Maximum Power Point Tracker of
Wind Energy Generation Systems using Matrix Converters

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Dissertação para obtenção do Grau de Mestre em Engenharia
Electrotécnica e de Computadores

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Maio de 2011
**Agradecimentos**

Agradeço à Professora Sónia Pinto pelo excelente trabalho que desempenhou como Orientadora desta dissertação, o que se deveu sobretudo à disponibilidade e flexibilidade no esclarecimento de dúvidas e resolução de problemas, assim como todo o apoio e conselhos dados ao longo do trabalho. Agradeço igualmente ao Professor Fernando Silva, sobretudo por todas as opiniões e sugestões que em muito contribuíram para o sucesso do mesmo.

À minha família, especialmente aos meus pais, agradeço todo o apoio e motivação que me deram ao longo do meu percurso académico. Além disso deixo o meu obrigado a todos os meus amigos, professores e colegas que de certa forma contribuíram para o meu sucesso.
Resumo

Atualmente, a maioria das turbinas eólicas está equipada com Máquinas de Indução Duplamente Alimentadas e com conversores AC-DC-AC para extrair a energia cinética do vento e gerar energia elétrica.

O conversor AC-DC-AC é instalado entre o rotor do gerador e a rede elétrica, a fim de controlar a velocidade do eixo da turbina e, consequentemente, a potência gerada. Estes conversores têm um andar DC intermédio para o armazenamento de energia, que apresenta o inconveniente de aumentar não apenas o peso e o tamanho do conversor, mas também as perdas e os custos, diminuindo o tempo de vida útil do sistema. Uma alternativa para estes conversores são de Conversores Matriciais, que executam a conversão AC-AC directamente, não necessitando do andam DC intermédio.

O objectivo principal deste trabalho é o estudo do seguidor de potência máxima do sistema (MPPT - "Maximum Power Point Tracker") num sistema equipado com um conversor matricial. Para atingir esse objectivo foi criado o modelo do conversor combinado com a técnica de modelação de vectores no espaço e o controlo por modo de deslizamento, a fim de aplicar ao rotor da Máquina de Indução Duplamente Alimentada as correntes necessárias para seguir um binário de referência estabelecido. Por sua vez, o binário de referência é definido de acordo com a velocidade do vento e com base no modelo da turbina criado, com o intuito de gerar o máximo de energia possível.

O sistema foi desenvolvido utilizando a plataforma Matlab Simulink e duas técnicas de controlo diferentes foram aplicadas para o seguimento da potência máxima disponível: o controlo de binário e controlo de velocidade, com a finalidade de comparação posterior dos resultados.

Com as características mencionadas, o dimensionamento adequado do filtro e o aproveitamento das propriedades do conversor matricial, foi possível garantir um factor de potência quase unitário da potência injectada na rede e da potência do conversor, seguindo sempre o binário de referência definido.

Palavras-chave: Máquina de Indução Duplamente Alimentada; Aerogerador; Conversor Matricial; Modelação de Vectores no Espaço; Controlo por Modo de Deslizamento; Seguidor de Potência Máxima.
Abstract

Nowadays most of the wind turbines are equipped with a Double Fed Induction Generator (DFIG) combined with a AC-DC-AC converter to extract the kinetic energy of the wind and convert it into electrical energy.

The AC-DC-AC converter is installed between the rotor of the generator and the electrical grid in order to control the wind turbine shaft speed and consequently the generated power. These converters have an intermediate DC-link for energy storage, which increases the total weight and size of the converter, as well as the losses and the system costs, and decreases the overall lifetime of the system. An alternative to these converters are Matrix Converters (MC), that do not require the DC-link and are able to perform the direct AC-AC conversion, allowing the maximum wind power extraction.

The main goal of this work is to design a Maximum Power Point Tracker (MPPT) for the wind power system equipped with a MC. To achieve this goal a model of the converter combined with the Space Vector Representation (SVR) and the Sliding Mode Control (SMC) is created, and used to guarantee that the established reference torque is followed, controlling the DFIG rotor currents.

The whole system has been developed using the Matlab Simulink platform and two different control techniques are used to achieve the Maximum Power Point Tracking: the torque control and the speed control. The results obtained with both approaches are compared.

With the previous features, the appropriate filter scaling and taking advantage of the MC properties it is possible to ensure a nearly unitary power factor of the injected power into the grid and of the power at the MC input circuit, always tracking the established reference torque.

Keywords: Doubly Fed Induction Generator; Wind Turbine; Matrix Converter; Space State Vector; Sliding Mode Control; Maximum Power Point Tracker.
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List of Acronyms

AC – Alternating Current

ASG – Adjustable Speed Generator

DC – Direct Current

DFIG – Doubly-Fed Induction Generator

GTO – Gate Turn-off Thyristor

IGBT – Insulated Gate Bipolar Transistor

MC – Matrix Converter

MOSFET – Metal Oxide Semiconductor Field Effect Transistor

MPPT – Maximum Point Power Tracker

PF – Power Factor

PWM – Pulse Width Modulation

rpm – Rotations per minute

SMC – Sliding Mode Control

SVM – Space Vector Modulation

SVR – Space Vector Representation
List of Symbols

\[ A \] \quad \text{Area swept by the wind turbine blades}

\[ C_f \] \quad \text{Input filter capacitor}

\[ C_p \] \quad \text{Performance coefficient or power coefficient of the wind power turbine}

\[ C \] \quad \text{Concordia transformation matrix}

\[ C(s) \] \quad \text{Speed controller compensator}

\[ D \] \quad \textit{Park transformation matrix}

\[ e_{iq} \] \quad \text{Error of the q component of the input current}

\[ E_k \] \quad \text{Kinetic energy}

\[ e_{a}, e_{b} \] \quad \text{Error between references and measured values}

\[ f \] \quad \text{Generator frequency}

\[ f_c \] \quad \text{Filter cut-off frequency}

\[ G \] \quad \text{Gear ratio}

\[ I \] \quad \text{Current vectors in stator and rotor windings}

\[ I_t \] \quad \text{MC input current}

\[ I_{lef} \] \quad \text{MC input current RMS value}

\[ i_o \] \quad \text{MC output current}

\[ I_{oef} \] \quad \text{MC output current RMS value}

\[ i_{rref} \] \quad \text{MC reference currents}

\[ i_{rdref} \] \quad i_{rd} \text{ reference current}

\[ i_{rqref} \] \quad i_{rq} \text{ reference current}

\[ i_d, i_q, i_0 \] \quad \text{Input currents in d, q, 0 coordinates}
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$i_{qref}$</td>
<td>Reference value of $i_q$ current</td>
</tr>
<tr>
<td>$i_{ra}, i_{rq}$</td>
<td>Rotor currents in dq coordinates</td>
</tr>
<tr>
<td>$i_{sa}, i_{sq}$</td>
<td>Stator currents in dq coordinates</td>
</tr>
<tr>
<td>$i_a, i_{\beta}, i_0$</td>
<td>Output currents in $\alpha, \beta, 0$ coordinates</td>
</tr>
<tr>
<td>$i_{a}^<em>, i_{\beta}^</em>$</td>
<td>Rotor reference currents in $\alpha, \beta$ coordinates</td>
</tr>
<tr>
<td>$i_a, i_b, i_c$</td>
<td>MC input currents</td>
</tr>
<tr>
<td>$i_A, i_B, i_C$</td>
<td>MC output currents</td>
</tr>
<tr>
<td>$J$</td>
<td>Total shaft moment inertia</td>
</tr>
<tr>
<td>$k_q$</td>
<td>Gain of $S_q$ function</td>
</tr>
<tr>
<td>$k_\alpha$</td>
<td>Gain of $S_\alpha$ function</td>
</tr>
<tr>
<td>$k_\beta$</td>
<td>Gain of $S_\beta$ function</td>
</tr>
<tr>
<td>$L$</td>
<td>Matrix of the inductance coefficients</td>
</tr>
<tr>
<td>$L$</td>
<td>Input filter inductance</td>
</tr>
<tr>
<td>$L_r$</td>
<td>Matrix of the rotor self-inductance coefficients</td>
</tr>
<tr>
<td>$L_s$</td>
<td>Matrix of the stator self-inductance coefficients</td>
</tr>
<tr>
<td>$L_s, L_r$</td>
<td>Stator and rotor self-inductance coefficients</td>
</tr>
<tr>
<td>$M$</td>
<td>Mass of the turbine</td>
</tr>
<tr>
<td>$M$</td>
<td>Matrix of the mutual inductance coefficients</td>
</tr>
<tr>
<td>$M_r$</td>
<td>Matrix of the rotor mutual inductance coefficients</td>
</tr>
<tr>
<td>$M_s$</td>
<td>Matrix of the stator mutual inductance coefficients</td>
</tr>
<tr>
<td>$p$</td>
<td>Pair of poles of the generator</td>
</tr>
<tr>
<td>$P_{av}$</td>
<td>Wind power available in the area swept by the wind turbine blades</td>
</tr>
<tr>
<td>$P_e$</td>
<td>Electrical power extracted from the wind</td>
</tr>
</tbody>
</table>
\( P_{in} \)  Matrix Converter input power
\( P_m \)  Mechanical power extracted from the wind
\( P_{out} \)  Matrix Converter output power
\( Q_{grid} \)  Reactive power flow to the grid
\( Q_r \)  Reactive power at the MC input
\( R \)  Turbine radius
\( R_f \)  Input filter resistance
\( r_i \)  Equivalent resistance related to the power that crosses the converter
\( r_o \)  MC output equivalent resistance
\( R_m \)  Matrix of the windings resistance
\( r_s, r_r \)  Stator and rotor resistances
\( S \)  Matrix with the ON/OFF state of the 9 switches
\( S_q \)  Control function for \( q \) component of the input current
\( S_{\alpha}(e_{\alpha, t}), S_{\beta}(e_{\beta, t}) \)  Control function for \( \alpha \) and \( \beta \) components of the output currents
\( S_{cs} \)  Matrix that represents MC relation between line-to-line output voltages and line-to-neutral input voltages
\( S_{ij}( i, j \in \{1, 2, 3\}) \)  Matrix converter switch connecting input phase \( i \) to output phase \( j \)
\( t \)  Time
\( T \)  Blondel-Park transformation matrix
\( T_c \)  Load torque
\( T_{em} \)  Electromagnetic torque
\( T_m \)  Mechanical torque extracted from the turbine rotor
\( T_{MPPT} \)  Torque applied to the generator to guarantee maximum power point tracking
\( T_{ref} \)  
Reference torque of the system

\( u \)  
Wind speed

\( U \)  
Vector of DFIG stator and rotor voltages

\( u_{rd}, u_{rq} \)  
Rotor voltages in dq coordinates

\( u_{sd}, u_{sq} \)  
Stator voltages in dq coordinates

\( V_{ef} \)  
Effective MC input voltage

\( v_{rms} \)  
Effective voltage at filter’s input

\( V_{oef} \)  
Effective MC output voltage

\( v_a, v_b, v_c \)  
MC line-to-neutral input voltage

\( v_A, v_B, v_C \)  
MC line-to-neutral output voltage

\( v_{AB}, v_{BC}, v_{CA} \)  
MC line-to-line output voltage

\( v_{\alpha}, v_{\beta}, v_0 \)  
Matrix Converter output voltages in \( \alpha, \beta, 0 \) coordinates

\( Z_f \)  
Input filter characteristic impedance

\( \mu_i, \mu_o \)  
Argument of MC output currents vectors

\( \beta \)  
Pitch angle of the wind turbine blades [rad]

\( \Delta \)  
Hysteretic comparator error

\( \delta_o \)  
Argument of MC output voltages vectors

\( \eta \)  
Matrix Converter Efficiency

\( \theta \)  
Rotor angular position

\( \lambda \)  
Tip-speed ratio

\( \lambda_i \)  
Auxiliary variable

\( \rho \)  
Air density

\( \phi_{out} \)  
Phase angle of the output load
<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\Psi_{rd}, \Psi_{rq}$</td>
<td>Rotor flux, in dq coordinates system</td>
</tr>
<tr>
<td>$\Psi_{sd}, \Psi_{sq}$</td>
<td>Stator flux, in dq coordinates system</td>
</tr>
<tr>
<td>$\omega$</td>
<td>Network angular frequency</td>
</tr>
<tr>
<td>$\omega_{dq}$</td>
<td>Angular speed of dq reference frame</td>
</tr>
<tr>
<td>$\omega_m$</td>
<td>Angular speed of the generator shaft</td>
</tr>
<tr>
<td>$\omega_{mref}$</td>
<td>Angular speed reference of the generator shaft</td>
</tr>
<tr>
<td>$\omega_s$</td>
<td>Stator voltages angular speed</td>
</tr>
<tr>
<td>$\omega_t$</td>
<td>Angular speed of the turbine shaft</td>
</tr>
<tr>
<td>$\omega_{T_{opt}}$</td>
<td>Optimum angular speed of the turbine shaft generated by the wind</td>
</tr>
<tr>
<td>$\omega_p$</td>
<td>Filter angular cut-off frequency</td>
</tr>
<tr>
<td>$\zeta$</td>
<td>Damping coefficient of the filter</td>
</tr>
</tbody>
</table>
1. INTRODUCTION

1.1. Context and Motivation

Climate change concerns, together with high oil prices, have been leading to most governments awareness of global energy issues. This has resulted in renewable energy legislation and standards and to government incentives to renewable energy production and commercialization [1]. Nowadays, renewable energies as the wind, sun, water, geothermal heat and biomass, supply 19% of the global final energy consumption (Figure 1.1) [2].

![Figure 1.1 - Renewable energy share of global final energy consumption in 2008](image)

Despite the global economic crisis, wind power is one of the most promising renewable energies and its capacity installation in 2009 reached a record of 38GW. This represented a growth rate of 31.7% and brought the global total to 159GW [2]. Figure 1.2 presents the worldwide installed capacities in the countries with the highest installed wind capacity.

In some countries and regions wind has become one of the largest electricity sources. For example, in Portugal, in 2009, the wind generation was 15% of the total consumption [2] and represented 51.8% of the renewable energy sources in the country [3].
The first wind turbines had a rated power of 200 kW, using a simple squirrel-cage induction machine directly connected to a three-phase power grid [4]. This pioneer technology was usually operated with nearly constant speed and frequency, extracting power from a limited wind speed range, wasting a lot of the available wind power. However, the development of this technology led to the modern high-power wind turbines up to 7.5 MW [5], capable of adjustable speed operation and extraction of the maximum wind energy [4], [6].

There are wind turbines equipped with a synchronous machine as generator, with or without gearbox, where the voltage and frequency are set to the network connection using a AC-DC-AC [6], equipped with a an Adjustable Speed Generator (ASG). However, the converter processes all the system power, and the system efficiency depends highly on the converter and filters efficiency, resulting in more expensive and complex projects [4].

The use of Doubly Fed Induction Generator (DFIG) together with AC-AC converters may bring several advantages, mainly due to the fact that the power processed by the converter and filter, is only the slip recovery power, which is around 25% of the total system power. Thus it is possible to generate active power through the rotor and the stator and control the reactive power [4], [7], [8].

The most commonly used three-phase AC-AC converter is the rectifier-inverter back to back structure [9], [10], [11] (Figure 1.3). However, the intermediate DC-link storage components (electrolytic capacitors), increase the converter total weight and size, as well as the losses and the system cost [4], decreasing the overall lifetime.
Matrix Converter (MC) are bidirectional single-stage AC-AC converters, able to supply output voltages with variable frequency, guaranteeing adjustable input displacement angle [9]. They are simple and compact, without dc-link and no energy storage elements [10], [11], as shown in Figure 1.4. These features make the MC a lighter, cheaper and less bulky converter than the conventional AC-DC-AC, and can also present higher efficiency depending on the semiconductors control [9]. In the last years they have been used in aerospace, transportation and industrial applications.

However, these converters have the output voltage limited to $\sqrt{3}/2$ of input voltage, and due to the input/output coupling, as a result of nearly no energy storage components, the output voltages are more sensitive to the input disturbances, and the control is more complex.

In the proposed structure, the converter is connected between the DFIG rotor and the grid through a filter, as shown in Figure 1.5.
The output voltages and input currents obtained for each one of the MC switches state are represented as vectors known as State Space Vectors [12], [13]. Based on this representation, the vectors are chosen to guarantee that the converter currents or voltages follow the desired reference values.

The reference values are established based on the Maximum Power Point Tracker (MPPT), which returns the optimum turbine speed and torque according to the wind speed. Based on this approach, two different controllers are designed: torque controller and speed controller. In the first, the matrix converter reference currents are established based on the torque reference, and are directly controlled based on the Space Vector Representation. In the second approach, a linear speed controller is designed for the DFIG. Based on the speed error a reference for the DFIG torque is established.

The Sliding Mode Control (SMC) together with the Space Vector Representation technique is used to control the MC input and output currents. As the switching occurs just in time, this technique guarantees fast response times and precise control actions, ensuring that the input and output currents track their references, with input power factor regulation independent of the input filter parameters [14].
1.2. Purpose

The main purpose of this thesis is to analyse and evaluate the use of a matrix converter to control a DFIG in a wind turbine, guaranteeing the maximum power extraction from the available wind.

To achieve this goal the MC model and two control methods are designed to guarantee MPPT: torque control and speed control. Also, the two control approaches must guarantee an almost unitary power factor of the MC and the DFIG.

1.3. Thesis Organization

This thesis is organized in six chapters.

Chapter 1 presents the introduction, the main purpose of the thesis and its organization.

Chapter 2 introduces the wind turbine characteristics and model, the torque delivered to the generator shaft and both MPPT control systems: speed control and torque control.

Chapter 3 is dedicated to the doubly fed induction generator, its model, the stator flux oriented control as well as the power factor control of the whole system.

Chapter 4 presents the matrix converter model, explaining how the space state vectors and the sliding mode control can generate the desired output current and input current phase. In addition the MC input filter is sized, to reduce the high frequency currents injected in the electrical grid.

In chapter 5 the simulation results are presented, regarding the MC input and output currents, the filter efficiency, the power factor in different points of the circuit and the comparison between the two MPPT techniques.

Chapter 6 presents the conclusions of the developed work and some suggestions for future work.
2. **WIND TURBINE**

2.1. **Introduction**

Wind energy has been one of the most important and promising sources of renewable energy all over the world. This has resulted in the rapid development of wind turbine related technology in the last years [15].

These renewable wind energy systems are used to convert the kinetic energy of the flowing air (wind) into electricity. The mechanical power at the turbine depends on the speed of air flow across it, making it widely variable with the intensity and wind direction, since the available power depends on a cubic factor of the speed. However, the large inertia of the wind turbine acts as a low-pass filter, and, in practice, the shaft of the turbine rotates at a speed less subject to variations in air flow.

Doubly-fed induction generators (DFIG) have become very popular in the last few years for wind energy generation systems, as they allow a significant reduction of the power converters size and cost, when compared to full rated power converter systems. This is due to the fact that DFIG power converters are connected to the induction machine rotor, which only processes 25% - 30% of the total system power (the slip power of the rotor) [8].

2.2. **Wind turbine components**

Based on Figure 2.1 and Figure 2.2 the most important components of a wind turbine will be described.
Figure 2.1 - General configuration of a wind turbine

Rotor blades

The rotor blades are based on the same technology used to develop the airplanes wings. These are perchance one of the most complex components of the wind turbine and are used to extract the kinetic energy from the wind and control the available power, to avoid exceeding the nominal power and damage the wind turbine. This control can be made using two different technologies [6], [16]:

Figure 2.2 – Main wind turbine components
• **Stall** – The profile of the blades is designed in order to get aerodynamic losses after a certain wind speed;

• **Pitch** – It is based on changing the longitudinal axis of the blades, which is called pitch angle. Thus the blades come into loss but in a more controlled way and the desired power zone can be better tracked.

Another important feature to consider is the position of the rotor blades relatively to the tower. There are two possibilities [6]:

• **Upwind** – They have the rotor facing the wind. The basic advantage of upwind designs is that the wind shade behind the tower is avoided. However it needs a yaw mechanism to keep the rotor facing the wind. By far the vast majority of wind turbines have this design.

• **Downwind** – This kind of turbines have the rotor placed on the lee side of the tower. As an advantage they may be built without a yaw mechanism, if the rotor and nacelle have a suitable design to guarantee that the wind is passively followed.

**Nacelle**

The nacelle is the cabin of the generator where is the main shaft, yaw system, gearbox, brake, hydraulics system, generator, power converter and automation systems [6], among other equipments.

**Gearbox**

The gearbox connects the low-speed shaft to the high-speed shaft and increases the rotational speeds from about 30 to 60 rotations per minute (rpm), on the turbine side, to about 1200 to 1500 rpm, the rotational speed required by most generators to produce electricity.

In this work, the gearbox is modelled as a gain, thus the angular speed and the torque relationships, between the input and output of the gearbox, are given by (2.1):

\[
G = \frac{\omega_m}{\omega_t} = \frac{T_t}{T_g}
\]  

(2.1)

The angular speed ($\omega_m$ in rpm) of the generator is given by (2.2).
Electrical Generator

The generator converts the mechanical energy available in the high-speed shaft into electrical energy [6].

Mechanical Brakes

A mechanical friction brake and its hydraulic system halt the turbine blades during maintenance and overhaul. A hydraulic disc brake on the yaw mechanism maintains the nacelle desired position [6].

Yaw Mechanism and Four-Point Bearing

Yaw Mechanism and Four-Point Bearing rotate and place the turbine directly into the wind in order to generate maximum power. Typically, four yaw sensors monitor the wind direction and activate the yaw motors to face the prevailing wind. Under high speed winds the yaw mechanism turns the blades 90 degrees from the direction of the wind to reduce stress on internal components and avoid overspeed conditions [16].

2.3. Wind power

The available energy in the wind is the kinetic energy associated to the movement of a air cylinder moving across the blades area with a constant speed \( u \).

\[
E_k = \frac{1}{2} m u^2
\]  

(2.3)

Considering \( m = \rho A u \ [Kg/s] \) the mass of air that crosses the blades area per second, the power available in the area \( A \) swept by the wind turbine blades is given by (2.4):

\[
P_{av} = \frac{1}{2} \rho A u^3
\]

(2.4)

It is impossible to extract all the power from the wind because some flow must be maintained through the turbine blades area. The application of fluid mechanics concepts demonstrates that there is a theoretical maximum for the efficiency of power extraction from the wind, known as Betz limit which is 59.3% of the power in the area swept by the wind turbine blades [6].
As a result, the wind turbine power coefficient \( C_p \) is defined as (2.5).

\[
C_p = \frac{P_m}{P_{av}}
\]  

(2.5)

Most of the wind turbine producers introduce the efficiency of the generator in \( C_p \), so the most usual expression is:

\[
C_p = \frac{P_e}{P_{av}}
\]  

(2.6)

\( C_p \) is calculated according to (2.7) and it depends on the pitch angle (\( \beta \)) and on the tip-speed ratio (\( \lambda \)).

\[
C_p = 0.22 \left( \frac{116}{\lambda_t} - 0.4\beta - 5 \right) e^{\frac{-12.5}{\lambda_t}}
\]  

(2.7)

Where:

\[
\lambda_t = \left( \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \right)^{-1}
\]  

(2.8)

The tip-speed ratio (\( \lambda \)) is given by:

\[
\lambda = \frac{\omega_{t} \cdot R}{u}
\]  

(2.9)

From (2.4) and (2.6) the electrical power can be written as in (2.10):

\[
P_e = \frac{1}{2} C_p (\beta, \lambda) \cdot \rho \cdot A \cdot u^3
\]  

(2.10)

The mechanical torque extracted from the turbine rotor is \( T_m \) and its value is given by (2.11).

\[
T_m = \frac{P_e}{\omega_m}
\]  

(2.11)

In this project the pitch angle of the wind turbine blades, \( \beta \), is considered zero. This way and assuming that the rotor angular speed can be described by (2.1), the mechanical torque used is calculated based on (2.12).
\[ T_m = \frac{1}{2} \rho \cdot A \cdot u^3 \cdot \frac{1}{G \cdot \omega_t} \cdot 0.22 \left[ \frac{116}{u \cdot \omega_t \cdot R - 0.035} - 5 \right] - \frac{12.5}{u \cdot \omega_t \cdot R - 0.035} \] (2.12)

2.4. MPPT – Maximum Point Power Tracking

Figure 2.3 shows the characteristic of the turbine used in this thesis, with \( P = 1.5MW \) and blades length \( R = 38.5m \), considering a fixed \( \beta \) and different constant wind speeds. These values are based on turbine Nordex S77 parameters (Appendix E).

![Figure 2.3 - Wind turbine characteristics for different wind speeds and \( \beta = 0 \)](image)

Figure 2.3 shows that for each power curve, correspondent to each constant wind speed, there is one point where the mechanical power extracted from the wind is maximum. Therefore to extract the maximum energy from the wind, the designed controllers should guarantee that the turbine is kept on the maximum power curve while the wind speed changes.

Two kinds of control are used to follow the maximum power point:
- Speed control – control of the generator speed, according to each wind speed;

- Torque control – control of mechanical torque delivered to the generator.

In both cases a reference value is established and the MC applies the space vectors necessary to follow this reference.

The pitch angle is set to zero in order to maximize the mechanical power delivered to the generator. However, it is important to mention that the pitch control is usually activated when the wind speed is higher than the nominal, in order to keep the nominal power of the generator.

2.4.1. MPPT – Speed control

To establish a MPPT reference, it is necessary to determine the maximum torque generated by the wind turbine.

Based on the equation (2.10) the electrical power extracted from the wind is given by (2.13).

\[
P_e = \frac{1}{2} 0.22 \left( \frac{116}{\left( \frac{1}{\omega_t R} + 0.08 \beta \right) - 0.035} - 0.4 \beta - 5 \right) e^{-\left( \frac{12.5}{\left( \frac{\omega_t R}{u} + 0.08 \beta \right) \beta^3 + 1} \right)} \cdot \rho \cdot A \cdot u^3 \tag{2.13}
\]

To achieve the optimum turbine speed \( \omega_{\text{opt}} \) which generates the maximum power, \( \beta \) is assumed to be zero. Then, to calculate the maximum value of the extracted power (2.13), its derivative is calculated and made equal to zero (2.14):

\[
\frac{dP_e}{d\omega_t} = 0 \tag{2.14}
\]

From (2.13) and (2.14) is obtained (2.15):

\[
\frac{dP_e}{d\omega_t} = -39.0576 \cdot A \cdot \rho \cdot (3.7267 \times 10^{-6}) \frac{u}{\omega_t R} \cdot (\omega_t \cdot R - 632497 \cdot u) \cdot u^4 \tag{2.15}
\]

Solving (2.15) the optimum turbine speed \( \omega_{\text{opt}} \) can be calculated according to (2.16):
\[ \omega_{\text{opt}} = \frac{6.32497 \cdot u}{R} \]  

(2.16)

Thus the generator speed reference \( \omega_{\text{mref}} \) is given by (2.17).

\[ \omega_{\text{mref}} = G \frac{6.32497 \cdot u}{R} \]  

(2.17)

To design the speed controller, it is assumed that the matrix converter may be modeled as a first order system, with one pole dependent on the switching period. The DFIG may be also modeled as a first order mechanical system with one dominant pole dependent on the generator inertia.

The block diagram of the controlled system is represented in Figure 2.4.

The reference torque \( T_{\text{ref}} \) is generated by the compensator. This reference will establish the reference currents \( i_{\text{ref}} \) for the matrix converter. The electromagnetic torque of the generator will depend on these currents. The generator speed will be dependent on the difference between the electromagnetic torque and the torque generated by the turbine.

The compensator \( C(s) \) choice is done admitting that it is a 2\(^{nd}\) order open-loop chain, without any poles at complex plane origin and with 2 real poles at \(-1/T_d\) and \(-K_d/J\).

The system has \( T_m \) as a perturbation, and to guarantee a zero static error the compensator needs the integral feature. This way, in steady state, the controller assures the insensibility of the system to this perturbation. However, an integral compensator is usually too slow, due to its poles, in closed-loop chain, near the complex plane origin. To guarantee faster response times, a proportional-integral controller (PI) [17] is used instead:

\[ C(s) = \frac{1 + T_e \cdot s}{T_p \cdot s} = K_p + K_i \cdot s \]  

(2.18)
From Figure 2.4 the closed-loop transfer function of the system is given by (2.19):

$$\frac{\omega_m}{\omega_{mref}} = \frac{1}{s^2 + \frac{1}{T_d^2} s + \frac{K_t}{T_p K_d T_d}}$$  \hspace{1cm} (2.19)

As a second order system it can be written in the standard form (2.20), where \(\omega_0\) is the natural frequency and \(\zeta\) the damping factor.

$$\frac{\omega_m}{\omega_{mref}} = \frac{\omega_0^2}{s^2 + 2\zeta \omega_0 s + \omega_0^2}$$  \hspace{1cm} (2.20)

In order to cancel the low frequency pole of the system at \(-K_d/J\), \(T_z\) is given by (2.21).

$$T_z = \frac{J}{K_d}$$  \hspace{1cm} (2.21)

Comparing (2.19) and (2.20) the compensator parameters can be calculated:

$$\omega_0 = \frac{1}{2\zeta T_d}$$  \hspace{1cm} (2.22)

$$T_p = \frac{1}{\omega_0^2 K_d T_d} = \frac{1}{\frac{1}{(2\zeta T_d)^2} K_d T_d}$$  \hspace{1cm} (2.23)

Finally all the speed controller parameters are calculated. To do that, it was used the Matlab code present in the Appendix F, and the results are in the Table 2.1.

<table>
<thead>
<tr>
<th>Table 2.1 - Speed Control Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>(K_t)</td>
</tr>
<tr>
<td>1</td>
</tr>
</tbody>
</table>
2.4.2. MPPT – Torque control

Knowing \( \omega_{T_{\text{opt}}} \) (2.16) and replacing it in (2.13) the maximum extractable electrical power is:

\[
P_{\text{max}} = \frac{1}{2} \cdot \rho \cdot A \cdot u^3 \cdot 0,22 \cdot 116 \cdot \frac{1}{1} - 5 \cdot e \cdot \frac{12,5}{6,32497 - 0,035}
\]  

(2.24)

The equation (2.25) is based on (2.11) and gives the relation between the turbine torque and the maximum electrical power.

\[
T_{\text{MMPT}} = \frac{P_{\text{max}}}{G \cdot \omega_{T_{\text{opt}}}}
\]  

(2.25)

From (2.24) and (2.25) the maximum torque that should be applied to the generator is defined by (2.26).

\[
T_{\text{MPPT}} = \frac{1}{2} \cdot \rho \cdot A \cdot u^3 \cdot 0,22 \cdot \frac{1}{G \cdot \omega_{T_{\text{max}}}} \cdot 116 \cdot \frac{1}{1} - 5 \cdot e \cdot \frac{12,5}{6,32497 - 0,035}
\]  

(2.26)

As \( \rho = 1,225 \, \text{kg/m}^3 \), it is possible to simplify (2.26) and obtain (2.27), that will be used to establish the reference torque.

\[
T_{\text{ref}} = T_{MPPT} = \frac{0,843213 \cdot R^2 \cdot u^3}{G \cdot \omega_{T_{\text{opt}}}}
\]  

(2.27)

The reference torque \( T_{\text{ref}} \) will then be used in order to define the reference current \( i_{\text{ref}} \), the one that the MC has to generate at the output, with the purpose of following the established maximum power point.
3. **DOUBLY-FED ELECTRICAL GENERATOR**

3.1. **Introduction**

In the last years, Doubly Fed Induction Generators (DFIG) has become the most attractive for wind energy generation systems. These wound-rotor asynchronous generators, have two independent active winding sets, and allow the extraction of energy not only from the stator but also from the rotor of the machine [18], [19], enabling the operation at variable speed. The rotating winding is connected to the grid through a matrix converter. The advantage of connecting the converter to the rotor is that variable-speed operation of the turbine is possible with a much smaller and therefore much cheaper converter, as the converter rated power is usually about 25% of the nominal generator's power [4].

Figure 3.1 shows how DFIG is connected the power generation schematics and how it is connected to the grid.

![DFIG and its connection to the grid](image)

Figure 3.1 - DFIG and its connection to the grid

As a regular three-phase induction machine, DFIG has three stator windings as well as rotor windings displaced 120° from each other. The rotor circuit position changes in relation to the stator according to an angle θ, which defines the rotor angular position [20], as shown in Figure 3.2.
The two poles machine model has its voltage output given by (3.1), while (3.2) expresses the equilibrium between the load torque $T_c$ and the electromagnetic torque $T_{em}$.

\[
U = R_m I + L \frac{dI}{dt} + \frac{\partial L}{\partial \theta} \omega_m I \quad (3.1)
\]

\[
\int \frac{d\omega_m}{dt} = T_{em} - T_c \quad (3.2)
\]

The electromagnetic torque $T$ is calculated by (3.3).

\[
T_{em} = \frac{1}{2} \int \omega \frac{\partial L}{\partial \theta} I \quad (3.3)
\]

The model is based on the machine inductance and resistance coefficients. Taking this into account the inductances matrix $L$ (3.4), can be divided into four sub-matrixes.

\[
L = \begin{bmatrix}
L_s & M_s \\
M_r & L_r
\end{bmatrix} \quad (3.4)
\]

Those sub-matrixes are:

- Matrix of the rotor mutual inductance coefficients (3.5);
- Matrix of the stator mutual inductance coefficients (3.6):

\[
M_s = \begin{bmatrix}
M \cos(\theta) & M \cos(\theta + \frac{2\pi}{3}) & M \cos(\theta + \frac{4\pi}{3}) \\
M \cos(\theta + \frac{2\pi}{3}) & M \cos(\theta) & M \cos(\theta + \frac{2\pi}{3}) \\
M \cos(\theta + \frac{4\pi}{3}) & M \cos(\theta + \frac{2\pi}{3}) & M \cos(\theta)
\end{bmatrix}
\] (3.6)

- Matrix of the rotor self-inductance coefficients (3.7):

\[
L_r = \begin{bmatrix}
L_r & -\frac{1}{2}M_r & -\frac{1}{2}M_r \\
-\frac{1}{2}M_r & L_r & -\frac{1}{2}M_s \\
-\frac{1}{2}M_r & -\frac{1}{2}M_s & L_r
\end{bmatrix}
\] (3.7)

- Matrix of the stator self-inductance coefficients (3.8):

\[
L_s = \begin{bmatrix}
L_s & -\frac{1}{2}M_s & -\frac{1}{2}M_s \\
-\frac{1}{2}M_s & L_s & -\frac{1}{2}M_s \\
-\frac{1}{2}M_s & -\frac{1}{2}M_s & L_s
\end{bmatrix}
\] (3.8)

The rotor and stator windings resistance matrix is:

\[
R_m = \begin{bmatrix}
r_s & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & r_s & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & r_s & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & r_r & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & r_r & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & r_r & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & r_r
\end{bmatrix}
\] (3.9)
To simplify the dynamic model of the machine Blondel-Park transformation is applied. First Concordia transformation (3.10) is applied and it consists in transforming a three-phase system (abc coordinates) into a bi-phase system (αβ coordinates) in which α and β coordinates are in quadrature.

\[
C = \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 & 1 \\ \frac{1}{2} & \frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} & \frac{1}{\sqrt{2}} \end{bmatrix}
\]  

(3.10)

\[
\begin{bmatrix} \alpha \\ \beta \\ 0 \end{bmatrix} = C^T \begin{bmatrix} a \\ b \\ c \end{bmatrix}
\]  

(3.11)

However, this transformation keeps θ dependence, therefore Park transformation (dq coordinates) is applied, generating a system that depends on ϕ which is the displacement between αβ and dq reference frames. These frames have the same origin as shows Figure 3.3.

![Figure 3.3 – Relation between αβ and dq reference frames](image)

Park transformation matrix is given by (3.18).

\[
D(\phi) = \begin{bmatrix} \cos \phi & -\sin \phi \\ \sin \phi & \cos \phi \end{bmatrix}
\]  

(3.12)
\[
[d] = D^T [\beta]
\] (3.13)

Finally the Blondel-Park transformation matrix is given by (3.14), which is the combination of Concordia transformation and Park transformation.

\[
T = \begin{bmatrix}
\cos \phi & -\sin \phi & \frac{1}{\sqrt{2}} \\
\frac{2}{3} \cos\left(\phi - \frac{2\pi}{3}\right) & \sin\left(\phi - \frac{2\pi}{3}\right) & \frac{1}{\sqrt{2}} \\
\cos\left(\phi - \frac{4\pi}{3}\right) & -\sin\left(\phi - \frac{4\pi}{3}\right) & \frac{1}{\sqrt{2}}
\end{bmatrix}
\] (3.14)

After applying Blondel-Park transformation, the dynamic behavior of the machine, in dq coordinates, is given by (3.16).

\[
\begin{align*}
 u_{sd} &= r_s i_{sd} + \frac{d\psi_{sd}}{dt} - \omega_{dq} \psi_{sq} \\
 u_{sq} &= r_s i_{sq} + \frac{d\psi_{sq}}{dt} + \omega_{dq} \psi_{sd} \\
 u_{rd} &= r_r i_{rd} + \frac{d\psi_{rd}}{dt} - (\omega_{dq} - p\omega_m) \psi_{rq} \\
 u_{rq} &= r_r i_{rq} + \frac{d\psi_{rq}}{dt} + (\omega_{dq} - p\omega_m) \psi_{rd}
\end{align*}
\] (3.16)

The relation between the linkage fluxes and the currents is:

\[
\begin{align*}
\psi_{sd} &= L_s i_{sd} + M i_{rd} \\
\psi_{sq} &= L_s i_{sq} + M i_{rq} \\
\psi_{rd} &= L_r i_{rd} + M i_{sd} \\
\psi_{rq} &= L_r i_{rq} + M i_{sq}
\end{align*}
\] (3.17)

The electromagnetic torque can be obtained as a function of the generator pair of poles (p), the linkage flux and the stator currents:

\[
T_{em} = p(i_{sq} \psi_{sd} - i_{sd} \psi_{sq})
\] (3.18)
3.2. Stator Flux Oriented Control

The adopted control used in this project is the stator flux oriented control in which the dq reference frame is attached to the stator linkage flux \( \Psi_s \). Consequently the q-component of the flux is zero.

\[
\begin{align*}
\Psi_{sd} &= \Psi_s \\
\Psi_{sq} &= 0
\end{align*}
\]

Combining (3.19) with (3.18) results into (3.20).

\[
T_{em} = p \cdot i_{sq} \Psi_{sd}
\]  

To obtain the reference torque, and consequently, the reference rotor current to control the generator, it is necessary to consider (3.19) and \( \Psi_{sq} \) that is given by (3.17), in order to get (3.22).

\[
0 = L_s \cdot i_{sq} + M \cdot i_{rq} 
\Rightarrow i_{sq} = \frac{-M}{L_s} \cdot i_{rq}
\]

\[
T_{em} = -p \cdot \frac{M}{L_s} \Psi_{sd} i_{rq}
\]  

Usually, for these large power generators the stator resistance can be neglected, since it is quite small in comparison to the stator reactance \( r_s << \omega_s L_s \). Therefore \( u_s \) (3.16) can be written as follows:

\[
\begin{align*}
\begin{cases}
u_{sd} & \approx \frac{d\Psi_{sd}}{dt} \\
\varepsilon_{sq} & \approx \omega_{dq} \Psi_{sd}
\end{cases}
\]

In a steady-state a reference frame synchronized with the stator has the same angular frequency \( \omega_{dq} \) of stator voltages:

\[
\omega_s = \omega_{dq} = \text{const}
\]

In order to determine the stator flux magnitude it is necessary to calculate the voltage \( u_{sd} \) integral, and the result is [21]:
\( \psi_{sd} = \frac{\sqrt{3}V_{ef}}{\omega_s} = \text{const} \)  \hspace{1cm} (3.25)

This way the components of the stator voltage take the value:

\[
\begin{cases}
  u_{sd} = 0 \\
  u_{sq} = \omega_s \psi_{sd} = \sqrt{3}V_{ef}
\end{cases}
\]  \hspace{1cm} (3.26)

Considering (3.22) and (3.25) the rotor q-component current is obtained as in (3.27).

\[ i_{rq} = - \frac{L_s}{p M \sqrt{3}V_{ef}} T_{em} \]  \hspace{1cm} (3.27)

Once the goal is to establish the rotor q-component reference current \( i_{rq\text{ref}} \), the one that returns the maximum output power, it is possible write the equation (3.28) that depends on the maximum corresponding torque \( (T_{\text{ref}}) \). The torque value is related with the wind power and is calculated according to (2.27), or given by the speed controller, depending on the desire control.

\[ i_{rq\text{ref}} = - \frac{L_s}{p M \sqrt{3}V_{ef}} T_{\text{ref}} \]  \hspace{1cm} (3.28)

### 3.2.1. Control of the global Power Factor of the system

The d-component of the reference current \( i_{rd\text{ref}} \) is used to control the power factor at the point of connection with the network.

Considering the reactive power of the stator as:

\[ Q_s = u_{sq} i_{sd} - u_{sd} i_{sq} \]  \hspace{1cm} (3.29)

Taking into account (3.17) and (3.19) the currents \( i_{sd} \) and \( i_{sq} \) are:
\[ i_{sd} = \frac{\psi_{sd} - M i_{rd}}{L_s} \]
\[ i_{sq} = -\frac{M}{L_s} i_{rq} \]  

(3.30)

Assuming also the stator voltages given by (3.26) and the currents by (3.30) the reactive power \( Q_s \) is as (3.32).

\[ Q_s = u_{sq} \frac{\psi_{sd} - M i_{rd}}{L_s} + u_{sd} \frac{M}{L_s} i_{rq} \]  

(3.31)

\[ Q_s = \frac{\sqrt{3} V_{ef}}{L_s} (\psi_{sd} - M i_{rd}) \]  

(3.32)

The current \( i_{rd,ref} \) establishes the reference current of the converter in order to guarantee the desired reactive power \( Q_s \).

\[ i_{rd,ref} = \frac{1}{M} \left( \psi_{sd} - \frac{Q_s}{\sqrt{3} V_{ef}} L_s \right) \]  

(3.33)

In chapter 4.3.4 the condition necessary to get an unitary power factor at the input of the MC is set. Consequently, it will be considered that the reactive power \( Q_r \) at the point of connection with the grid, as shown in Figure 3.4, will be almost zero.

![Diagram of reactive power flow](image)

**Figure 3.4 - Reactive power flow**

From Figure 3.4, the reactive power at the connection point with the network will be:
To achieve an unitary power factor condition (3.35) must be satisfied:

\[ Q_{grid} = Q_r + Q_s \Leftrightarrow Q_{grid} = Q_s \]  

(3.34)

Consequently the current \( i_{rd_{ref}} \) to generate the desired power factor will take the value (3.36).

\[ i_{rd_{ref}} = \frac{1}{M} \frac{\sqrt{3}V_{ef}}{\omega_s} \]  

(3.36)
4. MATRIX CONVERTER

4.1. Introduction

The basic topology of a cycloconverter was proposed and patented by Hazeltine in 1926. The main aim of this converter was to obtain a nearly sinusoidal voltage with variable frequency, obtained from a sequence of voltage segments provided by a polyphase AC supply [22].

The first cycloconverter prototypes used mercury arc valves with phase control. At the end of the fifties, new cycloconverter prototypes were proposed using line commutated semiconductors, which allowed lower conduction voltage drops and higher frequencies operation [22].

In the last years, the fast industrial development of power semiconductors and their packaging, have guaranteed lower volume converters, minimizing stray inductances. In addition, with the improvement of command and control circuits, these converters have become increasingly attractive [22].

The AC-AC matrix topology was first investigated in 1976 [23], [13]. However, the real development of Matrix Converters starts with the work of Venturini and Alesina published in 1980 [14], [23], [24]. They presented the power circuit of the converter as a matrix of bidirectional power switches and they introduced the name “Matrix Converter” (MC). Then in 1983 Braun and in 1985 Kastner and Rodriguez introduced the use of space vectors in the analysis and control of Matrix Converters [25]. In 1989, Huber introduced the Space Vector Modulation (SVM) applied to Matrix Converters [25]. Kastner and Rodriguez in 1985 and Neft and Schauder in 1992 confirmed experimentally that a MC with only 9 switches can be effectively used in the vector control of an induction motor with high quality input and output currents [24]. This modulation associated with sliding mode control, studied by Kulebakin in 1934 [26], allows a direct selection of the switches combinations necessary to control the matrix converter output voltages and input phase currents [22].

With this topology it is possible to obtain several advantages, when compared to the traditional AC-DC-AC converter. There are two basic advantages over the traditional rectifier-inverter-based back-to-back frequency changers: they do not require any intermediate DC-link reactive components and they are bidirectional so can regenerate energy back to the supply [27], [28].
Table 4.1 - Advantages and disadvantages of MC when compared to an AC-DC-AC back-to-back topology

<table>
<thead>
<tr>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>No intermediate DC stage</td>
<td>Large number of semiconductors</td>
</tr>
<tr>
<td>Allow power regeneration (bidirectional)</td>
<td>Amplitude output voltage smaller than input (\frac{v_o}{v_i}_{\text{max}} = \frac{\sqrt{3}}{2})</td>
</tr>
<tr>
<td>Input currents nearly sinusoidal</td>
<td>Semiconductors are more likely to suffer from perturbations</td>
</tr>
<tr>
<td>Nearly unity power factor</td>
<td>More complex control system</td>
</tr>
<tr>
<td>High reliability</td>
<td></td>
</tr>
<tr>
<td>High power density</td>
<td></td>
</tr>
<tr>
<td>Can work as AC-AC converter, DC-AC and AC-DC</td>
<td></td>
</tr>
<tr>
<td>Can work under high temperature conditions</td>
<td></td>
</tr>
</tbody>
</table>

In the last years Matrix Converters have been increasingly used in aerospace, transportation, renewable energies and industrial applications. Also, their use for wind generation systems is becoming more attractive because of the high power that a MC can process nowadays [29].

4.2. Matrix Converter model for three-phase systems

Three-phase MC connects the three-phase AC voltages on the input side, to the three-phase voltages on output side by a 3x3 matrix using bidirectional switches. A total of 9 bidirectional switches are needed, that allow the connecting of any output phase to any input phase. A second-order LC filter is used to filter the high frequency harmonics of the input current [9]. Apart from this filter, the matrix converter has no more reactive elements [22].
Each bidirectional switch results from 2 one-way switches and 2 diodes such as in Figure 4.2 [30], where $S_{1n}$ represents the semiconductors through which flows the negative load current and $S_{1p}$ represents the semiconductors through which flows the positive load current.

In this bidirectional switch arrangement it is usual to use Insulated Gate Bipolar Transistors (IGBT). However, Metal Oxide Semiconductor Field Effect Transistors (MOSFET) and Gate Turn-off Thyristors (GTO) have also been used [31].

Considering $S_{ij}(i,j \in \{1,2,3\})$ as a bidirectional switch, where $i$ and $j$ indexes represent the position of the switches of matrix $S$ (4.2), it is possible to establish a simple relationship between line-to-neutral input voltages $(v_a, v_b, v_c)$ and line-to-neutral output voltages $(v_{A}, v_{B}, v_{C})$ [31], [32].

$$S_{ij} = \begin{cases} 1 & \text{ON} \\ 0 & \text{OFF} \end{cases} \quad i,j \in \{1,2,3\}$$  \hspace{1cm} (4.1)
The transpose of matrix $S$ enables the relationship between the input currents $(i_a, i_b, i_c)$ and the converter output currents $(i_A, i_B, i_C)$.

\[
\begin{bmatrix}
    i_a \\
    i_b \\
    i_c \\
\end{bmatrix} = [S]^T \begin{bmatrix}
    i_A \\
    i_B \\
    i_C \\
\end{bmatrix}
\] (4.4)

$S_{CS}$ matrix relates line-to-line output voltages $(v_{AB}, v_{BC}, v_{CA})$ to line-to-neutral input voltages $(v_a, v_b, v_c)$ (Appendix A).

\[
[S_{CS}] = \begin{bmatrix}
    S_{11} - S_{21} & S_{12} - S_{22} & S_{13} - S_{23} \\
    S_{21} - S_{31} & S_{22} - S_{32} & S_{23} - S_{33} \\
    S_{31} - S_{11} & S_{32} - S_{12} & S_{33} - S_{13} \\
\end{bmatrix}
\] (4.5)

From (3.5), the output line-to-line voltage is given by (4.6).

\[
\begin{bmatrix}
    v_{AB} \\
    v_{BC} \\
    v_{CA} \\
\end{bmatrix} = [S_{CS}] \begin{bmatrix}
    v_a \\
    v_b \\
    v_c \\
\end{bmatrix}
\] (4.6)

From (4.1), considering two states for each bidirectional switch, there are 512 ($2^9$) possible states for a total of the 9 MC switches. However, MC operates between a voltage source and a current source so it is necessary to ensure that there are no situations of input voltages short-circuits nor output current interruption (open circuit) (Figure 3.4). To ensure this condition one and only one of the switches of each of the three groups of switches ($S_{ij}/S_{2j}/S_{3j}$) must be turned ON [22], [33].
Figure 4.3 - Undesirable situations in MC: (a) short circuit of input sources (b) open circuit of inductive load

In each row of $S$ matrix only one switch should be turned ON:

$$\sum_{j=1}^{3} S_{ij} = 1, \text{ i.e.} \{1,2,3\}$$

Consequently, there are only $27 \ (3^3)$ possible states of operation for the MC, which are presented in Table 4.2 [22], [27].
Table 4.2 - MC switch state combinations and corresponding line-to-neutral and line-to-line output voltages and input currents

| Group | Possible state | S11 | S12 | S13 | S21 | S22 | S23 | S31 | S32 | S33 | VA | VB | VC | VAB | VBC | VCA | ia | ib | ic |
|-------|----------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| I     | 1               | 1   | 0   | 0   | 0   | 1   | 0   | 0   | 0   | 1   | v_a | v_b | v_c | v_ab | v_bc | v_ca | i_a | i_b | i_c |
|       | 2               | 1   | 0   | 0   | 0   | 0   | 1   | 0   | 1   | 0   | v_a | v_c | v_b | v_ca | v_bc | v_ab | i_a | i_c | i_b |
|       | 3               | 0   | 1   | 0   | 1   | 0   | 0   | 0   | 0   | 1   | v_a | v_b | v_c | -v_ab | -v_ca | v_bc | i_b | i_a | i_c |
|       | 4               | 0   | 1   | 0   | 0   | 0   | 1   | 1   | 0   | 0   | v_b | v_c | v_a | v_bc | v_ca | v_ab | i_c | i_a | i_b |
|       | 5               | 0   | 0   | 1   | 1   | 0   | 0   | 0   | 1   | 0   | v_c | v_a | v_b | v_ca | v_ab | v_bc | i_b | i_c | i_a |
|       | 6               | 0   | 0   | 1   | 0   | 1   | 0   | 0   | 0   | 1   | v_c | v_b | v_a | v_bc | v_ab | v_ca | i_c | i_b | i_a |

| II    | 7               | 1   | 0   | 0   | 0   | 1   | 0   | 0   | 1   | 0   | v_a | v_b | v_b | v_ab | 0   | -v_ab | i_a | -i_a | 0   |
|       | 8               | 0   | 1   | 0   | 1   | 0   | 0   | 1   | 0   | 0   | v_b | v_a | v_a | -v_ab | 0   | v_ab  | -i_a | i_a  | 0   |
|       | 9               | 0   | 1   | 0   | 0   | 0   | 1   | 0   | 1   | 0   | v_b | v_c | v_c | v_bc | 0   | -v_bc | 0   | i_a  | -i_a |
|       | 10              | 0   | 0   | 0   | 1   | 0   | 1   | 0   | 0   | 1   | v_c | v_b | v_b | v_bc | 0   | v_bc  | 0   | -i_a | i_a  |
|       | 11              | 0   | 0   | 1   | 0   | 0   | 1   | 0   | 1   | 0   | v_c | v_a | v_a | v_ca | 0   | -v_ca | 0   | i_a  | 0   |
|       | 12              | 1   | 0   | 0   | 0   | 0   | 1   | 0   | 0   | 1   | v_a | v_c | v_c | -v_ca | 0   | v_ca  | i_a  | 0   | -i_a |
|       | 13              | 0   | 1   | 0   | 1   | 0   | 0   | 0   | 1   | 0   | v_b | v_a | v_b | -v_ab | v_ab | 0   | i_b  | 0   | -i_b |
|       | 14              | 1   | 0   | 0   | 0   | 1   | 0   | 1   | 0   | 0   | v_a | v_b | v_a | v_ab | -v_ab | 0   | -i_b | i_b  | 0   |
|       | 15              | 0   | 0   | 0   | 1   | 0   | 1   | 0   | 0   | 0   | v_b | v_b | v_c | v_bc | v_bc | 0   | 0   | i_b  | -i_b |
|       | 16              | 0   | 1   | 0   | 0   | 0   | 1   | 0   | 1   | 0   | v_b | v_c | v_b | v_bc | v_bc | 0   | 0   | -i_b | i_b  |
|       | 17              | 1   | 0   | 0   | 0   | 0   | 1   | 1   | 0   | 0   | v_a | v_c | v_c | -v_ca | v_ca | 0   | -i_b | 0   | i_b  |
|       | 18              | 0   | 0   | 1   | 1   | 0   | 0   | 0   | 0   | 1   | v_c | v_a | v_c | v_ca | -v_ca | 0   | i_b  | 0   | -i_b |
|       | 19              | 0   | 1   | 0   | 0   | 1   | 0   | 1   | 0   | 0   | v_b | v_b | v_a | 0   | -v_ab | v_ab | i_c  | -i_c | 0   |
|       | 20              | 1   | 0   | 0   | 1   | 0   | 0   | 0   | 1   | 0   | v_a | v_a | v_b | 0   | v_ab | -v_ab | -i_c | i_c  | 0   |
|       | 21              | 0   | 0   | 1   | 0   | 0   | 1   | 0   | 1   | 0   | v_c | v_b | v_b | 0   | -v_bc | v_bc | i_c  | -i_c | 0   |
|       | 22              | 0   | 1   | 0   | 0   | 0   | 1   | 0   | 0   | 1   | v_b | v_c | v_b | 0   | v_bc | v_bc | 0   | -i_c | i_c  |
|       | 23              | 1   | 0   | 0   | 1   | 0   | 0   | 0   | 0   | 1   | v_a | v_b | v_c | 0   | -v_ca | v_ca | -i_c | 0   | i_c  |
|       | 24              | 0   | 0   | 1   | 0   | 0   | 1   | 1   | 0   | 0   | v_c | v_b | v_a | 0   | v_ca | -v_ca | i_c  | 0   | -i_c |

| III   | 25              | 1   | 0   | 0   | 0   | 1   | 0   | 0   | 1   | 0   | v_a | v_a | v_a | 0   | 0   | 0   | 0   | 0   | 0   |
|       | 26              | 0   | 1   | 0   | 0   | 1   | 0   | 0   | 1   | 0   | v_b | v_b | v_b | 0   | 0   | 0   | 0   | 0   | 0   |
|       | 27              | 0   | 0   | 1   | 0   | 0   | 1   | 0   | 0   | 1   | v_c | v_b | v_c | 0   | 0   | 0   | 0   | 0   | 0   |

Analyzing Table 4.2, the connections between MC input and output phases can be divided into three different groups according to their properties, as presented in Table 4.3.
### Table 4.3 - Classification of switch state combinations

<table>
<thead>
<tr>
<th>Number of combinations</th>
<th>State property</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Group I</strong></td>
<td>6 combinations</td>
</tr>
<tr>
<td></td>
<td>Each output phase is connected to a different input phase</td>
</tr>
<tr>
<td><strong>Group II</strong></td>
<td>3x6 combinations</td>
</tr>
<tr>
<td></td>
<td>Two output phases are connected to the same input phase</td>
</tr>
<tr>
<td><strong>Group III</strong></td>
<td>3 combinations</td>
</tr>
<tr>
<td></td>
<td>Three output phases are connected to the same input phase</td>
</tr>
</tbody>
</table>

#### 4.3. Matrix converter control

The first investigation and work on MC modulation and control was mainly concerned about the output voltage control, without taking into account the harmonic content of the input currents [9], [22]. High frequency Venturini PWM method represented a great contribution to MC modulation strategies, since high frequency switching is capable of guaranteeing nearly sinusoidal output voltages and input currents, ensuring reduced harmonic contents, when compared to previous modulation methods [14], [22]. Later, Huber introduced the Space Vector Modulation (SVM), based on the representation as vectors (in the α-β plane), of all the possible combinations of matrix converter output voltages and input currents.

In this work are used the state space vector, introduced by SVM, combined with the Sliding Mode Control technique.

#### 4.3.1. Matrix Converter space vectors

The space vectors [12], [13], consist in the representation, on the α-β plan, of the MC output voltages or input currents according to the switches state. This representation is obtained applying Concordia transformation (3.10) to the three-phase voltages or currents in abc coordinates.

Thus the output voltages in α, β, 0 coordinates may be obtained from (4.8) and the input currents from (4.9).

\[
\begin{bmatrix}
V_a \\
V_\beta \\
V_0
\end{bmatrix} = C^T
\begin{bmatrix}
V_{AB} \\
V_{BC} \\
V_{CA}
\end{bmatrix}
\] (4.8)
The voltages and currents vectors are characterized by their module and argument as presented in Table 4.4.

\[
\begin{bmatrix}
i_a \\
i_b \\
i_c
\end{bmatrix} = C^T \begin{bmatrix}
i_a \\
i_p \\
i_c
\end{bmatrix} \quad (4.9)
\]
### Table 4.4 – State vectors of output voltage and input current

<table>
<thead>
<tr>
<th>Group</th>
<th>Vector</th>
<th>Name</th>
<th>$v_{\text{AB}}$</th>
<th>$v_{\text{BC}}$</th>
<th>$v_{\text{CA}}$</th>
<th>$V_o$</th>
<th>$\delta_o$</th>
<th>$I_i$</th>
<th>$\mu_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1</td>
<td>$1r$</td>
<td>$v_{\text{AB}}$</td>
<td>$v_{\text{BC}}$</td>
<td>$v_{\text{CA}}$</td>
<td>$v_i$</td>
<td>$\delta i$</td>
<td>$I_o$</td>
<td>$\mu_o$</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>$2r$</td>
<td>$-v_{\text{CA}}$</td>
<td>$-v_{\text{BC}}$</td>
<td>$-v_{\text{AB}}$</td>
<td>$-v_i$</td>
<td>$-\delta i + \frac{4\pi}{3}$</td>
<td>$I_o$</td>
<td>$-\mu_o$</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>$3r$</td>
<td>$-v_{\text{AB}}$</td>
<td>$-v_{\text{BC}}$</td>
<td>$-v_{\text{CA}}$</td>
<td>$-v_i$</td>
<td>$-\delta i$</td>
<td>$I_o$</td>
<td>$-\mu_o + \frac{2\pi}{3}$</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>$4r$</td>
<td>$v_{\text{BC}}$</td>
<td>$v_{\text{CA}}$</td>
<td>$v_{\text{AB}}$</td>
<td>$v_i$</td>
<td>$\delta i + \frac{4\pi}{3}$</td>
<td>$I_o$</td>
<td>$\mu_o + \frac{2\pi}{3}$</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>$5r$</td>
<td>$v_{\text{CA}}$</td>
<td>$v_{\text{BC}}$</td>
<td>$v_{\text{AB}}$</td>
<td>$v_i$</td>
<td>$\delta i + \frac{2\pi}{3}$</td>
<td>$I_o$</td>
<td>$\mu_o + \frac{4\pi}{3}$</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>$6r$</td>
<td>$-v_{\text{BC}}$</td>
<td>$-v_{\text{CA}}$</td>
<td>$-v_{\text{AB}}$</td>
<td>$-v_i$</td>
<td>$-\delta i + \frac{2\pi}{3}$</td>
<td>$I_o$</td>
<td>$-\mu_o + \frac{4\pi}{3}$</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>$+1$</td>
<td>$v_{\text{AB}}$</td>
<td>$0$</td>
<td>$-v_{\text{AB}}$</td>
<td>$\frac{2}{\sqrt{3}}v_{\text{AB}}$</td>
<td>$0$</td>
<td>$\sqrt{3}I_d$</td>
<td>$-\frac{\pi}{6}$</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>$-1$</td>
<td>$-v_{\text{AB}}$</td>
<td>$v_{\text{AB}}$</td>
<td>$\frac{2}{\sqrt{3}}v_{\text{AB}}$</td>
<td>$0$</td>
<td>$-\sqrt{3}I_d$</td>
<td>$-\frac{\pi}{6}$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>$+2$</td>
<td>$v_{\text{BC}}$</td>
<td>$0$</td>
<td>$-v_{\text{BC}}$</td>
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<td>$\sqrt{3}I_d$</td>
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</tr>
<tr>
<td></td>
<td>10</td>
<td>$-2$</td>
<td>$-v_{\text{BC}}$</td>
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<td>$v_{\text{BC}}$</td>
<td>$-\frac{2}{\sqrt{3}}v_{\text{BC}}$</td>
<td>$0$</td>
<td>$-\sqrt{3}I_d$</td>
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</tr>
<tr>
<td>II-a</td>
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<td>$v_{\text{CA}}$</td>
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<td>$-v_{\text{CA}}$</td>
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<tr>
<td></td>
<td>12</td>
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<td>$v_{\text{CA}}$</td>
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<tr>
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<td>$v_{\text{AB}}$</td>
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<td>$\sqrt{3}I_d$</td>
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<tr>
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<td>14</td>
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<td>$v_{\text{CA}}$</td>
<td>$0$</td>
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<td>$\sqrt{3}I_d$</td>
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<td></td>
<td>18</td>
<td>$-6$</td>
<td>$v_{\text{CA}}$</td>
<td>$-v_{\text{CA}}$</td>
<td>$0$</td>
<td>$-\frac{2}{\sqrt{3}}v_{\text{CA}}$</td>
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<td>$v_{\text{AB}}$</td>
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<td>$\frac{4\pi}{3}$</td>
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<td>$-\frac{2}{\sqrt{3}}v_{\text{BC}}$</td>
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<td>$v_{\text{CA}}$</td>
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<td>$\sqrt{3}I_d$</td>
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<td>24</td>
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<td>$v_{\text{CA}}$</td>
<td>$-v_{\text{CA}}$</td>
<td>$-\frac{2}{\sqrt{3}}v_{\text{CA}}$</td>
<td>$\frac{4\pi}{3}$</td>
<td>$-\sqrt{3}I_d$</td>
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<tr>
<td>III</td>
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<td>$-\delta i$</td>
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<td>$0$</td>
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<td>$0$</td>
<td>$-\delta i$</td>
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<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
<td>$-\delta i$</td>
<td>$0$</td>
<td>$0$</td>
</tr>
</tbody>
</table>
The table is divided in three groups according to the connections between input and output phases. However, group II is subdivided into three different subgroups each one with symmetrical vectors that belong to the same regions of α-β plan. To simplify the selection process, vectors of group I are not used, as they have not fix argument.

Since the output voltages of the MC are applied to the rotor windings of the induction generator, it is advantageous to consider \( v_A', v_B' \) and \( v_C' \) as shown in Figure 4.4, in order to get a balanced system (4.10).

\[
v_A' + v_B' + v_C' = 0
\]  

(4.10)

\[\begin{align*}
v_A' &= \frac{2v_{AB} + v_{BC}}{3} \\
v_B' &= \frac{2v_{BC} + v_{CA}}{3} \\
v_C' &= \frac{2v_{CA} + v_{AB}}{3}
\end{align*}\]  

(4.11)

Thus, all the matrix converter output voltage vectors are calculated (Table 4.4) considering these line-to-neutral voltages:

Figure 4.4 - Voltage on DFIG’s rotor windings
The wind generation system will be controlled based on the presented Space Vector Representation.

### 4.3.2. Sliding mode control

Sliding mode control is a non-linear control approach which guarantees precise control actions and fast response times, ensuring that the input and output currents track their references [14]. This nonlinear control technique can compensate the phase displacement introduced by the input LC filter.

Table 4.5 presents the advantages and disadvantages of these controllers when compared to the traditional linear control techniques [34].

<table>
<thead>
<tr>
<th>Sliding Mode Control</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reduce the system's order</td>
<td>More system's information needed</td>
<td></td>
</tr>
<tr>
<td>Less sensitivity to external disturbances</td>
<td>No short-circuit limitation, despite the fact that is possible to obtain</td>
<td></td>
</tr>
<tr>
<td>Less sensitivity to parameters variations</td>
<td>May be more difficult to design filters due to variable switching frequency</td>
<td></td>
</tr>
<tr>
<td>Reduce the sensitivity to nonlinearities like dead times and voltage drops driving</td>
<td>Non-null static error may occur</td>
<td></td>
</tr>
<tr>
<td>Integrated commands (modulators) and control (regulators) circuits</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Despite the presented disadvantages, still sliding mode controllers may be easily designed and implemented for most power converters, as Matrix Converters.

SMC is a high frequency switching control, which guarantees that the controlled variables follow the established reference surfaces, also called sliding surfaces, in order to minimize the difference between the references and the variables to control (error). This error would be zero for infinite switching frequencies, however, due to the physical limitations of the semiconductors it is not possible to achieve this result. To overcome this problem, it is usual to bound the error, using hysteresis comparators. This way every time that the maximum error (Δ) is reached, the controller system selects the vector to apply, in order to reduce the error, guaranteeing that it remains inside the defined hysteresis boundaries as shown in Figure 4.5 [14], [34].
4.3.3. Output current control

To extract the maximum power from the wind turbine the reference surface is established based on the output currents references.

Applying Concordia transformation to the reference currents the $\alpha$-component ($i_a^*$) and $\beta$-component ($i_\beta^*$) of the output currents are obtained. The controller should minimize the current errors (4.12).

$$
\begin{cases}
    e_a = i_a^* - i_a \\
    e_\beta = i_\beta^* - i_\beta
\end{cases}
$$ (4.12)

The sliding surfaces are given by (4.13) where gains $k_a$ and $k_\beta$ must be greater than zero with upper limit bounded by the semiconductors switching frequency [22], [14]:

$$
\begin{cases}
    S_a(e_a, t) = k_a(i_a^* - i_a) \\
    S_\beta(e_\beta, t) = k_\beta(i_\beta^* - i_\beta)
\end{cases}
$$ (4.13)

To ensure exactly zero error in the controlled currents, it would be necessary to impose an infinite switching frequency. However, due to the power semiconductors physical limitations (maximum switching frequency) this solution is not achievable.

In order to guarantee that the system slides along the reference surface, it is required to verify the stability condition (4.14), [14], [22], [35]:

$$
\begin{cases}
    S_a(e_a, t)S_a(e_a, t) < 0 \\
    S_\beta(e_\beta, t)S_\beta(e_\beta, t) < 0
\end{cases}
$$ (4.14)

Based on the stability condition (4.14), the space vectors are chosen according to Table 4.6.
Table 4.6 - Criteria used to choose the space vectors

<table>
<thead>
<tr>
<th>$s_{a,b}(e_{a,b}, t)$</th>
<th>Chosen Space Vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&gt; \Delta$</td>
<td>To choose a vector capable of increasing the output current ($i_a$ or $i_b$)</td>
</tr>
<tr>
<td>$&lt; - \Delta$</td>
<td>To choose vector capable of decreasing the output current ($i_a$ or $i_b$)</td>
</tr>
<tr>
<td>$&gt; - \Delta$ and $&lt; \Delta$</td>
<td>To choose vector which does not significantly change the output current ($i_a$ or $i_b$)</td>
</tr>
</tbody>
</table>

To know the effect of each vector it is necessary to determine in every moment which is the maximum and minimum vector considering the $\alpha$-$\beta$ components. Due to the fact that the vectors have varying amplitude and phase it is necessary to divide the period in 12 zones as shown in Figure 4.6 [14], [22]. In each zone the vectors with the highest amplitude are used to compensate the error, in order to guarantee the stability conditions (4.14). The group III of Table 4.4 has the null vectors (25, 26 and 27), which can be used when necessary ($s_{a,b}(e_{a,b}, t) = 0$).

![Figure 4.6 - Time division of input phase-to-phase voltages](image)

To understand the vectors representation Figure 4.7, it is considered, as an example, that the input voltage is in zone 1. Based on Figure 4.6 and Table 4.4, the vectors from group II-C are: “+7”, “-7”, “+8”, “-8”, “+9”, “-9”. These are all in the same direction ($4\pi/3$ rad), and it is necessary to know which one is the maximum value in the first voltage zone.

According to Figure 4.6 voltage $v_{ac}$ has the highest value. As a result, the vector that depends on $v_{ac}$ is the greatest in this direction, “+9” and “-9”, as shown in Figure 4.7. Following the same logic it is
possible to obtain all the vectors representation for each input voltage zone. Appendix B has the representation of all the output voltage vectors for the 12 zones.

![Diagram of voltage vectors](image)

**Figure 4.7 - MC output voltage vectors for the 1st zone of the input voltage**

Applying three-level hysteresis comparators (“-1”, “0”, “1”), to the sliding surfaces $S_\alpha$ and $S_\beta$, nine possible error combinations are obtained. The logic levels are defined in the next table for $S_\alpha$. For $S_\beta$ the same thinking must be followed.

<table>
<thead>
<tr>
<th>$S_\alpha$</th>
<th>$k_\alpha(i_\alpha^* - i_\alpha) &lt; -\Delta$</th>
<th>$-\Delta &lt; k_\alpha(i_\alpha^* - i_\alpha) &lt; \Delta$</th>
<th>$k_\alpha(i_\alpha^* - i_\alpha) &gt; \Delta$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-1</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>

According to the time division the maximum current vectors for each voltage zone are in Table 4.8. According to the zone location, and depending on all the error combinations of $S_\alpha$ and $S_\beta$, the vectors are chosen in order to control the output voltages of the MC, and indirectly the currents in DFIG’s rotor.
Table 4.8 - Output voltage vectors that should be used in each input voltage zone

<table>
<thead>
<tr>
<th>$S_m$</th>
<th>$S_y$</th>
<th>Zone 12 and 1</th>
<th>Zone 2 and 3</th>
<th>Zone 4 and 5</th>
<th>Zone 6 and 7</th>
<th>Zone 8 and 9</th>
<th>Zone 10 and 11</th>
</tr>
</thead>
<tbody>
<tr>
<td>-1</td>
<td>-1</td>
<td>-9; +7</td>
<td>-9; +8</td>
<td>+8; -7</td>
<td>-7; +9</td>
<td>+9; -8</td>
<td>-8; +7</td>
</tr>
<tr>
<td>-1</td>
<td>0</td>
<td>+3; -1</td>
<td>+3; -2</td>
<td>-2; +1</td>
<td>+1; -3</td>
<td>-3; +2</td>
<td>+2; -1</td>
</tr>
<tr>
<td>-1</td>
<td>1</td>
<td>-6; +4</td>
<td>-6; +5</td>
<td>+5; -4</td>
<td>-4; +6</td>
<td>+6; -5</td>
<td>-5; +4</td>
</tr>
<tr>
<td>0</td>
<td>-1</td>
<td>-9; +7; +6; -4</td>
<td>-9; +8; +6; -5</td>
<td>+8; -7; -5; +4</td>
<td>-7; +9; +4; -6</td>
<td>+9; -8; -6; +5</td>
<td>-8; +7; +5; -4</td>
</tr>
<tr>
<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>0</td>
<td>1</td>
<td>-6; +4; +9; -7</td>
<td>-6; +5; +9; -8</td>
<td>-8; +7; +5; -4</td>
<td>+7; -9; -4; +6</td>
<td>-9; +8; +6; -5</td>
<td>+8; -7; -5; +4</td>
</tr>
<tr>
<td>1</td>
<td>-1</td>
<td>+6; -4</td>
<td>+6; -5</td>
<td>-5; +4</td>
<td>+4; -6</td>
<td>-6; +5</td>
<td>+5; -4</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>-3; +1</td>
<td>-3; +2</td>
<td>+2; -1</td>
<td>-1; +3</td>
<td>+3; -2</td>
<td>-2; +1</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>+9; -7</td>
<td>+9; -8</td>
<td>-8; +7</td>
<td>+7; -9</td>
<td>-9; +8</td>
<td>+8; -7</td>
</tr>
</tbody>
</table>

In the previous table, there are always at least 2 different vectors, those with the highest amplitude, that minimize the error ($e_\alpha$ and $e_\beta$). This extra degree of freedom will be used to control the MC input power factor.

4.3.4. Input current and power factor control

In order to guarantee a nearly unitary MC input power factor it is useful to consider Blondel-Park transformation (3.14).

With the purpose of getting an unity power factor at the MC input, the reactive power $Q_r$ must be zero. So the MC must apply the vectors necessary to generate a certain input current and satisfy this condition.

Applying the Blondel-Park transformation to the input voltages results into:
Considering a reference frame synchronous with the grid voltage \( v_a \), then \( \Phi = \omega t \) and therefore, in the new coordinate system, the grid voltages will be (4.16):

\[
\begin{aligned}
\begin{cases}
v_d = \sqrt{3}V_\text{ef} \cos(\omega t - \Phi) \\
v_q = \sqrt{3}V_\text{ef} \sin(\omega t - \Phi)
\end{cases}
\end{aligned}
\] (4.15)

The reactive power in dq coordinates is (4.17).

\[
Q_r = v_q i_d - v_d i_q
\] (4.17)

Since the voltage \( v_q \) is zero, the reactive power \( Q_r \) only depends on \( i_q \) and \( v_d \).

\[
Q_r = -v_d i_q
\] (4.18)

Thus the reference current \( i_{q\text{ref}} \) necessary to generate an unitary power factor is zero:

\[
i_{q\text{ref}} = 0
\] (4.19)

Due to the physical limitations of the semiconductors, current \( i_q \) cannot be exactly made equal to zero, as it would imply an infinite switching frequency. Then, the control goal will be to keep \( i_q \) as close to zero as possible, guaranteeing a nearly zero error (4.20) as well:

\[
e_{i_q} = i_{q\text{ref}} - i_q
\] (4.20)

From (4.20), the input current sliding surface will be (4.21) where gain \( k_q \) should be higher than zero.

\[
S_q = k_q(i_{q\text{ref}} - i_q)
\] (4.21)

In order to guarantee that the system slides along the reference surface, the stability condition (4.22) must be verified:
Based on the stability condition (4.22), the space vectors are chosen according to Table 4.9.

Table 4.9 - Criteria used to choose the space vector to obtain an almost unitary PF

<table>
<thead>
<tr>
<th>$S_q(e_{iq}, t)$</th>
<th>Chosen Space Vector</th>
</tr>
</thead>
<tbody>
<tr>
<td>$&gt; \Delta$</td>
<td>Vector capable of increasing $i_q$</td>
</tr>
<tr>
<td>$&lt; -\Delta$</td>
<td>Vector capable of decreasing $i_q$</td>
</tr>
</tbody>
</table>

The vectors are chosen in order to guarantee that the sliding surface $S_q$ result is nearly equal to zero.

Thus, it is necessary to know the amplitude of each input current vector at each time instant, using a methodology similar to the one used for the output voltage vectors. This results in dividing the output current period in 12 distinct zones and represent the current space vectors in the $\alpha$-$\beta$ plan according to each zone. Following the same logic as used to voltage vectors, all input current vectors are defined for each output current zone, which are represented in Appendix C.

Figure 4.8 shows an example of the input currents vectors representation for the zone 1 of the output current ($0 < \phi_i < \frac{\pi}{6}$).

As DQ axes are constantly rotating it is not possible to locate the exact position of each vector available relatively to DQ plan, nevertheless it is possible to define the space region where these
axes can be found, according to the input voltage location. Figure 4.9 illustrates the location of the d and q axis relatively to αβ axes.

![Figure 4.9 - Axis d and q according to the input voltage zone](image)

Considering that both the input voltages and the output currents are in zone 12 or 1 (Figure 4.10), and the rotor current errors are $S_d = -1$ and $S_β = -1$, then the maximum vectors that should be chosen are the vector “-9”, with a negative q component, if it is necessary to reduce the q component of the input current, or “+7” if it is necessary to increase it, given that in this zone it has a positive q component [8].

![Figure 4.10 - Axis q and d location when the input voltage is in the zone 12 or 1 and the output currents are at the zones 12 or 1](image)

Table 4.10 shows all the maximum amplitude vectors according to each output current zone when the input voltage in the 1st or 12th zone. Applying this vectors it is guaranteed that the errors $S_d$, $S_β$ and $S_q$ are minimized in order to obtain a nearly unitary power factor.
### Table 4.10 - Current vectors that should be used in each output current zone when the input voltage is in the zone 12 or 1

<table>
<thead>
<tr>
<th>Output Current Zone</th>
<th>Zone 12 and 1</th>
<th>Zone 2 and 3</th>
<th>Zone 4 and 5</th>
<th>Zone 6 and 7</th>
<th>Zone 8 and 9</th>
<th>Zone 10 and 11</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\phi_i \in \left[ -\frac{\pi}{6}, \frac{\pi}{6} \right]$</td>
<td>$S_{\alpha}=-1$</td>
<td>$S_{\beta}=0$</td>
<td>$S_q=1$</td>
<td>$S_q=1$</td>
<td>$S_q=-1$</td>
<td>$S_q=1$</td>
</tr>
<tr>
<td>$-1$</td>
<td>$-9$</td>
<td>$+7$</td>
<td>$-9$</td>
<td>$+7$</td>
<td>$+7$</td>
<td>$-9$</td>
</tr>
<tr>
<td>$-1$</td>
<td>$+3$</td>
<td>$-1$</td>
<td>$+3$</td>
<td>$-1$</td>
<td>$+4$</td>
<td>$-6$</td>
</tr>
<tr>
<td>$-1$</td>
<td>$-6$</td>
<td>$+4$</td>
<td>$+4$</td>
<td>$-6$</td>
<td>$+4$</td>
<td>$-6$</td>
</tr>
<tr>
<td>$0$</td>
<td>$-9$</td>
<td>$+7$</td>
<td>$-9$</td>
<td>$+7$</td>
<td>$-9$</td>
<td>$+7$</td>
</tr>
<tr>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
<td>$0$</td>
</tr>
<tr>
<td>$0$</td>
<td>$-7$</td>
<td>$+9$</td>
<td>$-7$</td>
<td>$+9$</td>
<td>$-7$</td>
<td>$+9$</td>
</tr>
<tr>
<td>$1$</td>
<td>$-4$</td>
<td>$+6$</td>
<td>$+6$</td>
<td>$-4$</td>
<td>$+6$</td>
<td>$-4$</td>
</tr>
<tr>
<td>$1$</td>
<td>$+1$</td>
<td>$-3$</td>
<td>$+1$</td>
<td>$-3$</td>
<td>$+6$</td>
<td>$-4$</td>
</tr>
<tr>
<td>$1$</td>
<td>$-7$</td>
<td>$+9$</td>
<td>$-7$</td>
<td>$+9$</td>
<td>$-7$</td>
<td>$+9$</td>
</tr>
</tbody>
</table>

Appendix D contains all tables necessary to define the vectors according to the input voltage zone, output current zone, $S_\alpha$, $S_\beta$, and $S_q$.

### 4.4. Matrix Converter Input Filter

The switching process of the semiconductors leads to high-frequency harmonics in the network currents. These current harmonics cause additional losses on the utility system and may excite electrical resonance, generating large overvoltages [36], [37]. Thus a second order low pass filter is used in order to minimize the harmonic content of the currents injected into the network. This filter is installed between the converter and the network as shown in Figure 4.11.
The proposed filter is designed taking into consideration the maximum allowed displacement factor introduced by the filter and also the ripple present at the capacitor voltages [38].

The sliding mode control, which allows a near unity input power factor of the whole converter, requires a MC able to fully compensate the input displacement factor introduced by the filter [38].

Figure 4.12 presents the single phase equivalent of the filter circuit. The transfer function of the filter is obtained based on this schematics.

As a first approach, to calculate the maximum capacitance of the filter the resistance $R_f$ has been neglected, since the impedance $R_f//L_f \approx L_f$. The maximum acceptable capacitance is given by (4.23), assuming that the maximum acceptable displacement factor introduced by the input filter is $\pi/6$ [38].
\[ C_f < \frac{\tan\left(\frac{\pi}{6}\right)}{3\omega V_{\text{ref}}^2} P_{\text{out}} \]  

(4.23)

The desired damping coefficient should be a value between 0.5 < \( \zeta < 0.7 \). The filter cut-off frequency should be at least one decade above the grid frequency and one decade below the switching frequency [38]. Once the switching frequency is not constant, depending on the control system demand, the cut-off frequency, \( f_c \), is establish as 500Hz.

The cut-off angular frequency of the filter is represented by (4.24), and the filter characteristic impedance by (4.26), where \( H_p \) is only an auxiliary parameter.

\[ \omega_p = 2\pi f_c \]  

(4.24)

\[ H_p \leq \frac{1}{2\zeta^2} \]  

(4.25)

\[ Z_f = \frac{(2\zeta^2 H_p - 1)}{\zeta H_p} r_i \approx \frac{L}{\sqrt{C}} \]  

(4.26)

Admitting that the MC efficiency is \( \eta \), and the input and output power factor is nearly one, it is possible to define the equation (4.29).

\[ \eta P_{\text{in}} = P_{\text{out}} \]  

(4.27)

\[ \eta V_{\text{ref}} I_{\text{ref}} = V_{\text{oef}} I_{\text{oef}} \]  

(4.28)

\[ I_{\text{ref}} = \frac{V_{\text{oef}} I_{\text{oef}}}{\eta V_{\text{ref}}} \]  

(4.29)

As presented in Table 4.1 the output voltage is \( \sqrt{3}/2 \) of the input voltage, so the input and output currents are related as the equation (4.30) shows.
The output equivalent resistance, $r_o$, is calculated considering the single phase equivalent of the circuit, which means 1/3 of the output power.

\[ r_o = \frac{V_{oef}}{I_{oef}} = \frac{V_{oef}^2}{P_o} \frac{1}{3} \]  \hspace{1cm} (4.31)

To calculate $Z_f$, it is necessary the equivalent resistance related to the power that crosses the converter, $r_i$, and is given by:

\[ r_i = -\eta \frac{4}{3} r_o \]  \hspace{1cm} (4.33)

So now it is possible to calculate $L_f$, $C_f$ and $R_f$ based on the following equations [17]:

\[ R_f = \frac{r_i Z_f}{2 \xi (r_i - Z_f)} \]  \hspace{1cm} (4.34)

\[ C_f = \frac{1}{Z_f \omega_p} \]  \hspace{1cm} (4.35)

\[ L_f = \frac{Z_f}{\omega_p} \]  \hspace{1cm} (4.36)

Using the correspondent equation, and adjusting $H_p$ to satisfy the capacitor limit (4.23), the filter parameters are as presented in Table 4.11. The calculations made are presented in Appendix F.
### Table 4.11 – Filter Parameters

<table>
<thead>
<tr>
<th>$V_{inf}$ (V)</th>
<th>$I_{inf}$ (A)</th>
<th>$V_{oef}$ (V)</th>
<th>$P_{out}$ (kW)</th>
<th>$\eta$ (%)</th>
<th>$f_c$ (Hz)</th>
<th>$\zeta$</th>
<th>$r_o$ (Ω)</th>
<th>$r_i$ (Ω)</th>
<th>$Z_f$ (Ω)</th>
<th>$C_{max}$ (μF)</th>
<th>$C_f$ (μF)</th>
<th>$R_f$ (Ω)</th>
<th>$L_f$ (μH)</th>
</tr>
</thead>
<tbody>
<tr>
<td>690</td>
<td>217.39</td>
<td>597.56</td>
<td>450</td>
<td>98.5</td>
<td>500</td>
<td>$\sqrt{2}/2$</td>
<td>2.38</td>
<td>-3.12</td>
<td>0.55</td>
<td>214</td>
<td>194</td>
<td>0.34</td>
<td>174</td>
</tr>
</tbody>
</table>
5. Simulation Results

5.1. Simulation

Two different methods are used to extract the maximum power of the wind generation system: the torque control and the speed control, presented in chapter 2. A model of the whole system was created in MatLab/Simulink and the results obtained with the two methods are compared.

In Appendix F the file with all the parameters and calculations necessary to run the simulation is presented and in Appendix G the most important Simulink block diagrams are shown.

A wind speed chart was established according to some real speed records as shown in Figure 5.1. These records are discrete and correspond to the average speed per hour. However, due to hardware limitations, the simulation was reduced to 48 seconds, based on 48 hours of wind records. Once the simulation time had to be reduced, the moment of inertia of the whole system had to be reduced to acceptable values that allow the turbine speed vary in this time scale.

The measurement place of all the presented currents, active power and power factor is clarify in Appendix H. In this appendix it is clear where all the following graphics were obtained.

![Figure 5.1 - Wind Speed chart](image)

Based on the wind speed the control system generates a reference torque $T_{ref}$, and from this the MC reference currents $i_{ref}$ are set. Thus the MC generates the output currents $i_{ABC}$ as close as possible to the references. Figure 5.2 presents an example of the MC output currents.
When the generator reaches the synchronous speed, the rotor phases change, as shown in Figure 5.3, and the energy processed by the induction generator rotor starts to flow from the rotor to the grid.

Figure 5.3 - Rotor currents when the generator reaches the synchronous speed

Figure 5.4 presents induction generator stator currents. The fundamental frequency is 50Hz.
After the rotor and stator currents presentation the network currents (Figure 5.5), result of the whole system behaviour, are analysed.

The filter is used to minimize the high frequency harmonics introduced into the grid by the MC. Figure 5.6 shows the input current of the filter, which is demanded from the network. Despite the high frequency noise, it has a sinusoidal shape with a zero mean value, which is much better, from the point of view of power quality, than the currents at the output of the filter (MC input), as presented in the Figure 5.7.
In chapter 4.3.4 the reference current $i_{q,ref}$ was calculated in order to guarantee a nearly unitary input power factor and as Figure 5.8 shows the filter input current is in phase with the network voltage, when the rotor spins under the synchronous speed and is consuming energy from the network. Figure 5.9 shows the same variables but 180° out of phase, what happens when the generator rotates above the synchronous speed and the rotor delivers power to the grid.
Other significant results come from the reference current $i_{rd,ref}$, calculated in chapter 3.2.1. This reference was calculated in order to guarantee an unitary power factor of the stator power and the power changed with the system. As Figure 5.10 and Figure 5.11 show the network voltage is 180° out of phase with the stator and network current, keeping $Q_s \approx 0$ and supplying active power to the grid.
To track the maximum power point, two strategies are used: the torque control and the speed control. The chapter 2.4 presents the speed reference $\omega_{\text{ref}}$ and the torque reference $T_{\text{ref}}$ used to extract the maximum power from the wind. The use of each of these two approaches generate different results that are going to be analyzed by the comparison between them.

The numerical results obtained are presented in the next 3 tables. The calculation of the results from the Table 5.2 and Table 5.3 are in the Appendix I.
Table 5.1 – Energy results

<table>
<thead>
<tr>
<th></th>
<th>Torque control</th>
<th>Speed control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Available wind energy [W.h]</td>
<td>13668</td>
<td>13668</td>
</tr>
<tr>
<td>Turbine delivered energy [W.h]</td>
<td>13490</td>
<td>13653</td>
</tr>
<tr>
<td>Generated energy [W.h]</td>
<td>13073</td>
<td>13122</td>
</tr>
<tr>
<td>Energy inserted into the network [W.h]</td>
<td>12828</td>
<td>12879</td>
</tr>
</tbody>
</table>

Table 5.2 - Energy ratios

<table>
<thead>
<tr>
<th></th>
<th>Torque control</th>
<th>Speed control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cp (%)</td>
<td>40.7</td>
<td>41.2</td>
</tr>
<tr>
<td>Generator efficiency (%)</td>
<td>96.9</td>
<td>96.1</td>
</tr>
<tr>
<td>MPPT efficiency (%)</td>
<td>93.9</td>
<td>94.2</td>
</tr>
<tr>
<td>Rotor generated energy (%)</td>
<td>1.7</td>
<td>5.3</td>
</tr>
<tr>
<td>Stator generated energy (%)</td>
<td>98.3</td>
<td>94.7</td>
</tr>
</tbody>
</table>

Table 5.3 - System losses

<table>
<thead>
<tr>
<th></th>
<th>Torque control</th>
<th>Speed control</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global losses (%)</td>
<td>4.91</td>
<td>5.67</td>
</tr>
<tr>
<td>Generator losses (%)</td>
<td>3.09</td>
<td>3.89</td>
</tr>
<tr>
<td>Converter losses (%)</td>
<td>1.75</td>
<td>1.72</td>
</tr>
<tr>
<td>Filter losses (%)</td>
<td>0.096</td>
<td>0.103</td>
</tr>
</tbody>
</table>

Both control methods set a certain reference torque $T_{ref}$ and the MC reacts in order to follow this reference. As it can be seen in Figure 5.12 and Figure 5.13 the reference torque is followed by the system in both situations.

Figure 5.12 - Torque control: electromagnetic torque and reference torque
The torque control has a continuous $T_{ref}$ and works in a lower range of $T_{em}$ than the speed control. This difference is noticed in the stator and rotor currents that are more constant for the torque control as the comparison between Figure 5.14 and Figure 5.15 proves.
For the speed control case, the speed of the generator, as expected, is much more sensitive to wind speed, than it is for the torque control case. However, the goal of following the optimum speed was satisfied as Figure 5.17 shows. For a better visualization of the reference speed tracking the Figure 5.18 shows a more detailed part of the Figure 5.17.
Due to the fact that $T_m$ is not constant it works has a perturbations to the speed control system (Figure 2.4) so it generates the presented static error.

The next figures show the rotor and stator power as well as the power delivered to the network for both control situations.
Figure 5.19 - Torque control: stator and rotor active power

Figure 5.20 – Speed control: stator and rotor active power
In the speed control case the delivered power to the network reaches almost $2MW$, much higher than the nominal power of the generator, which is an undesired situation. This overpower generation happens when the wind speed drops too fast. When $\omega_m$ is much higher than $\omega_{ref}$, the reference torque generated by the speed controller reaches high values in order to deliver the stored power in the wind turbine and reduce the generator speed as soon as possible.
The power factor at the point of connection to the grid, for both cases, is nearly one during most part of the simulation. However, the torque control guarantees a more stable value as Figure 5.23 and Figure 5.24 show.

Figure 5.23 - Torque control: power factor of the network power

Figure 5.24 - Speed control: power factor of the network power
5.2. Conclusion

Table 5.4 presents the most important results obtained for both control methods.

**Table 5.4 - Torque and speed control results**

<table>
<thead>
<tr>
<th></th>
<th>Torque control</th>
<th>Speed control</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Range of the reference torque</strong></td>
<td>Between -2770N.m and -8260N.m</td>
<td>Between -420N.m and -11000N.m</td>
</tr>
<tr>
<td><strong>Rotor speed range</strong></td>
<td>Within 1118rpm and 1738rpm</td>
<td>Within 1002rpm and 1980rpm</td>
</tr>
<tr>
<td><strong>Range of active power delivered to the network</strong></td>
<td>Between 0.32MW and 1.48MW</td>
<td>Between 0.02MW and 2MW</td>
</tr>
<tr>
<td><strong>Fraction of available wind energy delivered to the network</strong></td>
<td>93.9%</td>
<td>94.2%</td>
</tr>
<tr>
<td><strong>MC losses</strong></td>
<td>1.75% of the generated power</td>
<td>1.72% of the generated power</td>
</tr>
</tbody>
</table>

Table 5.4 reveals that the fraction of the available wind energy delivered to the network is slightly larger (0.37%) for the speed control case. However, in the torque control method the reference torque is set continuously and within a smaller range of values avoiding the fast changes of the rotor current and consequently the generated power when the wind speed changes. Another important detail is that when the wind speed drops too fast, the speed controller forces the system to generate power above the nominal value.

In spite of delivering higher power to the grid, the speed control brings some undesired situations. Therefore, until these situations are not overcome it is possible to conclude that for regions where the wind speed vary too quickly the best MPPT solution is the torque control.
6. Conclusions

The main goal of this work was to evaluate the use of Matrix Converters in Wind Energy Generation Systems using Doubly-Fed Induction Generators, guaranteeing the maximum power extraction from the available wind. To track the Maximum Power Point, two different control techniques were tested: speed control and the torque control. To simulate these models it was used the Matlab Simulink platform.

By running both simulations, for the same wind speed chart, and analyzing the final results it was possible to conclude, that:

- The MC using Space State Vectors and SMC is a reliable converter to use with wind generators;
- The input currents of the MC, the stator currents as well as the network currents are almost sinusoidal;
- Nearly unitary power factor at the MC input circuit, at the stator and at the connection point to the grid;
- The MC is bidirectional delivering power to the rotor when it works under the synchronous speed and allows the rotor to supply power to the network above this speed;
- The reference torque was followed by the system during all the simulation.

In spite of the higher efficiency of the speed control technique, it is very sensible to wind speed variations causing highly variable rotor currents and generated power. This variability is something undesired to the electrical grid that needs to satisfy the instantaneous load demand.

However, the combination of these two controls could probably be a good solution to extract the maximum power from the wind which is something to implement and analyse with a real system.

In the future may be interesting the development of a MPPT model closer to the reality, using the wind records and inertia coefficients in a real scale. After this, a laboratory work using a real wind turbine combined with the MC could reveal some more interesting conclusions.
REFERENCES

3. ERSE; Informação sobre Produção em Regime Especial, December 2009.
5. ENERCON GmbH; ENERCON Wind Energy Converters. Product Overview, Germany, July 2010.


Appendix A  Construction of $S_{CS}$ matrix

The relationship between line-to-neutral voltage and line-to-line voltage is given by (A.1).

$$
\begin{align*}
V_{AB} &= V_A - V_B \\
V_{BC} &= V_B - V_C \\
V_{CA} &= V_C - V_A \\
\end{align*}
$$

(A.1)

Considering (A.2) it is possible to define line-to-neutral output voltages as (A.3).

$$
\begin{bmatrix}
V_A \\
V_B \\
V_C \\
\end{bmatrix} = [S]
\begin{bmatrix}
V_a \\
V_b \\
V_c \\
\end{bmatrix}
$$

(A.2)

$$
\begin{align*}
V_A &= S_{11}V_a + S_{12}V_b + S_{13}V_c \\
V_B &= S_{21}V_a + S_{22}V_b + S_{23}V_c \\
V_C &= S_{31}V_a + S_{32}V_b + S_{33}V_c \\
\end{align*}
$$

(A.3)

Substituting (A.3) into (A.1), line-to-line output voltages can be expressed by:

$$
\begin{align*}
V_{AB} &= (S_{11}V_a + S_{12}V_b + S_{13}V_c) - (S_{21}V_a + S_{22}V_b + S_{23}V_c) \\
V_{BC} &= (S_{21}V_a + S_{22}V_b + S_{23}V_c) - (S_{31}V_a + S_{32}V_b + S_{33}V_c) \\
V_{CA} &= (S_{31}V_a + S_{32}V_b + S_{33}V_c) - (S_{11}V_a + S_{12}V_b + S_{13}V_c) \\
\end{align*}
$$

(A.4)

Putting $v_a$, $v_b$, and $v_c$ in evidence:

$$
\begin{align*}
V_{AB} &= v_a(S_{11} - S_{21}) + v_b(S_{12} - S_{22}) + v_c(S_{13} - S_{23}) \\
V_{BC} &= v_a(S_{21} - S_{31}) + v_b(S_{22} - S_{32}) + v_c(S_{23} - S_{33}) \\
V_{CA} &= v_a(S_{31} - S_{11}) + v_b(S_{32} - S_{12}) + v_c(S_{33} - S_{13}) \\
\end{align*}
$$

(A.5)

According to (A.5) $S_{CS}$ is defined by (A.6) and allow the relation between input and output voltages as given by (A.7).

$$
[S_{CS}] = \begin{bmatrix}
S_{11} - S_{21} & S_{12} - S_{22} & S_{13} - S_{23} \\
S_{21} - S_{31} & S_{22} - S_{32} & S_{23} - S_{33} \\
S_{31} - S_{11} & S_{32} - S_{12} & S_{33} - S_{13} \\
\end{bmatrix}
$$

(A.6)

$$
\begin{bmatrix}
V_{AB} \\
V_{BC} \\
V_{CA} \\
\end{bmatrix} = [S_{CS}]
\begin{bmatrix}
V_a \\
V_b \\
V_c \\
\end{bmatrix}
$$

(A.7)
Appendix B  
Time division of the MC input phase-to-phase voltages

The time division of input voltages is necessary in order to know the maximum current vectors at anytime. This knowledge is used to minimize the errors of the rotor currents as soon as possible using those vectors.

Each voltage zone has its own output voltage vectors representation as shown in Table B.1.

Table B.1 - MC voltage output vectors in each input voltage zone

<table>
<thead>
<tr>
<th>Zone 1</th>
<th>Zone 2</th>
<th>Zone 3</th>
<th>Zone 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>$0 &lt; \phi_u &lt; \frac{\pi}{6}$</td>
<td>$\frac{\pi}{6} &lt; \phi_u &lt; \frac{2\pi}{6}$</td>
<td>$\frac{2\pi}{6} &lt; \phi_u &lt; \frac{3\pi}{6}$</td>
<td>$\frac{3\pi}{6} &lt; \phi_u &lt; \frac{4\pi}{6}$</td>
</tr>
</tbody>
</table>
Zone 5 – \(\left\langle \frac{4\pi}{6} < \phi_u < \frac{5\pi}{6} \right\rangle\)

Zone 6 – \(\left\langle \frac{5\pi}{6} < \phi_u < \pi \right\rangle\)

Zone 7 – \(\left\langle \pi < \phi_u < \frac{7\pi}{6} \right\rangle\)

Zone 8 – \(\left\langle \frac{7\pi}{6} < \phi_u < \frac{8\pi}{6} \right\rangle\)

Zone 9 – \(\left\langle \frac{8\pi}{6} < \phi_u < \frac{9\pi}{6} \right\rangle\)

Zone 10 – \(\left\langle \frac{8\pi}{6} < \phi_u < \frac{9\pi}{6} \right\rangle\)
Zone 11 - \( \left( \frac{9\pi}{6} < \phi_u < \frac{10\pi}{6} \right) \)

Zone 10 - \( \left( \frac{10\pi}{6} < \phi_u < \frac{11\pi}{6} \right) \)
Appendix C  

Time division of MC output currents

Dividing the output currents into 12 zones, allows the representation of the input current vector as presented is in Table C.1.

Table C.1 - MC input current vectors in each output current zone

<table>
<thead>
<tr>
<th>Zone 1: 0 &lt; φ₁ &lt; π/6</th>
<th>Zone 2: π/6 &lt; φ₁ &lt; 2π/6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zone 3: 2π/6 &lt; φ₁ &lt; 3π/6</td>
<td>Zone 4: 3π/6 &lt; φ₁ &lt; 4π/6</td>
</tr>
</tbody>
</table>
Zone 5 - \( \left( \frac{4\pi}{6} < \phi_1 < \frac{5\pi}{6} \right) \)

Zone 6 - \( \left( \frac{5\pi}{6} < \phi_1 < \pi \right) \)

Zone 7 - \( \left( \pi < \phi_1 < \frac{7\pi}{6} \right) \)

Zone 8 - \( \left( \frac{7\pi}{6} < \phi_1 < \frac{8\pi}{6} \right) \)

Zone 9 - \( \left( \frac{8\pi}{6} < \phi_1 < \frac{9\pi}{6} \right) \)

Zone 10 - \( \left( \frac{9\pi}{6} < \phi_1 < \frac{10\pi}{6} \right) \)
zone 11 - \(\left(\frac{10\pi}{6} < \phi_i < \frac{11\pi}{6}\right)\)

zone 12 - \(\left(\frac{11\pi}{6} < \phi_i < 2\pi\right)\)
Appendix D  

Vectors used to control the output current and the input power factor

Table D.1 - Control vector for input voltage zone - 12 or 1

<table>
<thead>
<tr>
<th>Zone 12 and 1</th>
<th>Zone 2 and 3</th>
<th>Zone 4 and 5</th>
<th>Zone 6 and 7</th>
<th>Zone 8 and 9</th>
<th>Zone 10 and 11</th>
</tr>
</thead>
<tbody>
<tr>
<td>((-\pi/6 &lt; \phi_i &lt; \pi/6))</td>
<td>((\pi/6 &lt; \phi_i &lt; 3\pi/6))</td>
<td>((3\pi/6 &lt; \phi_i &lt; 5\pi/6))</td>
<td>((5\pi/6 &lt; \phi_i &lt; 7\pi/6))</td>
<td>((7\pi/6 &lt; \phi_i &lt; 9\pi/6))</td>
<td>((9\pi/6 &lt; \phi_i &lt; 11\pi/6))</td>
</tr>
<tr>
<td>(S_a)</td>
<td>(S_b)</td>
<td>(Sq)</td>
<td>(Sq)</td>
<td>(Sq)</td>
<td>(Sq)</td>
</tr>
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<td>-1</td>
<td>-1</td>
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<td>-7</td>
<td>-8</td>
<td>-9</td>
</tr>
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</tr>
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<td>+5</td>
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</tr>
<tr>
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<td>-7</td>
<td>-8</td>
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<td>0</td>
<td>0</td>
<td>0</td>
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<td>0</td>
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<td>+9</td>
<td>+9</td>
<td>-8</td>
</tr>
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<td>1</td>
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<td>-4</td>
<td>-1</td>
<td>-6</td>
<td>+6</td>
</tr>
<tr>
<td>1</td>
<td>0</td>
<td>+1</td>
<td>-3</td>
<td>-3</td>
<td>+2</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>-7</td>
<td>+9</td>
<td>+9</td>
<td>-8</td>
</tr>
</tbody>
</table>

Table D.2 - Control vector for input voltage zone - 2 or 3

<table>
<thead>
<tr>
<th>Zone 12 and 1</th>
<th>Zone 2 and 3</th>
<th>Zone 4 and 5</th>
<th>Zone 6 and 7</th>
<th>Zone 8 and 9</th>
<th>Zone 10 and 11</th>
</tr>
</thead>
<tbody>
<tr>
<td>((-\pi/6 &lt; \phi_i &lt; \pi/6))</td>
<td>((\pi/6 &lt; \phi_i &lt; 3\pi/6))</td>
<td>((3\pi/6 &lt; \phi_i &lt; 5\pi/6))</td>
<td>((5\pi/6 &lt; \phi_i &lt; 7\pi/6))</td>
<td>((7\pi/6 &lt; \phi_i &lt; 9\pi/6))</td>
<td>((9\pi/6 &lt; \phi_i &lt; 11\pi/6))</td>
</tr>
<tr>
<td>(S_a)</td>
<td>(S_b)</td>
<td>(Sq)</td>
<td>(Sq)</td>
<td>(Sq)</td>
<td>(Sq)</td>
</tr>
<tr>
<td>-1</td>
<td>-1</td>
<td>-9</td>
<td>-7</td>
<td>-8</td>
<td>-9</td>
</tr>
<tr>
<td>-1</td>
<td>0</td>
<td>+3</td>
<td>-1</td>
<td>-2</td>
<td>+3</td>
</tr>
<tr>
<td>-1</td>
<td>1</td>
<td>+4</td>
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<td>-6</td>
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<td>-7</td>
<td>+9</td>
<td>+9</td>
<td>-8</td>
</tr>
</tbody>
</table>
### Table D.3 - Control vector for input voltage zone - 4 or 5

<table>
<thead>
<tr>
<th>Output Current Zone</th>
<th>Zone 12 and 1</th>
<th>Zone 2 and 3</th>
<th>Zone 4 and 5</th>
<th>Zone 6 and 7</th>
<th>Zone 8 and 9</th>
<th>Zone 10 and 11</th>
</tr>
</thead>
<tbody>
<tr>
<td>( -\frac{\pi}{6} &lt; \phi_i &lt; \frac{\pi}{6} )</td>
<td>( -\frac{\pi}{6} &lt; \phi_i &lt; \frac{3\pi}{6} )</td>
<td>( \frac{3\pi}{6} &lt; \phi_i &lt; \frac{5\pi}{6} )</td>
<td>( \frac{5\pi}{6} &lt; \phi_i &lt; \frac{7\pi}{6} )</td>
<td>( \frac{7\pi}{6} &lt; \phi_i &lt; \frac{9\pi}{6} )</td>
<td>( \frac{9\pi}{6} &lt; \phi_i &lt; \frac{11\pi}{6} )</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>( S_\alpha )</th>
<th>( S_\beta )</th>
<th>( S_{q=1} )</th>
<th>( S_{q=-1} )</th>
<th>( S_{q=1} )</th>
<th>( S_{q=-1} )</th>
<th>( S_{q=1} )</th>
<th>( S_{q=-1} )</th>
<th>( S_{q=1} )</th>
<th>( S_{q=-1} )</th>
<th>( S_{q=1} )</th>
<th>( S_{q=-1} )</th>
<th>( S_{q=1} )</th>
</tr>
</thead>
<tbody>
<tr>
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<td>-7</td>
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<td>+7</td>
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<tr>
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<td>+9</td>
<td>-8</td>
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</tbody>
</table>

### Table D.4 - Control vector for input voltage zone - 6 or 7

<table>
<thead>
<tr>
<th>Output Current Zone</th>
<th>Zone 12 and 1</th>
<th>Zone 2 and 3</th>
<th>Zone 4 and 5</th>
<th>Zone 6 and 7</th>
<th>Zone 8 and 9</th>
<th>Zone 10 and 11</th>
</tr>
</thead>
<tbody>
<tr>
<td>( -\frac{\pi}{6} &lt; \phi_i &lt; \frac{\pi}{6} )</td>
<td>( -\frac{\pi}{6} &lt; \phi_i &lt; \frac{3\pi}{6} )</td>
<td>( \frac{3\pi}{6} &lt; \phi_i &lt; \frac{5\pi}{6} )</td>
<td>( \frac{5\pi}{6} &lt; \phi_i &lt; \frac{7\pi}{6} )</td>
<td>( \frac{7\pi}{6} &lt; \phi_i &lt; \frac{9\pi}{6} )</td>
<td>( \frac{9\pi}{6} &lt; \phi_i &lt; \frac{11\pi}{6} )</td>
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<table>
<thead>
<tr>
<th>( S_\alpha )</th>
<th>( S_\beta )</th>
<th>( S_{q=1} )</th>
<th>( S_{q=-1} )</th>
<th>( S_{q=1} )</th>
<th>( S_{q=-1} )</th>
<th>( S_{q=1} )</th>
<th>( S_{q=-1} )</th>
<th>( S_{q=1} )</th>
<th>( S_{q=-1} )</th>
<th>( S_{q=1} )</th>
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Table D.5 - Control vector for input voltage zone - 8 or 9

<table>
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<th>Output Current Zone</th>
<th>Zone 12 and 1</th>
<th>Zone 2 and 3</th>
<th>Zone 4 and 5</th>
<th>Zone 6 and 7</th>
<th>Zone 8 and 9</th>
<th>Zone 10 and 11</th>
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<tbody>
<tr>
<td></td>
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<td>(\frac{3\pi}{6} &lt; \phi_i &lt; \frac{5\pi}{6})</td>
<td>(\frac{5\pi}{6} &lt; \phi_i &lt; \frac{7\pi}{6})</td>
<td>(\frac{7\pi}{6} &lt; \phi_i &lt; \frac{9\pi}{6})</td>
<td>(\frac{9\pi}{6} &lt; \phi_i &lt; \frac{11\pi}{6})</td>
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<tr>
<td>(S_{\alpha})</td>
<td>(S_{\beta})</td>
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<td>(S_{q} = 1)</td>
<td>(S_{q} = -1)</td>
<td>(S_{q} = 1)</td>
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Table D.6 - Control vector for input voltage zone - 10 or 11

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<th>Zone 12 and 1</th>
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<th>Zone 4 and 5</th>
<th>Zone 6 and 7</th>
<th>Zone 8 and 9</th>
<th>Zone 10 and 11</th>
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</thead>
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<tr>
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<td>(\frac{\pi}{6} &lt; \phi_i &lt; \frac{3\pi}{6})</td>
<td>(\frac{3\pi}{6} &lt; \phi_i &lt; \frac{5\pi}{6})</td>
<td>(\frac{5\pi}{6} &lt; \phi_i &lt; \frac{7\pi}{6})</td>
<td>(\frac{7\pi}{6} &lt; \phi_i &lt; \frac{9\pi}{6})</td>
<td>(\frac{9\pi}{6} &lt; \phi_i &lt; \frac{11\pi}{6})</td>
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<tr>
<td>(S_{\alpha})</td>
<td>(S_{\beta})</td>
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<td>(S_{q} = -1)</td>
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<td>-5</td>
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<tr>
<td>1</td>
<td>1</td>
<td>+9</td>
<td>-7</td>
<td>-8</td>
<td>+9</td>
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## Appendix E  Wind Turbine data sheet

### Nordex S77/1500 (1.5 MW)

### Technical specifications

<table>
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<tr>
<th>Section</th>
<th>Details</th>
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<tr>
<td>Number of blades</td>
<td>3</td>
</tr>
<tr>
<td>Rotor speed</td>
<td>9.9-17.3 rpm</td>
</tr>
<tr>
<td>Rotor diameter</td>
<td>77 m</td>
</tr>
<tr>
<td>Swept area</td>
<td>4,657 qm</td>
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<tr>
<td>Power regulation</td>
<td>Pitch</td>
</tr>
<tr>
<td>Rated power from</td>
<td>13 m/s</td>
</tr>
<tr>
<td>Cut-in wind speed</td>
<td>3.5 m/s</td>
</tr>
<tr>
<td>Cut-out wind speed</td>
<td>for tubular towers: 25 m/s for lattice towers: 20 m/s</td>
</tr>
<tr>
<td>Survival wind speed</td>
<td>for tubular towers: 25 m/s for lattice towers: 20 m/s</td>
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<tr>
<td>Pitch regulation</td>
<td>Individual electromotive pitch</td>
</tr>
<tr>
<td>Total weight</td>
<td>c. 34,000 kg</td>
</tr>
<tr>
<td><strong>Blades</strong></td>
<td></td>
</tr>
<tr>
<td>Blade length</td>
<td>37.5 m</td>
</tr>
<tr>
<td>Material</td>
<td>Glass fibre-reinforced plastic</td>
</tr>
<tr>
<td>Weight</td>
<td>c. 6,500 kg</td>
</tr>
<tr>
<td><strong>Gearbox</strong></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Combined planetary and spur gear</td>
</tr>
<tr>
<td>Gear ratio</td>
<td>1:104</td>
</tr>
<tr>
<td>Weight</td>
<td>c. 14,000 kg</td>
</tr>
<tr>
<td>Oil quantity</td>
<td>250 l</td>
</tr>
<tr>
<td>Oil change</td>
<td>Semi-annual check, change as required</td>
</tr>
<tr>
<td><strong>Generator</strong></td>
<td></td>
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<tr>
<td>Power</td>
<td>1,500 kW (adjustable)</td>
</tr>
<tr>
<td>Voltage</td>
<td>690 V</td>
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<tr>
<td>Type</td>
<td>Double-fed asynchronous generator, air-cooled</td>
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<tr>
<td>Speed</td>
<td>1,000 - 1,950 rpm ± 10 %</td>
</tr>
<tr>
<td>Enclosure class</td>
<td>IP 54</td>
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<tr>
<td><strong>Main shaft bearing</strong></td>
<td>Self-aligning roller bearing</td>
</tr>
<tr>
<td><strong>Yaw system</strong></td>
<td></td>
</tr>
<tr>
<td>Yaw bearing</td>
<td>Four-point bearing</td>
</tr>
<tr>
<td>Brake</td>
<td>Hydraulic disc brake with 10 calipers</td>
</tr>
<tr>
<td>Yaw drive</td>
<td>4 induction motors</td>
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<tr>
<td>Speed</td>
<td>c. 0.75 °/s</td>
</tr>
<tr>
<td><strong>Control System</strong></td>
<td></td>
</tr>
<tr>
<td>Type</td>
<td>Microprocessor</td>
</tr>
<tr>
<td>Grid connection</td>
<td>Via IGBT converter</td>
</tr>
<tr>
<td>Scope of monitoring</td>
<td>More than 300 different parameters, e.g. temperature sensors, hydraulic sensors, pitch parameters, vibration, speed, generator torque, wind speed and direction, etc.</td>
</tr>
<tr>
<td><strong>Recording</strong></td>
<td>Production data, event list, long and short-term trends</td>
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<tr>
<td><strong>Brake</strong></td>
<td></td>
</tr>
<tr>
<td>Design</td>
<td>Three independent systems, fail safe (individual pitch)</td>
</tr>
<tr>
<td>Operational brake</td>
<td>Electromotive blade pitch</td>
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<tr>
<td>Secondary brake</td>
<td>Disc brake</td>
</tr>
<tr>
<td><strong>Tower</strong></td>
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</tr>
<tr>
<td>Type</td>
<td>Modular steel tower, cylindrical, upper segment conical, lattice tower, hot-dip galvanized</td>
</tr>
<tr>
<td>Hub heights</td>
<td>Tubular tower 61.5 m, Certificate IEC 3a, DIBt 2 on request</td>
</tr>
<tr>
<td></td>
<td>Tubular tower 80 m, 85 m, 90 m, 100 m Certificate-te DIBt 2</td>
</tr>
<tr>
<td></td>
<td>Lattice tower 96.5 m, Certificate DIBt 2</td>
</tr>
<tr>
<td></td>
<td>Lattice tower 111.5 m, Certificate DIBt 2</td>
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</table>
Appendix F  Simulink Parameters

This appendix has the program used in Matlab to calculate the parameters used in Simulink.

%------------------------------------------------------------------------
%                     Parameter for AC-AC converter                     %
% Functionality: This program defines the values used in the Simulink %
% simulation                                    %
% Author: Luís Filipe Patrício Afonso            %
%------------------------------------------------------------------------
%---------------------------------------------------------------Network-------------------

v_network_rms = 690; % Voltage effective value [V]
Vef = v_network_rms;
v_network_amp = sqrt(2)*v_network_rms;
f_network_Hz = 50; % Frequency in [Hz]
f_network_rad = 2*pi*f_network_Hz;

%---------------------------------------------Wind Turbine-------------------

%DFIG
P_DFIG = 1.5e6; % Generator power [MW]
ws = f_network_rad; % Stator angular speed
wm_initial = 700*pi/30; % Initial speed of the generator

rs = 2.2e-3; % Stator winding resistance [ohm]
rr = 1.8e-3; % Rotor winding resistance [ohm]
Ls = 3.02e-3; % Stator self-inductance [H]
Lr = 2.95e-3; % Rotor self-inductance [H]
M = 2.9e-3; % Mutual inductance [H]
p = 2; % Pares of poles

L=[Ls,0,M,0
  0,Ls,0,M
  M,0,Lr,0
  0,M,0,Lr];
Linv=inv(L);

Jger=100; % Generator moment of inertia [Kg*m^2]

% Turbine

mass=500; % Turbine mass [Kg]
Rturb=77/2; % Turbine radius [m]
Jturb=2/3*mass*Rturb^2; % Turbine moment of inertia [Kg*m^2]

G=104; % Gearbox ratio

Jin=Jger+Jturb/(G^2); % Total moment of inertia [Kg*m^2]
\text{kd} = 0.05; \text{Friction \ [N.m.s]}\\

\%------------------------Converter input filter------------------------\%

\text{Pconv\_phase} = \text{P\_DFIG*0.30/3; \%Power through each phase}\\
\text{Vout\_max} = \text{sqrt(3)*v\_network\_rms/2; \%Nominal MC output voltage \ [V]}\\
\text{Iin\_max} = \text{Pconv\_phase/690; \%Maximum MC input current \ [A]}\\
\text{ef} = 0.985; \text{\%MC efficiency}\\
\text{zeta} = \text{sqrt(2)/2; \%Damping ratio}\\
\text{Hp} = 0.89*(1/(2*zeta^2)); \text{\%Auxiliary parameter}\\

\text{ro} = \text{Vout\_max^2/Pconv\_phase; \%Output equivalent resistance of the converter}\\
\text{ri} = -\text{ro*ef*v\_network\_rms^2/Vout\_max^2; \%Equivalent resistance related to the power that crosses each phase}\\

\text{Zf} = (2*zeta^2*Hp - 1)*ri/(zeta*Hp); \text{\%Characteristic impedance of the filter}\\
\text{wp} = 2*pi*500; \text{\%Cut-off frequency \ [rad/s]}\\
\text{Cf\_aux} = 1/(Zf*wp); \text{\%Total filter capacitor \ [F]}\\
\text{Cf} = \text{Cf\_aux/3 \%Triangle capacitors}\\
\text{Cmax} = (\text{tan(pi/6)}*(P\_DFIG/3)/(3*f\_network\_rad*v\_network\_rms^2))/3; \text{\%Maximum acceptable value for Cf \ [F]}\\
\text{Lf} = Zf/wp \text{\%Filter inductance \ [H]}\\
\text{Rf} = ri*Zf/(2*zeta*ri - Zf) \text{\%Filter resistance \ [ohm]}\\

%---------------------------------------------Matrix Converter-------------------% \%

%Gain used to control the tracking of the input and output current reference\\
\text{K input current control} = 5;\\
\text{K output current control} = 5;\\
\text{k voltage} = 10; \text{\%Gain used in the input voltage zone detection}\\
\text{k current} = 25; \text{\%Gain used in the output current zone detection}\\
\text{L in} = 2; \text{\%Hysteresis comparator limit for the input current control (iq)}\\

%Hysteresis comparator limits for the output current control (ir\_alpha; ir\_beta)\\
\text{Lmax\_out} = 5;\\
\text{Lmin\_out} = 0.5;\\

%---------------------------------------------Speed Control------------------------% \%

%Proportional Integral controller\\
\text{KT} = 1;\\
\text{Td} = 1e-3;\\
\text{Tz} = \text{Jin/kD};\\
\text{zeta} = \text{sqrt(2)/2};
\[ w = \frac{1}{2 \zeta T_d}; \]
\[ T_p = \frac{K_T}{(w^2 k_D T_d)}; \]

\[ kp = \frac{T_z}{T_p}; \]
\[ ki = \frac{1}{T_p}; \]

%---------------------------------Auxiliary parameters -------------------------------
\[ Ts = 1e^{-5}; \text{ %Simulink fixed-step size} \]
\[ Cs = 5e^{-7}; \text{ %Snubber capacity of the ideal switch} \]
\[ Rs = 500; \text{ %Snubber resistance of the ideal switch} \]
\[ Ron = 3.3e^{-3}; \text{ %Semiconductors internal resistance} \]
Appendix G  Matlab Simulink Schematics

This appendix presents the most important Matlab Simulink schematics, used to simulate the system.

Figure G.1 – Global system

Figure G.2 - Input Filter
Figure G.3 - Voltage zone identification

Figure G.4 - Input current analyzer

Figure G.5 - Space Vector choice
Figure G.6 - Control signals generator

Figure G.7 - Matrix Converter
Figure G.8 - Turbine optimum power and reference torque

Figure G.9 - Speed controller
Appendix H  Measurements place

In order to make sure that all the presented results in Chapter 5 are clear, based on Figure H.1, Table H.1 shows where all the currents, active power and power factor measurements were done.

![Figure H.1 - Measurements zones](image)

Table H.1 - Currents, Active and Power Factor measurement place

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<th>Measurement Zone</th>
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<tr>
<td>Figure 5.22</td>
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Appendix I  Energy ratios and losses

After getting the energy results from the simulation, the calculation of the energy ratios and the different losses of the system was done assuming the following symbols and formulas:

\[ E_{\text{network}} \] – Energy delivered to the network [W.s]
\[ E_{\text{generated}} \] – Energy generated by the DFIG [W.s]
\[ E_{\text{turbine}} \] – Energy delivered from the turbine to the system [W.s]
\[ E_{\text{optimum}} \] – Maximum of available wind energy [W.s]
\[ E_{\text{wind}} \] – Total energy in the wind [W.s]
\[ E_{\text{grotor}} \] – Energy generated by the rotor [W.s]
\[ E_{\text{gstatr}} \] – Energy generated by the stator [W.s]
\[ E_{\text{LMC}} \] – Energy correspondent to the MC losses [W.s]
\[ E_{\text{filter}} \] – Energy correspondent to the filter losses [W.s]

\( C_p \) - Performance coefficient or power coefficient for the wind power
\( \eta_{\text{DFIG}} \) – Efficiency of the generator
\( \eta_{\text{MPPT}} \) - Efficiency of all the process of extracting the maximum power and deliver it to the network
\( E_{\text{rotor}} \) – Fraction of the generated energy by the rotor
\( E_{\text{stator}} \) – Fraction of the generated energy by the stator

\( L_{\text{global}} \) – Global losses of the system
\( L_{\text{DFIG}} \) – Generator losses
\( L_{\text{MC}} \) – Matrix Converter losses
\( L_{\text{filter}} \) – Filter losses

\[ C_p = \frac{E_{\text{turbine}}}{E_{\text{wind}}} \] (H.1)
The MC uses ideal switches in the Simulink schematics. Thus, the MC losses are the result of the conduction losses and the snubber circuit losses. Since there are no switching losses covered by this Simulink block, they are included by the snubber circuit. The values used are:

- $C_s = 0.5 \mu F$ for the snubber capacity of the ideal switch;
- $R_s = 500 \Omega$ for the snubber resistance of the ideal switch;
- $R_{on} = 3.3 m\Omega$ for the switches internal resistance.