which has the value of $\rho = 1.225$ (kg/m$^3$) at the temperature of 15 °C. Thus, and considering $m = \rho A u$, the available power in the swept area depends on the cube of the wind speed and it is given by (2.2):

$$P_{av} = \frac{d}{dt}(E_{cin}) = \frac{1}{2} \rho A u^3$$  \hspace{1cm} (2.2)

It is important to notice that the power calculated in (2.2) is highly dependent on the wind speed. Therefore, the wind turbines location is critical to the economic success of a wind energy project.

The available power in (2.2) is not totally converted into mechanical power in the turbine main shaft because there is still some air flow exiting the turbine blades with speed different from zero. Hence, the theoretical maximum for the efficiency of power extraction from the wind is known as the Betz limit, which has a value of $16/27 \approx 59.3\%$ of the power in the swept area, $A$. This value results in the application of fluid mechanics concepts [20]. The wind turbine power coefficient, which quantifies the efficiency of power extraction, is defined as $C_{pm}$ (2.3):

$$C_{pm} = \frac{P_m}{P_{av}}$$  \hspace{1cm} (2.3)

Where $P_m$ is the mechanical power available in the main shaft of the turbine. Modern wind turbines are only able to convert 50% of the available power, representing more than 80% of the Betz limit.

The efficiency of the generator is often given by wind turbine producers in $C_p$:

$$C_p = \frac{P_e}{P_{av}}$$  \hspace{1cm} (2.4)

From (2.2) and (2.4) it is possible to calculate the electrical power, $P_e$:

$$P_e = \frac{1}{2} C_p A \rho u^3$$  \hspace{1cm} (2.5)

The tip speed ratio, $\lambda$, relates the tip linear velocity (m/s) of a blade with its radius $R$ (m), spinning with an angular speed of $\omega_T$ (rad/s), with the wind speed $u$ (m/s) and it is given by (2.6):

$$\lambda = \frac{\omega_T R}{u}$$  \hspace{1cm} (2.6)
The calculation of $C_p$ involves the values of $\lambda$ and the pitch angle ($\beta$), according to the expression given in (2.7):

$$C_p(\lambda, \beta) = 0.22 \left( \frac{116}{\lambda_i} - 0.4\beta - 5.0 \right) e^{\left( \frac{-12.5}{\lambda_i} \right)}$$  \hspace{1cm} (2.7)

Where:

$$\lambda_i = \frac{1}{\lambda + 0.08\beta - 0.035 \beta^3 + 1}$$  \hspace{1cm} (2.8)

It is assumed that the pitch angle of the wind turbine blades, $\beta$, is considered zero.

According to (2.2) and (2.4), the electrical power is given by (2.9):

$$P_e = \frac{1}{2} C_p(\lambda, \beta) A \rho u^3$$  \hspace{1cm} (2.9)

The angular speed of the generator’s rotor, $\omega_m$ (rad/s), is defined by (2.10):

$$\omega_m = G \omega_T$$  \hspace{1cm} (2.10)

Where $G$ is the gain of the gearbox ratio, given in (2.12), and $\omega_T$ (rad/s) is the angular speed of the turbine.

The mechanical torque extracted from the turbine rotor, $T_m$ (Nm), is given by (2.11).

$$T_m = \frac{P_e}{\omega_m}$$  \hspace{1cm} (2.11)

The gain of the gearbox ratio relates the angular speeds and the torque. These relationships are given by (2.12), where $T_g$ (Nm) is the mechanical torque of the generator.

$$G = \frac{\omega_m}{\omega_T} = \frac{T_m}{T_g}$$  \hspace{1cm} (2.12)

From (2.8), (2.9) and (2.10), the mechanical torque used is calculated by (2.13):

$$T_m = \frac{1}{2} A \rho u^3 \frac{0.22}{G \omega_T} \left( \frac{116}{u} - 1 \right) e^{\left( \frac{-12.5}{u} \right)} \left( \frac{u}{\omega_T R} - 0.035 \right)$$  \hspace{1cm} (2.13)
2.3. Maximum Power given by the MPPT

Despite its major advantages, wind energy presents an unpredictable nature. As a result, the electrical power produced often changes significantly due to rapid variation of wind speed. Therefore, the maximum power extraction out of wind energy is urgent and necessary to make wind energy systems more effective and viable [22].

At very low wind speeds, there is insufficient torque held by the wind on the turbine blades to make them rotate. Also, the power extracted at this speed will not compensate the mechanical wear in the system. However, as the speed increases, the wind turbine begins to rotate and generate electrical power. The minimum speed at which the turbine blades overcome friction and begin to rotate is called the cut-in speed, \( u_0 \). As the wind speed rises above this threshold, the produced electrical power follows the trend in Figure 2.2. At rated output wind speed, \( u_N \), the output power reaches the limit that the electrical generator is capable of: the rated output power. At higher wind speeds, the turbine aerodynamic control adjusts the blades angles to limit the power to this maximum level, between \( u_N \) and \( u_{\text{max}} \), maintaining the rated output power.

![Figure 2.2 - Wind turbine output power with steady wind speed](image)

Finally, for values of wind speed above \( u_N \), the forces applied on the turbine structure intensify and, at some point, there is a risk of damaging the rotor and all components directly attached to it. Thus, a braking system is employed to bring the rotor to rest. This is called the cut-out speed, \( u_{\text{max}} \).

Consequently, it is possible to define two control strategies given the wind speed: a tracking point of the maximum power between \( u_0 \) and \( u_N \) and a pitch control that performs for wind speeds higher than \( u_N \).

To follow the maximum power point two approaches are used:

- Torque control: control of the mechanical torque given a reference value established by the MPPT, which is dependent of the wind speed;
- Speed control: control of the generator speed, according to an optimum value based on each wind speed.
In this thesis the speed control is employed between \( u_o \) and \( u_n \). The optimum turbine speed, \( \omega_{\text{Topt}} \), is calculated for each wind speed. Based on equation (2.9), the electrical power extracted in this region is given by (2.14):

\[
P_e = \frac{1}{2} A \rho u^3 0.22 \left( \frac{1}{\frac{\omega R}{u} + 0.08\beta - 0.035\beta^3 + 1} \right)^{-1} - 0.4\beta - 5 - \frac{12.5}{\left( \frac{\omega R}{u} + 0.08\beta - 0.035\beta^3 + 1 \right)}
\]

(2.14)

The pitch angle is assumed to be zero (\( \beta = 0^\circ \)) to maximize \( C_p \). As the electrical power is proportional to \( C_p \) in (2.9), the value of \( \omega_{\text{Topt}} \) leads to maximum values of the power obtained from (2.14). Those values are to be calculated by equalizing its derivative to zero, as shown in (2.15).

\[
\frac{dP_e}{d\omega_T} = 0
\]

(2.15)

From (2.14) and (2.15) the optimum turbine speed is given by (2.16):

\[
\omega_{\text{Topt}} = \frac{6.32497}{R} u
\]

(2.16)

As a result of the combination of (2.12) with (2.16), the corresponding generator speed is also optimal, \( \omega_{\text{m,ref}} \) (2.17), and dependent on the gain of the gearbox.

\[
\omega_{\text{m,ref}} = \omega_{\text{Topt}} G = \left( \frac{6.32497}{R} u \right) G
\]

(2.17)

To control the turbine speed, it is mandatory to design a speed controller able to track the maximum power point. This controller will be designed in Chapter 4.

### 2.4. Modelling of the Doubly-Fed Induction Generator

The doubly-fed induction generator is currently the system of choice for multi-MW wind turbines, as it has become the most attractive technology for this generation systems. The generator’s rotor must be able to operate at variable rotational speed to reach optimum aerodynamic efficiency. The DFIG system enables the operation in both sub-synchronous and sup-synchronous modes with a rotor range around the synchronous speed [7]. Since this wound-rotor asynchronous generator has two independent active winding sets, it allows the extraction of energy from the stator and from the rotor of the machine. The stator is directly connected to the grid, as shown in Figure 1.6, while the rotor winding is connected to the grid through a back-to-back converter (AC/DC - DC/AC). The fact that both stator and rotor are connected to electrical sources establishes the term “doubly-fed”.

The main advantage of using the power electronic converter connected to the rotor is that the converter only needs to be rated to handle a fraction of the nominal generator power, typically about 20-
30%. Therefore, the losses in the back-to-back converter can be reduced and the system cost and size are smaller due to the partially rated power electronics.

The three-phase induction machine has three stator and rotor windings displaced 120° from each other. Taking into account an induction machine with one pair of poles, the changing position of the rotor relatively to the stator, shown in Figure 2.3, is quantified by the rotor angular speed, $\Theta$ [24].

![Figure 2.3 - Stator and rotor relative position imposed by $\Theta$](image)

The generator dynamic performance can be expressed by the simplified equation (2.18), relating the matrices of the output voltage $V$, currents and fluxes from both stator and rotor ($I$ and $\Psi$, respectively), and by the equilibrium between the electromagnetic torque, $T_{em}$, and the load torque, $T_c$, (2.21) [24].

$$V = R_m I + \frac{d\Psi}{dt}$$  \hspace{1cm} (2.18)

Where $\Psi$ is the matrix of the machine flux and it is given by (2.19).

$$\Psi = L I$$  \hspace{1cm} (2.19)

According to (2.19), the matrix of the output voltages $V$ can be rewritten to (2.20).

$$V = R_m I + L \frac{dI}{dt} + \frac{\partial L}{\partial \Theta} \omega_m I$$  \hspace{1cm} (2.20)

The turbine rotates at a speed that obeys Newton’s second law (2.21). The load torque, $T_c$, is a mechanical torque produced by the interaction of the wind with the turbine blades.

$$J \frac{d\omega_m}{dt} = T_{em} - T_c$$  \hspace{1cm} (2.21)
The magnetic co-energy is given by (2.22).

$$W_m^c = \frac{1}{2} I^T L I$$

(2.22)

Thus, the electromagnetic torque is written by (2.23).

$$T_{em} = \frac{\partial W_m^c}{\partial \Theta} = \frac{\partial}{\partial \Theta} \left( \frac{1}{2} I^T L I \right) = \frac{1}{2} I^T \frac{\partial L}{\partial \Theta} I$$

(2.23)

The inductance and resistance coefficients are part of the machine model. The inductance values are included in the matrix $L$ (2.24), composed by four sub-matrices:

$$L = \begin{bmatrix} L_s & M_s \\ M_r & L_r \end{bmatrix}$$

(2.24)

- **Stator self-inductance coefficients (2.25):**

$$L_s = \begin{bmatrix} L_s & \frac{1}{2} M_s & \frac{1}{2} M_s \\ \frac{1}{2} M_s & L_s & \frac{1}{2} M_s \\ \frac{1}{2} M_s & \frac{1}{2} M_s & L_s \end{bmatrix}$$

(2.25)

- **Stator mutual inductance coefficients (2.26):**

$$M_s = \begin{bmatrix} M \cos(\Theta) & M \cos(\Theta + \frac{2\pi}{3}) & M \cos(\Theta + \frac{4\pi}{3}) \\ M \cos(\Theta + \frac{2\pi}{3}) & M \cos(\Theta) & M \cos(\Theta + \frac{4\pi}{3}) \\ M \cos(\Theta + \frac{4\pi}{3}) & M \cos(\Theta + \frac{2\pi}{3}) & M \cos(\Theta) \end{bmatrix}$$

(2.26)

- **Rotor self-inductance coefficients (2.27):**

$$L_r = \begin{bmatrix} L_r & \frac{1}{2} M_r & \frac{1}{2} M_r \\ \frac{1}{2} M_r & L_r & \frac{1}{2} M_r \\ \frac{1}{2} M_r & \frac{1}{2} M_r & L_r \end{bmatrix}$$

(2.27)

- **Rotor mutual inductance coefficients (2.28):**

$$M_r = \begin{bmatrix} M \cos(\Theta) & M \cos(\Theta + \frac{4\pi}{3}) & M \cos(\Theta + \frac{2\pi}{3}) \\ M \cos(\Theta + \frac{4\pi}{3}) & M \cos(\Theta) & M \cos(\Theta + \frac{2\pi}{3}) \\ M \cos(\Theta + \frac{2\pi}{3}) & M \cos(\Theta + \frac{4\pi}{3}) & M \cos(\Theta) \end{bmatrix}$$

(2.28)
The windings resistance matrix, $R_m$, is given by (2.29):

$$R_m = \begin{bmatrix}
  r_s & 0 & 0 & 0 & 0 \\
  0 & r_s & 0 & 0 & 0 \\
  0 & 0 & r_s & 0 & 0 \\
  0 & 0 & 0 & r_r & 0 \\
  0 & 0 & 0 & 0 & r_r
\end{bmatrix}$$ (2.29)

The model of the machine equations can be represented in an orthogonal reference frame, using Concordia transformation (2.30). This transformation allows the representation of a three-phase system (abc coordinates) as an orthogonal bi-phase system ($\alpha\beta0$ coordinates).

$$C = \frac{1}{\sqrt{3}} \begin{bmatrix}
  1 & 0 & \frac{1}{\sqrt{2}} \\
  \frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \\
  \frac{1}{2} & \frac{\sqrt{3}}{2} & -\frac{1}{\sqrt{2}}
\end{bmatrix}$$ (2.30)

The voltages and currents can be calculated in the $\alpha\beta$ frame using the transpose of matrix $C$.

$$\begin{bmatrix}
  \alpha \\
  \beta \\
  0
\end{bmatrix} = C^T \begin{bmatrix}
  a \\
  b \\
  c
\end{bmatrix}$$ (2.31)

Assuming the homopolar component is null (in a balanced three-phase system the sum of the three-phase voltages and currents is zero), the result of the Concordia transformation is a bi-phase orthogonal reference frame with $\alpha\beta$ coordinates (2.32).

$$\begin{bmatrix}
  a \\
  b \\
  c
\end{bmatrix} = \frac{2}{\sqrt{3}} \begin{bmatrix}
  1 & \frac{1}{\sqrt{3}} & \frac{1}{2} \\
  \frac{1}{2} & \frac{2}{\sqrt{3}} & \frac{1}{2} \\
  \frac{1}{2} & \frac{2}{\sqrt{3}} & \frac{1}{2}
\end{bmatrix} \begin{bmatrix}
  \alpha \\
  \beta
\end{bmatrix}$$ (2.32)

The inductances’ position in $\alpha\beta$ coordinates depends on the angular position of the rotor, $\Theta$ [24]. So, the application of Park transformation ($dq$ coordinates) results in a system that depends on $\Phi$ (the displacement between $\alpha\beta$ and $dq$ reference frames), although both reference frames have the same origin, represented in Figure 2.4.
In addition, the bi-phase system in dq coordinates is synchronized with the grid voltages ($\Phi = \omega t$). Thus, the Park transformation matrix is given by (2.33).

$$P = \begin{bmatrix} \cos \Phi & -\sin \Phi \\ \sin \Phi & \cos \Phi \end{bmatrix}$$ \hfill (2.33)

$$\begin{bmatrix} d \\ q \end{bmatrix} = P^T \begin{bmatrix} \alpha \\ \beta \end{bmatrix}$$ \hfill (2.34)

From the combination of the Concordia and Park transformations results the Blondel-Park transformation matrix, given by (2.35).

$$T = \frac{2}{\sqrt{3}} \begin{bmatrix} \cos \Phi & -\sin \Phi & \frac{1}{\sqrt{2}} \\ \cos \left(\Phi - \frac{2\pi}{3}\right) & \sin \left(\Phi - \frac{2\pi}{3}\right) & \frac{1}{\sqrt{2}} \\ \cos \left(\Phi - \frac{4\pi}{3}\right) & \sin \left(\Phi - \frac{4\pi}{3}\right) & \frac{1}{\sqrt{2}} \end{bmatrix}$$ \hfill (2.35)

$$\begin{bmatrix} d \\ q \end{bmatrix} = T^T \begin{bmatrix} a \\ b \\ c \end{bmatrix}$$ \hfill (2.36)

As with the Concordia matrix (2.30), the Blondel-Park transformation is also represented by an orthogonal matrix, as it expresses the product of two orthogonal matrices.

The equations of the DFIG dynamics in dq coordinates (2.37) can be obtained by applying the Blondel-Park transformation to the induction machine equations.
\[
\begin{align*}
\begin{cases}
    u_{sd} &= r_s i_{sd} + \frac{d\psi_{sd}}{dt} - \omega_{dq} \psi_{sq} \\
    u_{sq} &= r_s i_{sq} + \frac{d\psi_{sq}}{dt} + \omega_{dq} \psi_{sd} \\
    u_{rd} &= r_r i_{rd} + \frac{d\psi_{rd}}{dt} - (\omega_{dq} - n_{pp} \omega_m) \psi_{rq} \\
    u_{rq} &= r_r i_{rq} + \frac{d\psi_{rq}}{dt} + (\omega_{dq} - n_{pp} \omega_m) \psi_{rd}
\end{cases}
\end{align*}
\] (2.37)

The relation between the linkage fluxes and the currents is given by matrix \( X \) (2.38).

\[
X = \begin{bmatrix}
L_s & 0 & M & 0 \\
0 & L_s & 0 & M \\
M & 0 & L_r & 0 \\
0 & M & 0 & L_r
\end{bmatrix}
\] (2.38)

\[
\begin{bmatrix}
\psi_{sd} \\
\psi_{sq} \\
\psi_{rd} \\
\psi_{rq}
\end{bmatrix} = X \begin{bmatrix}
i_{sd} \\
i_{sq} \\
i_{rd} \\
i_{rq}
\end{bmatrix}
\] (2.39)

The electromagnetic torque is a function of the number of pair of poles, linkage fluxes and currents:

\[
T_{em} = n_{pp} \left( i_{sq} \psi_{sd} - i_{sd} \psi_{sq} \right)
\] (2.40)
3. Back-to-back Converter

Nowadays, power electronics have become a crucial technology for the energy development conservation, particularly for renewable energy. Power electronic converters use power semiconductor devices and circuits combined with control systems designed to meet stipulated requirements [26].

In the case of wind energy, converters are used to match the characteristics of wind turbines with the requirements of grid connections, including frequency, voltage, control of active and reactive power, harmonics, among others.

3.1. Introduction

Power converters have been used for a widespread range of applications, mainly for transportation (electric/hybrid vehicles, electric locomotives and trucks), utilities (line transformers, generating systems, grid interfaces for alternative energy resources such as wind turbines, solar panels, and fuel cells, energy storage, battery chargers) and industry/commerce (motor drive systems, electric machinery and tools, factory automation process control) [26].

AC/AC power electronic converters fall into two categories: direct power conversion, with only one conversion stage - AC/AC - and indirect power conversion, with two stages - AC/DC and DC/AC. Both categories are shown in Figure 3.1.

![Figure 3.1 - Topologies for AC/AC power electronics: (a) Matrix converter with one conversion level; (b) Back-to-back converter with two conversion levels and a common DC-link](image)

With the first configuration rises the potential for significant size and weight reductions in its applications, as the matrix converter lacks (almost totally) energy storage elements, such as DC-link capacitors [9].
An indirect power conversion requires an AC/DC and a DC/AC converter both connected through a common DC-link. In this work two VSCs are used, one directly connected to the rotor of the generator and the other to the grid.

Two major advantages of the back-to-back converter topology are the following:

- The rated power of both converters needs only to be around 20-30% of the total power. For this reason, the total cost of the system can be reduced. Therefore, the losses in both power electronic converters can also be lowered, compared to the topology where the converter is connected directly in line with the generator;
- The RSC and the GSC allow a bidirectional power flow. This dual operation is reflected in handling the slip power in both directions: in a sup-synchronous operation ($\omega_r > \omega_s$), the power flows from the stator and rotor to the grid. In this case, the rotor side converter operates as a rectifier and the grid side converter as an inverter. In a sub-synchronous operation ($\omega_r < \omega_s$) there is absorption of power from the grid to provide excitation for the rotor windings, where the RSC acts as an inverter and the GSC as a rectifier.

Furthermore, the DC-link between the two converters keeps the voltage ripple controlled and enables the decoupling of both converters control.

However, this arrangement has its own disadvantages. Firstly, the presence of a heavy and bulky DC-link capacitor increases the costs and reduces the overall lifetime of the system. Secondly, due to the presence of two VSCs, the switching losses associated to each leg of both converters increase.

### 3.2. Rotor Side Converter

This converter is designed to have three legs, each with two groups of semiconductors (IGBT + anti-parallel diode), as shown in Figure 3.2.

![Figure 3.2 - Rotor side converter representation](image)

Due to topological constraints, the two semiconductors in the same leg must be at complementary states, otherwise a short-circuit through the leg could occur. The states of each semiconductor in the same leg $k$ ($k = A, B, C$) can be represented by a function $\gamma_k$, defined by (3.1):
\[
\gamma_k = \begin{cases} 
1 & \rightarrow S_{1k} \text{ is ON and } S_{2k} \text{ is OFF} \\
0 & \rightarrow S_{1k} \text{ is OFF and } S_{2k} \text{ is ON} 
\end{cases}
\]  

(3.1)

Depending on the values of \( \gamma_k \), the output voltages of the converter can only be expressed by 2\(^3\) operational states [27]. Each operational state is represented by a state-space vector in the \( \alpha\beta \) orthogonal frame (Figure 3.3), using Concordia transformation (2.30). In Table 3.1 are listed all state-space vectors and the corresponding output voltages.

Table 3.1 - RSC state-space vectors and corresponding output voltages

<table>
<thead>
<tr>
<th>Vector</th>
<th>( \gamma_A )</th>
<th>( \gamma_B )</th>
<th>( \gamma_C )</th>
<th>( V_{AB} )</th>
<th>( V_{BC} )</th>
<th>( V_{CA} )</th>
<th>( V_\alpha )</th>
<th>( V_\beta )</th>
</tr>
</thead>
<tbody>
<tr>
<td>V0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>V1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>( U_{DC} )</td>
<td>0</td>
<td>0</td>
<td>( -\sqrt{2}/3 U_{DC} )</td>
<td>0</td>
</tr>
<tr>
<td>V2</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>( U_{DC} )</td>
<td>0</td>
<td>( U_{DC}/\sqrt{6} )</td>
<td>( U_{DC}/\sqrt{2} )</td>
</tr>
<tr>
<td>V3</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>( -U_{DC} )</td>
<td>( U_{DC} )</td>
<td>0</td>
<td>( -\sqrt{2}/3 U_{DC} )</td>
<td>0</td>
</tr>
<tr>
<td>V4</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>( -U_{DC} )</td>
<td>( U_{DC} )</td>
<td>0</td>
<td>( U_{DC}/\sqrt{6} )</td>
<td>( -U_{DC}/\sqrt{2} )</td>
</tr>
<tr>
<td>V5</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>( U_{DC} )</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>( 0 )</td>
</tr>
<tr>
<td>V6</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>( 0 )</td>
<td>( U_{DC}/\sqrt{2} )</td>
</tr>
<tr>
<td>V7</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>( 0 )</td>
<td>( 0 )</td>
</tr>
</tbody>
</table>

Figure 3.3 - RSC state-space vectors location on the \( \alpha\beta \) frame

The output voltages of this converter are directly applied to the rotor windings of the DFIG. In the analysis, it is considered a balanced system with \( V_A', \ V_B' \) and \( V_C' \) according to (3.2) and Figure 3.4.
With the rotor side converter, it is possible to control the current flowing in the stator to adjust torque and, consequently, the rotating speed. Analyzed in Chapter 4, the rotor flux position is optimally oriented with respect to the stator flux. This control will contribute to the active power balance in normal operation when extracting the maximum power from the wind turbine. Lastly, this converter should be able to handle variable frequencies, depending on the wind speed, and voltage amplitude of the generator to control the speed.

3.3. Grid Side Converter

This power converter, as well as the RSC, is designed to have three legs, each with two groups of semiconductors (IGBT + anti-parallel diode). Its scheme is represented in Figure 3.5.
Due to topological constraints, both semiconductors in the same leg must be at complementary states, otherwise a short-circuit through the leg could occur. The states of each semiconductor device in the same leg $k$ (k = A, B, C) can be represented by a function $\gamma_k$, as in the RSC (3.1).

Depending on the values of $\gamma_k$, the output voltages of the converter can only be expressed by $2^3$ operational states, each one corresponding to a different state-space vector. As the GSC converts power in a opposite way from the RSC, it generates Table 3.2, where each state-space vector and the respective output voltages are listed.

<table>
<thead>
<tr>
<th>Vector</th>
<th>$\gamma_A$</th>
<th>$\gamma_B$</th>
<th>$\gamma_C$</th>
<th>$V_{AB}$</th>
<th>$V_{BC}$</th>
<th>$V_{CA}$</th>
<th>$V_\alpha$</th>
<th>$V_\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>V0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>V1</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>- $U_{DC}$</td>
<td>0</td>
<td>$U_{DC}$</td>
<td>$-\frac{2}{3} U_{DC}$</td>
<td>0</td>
</tr>
<tr>
<td>V2</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>- $U_{DC}$</td>
<td>$U_{DC}$</td>
<td>$-\frac{U_{DC}}{\sqrt{6}}$</td>
<td>$-\frac{U_{DC}}{\sqrt{2}}$</td>
</tr>
<tr>
<td>V3</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>$U_{DC}$</td>
<td>- $U_{DC}$</td>
<td>$U_{DC}$</td>
<td>$\frac{U_{DC}}{\sqrt{6}}$</td>
<td>$-\frac{U_{DC}}{\sqrt{2}}$</td>
</tr>
<tr>
<td>V4</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>$U_{DC}$</td>
<td>0</td>
<td>- $U_{DC}$</td>
<td>$\frac{2}{3} U_{DC}$</td>
<td>0</td>
</tr>
<tr>
<td>V5</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>$U_{DC}$</td>
<td>- $U_{DC}$</td>
<td>$\frac{U_{DC}}{\sqrt{6}}$</td>
<td>$\frac{U_{DC}}{\sqrt{2}}$</td>
</tr>
<tr>
<td>V6</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>- $U_{DC}$</td>
<td>$U_{DC}$</td>
<td>0</td>
<td>$-\frac{U_{DC}}{\sqrt{6}}$</td>
<td>$\frac{U_{DC}}{\sqrt{2}}$</td>
</tr>
<tr>
<td>V7</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

In terms of state-space vectors location, their disposition is also reversed from the RSC, as shown in Figure 3.6.
The grid side converter aims to maintain the DC-link voltage at a constant level, regardless the wind speed. Furthermore, this converter operates at the grid frequency and must comply with its codes, meaning it should have the ability to control reactive power, by absorbing or injecting it in the grid.
4. System Control

In this chapter it is designed the generator speed controller, the currents non-linear control with state-space vectors both for RSC and GSC, and the DC-link voltage controller. Then, the system performance is assessed in the presence of a voltage sag.

4.1. Control of the Doubly-Fed Induction Generator

The concept of field orientation (or vector) control of an induction motor drive system is based on the decoupled torque and flux control in AC motors. This technique is assumed in this project.

In a wind power generating system, control schemes for the doubly-excited induction machine are expected to achieve the following objectives: 1) The generator is required to track a given torque-speed curve, for MPPT; 2) The stator output voltage frequency and voltage must be constant; 3) Flexible reactive power control is achievable.

The stator field orientation control is based on the stator flux dq model, where the reference frame rotates synchronously with respect to the stator linkage flux, with its d-axis overlapping the instantaneous axis of the stator flux. Therefore, the rotating speed of the dq reference frame, \( \omega_{dq} \), is equal to the angular frequency of the stator voltage, \( \omega \), and the q-component of the flux, \( \Psi_{sq} \), is zero. As a result, the system equations in (2.37) are reduced to the following:

\[
\begin{align*}
\begin{cases}
    u_{sd} &= r_{sd} i_{sd} + \frac{d\Psi_{sd}}{dt} \\
    \Psi_{sd} &= L_{s} i_{sd} + M i_{rd}
\end{cases}
\end{align*}
\] (4.1)

\[
\begin{align*}
    u_{sq} &= r_{sq} i_{sq} + \omega \Psi_{sd} \\
    \Psi_{sq} &= 0 = L_{s} i_{sq} + M i_{rq}
\end{align*}
\] (4.2)

The electromagnetic torque presented in (2.40) is now given by (4.3):

\[
    T_{em} = n_{pp} i_{sq} \Psi_{sd}
\] (4.3)

The level of the stator flux remains approximately unchanged, as the magnitude and frequency of the stator voltage is constant. Therefore, torque control can be most conveniently achieved by controlling the rotor current component orthogonal to the stator flux. Given \( \Psi_{sq} \) in (4.2), the electromagnetic torque can be written according to (4.4), regarding the \( i_{rq} \).

\[
    T_{em} = n_{pp} \Psi_{sd} \left( \frac{M}{L_{s}} i_{rq} \right)
\] (4.4)

The d-component of the stator voltage in (4.1) can be simplified to (4.5) and the q-component to (4.6) by neglecting the stator resistance. This procedure can be adopted to large power generators, since the resistance is much smaller than the stator reactance \( (r_{s} \ll \omega L_{s}) \) [28].

\[
    u_{sd} \approx \frac{d\Psi_{sd}}{dt}
\] (4.5)
The application of the integration rules allows the calculation of the stator flux $\Psi_{sd}$ magnitude, resulting in (4.7).

$$u_{sq} = \omega \Psi_{sd}$$  \hspace{1cm} (4.6)

$$\Psi_{sd} = \frac{\sqrt{3}}{\omega} V_{ef}$$  \hspace{1cm} (4.7)

As the stator flux is a constant, both (4.5) and (4.6) can be rewritten.

$$u_{sd} = 0$$  \hspace{1cm} (4.8)

$$u_{sq} = \sqrt{3} V_{ef}$$  \hspace{1cm} (4.9)

The $q$-component of the rotor current (4.10) can be obtained considering the electromagnetic torque (4.4) and the stator flux (4.7).

$$i_{rq} = -\frac{\omega L_s}{n_{pp} M \sqrt{3} V_{ef}} T_{em}$$  \hspace{1cm} (4.10)

The $q$-component of the rotor reference current $i_{rq\_ref}$ (4.11) returns the maximum output power, as it depends on the maximum corresponding torque, $T_{MPPT}$.

$$i_{rq\_ref} = -\frac{\omega L_s}{n_{pp} M \sqrt{3} V_{ef}} T_{MPPT}$$  \hspace{1cm} (4.11)

The reactive power at the terminal of the stator winding is expressed by (4.12):

$$Q_s = (u_{sq} i_{sd} - u_{sd} i_{sq})$$  \hspace{1cm} (4.12)

From (4.6) and (4.8), with the stator flux remaining unchanged, the reactive power is now given by (4.13).

$$Q_s = \omega \Psi_{sd} i_{sd}$$  \hspace{1cm} (4.13)

As indicated in the $d$-component of the stator flux in (4.1), $i_{sd}$ is controllable by $i_{rd}$. Thus, from (4.14), the $d$-component of the rotor current, $i_{rd}$, can be controlled to regulate the reactive power.

$$Q_s = \omega \Psi_{sd} \left( \frac{\Psi_{sd} - M i_{rd}}{L_s} \right)$$  \hspace{1cm} (4.14)

From (4.4) and (4.14), the initial goal of controlling the torque via $i_{rq}$ and controlling the reactive power via $i_{rd}$ (both are essentially decoupled) is accomplished [29].
4.2. Speed controller of the wind turbine

A speed controller is proposed with the aim of tracking the maximum power point. The generator speed is compared with the reference value (2.17) and the resulting error is the input of the compensator. It generates the reference torque that will establish the reference currents for the rotor side converter, in the back-to-back converter. The electromagnetic torque of the generator, \( T_{em} \), will be generated according to these currents. The generator speed, \( \omega_m \), depends on the difference between the electromagnetic torque and the torque generated by the turbine, \( T_m \), according to the wind speed. The block diagram of the speed control system is represented in Figure 4.1 [30].

![Block diagram of the wind turbine speed controller](image)

Figure 4.1 - Block diagram of the wind turbine speed controller

In this model, the back-to-back converter is represented by a first order system, having one pole dependent on the switching period of the semiconductors. The DFIG is also represented as a first order system, with a pole dependent on the system inertia.

The compensator \( C(s) \) choice is done admitting a second order open-loop chain as the transfer function of the system, without any poles at the complex plan origin and with two real poles at \(-1/T_d\) and \(-K_d/J_{total}\). [30].

The system has the mechanical torque generated by the turbine, \( T_m \), as a perturbation and, to guarantee the insensibility of the system to the perturbation, it is necessary to have the generator speed following its reference with a zero static error. Thus, the compensator requires the integral feature. Nevertheless, due to its poles (in closed-loop chain) near the complex plain origin, an integral compensator usually is too slow. A proportional-integral controller (PI) is then used to assure faster time responses:

\[
C(s) = K_p + \frac{K_i}{s} = \frac{1 + sT_z}{sT_p} \tag{4.15}
\]

The transfer function of a second order system has a general form (4.16), where \( \omega_0 \) is the natural frequency of the system and \( \zeta \) the damping factor.

\[
H(s) = \frac{\omega_0^2}{s^2 + 2\zeta\omega_0s + \omega_0^2} \tag{4.16}
\]

In the case of the Figure 4.1, the closed-loop transfer function of the system is given by (4.17).
\[
\frac{\omega_m}{\omega_{m,\text{ref}}} = \frac{1}{s^2 + \frac{1}{T_d} s + \frac{K_d}{T_p K_d T_d}}
\]  

(4.17)

In order to cancel the low frequency pole at \(-K_d/J_{\text{Total}}\), and considering (4.15), \(T_z\) is given by (4.18).

\[
T_z = \frac{J_{\text{Total}}}{K_d}
\]

(4.18)

Comparing the general form at (4.16) with the transfer function (4.17) it is possible to obtain the parameters at (4.19) and (4.20).

\[
\omega_0 = \frac{1}{2\zeta T_d}
\]

(4.19)

\[
T_p = \frac{1}{\omega_0^2 K_d T_d} = \frac{1}{(2\zeta T_d)^2} K_d T_d
\]

(4.20)

The computation of all controller parameters results in Table 4.1.

<table>
<thead>
<tr>
<th>(K_t)</th>
<th>(T_d) [s]</th>
<th>(T_z) [s]</th>
<th>(T_p) [s]</th>
<th>(\zeta)</th>
<th>(K_p)</th>
<th>(K_i)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>(10^{-3})</td>
<td>2.91x10(^3)</td>
<td>40x10(^{-2})</td>
<td>(\sqrt{2}/2)</td>
<td>7.28x10(^4)</td>
<td>25</td>
</tr>
</tbody>
</table>

4.3. Design of currents controllers for both converters

The high commutation frequency of each IGBT allows faster responses times from the system. For the rated power, the semiconductors are switched at 5 kHz. The commutation process is performed in a way that the controlled variables follow the established references, within a minimal margin of error – difference between the reference and the variable to be controlled. An ideal case would be having the error equal to zero for infinite frequencies, which is impossible due to physical limitations of the semiconductors. A solution is to have hysteresis blocks in order to limit the error: as soon as the maximum error (\(\Delta\)) is reached, the controller system selects a vector from Table 3.1 or Table 3.2 to apply, depending on the power converter analyzed. The aim of this selection is to minimize the error, bounding it inside the defined hysteresis boundaries (Figure 4.2).
4.3.1. Rotor Side Converter

The extraction of the maximum power is performed by the MPPT speed controller, where the output $T_{MPPT}$ will dictate the reference currents. The rotor side converter will establish the output currents that will follow the reference.

As for the reference and output currents, both $\alpha$ and $\beta$ components are obtained using Concordia transformation. The resulting error is given by (4.21):

$$\begin{align*}
    e_\alpha &= i_{\alpha,\text{ref}} - i_\alpha \\
    e_\beta &= i_{\beta,\text{ref}} - i_\beta
\end{align*}$$

(4.21)

The sliding surfaces for the $\alpha$ and $\beta$ components are presented in (4.22).

$$\begin{align*}
    S_\alpha(e_\alpha, t) &= k_\alpha (i_{\alpha,\text{ref}} - i_\alpha) \\
    S_\beta(e_\beta, t) &= k_\beta (i_{\beta,\text{ref}} - i_\beta)
\end{align*}$$

(4.22)

The value that results from each three level hysteresis blocks is then applied to the $\alpha$ and $\beta$ commutation surfaces. From Figure 4.3, when the $\alpha$-component is summed with the $\beta$-component, three levels of output are possible: +1, 0 and -1.

![Figure 4.3 - Schematics for both $S_\alpha$ and $S_\beta$ commutation functions](image)
The stability of the system is guaranteed if the condition (4.23) is verified:

$$\begin{align*}
S_a(e_\alpha, t), \dot{S}_a(e_\alpha, t) &< 0 \\
S_\beta(e_\beta, t), \dot{S}_\beta(e_\beta, t) &< 0
\end{align*}$$

(4.23)

Based on the stability criteria from (4.23), the state-space vectors are chosen according to:

- **If** $S_a(e_\alpha, t) > \Delta$, **then** $i_{\alpha, \text{ref}} > i_\alpha$. In this case, the system reaction is to increase the output current $i_\alpha$ and lower $S_a(e_\alpha, t)$. As the commutation function $S_a$ decreases, its derivative $\dot{S}_a(e_\alpha, t)$ starts to present negative values. As $S_a(e_\alpha, t)$ decreases and $\dot{S}_a(e_\alpha, t)$ now has a negative value, the stability condition from (4.23) is verified.

- **If** $S_a(e_\alpha, t) < -\Delta$, **then** $i_{\alpha, \text{ref}} < i_\alpha$. In this case, the system reaction is to decrease the output current $i_\alpha$ and increase $S_a(e_\alpha, t)$. As the commutation function $S_a$ rises, its derivative $\dot{S}_a(e_\alpha, t)$ starts to present positive values. As $S_a(e_\alpha, t)$ increases and $\dot{S}_a(e_\alpha, t)$ now has a positive value, the stability condition from (4.23) is verified.

- **If** $-\Delta < S_a(e_\alpha, t) < \Delta$, **then** $i_{\alpha, \text{ref}} \approx i_\alpha$, the system must choose a vector that does not change the value of $i_\alpha$, as it is already inside the hysteresis limits.

Note that the same logic is applied to $S_\beta(e_\beta, t)$. The vector choice criteria is presented in Table 4.2, according to position of both commutation functions [16].

<table>
<thead>
<tr>
<th>$S_{\alpha, \beta}(e_{\alpha, \beta}, t)$</th>
<th>Vector choice criterion</th>
<th>Output of $S_{\alpha, \beta}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&gt; \Delta$</td>
<td>Vector chosen must be able to increase the output current ($i_\alpha$ or $i_\beta$)</td>
<td>+1</td>
</tr>
<tr>
<td>$&lt; -\Delta$</td>
<td>Vector chosen must be able to decrease the output current ($i_\alpha$ or $i_\beta$)</td>
<td>-1</td>
</tr>
<tr>
<td>$-\Delta &lt; \text{and} &lt; \Delta$</td>
<td>Vector chosen does not significantly change the output current ($i_\alpha$ or $i_\beta$)</td>
<td>0</td>
</tr>
</tbody>
</table>

To better understand Figure 4.3 and Table 4.2, a practical example is given: if $S_a = 1$ and $S_\beta = 1$, the vector to be applied must increase both $\alpha$-component and $\beta$-component of the current (according to Table 4.2) because $i_{\alpha, \text{ref}} > i_\alpha$ and $i_{\beta, \text{ref}} > i_\beta$. Therefore, from Table 4.3, the only vector with positive $V_\alpha$ and $V_\beta$ is $V_2$, where the states of the semiconductors for each leg are $\gamma_A = 1$, $\gamma_B = 1$ and $\gamma_C = 0$. All $3^2$ possible error combinations and the chosen vector are presented in Table 4.3.
Table 4.3 - Strategy for vector choice in the RSC

<table>
<thead>
<tr>
<th>$e_{\beta}$</th>
<th>$e_{\alpha}$= +1</th>
<th>$e_{\alpha}$= 0</th>
<th>$e_{\alpha}$= -1</th>
</tr>
</thead>
<tbody>
<tr>
<td>$e_{\beta}$= +1</td>
<td>V2</td>
<td>V2 or V3</td>
<td>V3</td>
</tr>
<tr>
<td>$e_{\beta}$= 0</td>
<td>V1</td>
<td>V0 or V7</td>
<td>V4</td>
</tr>
<tr>
<td>$e_{\beta}$= -1</td>
<td>V6</td>
<td>V5 or V6</td>
<td>V5</td>
</tr>
</tbody>
</table>

4.3.2. Grid Side Converter

All the logic behind the output currents control of the RSC is also applied to the GSC. In the latter, the error in (4.21), both commutation functions in (4.22) and the stability criteria (4.23) are conditions employed in the respective control. Moreover, the schematics in Figure 4.3 are the same, as the operational principle of the power converter is identical to the RSC. Based on this, the state-space vectors are chosen according to the following rules, similar to the RSC:

- If $S_{\alpha}(e_{\alpha}, t) > \Delta$, then $i_{\alpha, \text{ref}} > i_{\alpha}$. In this case, the system reaction is to increase the output current $i_{\alpha}$ and lower $S_{\alpha}(e_{\alpha}, t)$. As the commutation function $S_{\alpha}$ decreases, its derivative $\dot{S}_{\alpha}(e_{\alpha}, t)$ starts to present negative values. As $S_{\alpha}(e_{\alpha}, t)$ decreases and $\dot{S}_{\alpha}(e_{\alpha}, t)$ now has a negative value, the stability condition from (4.23) is verified.

- If $S_{\alpha}(e_{\alpha}, t) < -\Delta$, then $i_{\alpha, \text{ref}} < i_{\alpha}$. In this case, the system reaction is to decrease the output current $i_{\alpha}$ and increase $S_{\alpha}(e_{\alpha}, t)$. As the commutation function $S_{\alpha}$ rises, its derivative $\dot{S}_{\alpha}(e_{\alpha}, t)$ starts to present positive values. As $S_{\alpha}(e_{\alpha}, t)$ increases and $\dot{S}_{\alpha}(e_{\alpha}, t)$ now has a positive value, the stability condition from (4.23) is verified.

- If $-\Delta < S_{\alpha}(e_{\alpha}, t) < \Delta$, $i_{\alpha, \text{ref}} \approx i_{\alpha}$, the system must choose a vector that does not change the value of $i_{\alpha}$, as it is already inside the hysteresis limits.

The same logic is applied to $S_{\beta}(e_{\beta}, t)$. The vector choice criteria is presented in Table 4.4, according to position of both commutation functions [16].

Table 4.4 - Vector choice criteria for the GSC according to $S_{\alpha, \beta}(e_{\alpha, \beta}, t)$

<table>
<thead>
<tr>
<th>$S_{\alpha, \beta}(e_{\alpha, \beta}, t)$</th>
<th>Vector choice criterion</th>
<th>Output of $S_{\alpha, \beta}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&gt; \Delta$</td>
<td>Vector chosen must be able to increase the output current ($i_{\alpha}$ or $i_{\beta}$)</td>
<td>+1</td>
</tr>
<tr>
<td>$&lt; -\Delta$</td>
<td>Vector chosen must be able to decrease the output current ($i_{\alpha}$ or $i_{\beta}$)</td>
<td>-1</td>
</tr>
<tr>
<td>$-\Delta &lt;$ and $&lt; \Delta$</td>
<td>Vector chosen does not significantly change the output current ($i_{\alpha}$ or $i_{\beta}$)</td>
<td>0</td>
</tr>
</tbody>
</table>
To better understand Figure 4.3 and Table 4.4, a practical example is given, different from the GSC’s: if \( S_\alpha = 1 \) and \( S_\beta = -1 \), the vector to be applied must increase the \( \alpha \)-component of the current and decrease its \( \beta \)-component of the current (according to Table 4.4) because \( i_{\alpha_{\text{ref}}} > i_\alpha \) and \( i_{\beta_{\text{ref}}} < i_\beta \). Therefore, from Table 3.2, the only vector with positive \( V_\alpha \) and negative \( V_\beta \) is \( V_3 \), where the states of the semiconductors for each leg are \( \gamma_A = 1 \), \( \gamma_B = 0 \) and \( \gamma_C = 1 \). All 3\(^2\) possible error combinations and the chosen vector are presented in Table 4.5.

<table>
<thead>
<tr>
<th>( e_\alpha )</th>
<th>( e_\beta )</th>
<th>( e_\alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(+1)</td>
<td>(+1)</td>
<td>(+1)</td>
</tr>
<tr>
<td>(-1)</td>
<td>(-1)</td>
<td>(-1)</td>
</tr>
</tbody>
</table>

This converter guarantees a nearly unitary input power factor: for that, both grid voltage and current must be 180° out of phase, meaning the reactive power \( Q \) must be nearly zero. It is useful to consider the application of the Blondel-Park transformation (2.35) to the input grid voltages, resulting in (4.24):

\[
\begin{align*}
\mathbf{u}_d_{\text{grid}} &= \sqrt{3} V_{\text{ef}} \cos(\omega t - \Phi) \\
\mathbf{u}_q_{\text{grid}} &= \sqrt{3} V_{\text{ef}} \sin(\omega t - \Phi)
\end{align*}
\]

(4.24)

Considering a reference frame synchronous with the grid voltage, \( \Phi = \omega t \). Now, (4.24) can be rewritten in (4.25), where the new \( dq \) grid voltages will be:

\[
\begin{align*}
\mathbf{u}_d_{\text{grid}} &= \sqrt{3} V_{\text{ef}} \\
\mathbf{u}_q_{\text{grid}} &= 0
\end{align*}
\]

(4.25)

The active and reactive power, also in \( dq \) coordinates, are (4.26).

\[
\begin{align*}
P &= \mathbf{u}_d_{\text{grid}} \mathbf{i}_d + \mathbf{u}_q_{\text{grid}} \mathbf{i}_q \\
Q &= \mathbf{u}_q_{\text{grid}} \mathbf{i}_d - \mathbf{u}_d_{\text{grid}} \mathbf{i}_q
\end{align*}
\]

(4.26)

In (4.25) \( u_q_{\text{grid}} \) is zero. Therefore, the reactive power in now controlled by the \( q \)-component of the input current (4.27).

\[
\begin{align*}
P &= \mathbf{u}_d_{\text{grid}} \mathbf{i}_d \\
Q &= - \mathbf{u}_d_{\text{grid}} \mathbf{i}_q
\end{align*}
\]

(4.27)

A nearly unitary power factor in the connection to the grid is required in normal operation conditions. It is mandatory to have \( i_\beta \) controlled to be zero, resulting in (4.28):

\[
i_{\beta_{\text{ref}}} = 0
\]

(4.28)
Due to limited capacity of DFIG converters, the reactive power reference of the grid side converter is kept zero in normal operation mode, in order to decrease the current and losses in both converters. The reactive power control is similar to the currents control for both converters, as analyzed above. Thus, the reactive power resulting error is given by (4.29).

\[ e_Q = Q_{\text{ref}} - Q \]  \hspace{1cm} (4.29)

The commutation function \( S_Q \) is presented in (4.30).

\[ S_Q(Q, t) = k_Q(Q_{\text{ref}} - Q) \]  \hspace{1cm} (4.30)

To guarantee the system stability it is mandatory to have:

\[ S_Q(e_Q, t) S_Q(e_Q, t) < 0 \]  \hspace{1cm} (4.31)

Based on the stability criteria, the system has to guarantee:

- If \( S_Q(e_Q, t) > \Delta \), then \( Q_{\text{ref}} > Q \). In this case, the system reaction is to increase the \( Q \) and lower \( S_Q(e_Q, t) \). As the commutation function \( S_Q \) decreases, its derivative \( S_Q(e_Q, t) \) starts to get negative values. As \( S_Q(e_Q, t) \) decreases and \( S_Q(e_Q, t) \) now has a negative value, the stability condition from (4.31) is verified.

- If \( S_Q(e_Q, t) < -\Delta \), then \( Q_{\text{ref}} < Q \). In this case, the system reaction is to decrease the \( Q \) and increase \( S_Q(e_Q, t) \). As the commutation function \( S_Q \) rises, its derivative \( S_Q(e_Q, t) \) starts to get positive values. As \( S_Q(e_Q, t) \) increases and \( S_Q(e_Q, t) \) now has a positive value, the stability condition from (4.31) is verified.

- If \(-\Delta < S_Q(e_Q, t) < \Delta \), \( Q_{\text{ref}} \approx Q \), the system must choose a vector that does not change the value of \( Q \), as it is already bounded by hysteresis upper and lower limits.

The vector choice criteria is presented in Table 4.6, according to position of the commutation function, \( S_Q \).

<table>
<thead>
<tr>
<th>( S_Q(e_Q, t) )</th>
<th>Vector choice criteria</th>
<th>Output of ( S_Q )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( &gt; \Delta )</td>
<td>Vector chosen must be able to increase ( Q )</td>
<td>+1</td>
</tr>
<tr>
<td>( &lt; -\Delta )</td>
<td>Vector chosen must be able to decrease ( Q )</td>
<td>-1</td>
</tr>
<tr>
<td>(-\Delta &lt; ) and (&lt; \Delta )</td>
<td>Vector chosen does not significantly change ( Q )</td>
<td>0</td>
</tr>
</tbody>
</table>
4.4. DC-Link voltage control

Apart from controlling the active and reactive power delivered to the grid, the grid side converter also controls the voltage in the DC-link. The controller output is the d-component reference value for the internal current control system. In this way, the current d-component controls the active power, while the q-component the reactive power (4.27).

The block diagram in Figure 4.4 represents the voltage control scheme. In this model, the grid side converter is represented by a first order system, having one pole dependent on the period of the grid voltage ($T_{dv}$). Note that $\alpha_v = 0.01$ and $\alpha_i = 0.01$ are the measuring factors gains present in all voltage and current measurement devices of the system.

![Figure 4.4 - Block diagram for the DC-link voltage controller](image)

The selection of the compensator $C(s)$ is the key. A PI (4.32) is chosen to guarantee zero steady-state error to allow relatively fast response.

$$C(s) = K_p + \frac{K_i}{s}$$  \hspace{1cm} (4.32)

The expression of the capacitor in the DC-Link is given by (4.33):

$$C = \frac{2 \times 0.25 \times P_e \times \Delta t}{U_{DC_{max}}^2 - U_{DC_{min}}^2}$$  \hspace{1cm} (4.33)

The factor $0.25 \times P_e$ refers to the power flowing through the DC-Link, which is about 25% of the wind turbine power, $P_e$.

In this case, the proportional gain, $K_p$, and the integral gain, $K_i$ are given by (4.34) and (4.35), respectively [31].

$$K_p = \frac{2.15 \times \alpha_i}{1.75^2 \times \alpha_v \times G_i \times T_{dv}}$$  \hspace{1cm} (4.34)

$$K_i = \frac{C \times \alpha_i}{1.75^3 \times \alpha_v \times G_i \times T_{dv}^2}$$  \hspace{1cm} (4.35)

The gain $G_i$ is defined by (4.36), where $\eta_{conv}$ is the total efficiency of the back-to-back converter.

$$G_i = \frac{3 \times V_{ef}}{U_{DC}}$$  \hspace{1cm} (4.36)
The computation of all controller parameters is presented in Table 4.7.

Table 4.7 - Parameters of the DC-link voltage controller

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>0.01</td>
<td>0.01</td>
<td>0.25</td>
<td>0.02</td>
<td>0.95</td>
<td>2000</td>
<td>0.107</td>
<td>0.98</td>
<td>3.57</td>
<td>47.44</td>
</tr>
</tbody>
</table>

Note that the compensator block is a conventional PI controller with anti-windup (Figure 4.5) which goal is to get a faster recovery of the Udc voltage to safer values, in the occurrence of a voltage dip. By means of reducing the integral gain as soon as the value of $i_d_{\text{ref}}$ reaches its saturation level, the controller tends to invert the natural upward trend (in absolute values) of the DC-link voltage.

Figure 4.5 - Block diagram of the PI controller with anti-windup for the DC-link voltage control

4.5. **Turbine control in the presence of a voltage dip**

In case of occurrence of a voltage dip in the grid, over-currents or over-voltages will be induced in the rotor windings, due to the magnetic coupling between the stator and the rotor. By allowing the rotor to temporarily accelerate, wind energy continuously captured by the wind turbine during a fault can be stored as kinetic energy, while the DC-link capacitor will charge due to a sharp rise of the currents [32]. Consequently, in these conditions, the main goal of the system is to stay connected to the grid, instead of extracting the maximum power from the wind.

This behavior might result in serious harm to power electronic devices and to the wind turbine. The LVRT capability is achieved through a by-pass for the excessive rotor’s energy and the DC-link over-voltage. A commonly used hardware to provide a safe path to the transient currents is the crowbar protection. This device is based on a three-phase diode rectifier, the crowbar resistor $R_{cb}$ and an IGBT switch. It is connected between the RSC and the rotor of the generator, as shown in Figure 4.6.
An active crowbar can be in operation whenever needed (both turn on and turn off control) due to its only controlled component, the IGBT switch. However, a passive protection uses a thyristor as a switch, which can only control the turn on, but not the turn off. Whenever the DC-link voltage is higher than a defined threshold, the crowbar is instantaneously turned on and should be kept in operation until the DC-link voltage decreases below the referred threshold (Figure 4.7). This way, a by-pass path is created and the resistance $R_{cb}$ is connected in series with the rotor circuit.

The rotor active crowbar should successfully limit the rotor over-current and protect the DC-link capacitor. Therefore, it is crucial to compute the value of the resistor, $R_{cb}$: on one hand, a small value will not resist the rotor over-current; on another hand, for higher values, the capacitor will charge due to excessive currents flowing to the RSC, resulting in an overvoltage in the DC-link. The relationship between the fault current and the $R_{cb}$ is described by (4.37).

$$I_{r_{\text{max}}} = \frac{U_s}{\sqrt{(\omega_s L_\sigma)^2 + R_{cb}^2}}$$

(4.37)

Where $L_\sigma$ is the stator and rotor total leakage reactance (4.38).

$$L_\sigma = L_r + L_s$$

(4.38)

From (4.38) it is possible to establish a minimum value of $R_{cb}$ [33], shown in (4.39):
Besides being able to stay connected during voltage sags, grid connection requirements are being reinforced to request reactive power support by wind turbines during these events. To meet this challenging necessity, the reactive current injected in the grid by the GSC must follow the trend of Figure 4.8.

\[
R_{cb\_min} = \frac{\sqrt{U_s^2 - \omega_s^2(L_r+L_s)^2 I_{r\_max}^2}}{I_{r\_max}} \tag{4.39}
\]

The grid side converter, besides controlling the voltage in the common DC-link, also controls the reactive power by means of the current q-component \((4.41)\). Thus, in the event of a voltage sag, \(i_{q\_ref}\) follows the trend presented in both faulty zones of Figure 4.8. When the sag is cleared, the system returns to its normal operation in Zone (2) in order to get a nearly unitary power factor.

\[
Q = -u_{d\_grid} i_{q\_ref} \tag{4.41}
\]
Although the trend of Figure 4.8 being strictly followed by \(i_{q, \text{ref}}\), the reactive power does not have the same behavior, as it also depends on the d-component of the grid voltage, \(u_{d, \text{grid}}\). The following analysis is based on the absolute values of the three variables in (4.41). An early recover of the grid voltage while \(i_{q, \text{ref}}\) is still constant at 0.9 pu makes the reactive power increase in absolute values from \(t = 0.5 \text{ s; } 1 \text{ s}\). While the recovery of the grid voltage is still ongoing (\(u_{d, \text{grid}}\) increasing), the q-component of the grid current starts to decrease with a higher slope than the grid voltage. Thus, the product (4.41) decreases in absolute values from \(t = 1 \text{ s; } 1.5 \text{ s}\). This logic is explained in Table 4.8.

### Table 4.8 - Evolution of the reactive power during the voltage dip, considering \(u_{d, \text{grid}}\) and \(i_{q, \text{ref}}\)

<table>
<thead>
<tr>
<th>Time [s]</th>
<th>(i_{q, \text{ref}}) [pu]</th>
<th>(u_{d}) [pu]</th>
<th>(Q)</th>
</tr>
</thead>
<tbody>
<tr>
<td>([0; 0.2])</td>
<td>0.9</td>
<td>0.2</td>
<td>constant</td>
</tr>
<tr>
<td>([0.2; 0.5])</td>
<td>0.9</td>
<td>0.2</td>
<td>constant</td>
</tr>
<tr>
<td>([0.5; 1])</td>
<td>0.25 - 2.25 × ([0.5; 0.8])</td>
<td>0.5</td>
<td>([0.5; 0.8])</td>
</tr>
<tr>
<td>([1; 1.5])</td>
<td>0.25 - 2.25 × ([0.5; 0.8])</td>
<td>0.25</td>
<td>([0.5; 0.8])</td>
</tr>
</tbody>
</table>
5. Simulation results

A model of the whole wind generation system was created in Matlab/Simulink. The results were obtained for both operational situations: a normal performance of the turbine under a specific wind speed record and a performance under a voltage dip in the grid. Some wind turbine and DFIG parameters are presented in Table 5.1.

<table>
<thead>
<tr>
<th>R [m]</th>
<th>P [MW]</th>
<th>r_s [mΩ]</th>
<th>r_r [mΩ]</th>
<th>L_s [mH]</th>
<th>L_r [mH]</th>
<th>M [mH]</th>
<th>n_{pp}</th>
<th>V_{ef} [V]</th>
</tr>
</thead>
<tbody>
<tr>
<td>38.5</td>
<td>1.5</td>
<td>2.2</td>
<td>1.8</td>
<td>3.02</td>
<td>2.95</td>
<td>2.9</td>
<td>2</td>
<td>690</td>
</tr>
</tbody>
</table>

In Appendix A is presented the wind turbine datasheet, where the remaining parameters are specified.

5.1. Results obtained under normal operation conditions

The wind speed variation used in the simulations is pictured in Figure 5.1, where the average speed per hour is represented. In the simulation, each second corresponds to an actual hour due to some hardware boundaries. Thus, in this case, the period of the simulation is 24 seconds, which reflects 24 hour of wind records. This reduction of the simulation time also brings a reduction of the total moment of inertia in order to allow the turbine to successfully vary in this time range.

![Wind speed profile](image)

The wind turbine is equipped with a speed controller that imposes an optimal generator speed (established as the reference) to track the maximum power point (MPP). This controller is sensitive to the wind speed, as the system responds rapidly to wind oscillations. Thus, the extraction of power rises as the wind reaches higher average speed values. From Figure 5.2 it is possible to show that not only
the objective of tracking the generator reference speed was accomplished, but also the high sensivity of the controller to wind speed variations.

![Figure 5.2 - Speed controller performance](image)

However, a minor static error of $\omega_{\text{gen}}$ comparatively to $\omega_{\text{m, ref}}$ is always present due to a perturbation imposed by $T_m$ to the speed controller (Figure 4.1), as it is not constant through the wind turbine operation.

The output of the speed controller is the reference torque. As the system equations were written using motor convention, the electromagnetic torque of the DFIG is negative. The reference torque is calculated based on the optimal generator speed (2.17). In Figure 5.3 it is shown that the electromagnetic torque strictly follows the reference to extract as much power from the wind as possible.

![Figure 5.3 - Reference and electromagnetic torques](image)

The rotor is directly connected to the RSC. The waveform of the output voltage of the rotor is a result of the state-space vector control applied to the RSC. Therefore, the voltage is switched at a high frequency due to the presence of semiconductors in the power converter, allowing a high frequency commutation. Furthermore, the ripple verified in the voltage of the common DC-link is reflected in the rotor.
The rotor current waveforms visualized in Figure 5.4 have sharp fluctuations as a result of the speed controller. It is noticeable that for $t = [2\ s; 6\ s]$ and $t = 18\ s$ the currents present a lower frequency since in both zones the generator speed is around 1500 RPM, when the slip is nearly zero.

![Figure 5.4 - Output current of the rotor](image)

Figure 5.5 displays a transition of the generator from sup-synchronous operation ($t < 17.5\ s$) to sub-synchronous ($t > 18.5\ s$). From $17.5\ s$ to $18.5\ s$ the generator reaches the synchronism speed (slip is zero), where all three phases change and the energy starts to flow from the grid to the rotor. The currents in Figure 5.6 have a frequency equal to the grid’s, as the stator is directly connected to it. As expected, the stator currents have a higher amplitude when the torque reaches higher values.

![Figure 5.5 - Rotor currents behavior at the synchronism speed](image)
The currents in Figure 5.4 are a result of the reference torque established by the speed controller, $T_{MPPT}$, as $i_{rq_{ref}}$ depends on this value through (4.11). The track of $i_{rq_{ref}}$ is possible via inverse Park transformation and both $q\beta$-components are illustrated in Figure 5.7.

In the DC-link it is natural to observe a voltage floating around the established $U_{DC}$ (reference voltage) through a ripple. As shown in both Figure 5.8 and Figure 5.9, when the wind speed increases, currents flowing through the back-to-back converter will rise and charge the capacitor; on the other hand, when the wind speed decreases, those currents will have a lower amplitude and reduce the voltage in the DC-link, discharging the capacitor.
The GSC is responsible for the controlling the DC-link voltage, as it is equipped with a compensator, specifically a PI controller (Figure 4.4). Its output is the d-component of the reference current, plotted in Figure 5.9 and crucial to control the GSC currents.

The abc currents of this converter are a direct result of the Blondel-Park transformation. Figure 5.10 is a confirmation that these currents oscillate in respect to the reference d-component generated by the DC-link voltage.
When it comes to the grid connection, both voltages and currents have a frequency equal to 50 Hz and, in a sup-synchronous operation, the power in the rotor flows from the DFIG system to the grid. As the system was initially designed for the power to flow from the grid to the system (opposite direction), it is expected to have both voltage and current 180° out of phase, as shown in Figure 5.11.

Furthermore, this behavior reflects an almost unitary power factor. It is a result of the control applied to the GSC, setting $i_{q,ref}$ to zero. As this converter is responsible for the reactive power control in the connection to the grid, it is also expected to have a waveform of the reactive power near zero var.
On the other hand, in a sub-synchronous operation, there is an absorption of power from the grid. In this case, as the power flows in the direction initially set for the system, it is expected to have both voltage and current in phase, as shown in Figure 5.12.

![Figure 5.12 - Voltage and current in phase at network connection](image)

Both Figure 5.13 and Figure 5.14 represent the power delivered to the grid. The highest peaks in the active power (for instance at t = 9.5 s, at t = 12.5 s and at t = 16.5 s) correspond to a higher slope in absolute values, regarding the wind speed profile. In the mentioned cases, the wind speed drops relatively fast and the reference torque generated by the speed controller also reaches higher values. The stored power in the wind turbine, originated by those peaks in the wind speed, must be delivered to adjust the generator speed to the new imposed value by the controller.

![Figure 5.13 - Active power in the connection to the grid](image)
The reactive power of Figure 5.14 is maintained almost zero var by the GSC for the whole simulation, as it imposes \(i_{\text{q,ref}}\) also zero. This waveform validates the unitary power factor referred above.

![Figure 5.14 - Reactive power in the connection to the grid](image)

The next subchapter contains the results acquired while the system is under a voltage sag. A comparison between the wind turbine response with and without the activation of the crowbar is made.
5.2. Results obtained for a voltage dip

In a voltage dip operation mode, the system is subjected to a sag with $V_{pu} = 0.2$ pu (depth of 80%) through 500 ms and a total duration of 2 seconds. This waveform is presented in Figure 5.15, according to [11], and the results of the system reaction are given in this chapter.

![Graph showing voltage dip profile](image)

**Figure 5.15 - Voltage dip profile in the Point of Common Coupling (PCC)**

To have a more realistic model, the value of the system total inertia was changed from $J_{total} = 146$ kgm$^2$ (in Chapter 5.1) to $J_{total} = 2500$ kgm$^2$, in the presence of a voltage dip. This value reflects an attempt to acquire more accurate results regarding grid faults. Once the order of magnitude of the voltage dip total duration is the second, the wind speed of $u = 11.5$ m/s was kept constant the whole period of the simulation.

During a fault, the wind energy captured by the wind turbine is partially stored as kinetic energy, increasing the generator speed, and will also charge the DC-link capacitor, that may charge to dangerous and harmful values. As the currents flowing through the semiconductors are limited by the current controllers, the concern relies on the voltage values reached by the capacitor while charging. The continuity, over time, under unsafe values can seriously damage the DC-link and, therefore, the power converters. Without the crowbar protection, in Figure 5.16 it is visible that the voltage in the DC-link reaches higher values for a significant period of time, compromising the integrity of the system’s components. Only at $t = 13$ s the system recovers its control and its normal operation.
The over-voltage in the common DC-link triggers the d-component of the GSC current, as the PI controller in Figure 4.4 has $U_{DC}$ as input. Consequently, if the voltage increases abruptly, the reference current $i_{d\_ref}$ will also rise, leading to over-currents in the semiconductors. As mentioned above, the system is equipped with inner limitation for the currents to maintain integrity of the system in unexpected situations. In the GSC’s case, the limit is set to 1000 A, as a higher value might destroy the semiconductors. Figure 5.17 shows the evolution of $i_{d\_ref}$ with the referred limitation in blue and the evolution without the limitation, in orange. Without limitation, $i_{d\_ref}$ would reach 2200 A that would be catastrophic for the power converter integrity.
From Figure 5.18, in the interval of $t = [11.7 \text{ s}; 13 \text{ s}]$ it is visible that the currents in the converter are still recovering from the peak voltage in the DC-link originated by the voltage dip. However, with such an abrupt spike, the converter cannot immediately regain the full control of the currents. Indeed, from about $t = 11.7 \text{ s}$, the power converter partially recovers the control, as $i_{d, \text{ref}}$ slowly starts to decrease, and eventually stabilizes at $t = 13.3 \text{ s}$. The transition of a partial control to a full control of the currents is represented by Figure 5.19.

![Figure 5.18 - abc currents in the GSC without crowbar activation](image1)

![Figure 5.19 - abc currents detail in the GSC without crowbar activation](image2)

Relatively to the rotor, as the voltage in the DC-link rises and remains in higher values for a significant period of time, the rotor voltage has the exactly same behavior, plotted in Figure 5.20: from $t = [10.2 \text{ s}; 10.9 \text{ s}]$ it is visible an over-voltage performance (as well as the DC-link waveform of Figure
5.16), harmful to the system. It is also evident that the rotor voltage restores its natural behavior at $t = 13 \text{ s}$.

![Rotor voltage without the crowbar protection](image)

**Figure 5.20 - Rotor voltage without the crowbar protection**

The introduction of the crowbar protection enables a safer performance from the wind turbine, protecting its components from overvoltages. As soon as the voltage in the capacitor reaches a defined limit, the crowbar is triggered (Figure 4.7) to by-pass the excessive energy flowing from the rotor to the crowbar resistor, $R_{cb}$. Thus, for 46 ms, this protection is activated in order to absorb a large amount of energy (behaving as a by-pass). Figure 5.21 shows the crowbar current waveform.

![Crowbar current waveform](image)

**Figure 5.21 - Current flowing in the crowbar protection when it is activated**
With this alternative path for the surplus energy in the system to flow, the voltage in the DC-link is reduced to safer values, as observed in Figure 5.22. Furthermore, it is visible that at $t = [10.3 \text{ s}; 13 \text{ s}]$ the system does not totally recover its full control. On the other hand, from $t = 13 \text{ s}$ it is clear that as the grid voltage recovers, the voltage in the capacitor returns to its nominal values and the system to its normal operation.

![Figure 5.22 - DC-link voltage waveform obtained with the crowbar protection](image)

For a faster voltage recovery, the activation of this hardware enables the anti-windup effect on the DC-link voltage controller (Figure 4.5), as the $i_{d,\text{ref}}$ overcomes its maximum value, shown in Figure 5.23. A faster control of the capacitor’s voltage is extremely important to avoid damaging the IGBTs of the power converter. The control of the voltage is rapidly restored due to this effect, as shown in detail in Figure 5.24.

![Figure 5.23 - Anti-windup effect assisting the GSC $i_{d,\text{ref}}$ recovery](image)
Comparatively to the situation where no LVRT equipment was used (Figure 5.18), with a crowbar device the converter recovers full control of its currents sooner than without crowbar. In fact, it only loses partially the control at $t = [10.8 \text{ s}; 11.5 \text{ s}]$. The currents start to decrease earlier with the activation of the crowbar and the GSC (controlling the DC-link) returns its normal operation, shown in Figure 5.25.

A detail of the transition from the partial control of the currents in the GSC (when the system is trying to recover from the sag) to full control is represented in Figure 5.26. This shift occurs about 2 s earlier than the case with no crowbar activated.
Figure 5.26 illustrates the waveform of the rotor voltage in the presence of a grid fault. As referred in the last chapter, it mirrors the behavior of both semiconductors in the RSC (high frequency commutation) and the capacitor voltage in the common DC-link (voltage switching between $U_{DC}$ and $-U_{DC}$).

![Figure 5.26 - Detail of the GSC currents with crowbar activation](image)

The rotor currents of Figure 5.28 present an initial transient peak due to the abrupt loss of 80% of the voltage grid. However, as the crowbar protection is enabled, the amplitude of the rotor currents reduces to safer values (Figure 5.28) at $t = 10.35$ s. At $t = 13$ s the voltage grid is recovered, and the wind turbine recovers its normal operation.

![Figure 5.27 - Rotor voltage with the crowbar protection](image)
For a specific wind speed, the system tracks a specific MPP imposed by the speed controller. However, in the presence of a voltage dip, the turbine attempts to inject currents with a higher amplitude in order to balance the lack of power, due to the voltage sag. For that to happen, the generator needs to increase its rotational speed, as the reference torque also rises to impose these currents. In Figure 5.29 is visualized the expected increment on the generator speed.

The waveform of Figure 5.30 shows the torque in the DFIG and Figure 5.31 the active power injected in the grid, both obtained in the occurrence of a grid fault from t = 10 s to t = 13 s, with the profile presented in Figure 5.15. During that period, the low voltage measured at the stator terminals leads to a reduction in the both the stator and rotor leakage fluxes. Therefore, the electromagnetic torque and
the active power decrease momentarily. Until the voltage is almost recovered (at \( t = 13 \) s with voltage grid at 0.9 pu), there is a torque increment (in absolute values), which generates more output power. As soon as the fault is cleared, the system returns to its normal operation, with MPPT operation.

Figure 5.30 - Torque in the DFIG when a grid fault occurs from \( t = 10 \) s to \( t = 13 \) s

Figure 5.31 - Active power when there is a voltage dip from \( t = 10 \) s to \( t = 13 \) s

According to DGEG, the wind turbine must inject reactive power to help the grid voltage recover in faulty conditions. The reactive power injected depends on \( i_{q_{\text{ref}}} \) of the GSC (4.41), which must strictly follow the pattern of Figure 4.8. After fault clearance, the system must return to its normal operation, maintaining an almost unitary power factor. This is accomplished in Figure 5.32. Note that due to the motor convention used throughout this work, the GSC must inject a negative current in the grid.
The reactive power injected has the waveform shown in Figure 5.34, following partially the trend of $i_{q_{\text{ref}}}$. This power also depends on $u_{d_{\text{grid}}}$, the d-component of the grid voltage (Figure 5.33). The current $i_{q_{\text{ref}}}$ stays in 0.9 pu from the depth of 80% to 50%, that is, from $t = [10 \text{ s}; 11.26 \text{ s}]$. However, at $t = 10.5 \text{ s}$, the voltage recovery begins. Thus, the product $(4.41)$ starts to increase its absolute value, as seen in the reactive power waveform. After that, as $i_{q_{\text{ref}}}$ decreases faster than the increment of $u_{d_{\text{grid}}}$, the reactive power has a reduction of its value until it reaches zero var. This behavior is represented in Figure 5.34 and is also explained in Table 4.8.
The stator currents represented in Figure 5.35 have the expected behavior under a voltage sag, as they present an initial peak amplitude related to the sudden loss of 80% of grid voltage. The fault recovery is directly related to the lower magnitudes in the stator currents. Similarly to Figure 5.28, at $t = 10.35$ s is also viewable a reduction of the stator current amplitude due to the activation of the crowbar.

As the grid voltage reaches 0.9 pu, the system recovers its normal operation and the results obtained are similar to the ones obtained in subchapter 5.1. Thus, it is shown that the speed controller of the wind turbine, alongside the power converters control (on the rotor side and on the grid side), allow the system to recover from a grid fault.
6. Conclusions

The primary goal of this work was to analyze the capability of a wind turbine equipped with a DFIG to stay connected to the grid under a severe voltage dip. The wind turbine has a back-to-back power converter connected to the rotor windings, while the stator is directly connected to the grid.

In normal operation conditions, the main goal of the wind turbine is to guarantee the maximum output power by the employed MPPT. For that to be achieved, it was implemented a speed controller. However, when a voltage dip is detected, a different operation mode is required to avoid over-currents and over-voltages in both the generator and the common DC-link. An active crowbar protection is activated in order to create a by-pass for the energy excess, protecting the back-to-back converter and the generator itself.

By running the simulation for the normal operation mode, it was verified that the generator speed strictly followed the reference speed. Furthermore, the electromagnetic torque of the generator also kept track of the reference torque produced by the speed controller. In fact, for each variation in the wind speed, the system was able to extract the maximum power. It is also important to mention that the DC-link voltage was controlled the whole simulation, including the variations that resulted from the wind speed changes. In addition, the state-space vector-based control was successful in controlling the currents flowing in the RSC and the GSC, guaranteeing nearly unitary power factor in normal operating conditions.

To simulate a voltage dip in the grid, the total inertia was increased nearly 18 times and the wind speed was kept constant at \( u = 11.5 \) m/s. Without the activation of the crowbar protection, the DC-link voltage reached an unsafe and harmful value, leading to a partial loss in the currents control of the grid side converter. In addition, as the rotor voltage mirrors the behavior of the DC-link, a voltage dip induces over-voltages in the rotor, capable of damaging the equipment. As the reference currents in the system are limited to guarantee the integrity of its components, the turbine prevents high magnitude currents from destroying the semiconductors in the rotor side converter. However, with the activation of the crowbar, the excessive energy from the rotor is by-passed to the crowbar resistor, enabling a faster recovery of the currents full control in the grid side converter. As a result, the common DC-link takes safer values of the voltage, as well as the rotor voltage. Moreover, the reactive support is achieved, as the wind turbine implements the trend (of reactive current) requested by the grid operator. Finally, once the fault is cleared, the wind turbine resumes its normal operation: the MPPT is obtained, currents and voltage in the back-to-back power converter are fully controllable and the pursuit of a unitary power factor restarts.

To conclude, this work accomplished its main objective, as the wind turbine continues to operate under a voltage sag, avoiding a disconnection from the grid. An active crowbar protection enabled this performance, as it protected the converters from the excess energy generated during the fault. While under a voltage dip, the system disables the MPPT operation, restarting the maximum power extraction as soon as the voltage grid recovers to nominal values (\( V_{\text{ef}} > 0.9 \) pu).
6.1. Future work

Further work is needed to study the implementation of an active crowbar in systems where the generator and the power converters are installed in a different topology from the one studied. Hence, it is important to consider a distinct approach not only for the currents control (for example, linear control) but also for the crowbar protection circuit. Indeed, a combination of several methods to improve the corresponding control strategy and protection scheme can play a role to form an even more robust system to meet the LVRT requirements.

It is also essential the need for further deepening researches regarding the operation time of the crowbar system, as it must be reduced to enable a faster restart of the RSC and, consequently, restoring a normal operation from the wind turbine. Besides, it is important to develop studies and laboratory work in order to attend the need of LVRT for asymmetrical grid faults, as they are the most common type of voltage sags in the electrical system.
References


[34] DGEG, Requisitos Transitórios a Aplicar na Ligação de Geradores de Electricidade à Rede Eléctrica de Serviço Público (RESP) de Geradores PV e CPV, 12 February 2018.
## Appendix A – Wind turbine datasheet

### Nordex S77/1500 kW

#### Rotor
- **Number of blades**: 3
- **Rotor speed**: 9.9 – 17.3 RPM
- **Rotor diameter**: 77 m
- **Swept area**: 4657 m²
- **Power regulation**: Pitch
- **Cut-in wind speed**: 3 m/s
- **Cut-out wind speed**: for tubular towers 25 m/s, for lattice towers 20 m/s
- **Survival wind speed**: 50.1 m/s (at 85 m hub height)
- **Pitch regulation**: Individual electromotive pitch
- **Total weight**: c. 34000 kg

#### Blades
- **Blade length**: 37.5 m
- **Material**: GRP (Glass fibre-reinforced plastic)
- **Weight**: c. 6500 kg

#### Gearbox
- **Type**: Combined planetary and spur gear
- **Gear ratio**: 1 : 104
- **Weight**: c. 14000 kg
- **Oil quantity**: 350 L
- **Oil change**: Bi-annual check, change as required
- **Main shaft bearing**: Self-aligning roller bearing

#### Generator
- **Power**: 1500 kW (adjustable)
- **Voltage**: 690 V
- **Type**: Double fed asynchronous generator, air-cooled
- **Speed**: 1000 – 1800 RPM ± 10%
- **Enclosure class**: IP 54
- **Coupling**: Multiple steel disc, insulated
- **Efficiency**: Efficiency c. 95% at full load, (electrical system overall)
- **Weight**: c. 7000 kg
- **Power factor**: 0.9 ind. to 0.95 kap.

#### Yaw system
- **Yaw bearing**: Four-point bearing
- **Brake**: Hydraulic disc brake with 10 calipers
- **Yaw drive**: 4 induction motors
- **Speed**: 0.75 º/s

#### Control system
- **Type**: Microprocessor
- **Grid connection**: Via IGBT converter
- **Scope of monitoring**: Remote monitoring of more than 300 different parameters, e.g. temperature sensors, hydraulic sensors, pitch parameters, vibration, speed, generator torque, wind speed and direction, etc.
- **Recording**: Production data, event list, long and short-term trends

#### Brake
- **Design**: Three independent systems, fail safe (individual pitch)
- **Operational brake**: Electromotive blade pitch
- **Secondary brake**: Disc brake
| Tower Type       | Tubular tower 61.5 m, Certificate, IEC 3a, DIBt 2 on request  
                | Tubular tower 80 m, 85 m, 90 m, 100 m, Certificate DIBt 2  
                | Lattice tower 96.5 m, Certificate DIBt 2  
                | Lattice tower 111.5 m, Certificate DIBt 2 |
|------------------|----------------------------------------------------------|
| Hub heights      | Modular steel tower, cylindrical upper segment conical, lattice tower, hot-dip galvanized |
Appendix B – Simulink numerical parameters

In this appendix is presented the Matlab numerical parameters for the system simulation in Simulink.

```matlab
%***************************************************************************
% Parameters for the Simulink simulation
% Author: Pedro Manuel Escaleira Marques da Fonte
%***************************************************************************

%Grid
V_ef = 690; % [V]
V_ef_simples_pico = sqrt(2)*V_ef; % [V]
freq_Hz = 50; %[Hz]
freq_rad = 2*pi*freq_Hz; %[rad/s]

%DFIG
Pg = 1.5e6; % [W]
ws = freq_rad; % [rad/s]
n_pp = 2; %Pairs of poles
wm_initial = 1865*pi/30 %Initial speed of the generator [rad/s]
Jgen = 100; %[Kg*m^2]

%Stator
rs = 2.2e-3; %Stator winding resistance [Ohm]
Ls = 3.02e-3; %Stator self-inductance [H]

%M
M = 2.9e-3; %Mutual inductance [H]

L_matrix = [Ls,0,M,0
            0,Ls,0,M
            M,0,Lr,0
            0,M,0,Lr];
L_matrix_inv = inv(L_matrix);

%Wind Turbine
Rturb = 77/2; %[m]
swept_area = pi*Rturb^2; %[m^2]
G = 104;
turb_mass = 500; %[Kg]
ro_air = 1.225; %[kg/m^3]
fric_coef = 0.05; % [N.m.s]

Jturb = (2/3)*turb_mass*Rturb^2; %[Kg*m^2]
```
% Speed Controller

KT = 1;  
Td = 1e-3;  
Tz = Jtotal/fric_coef;  
zeta = sqrt(2)/2;  
w = 1/(2*zeta*Td);  
Tp = KT/(w^2*fric_coef*Td);  

kp_speed = Tz/Tp;  
ki_speed = 1/Tp;  

% DC-link

Udc = 2000; % [V]  
Udc_max = 2000; % [V]  
Udc_min = 1500; % [V]  
delta = 0.25; % [s]  

C = (2*0.25*Pg*delta)/(Udc_max^2 - Udc_min^2); % [F]  

% Controller  

alfa_i = 0.01;  
alfa_v = 0.01;  
T_dv = 0.02; % [s]  
rend_conv = 0.95;  

Gi = rend_conv*(3*V_ef/Udc);  
K_p = (2.15*C*alfa_i)/(1.75^2*alfa_v*Gi*T_dv);  
K_i = (C*alfa_i)/(1.75^3*alfa_v*Gi*(T_dv^2));  
K_w = 0.4;
Appendix C – Matlab Simulink Models

The content of this appendix refers to the most important schematics used in Matlab Simulink.

Figure C.1 - DFIG model

Figure C.2 - RSC currents control
Figure C.3 - Crowbar protection

Figure C.4 - Wind turbine optimum power and MPPT reference torque