Abstract

This project is based on the modeling and controlling of an offshore wind turbine with a PMSG (Permanent Magnet Synchronous Generator) topology. This topology is gaining relevance nowadays in offshore wind turbines due the lack of a gear box which makes a machine easier to maintain and reduces the losses.

All the components of the wind turbine will be modeled, from the turbine where the power is extracted from the wind to the grid where the power is injected. During the process there are different components to take into account such as the converters and the controllers.

In this project the performance of a three-phase system to a poly-phase system is also compared, concretely the modeling of a six-phase system, thanks to an in-depth analysis under different wind conditions.

Last but not least, there will be a brief study in the environmental impact.

Contents

Abstract **1**

Preface **9**
Previous requirements . . . 9

1 Introduction **11**
1.1 Objectives . . . 11
1.2 Scope of the project . . . 11
1.3 State-of-the-art . . . 11
1.3.1 Energy situation . . . 11
1.3.2 Renewable sources . . . 12
1.3.3 Wind Energy . . . 14
1.3.4 PMSG topology . . . 15

2 General Scheme **16**

3 Modelling **18**
3.1 Wind speed . . . 18
3.2 Wind turbine modelling . . . 18
3.3 Poly-phase Permanent Magnet Synchronous Generator (PMSG) . . . 23
3.3.1 Three-phase PMSG . . . 26
3.3.2 Six-phase PMSG . . . 27
3.4 Converter . . . 28
3.5 Electric grid . . . 31

4 Wind Turbine control **33**
4.1 Grid side control . . . 33
4.1.1 Voltage Regulator Control (DC side) . . . 34
4.1.2 Current Loop Control for the inverter (AC side) . . . 37
4.2 Generator side control . . . 39
4.2.1 Three-phase system control . . . 39
4.2.1.1 Current Loop Control for the converter . . . 40
4.2.2 Six-phase system control . . . 41

5 Simulation and analysis **44**
5.1 Constant wind speed . . . 44
5.1.1 Three-phase wind generator . . . 50
5.1.2 Six-phase wind generator . . . 53
5.2 Wind speed variation . . . 58
5.3 Simulation for a range of wind speeds . . . 64

6 Environmental impact **65**
6.1 Visual impact 65
6.2 Acoustic impact 65
6.3 Shade 66
6.4 Fauna and flora impact 67
6.5 Air and maritime traffic 67

A Park transformation **68**

B Clarke transformation **70**

C Phase Locked Loop **73**

D Data proposed for the analysis **74**

Conclusion **75**

Acknowledgments **76**

References **77**

List of Figures

1.1 World's Primary energy consumption evolution (1990-2011) [2] . . . 12
1.2 Evolution of the consume of the diferent tyoes of energy in Spain in MTpe form 1970 until 2012. [3] . . . 13
1.3 Comparison between the energy production in Spain in 2001 and 2013 . . . 13
1.4 Renewable energy contribution in the electric generation in Spain[5] . . . 14
2.1 General scheme of a wind turbine connected to the electrical grid . . . 17
3.1 Current tube effect . . . 19
3.2 Power generated for different lengths of the blade . . . 20
3.3 Power generated for different wind speeds . . . 21
3.4 Power coefficient for different values of tip speed ratio for pitch angle = 0 . . . 22
3.5 Emf induced to a square loop by moving magnets . . . 23
3.6 Types of permanent magnets synchronous generators . . . 24
3.7 Three-phase PMSG scheme with one pole pair . . . 25
3.8 Angular speed function of pole pairs for synchronous generators connected to a 50 Hz grid . . . 25
3.9 Scheme of a back-to-back converter [8] . . . 28
3.10 Modelling of the AC and DC side of a VSC inverter [10] . . . 29
3.11 Three-phase system connection between the AC side of a back-to-back converters and the electric grid [10] . . . 32
3.12 Six-phase system connection between the AC side of two back-to-back converters and the electric grid . . . 32
4.1 Grid side control general scheme[8] . . . 33
4.2 DC side modelling of the converter and the inverter [10] . . . 34
4.3 Voltage regulator modelling scheme [6] . . . 35
4.4 Control of the voltage capacitor with a given value ($E_{dc}{}^{*}$) . . . 36
4.5 Current loop control scheme [10] . . . 37
4.6 Current loop control answer for a step input . . . 38
4.7 Generator side control general scheme of a three-phase system [8] . . . 39
4.8 Generator side control general scheme of a six-phase system . . . 42
5.1 Wind speed simulated for the analysis . . . 44
5.2 Wind power vs Turbine power . . . 45
5.3 Power cycle from the wind to the grid . . . 45
5.4 Three-phase and six-phase machines: Comparison of powers . . . 46
5.5 Six-phase machine: Generated power vs power transmitted through abc and def converters . . . 47
5.6 Three-phase machine: Grid voltages in both ABC and qd0 frame . . . 47
5.7 Three-phase machine: Grid currents in both ABC and qd0 frame . . . 48
5.8 Six-phase machine: Grid voltages in both ABC and qd0 frame . . . 48
5.9 Six-phase machine: Grid currents in both ABC and qd0 frame . . . 49
5.10 Three-phase machine: Voltage regulator control . . . 50
5.11 Three-phase machine: abc and qd inverter current . . . 51
5.12 Three-phase machine: abc and qd inverter voltage . . . 51

5.13 Three-phase machine: abc and qd stator current . . . 52
5.14 Three-phase machine: abc and qd stator voltage . . . 52
5.15 Six-phase machine: qd(abc) inverter current control . . . 53
5.16 Six-phase machine: qd(def) inverter current control . . . 53
5.17 Six-phase machine: Voltage regulator control for the different VSC back to back converters . . . 54
5.18 Six-phase machine: abc and qd(abc) inverter current . . . 54
5.19 Six-phase machine: abc and qd(abc) inverter voltage . . . 55
5.20 Six-phase machine: def and qd(def) inverter current . . . 55
5.21 Six-phase machine: def and qd(def) inverter voltage . . . 56
5.22 Six-phase machine: xy stator current control . . . 56
5.23 Six-phase machine: abcdef and qdxy stator current . . . 57
5.24 Six-phase machine: abcdef and qdxy stator voltage . . . 57
5.25 Wind speed simulated for the analysis . . . 58
5.26 Power coefficient obtained for a wind speed variation . . . 59
5.27 Six-phase machine: Generated power vs power transmitted through abc and def converters . . . 59
5.28 Six-phase machine: Electric Torque vs Mechanical Torque . . . 60
5.29 Six-phase machine: Voltage regulator control for the different VSC back to back converters . . . 60
5.30 Six-phase machine: abc and qd(abc) inverter current . . . 61
5.31 Six-phase machine: abc and qd(abc) inverter voltage . . . 61
5.32 Six-phase machine: def and qd(def) inverter current . . . 62
5.33 Six-phase machine: def and qd(def) inverter voltage . . . 62
5.34 Six-phase machine: abcdef and qdxy stator current . . . 63
5.35 Six-phase machine: abcdef and qdxy stator voltage . . . 63
5.36 Six-phase machine: Electric torque and power generated for a range of wind speeds . . . 64
6.1 Visual impact of offshore wind turbines for different distances to the shore . . . 65
6.2 Types of foundations for seabed's depth . . . 66
6.3 Intensity of the sound function of the distance from the wind turbine . . . 66
A.1 abc frame . . . 69
A.2 qd0 frame . . . 69
B.1 abcdef frame . . . 71
B.2 $\alpha\beta xyz_1z_2 frame$ . . . 71
B.3 qdxyz$_1z_2 frame$ . . . 72
C.1 Phase Locked Loop scheme . . . 73

Nomenclature

Superscripts

ˆ	Estimated value
*	Reference value

Subscripts

abc	Three-phase
abcdef	Six-phase
dq0	Components of the Park transformation
dqxyz$_1$z$_2$	Components of the Clarke plus rotation transformation
l	Related to the inverter
z	Related to the grid
r	Related to the rotor
s	Related to the stator
t	Related to the turbine
w	Related to the wind
min	Minimum value
max	Maximum value
opt	Optimum value

Acronyms

VSC	Voltage Source Converter
PMSG	Permanent Magnet Synchronous Generator
AC	Alternate Current
DC	Direct Current
PLL	Phase Locked Loop
IGBT	Insulated Gate Bipolar Transistor
PWM	Pulse-Width Moldulation
AWEA	American Wind Energy Association

Preface

During the next few years, a high number of offshore wind farms will be installed. The wind turbines installed in these places will not only be efficient but also designed to be compact, lightweight, reliable and with an important reduction in maintenance. The multiphase permanent magnet synchronous generator is a topology proposed by manufacturers.

In this project the multiphase PMSG topology will be analyzed and it will also be compered to the operation of the wind turbine according to the number of phases proposed.

Previous requirements

This is some previous knowledge required to carry out this project.

- **MATLAB:** Mathematical program responsible for the operation
- **Simulink:** Simulation program responsible for the analysis
- **Electrical machinery:** Understand the operation of permanent magnet machines.
- **Power electronics:** Understand the control of power converters.

1 Introduction

1.1 Objectives

The main objective of this project is to carry out an in-depth analysis on the performance of the multiphase PMSG topology for offshore wind turbines.

This analysis will allow a comparative between the three-phase and six-phase systems and the variation in the operation for different wind conditions.

1.2 Scope of the project

First of all, the project will introduce wind energy, concretely, its actual situation and evolution.

In order to achieve the objectives stated, a deep study on the modelling of wind turbines components and its control will be done.

Then a simulation and analysis for different conditions of wind differentiating three-phase systems from six-phase systems will be carried out.

Finally an environmental impact is carried out for offshore wind turbines.

The project ends with the conclusions of the operation and analysis obtained from the simulation.

1.3 State-of-the-art

The purpose of this chapter is to give an insight into the general situation of the energy and its historical evolution up to the wind turbine topology explained in this project.

1.3.1 Energy situation

Nowadays, energetic consumption is growing fast in our society. The increase in comfort, automation and the growth of developing countries requires an energy industry which can provide a continuous and adaptable supply to the demand as well as reliability and regularity [1]. Figure 1.1 depicts the evolution of Energy consumption since 1990.

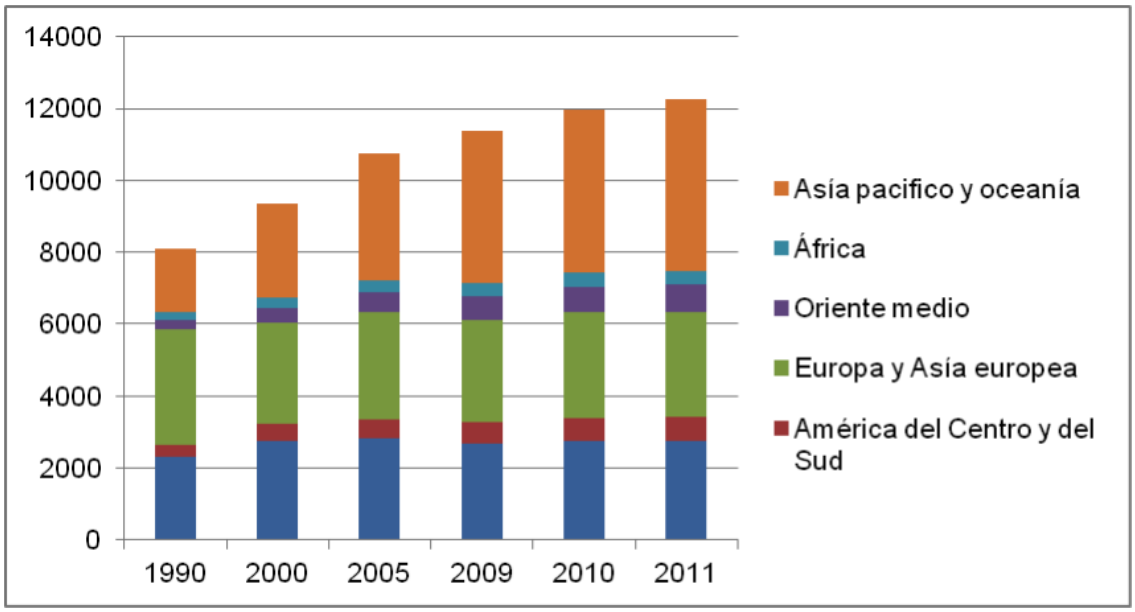


Figure 1.1: World's Primary energy consumption evolution (1990-2011) [2]

Both the increase in the energy demand and the negative outlook for fossil fuels resources leads to the need for new ways of producing energy.

The well-known renewable sources are the answer to that question. With limitless supply they not only can provide energy to the world but also they can avoid the emission of polluting gases. These green energies have emerged because of the need to solve some of the world's issues. Ozone layer, acid rain and global warming are some of the main troubles we have to fight against in order to keep the world safe and make it a place to live as long as the human being exists. The first step to fight these world's issues is to decrease both the emissions of CO_2 and the contaminant wastes.

1.3.2 Renewable sources

The renewable sources don't generate any polluting wastes and their primary energy is something as pure as the wind speed, the heat of the sun, the warmth of the earth and the strength of the water. Nevertheless, as everything in this world, this energy also brings some drawbacks which have to be taken into account. The main one is that we can not rely entirely on these sources as we are not able to control their production because it depends on the weather. That is why renewable energy will only be an auxiliary resource. In terms of efficiency, the energy produced is much lower than other sources due to fact that the time of generation is conditioned and limited.

Despite these drawbacks, the importance and the need of renewable resources is real. That is the reason for the recent increase in renewable energy consumption and why they are

spreading worldwide. Concretely wind energy is one of the biggest bets globally. If we take a look into the Energetic demand in Spain, depicted in Figure 1.2, we can conclude that there has been a high investment in that kind of this kind of energy.

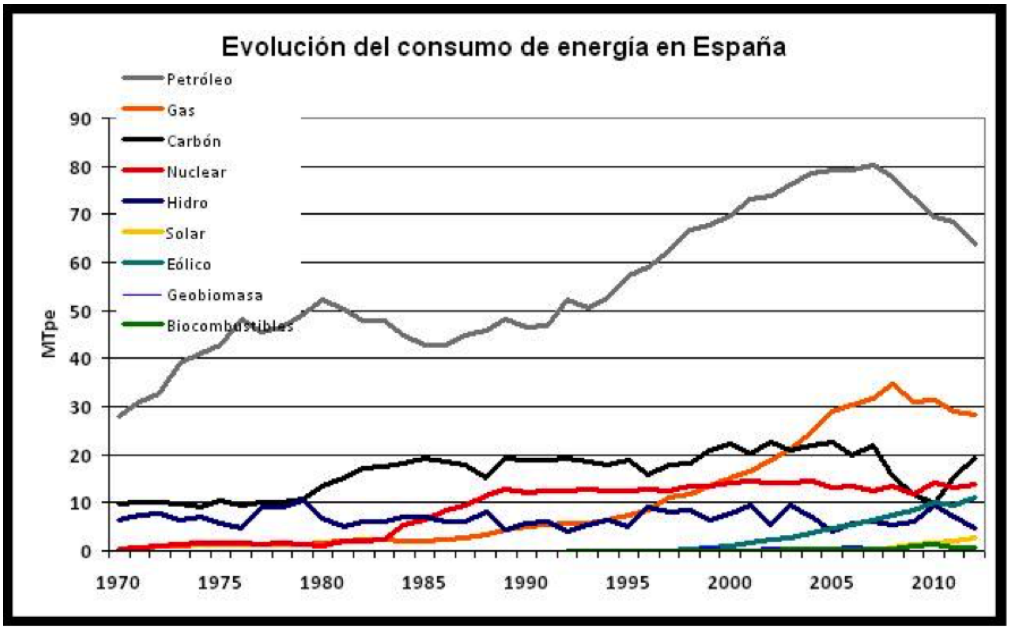


Figure 1.2: Evolution of the consume of the diferent tyoes of energy in Spain in MTpe form 1970 until 2012. [3]

Renewable sources allow the countries to achieve self-sufficiency because the supply is not only available everywhere but free. It could be the first step in putting an end to the dependence on other countries resources and the global energy market monopoly.

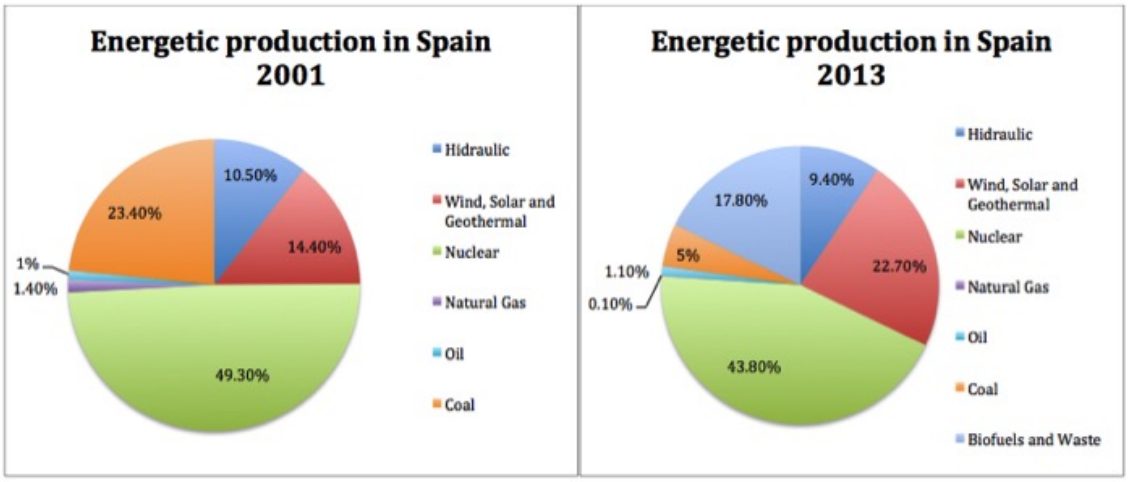


Figure 1.3: Comparison between the energy production in Spain in 2001 and 2013

Figure 1.3 shows how Spain has invested in the national production of renewable energy and compares the production between 2001 and 2013 [4]. It has to be taken into account

that there has been an increase in consumption, this implies that 20% of the consumption in 2001 versus 20% of the consumption in 2013 is not the same.

1.3.3 Wind Energy

Among the renewable resources, according to the graphic shown in Figure 1.4, the one which produces the most is wind energy. This energy is generated by the speed of the wind, concretely the kinetic energy generated by the air flow through the wind turbine.

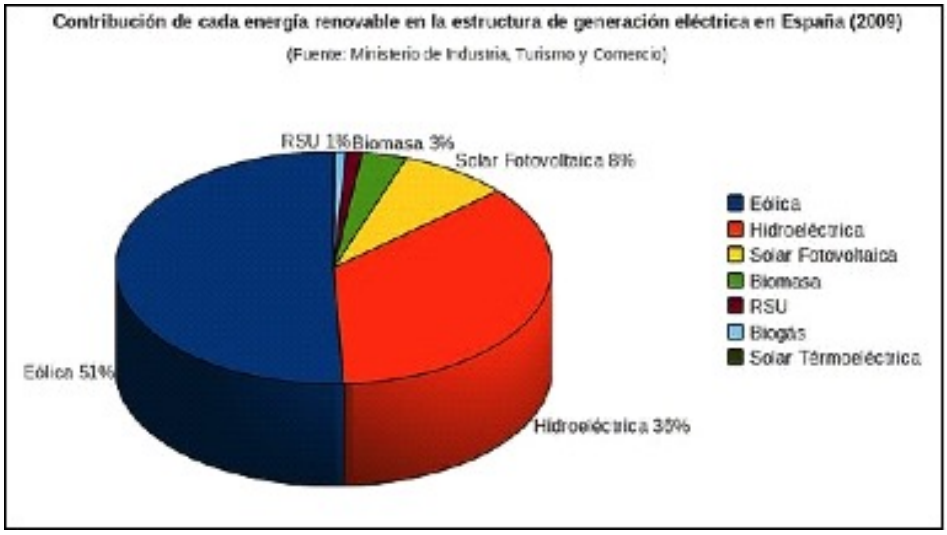


Figure 1.4: Renewable energy contribution in the electric generation in Spain[5]

The first use of it was around the year 3000 b.c. when Egyptians used the wind for sailing. After 5000 years of technological development there has been an amazing evolution in the way of using the wind speed. Nowadays, we build the well-known wind farms, which consist of a large number of wind turbines connected to the electric power grid. Most of the wind farms are built onshore but recently the offshore wind farms have gained popularity because of the reduction in visual impact and wind conditions presented.

"Due to the growing penetration of wind farms in the grid has arisen a number of issues for the proper operation of the grid. Namely, wind farms are known to be less robust to voltage sags than conventional energy generation plants. In the former days, when a deep voltage sag occurred due to a fault in the grid, wind farms would disconnect from the grid to avoid damaging the turbines. This sudden disconnection of power input to the grid would cause an imbalance which in some situations could lead to network instability. In order to do that, modern wind farms are required to be able to ride through voltage sags, that is, to remain connected while the fault is clear."[6]

In order to optimize energy extraction, some methods of controlling and optimizing to increase the power rating of wind turbines have appeared. Not only this but also these

methods allow precise control of active and reactive power injected to the grid and they can operate at a wide range of wind speeds.

1.3.4 PMSG topology

One of these methods is the so called PMSG (Permanent Magnet Synchronous Generator), this method is gaining relevance and spreading in the wind turbine world. This new topology appeared with the purpose of reducing the maintenance costs of offshore wind turbines, to operate at very low speeds according to wind speed and with a direct drive design of the wind turbine without a gearbox which suppress eliminates gearbox maintenance and possible failures it could cause. Although an investment in an electrical machine with higher manufacturing costs and a power converter with a higher rating is necessary, the PMSG topology has the machine completely isolated from the grid through the converter what makes the machine less sensible to grid fluctuations and ease the design of control methods, features that make the PMSG a suitable machine for offshore wind farms.

2 General Scheme

This chapter is going to focus on the general scheme of the wind turbine with a six phase PMSG. This scheme is based on:

- **Wind speed**
- **Wind turbine**
- **PMSG**
- **Back to back converters**
- **Electric grid**

The operation of the wind turbine is very simple. The kinetic energy of the wind makes the blades of the wind turbine rotate. This rotation of the turbine is harnessed by the PMSG to generate power. Despite having alternate current, the frequency is different from the grid so it has to go through the back to back converter, formed by 1 VSC converter and 1 VSC inverter, to achieve the desired frequency. These processes are done with the simultaneous operation of controllers which have to adapt to the different wind conditions to optimize the power extracted.

The difference between 3-phase and 6-phase PMSG is the multiples connections to the grid which let the wind turbine transfer energy in the case of a converter failure.

It is necessary to note that there is no need for gearbox due to the PMSG capacity to adapt to every wind speed.

Figure 2.1 shows the general scheme of the connections between the different components of a six-phase PMSG wind turbine.

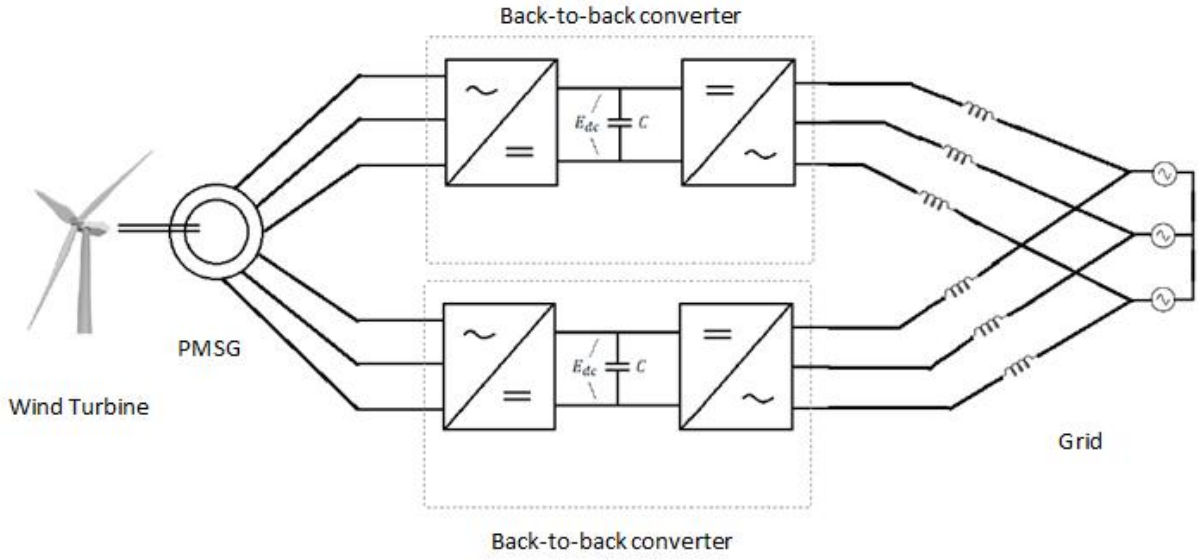


Figure 2.1: General scheme of a wind turbine connected to the electrical grid

3 Modelling

3.1 Wind speed

A wind turbine is a machine which generates electric energy from the kinetic energy of the wind through the wind turbine's blades.

This kinetic energy is generated by the air fluxes formed by the air mass movement from high to low atmospheric pressure areas. For offshore wind farms, sea breeze is used for power generation being the difference of pressure between the sea and the shore. This kind of wind has a high speed and as the wind farm is built in the middle of the sea there is no friction to slow down the wind letting the wind turbine benefit from the maximum speed.

Wind speed is something very complex to model as it depends on many factors such as height, temperature, surface, etc.

When studying these models it is common to use the mathematical equation (3.1), which represents the wind speed behaviour for any location taking into account 4 components [7].

$$v_w(t) = v_{wa}(t) + v_{wr}(t) + v_{wg}(t) + v_{wt}(t) \tag{3.1}$$

where $v_{wa}(t)$ is a constant component

$v_{wr}(t)$ is a common ramp component

$v_{wg}(t)$ is a gust component

$v_{wt}(t)$ is a turbulence component

However, in this project the wind will be modelled as a constant with an increase in speed to study how the wind turbine controller handles the operation and adapts to this variation. the horizontal component of speed will only be taken into account.

3.2 Wind turbine modelling

The turbine is the component which transforms the kinetic energy of the wind into mechanical energy.

$$E_k = \frac{1}{2}mV^2 \tag{3.2}$$

$$P_{wind} = \frac{1}{2}\dot{m}V_w^2 \tag{3.3}$$

$$\dot{m} = \rho A V_w \tag{3.4}$$

Where E_k is the kinetic energy

$\dot{m}$ is the mass air flow

V_w is the wind speed

ρ is the air density

A is the swept area

According to Betz's law, a wind turbine decreases the wind speed $\frac{2}{3}$ of its initial value. That is why the maximum wind power that can absorb an ideal wind turbine is $\frac{16}{27}$ (59,26%) of the kinetic energy of the wind. When the wind goes through the wind turbine an effect called current tube originated by the variation of velocity and area crossed by the wind is produced as Figure 3.1 shows.

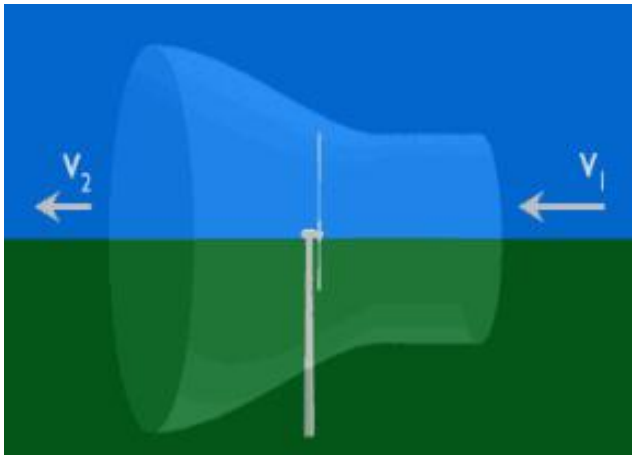


Figure 3.1: Current tube effect

When calculating the energy power we will add equation (3.3) to the wind power a dimensionless power coefficient (C_p) to take into account the efficiency of the wind transformation in mechanical energy as Albert Betz said. This coefficient will be physically limited by the Betz's law which states a C_p^{max}=$\frac{16}{27}$ for an ideal wind turbine.

$$P_{turbine} = \frac{1}{2}\rho A C_p V_w^3 \tag{3.5}$$

Where C_p is the power coefficient

Despite the real equation for calculating the electric power being equation (3.6) which takes into account the machine efficiency, in this project a wind turbine without losses will be simulated.

$$P_{electric} = \frac{1}{2}\rho\eta A C_p V_w^3 \tag{3.6}$$

Where η is the machine efficiency

It is worth noting that the swept area, circular section delimited by the edges of the blades, is proportional to the power generated. As Figure 3.2 depicts, if you double the length of the blade (radius) it increases the power generated 4 times.

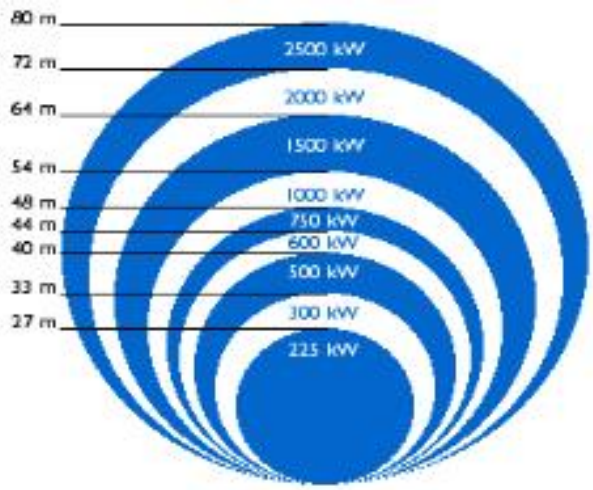


Figure 3.2: Power generated for different lengths of the blade

Regarding equation (3.6) we can observe that wind speed is a very important factor for power generation. Figure 3.3 shows the relation between wind speed and power energy where if the wind speed is doubled then it is obtained 8 times the power generated.

Taking into account this graphics it is clear that when building a wind turbine the wind speed distribution and the dimensions of the machine has to be considered.

As mentioned before, C_p value is limited according to Betz's law. However, its value can vary depending on the angle between the blades and the longitudinal axis (pitch angle) and the relation between the speed of the edge of the blade and the wind speed (tip speed ratio).

When modelling this power coefficient it is common to use the equation (3.7), where c_i are the characteristic parameters of the wind turbine obtained from statistical analysis of a

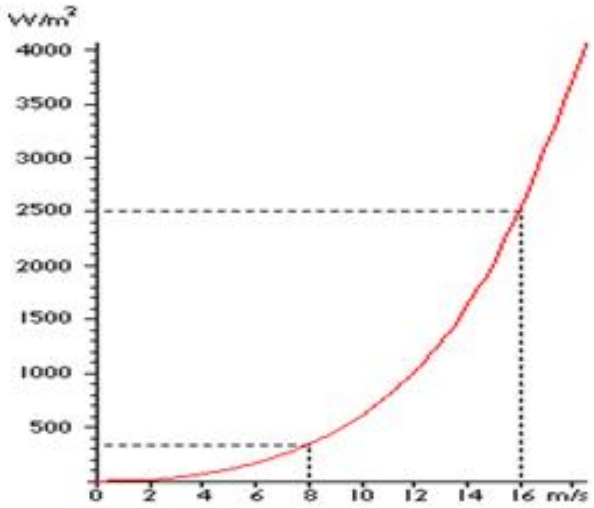


Figure 3.3: Power generated for different wind speeds

real turbine.

$$C_p(\Lambda, \beta) = c_1(c_2\frac{1}{\Lambda} - c_3\beta - c_4\beta^{c_5} - c_6)e^{-}c_7\frac{1}{\Lambda} \tag{3.7}$$

$$\frac{1}{\Lambda} = \frac{1}{\lambda + c_8\beta} - \frac{c_9}{1+\beta^3} \tag{3.8}$$

$$\lambda = \frac{w_t R}{v_w} \tag{3.9}$$

Where β is the pitch angle

λ is the tip speed ratio

w_t is the angular speed

v_w is the wind speed

R is the turbine radius

A thorough study in the equation (3.7) leads to the conclusion that the maximum C_p is obtained from a 0 degree value pitch. That is not strange at all because the angle pitch is an angle which varies when the wind speed is high enough to damage the structure of the blades in order to reduce the wind impact and consequently the wind power absorbed.

In this project the C_p has been modelled using a look-up table with measured data and following the approximation stated in equation (3.10) which means that the pitch angle is constant with a value of 0.

$$\frac{1}{\Lambda} \equiv \frac{1}{\lambda} \tag{3.10}$$

Figure 3.4 shows the relation between the C_p and the tip speed ratio, where the optimum C_p is not only obtained with a 0 degrees pitch angle but also there has to be a λ^{opt} of 7. Figure 3.4 also depicts the optimum value of C_p; C_p^{opt}=0,45 which as explained has to be under Betz's limit for a real wind turbine.

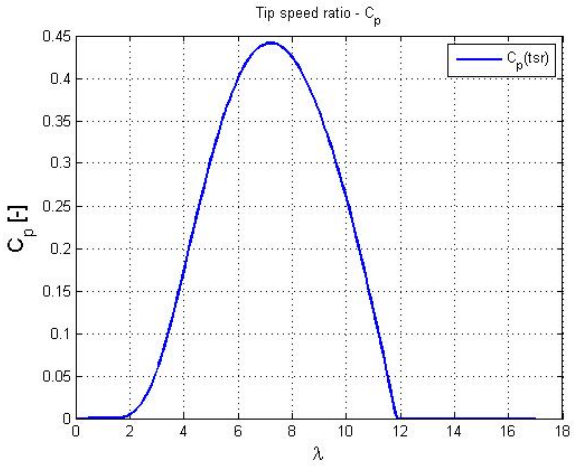


Figure 3.4: Power coefficient for different values of tip speed ratio for pitch angle = 0

Finally, when modelling the wind turbine it is interesting to obtain the mechanical torque thanks to the equation (3.11).

$$P_{turb} = w_t \Gamma_t \tag{3.11}$$

$$\Gamma_t = \frac{1}{2} \rho A C_p V_w^3 \frac{1}{w_t} \tag{3.12}$$

Equation (3.13) is the expression ofthe wind turbine transmission model. The one mass simple transmission model is used, where the mechanic dynamic of the whole turbine, the transmission and the generator axis are modelled as one single mechanical inertia affected by the turbine's and the generator's torque.

$$\Gamma_t + \nu \Gamma_m = J_t \frac{d}{dt} w_t \tag{3.13}$$

$$w_r = \nu w_t \tag{3.14}$$

Where Γ_t is the turbine's torque and Γ_m is the generator's torque

ν is the transmission relation

J_t is the whole inertia of the turbine seen from the low axis

w_r is the angle speed of the rotor and w_t is the angle speed of the turbine

3.3 Poly-phase Permanent Magnet Synchronous Generator (PMSG)

This chapter details the modelling of both a typical PMSG and a six-phase PMSG, which are quite similar but some differences have to be taken into account when modelling.

The permanent magnet synchronous generator is a kind of generator made up of a set of magnets in the rotor and a set of coils in the stator. The rotation of the magnets while the coils are fixed generates current induction, as it is shown in Figure 3.7, according to the Faraday and Lorentz's law.

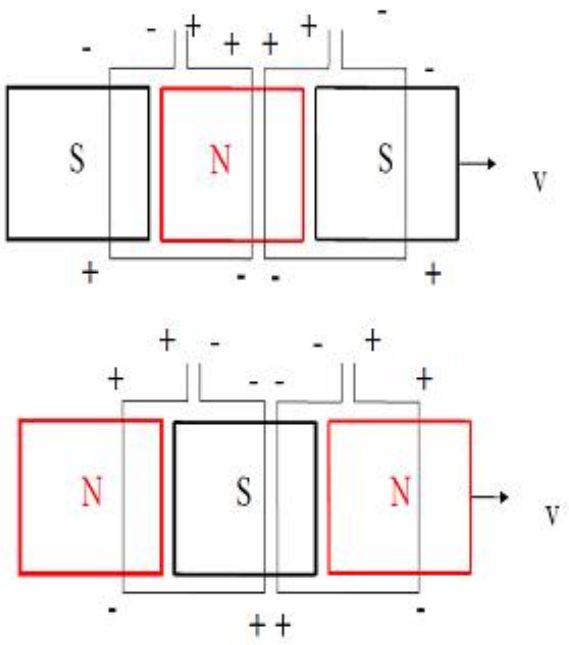
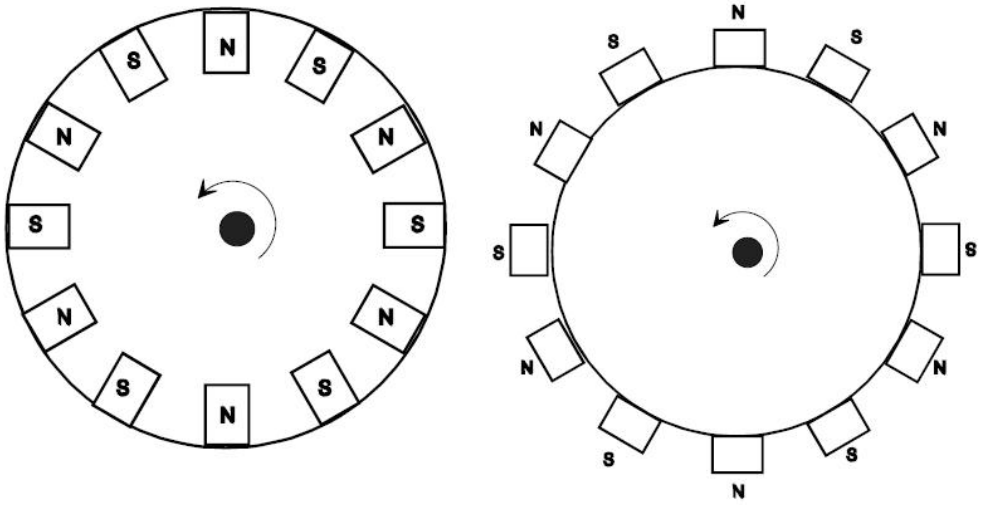


Figure 3.5: Emf induced to a square loop by moving magnets

Two types of PMSG depending on the position of the magnets exist:

- **Axial flow generators:** The rotation of the shaft is parallel to the magnetic field of the magnets
- **Radial flow generators:** The rotation of the shaft is perpendicular to the magnetic field of the magnets



(a) Axial flow generators (b) Radial flow generators

Figure 3.6: Types of permanent magnets synchronous generators

Unlike the common generators made up of external excitation circuit, PMSG are much more efficient and compact. They do not need to have a gear box which prevents possible failures and reduces maintenance. This kind of disposition is called direct-drive, where the turbine is directly connected to the generator, but it requires a high number pole pair [8].

As it has been explained the turbine rotates thanks to the kinetic energy of the wind, this rotation is transmitted to the rotor (equation (3.14)). In this project this transmission has been considered $\nu = 1$ which it means that $w_r = w_t$ so the rotor and the turbine rotate at the same speed. This rotation of the magnetic field of the rotor generates a variation in the magnetic flow to the stator coils which induces as many tensions as phases the generator has.

The relation between the angular speed of the rotor and the stator depends on the pole pair (equation (3.17)).

$$w_s = p w_r \tag{3.15}$$

Where w_s is the angular speed of the stator

p is the pair of poles

w_r is the angular speed of the rotor

The phase shift between the induced tensions depend on the position of the stator coils (windings). Therefore for a three-phase PMSG there is a 120º phase shift whereas the phase shift of a six-phase PMSG is 30º between the nearest winding but it could be divided in two groups of three windings shifted 120º representing two typical three-phase systems.

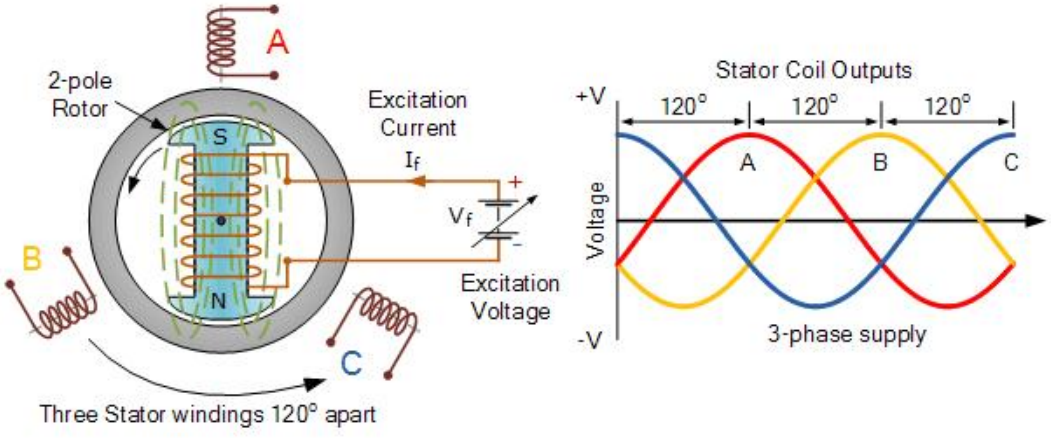


Figure 3.7: Three-phase PMSG scheme with one pole pair

The term synchronous means that the generator frequency is the same as the frequency of the grid, as it shows Figure 3.8. However, there is the chance to use converters which allow the generator to rotate at different speeds from the grid and give tension at the frequency required by the grid for a wide range of wind speeds.

$$f_s = \frac{w_s}{2\pi} \tag{3.16}$$

$$f_r = p\frac{w_r}{2\pi} \tag{3.17}$$

Number of Individual Poles	2	4	8	12	24	36	48
Rotational Speed (rpm)	3,000	1,500	750	500	250	167	125

Figure 3.8: Angular speed function of pole pairs for synchronous generators connected to a 50 Hz grid

In this project a VSC back-to-back converter is used. The number of converters depend on the number of phases of the PMSG. Therefore, each converter is designed to handle three phases, so a six-phase PMSG will be connected to two converters, three phases for each one.

Some differences exist in modelling depending on the phases of the PMSG. Despite being closely related, each type will follow its own expressions and simplifications.

3.3.1 Three-phase PMSG

The three-phase system (abc) is simplified thanks to the Park transformation where the tensions and currents will be expressed in two components dq0 as the third will be of value 0.

$$\frac{d}{dt}i_{s,qd} = \begin{pmatrix} \frac{-r_s}{L_q} & \frac{-w_s L_d}{L_q} \\ \frac{w_s L_q}{L_d} & \frac{-r_s}{L_d} \end{pmatrix} i_{s,qd} - \phi_m w_s \begin{pmatrix} \frac{1}{L_q} \\ 0 \end{pmatrix} + \begin{pmatrix} \frac{1}{L_q} & 0 \\ 0 & \frac{1}{L_d} \end{pmatrix} v_{s,qd} \tag{3.18}$$

$$L_q = L_{ls} + \frac{3}{2}(L_A - L_B) \tag{3.19}$$

$$L_d = L_{ls} + \frac{3}{2}(L_A + L_B) \tag{3.20}$$

Where L_A, L_B and L_{ls} are inductances characteristics of the generator

$i_{s,qd}$ and $v_{s,qd}$ are the currents and tensions in the stator after the Park transformation

ϕ_m is the magnetic flow generated by magnets of the rotor

w_s is the angular speed of the stator

L_q and L_d are the quadrature and the and direct self-inductances, parameters to make the expression much simpler.

In this project it has been considered a radial flow generator like Figure 3.6 (b), where it is possible to approximate $L_B = 0$ so $L_q = L_d$.

The power generated by a three-phase PMSG is expressed through the common power equation (3.21). Applying equation (3.18), Equation 3.22 can be obtained. Its value will be quite similar to the turbine power because of the lack of losses in the generator. The same thing happens with the torque which is the power divided by the angular speed of the stator (equation (3.23)).

$$P_{gen} = \frac{3}{2}(v_{sq} i_{sq} + v_{sd} i_{sd}) \tag{3.21}$$

$$P_{gen} = \frac{3}{2}\phi_m w_s i_{sq} \tag{3.22}$$

$$\Gamma_{gen} = \frac{3}{2}\phi_m p i_{sq} \tag{3.23}$$

3.3.2 Six-phase PMSG

Those kinds of generators have two sets of three-phase windings shifted thirty degrees.

Unlike in a three-phase system, in a six-phase system (abcdef) the simplification is done through the Clarke transformation plus a rotation in order to obtain the parameters $dqxyz_1z_2$ where the $z_1 - z_2$ are the zero-sequence components of both three-phase sets of windings with a value of 0. That is why this components will not be taken into account in neither the model nor the equations [9].

$$\frac{d}{dt}i_{sd} = (v_{sd} - r_s i_{sd} + L_q w_s i_{sq})/L_d \tag{3.24}$$

$$\frac{d}{dt}i_{sq} = (v_{sq} - r_s i_{sq} - L_q w_s i_{sd} - w_s \phi_m)/L_q \tag{3.25}$$

$$\frac{d}{dt}i_{sx} = (v_{sx} - r_s i_{sx})/L_{ls} \tag{3.26}$$

$$\frac{d}{dt}i_{sy} = (v_{sy} - r_s i_{sy})/L_{ls} \tag{3.27}$$

The components x,y will be set to 0 through the controller to make the wind turbine more efficient.

Equations (3.24) to (3.27) take into account the $\frac{3}{2}$ term characteristic when calculating the power or the torque. Therefore, the expressions of the power and the torque generated in a six-phase PMSG are equations (3.28) and (3.29) respectively.

$$P_{gen} = \phi_m w_s i_{sq} \tag{3.28}$$

$$\Gamma_{gen} = \phi_m p i_{sq} \tag{3.29}$$

3.4 Converter

The PMSG is connected to the grid through converters in order to transform the generator frequency to the grid frequency. To do that, in this project a back-to-back converter is used (Figure 3.9), which is composed of two VSCs (Voltage Source Converter): one converter or rectifier (AC/DC) and one inverter (DC/AC). The connection between them is done through a DC bus formed by a shunt capacitor with a voltage called E_{dc}.

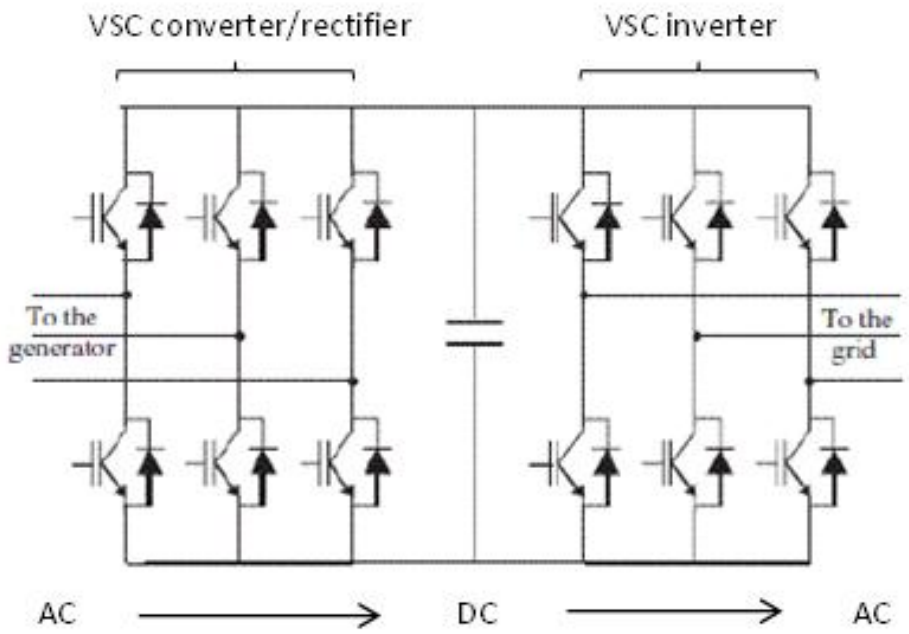


Figure 3.9: Scheme of a back-to-back converter [8]

The VSC converters, are composed of 6 IGBT (Insulated-Gate Bipolar Transistors) which can provide fast switching and modulate any desired voltage. Despite being able to control active and reactive power, providing black start capability and injecting reduced harmonic currents which allows the use of lighters filters, the VSC converters have high losses due to the high switching frequency.

The DC side is modelled as a direct current source and a shunt capacitor while the AC side (Grid side) is modelled as three tension sources connected to the grid because it is a three phase system. Figure 3.10 depicts the modelling of the DC and AC side of a VSC inverter. For six-phase generators, in this project two back to back converters are used each one for three phases (Figure 2.1).

This modelling simplifies the system to an ideal converter where the switching of the IGBTs have no losses and with a high switching frequency. So the power in the DC side has to be the same as in the AC side in order to ensure the ideal energetic balance (equation

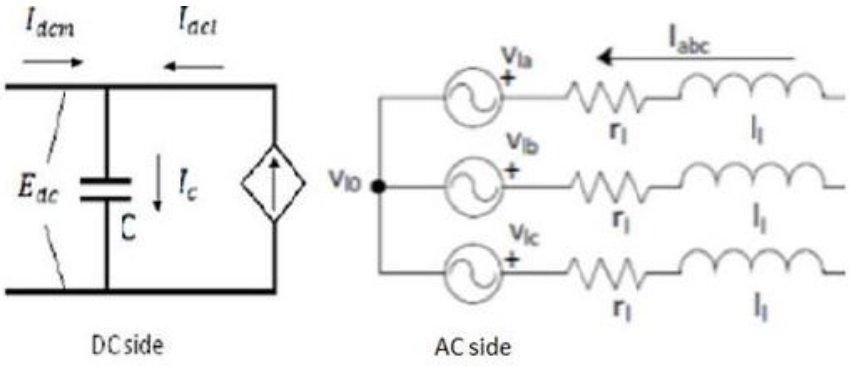


Figure 3.10: Modelling of the AC and DC side of a VSC inverter [10]

(3.33)).

$$P_{dc} = P_{ac(z)} \tag{3.30}$$

$$P_{dc} = E_{dc} I_{dcl} \tag{3.31}$$

$$P_{ac(z)} = v_{la} I_{la} + v_{lb} I_{lb} + v_{lc} I_{lc} \tag{3.32}$$

$$E_{dc} I_{dcl} = v_{la} I_{la} + v_{lb} I_{lb} + v_{lc} I_{lc} \tag{3.33}$$

$$E_{dc} = E_{dc0} + \frac{1}{C} + \int_0^t I_{dc} = E_{dc0} + \frac{1}{C} + \int_0^t (I_{dcl} - I_{dcm}) \tag{3.34}$$

Where P_{ac} is the active power exchanged between the AC side of the VSC converter and the grid

P_{dc} is the power in the DC side of the VSC converter

E_{dc} is the DC bus voltage

The connection between the AC side of the VSC inverter and the grid is done with a resistance and an inductance which work as filters following the equation (3.35). Nevertheless, in this project a simplification is applied with the Park transformation (Section A) that

changes the reference frames form abc to dq0, obtaining equation (3.36) where the third component 0 has not be taken into account as its value is 0.

$$\begin{pmatrix} v_{za} \\ v_{zb} \\ v_{zc} \end{pmatrix} - \begin{pmatrix} v_{la} \\ v_{lb} \\ v_{lc} \end{pmatrix} - (v_{l0} - v_{z0}) \begin{pmatrix} 1 \\ 1 \\ 1 \end{pmatrix} = \begin{pmatrix} r_l & 0 & 0 \\ 0 & r_l & 0 \\ 0 & 0 & r_l \end{pmatrix} \begin{pmatrix} I_{za} \\ I_{zb} \\ I_{zc} \end{pmatrix} + \begin{pmatrix} l_l & 0 & 0 \\ 0 & l_l & 0 \\ 0 & 0 & l_l \end{pmatrix} \frac{d}{dt} \begin{pmatrix} I_{za} \\ I_{zb} \\ I_{zc} \end{pmatrix} \quad (3.35)$$

$$\begin{pmatrix} v_{zq} \\ v_{zd} \end{pmatrix} - \begin{pmatrix} v_{lq} \\ v_{ld} \end{pmatrix} = \begin{pmatrix} r_l & l_l w_z \\ l_l w_z & r_l \end{pmatrix} \begin{pmatrix} I_{zq} \\ I_{zd} \end{pmatrix} + \begin{pmatrix} l_l & 0 \\ 0 & l_l \end{pmatrix} \frac{d}{dt} \begin{pmatrix} I_{zq} \\ I_{zd} \end{pmatrix} \quad (3.36)$$

The connection between the AC side (Generator side) and the DC side follows the same principle where the DC side will be modelled as a current source where the current I_{dcm} is provided by equation (3.38). Like in the inverter/grid connection the generator/converter has to ensure the power balance. Therefore the power generated will be equal to the power in the DC side assuming no mechanical losses [8].

$$P_{dc} = P_{ac(s)} \quad (3.37)$$

$$P_{dc} = E_{dc} I_{dcm} \quad (3.38)$$

$$P_{ac(s)} = v_{sa} i_{sa} + v_{sb} i_{sb} + v_{sc} i_{sc} \quad (3.39)$$

In six-phase PMSG there will be two VSC back to back converters where the power transmitted will be divided in these two ways. Then the power for the abc converter and def converter will follow the equations (3.40) to (3.42) and (3.43) to (3.45) respectively.

$$P_{dc(abc)} = P_{ac(s)} \quad (3.40)$$

$$P_{dc(abc)} = E_{dc(abc)} I_{dcm(abc)} \quad (3.41)$$

$$P_{ac(s)} = v_{sa} i_{sa} + v_{sb} i_{sb} + v_{sc} i_{sc} \quad (3.42)$$

$$P_{dc(def)} = P_{ac(s)} \quad (3.43)$$

$$P_{dc(def)} = E_{dc(def)} I_{dcm(def)} \tag{3.44}$$

$$P_{ac(s)} = v_{sd} i_{sd} + v_{se} i_{se} + v_{sf} i_{sf} \tag{3.45}$$

3.5 Electric grid

The electric grid is modelled by three tension sources with the same voltage and a shift phase of 120º between them, following the equations (3.46) to (3.48). As this is a European project, grid frequency will be modeled as 50Hz, unlike the 60Hz typical of America.

$$v_{za} = \sqrt{2} V_{ef} cos(w_z t + \theta_0) \tag{3.46}$$

$$v_{zb} = \sqrt{2} V_{ef} cos(w_z t + \theta_0 - \frac{2\pi}{3}) \tag{3.47}$$

$$v_{zc} = \sqrt{2} V_{ef} cos(w_z t + \theta_0 + \frac{2\pi}{3}) \tag{3.48}$$

$$w_z = 2\pi f_z \tag{3.49}$$

$$V_{ef} = \frac{V_{peak}}{\sqrt{2}} \sqrt{3} \tag{3.50}$$

Where θ_0 is the initial phase electric angle

V_{ef} is the effective voltage of the grid

V_{peak} is the maximum voltage of the grid

As said before, the connection between the grid and the VSC inverters is done by inductances which filters the voltages leading to the grid.

Figure 3.11 shows the connection between a three-phase PMSG with a back-to-back converter to the grid.

Then Figure 3.12 shows the connection between a six-phase PMSG with two back-to-back converters to the grid.

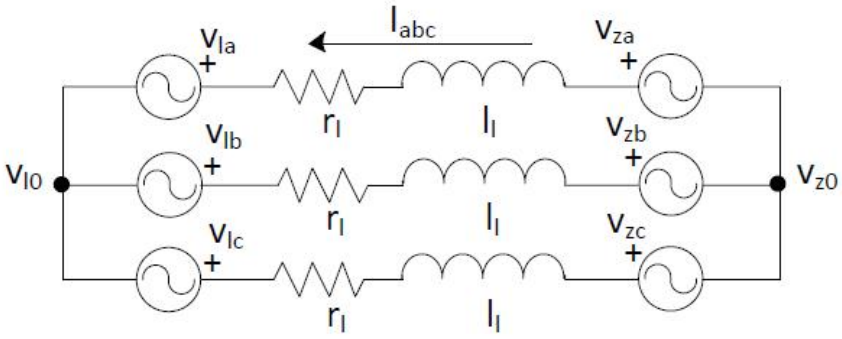


Figure 3.11: Three-phase system connection between the AC side of a back-to-back converters and the electric grid [10]

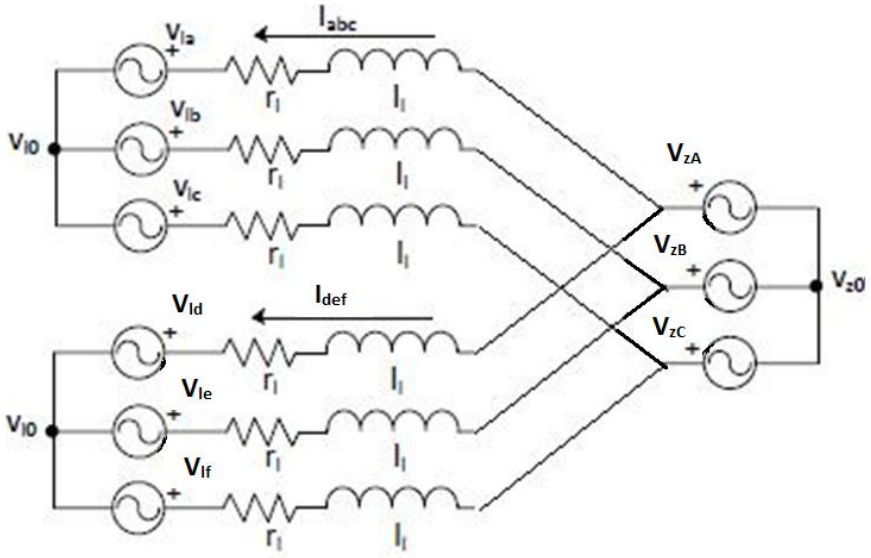


Figure 3.12: Six-phase system connection between the AC side of two back-to-back converters and the electric grid

Applying the Kirchhoff laws in Figure 3.12, equation (3.51) for six-phase systems is obtained.

$$I_{zABC} = I_{labc} + I_{ldef} \tag{3.51}$$

4 Wind Turbine control

The purpose of control is to optimize the energy yield for a wide range of wind conditions and to limit the torque and power caused by the drive train in order to reduce the structural loads and maximize its lifetime.

In this project, the control of the turbine will be studied in two steps: the grid side and the generator side.

4.1 Grid side control

The main objective in the control of the grid side is to adapt the current of the inverter to the grid. By controlling inverter tensions it is possible to control the currents and the power injected to the grid.

The control scheme is based on a controller which allows current regulation on the AC side and a controller to regulate the tensions of DC side (bus).

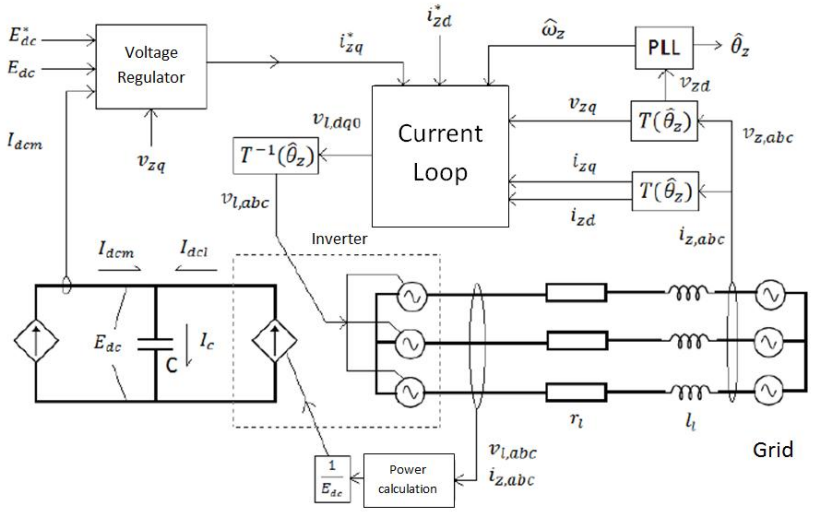


Figure 4.1: Grid side control general scheme[8]

The grid requires active and reactive power which can be given precisely thanks to the control of currents with the equations (4.1) and (4.2).

$$P^* = \frac{3}{2}(v_{zq}i^*_{zq} + v_{zd}i^*_{zd}) \tag{4.1}$$

$$Q^* = \frac{3}{2}(v_{zq}i^*_{zd} + v_{zd}i^*_{zq}) \tag{4.2}$$

Therefore, the expressions (4.3) and (4.4) will be the equations applied in the controller to find the desired currents. Where the i^*_{zq} will be provided by the voltage regulator and the i^*_{zd} will be a parameter imposed by the grid reactive power (Q^*)

As the controllers work with tensions and currents in the qd0 reference frame to adjust the electrical grid angle, a Phase Locked Loop (PLL) is required (explained in Section C). The PLL will guarantee a $v_{zd} = 0$.

$$i^*_{zq} = \frac{2}{3}\frac{P^*}{v_{zq}} \tag{4.3}$$

$$i^*_{zd} = \frac{2}{3}\frac{Q^*}{v_{zq}} \tag{4.4}$$

4.1.1 Voltage Regulator Control (DC side)

The voltage regulator works in the DC side of the inverter and its objective is to kee the bus voltage constant with the desired value E^*_{dc}. When this constant value is achieved, the current $|I_{dcm}|$ becomes equal to $|I_{dcl}|$ because the $I_c = 0$. Therefore the power generated in the PMSG will be totally transmitted without losses to the AC side of the inverter. However, part of the power will be lost when injecting the power into the grid due to the resistances which act as filters.

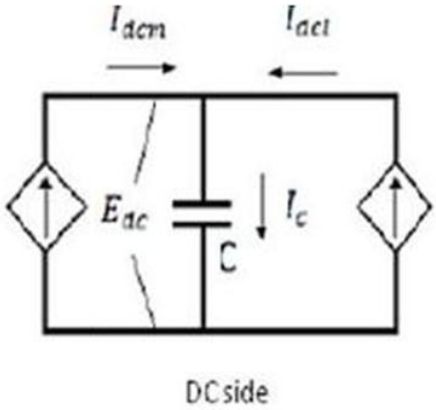


Figure 4.2: DC side modelling of the converter and the inverter [10]

This control is done through the capacitor which allows voltage regulation. The equation of the capacitor equation (4.5) corroborates that when the tension of the capacitor E_{dc}^* is constant in time, the current of the capacitor I_c is 0.

$$I_c = C\frac{dE_{dc}}{dt} \tag{4.5}$$

After applying the Laplace transformation, he equation (4.9) is obtained where the current and the tension are related.

$$\frac{E_{dc}(s)}{I_c(s)} = \frac{1}{Cs} \tag{4.6}$$

Figure 4.3 depicts the modelling of the voltage regulator where the input is the E_{dc}^* imposed for regulating the voltage capacitor. The output of the DC voltage controller will provide the i_{lq}^* used in the current loop. As explained, for three-phase PMSG this $i_{lq}^* = i_{zq}^*$ whereas for a six-phase PMSG it has to be considered both ${i_{lq}}^*$ and i_{lx}^* to obtain i_{zq}^*.

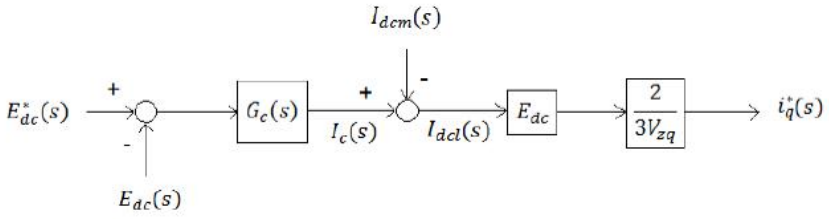


Figure 4.3: Voltage regulator modelling scheme [6]

$$G_c(s) = \frac{K_p s + K_i}{s} \tag{4.7}$$

$$k_p = 2Cw_n\xi \tag{4.8}$$

$$k_i = Cw_n^2 \tag{4.9}$$

Where $G_c(s)$ is a PI controller which will ensure the value of the current capacitor to the desired value (E_{dc}^*), as it can be seen in Figure 4.4.

w_n and ξ are parameters characteristics of a second order system

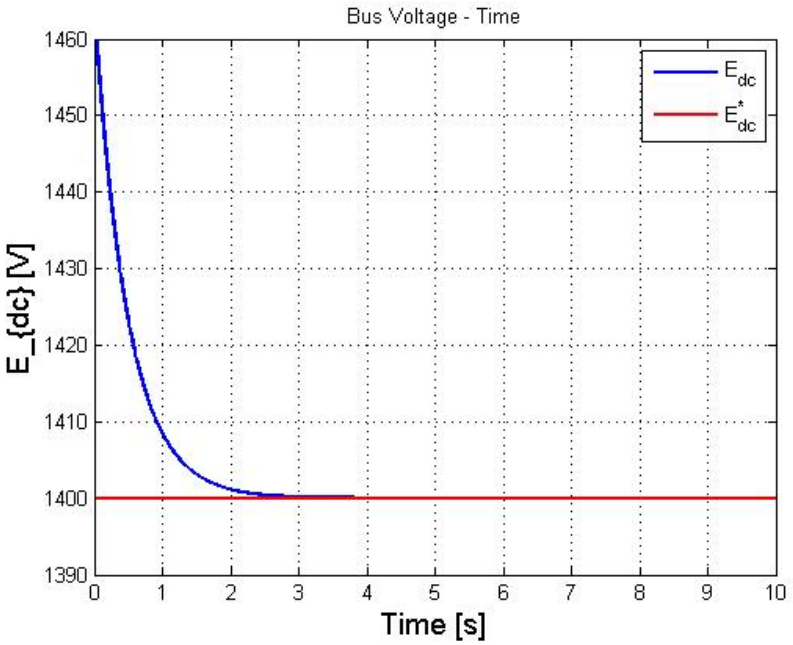


Figure 4.4: Control of the voltage capacitor with a given value ($E_{dc}{}^{*}$)

Applying Kirchhoff it is easily obtained the equation (4.10).

$$I_c = I_{dcm} + I_{dcl} \tag{4.10}$$

Where I_c is the current of the capacitor

I_{dcm} is the current transferred from the generator to the DC bus

I_{dcl} is the current transferred from the DC bus to the converter

Therefore by applying the control and imposing the voltage of the capacitor we will obtain a current in the capacitor I_c. Knowing the current that comes from the generator I_{dcm} and applying equation (4.10), it is easy to discover the current transferred to the inverter I_{dcl}. With equation (4.11) it is possible to obtain the power of the AC side of the inverter which in order to guarantee the power balance will be used to calculate i_{lq}^{*} through equation (4.3) applied to the converter.

$$P_{ac} = E_{dc} I_{dcm} \tag{4.11}$$

The graphic of the voltage capacitor in Figure 4.4 depicts a peak characteristic of a second order system before becoming steady.

One of the conditions to have stable system response is that the DC voltage loop has to be much slower than the current of the controller.

4.1.2 Current Loop Control for the inverter (AC side)

Once the voltage regulator gives the desired i_{lq}^*, the current loop begins controlling the currents of the converters transferred to the grid and the desired voltage adapted to the grid is obtained.

Among the different controlling methods, in this project the method used for controlling the dq currents is to decoupling and controlling separately i_q and i_d.

$$\begin{pmatrix} v_{lq} \\ v_{ld} \end{pmatrix} = \begin{pmatrix} -\hat{v}_{lq} + v_{zd} - l_l w_s i_{ld} \\ -\hat{v}_{ld} + l_l w_s i_{lq} \end{pmatrix} \tag{4.12}$$

where the parameters to control will be $\hat{v}_{lq}$ and $\hat{v}_{ld}$ which follows equations (4.13) and (4.14).

$$\hat{v}_{lq}(s) = r_l i_{zq} + l_l \frac{di_{zq}}{dt} \tag{4.13}$$

$$\hat{v}_{ld}(s) = r_l i_{zd} + l_l \frac{di_{zd}}{dt} \tag{4.14}$$

The modelling of the current loop controller is shown in Figure 4.5 where it is represented equation (4.29) which decouples the qd currents.

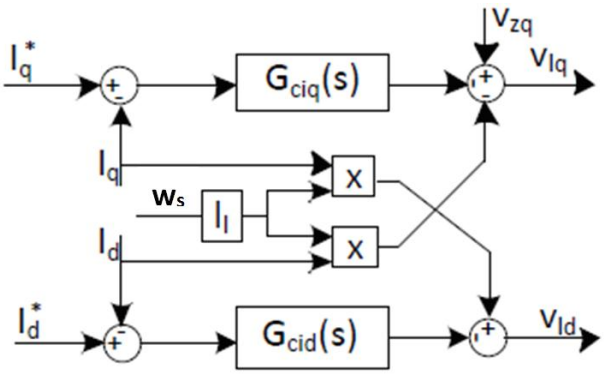


Figure 4.5: Current loop control scheme [10]

Where the $G_{ciq}(s)$ and $G_{cid}(s)$ are PI controllers for the quadrature and direct current respectively as it is shown in equation (4.15).

$$G_{ciq}(s) = G_{cid}(s) = \frac{K_p s + K_i}{s} \tag{4.15}$$

Unlike the voltage regulator control, the current loop is a first order system. Therefore the response will not have any peak and will follow the typical first order response as it is shown in Figure 4.6 for a step input.

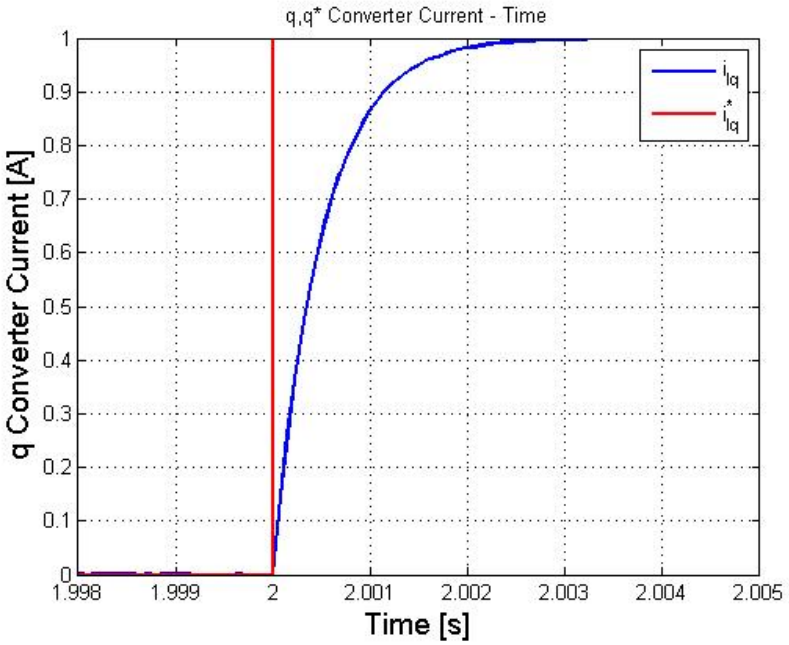


Figure 4.6: Current loop control answer for a step input

The PI control parameters are defined in equations (4.16) and 4.17.

$$K_p = \frac{l_l}{\tau} \tag{4.16}$$

$$K_i = \frac{r_l}{\tau} \tag{4.17}$$

where r_l and l_l are the inductances of the inverter.

τ is the time constant of the electrical system. The constant depends on the physical restrictions of the inverter and its value it could be approximated to 10 times faster than the switching frequency of the converter.

4.2 Generator side control

The generator side control works similar to the grid side control where the objective is to control the converter AC side voltages to obtain the desired currents of the stator (i^*_{sq} and i^*_{sd}) for three-phase systems and (i^*_{sq}, i^*_{sd}, i^*_{sx} and i^*_{sy}) for six-phase systems.

The control for a three-phase system and a six-phase system is different because the machines follow different equations.

4.2.1 Three-phase system control

Figure 4.7 shows the control of a converter connected to a three-phase PMSG. The control of the angular speed of the turbine (w_t) allow to regulate the power generated and it is done through the achievement of the desired currents in the current loop (i^*_{sq}, i^*_{sd}).

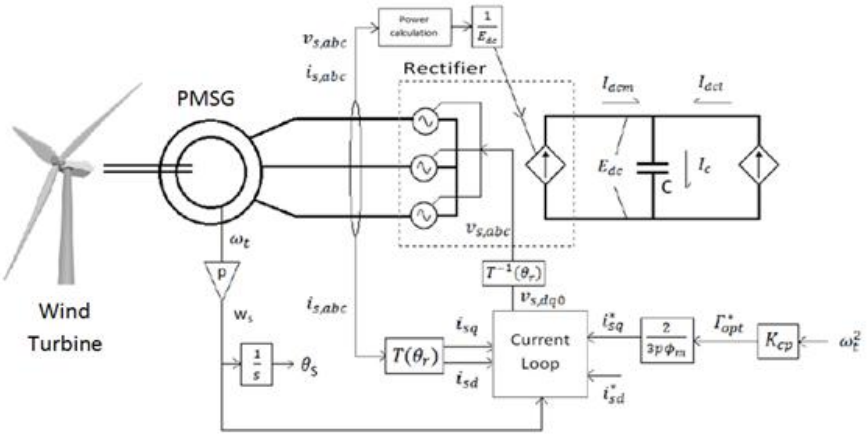


Figure 4.7: Generator side control general scheme of a three-phase system [8]

As the controller pursuits the optimum power generated, the desired quadrature current (i^*_{sq}) is calculated through the optimum electrical torque with equation (4.18).

$$\Gamma^*_{opt} = k_{cp} w_t^2 \tag{4.18}$$

For calculating the optimum power generated for a wide range of wind conditions it is used a controller which guarantees the stability of the tip speed ratio. Therefore, for a specific turbine rotation it will be calculated an optimum electrical torque for stabilizing the turbine rotation.

The optimum torque depends basically on the C_p, this parameter could be controlled through the pitch angle and the tip speed ratio. In this project the pitch angle has been

considered zero ($\beta = 0$). Then equation (4.19) represents the optimum torque achieved for a wind speed (w_t) through the term k_{cp} with a pitch angle of 0. This parameter provides the optimum power absorbed from the wind with an optimum tip speed ratio for achieving the maximum C_p [6].

$$k_{cp} = \frac{c_1 e^{-(\frac{c_6 c_7 + c_2}{c_2})}(c_2 c_7 c_9 + c_6 c_7 + c_2)^3}{c_2^2 c_7^4} \frac{1}{2} \rho A R^3 \tag{4.19}$$

Once the optimum torque is calculated, the i_{sq}^* is obtained thanks to equation (4.20).

$$i_{sq}^* = \frac{2\Gamma_{opt}^*}{3p\phi_m} \tag{4.20}$$

The direct component of the stator current can be either controlled in order to regulate the inversor voltages.

4.2.1.1 Current Loop Control for the converter

The control of the converter is realized through a current loop control where, as it has been explained in Section 4.1.2 thanks to the control of the stator currents it is obtained the stator tensions.

Therefore, the expressions of decoupling and controlling will be similar but applied to the stator parameters [10].

$$\begin{pmatrix} v_{sq} \\ v_{sd} \end{pmatrix} = \begin{pmatrix} \hat{v}_{sq} + w_s L_d i_{sd} + \phi_m w_s \\ \hat{v}_{sd} - w_s L_q i_{sq} \end{pmatrix} \tag{4.21}$$

where the parameters to control will be $\hat{v}_{sq}$ and $\hat{v}_{sd}$ which follows equations (4.22) and (4.23).

$$\hat{v}_{sq}(s) = r_s i_{sq} + L_q \frac{di_{sq}}{dt} \tag{4.22}$$

$$\hat{v}_{sd}(s) = r_s i_{sd} + L_d \frac{di_{sd}}{dt} \tag{4.23}$$

As in this project it is considered a radial flow generator, we can approximate $L_q = L_d$ so the PI controllers will be equal as they depend on this parameters.

$$G_{cisq}(s) = G_{cisd}(s) = \frac{K_p s + K_i}{s} \tag{4.24}$$

Despite having the same value, the expression of their k_p for the quadrature and direct current are different.

$$K_{iq} = K_{id} = \frac{r_s}{\tau} \tag{4.25}$$

$$K_{pq} = \frac{L_q}{\tau} \tag{4.26}$$

$$K_{pd} = \frac{L_d}{\tau} \tag{4.27}$$

4.2.2 Six-phase system control

The control of a converter in a six-phase system is quite similar to a three-phase system. The stator current desired (i^*_{sq}) is calculated according to the optimum value of the electrical torque to get the maximum power absorbed from the wind. However, the component q of the current has been calculated through Clarke transformation (Section B) unlike in a three phase system, therefore when calculating (i^*_{sq}) it will not be taken into account the $\frac{2}{3}$ as it is shown in equation (4.28) [9].

$$i^*_{sq} = \frac{\Gamma^*_{opt}}{p\phi_m} \tag{4.28}$$

Figure 4.8 shows the control of a converter connected to a six-phase PMSG.

Where the $d, x, y, z_1 z_2$ is set to 0 in this project because this parameters do not contribute to the torque production and they are only losses. The currents d,q,x,y are controlled with four independent PI controllers.

The current loops generate the voltage references which will produce the desired control action on the machine. Then this currents are measured and feed-back to the controllers.

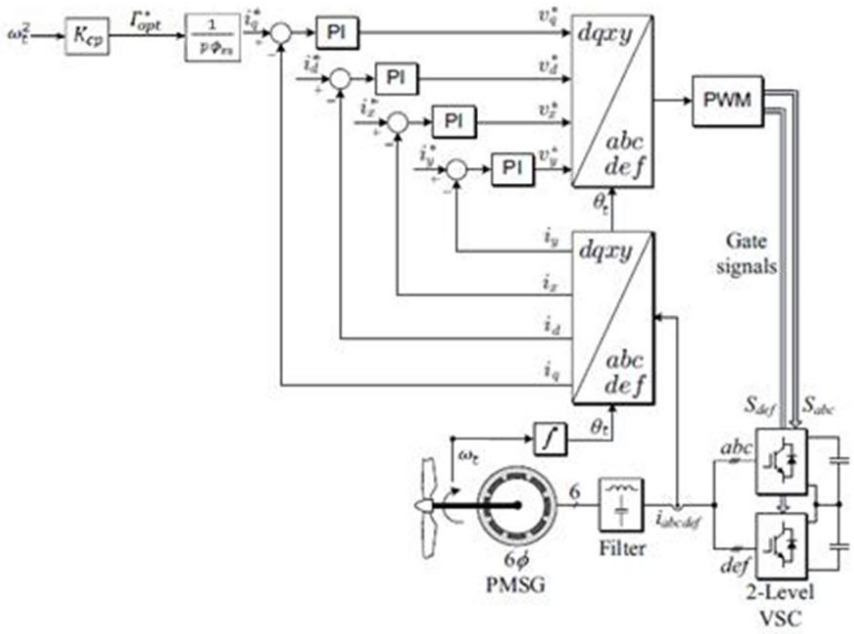


Figure 4.8: Generator side control general scheme of a six-phase system

The expressions of decoupling and controlling will be similar but applied to the four main components.

$$\begin{pmatrix} v_{sq} \\ v_{sd} \\ v_{sx} \\ v_{sy} \end{pmatrix} = \begin{pmatrix} \hat{v}_{sq} + w_s L_d i_{sd} + \phi_m w_s \\ \hat{v}_{sd} - w_s L_q i_{sq} \\ \hat{v}_{sx} \\ \hat{v}_{sy} \end{pmatrix} \tag{4.29}$$

where the parameters to control will be $\hat{v}_{sq}$, $\hat{v}_{sd}$, $\hat{v}_{sx}$ and $\hat{v}_{sy}$. The expressions of the first two parameters are described in Section 4.2.1.1 while the expression of the last two are equations (4.30) and (4.31)

$$\hat{v}_{sx}(s) = r_s i_{sx} + L_{ls} \frac{di_{sx}}{dt} \tag{4.30}$$

$$\hat{v}_{sy}(s) = r_s i_{sy} + L_{ls} \frac{di_{sy}}{dt} \tag{4.31}$$

The parameters of the PI controllers of the xy components of the current are equations (4.32) and (4.33). Unlike qd, the parameters for qd will be the same as both of them depend

only on r_s and L_{ls}.

$$K_{ix} = K_{iy} = \frac{r_s}{\tau} \tag{4.32}$$

$$K_{px} = K_{py} = \frac{L_{ls}}{\tau} \tag{4.33}$$

5 Simulation and analysis

In this chapter it is going to be made a deep analysis of a three-phase and six-phase PMSG for offshore wind turbines. It has been used the well-known mathematical program MATLAB for modeling the components of the wind turbine through the different equations explained along the project.

The values of the parameters used in the simulation are in Section D which represents a typical offshore wind turbine. It will be performance the analysis for constant wind conditions and for an increase in the wind speed in order to study the controlling of the machine adapting to variable conditions.

5.1 Constant wind speed

Therefore, for this first analysis it will be simulated a constant wind speed (V_w) depicted in Figure 5.1.

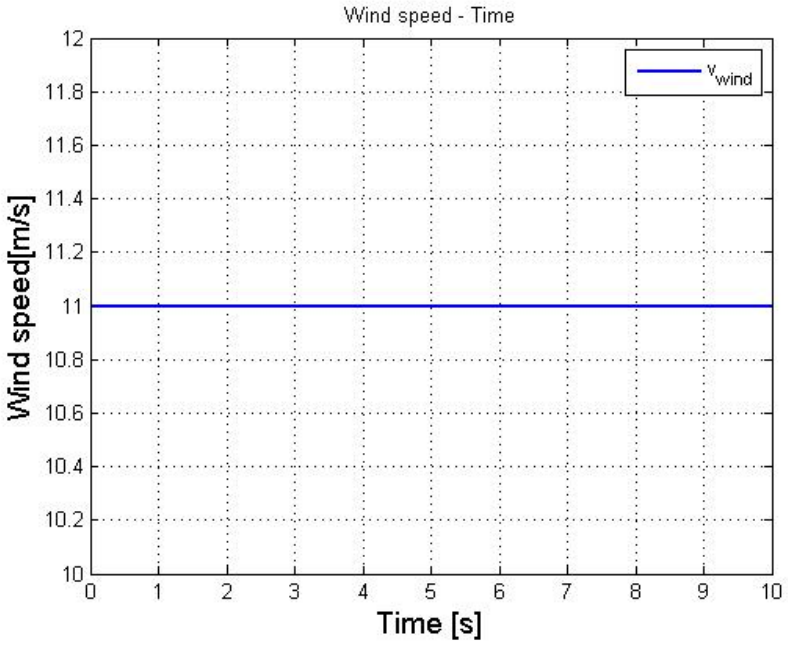


Figure 5.1: Wind speed simulated for the analysis

Figure 5.2 shows how the power absorbed from the wind is conditioned by the C_p parameter. As it is shown in Figure 3.4, in this project for the c_i , pitch angle and wind conditions selected, the C_p^{opt} would represent an efficiency of power wind absorbed of 45%. Therefore, the power of the turbine will be the 45% of the wind power.

Nevertheless, once extracted this kinetic energy from the wind, there will be few losses

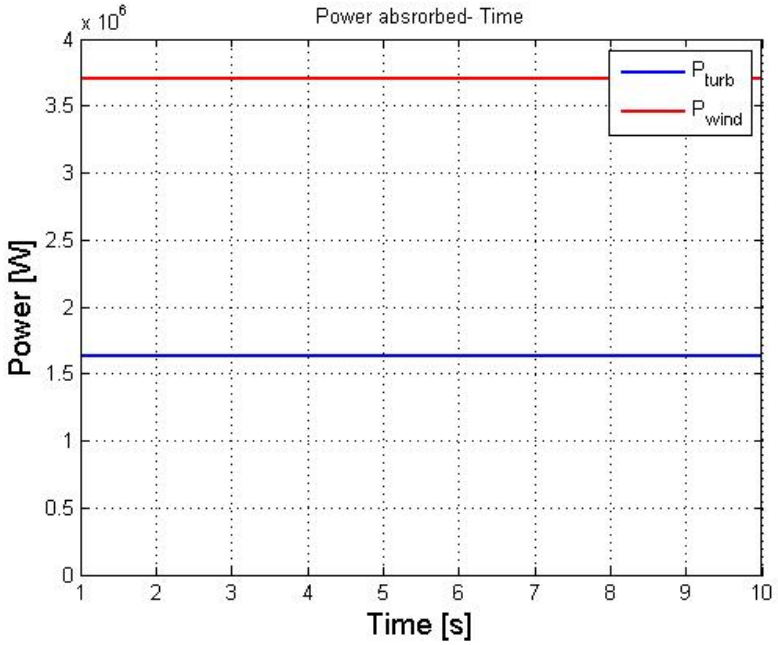
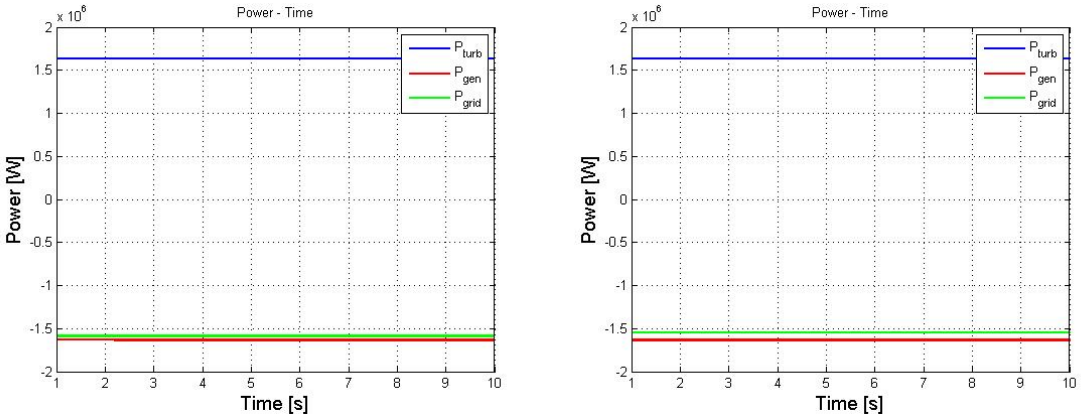


Figure 5.2: Wind power vs Turbine power

inside the machine when transmitting the power to the grid as the modeling it is done assuming only losses in the machine and the filters whereas the converters and the mechanical losses are not considered. Figure 5.4 depicts the turbine power, extracted from the blades rotation, the generated power, obtained from the PMSG and the grid power which is the power after the back to back converter action in order to injected energy to the grid, where the value of those three powers are barely the same due to the reduced losses. Actually, power generated and turbine power are equal due to the control of the torque but the grid power is a little bit lower because of the filters. The power obtained in a three phase system is nearly the same of the one obtained in a six-phase system but with more losses as the current in the three-phase system converter is higher and less efficient.

Figure 5.3: Power cycle from the wind to the grid

When comparing a three-phase system to a six-phase system it is important to highlight the increasing number of connections to the grid as it is shown in Figure 2.1, that means that the power generated in the PMSG is transmitted to the grid through different ways. In a six-phase system, half of the power will be transmitted through one VSC back to back converter and the other half across the other VSC. As the number of phases increases, less current will be transmitted through the converters but more devices will be needed. Figure 5.5 represents how half of the generated power leads to the abc converter and the other half will lead to the def converter, despite the abc converter power being represented on Figure



(a) Three-phase machine: Comparison of powers (b) Six-phase machine: Comparison of powers

Figure 5.4: Three-phase and six-phase machines: Comparison of powers

5.5 with a red line, it is not appreciated because it has the same value of the def converter.

The VSC back to back converters are an important part in the process of transmitting the power generated to the grid. Its main purpose is to inject to the grid the power generated by the wind turbine. In this simulation the grid has been modeled as European electric grid defined by a frequency of $f_z = 50$ Hz and with an specific wind farm voltage of $V_{zeff} = 690$ V.

Figure 5.6 (a) shows the three-phase grid voltages where the peak phase to neutral voltage will be $V_{peak} = 563,38$ V regarding equation (3.50). Thanks to the PLL action (Section C) the v_{zd} will be set to 0 V as it can be seen in Figure 5.6 (b), where v_{zq}=V_{peak}. As it has been explained along the project qd0 frame is obtained after Park transformation applied to abc frame with the electric angle calculated by the PLL.

Figure 5.7 (a) shows the currents of the three-phase grid injected by a three-phase machine, it is interesting to compare these currents to the voltages depicted in Figure 5.6 (a) where it can be seen that they not only have the same frequency but also they are 0 degrees shifted. Therefore, the wind generation system is injecting only active power to the grid.

The voltage and currents injected from the six-phase machine is depicted in Figure 5.8 and Figure 5.9, where theoretically, have less losses than the common three-phase machine.

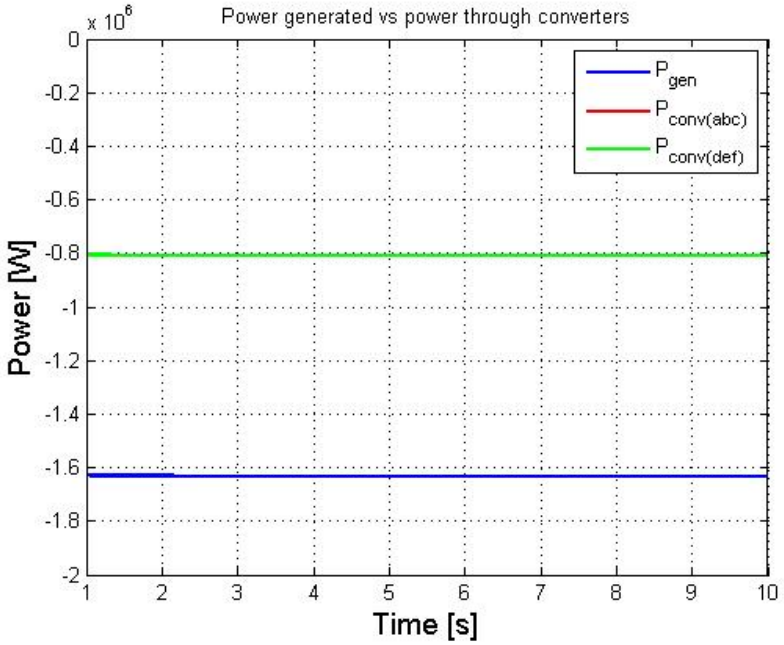
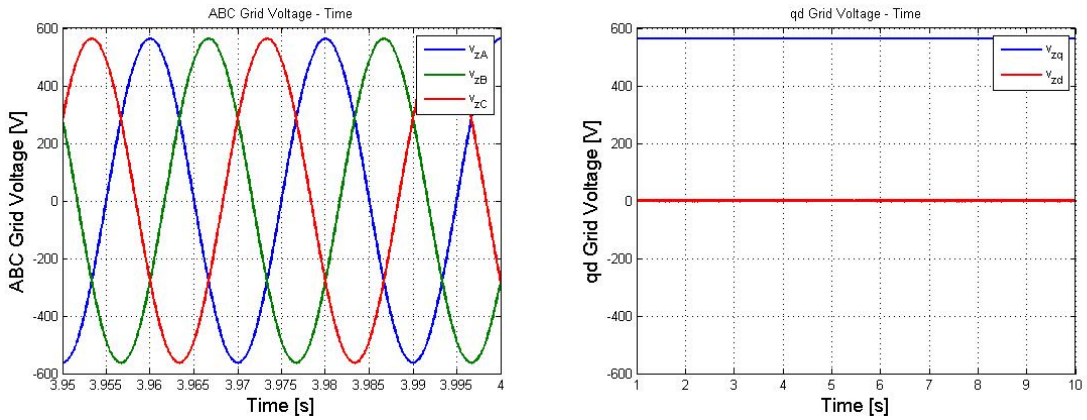


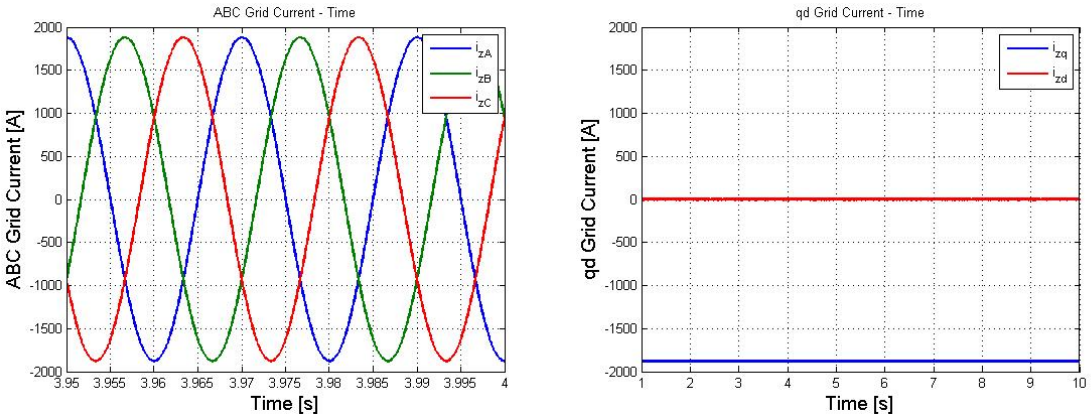
Figure 5.5: Six-phase machine: Generated power vs power transmitted through abc and def converters



(a) ABC grid voltages

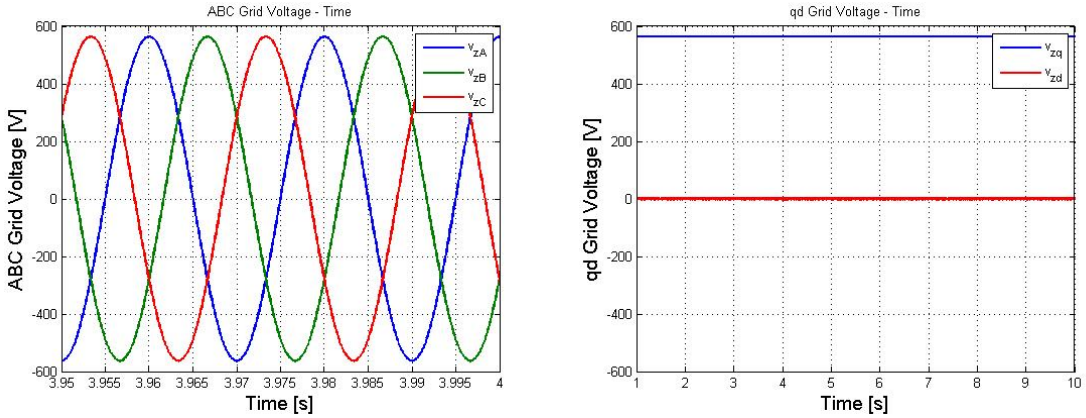
(b) qd0 grid voltages

Figure 5.6: Three-phase machine: Grid voltages in both ABC and qd0 frame



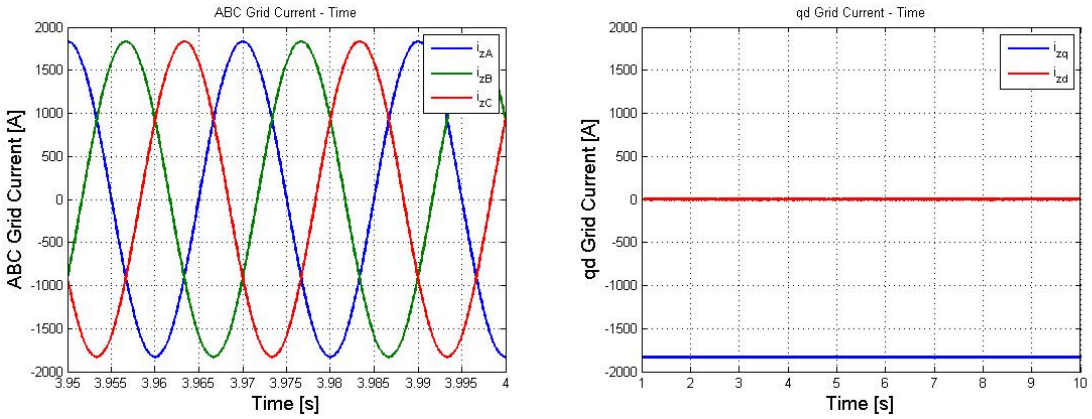
(a) ABC grid currents (b) qd0 grid currents

Figure 5.7: Three-phase machine: Grid currents in both ABC and qd0 frame



(a) ABC grid voltages (b) qd0 grid voltages

Figure 5.8: Six-phase machine: Grid voltages in both ABC and qd0 frame



(a) ABC grid currents

(b) qd0 grid currents

Figure 5.9: Six-phase machine: Grid currents in both ABC and qd0 frame

5.1.1 Three-phase wind generator

Figures 5.10 to 5.14 are obtained from the simulation of constant wind (Figure 5.1) for a three-phase machine.

The main objective of the wind turbine controllers is to obtain the optimum power generated and inject it to the electric grid. To do so, it is essential that the different components of the wind turbine, mainly the converters, follow the desired parameters in order to reduce overloads and adapt the power to the grid. Therefore, the currents of the inverter will be set by the controllers (current loop) where as it is explained in Section 4.1, the i_{lq} it is obtained from an i_{lq}^* provided from imposing a voltage capacitor desired (E_{dc}^*) through the voltage regulator. On the other hand, i_{ld} will follow i_{ld}^*, which is obtained from the reactive power stated by the grid (Q^*) that in this simulation will be set to 0 var.

Figure 5.10 depicts the action of the voltage regulator where the voltage of the capacitor E_{dc} follows the desired parameter $E_{dc}^* = 1400$ V in order to transfer the power from the DC side to the AC grid. It is interesting to appreciate the voltage peak, characteristic of a second order system, of the voltage when adapting to the voltage desired.

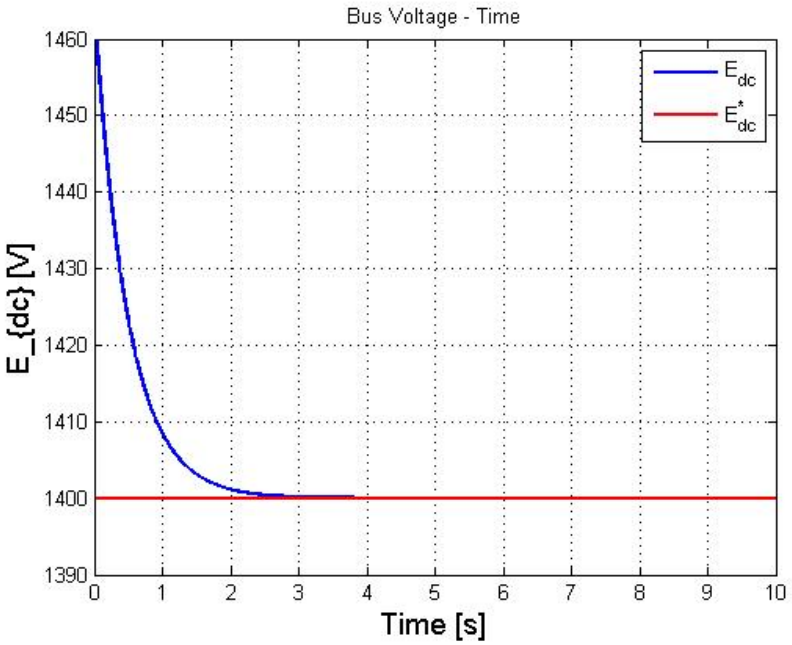
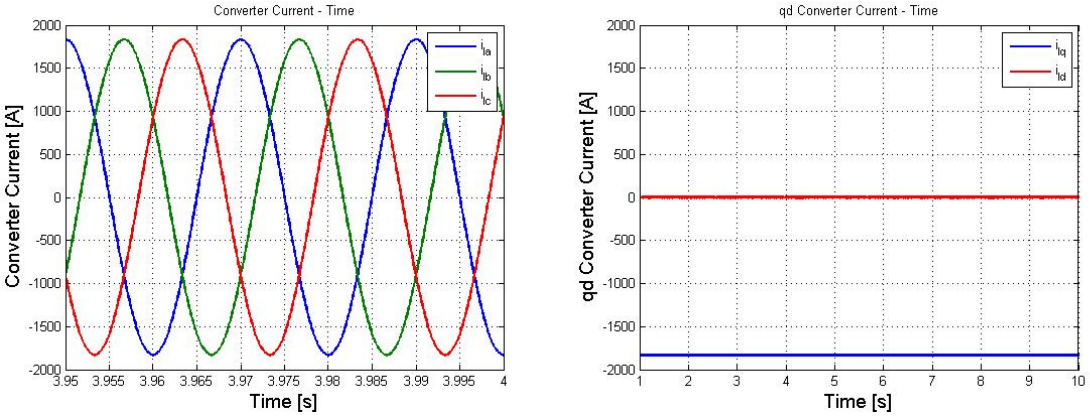


Figure 5.10: Three-phase machine: Voltage regulator control

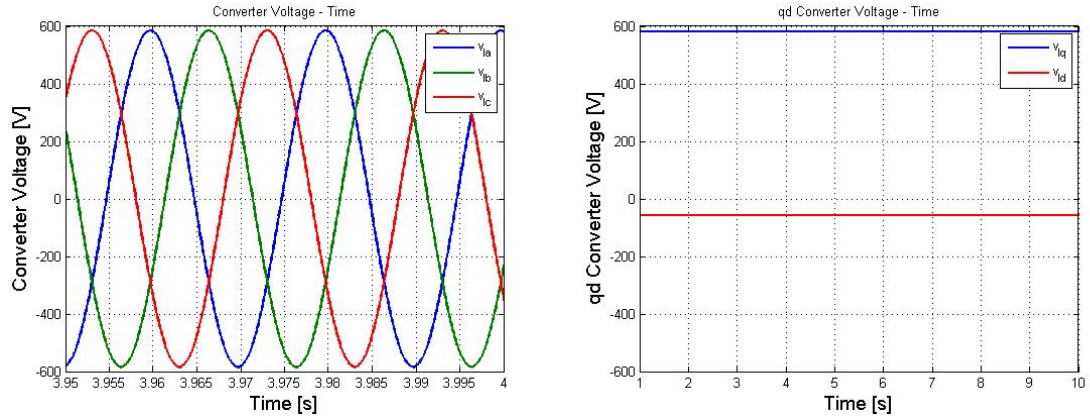
Then, for three-phase systems, the currents obtained in the inverter in abc reference frame are depicted in Figure 5.11 (a). Thanks to the current loop the voltages obtained are shown in Figure 5.12 (b).

Finally, the three-phase generator currents and voltages applied by the rectifier are shown in Figure 5.13 and Figure 5.14.



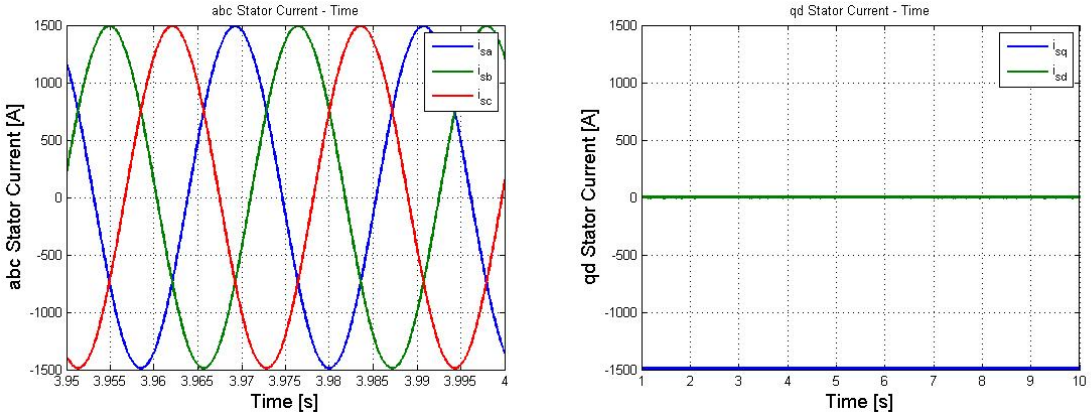
(a) abc inverter current (b) qd inverter current

Figure 5.11: Three-phase machine: abc and qd inverter current



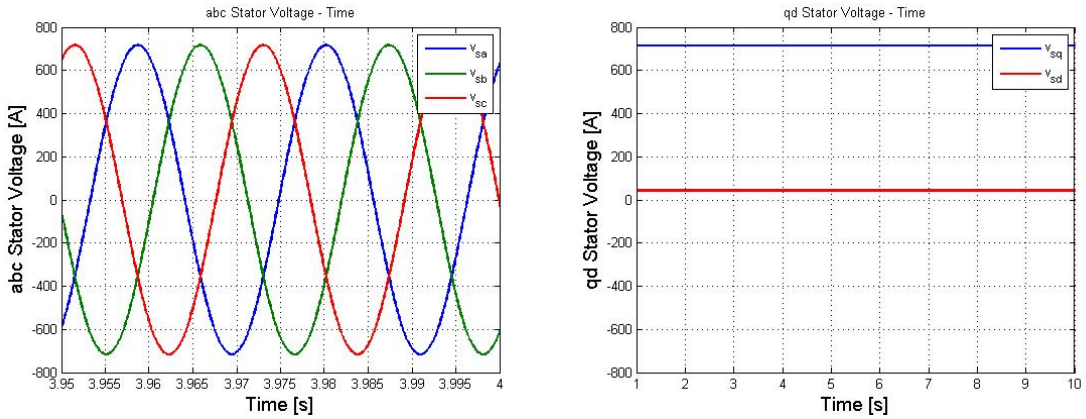
(a) abc inverter voltage (b) qd inverter voltage

Figure 5.12: Three-phase machine: abc and qd inverter voltage



(a) abc stator current (b) qd stator current

Figure 5.13: Three-phase machine: abc and qd stator current



(a) abc stator voltage (b) qd stator voltage

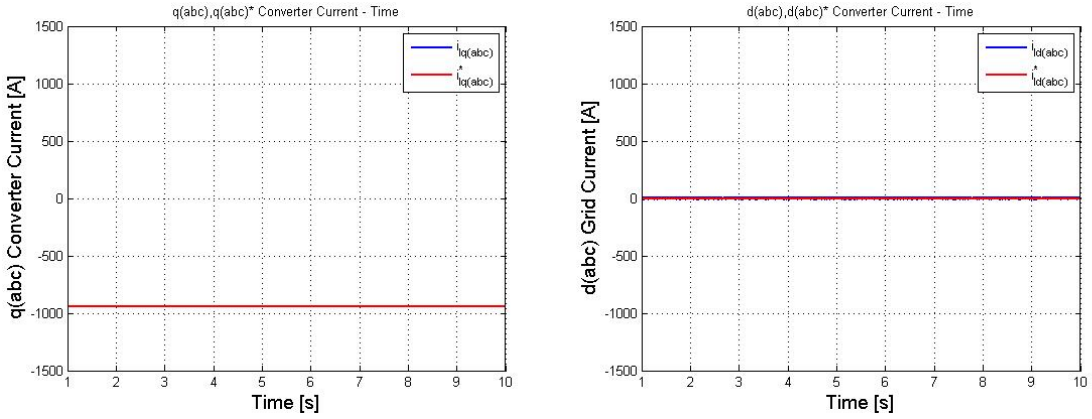
Figure 5.14: Three-phase machine: abc and qd stator voltage

This simulation shows a proper operation of the controllers desing for a wind generation system based on a three-phase PMSG.

5.1.2 Six-phase wind generator

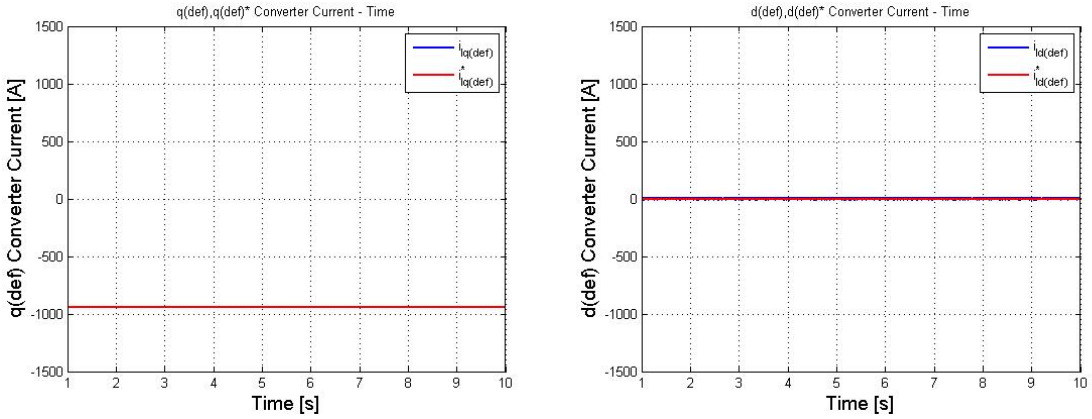
Figures 5.15 to 5.24 are obtained from the simulation of constant wind (Figure 5.1) for a six-phase machine.

As it has been explained, when referring to six-phase systems, there will be two different power channels compounded by two back to back converters. Therefore, the number of parameters to control will be doubled. Regarding the grid side converters, two different current control loops are included to regulate $i_{ld(abc)}$ and $i_{ld(def)}$, one for each converter. Also, as an outer loop, two voltage control loops are implemented to regulate the DC bus voltage $E_{dc(abc)}$ and $E_{dc(def)}$. The operation of the current controllers is shown in Figure 5.15 and Figure 5.16. Figure 5.17 show the operation of both voltage regulators. In all cases, both current and voltage references are tracked properly.



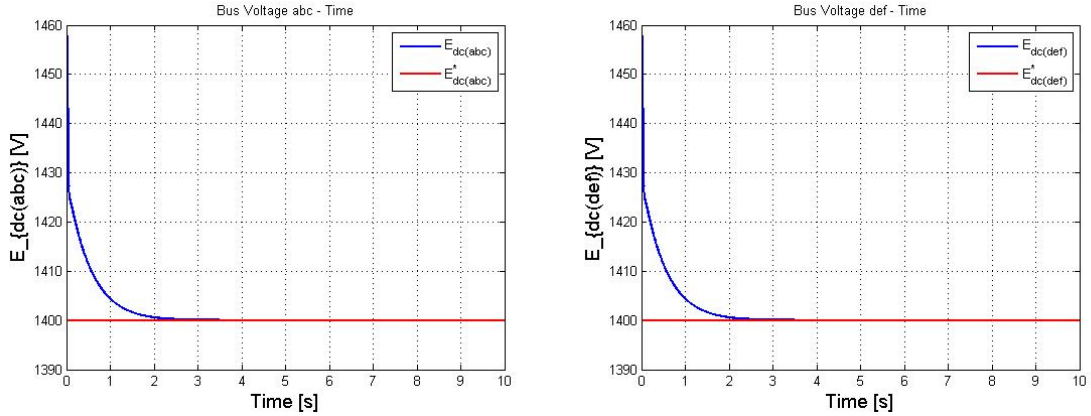
(a) q(abc) inverter current control (b) d(abc) inverter current control

Figure 5.15: Six-phase machine: qd(abc) inverter current control



(a) q(def) inverter current control (b) d(def) inverter current control

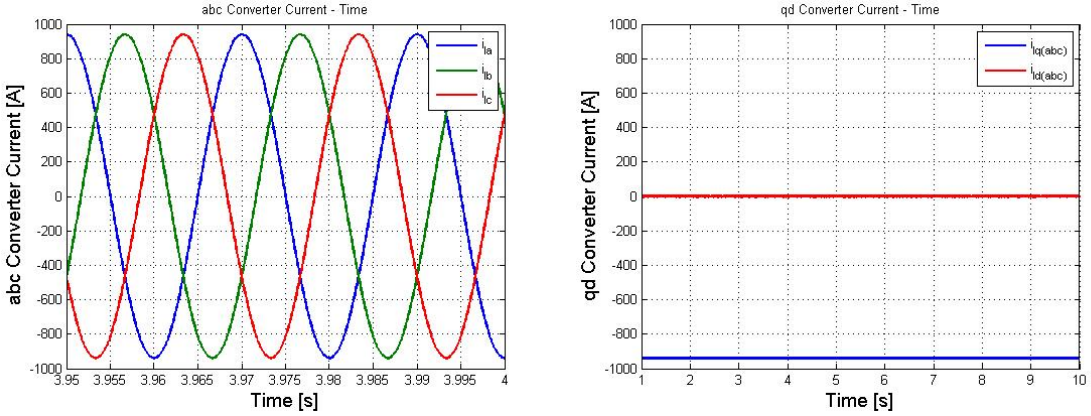
Figure 5.16: Six-phase machine: qd(def) inverter current control



(a) (abc) Voltage regulator control (b) (def) Voltage regulator controll

Figure 5.17: Six-phase machine: Voltage regulator control for the different VSC back to back converters

Figure 5.18 and Figure 5.20 show the currents flowing through the two different grid side converters. It can be seen that compared to the conventional three-phase machine, the current rating is reduced as the power is transferred through two different channels.

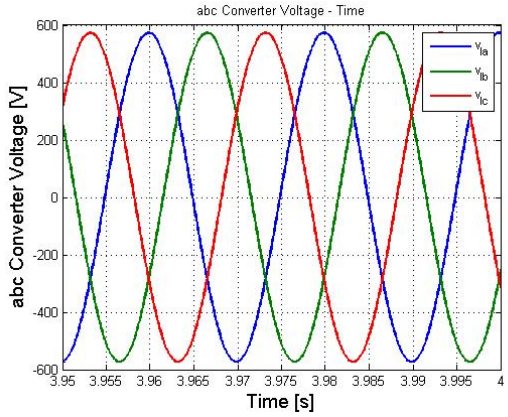


(a) abc inverter current (b) qd(abc) inverter current

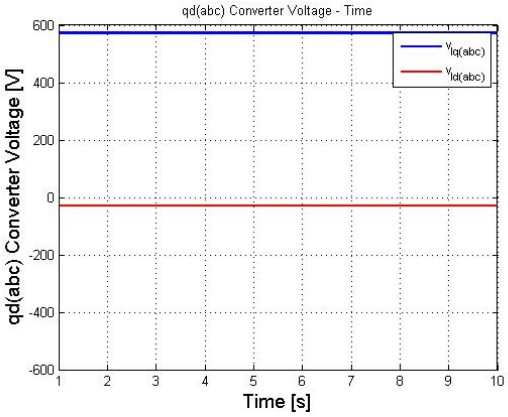
Figure 5.18: Six-phase machine: abc and qd(abc) inverter current

Regarding the machine side, the current controller proposed in Section 4.2.2 has been implemented. The i^*_{sq} current (active power current) will be calculated in order to obtain the optimum electrical torque for the wind condition required which provides the maximum power for the generator. Besides, the i^*_{sd} (reactive power current) set-point is set to zero in order to maximize the operational efficiency of the machine.

However, not only these currents must be regulated, but also the currents in the xy (i^*_{sx}, i^*_{sy}), obtained after applying the machine transformation (Section B) must be regulated

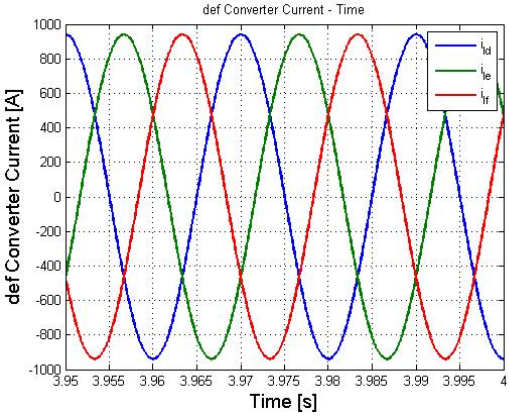


(a) abc inverter voltage

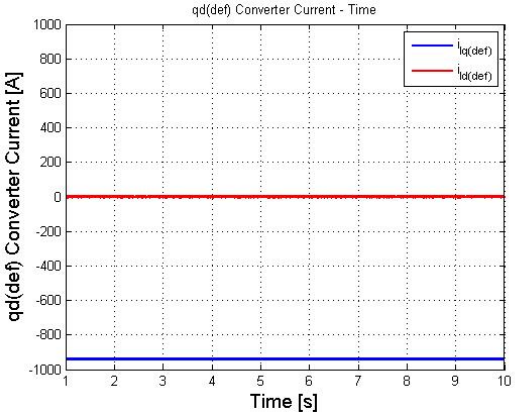


(b) qd(abc) inverter voltage

Figure 5.19: Six-phase machine: abc and qd(abc) inverter voltage

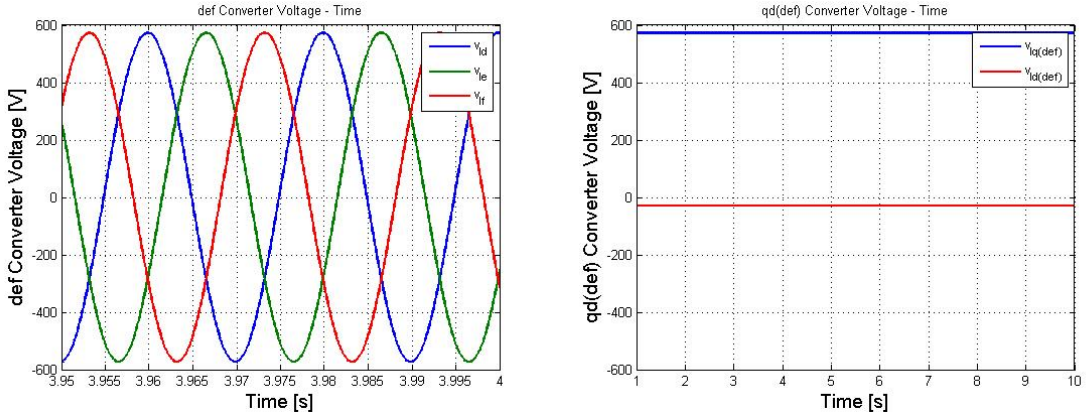


(a) def inverter current



(b) qd(def) inverter current

Figure 5.20: Six-phase machine: def and qd(def) inverter current



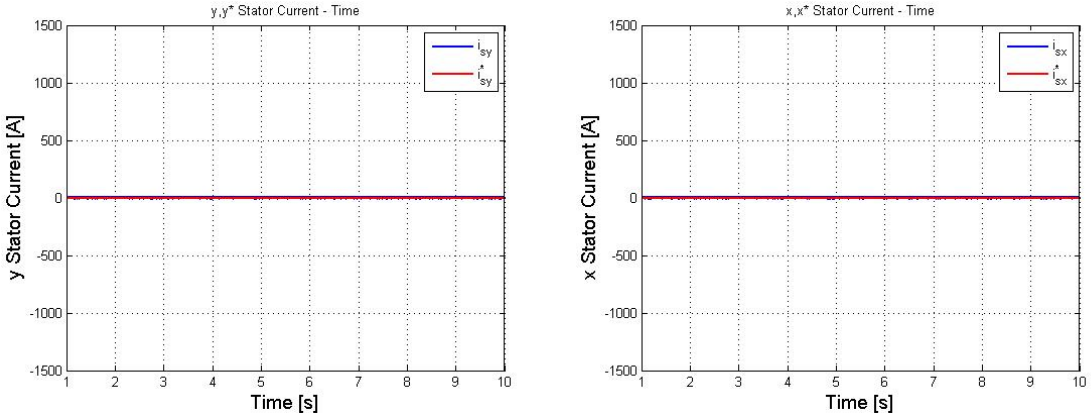
(a) def inverter voltage

(b) qd(def) inverter voltage

Figure 5.21: Six-phase machine: def and qd(def) inverter voltage

to zero in order to operate the machine with a maximum efficiency, as this currents are not producing any torque. The xy zero current regulation is achieved by two different controllers, as it can be seen in Figure 5.22.

Figure 5.23 show the currents flowing through the machine stators and the machine side converter. It can be seen that compared to the conventional three-phase machine, the current rating is reduced as the power is transferred through two different channels.

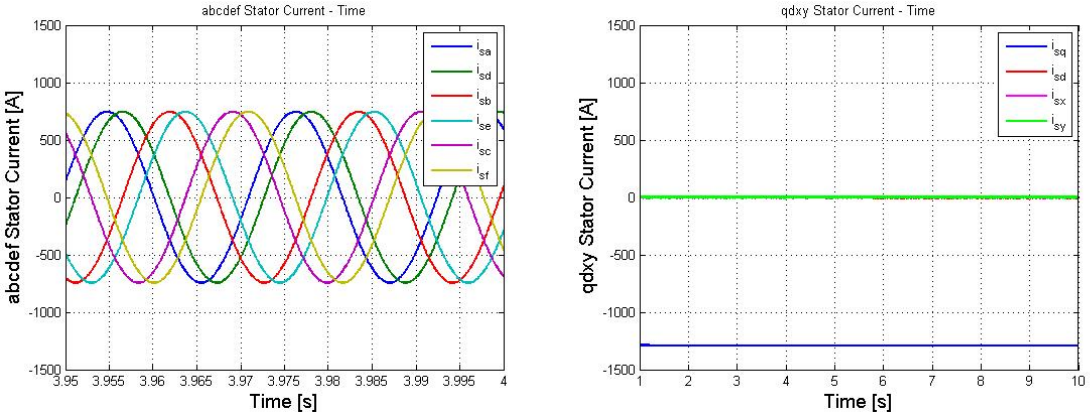


(a) x stator current control

(b) y stator current control

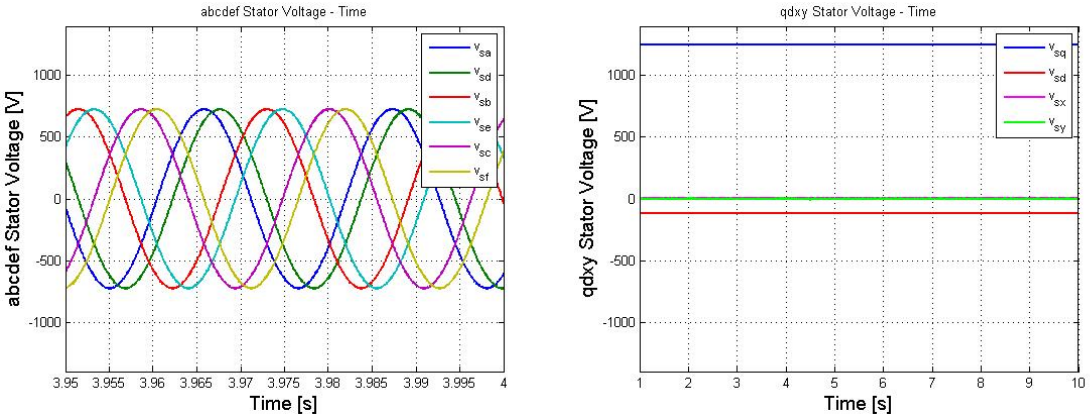
Figure 5.22: Six-phase machine: xy stator current control

Based on the mentioned controllers, the currents and voltages in the $abcdef$ reference frame obtained are shown in Figure 5.23 and Figure 5.24 respectively.



(a) abcdef stator current (b) qdxy stator current

Figure 5.23: Six-phase machine: abcdef and qdxy stator current



(a) abcdef stator voltage (b) qdxy stator voltage

Figure 5.24: Six-phase machine: abcdef and qdxy stator voltage

5.2 Wind speed variation

In this section, the previous explained simulation model is executed again considering a stepwise wind speed change (Figure 5.25). The wind starts with a speed of v_w=11 m/s and in the second 4 there is an increase of the 10%.

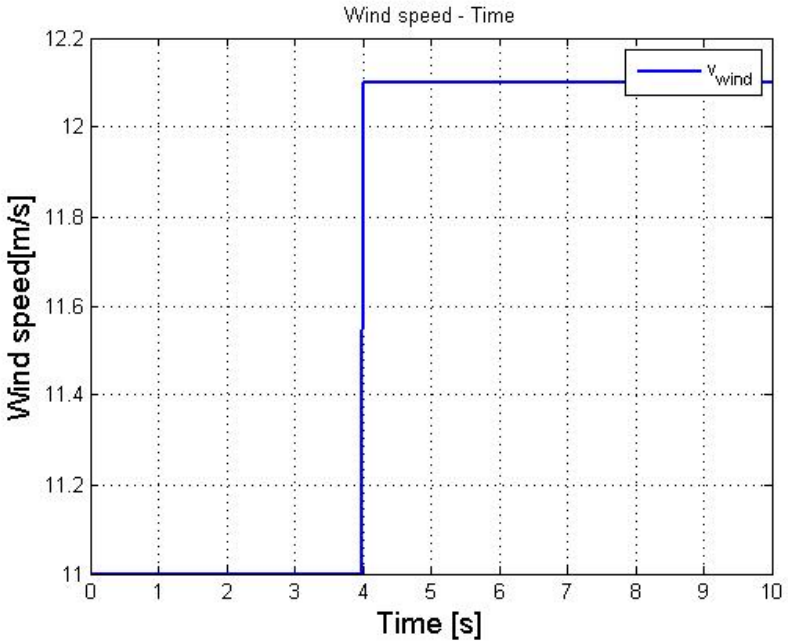


Figure 5.25: Wind speed simulated for the analysis

Figure 5.26 depicts how the control it is regulated to achieve the optimum C_p for a variation in wind speed in second 4.

The power obtained (Figure 5.27) will increase as it depends directly on the speed as well as the torque(Figure 5.28). Currents and voltages will be affected too, due to the control for the new optimum torque. The following figures represents those results.

The voltage of the capacitor depicted in Figure 5.29 shows two voltage oscillation peaks according to the increases in the wind speed because of the change on the incoming power from the machine.

This simulations show that the system behaves properly in front of a wind speed increase. The optimum torque control is able to reach the new maximum power point, increasing the current i_{sq} flowing through the machine by means of the current controllers. Also both voltage regulators are able to compensate the DC voltage deviation without a large voltage peak. Finally, grid side currents are also increased accordingly, based on the DC voltage regulators output.

Voltages in the stator, unlike the converter voltages will be barely increased as well as the

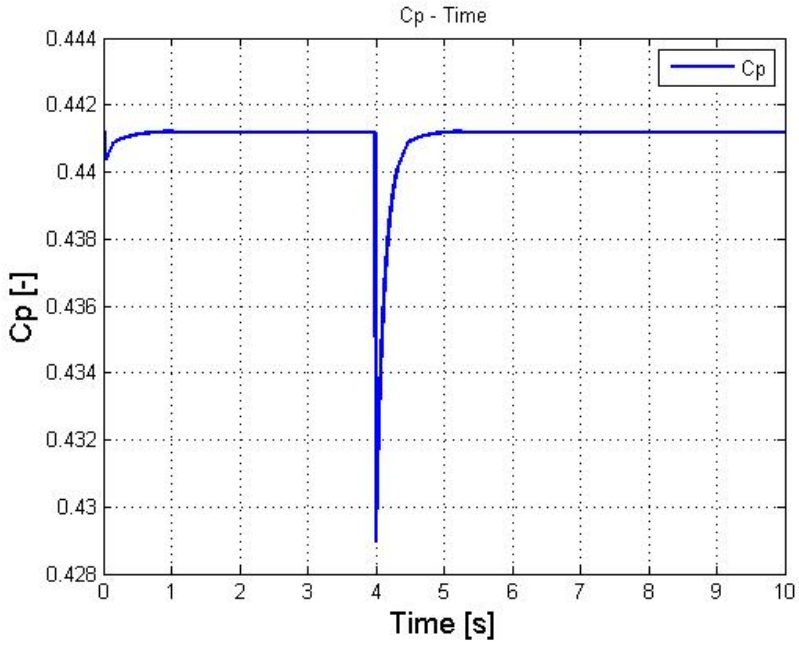


Figure 5.26: Power coefficient obtained for a wind speed variation

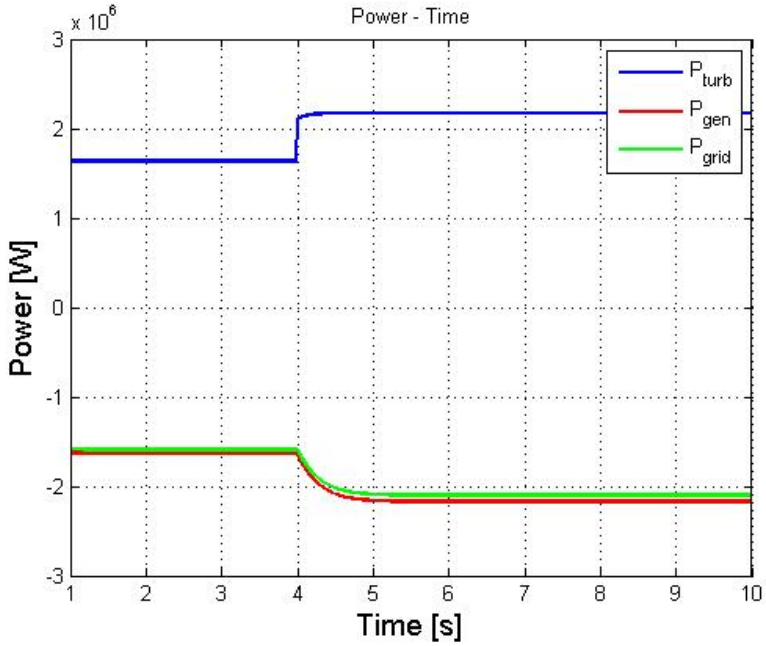


Figure 5.27: Six-phase machine: Generated power vs power transmitted through abc and def converters

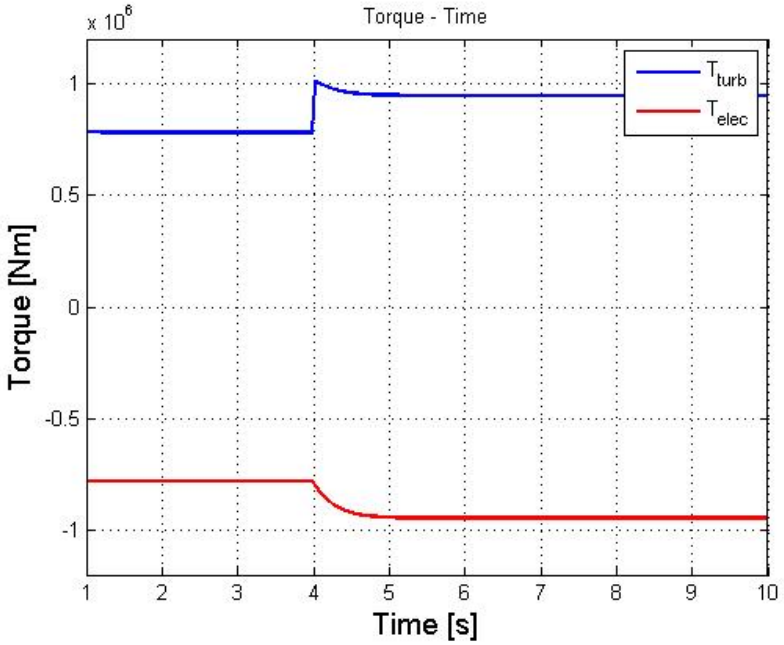
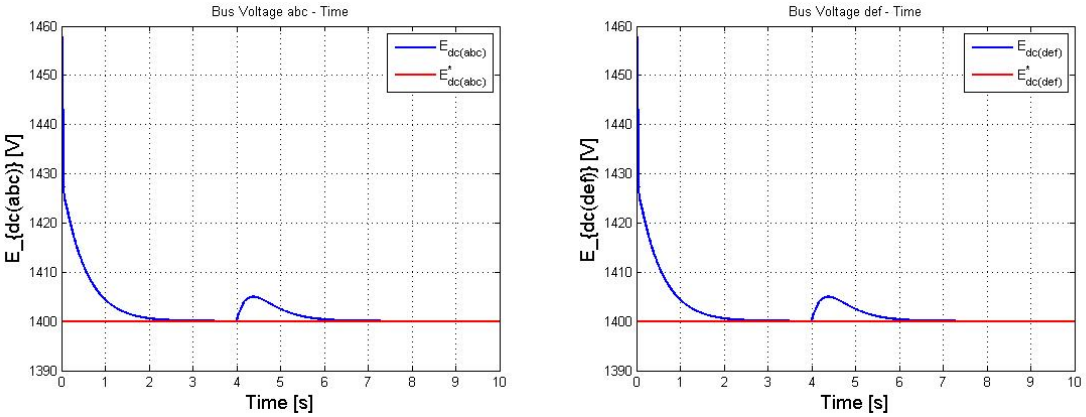


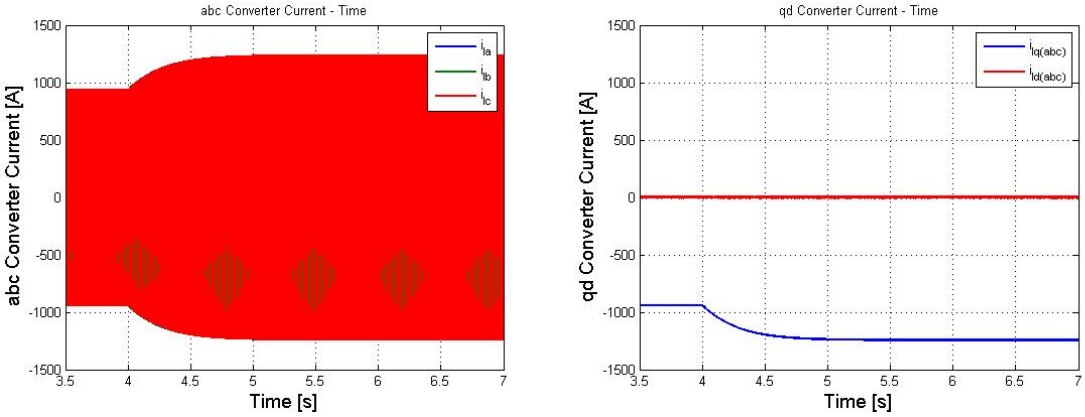
Figure 5.28: Six-phase machine: Electric Torque vs Mechanical Torque



(a) (abc) Voltage regulator control

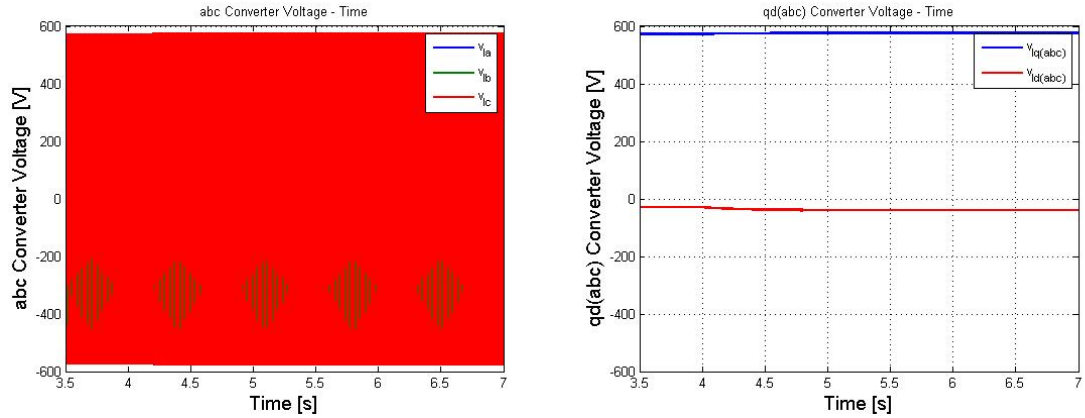
(b) (def) Voltage regulator controll

Figure 5.29: Six-phase machine: Voltage regulator control for the different VSC back to back converters



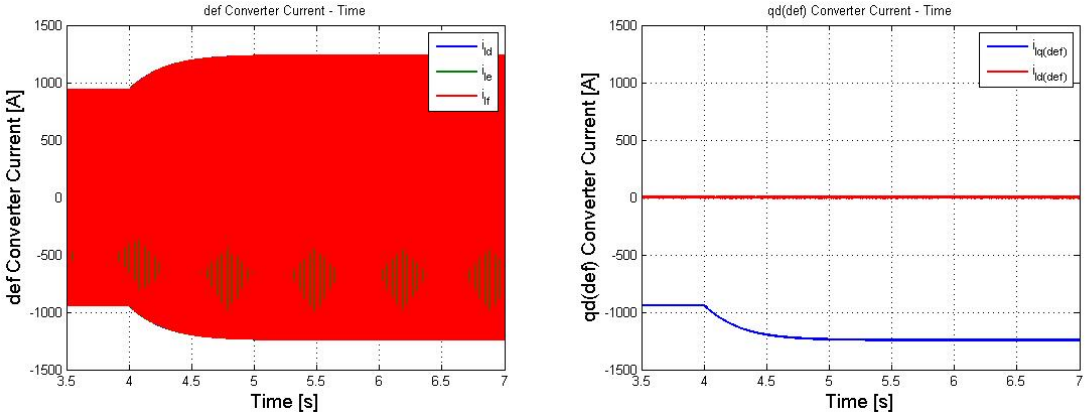
(a) abc inverter current (b) qd(abc) inverter current

Figure 5.30: Six-phase machine: abc and qd(abc) inverter current



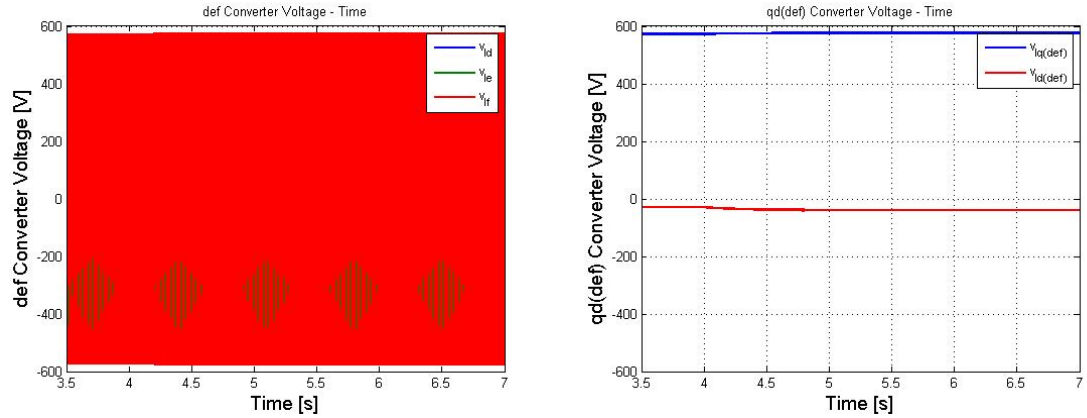
(a) abc inverter voltage (b) qd(abc) inverter voltage

Figure 5.31: Six-phase machine: abc and qd(abc) inverter voltage



(a) def inverter current (b) qd(def) inverter current

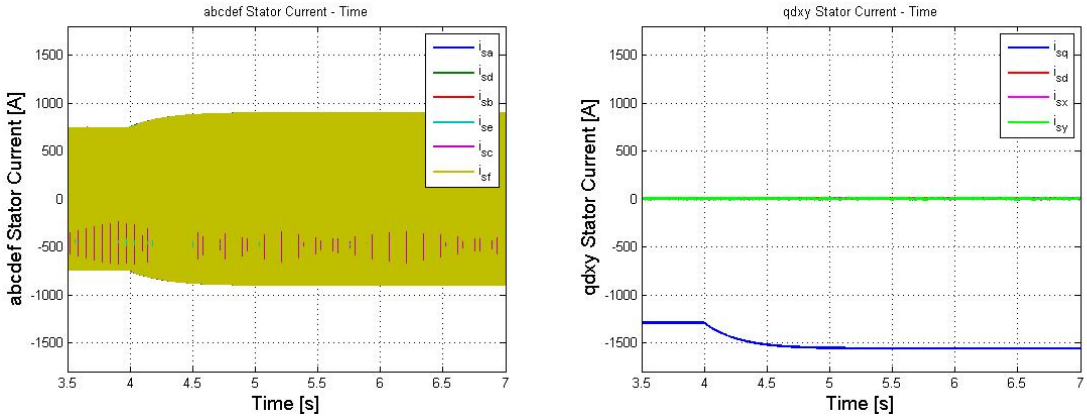
Figure 5.32: Six-phase machine: def and qd(def) inverter current



(a) def inverter voltage (b) qd(def) inverter voltage

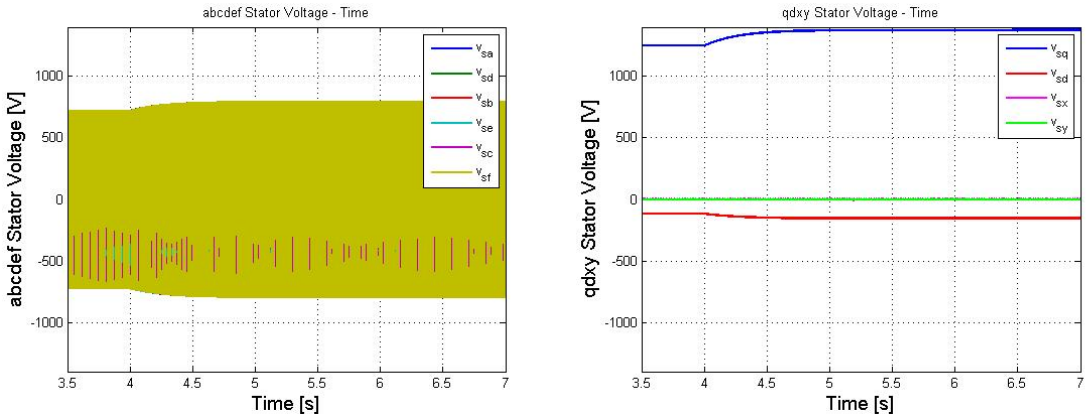
Figure 5.33: Six-phase machine: def and qd(def) inverter voltage

currents.



(a) abcdef stator current (b) qdxy stator current

Figure 5.34: Six-phase machine: abcdef and qdxy stator current



(a) abcdef stator voltage (b) qdxy stator voltage

Figure 5.35: Six-phase machine: abcdef and qdxy stator voltage

5.3 Simulation for a range of wind speeds

The simulation of a wind turbine six-phase PMSG for a wide range of wind speeds has been studied and analyzed. Figure 5.36 shows the power generated and the electric torque for wind speeds from 1 to 15 m/s. As it can be seen in Figure 5.36 the different values of power obtained follow equation (3.5), where the power depends on the wind speed (V_w^3). Therefore, a minimum increase in wind speed will highly increase the power generated.

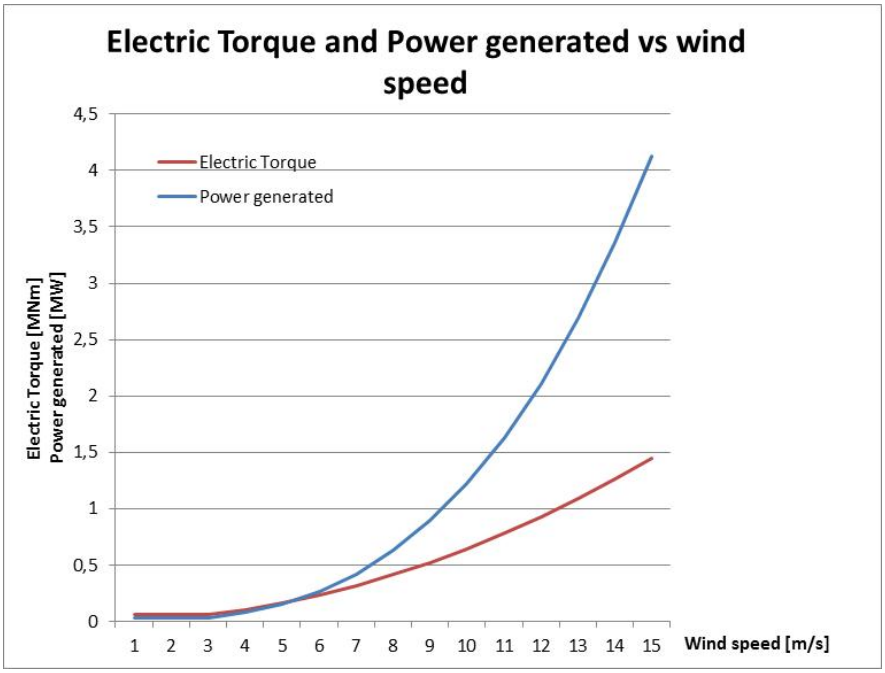


Figure 5.36: Six-phase machine: Electric torque and power generated for a range of wind speeds

Regarding the torque values, it has to be mentioned that increases as well as power generated and it is the parameter which will provide the desired currents for the different values of wind speed.

The more wind speed, the more power generated will be reached. However, there is a limit speed for wind turbines of producing energy, known as cut-out speed. When the speed of the wind is over 25 m/s approximately, the wind turbine has to be controlled in order to stop producing energy because these high velocities could cause serious damage in the wind turbine blades and the machine. In the same way, there are the so called cut-in speed which is the lowest speed in which there is enough torque exerted by the wind on the turbine blades to make them rotate and generate power.

6 Environmental impact

As for the environmental impact, it has to be taken into account the impact on the society, the fauna and the flora.

6.1 Visual impact

Wind turbines are highly visible elements because they are built with an average height of 150m so as to optimize the wind speed. In order to reduce the visual impact there have appeared some methods such as build the wind turbines in a simple geometric disposition, paint the wind turbines with the color of the landscape or reducing the number of wind turbines built by the construction of bigger wind turbines which generate more energy.

However, Figure 6.1 shows how this effect is highly reduced in offshore wind farms due to the lack of visibility in long distances.

Figure 6.1: Visual impact of offshore wind turbines for different distances to the shore

The farther the wind turbine is built, the more reduced the visual impact will be but the higher cost will have. As the distance from the coast increases, it increases the deep too, increasing the wire needed to lead the electricity to the coast and the complexity of the foundation. Figure 6.2 depicts four different types of foundation related to the depth of the seabed.

6.2 Acoustic impact

Nowadays, the acoustic impact is a secondary problem because it has been come across to a solution with the creation of blades designed for reducing the sound when they are rotating. Another reason to underestimate this impact is that the nature can not be considered in

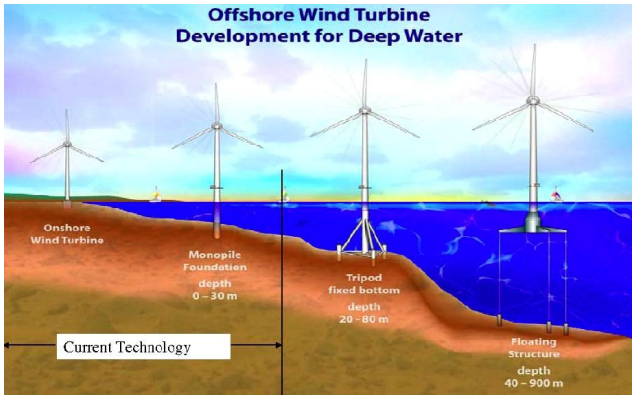


Figure 6.2: Types of foundations for seabed's depth

silence, whose sound would mask the noise of the machine. In offshore terms, this impact is highly reduced because with a distance of 400m the sound of a wind turbine would be the same as the sound of a refrigerator (36,9dB) as it can be seen in Figure 6.3.

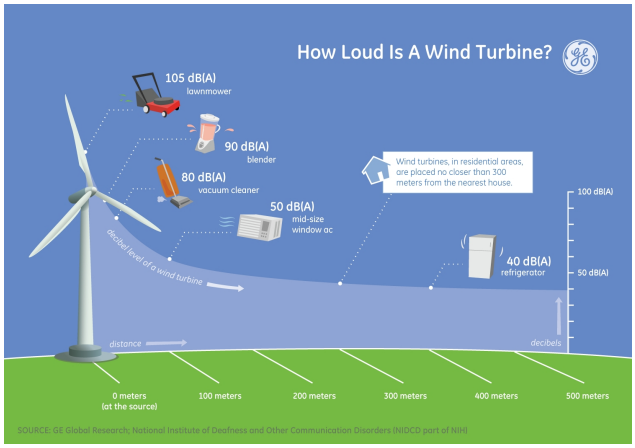


Figure 6.3: Intensity of the sound function of the distance from the wind turbine

6.3 Shade

The shade of the wind turbine could cause a flickering effect when the blades are rotating. Nevertheless, this effect only has to be considered if the wind turbine is built up on a rural place with people nearby. As we are focusing on offshore wind turbines, this effect could be despised.

6.4 Fauna and flora impact

Offshore wind farms are not supposed to affect aquatic wildlife whereas the rotation of the blades can harm birds and other flying species. Despite one of the solutions is to paint the wind turbine with a visible color in order to make the blades visible for animals, it would not be a suitable solution according to visual impact. Therefore, with a previous study of the emplacement, the wind farm construction has to avoid areas with high density of flying species. When an offshore wind farm is pretended to be built, it has to be taken into account the ecosystem of the seabed. That is the reason why some areas are protected and even these areas have optimum wind speeds, there is no option in building the wind farm. Despite those restrictions when building up a wind farm, it is well known that this kind of energy protects the enviroment by reducing the emission of CO2. According to the American Wind Energy Association (AWEA), 1MWh/year reduce the emission of 590 kg of CO2. A 10 MW wind farm would reduce the production of 28480 Tones of CO2 emited during 1 year.

6.5 Air and maritime traffic

Regarding air traffic, according to the law the edge of the blades of the wind turbines are red-colored and they can have added some lights for preventing of air accidents. When the wind farm is built there is no chance of fishing and sailing the area, so the emplacement it has to be carefully studied avoiding maritime routes.

A Park transformation

The park transformation is a common method used when simulating systems to change the abc frame to the dq0 frame where this new parameters eliminate the oscillating component and makes the equations and controlling much mores simpler.

The expressions when transforming would be Equation A.1 for achieving qd0 frame and its inverse (Equation A.2) if it is wanted the abc frame [10].

$$\begin{pmatrix} x_q \\ x_d \\ x_0 \end{pmatrix} = \left(T_{qd0}\right) \begin{pmatrix} x_a \\ x_b \\ x_c \end{pmatrix} \tag{A.1}$$

$$\begin{pmatrix} x_a \\ x_b \\ x_c \end{pmatrix} = \left(T_{qd0}\right)^{-1} \begin{pmatrix} x_q \\ x_d \\ x_0 \end{pmatrix} \tag{A.2}$$

The transformation matrix depends on a given angle and it is represented in the Equation A.3.

$$T(\theta) = \frac{2}{3} \begin{pmatrix} \cos(\theta) & \cos(\theta - \frac{2\pi}{3}) & \cos(\theta + \frac{2\pi}{3}) \\ \sin(\theta) & \sin(\theta - \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{pmatrix} \tag{A.3}$$

and its inverse represented in Equation A.4

$$T^{-1}(\theta) = \begin{pmatrix} \cos(\theta) & sin(\theta) & 1 \\ \cos(\theta - \frac{2\pi}{3}) & \sin(\theta - \frac{2\pi}{3}) & 1 \\ \cos(\theta + \frac{2\pi}{3}) & \sin(\theta + \frac{2\pi}{3}) & 1 \end{pmatrix} \tag{A.4}$$

Where the 0 component could be depreciated if the angle (θ) used in the transformation is equal to the grid angle.

As it has been said, the park transformation it is used for three-phase systems (abc). Therefore, in this project, the park transformation is applied only to the inverter control, the grid side.

For the three-phase PMSG the angle used will be the electric angle calculated by integrating the angular speed of the stator.

Figure A.1 depicts a three-phase system in the abc frame while Figure A.2 shows a three-phase system in the qd0 frame after applying the Park transformation.

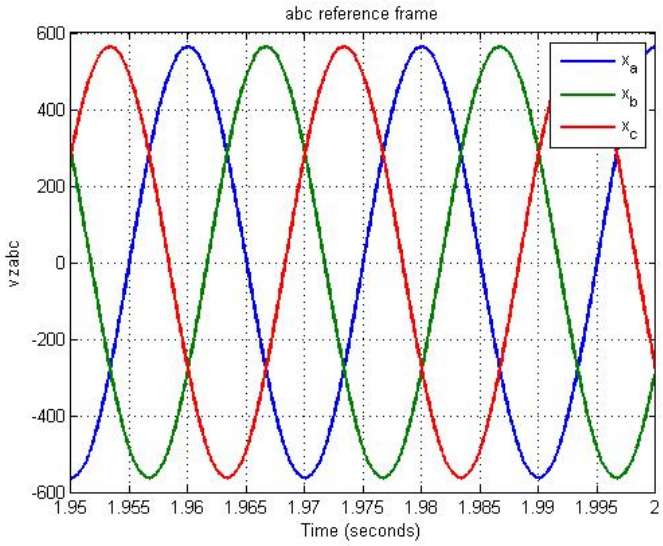


Figure A.1: abc frame

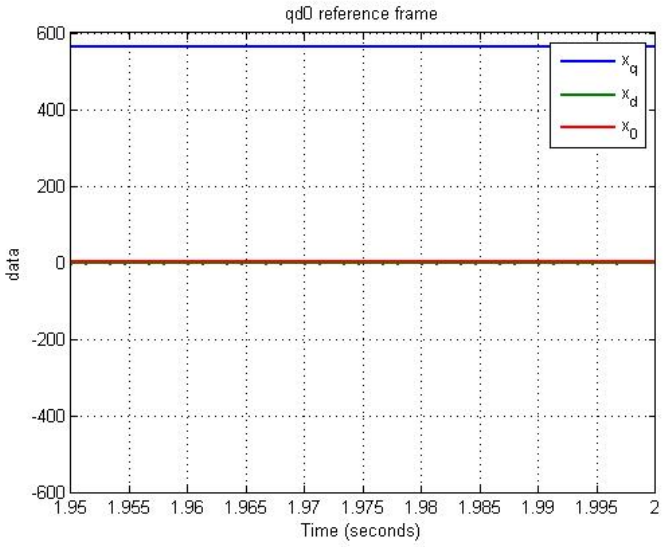


Figure A.2: qd0 frame

B Clarke transformation

In this project, for the generator side, the six-phase system side, it is applied the well known Clarke transformation. This transformation will change the abcdef frame to the $\alpha\beta xyz_1z_2$ frame. Then a rotation will be applied to $\alpha\beta$ components in order to obtain the desired dq components [9].

Clarke transformation is represented in Equation B.1.

$$T = \sqrt{\frac{1}{3}} \begin{pmatrix} 1 & \cos(4\alpha) & \cos(8\alpha) & \cos(\alpha) & \cos(5\alpha) & \cos(9\alpha) \\ 0 & \sin(4\alpha) & \sin(8\alpha) & \sin(\alpha) & \sin(5\alpha) & \sin(9\alpha) \\ 1 & \cos(8\alpha) & \cos(4\alpha) & \cos(\alpha) & \cos(9\alpha) & \cos(5\alpha) \\ 0 & \sin(8\alpha) & \sin(4\alpha) & \sin(\alpha) & \sin(9\alpha) & \sin(5\alpha) \\ \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & 0 & 0 & 0 \\ 0 & 0 & 0 & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} & \frac{1}{\sqrt{2}} \end{pmatrix} \tag{B.1}$$

Where $\alpha = \frac{\pi}{6}$, it is the shifting angle between the two sets of three-phase windings (abc-def).

Then the rotation applied to the $\alpha\beta$ components will be represented in the Equation B.2.

$$R(\theta) = \begin{pmatrix} \cos(\theta) & -\sin(\theta) \\ (\theta) & \cos(\theta) \end{pmatrix} \tag{B.2}$$

And its inverse for transforming dq into $\alpha\beta$ is represented in Equation B.3.

$$R^{-1}(\theta) = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -(\theta) & \cos(\theta) \end{pmatrix} \tag{B.3}$$

Where θ will be the electric angle as it is explained in Section 4.32. It has to be taken into account that this transformation implies the characteristic $\frac{3}{2}$ term of power and torque expressions.

Figure B.1 depicts a six-phase system in the abcdef frame while Figure B.2 shows a six-phase system in the $\alpha\beta xyz_1z_2$ after applying the Clarke transformation. Then Figure B.3 represents a six phase system in the $dqxyz_1z_2$ frame after applying the rotation.

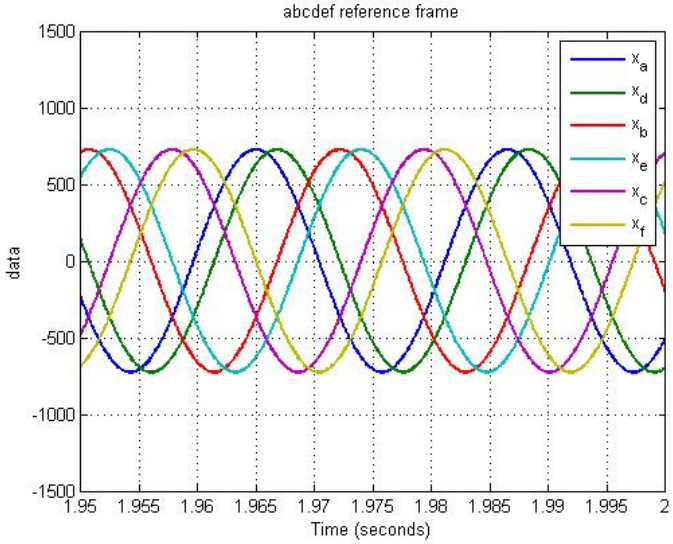


Figure B.1: abcdef frame

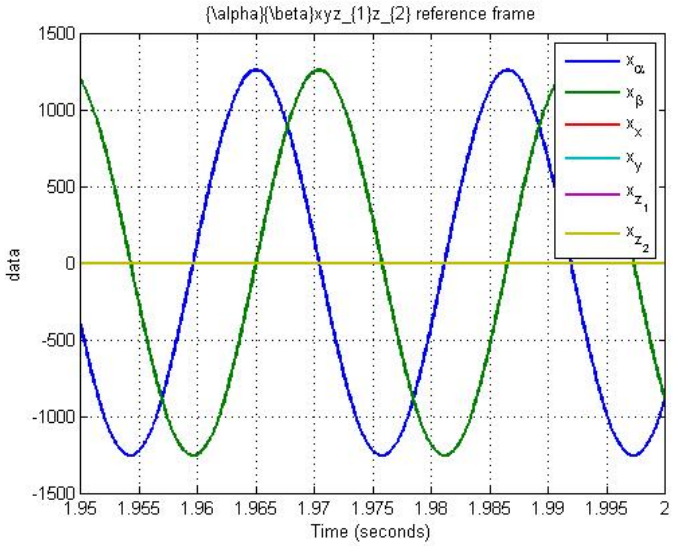


Figure B.2: $\alpha\beta xyz_1z_2 frame$

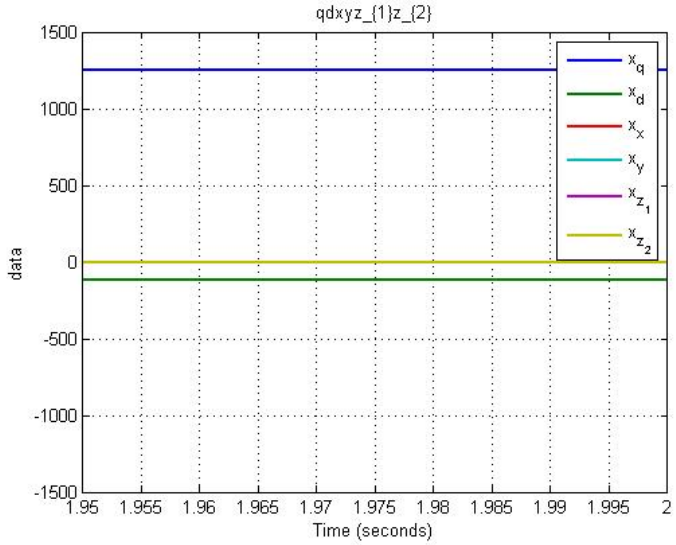


Figure B.3: qdxyz$_1z_2 frame$

C Phase Locked Loop

The Phase Locked Loop (PLL) is used to determine the electric angle of the grid in order to obtain $v_{zd} = 0$ when applying the park transformation and moving to qd0 frame. As it can be seen in Figure C.1, the input of the PLL is the direct component of the tension and the output will be the angular speed, which has to be integrated in order to obtain the grid angle[10].

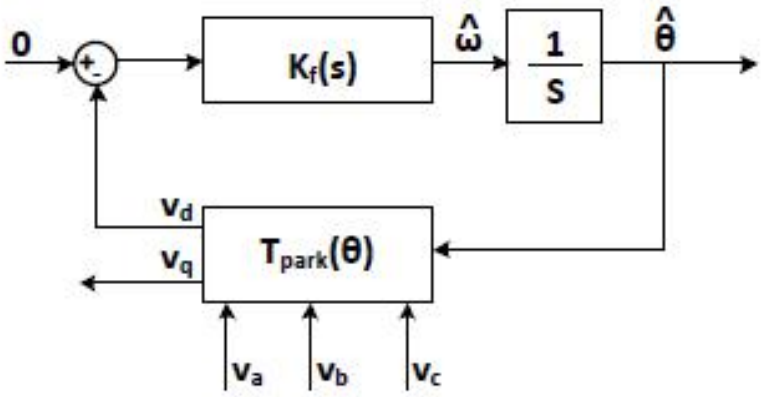


Figure C.1: Phase Locked Loop scheme

$k_f(s)$ is a PI controller which follows a second order system as it can be seen in Equation C.1.

$$k_f(s) = k_p(\frac{\frac{1}{\tau_{PLL} + s}}{s}) \tag{C.1}$$

where its components are calculated through Equations C.2 and C.3.

$$w_n = \sqrt{\frac{k_p E_m}{\tau_{PLL}}} \tag{C.2}$$

$$\xi = \frac{\sqrt{k_p E_m \tau_{PLL}}}{2} \tag{C.3}$$

Where E_m is the admitted peak voltage

ξ is the damping ratio

w_n is the electrical angular speed

D Data proposed for the analysis

In this section, the data used in the analysis carried out in this work is detailed.

Variable	Value
$V_{[zeff}$	690 V
w_z	100π rad/s
f_z	50 Hz
θ_z	90º
C	0,06 F
$L_{ls(3phase)}$	$0{,}01{\cdot}10^{-3}$H
l_l	10^{-5} H
$L_{q(3phase)}$	0,0001 H
$L_{d(3phase)}$	0,0001 H
r_l	0,01 Ω
$r_{s(3phase)}$	0,01 Ω
τ	$5{\cdot}10^{-4}$
R	38 m
A	πR^2 m^2
β	0º
ρ	1,225 kg/m^3
p	140
$E^*_{dc(abc)}$	1400 V
$E^*_{dc(def)}$	1400 V
J_{tot}	300000 kg·m^2
V_w	11 m/s
ϕ_m	2,5 Wb/(rad/s)
$Ł_{ls(6phase)}$	0,0001 H
$Ł_{q(6phase)}$	$3{\cdot}10^{-4}$H
$Ł_{d(6phase)}$	$3{\cdot}10^{-4}$H
$r_{s(6phase)}$	0,01 Ω

Variable	Value
c_1	0,73
c_2	151
c_3	0,58
c_4	0,002
c_5	2,14
c_6	13,2
c_7	18,4
c_8	-0,02
c_9	-0,003
I^*_{sd}	0 A
I^*_{sx}	0 A
I^*_{sy}	0 A
Q^*	0 VAr
w_{ini}	2,086 rad/s

Conclusion

This project has modeled and carried out an in-depth analysis in the control and operation of multiphase permanent magnet synchronous generator topology for offshore wind turbines. It has compared both three-phase PMSG and six-phase PMSG with their particular equations and modeling.

After the simulation, it has been confirmed how different controllers have been implemented in order to operate the machine with a maximum efficiency criteria achieving good results. The power achieved is injected into the grid under different wind conditions such as constant wind and a wind step speed which has been studied in the project.

As can be seen in the analysis, the current generated has a different frequency from that of the grid, therefore, needs to be transformed and adapted through the VSC back to back converters to the grid parameters. To achieve this, there are implemented controllers which impose those grid conditions and make the turbine much efficient.

Multiphase PMSG has been considered an interesting topology to implement in offshore wind turbines, not only because of the lower current loads received in their converters but also because if there is a problem in one of the stators, the machine could keep working and providing power to the grid; this is known as fault tolerant operation.

For future work, it would be interesting to study the possible variations in controlling this topology of generators when a failure occurs in one of the stators, where all the power generated will reach the grid through one of the VSC converters. What is more, this work could be done according to different number of phases installed, such as 9 or 12. Other things to study would be the variation in the pitch angle and its control which in this project is considered constant.

Acknowledgments

Firs of all I would like to thank Edu Prieto, the director of this project. The support received and the predisposition of helping me at any time has let to achieve this project.

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Finally, I would like to thank the support of all my family and friends who have made possible the realization of the project.

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