UNIVERSITAT POLITÈCNICA DE CATALUNYA

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Control of an offshore wind power plant

Emulated inertia

MEMORIA

Autor:	Alba Pallas Sanmartín
Director:	Jose Luís Domínguez
Co-director:	Oriol Gomis
Convocatòria:	Octubre 2016

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Cover Photography by Energy Business Europe

Supervisors' signatures:

Director **Co-Director**

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ABSTRACT

Undoubtedly, the energy sector is moving towards a more renewable and sustainable path. This means renewable energy will increase their penetration into the electric power grid. Wind Energy, in particular Offshore Wind Energy, is becoming the leader of the renewable energy in terms of future possibilities, and their technology is evolving to a more controllable devices.

Double Fed Induction Generator Wind Turbines (DFIG), also known in the industry as Type 3 Wind Turbines, and Fully Rated Converter-based Wind Turbines, Type 4, use power electronics to decouple the generator from the grid. Type 3 does this partially and Type 4 decouples completely the generator from the system. This allows variable wind speed operation and higher controllability for grid support.

They improve the grid support provided by Fixed Wind Speed Turbines, except for the Fast Primary Frequency Response which is related directly with the inertia stored in the system. These types of wind turbines are not able to provide natural inertia response due to their decoupling from the grid. If we increase the penetration of this kind of wind turbines without giving a solution to the Fast Primary Frequency Response we will be lowering the Frequency Response and enable disturbances in the grid.

This project proves how the Frequency control improves Frequency Response of the system in front of a sudden frequency drop even when the Percentage of Wind Energy Penetration is at the 30% level.

We also prove how Control values of inertia constant, Droop and operational wind speeds affects the Frequency Response, being a fundamental step to take into account the operational point of the turbine depending on the working wind speed and the tune of the Frequency control values depending on the turbine characteristics.

RESUMEN

Indudablemente, el sector energético se mueve hacia un futuro más renovable y sostenible. Eso significa que la penetración en el sistema eléctrico de energías renovables aumentará inevitablemente en unos años. La energía eólica, y cada vez más la energía eólica marina, están ganando importancia y notabilidad en cuanto a las posibilidades de futuro que pueden proporcionar y su tecnología está evolucionando hacia equipos mucho más controlables y competitivos.

Las turbinas con Generador Doblemente Alimentado (DFIG), conocidas como Aerogeneradores Tipo 3, y las turbinas con convertidor en línea (Fully Rated Converter), conocidas como Tipo 4, usan convertidores electrónicos para aislarse de la red. De este modo son capaces de trabajar en velocidades variables proporcionando una mayor generación y también nos proporciona mayor controlabilidad para dar soporte a la red.

Este tipo de turbinas mejoran el soporte a la red durante cualquier suceso inesperado, excepto en la Respuesta Frecuencial Primaria Rapida (FPFR) la cual está relacionada directamente con la inercia almacenada en el sistema. Este tipo de turbinas no son capaces de proveer de una respuesta inercial natural ante una caída de la frecuencia debido a que están aisladas de la frecuencia de la red. Si aumentamos la penetración de este tipo de turbinas sin poner solución a la falta de Respuesta Frecuencial Primaria Rapida estaremos disminuyendo la Respuesta Frecuencial del sistema y permitiendo perturbaciones en la red.

Este Proyecto demuestra que la implementación de un Control Frecuencial mejora la Respuesta Frecuencial del Sistema ante una caída de la frecuencia, incluso cuando la penetración llega a un 30% del total de la generación.

También demostramos que los valores que se utilicen de inercia y Droop en el Control Frecuencial y la velocidad de trabajo de la turbina pueden afectar a los resultados en la Respuesta Frecuecial del sistema. Por ello es fundamental tener en cuenta la velocidad de viento con la que trabajamos y el punto operacional en el que nos encontramos, y los valores escogidos deben ser los adecuados para el tipo de turbina con la que estamos trabajando.

ACKNOWLEDGMENT

I want to express my gratitude to Jose Luís Domínguez, my supervisor in this project. Thank you for your time and knowledge. I hope we'll meet again in the renewable energy sector.

And last but not least, I want to thank my parents. I won't be studying this master if it wasn't for their support and encouragement.

"There are no shortcuts to any place worth going."

— Beverly Sills

1. OBJECTIVE OF THE STUDY

The main objective of this project is to study the implementation of a frequency response control strategy for the enhancement of the fast primary frequency response of the doubly fed induction generator (DFIG) wind turbines when there is a frequency drop in the power system.

The wind power plant to be studied will be placed offshore, although the frequency response control can be implemented also in onshore wind turbines.

2. THEORETICAL FRAMEWORK

It is a reality that energy is a necessity. To assure it reaches all individual needs and respects the environment, the energy generation needs to move to a sustainable and renewable path.

Renewable energy is the type of energy which is obtained from natural endless sources, either there is a great quantity or it is capable of regeneration. Wind energy has been used for centuries, mainly for food production or water supply. It is nowadays that wind energy technology is used mainly for electricity production.

The huge increase of these and other renewable technologies and their integration into the electricity grid has set out problems for the security of the electric network.

The System Operators of the electricity networks ask for minimum requirements for all types of generators to connect to the grid. These requirements can be sum up in three main aspects. All generators have to provide:

- ✓ Grid support:
  - Voltage support
  - Frequency response
- ✓ And fault-ride through capability

Some of these requirements still need research and improvement.

In this project we are going to focus our attention in to the System Operators requirement for frequency response, in particular, the fast primary response also called inertia emulation or synthetic inertia.

2.1. WIND ENERGY TECHNOLOGY

Wind energy technology has evolved through the years. In this chapter we are going to review the different wind turbine types and their main advantages and disadvantages.

2.1.1. WIND TURBINE BASICS

Before starting with more complicated concepts it is necessary to define some basics.

PARTS OF A WIND TURBINE

The main components of a wind turbine are:

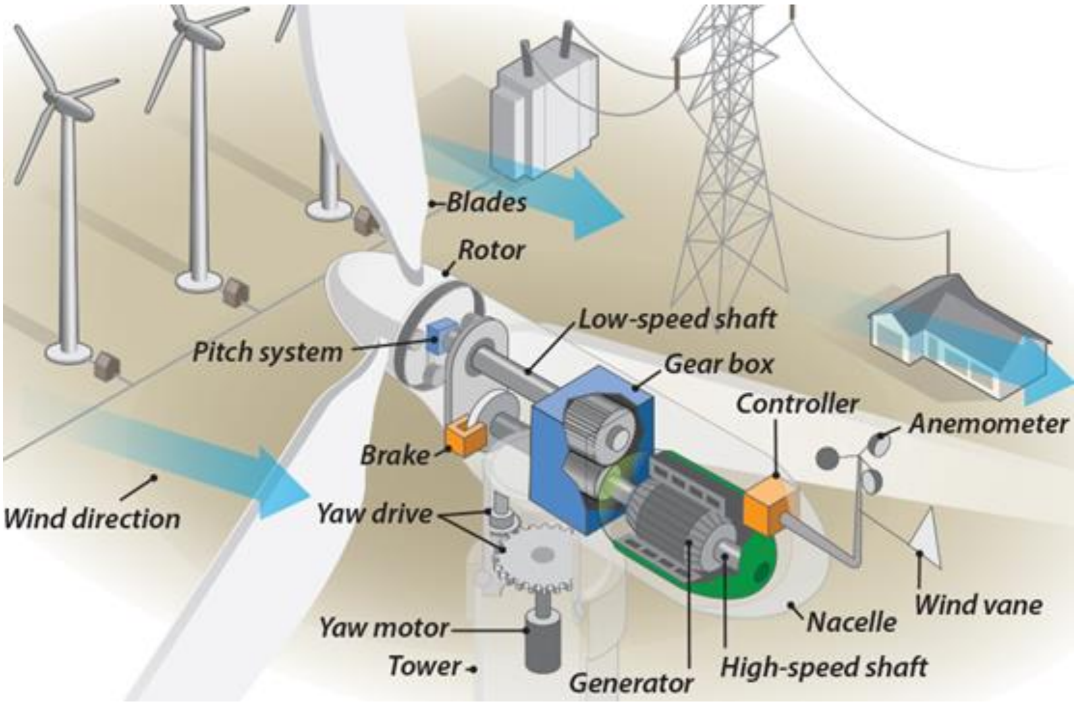


Figure 1 Components of a Wind Turbine [1]

The **blades** are the mechanical components that cause the rotor to spin. The most used configuration is the three-blade rotor.

The hub is a mechanical piece where the blades are placed. The hub and the blades form the **rotor**.

The **low speed shaft** rotates at the same speed than the rotor, usually 30-60 rpm. This low rotational speed need to increase to allow the generator to produce electricity. That increment of speed is obtained using a **gear box.**

Nowadays, there is a technology called **direct drive** that gets rid of the gear box by adding a multipole generator. This gearless wind turbine can work at the lower rotor speeds.

The **high speed-shaft** drives the generator. And the **generator** produces the AC electricity.

The **controller** starts up the wind turbine when the wind speed is over a certain speed value and it stops the wind turbine when the wind speed is higher than an established value to avoid the damage of the turbine.

The **anemometer** measures the wind speed and gives the information to the controller.

The **pitch** helps to control wind speed. It turns the blades out of the wind to control the speed of the rotor.

The **yaw drive** and **yaw motor** are used to orient the turbine to keep it facing the wind when the direction changes. The **wind vane** measures the direction and gives the information to the yaw drive.

The **brakes** stop the rotor when there is an emergency.

The **nacelle** contains the great part of the turbine components. The nacelle is supported by the **tower** which contains the access to the top for the maintenance team and other electric power devices like the transformer.

OTHER IMPORTANT KNOWLEDGE

After taking a look inside a wind turbine and finding out how all the pieces work together it is also important to know a few concepts related to wind turbine power generation.

The power extracted from the wind is calculated by the following equation:

$$P_{\mathrm{air}} = \frac{1}{2}\rho A v^3 \qquad (2.1)$$

Where:

ρ is the air density which depends on the temperature (typical value 1.225 kg/m3)

A is the swept area of the blades

and v is the wind speed

$$P_{\text{wind turbine}} = C_p P_{\text{air}} = C_p \times \frac{1}{2} \rho A v^3 \qquad (2.2)$$

The power transferred to the rotor, *Pwind turbine*, is reduced by the **Power Coefficient** (Cp). The Cp shows us how efficiently the turbine transforms the power of the wind into electricity. There is a maximum Cp value which is defined by the **Betz Limit**. The Betz limit states that there is no turbine that can extract more power from a wind stream than a 59.25%. Usually the Cp goes from 25% to 45%.

Another important concept we must define is the tip speed ratio. The **tip speed ratio** (λ) is the ratio between the tangential speed of the tip of the blade and the actual velocity of the wind:

$$\lambda = \frac{\omega R}{v} \qquad (2.3)$$

Both Cp and tip-speed ratio can be used to describe the performance of a wind turbine rotor.

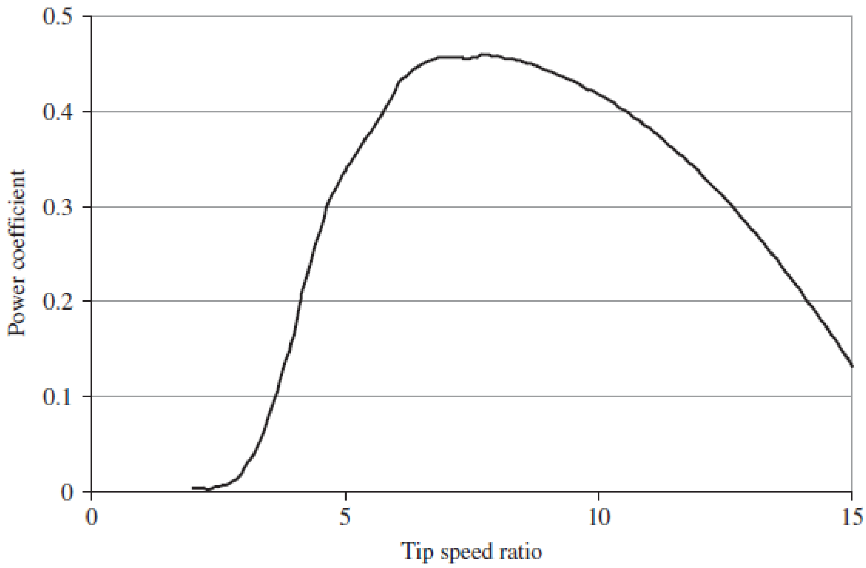


Figure 2 Power coefficient vs tip-speed ratio curve [2]

The maxim power coefficient is achieved only at one tip-speed ratio, see Figure 2. If we use fixed speed wind turbines this tip speed ratio which maximizes the Cp is only achieved once.

Working at variable speed gives us the chance to operate at maximum Cp over a great range of wind speeds.

The power generated by a wind turbine is described by its power curve, Figure 3. The power curve form is similar for all wind turbines. It is possible to differentiate four stages, each one represented by a characteristic wind speed value.

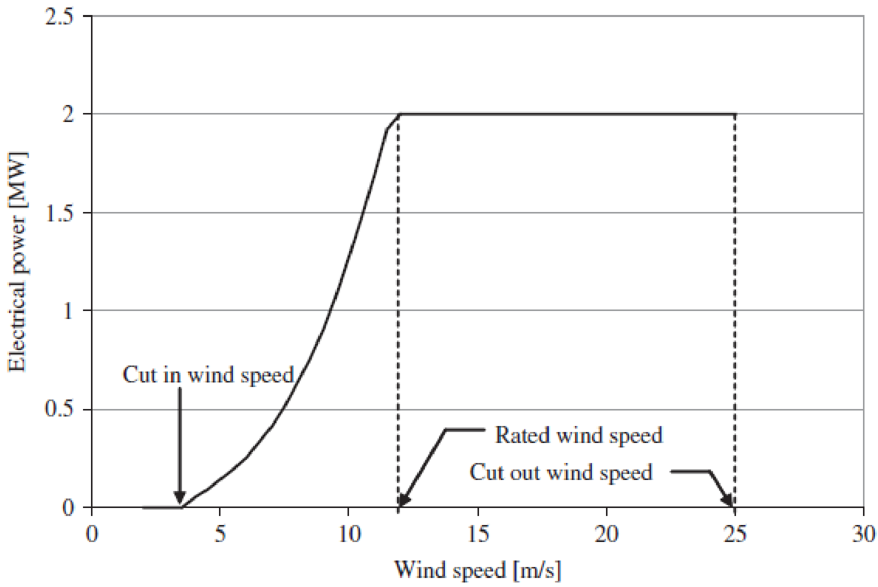


Figure 3 Example of a Power curve vs wind speed for a 2MW turbine [2]

The **start up speed** is the wind speed at which the rotor and the blades start to move but there is no useful power. In Figure 3 the start up speed is the horizontal line that is coincident with the x axe.

The **cut in wind speed** is the minimum wind speed at which the wind turbine will deliver useful power.

At higher wind speeds the power generation increases almost exponentially.

The **rated wind speed** is the wind speed at which the wind turbine will deliver the rated power. For higher wind speeds the wind turbine will deliver always the rated power, which is the limit the generator is capable of delivering.

The **cut out wind speed** is the maximum wind speed at which the wind turbine is allowed to work and deliver useful power. At higher speeds the wind turbine can be damaged.

2.1.2. A TREND TO GO OFFSHORE

The last two decades wind energy technology has evolved in such manner that nowadays wind energy is clearly one of the best options for the future of renewable electric energy generation.

First wind turbines that went out on the market were onshore but in the last few years there is a trend to go offshore. Figure 4, shows the increase of wind energy installations from 2001 to 2015 in Europe and a significant growth of the offshore wind in the past six years.

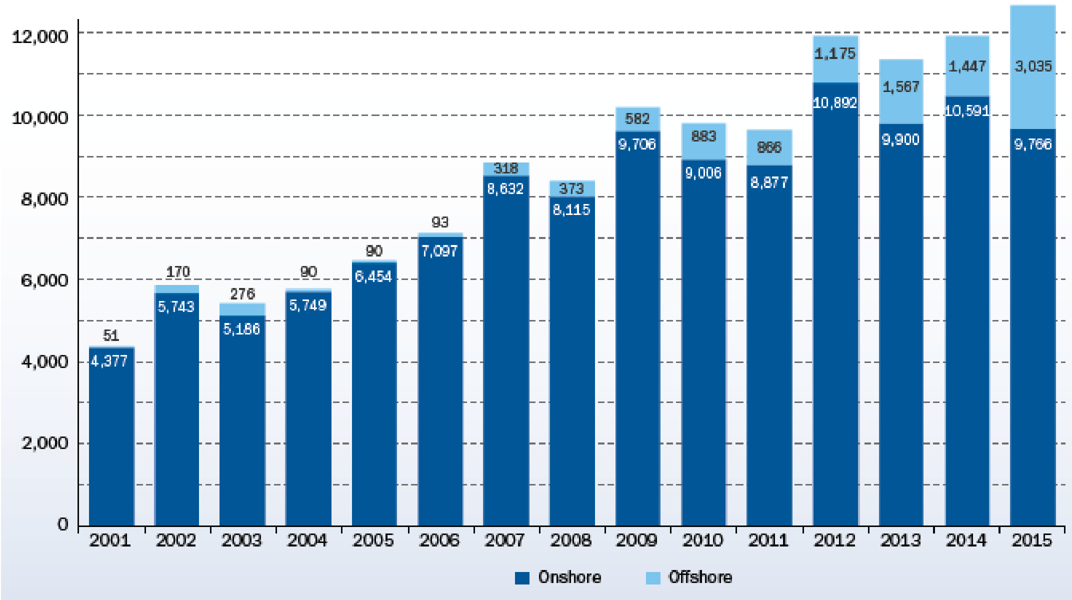


Figure 4 Onshore and Offshore annual installations [3]

The main reasons leading to that change are:

- ✓ There is a lack of available locations onshore. Not all locations onshore with good wind resources are available for the implementation of a wind power plant.
- ✓ There is a better wind resource offshore than there is onshore.
- ✓ Less social opposition and less visual impact
- ✓ Turbine rated power is higher for offshore wind turbines

But it is important to mention there are also a few drawbacks that are limiting the expansion of the offshore wind energy:

- ✓ Rough marine conditions. This affects the design, the construction and the maintenance of the wind turbines. Therefore the investment for offshore is twice the investment for the onshore technology [5].

This drawback is the one slowing down the growth and expansion of the offshore technology. However, there are countries that try to limit it by using legislation to protect and promote this and other emerging renewable technologies.

This could be the case of UK, which is nowadays the number one country in Europe with more offshore wind capacity installed (5,060.5 MW) representing 45.9% of the total, See Figure 5. Germany follows with 3,294.6 MW of installed capacity, a 29.9% of the total.

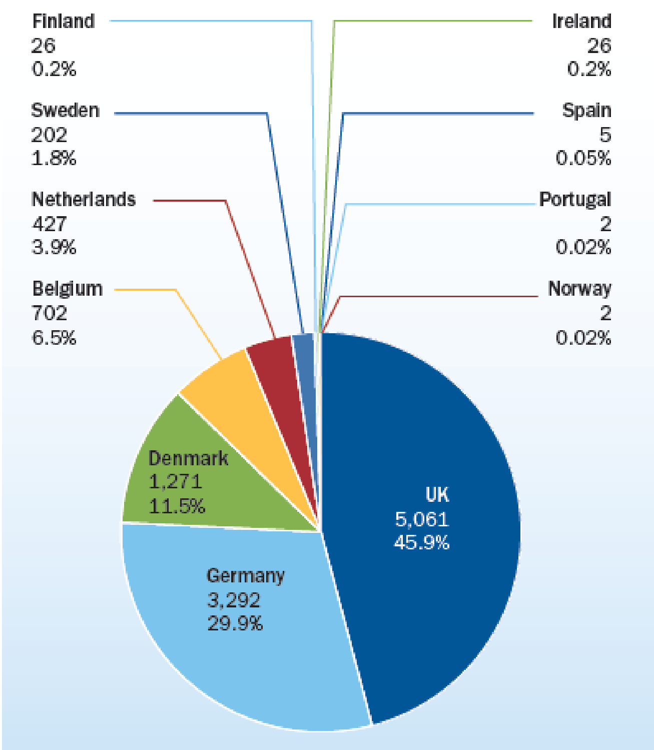


Figure 5 Installed Capacity cumulative share by country in Europe [4]

Another aspect of the offshore wind energy worth mentioning is related with the available locations offshore. It is well known that if we go far from the shore the waterdepth increases. Figure 6 shows the average water depth and distance to shore of the offshore wind farms installed in Europe: online, under construction and consented wind farms. The circle size represents the total power capacity of the wind farm.

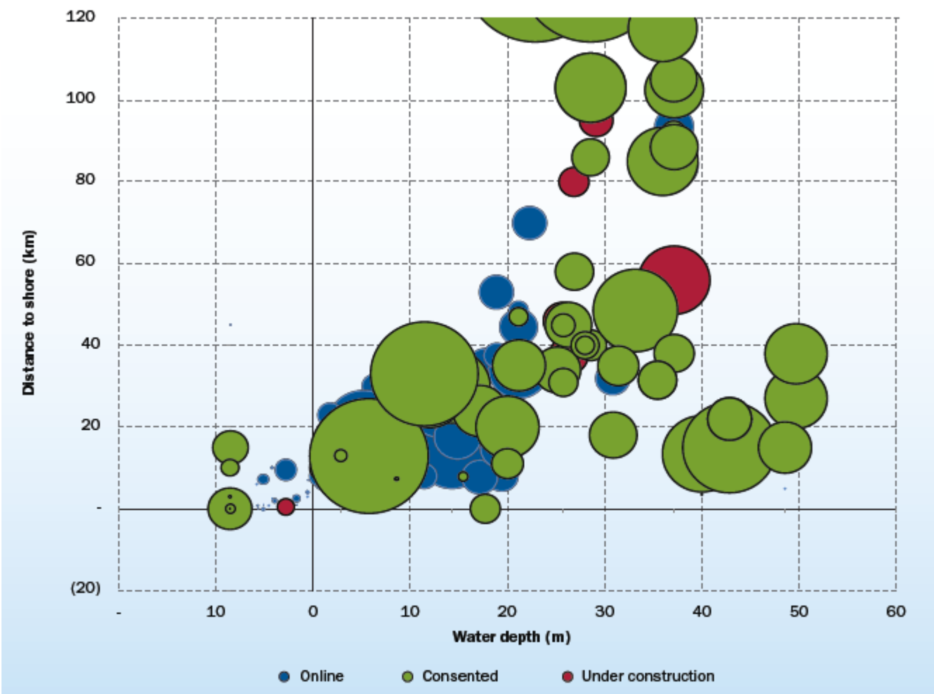


Figure 6 Average water depth and distance to shore of offshore wind farms [4]

At the end of 2015, the average water depth of grid-connected wind farms was 27.1 m and the average distance to shore was 43.3 km.

Monopile foundations are the most used technology for offshore wind nowadays. This technology is used for waterdepths under 40 meteres because it is not profitable to install it for higher waterdepths. We can see in Figure 6 that the greater part of the wind farms are located under 40m of waterdepth.

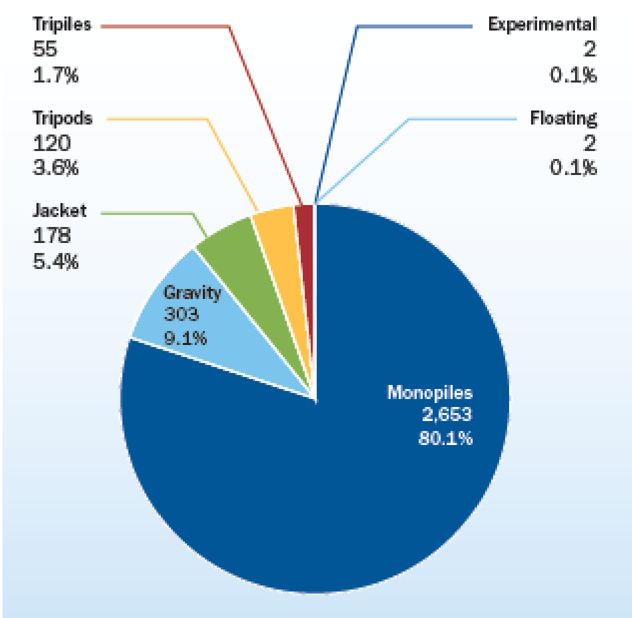


Figure 7 Share of Substructure Types for Online Wind Turbines 2015 [4]

Nevertheless, the future of offshore wind will be based on large scale projects located in deeper waters to have sufficient space for the large wind turbines to operate effectively.

This is the main reason why other foundation types are being tested and improved.

Floating foundations could be the solution for the waterdepth limitation. The advantatges of this type of technology are:

- ✓ Inexpensive foundation construction
- ✓ Less sensitive to water depth than other types
- ✓ Non-rigid, so lower wave loads

The disadvantages are:

- ✓ High mooring and platform costs
- ✓ Excludes fishing and navigation from areas of farm.

Floating foundations are a more expensive technology than monopole foundations but cost reduction potential is higher. It is believed that the costs of floating foundations could decline by 50% by 2030 [5].

2.1.3. TYPES OF WIND TURBINES

Type 1 FIXED SPEED WIND TURBINES

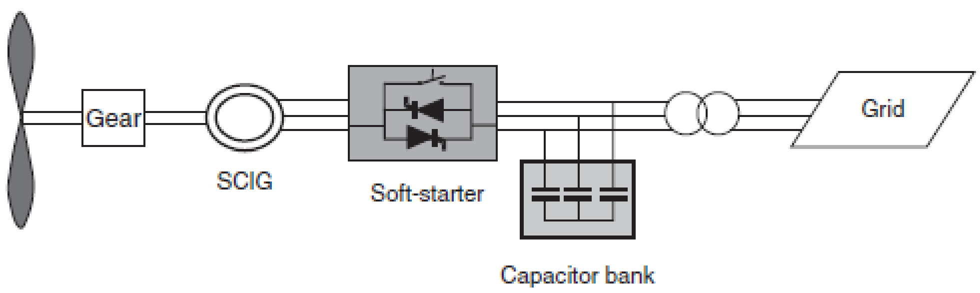


Figure 8 Type 1, Fixed Speed Wind Turbine diagram [6]

This type of wind turbines dominated the market during the 80s and 90s. It consisted in a three-bladed rotor, multiple-stage gearbox and a Squirrel Cage Induction Generator which was directly connected to the grid trough a transformer.

The Squirrel Cage Induction Generator needs to absorb reactive power to magnetize the generator, provided by a capacitor bank, and a soft starter used to start up the machine.

The main **advantages** of this first type of wind turbine are:

- ✓ The robustness of the system
- ✓ And the relatively low production costs.

Nevertheless, they presented several **disadvantages** that forced to change to another technology:

- ✓ The fact that this type of wind turbines operate at a constant speed means that ***we are not allowing the generator to extract the maximum available power*** from the wind.
- ✓ They don't fulfill the requirements of the grid: The Squirrel Cage Induction Generators need to absorb reactive power so they ***cannot provide reactive power*** in case of voltage drop, no voltage support.
- ✓ They are directly connected to the grid so is difficult to avoid their disconnection when there is a fault.

<u>Type 2 LIMITED VARIABLE SPEED WIND TURBINE</u>

The Limited Variable Speed Wind Turbines appeared during the 90s. They were the first step towards the variable speed wind turbines.

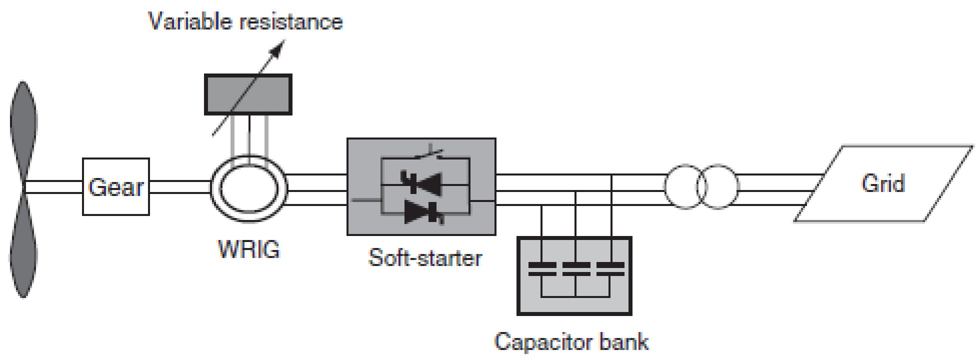


Figure 9 Type 2, Limited Variable Speed Wind Turbine diagram [6]

This type of wind turbine was similar to Type 1, but changed the Squirrel Cage Induction Generator to a Wound Rotor Induction Generator. This technology included a variable rotor resistance to **increase the speed operation range.**

However, this Type 2 or second generation of wind turbines had the **same disadvantages** than Type 1.

Type 3 VARIABLE SPEED WITH PARTIAL SCALE CONVERTER WIND TURBINE

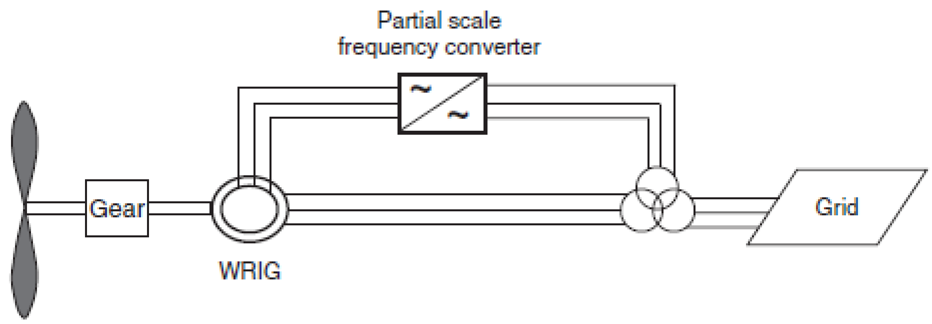


Figure 10 Type 3, Variable Speed Wind Turbine with Partial Scale Converter diagram [6]

The Type 3 consists on a Wound Rotor Induction Generator connected directly to the grid by the stator and partially through a partial scale converter connected to the rotor. This type of generator is called **Doubly Fed Induction Generator (DFIG)**.

The power converter decouples the network electrical frequency from the rotor mechanical frequency, enabling variable speed operation (± 30% of synchronous speed.)

Although we can achieve a **better fault ride-through capability and voltage support** because of the partial scale converter, the controllability can still be improved.

Type 4 FULL SCALE CONVERTER WIND TURBINE

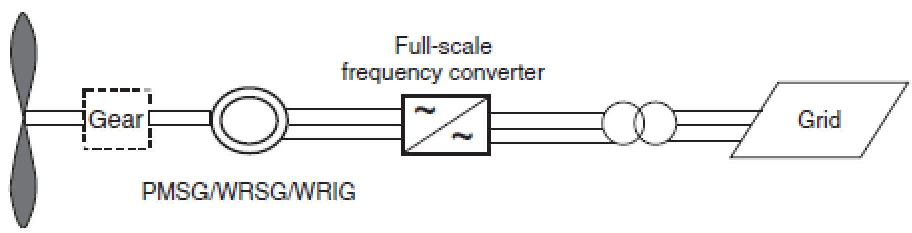


Figure 11 Type 4, Full Scale Converter wind turbine diagram [6]

This type of variable speed wind turbines with full scale converter decouple electrically the generator from the grid, which allows us to **maximize the operational speed range** that was limited with the previous wind turbine types.

The grid **operator requirements mentioned before can be satisfied** with a proper grid side converter.

This type of wind turbine works for different types of generators: Squirrel Cage Induction Generator, Wound Rotor Synchronous Generator and Permanent Magnet Synchronous Generator (PMSG).

2.1.4. DOUBLY FED INDUCTION GENERATOR WITH PARTIALLY SCALE CONVERTER

In this project we are going to work with a DFIG Wind Turbine (Type 3). These types of wind turbines are the most installed worldwide nowadays, although the market trend is changing to Type 4 Wind Turbines which give a higher controllability for grid support purposes and a full variable wind speed operation.

Nevertheless, these types of Generators have a few advantages over the rest of the technologies that are worth to mention:

- ✓ The rotor circuit is controlled by a power electronics converter. The induction generator is able to both import and export reactive power, this means better voltage support than Fixed Wind Speed Generators.
- ✓ The Partially Scale Converter allows working at a wider range of wind speeds than FWSG.
- ✓ The cost of the converter is lower when compared with other variable speed solutions because only a fraction of the mechanical power, typically 25-30%, is fed to the grid through the converter, the rest being fed to grid directly from the stator.
- ✓ The efficiency of the DFIG is better for the reason explained previously.

Generator type

In this project we are going to work with a **Doubly Fed Induction Generator (DFIG)**.

Gear box

Generators need high rotational speeds to produce electricity, and the gear box is used to increase the rotational speed of the low-speed shaft (30-60 rpm) to the fast-speed shaft (1000- 1800 rpm).

However, nowadays there is a trend to move toward a gearless technology called Direct Drive generators. These types of wind turbines avoid the use of the gear box by adding a great number of poles to the generator, which allows us to reduce the rotational speed of the rotor.

	Installed cost (2010 USD/kW)	Capacity factor (%)	Operations and maintenance (USD/kWh)	LCOE* (USD/kWh)
Onshore				
China/India	1 300 to 1 450	20 to 30	n.a.	0.06 to 0.11
Europe	1 850 to 2 100	25 to 35	0.013 to 0.025	0.08 to 0.14
North America	2 000 to 2 200	30 to 45	0.005 to 0.015	0.07 to 0.11
Offshore				
Europe	4 000 to 4 500	40 to 50	0.027 to 0.048	0.14 to 0.19

** Assumes a 10% cost of capital*

Figure 12 Wind Farm costs 2010, O&M comparison [5]

Offshore Wind can double the Operation and Maintenance costs of Onshore Wind, because of the difficulties of the offshore environment [5].

Gear box is a mechanical part that has friction losses, generates noise, has a life much below the expected life of wind turbines and require lubrication and constant maintenance. In offshore environments to use direct drive generators could mean less operation and maintenance costs and a longer wind turbine lifetime.

Although experts believe that technology is moving to a gearless wind turbine, we decided to work with Gear Box Wind Turbines because they are the most used technology nowadays.

Converter

For our case we are going to work with a **back-to-back voltage source converter**. In the next chapter we will define more deeply the characteristics of this type of converters.

In the figure below we find a simplified diagram of a DFIG Wind Turbine, similar to the one we are going to work with.

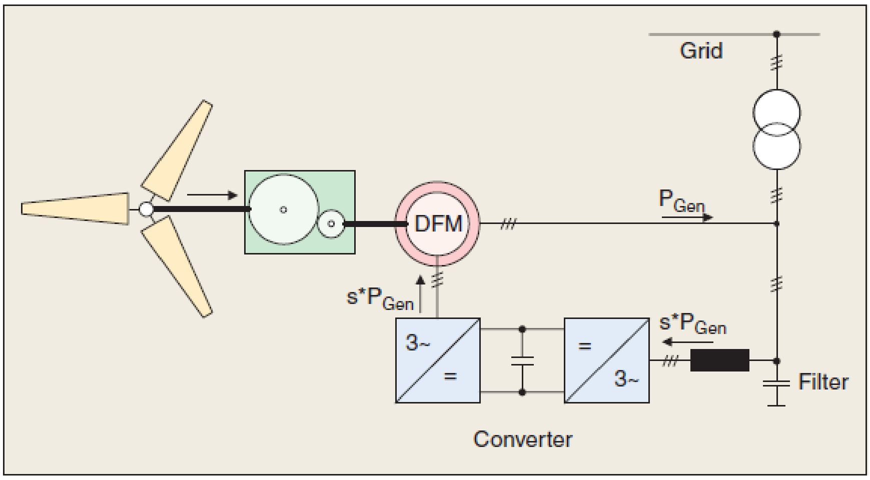


Figure 13 DFIG wind turbine diagram [7]

It is important to mention that the power electronic used it is formed by a **Generator side converter** (GSC) and a **Network side Converter** (NSC), both connected by a DC link.

2.2. POWER ELECTRONICS

Power electronics are devices that control and convert electric power, some of them allow wind turbines to work at variable-speed operation. Power converters are becoming more attractive for:

- ✓ Their capacity to improve and control the performance of the wind turbine
- ✓ Their easy control
- ✓ Their decreasing prices
- ✓ Their improving technology, they can handle higher currents and voltages

The power converters most used in turbine applications are:

Soft Starter

The Soft Starter is a power electronic component used in fixed speed wind turbines, Type 1 wind turbines. It is a simple and cheap device that helps reduce the in-rush current which could go up to 7 times the rated current. With the soft starter we avoid voltage disturbances on the grid.

Capacitor Bank

Capacitor Banks are used for fixed speed or limited variable-speed wind turbines, Type 1 and Type 2 wind turbines.

It is an electrical component that supplies the reactive power needed to magnetize the induction generator. It minimizes the absorption of reactive power from the grid.

Reactive Power Compensators

In addition to the power electronics named before, we can add a reactive power compensator to improve voltage support. Power electronic reactive power compensators can be connected to the wind farm point of connection to supply reactive power.

Two examples of reactive power compensators are the Static Var Compensators (SVC) and the Static Compensators (STATCOM).

Voltage Source Converters (VSC)

Voltage Source Converters are widely used for wind turbine application. The next figure shows the most used power electronics depending on the type of generator:

Generator	Power electronic conversion used
DFIG	Back-to-back VSCs connected to the rotor
Permanent magnet synchronous generator-based FRC	Diode bridge-VSC or back-to-back VSCs connected to the armature
Wound rotor synchronous generator-based FRC	Diode bridge-VSC or back-to-back VSCs connected to the armature and field

Figure 14 Power electronics in turbine wind turbine applications [2]

For **Doubly Fed Induction Generators (DFIG)**, the commonly used power electronic is a Back-to-Back VSC connected to the rotor.

<u>Diode Bridge VSC</u>

In this type of device the generated AC voltage is converted into DC using a diode bridge rectifier and then converted to AC using a Voltage Source Converter, which is formed by Insulated-gate bipolar transistors.

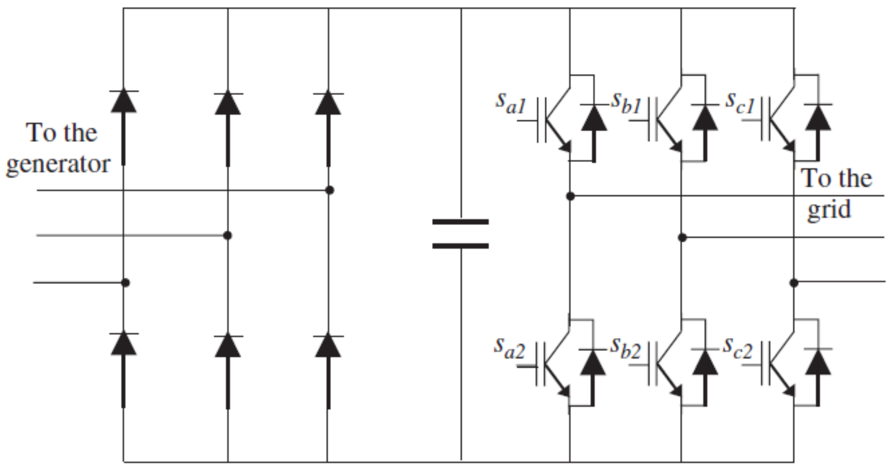


Figure 15 VSC with three-phase diode bridge [2]

This option is cheaper and simpler than the Back-to-Back VSC converter, but it does not give much controllability on the generator side. This type of VSC is not used for DFIG wind turbines; it can be used for Fully Rated Wind Turbines.

Back-to-Back VSC

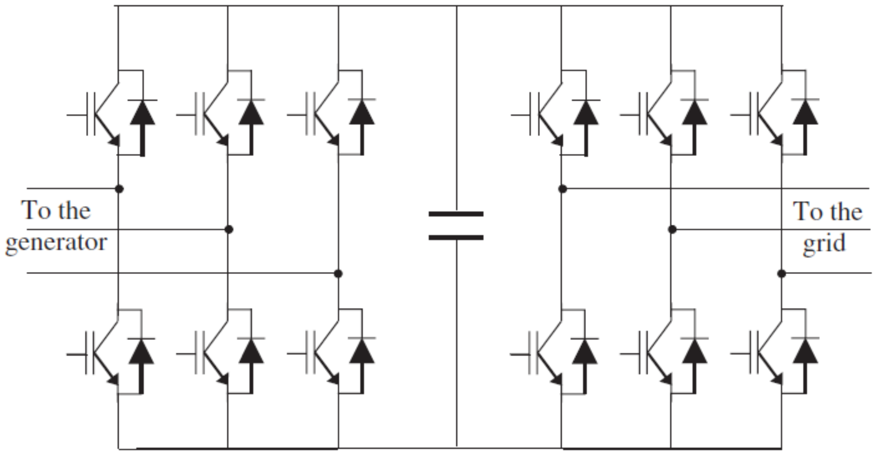


Figure 16 Back-to-Back VSC [2]

Back-to-Back Voltage source converters are formed by:

- ✓ **A Rectifier** that converts alternate current to DC current. Called **Generator Side Converter** (GSC). The GSC regulates the AC voltage at the generator side and the power generated. It can be a **Diode rectifier** or a **Voltage source Converter**.
- ✓ **A Dc link**: energy storage capacitors
- ✓ **An Inverter** that converts direct current to alternate current. Called **Network Side Converter** (NSC). The NSC regulates the reactive power and the voltage at the DC link. The most used device is the Voltage Source Converter.

Both GSC and NSC are VSCs. Each one has six Insulated-gate bipolar transistors (IGBT) controlled by a Pulse Wide Modulation technique (PWM).

This option gives more controllability on the generator side. It is the option we will implement in our project.

To completely understand the operation of a Voltage Source Converter it is important to define some concepts: **Insulated-gate bipolar transistor** (IGBT) and **Pulse Wide Modulation** (PWM).

Insulated-gate bipolar transistor

An **Insulated-gate bipolar transistor** (IGBT) is a switch with no moving parts. It has three terminals called Collector (C), Gate (G) and Emitter (E). The Collector and the Emitter form the conductance path, while the Gate controls the device.

The IGBT is a voltage-controlled device that requires only a small voltage on the Gate to allow conduction through the device.

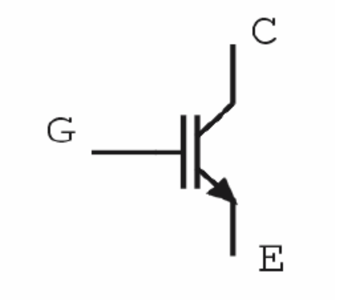


Figure 17 IGBT circuit symbol [8]

It is a unidirectional device, meaning it can only switch current from Collector to Emitter.

The main advantages of using the IGBT over other types of transistor devices are its high voltage capability and relatively fast switching speeds, among other characteristics. These make it a good choice for moderate speed, high voltage applications such as in pulse-width modulated (PWM), variable speed control.

To understand how an IGBT works inside a Voltage Source Converter we are going to explain the example of a **single-phase two level voltage source converter**.

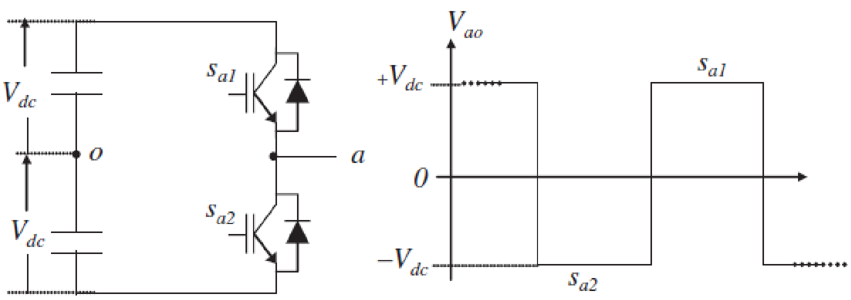


Figure 18 Single-phase two level VSC fundamental principles [2]

A single-phase voltage source converter is formed by two IGBTs connected in series. The IGBT acts as a switch, only two options are possible: electricity is allowed to flow through it or electricity is not allowed through it. This switching combination of the two IGBTs creates an output voltage waveform of two levels, as we see in Figure 18.

Depending on the duration of each switching state we obtain a different two level waveform.

It is possible to connect to the same capacitor three single-phase two level voltage source converters to form a three-phase converter.

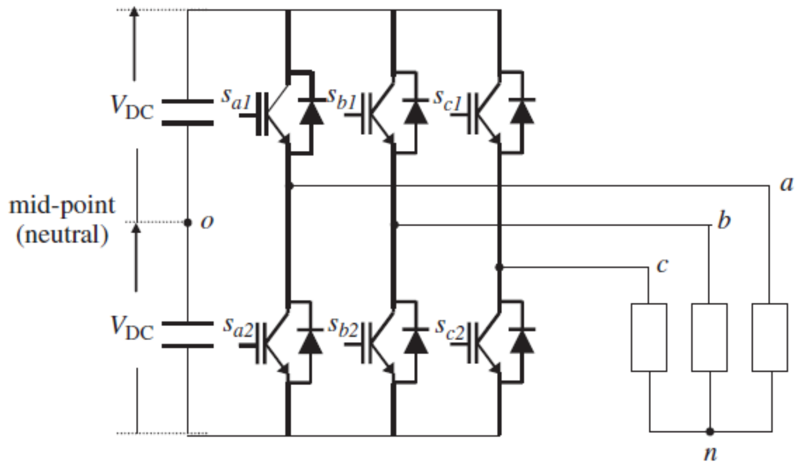


Figure 19 Three-phase two-level VSC [2]

Three output waves with the same waveform as the single-phase will be obtained for the three-phase two-level VSC.

In our case we need a sinusoidal waveform as output wave; to obtain it we need a switching control. The most used switching control for sinusoidal waveforms is the **Pulse Width Modulation (PWM)**.

Pulse Width Modulation (PWM)

There are different control strategies for PWM: square-wave operation, **carrier-based pulse-width modulation** (CB-PWM), switching frequency optimal PWM (SFO-PWM), sinusoidal regular sampled PWM (RS-PWM), non-regular sampled PWM (NRS-PWM), selective harmonic elimination PWM (SHEM), **space vector PWM (SV-PWM)** and hysteresis switching techniques.

We will not go further on this topic because it is outside our objective; however we will define two of the different control strategies to give a hint of how the switching control works:

Carrier-based PWM

The Carrier-based PWM is a classical Pulse Width Modulation switching control that uses a fixed-frequency reference sinusoidal signal (Vref) and compares it with a triangular carrier wave form (Vtri) to create a switching patter.

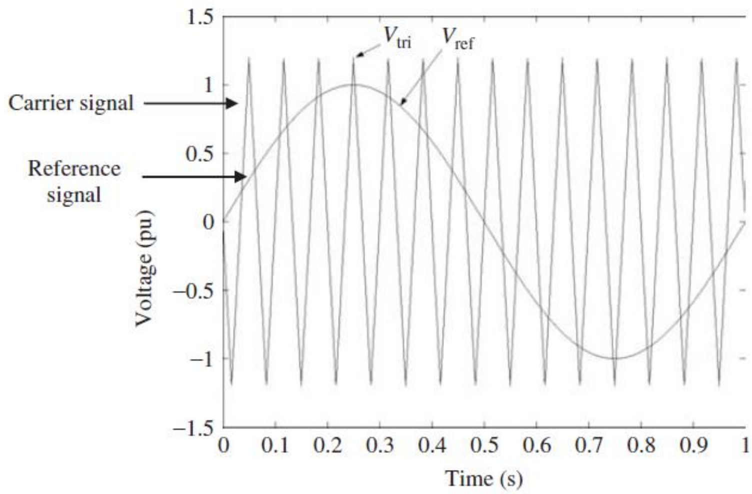


Figure 20 Carrier-Based PWM [2]

The intersections between the reference voltage (Vref) and the carrier waveform (Vtri) determine the switching instants:

$$S_{a1} = \begin{cases} 1 & V_{ref} > V_{tri} \\ 0 & V_{ref} < V_{tri} \end{cases}$$

$$S_{a2} = \begin{cases} 1 & V_{ref} < V_{tri} \\ 0 & V_{ref} > V_{tri} \end{cases}$$

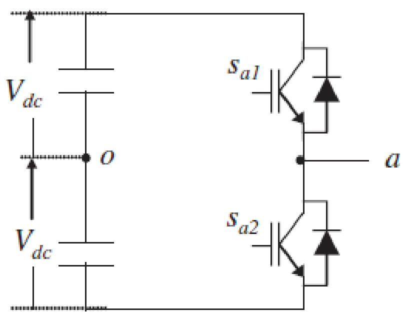


Figure 21 Switching pattern for a single-phase Two-level VSC [2]

When the Vtri is smaller than Vref the switch **Sa1** is **ON** and the switch **Sa2** is **OFF**. When the Vtri is higher than the Vref the switch **Sa1** is **OFF** and the switch **Sa2** is **ON**.

This creates an output waveform similar to the one shown in Figure 22.

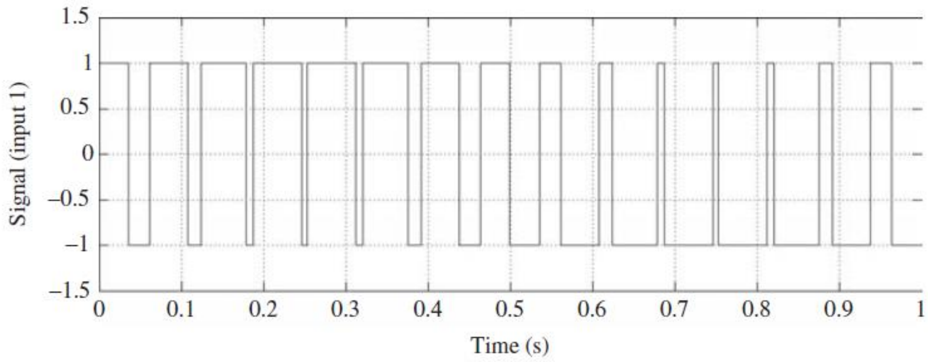


Figure 22 Output waveform example [2]

Within every carrier cycle, the average value of the output voltage becomes equal to the reference value.

Voltage Space Vector Switching (SV-PWM)

The most used switching control for Back-to-back Grid Side Generator is de **Voltage Space Vector Switching (SV-PWM)**.

This PWM is based on space vector representation of the switching voltages. It has the advantage of being easier to implement than other techniques.

S_a	S_b	S_c	v_{ao}	v_{bo}	v_{co}	Switching vector
0	0	0	$-V_{DC}$	$-V_{DC}$	$-V_{DC}$	V_0
1	0	0	$+V_{DC}$	$-V_{DC}$	$-V_{DC}$	V_1
1	1	0	$+V_{DC}$	$+V_{DC}$	$-V_{DC}$	V_2
0	1	0	$-V_{DC}$	$+V_{DC}$	$-V_{DC}$	V_3
0	1	1	$-V_{DC}$	$+V_{DC}$	$+V_{DC}$	V_4
0	0	1	$-V_{DC}$	$-V_{DC}$	$+V_{DC}$	V_5
1	0	1	$+V_{DC}$	$-V_{DC}$	$+V_{DC}$	V_6
1	1	1	$+V_{DC}$	$+V_{DC}$	$+V_{DC}$	V_7

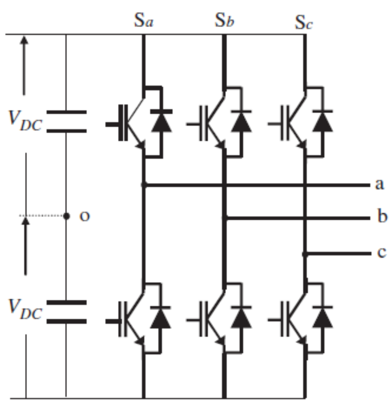


Figure 23 Three-phase two level VSC switching states [2]

A three-phase two-level VSC has three legs and six switches, each leg has two possible states ON (1) or OFF (0). The switches must be controlled to avoid turning ON the two switches at the same leg at the same time.

The converter is able to produce 8 possible switching positions, six active switching vectors and two zero vectors (V_0 y V_7):

In this technique the sequence of the switching vectors is selected in such a way that only one leg is switched to move from one switching vector to the next. The switching times of the switching vectors need to be calculated to obtain the desired output wave.

2.3. SYSTEM OPERATOR REQUIREMENTS

The System Operator is the entity responsible of the security in real time of the power system and the coordination of the supply and the demand avoiding fluctuations or interruptions of supply.

The System Operator specifies rules and codes that any generation plant must fulfill to connect to the grid.

The main purpose of the codes is to assure that any generating power plant connected to the grid can provide the adequate response in front of a sudden change. The main aspects to cover are:

- ✓ Grid support:

  - o Voltage support

  The voltage on the transmission grid is determined by the reactive power flows. Variable-speed wind turbines that use power electronics have the capability to control reactive power flow. For example, if voltage drops, variable wind speed turbines have the capability of injecting reactive power to increase the voltage back to the desired value.

  - o **Frequency response**

  Generating power units need to have the capability to increase or decrease the active power injected to the grid to control changes of frequency in the system.

  - And fault-ride through capability

  The system also needs that generating power units remain connected and support the grid when there is a fault, voltage drops of certain magnitudes and durations.

As mentioned before, this project will be focused only on the Frequency response for grid support.

2.4. FREQUENCY RESPONSE

The objective of this project is to study control strategies for first primary frequency response of Type 3 wind turbines. For that reason it is necessary to understand more precisely what is the frequency response that System Operators are requiring to the generating power plants.

All power systems need to balance generation with demand in real time. When there is an unbalance between generation and consumption the frequency, which is idealistically maintained in a pre-established value (50 Hz Europe/ 60 Hz USA), can vary drastically in a short period of time.

For example, if a big load is connected to the grid (or a big generating plant is disconnected) the **frequency of the system starts to drop**. This causes a natural deceleration on the generators who are in synchronism with the grid frequency.

The frequency of the system (f), 50 Hz in Europe, is equal to the synchronous rotational speed of the generator (ωs) multiplied by the number of pole pairs (p). If the frequency of the system drops so does the rotational speed:

$$\omega_s = \frac{2\pi f}{p} \qquad (2.4)$$

If no measures are taken, this deceleration will lead to an inevitable and continuous drop of the system frequency. This is one of the reasons why System Operators require to the generation power units connected to the grid to respond to a frequency drop by increasing their production through different strategies.

The opposite case is also possible. A sudden decrease in consumption (or big load disconnection) will lead to a frequency increase. Then generating units will have to decrease production to lower the frequency of the system back to the pre-established value.

In this project we will only analyze the case when there is a drop in the system frequency.

The frequency response of a generating unit is divided in two different services: **Continuous service** and **Occasional service**.

<u>Continuous Service</u>

The **continuous service** is the service in which the system frequency is maintained at a fixed frequency, in our case 50 Hz, inside established operational limits which depend on the country.

For example, in England the operational frequency is 50 Hz and the operational limit is ± 0.2 Hz. This means that the system is allowed to continuously work at a frequency between 50.2 Hz and 49.8 Hz.

This frequency control is achieved by using what is called a governors droop:

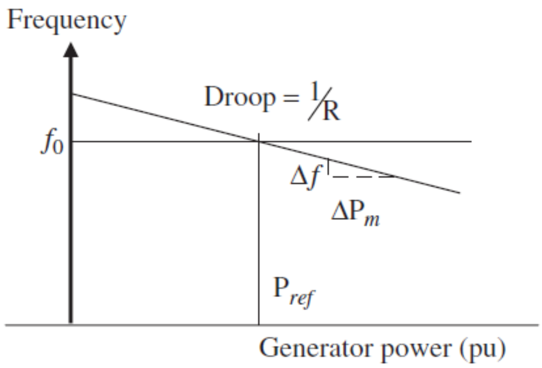


Figure 24 Governors droop of a wind turbine used for continuous service [2]

Normally the governors droop is between 3-5%. For example if we have a governor with a 5% droop it would vary the power output of the generator by 100% of rated power for a 5% deviation from nominal grid frequency.

This helps control the generators infront of small changes in frequency during continuous service.

Occasional service

Following the example of England, when frequency drops by more than 0.2 Hz additional generating capacity is contracted, called **Occasional services**. During occasional services the frequency of the system is allowed to deviate up to +0,5 Hz and -0,8 Hz.

The occasional services are divided in two responses: **Primary response** and **Secondary response**.

Primary response can be defined as the additional active power that can be delivered by a power generating unit that is available at 10 seconds and can be sustained for approximately 20 seconds.

Secondary response can be defined as the additional active power that can be delivered by a power generating unit that is available at 30 seconds and can be sustained for 30 minutes.

See Figure 25 as an example of frequency response during continuous service and occasional service. The example uses the operational limits of England and Wales grid codes.

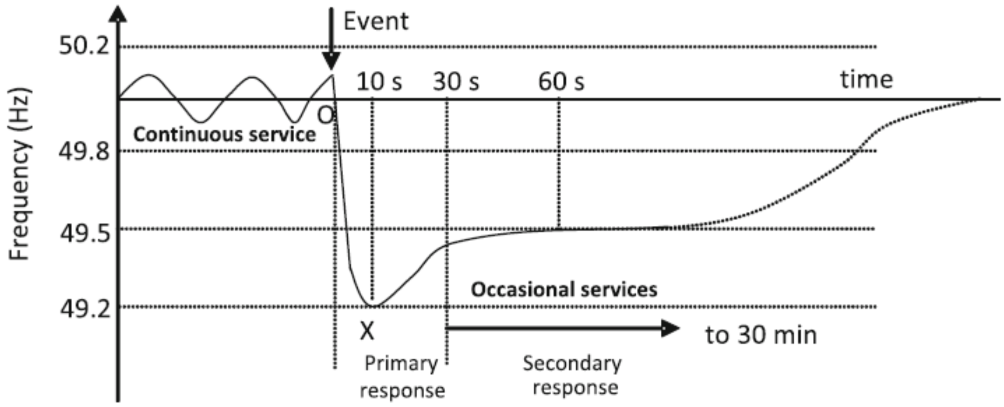


Figure 25 Example of frequency control using English codes [9]

In this project we are only interested in the Fast Primary Frequency Response.

Primary Frequency Response

The primary frequency response is divided also in two parts: **Fast Primary Response** and **Slow Primary response**.

Fast Primary Frequency Response

As previously seen, when there is a frequency drop on the system the Fixed Wind Speed Turbines (FWST) naturally decelerates the rotor speed of the generator. This deceleration results in the conversion of the kinetic energy stored in the machine into electrical energy. The **kinetic energy** in the rotating machine mass can be calculated as:

$$E_{\mathrm{k}} = \frac{1}{2} J\omega^2 \tag{2.5}$$

Where J is the moment of inertia of the wind rotor and ω is the rotational speed. We can also calculate the **Inertia constant** (H), which will give us the time that the generator can provide nominal power by only using its kinetic energy:

$$H = \frac{E}{S} = \frac{J\omega^2}{2S} \tag{2.6}$$

Where S is the nominal apparent power. Typical H values for wind turbines are between 2-6 seconds.

The natural reaction of FWST helps the system to start recovering from the frequency drop by injecting the power extracted from the kinetic energy stored in the rotating mass. This power injection or inertia response can only last a few seconds.

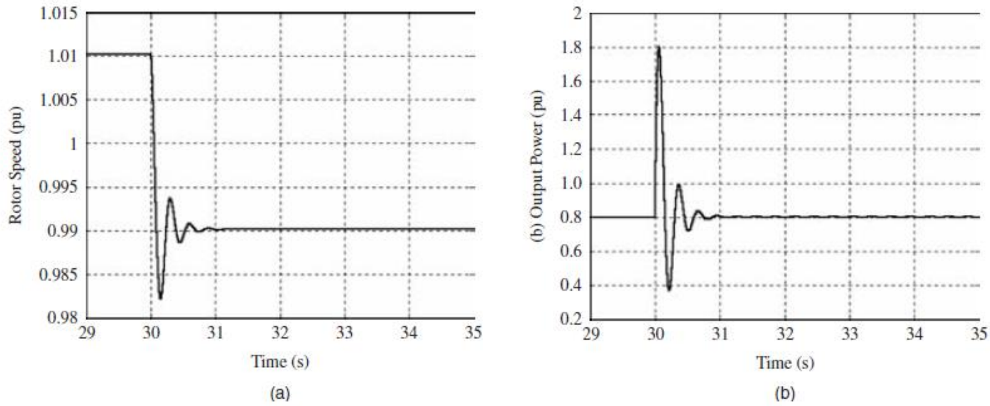


Figure 26 Fast Primary response of Fixed Speed Wind Turbine [2]

An example of Fixed Wind Speed Turbines natural inertia can be seen in Figure 26, at time equal to 30 seconds a sudden drop in the rotor speeds (frequency drop) results in an increase in power output.

The problem that we encounter is that nowadays the greater part of the wind turbines connected to the grid are type 3 and Type 4 wind turbines, variable speed wind turbines that use converters to decouple partially or completely the wind turbine from the grid. This means that for Type 3 and Type 4 generators the natural inertial response is not possible because the frequency on the grid side is independent of the frequency on the generator side.

This fact is causing a reduction on the whole system inertia.

To show the impact of the reduction of the system inertia in the frequency response of the system we are going to use a real example based on the United States Power System.

The **United States Power System** which is formed by three interconnections: Eastern Interconnection, Western Interconnection and Texas. The Figure 27 describes the Frequency Response in front of a frequency drop of the three systems.

As we can see, the rate of frequency fall of the Eastern Interconnection (blue line) is lower than the other two systems, because the stored system inertia is higher.

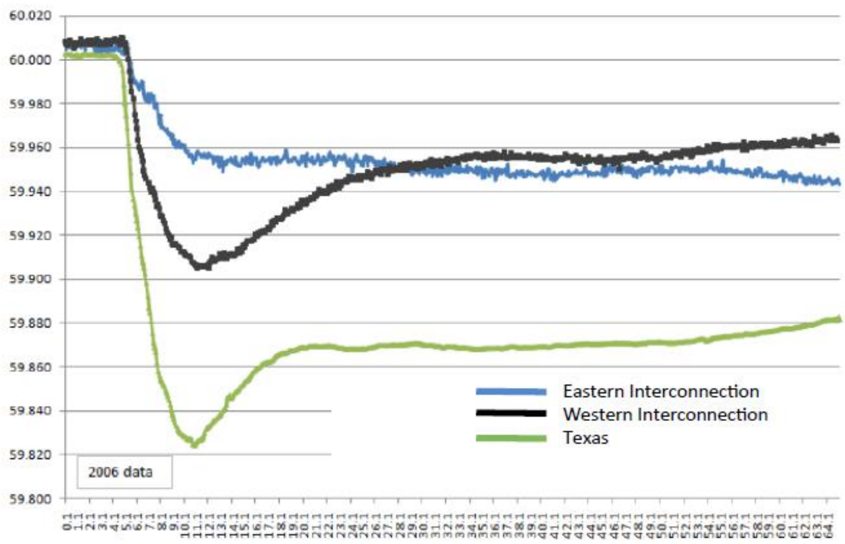


Figure 27 Frequency response US Power System [10]

We can affirm that **the rate of frequency drop is proportional to the stored inertia of the system**.

So if there is a sudden drop in the frequency of a system with high level of wind energy penetration (Type 3 and 4 wind turbines with no Frequency control) we can expect direct impact on **two important aspects**:

- ✓ The **rate of change of frequency (ROCOF)** increases. In this case, the frequency may drop very quickly during the OX Period.

- ✓ We hit minimum frequency values at shorter times so we need faster actions for frequency response. This is called **Maximum frequency deviation [NADIR]**.

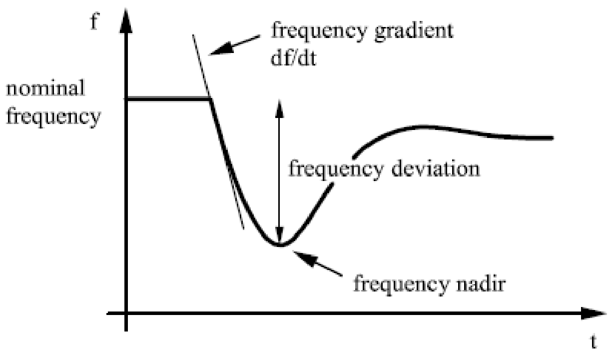


Figure 28 ROCOF and NADIR representation [11]

In Figure 28 we can see the graphic representation of ROCOF (called frequency gradient df/dt) and NADIR. Both of these quantities shall be kept as small as possible to guarantee a good frequency response.

The **Fast Primary Response** or inertia contribution to the system of Type 3 and 4 wind turbines is not achieved with conventional controls. Therefore, it is important to find a control strategy to emulate inertia and restart the Fast Primary Response of the system. This is the main objective of this project.

Slow Primary Frequency Response

We won't go into deep in **Slow Primary Response** or **Secondary Response** strategies, because is not part of the study. But we certainly think it is important to mention both responses briefly to have a notion of both concepts.

The **Slow Primary Response** is achieved by a governor action; an automatic droop control loop of the governor allows increasing the turbine's output. This is a slower response than the natural or emulated inertia.

With a proper droop control we can decrease the NADIR value, while with a proper inertia emulation control we can decrease the ROCOF.

Secondary Frequency Response

There are three **Secondary Response** strategies:

- **Pitch Angle Control:**

  This method consists in changing the pitch angle from an optimum value to a different pitch angle value leaving a margin to power generation in case of a drop in the frequency of the grid.

  For example in Figure 29, the point Q is placed in the power curve characteristic of the optimum pitch angle (-2º) at which we will obtain higher power ratings. Instead of working at -2º, we have the option to change the pitch angle value to one that produces less power, for example +2º at point P. This way in case of the need to increase power production we can change pitch angle to the optimum value and gain that energy we are spilling in continuous operation.

  For the Fixed Speed Wind Turbines this is the only method available to achieve energy reserve.

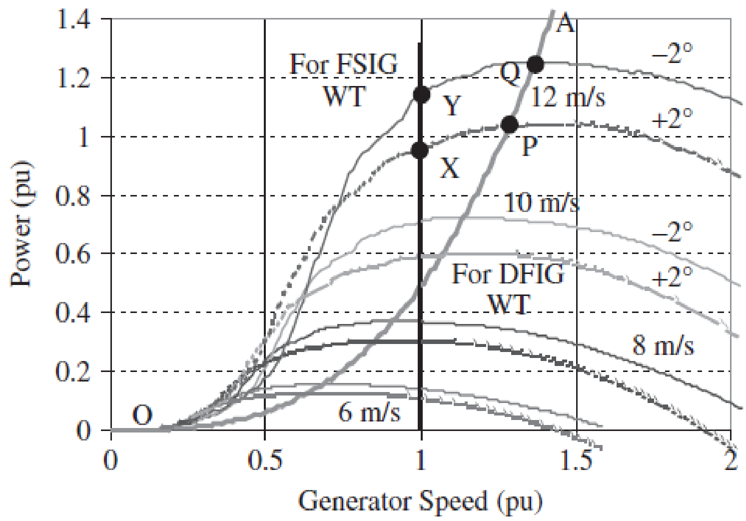


Figure 29 Secondary Response example [2]

- **Overspeeding:**

This method consists in working at a different generator speed than the optimum. For example, point Q is placed in the optimum pitch angle value and in the optimum generator speed value. If we decide to change generator speed and increase it without changing pitch angle we will be lower our power production.

When the system needs an injection of power the controls let the generator naturally decelerate and go back to optimum value to increase power production.

- **The use of energy storage:**

This could be an option for future implementations. Nowadays electric energy storage is not viable economically compared to the other two options.

2.4.1. EMULATED INERTIA

Manufacturers have started to integrate controls on Type 3 and 4 wind turbines in order to achieve the desired inertial response. This inertia is known as **emulated inertia** or **synthetic inertia**.

There are several methods to achieve emulated inertial response from fully rated converter wind turbines:

1- **Using the hidden inertia**

Using this method we are allowed to work at optimum power production speed and optimum pitch value, Figure 29. When there is a drop in frequency on the grid side the converter sends a command to the generator to decelerate.

As we already explain, the accumulated inertia is transformed then in electricity leading to a fast frequency response which is similar to the one that synchronous machines have naturally.

2- **Reserve capacity, pitch control**

With pitch control we can be working at different pitch value than the optimum and when the power converter gives the command that there is a frequency drop on the grid we can go back to optimum value.

3- **Overspeeding**

As explained in Secondary Frequency Response, Overspeeding consists in working at higher generator speed than the optimum. This way when the drop in frequency occurs we can decelerate our machine injecting the power produced by the inertia and achieving the optimum speed so we also increase the power production.

The most studied and used method is the Hidden Inertia, because is the only method that allows to work at optimal operational point, which means we are always producing the maximum power. The other two methods force us to work outside the optimum, so we are losing power at normal operation. Another reason to discard Pitch control is that it is a slow method, we need to give time to pitch control to move the blades and fast primary response need to be available at a few seconds after the frequency drop.

When implementing an emulated inertia control we need to take into account different aspects:

Wind speed

In Figure 30, we compare the emulated inertia response (EIR) of a wind turbine at different wind speeds. The reason we want to compare the same turbine at different speeds is because the stored energy on a machine depends on its rotational speed. Comparing different wind speeds will give as a more precise emulated inertia response tendency. We see that the emulated inertia which appears from second 2 to second 5 is similar when the wind speed is above 6 m/s. We can also observe that the frequency recovery changes with wind speed.

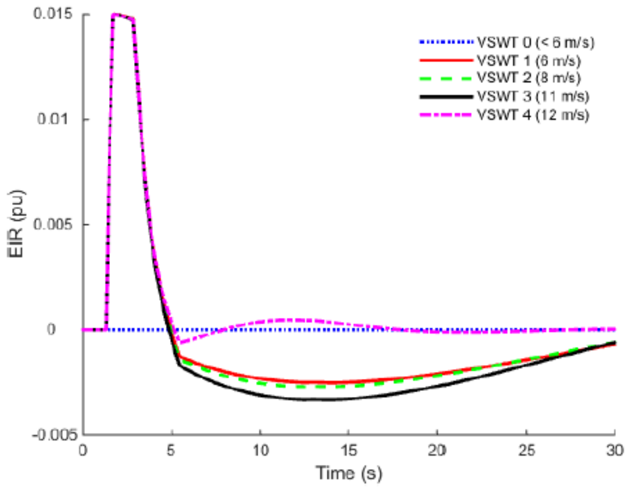


Figure 30 Emulated Inertia Response of a Wind Turbine at different wind speeds [10]

So we can conclude that emulated inertia could give a proper frequency response at the first seconds after the frequency drop. After this initial response the frequency recovery will vary depending on wind speed. Anyhow, it is important to point out that natural inertia is faster than the emulated inertia.

<u>The parameters of the Power electronic control</u>

During the implementation of the control for the emulated inertia it is important to tune the parameters in the right way.

Figure 31 shows us three types of frequency response depending on how we set the parameters of the emulated inertia control.

The first case is a Base case in which there is no Emulated inertia control, so the turbine remains decoupled from the frequency grid by the Power Electronic device, there is no injection of power therefore the frequency drops to the minimum.

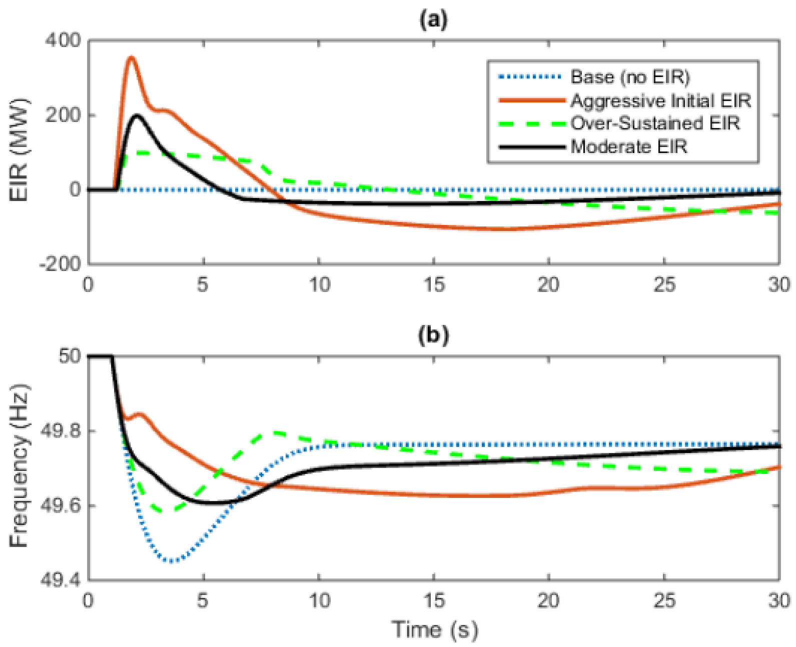


Figure 31 Tuning the power electronic response [10]

The second case is an aggressive initial Emulated Inertia in which we set the parameters to inject a high amount of power as fast primary response; this will lead to a new and inevitable frequency drop.

The third case is an over-sustained frequency Emulated Inertia in which the injection of power last more than the appropriate time leading to frequency decay.

And the last case is the moderate Emulated Inertia Response in which the balance between the quantity of power injected and time of the response is at such equilibrium that we can reach a proper frequency response.

2.5. GRID CODES

2.5.1. EUROPE

The European Network of Transmission System Operators for Electricity, known as ENTSO-E, is an association of 35 countries from all Europe founded and given legal mandate at 2009 by the EU's Third Legislative Package for the Internal Energy Market.

They act like the meeting point between the different System Operators on the market. Their main objectives are:

- ✓ Develop suitable response to the changing power system due to the increase of renewable energy generation while maintaining security of supply
- ✓ Flexibility
- ✓ Regional cooperation
- ✓ Etc.

They can achieve these objectives by cooperating mainly into drafting and implementing the grid codes.

Network Code on Requirements for Grid Connection Applicable to all Generators

This code is one of the main drivers for creating an efficient European (and global) market in generator technology and it is applicable to all type of generators that want to be connected to the grid.

The requirements are defined depending on the type of Power Generating module. A **Power Generating Module** is either a Synchronous Power Generating Module or a Power Park Module.

Power Park Module is a unit or ensemble of units generating electricity, which is connected to the Network non-synchronously or through power electronics, and has a single Connection Point to a transmission, distribution or closed distribution Network.

The Power Generating modules are classified based on its Connection Point voltage and the Maximum Capacity. The latter depends on the Relevant TSO (region).

The **Connection Point** is defined as "the interface at which the Power Generating Module is connected to a transmission, distribution or closed distribution Network".

The **Maximum Capacity** is “the maximum continuous Active Power which a Power Generating Module can feed into the Network”.

For the Offshore Power Park modules, the requirements are described at **Chapter 4: Requirements for Offshore Power Park Modules.**

The Article 18 defines the *General provisions* [12]:

1. *The requirements in this Chapter apply to the connection to the Network of Power Park Modules located offshore. A **Power Park Module** located offshore which does not have an Offshore **Connection Point** shall be considered as an Onshore Power Park Module and thus shall be compliant with the requirements set forth for the Power Park Modules situated onshore.*

For our study we will consider that the Power Park Module (an ensemble of units generating electricity) is placed offshore with an Offshore Connection Point. So we should follow the requirements for Frequency Stability set at **Article 19**: *Frequency Stability Requirements Applicable to Offshore Power Park Modules***:**

“The Frequency stability requirements defined respectively in Article 8(1) (a), (b), (c), (d) and (e), Article 10(2) and Article 16(2) (a) shall apply to any Offshore Power Park Module.”

All the articles mentioned are requirements for frequency response. However, as mentioned in previous sections, the objective of this project is focused on fast primary frequency response, also known as emulated inertia or synthetic inertia. And this topic requirement is defined on **Chapter 3, Requirements for Power Park Modules** in **Article 16 (2)**.

Article 16 (2) defines the Requirements for Type C Power Park Modules regarding Frequency Response. Although it is also required for Type D Power Park Modules and Offshore Power Park Modules, among others.

The Article defines the following statements [12]:

a) With regard to the capability of providing Synthetic Inertia to a low Frequency event:

1) The Relevant TSO shall have the right to require while respecting the provisions of Article 4(3), in co-operation with other TSOs in the relevant Synchronous Area, a Power Park Module, which is not inherently capable of supplying additional Active Power to the Network by its Inertia and which is greater than a MW size to be specified by the Relevant TSO, to install a feature in the control system which operates the Power Park Module so as to supply additional Active Power to the Network in order to limit the rate of change of Frequency following a sudden loss of infeed.

2) The operating principle of this control system and the associated performance parameters shall be defined by the Relevant TSO while respecting the provisions of Article 4(3).

To clarify the points defined previously, it is important to say that the **Article 4(3)** [12] mentions that "*The terms and conditions for connection and access to networks or their methodologies shall be established by the National Regulatory Authorities, or by the Member States in accordance with the rules of national law implementing Directive 2009/72/EC, and with the principles of transparency, proportionality and non-discrimination.*"

ENTSO-E Article 16 (2) recognizes the right to the relevant TSO of the region in which the Power Park Module is installed to ask for synthetic inertia response.

2.5.2. SPAIN

Spanish TSO, Red Eléctrica de España S.A. (REE), which is a member of the ENTSO-E has not include yet a code regarding emulating inertia.

There is a draft in Spanish legislation that mentions this important matter [13]: ***Separata del Borrador PO 12.2.: Technical requirements for wind energy, photovoltaic and all other generation plants which technology does not use a synchronous generator directly connected to the grid***

In particular the **Section 8.3.4.: Future perspective of technical requirements** speaks about emulated inertia and names a few non mandatory requirements for new synchronous generation units to guarantee minimum conditions for security of supply.

The requirements **are not mandatory**; this draft encourages to apply the requirements to improve the service and comes ahead of time of future legislation on the matter.

2.5.3. GREAT BRITAIN

The **National Grid Electricity Transmission** (NGET) is the relevant TSOE in England and Wales. NGET is responsible for ensuring that system supply and demand are balanced on a second by second basis, 24hours a day, 365 days a year in the Great Britain Transmission Network.

In reference of synthetic inertia **Grid Code Frequency Response Working Group** proposed in 2010 a possible control to assure emulated inertia for Type 4 Wind Turbines, see Figure 32.

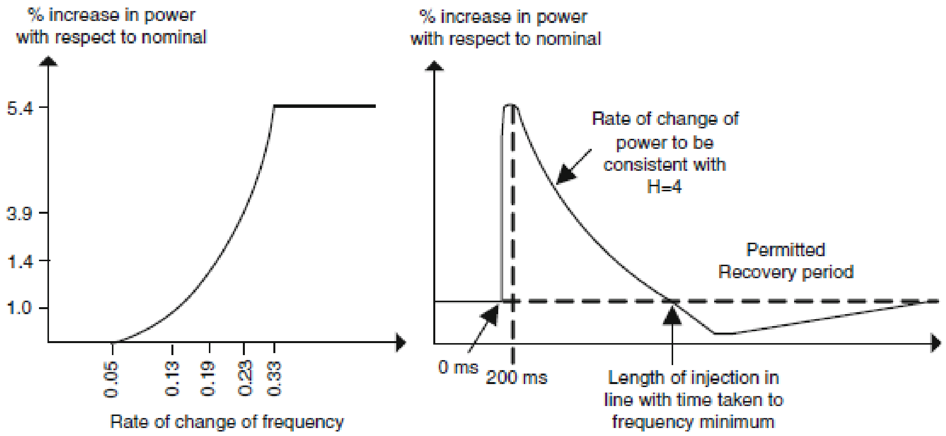


Figure 32 Proposed synthetic inertia by the National Grid frequency Response Group [14]

However, they finally decided not to include this requirement in their grid codes.

Synthetic inertia or fast primary frequency response is then a requirement needed by TSO to assure security of supply, although currently it is not a mandatory requirement the ENTSO-E and other TSOs are starting to taking into account this aspect as an important issue. Therefore, the study of new control strategies for synthetic inertia and their implementation is an important matter for the full development of renewable energies and their integration to the grid.

3. SIMULATION

The simulation used for the study is an existing Simscape Power Systems-MATLAB code created by Venkatesh Yadav [15], which was modified in order to achieve the objectives of the project.

The Simscape-MATLAB code simulates a grid system with three synchronous machines and a Wind Energy Power Plant that inject power to the grid at the same time that two loads are consuming the power generated.

Initially the system is completely balanced which means the generation matches the consumption.

This simulation is capable of simulate a decrease on the system frequency by adding and additional load.

The total duration of the grid system simulation is 50 seconds; the system frequency is set to drop at the 30 seconds mark, so our project will analyze the behavior of the system from the 25 second mark to the 50 second mark.

3.1. DESCRIPTION OF THE STUDY CASE

Before starting to describe the structure of the simulation, it is important to define the main parameters that will characterize the study.

WIND POWER PLANT CHARACTERISTICS

Number of wind turbines	N (*)
Default Wind speed	12 m/s (**)
Wind Turbine type	Type 3
Generator type	Doubly Fed Induction Generator (DFIG)
Type of converter	Back-to-back Voltage Source Converter with PWM
Wind Turbine Rated power	1.5 MW

Table 1 Wind Power Plant characteristics

*In the study we will modify this parameter to achieve different levels of Wind Energy Penetration in the system

** We will modify the default wind speed value to analyze the system behavior

GRID CHARACTERISTICS

Frequency of the grid	50 Hz
Initial total Load	1600MW
Additional Load	160MW
Number of synchronous turbines	3
Synchronous Turbine Rated Power (unit)	900MW

Table 2 Grid Characteristics

FREQUENCY CONTROL DEFAULT CHARACTERISTICS

Default inertia control constant (H)	5.04
Default Droop value	0.05

Table 3 Frequency control Default values

The Frequency control values, inertia control constant and Droop control, will be modified to study the frequency response of the system for the different scenarios.

3.2. SIMSCAPE POWER SYSTEMS SIMULATION DESCRIPTION

The simulation is composed by two different areas: **Area 1** and **Area 2** connected by a three-phase cable of 220km of length.

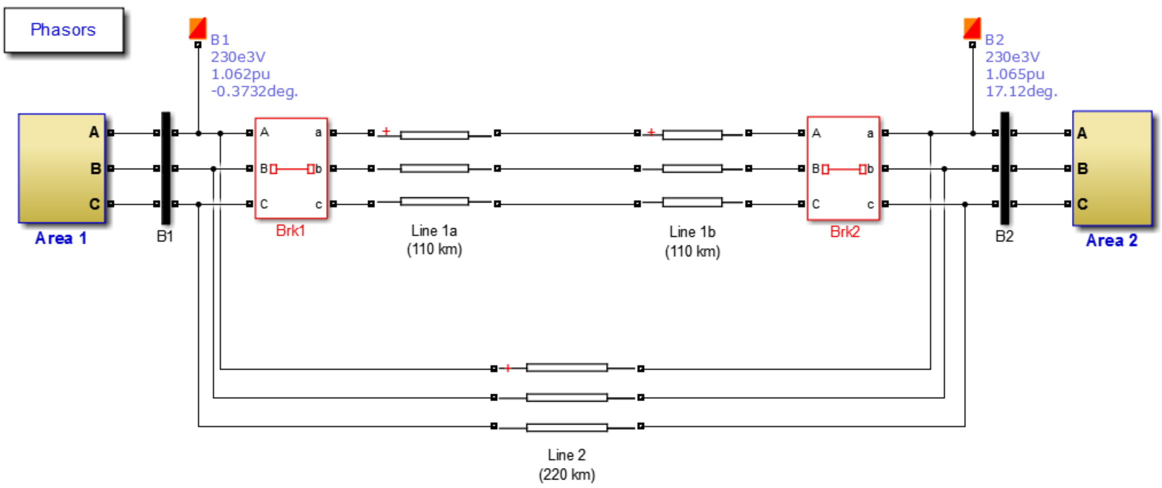


Figure 33 First level of the Simscape Power Systems Simulation [15]

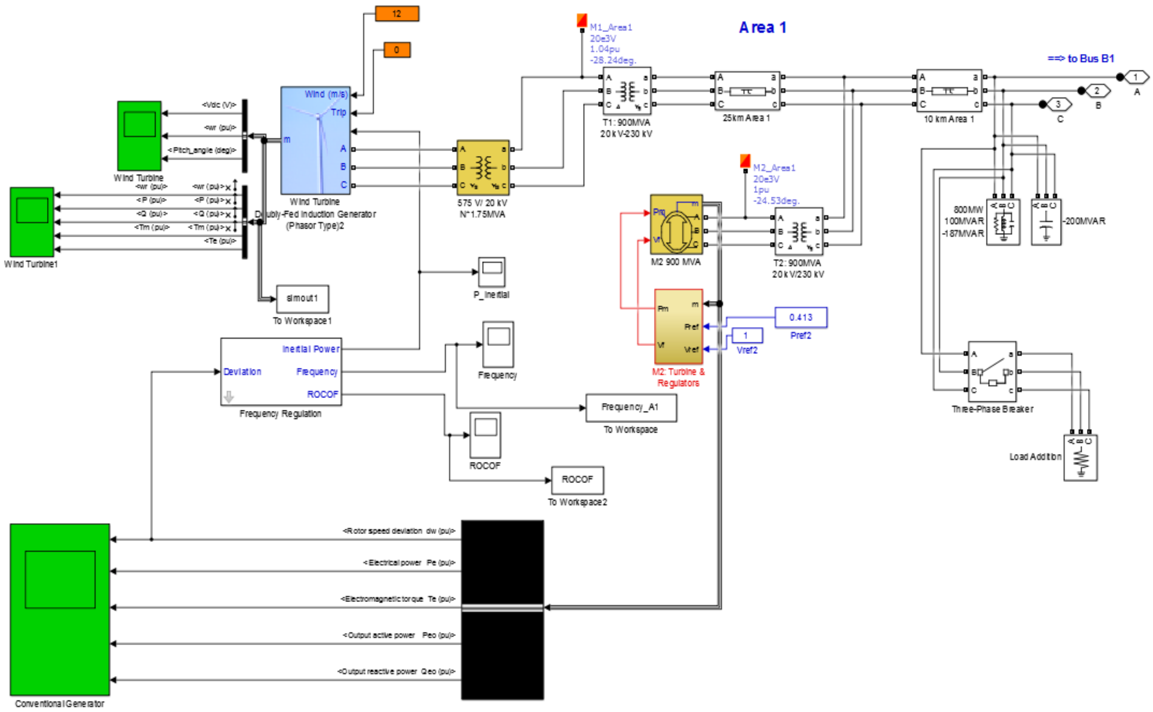


Figure 34 Second level Area 1 of the Simscape Power System Simulation [15]

Area 1 is composed by:

- ✓ The Wind Power Plant (WPP) with N number of wind turbines connected to the grid. The connection is made through two three-phase transformers, one represents the transformer which is placed inside each wind turbine and the other represents the transformer located at the substation.

- ✓ A 900MW Synchronous machine connected to the grid through a three-phase transformer 12 km away from the WPP. A regulation block is added to control the Power generated by the synchronous machine. This will allow us to increase or decrease the Wind Energy Penetration.

- ✓ One initial load of 800MW connected to the grid 10 km away from the Synchronous machine. Connected to this load there is a RLC Load that defines the active and reactive power we want to consume at this point.

- ✓ Additional mechanism connected to the initial load composed by a break and an additional load of 160MW. This mechanism is the one that will simulate the frequency drop of the system at time 30 seconds.

✓ **The frecuency control or Frequency regulation Block** controls two main parameters: the Inertia and the Droop of the Wind Power Plant (WPP).

Frequency control of the Wind Power Plant:

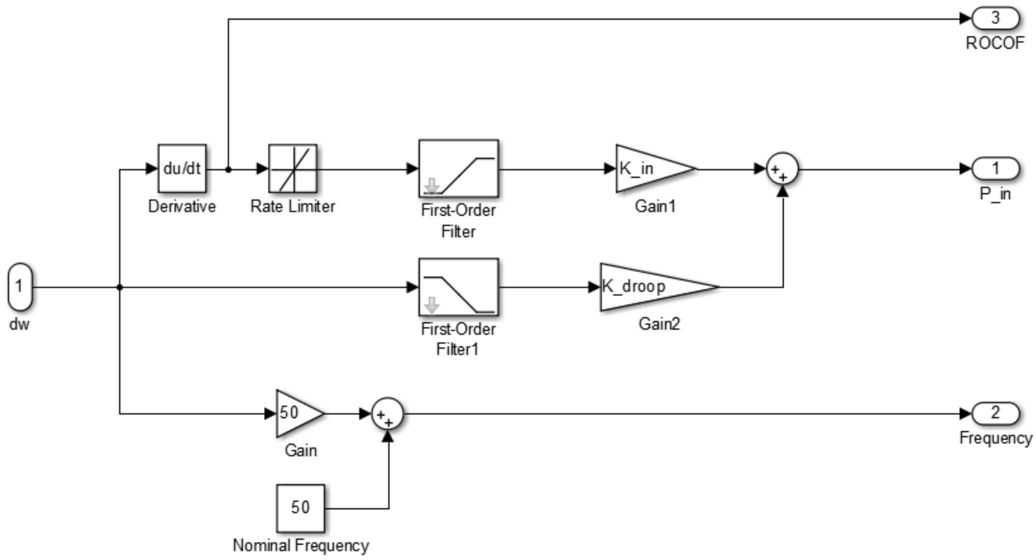


Figure 35 Close up of the Frequency control Droops [15]

The input data used for the Frequency control is the deviation of the rotor speed of the synchronous machine. The deviation of the speed will help us determine if there is a the deviation of the frequency on the system.

If we take a look inside the frequency control, figure 35, we can observe it is composed by two main proportional controls: the first one controls the Inertia that initialy is set at 2*5.04 and the second control is used for Droop control which as a default value of 1/5%.

From the first control, inertia control, we use a derivative block to know how fast the frequency is changing. From that derivative we can extract the ROCOF, Rate of Change of Frequency, which is the frequency gradient df/dt (see chapter 3.2.1).

The First-Order filters helps us avoid the response of the control infront of sudden changes in the system, avoids low frequencies in the case of the inertia control, and avoids high frequencies in the case of the Droop control.

Both controls result in the final Power gain of the frequency control.

The third control is just to know the real values of the frequency at each point.

Area 2 is composed by:

- ✓ One initial load of 800MW connected to the grid 220 km away from the Area 1. Connected to this load there is a RLC Load that defines the active and reactive power we want to consume at this point.
- ✓ Two 900MW Synchronous machines connected through a three-phase transformer at 10km and 35km away from the Load of the Area 2. A regulation block is added to each turbine to control the Power generated by the synchronous machine. This will allow us to increase or decrease the Wind Energy Penetration.
- ✓ In this Area 2 we also include a control that transforms the pu values of the frequency into Hz.

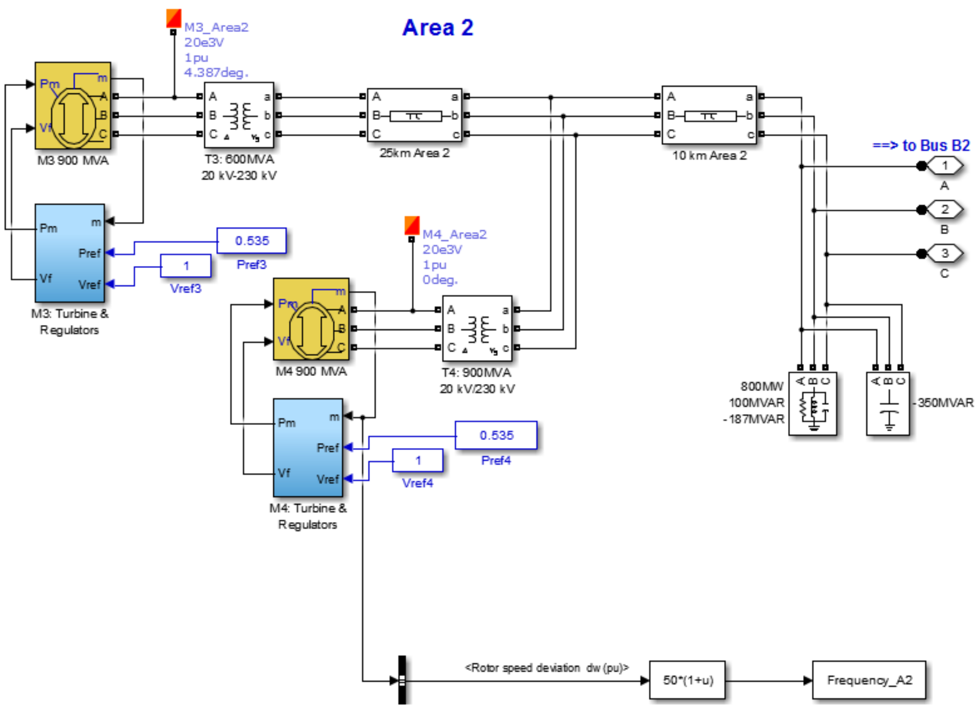


Figure 36 Second level Area 1 Simscape Power Systems Simulation [15]

3.3. SCENARIOS FOR THE SIMULATION

We are going to simulate different scenarios to analyze the behavior of the system in front of the change of different parameters.

The parameters we are going to change are:

- ✓ Wind energy penetration into the system.

At the same time for each wind energy penetration scenario:
- Inertia control
- Droop Control

✓ Wind speed of the WPP

Wind Energy Penetration

We will study the following level of wind energy penetrations: 10%, 15%, 20%, 25% and 30%. To do that first we need to set the values of the total number of wind turbines on the system and limit the power delivered from the Synchronous Machines in order to generate 1600MW and match the initial load.

The values for N, number of wind turbines operating at the Wind Power Plant, and Pref, percentage of power generated by the synchronous machine with respect of the nominal power; will be:

	N	Pref2	Pref3	Pref4
10% Penetration	160	0.537	0.535	0.535
15% Penetration	236	0.497	0.51	0.51
20% Penetration	316	0.476	0.476	0.476
25% Penetration	395	0.443	0.444	0.444
30% Penetration	469	0.413	0.414	0.414

Table 4 Parameter values to determine the different levels of Wind Energy Penetration of the System

These values are only used when the wind speed is set at the default value of 12 m/s.

For each level of Wind Energy Penetration we will also change the following parameters:

Default values

In this scenario we will leave wind speed, Inertia control constant and Droop control values as the default ones:

Wind speed: 12 m/s

Constant of Inertia: 5.04

Droop: 5%

No frequency control

In this scenario we will leave wind speed as default value and Inertia control constant and Droop control values will be **set to zero**.

This scenario will give us an idea of the frequency response of a system with energy penetration and no additional frequency control.

Inertia control

For each level of penetration we will simulate 5 different values for the Inertia control constant, leaving all the rest of the parameters set as the default ones (droop is kept at 5% and wind speed at 12 m/s):

Constant of inertia below default value H=5.04

H=0; H=2; H=4

Constant of inertia above default value H=5.04

H=6; H=10

Droop Control Values

For each level of penetration we will simulate 5 different values for the Droop, leaving all the rest of the parameters set as the default ones (Inertia control constant is kept at 5.04 and wind speed at 12 m/s):

Droop Values below default value 5%

0; 1%; 2%

Droop values above default value 5%

6%; 10%

Wind speed of the WPP

With the inertia constant and Droop set as the default values, H=0.54 and Droop 5%, and a level of wind energy penetration of 10% we will simulate different wind speeds:

Speeds below default value 12 m/s: 10 m/s

Speeds above default value 12 m/s: 15 m/s; 17m/s

4. RESULTS

In this chapter we decided to analyze only the most relevant cases over the more than 60 scenarios studied. In any case, all the results can be found on the Annexes of this project.

4.1. CASE 1: 10 % WIND ENERGY PENETRATION, DEFAULT WIND SPEED=12 m/s

For this first case we chose the scenario of the 10% of Wind Energy Penetration with a wind speed set at the default value of 12 m/s. The purpose of analyzing the results of this first case is study the scenario in which the Frequency control values of inertia and Droop are set to zero and compare it with the Scenario in which the Frequency control is set at the default values.

4.1.1. NO FREQUENCY CONTROL

By setting the Frequency control values at zero we expect to have a worse frequency response than if it there is Frequency control available for the Wind Turbines; because in this case, only the synchronous machines connected to the grid will be able to support the frequency response of the system with their natural inertia.

FREQUENCY RESPONSE

Area 1: Wind Turbine Area

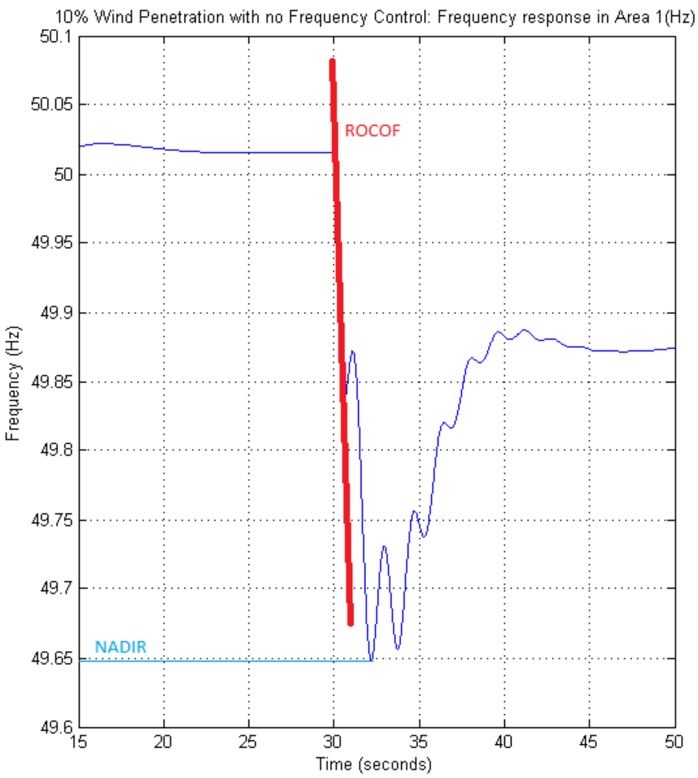


Figure 37 Frequency Response at Area 1, 10% Wind Energy Penetration No Frequency control

Area 2: Synchronous Machine

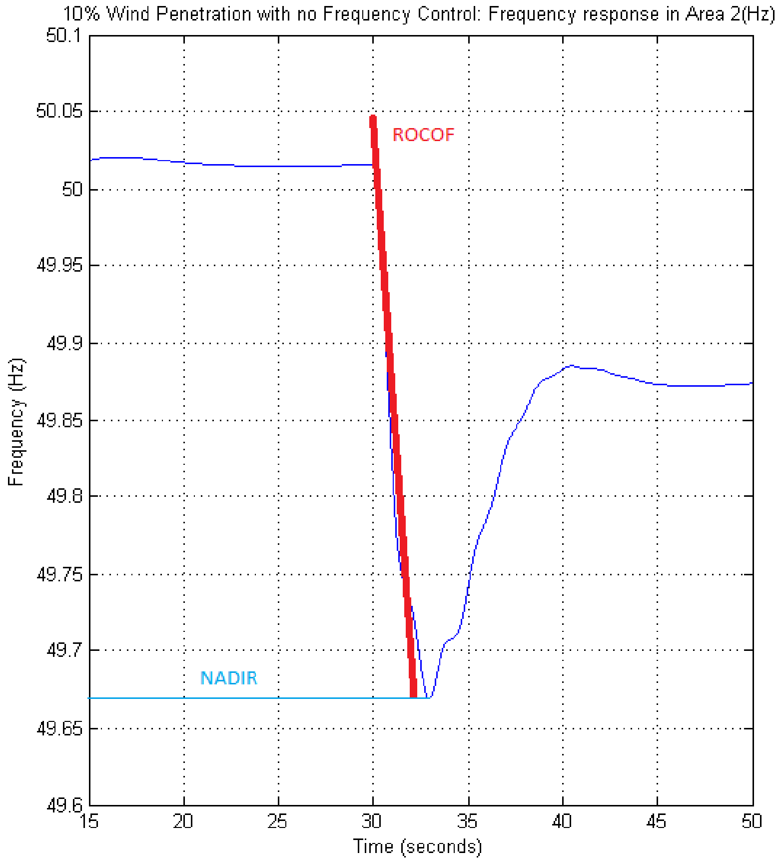


Figure 38 Frequency Response Area 2, 10% Wind Energy Penetration No Frequency control

The frequency response of both turbines is similar to the one show at the figure 25 (3.2.1. Frequency response chapter), where after and additional load is connected the frequency drops quickly until it reaches a minimum value called NADIR.

The first seconds after the frequency drops are known as Fast Primary Frequency Response and it is directly related with the system inertia capability. In this case, only synchronous machines will be able to provide this Fast Frequency Response, due to their natural inertia response. This is the main reason why the results in Area 2 are slightly better than in Area 1:

AREA 1	
% Wind Penetration	NADIR
10%	49,6479153

AREA 2	
% Wind Penetration	NADIR
10%	49,668918

Table 5 NADIR values of 10% Penetration and No frequency Control

Also, the Rate of Change of Frequency (ROCOF) of the Area 1, is higher than the ROCOF of the synchronous machine.

DFIG Wind turbines are partially decoupled from the grid. Therefore the frequency of the grid does not affect the rotor mechanical frequency. If there is not a control that forces the machine to react to the frequency drop they won't support the frequency of the grid.

POWER GENERATED BY THE WIND TURBINE

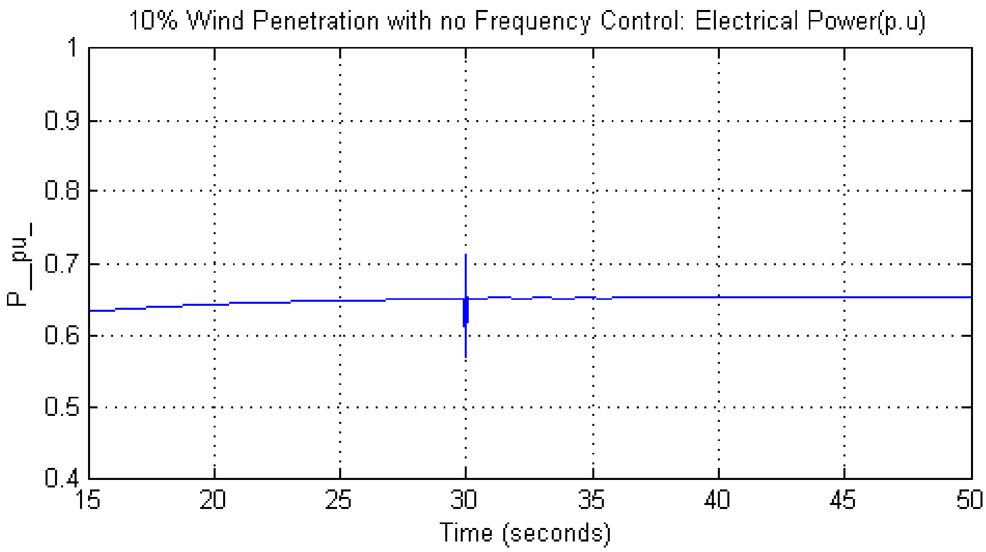


Figure 39 Power Generated by Wind turbine (pu), 10% Wind Energy Penetration No Frequency control

Another aspect we need to analyze is the Power Generated by the Wind Turbine. When there is a frequency drop the system needs to increase the generation or decrease the load consumption. In this case, we need to increase the total power output. As we see in the figure above, the Power Generated by the wind turbine remains the same after the 30 second mark. This means the Wind Power Plant is not giving the desired frequency response.

SPEED OF THE WIND TURBINE

Other aspect of the wind turbine behavior that we need to analyze is the speed of the wind turbine. When there is a frequency drop in the system synchronous machines starts to decelerate naturally, that kinetic energy stored in the rotating mass is then injected into the grid as electric power. As we have seen there is no increase in the power output of the turbine, and as we see in the figure below is because the speed of the wind turbine remains virtually the same.

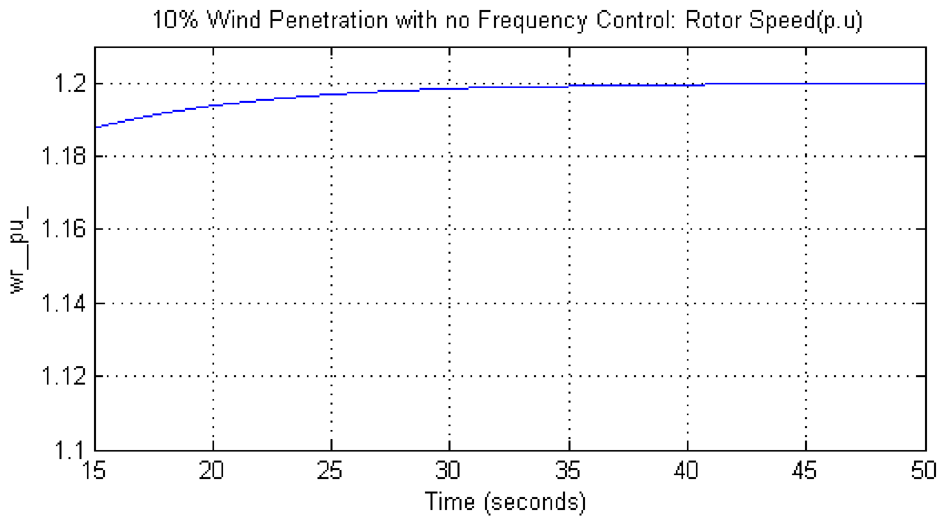


Figure 40 Wind turbine speed (pu), 10% Wind Energy Penetration No Frequency control

WIND TURBINE ELECTROMAGNETIC TORQUE

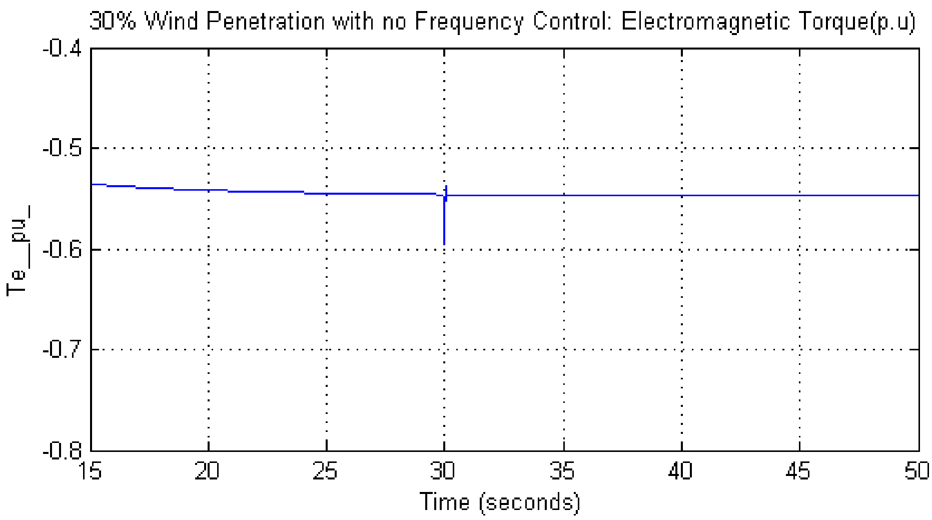


Figure 41 Wind turbine electromagnetic Torque, 10% Penetration No frequency Control

The Electromagnetic torque is related with both the power and the speed:

$$T = \frac{P}{\omega}$$

If power and speed are constant so it is the Electromagnetic Torque, as we see in figure 41.

4.1.2. DEFAULT VALUES OF INERTIA AND DROOP

In this new scenario we are setting the Inertia Control Constant value and the Droop Control value at default, H= 5.04 and Droop= 5%.

FREQUENCY RESPONSE

Area 1: Wind Turbine Area and Area 2: Synchronous Machine

With Frequency Control set at default values we can see an improvement on the ROCOF of the Area 1, figure 42, and also of the Area 2, figure 43.

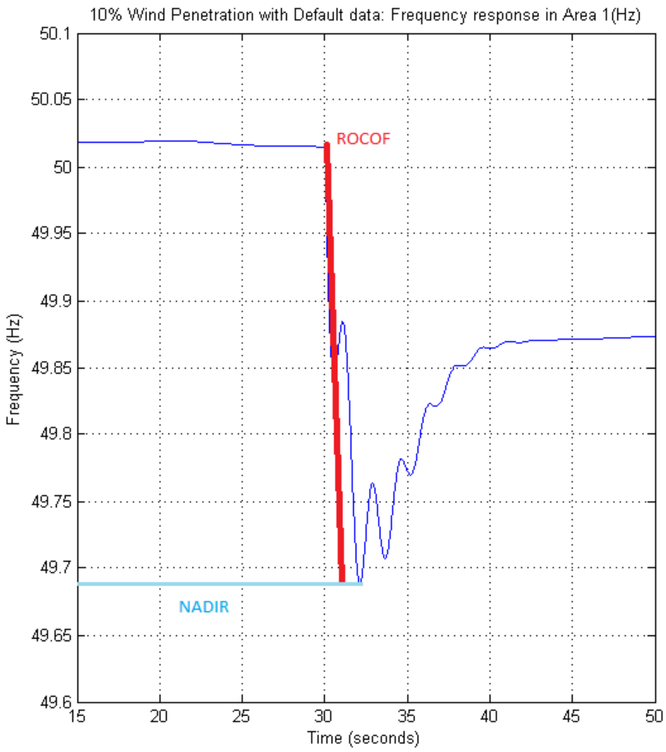


Figure 42 Frequency Response at Area 1, 10% Wind Energy Penetration Default Values

We can also see an improvement in the NADIR values. It increases a 0.09% with respect to the No Frequency Control scenario.

AREA 1		AREA 2	
% Wind Penetration	NADIR	% Wind Penetration	NADIR
10%	49,6884807	10%	49,7139706

Table 6 NADIR values of 10% Penetration and Frequency Control with Default values

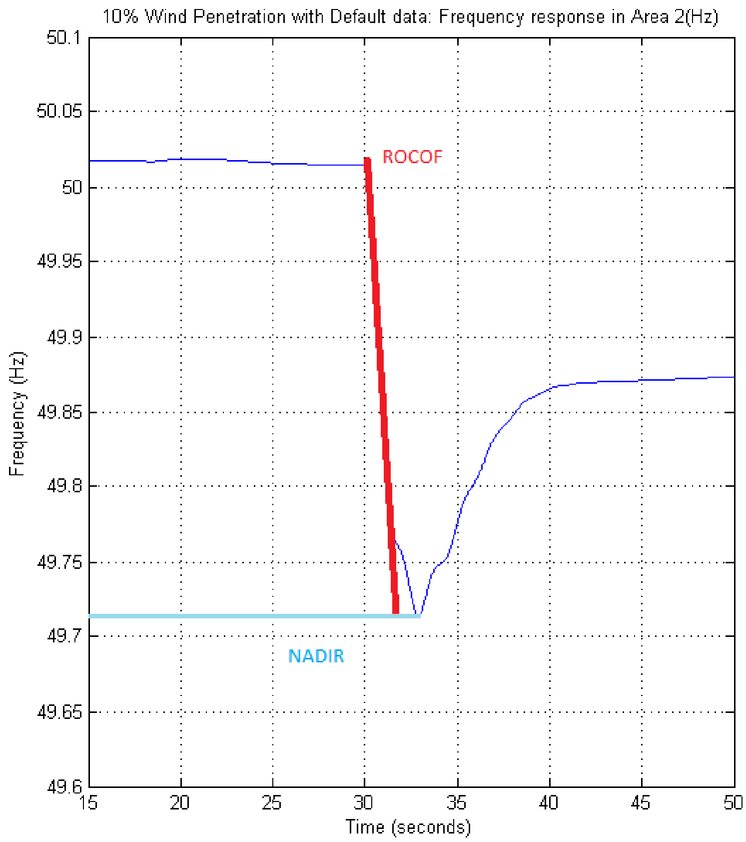


Figure 43 Frequency Response at Area 1, 10% Wind Energy Penetration Default Values

POWER GENERATED BY THE WIND TURBINE and SPEED OF THE WIND TURBINE

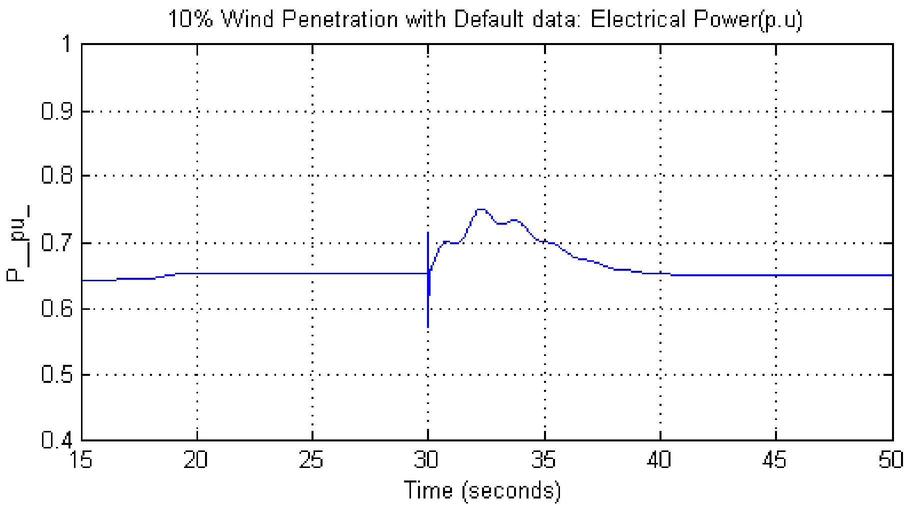


Figure 44 Power Generated by Wind turbine (pu), 10% Wind Energy Penetration Default Values

In this scenario we can see an increase in the Power output of the generator when the frequency starts to drop at 30 second mark.

The control when detects a significant frequency drop in the system orders the turbine to decelerate, figure 45.

As explained before, the kinetic energy stored in the rotating mass is injected into the grid as electric power, figure 44.

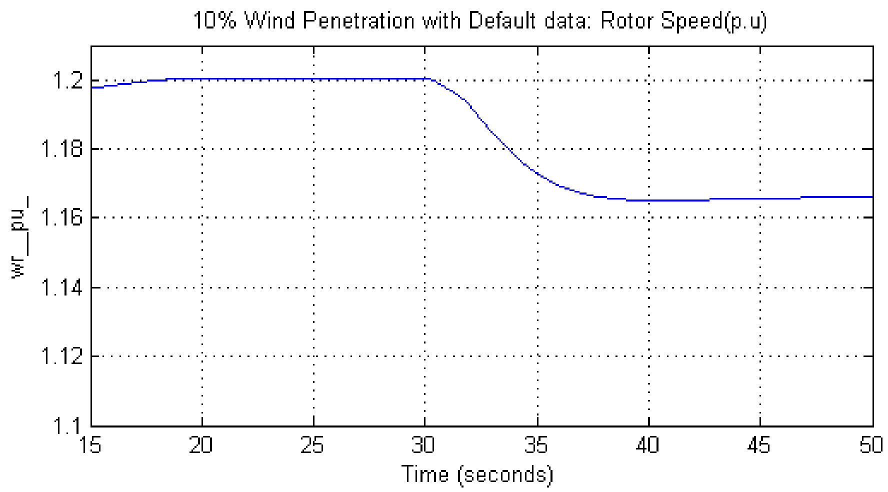


Figure 45 Wind turbine speed (pu), 10% Wind Energy Penetration Default Values

WIND TURBINE ELECTROMAGNETIC TORQUE

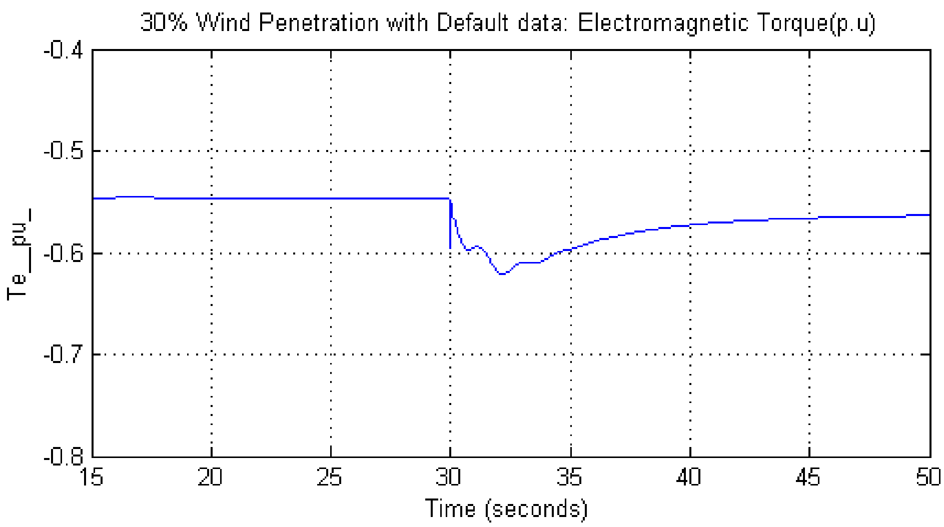


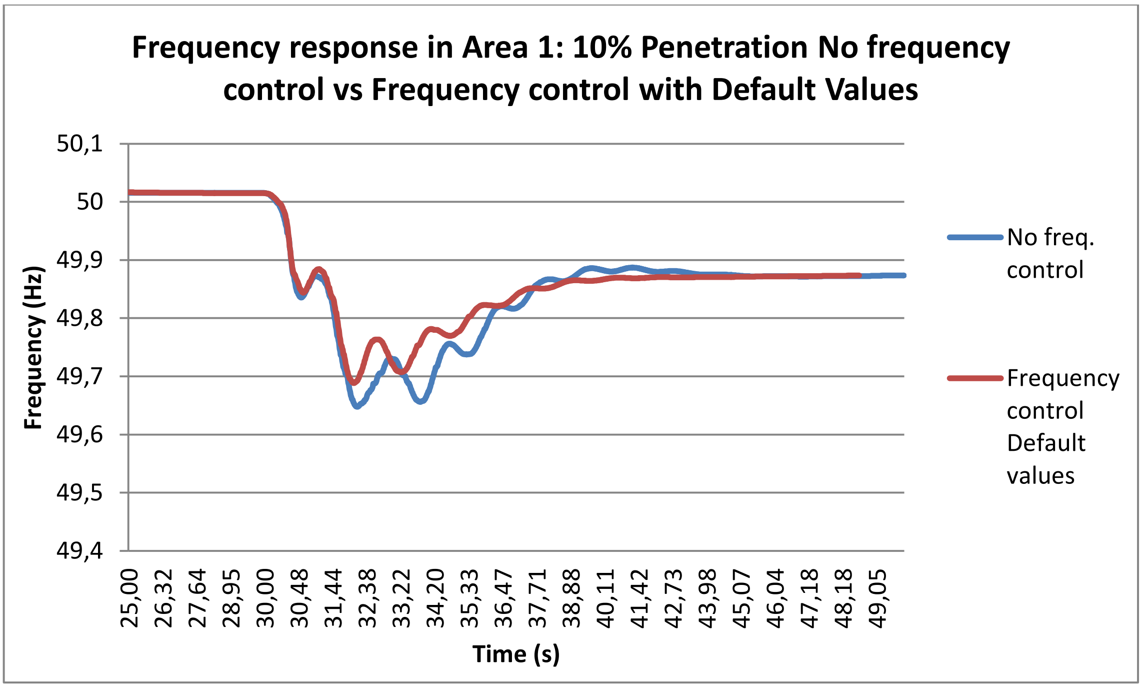
Figure 46 Wind Turbine Electromagnetic Torque, 10% Wind Energy Penetration Default Values

As we already know, electromagnetic torque is related with power and rotor speed. In this case both parameters are modified and therefore the electromagnetic torque.

4.1.3. COMPARISON OF NO FREQUENCY CONTROL VS FREQUENCY CONTROL WITH DEFAULT VALUES

FREQUENCY RESPONSE

Area 1: Wind Turbine Area and Area 2: Synchronous Machine



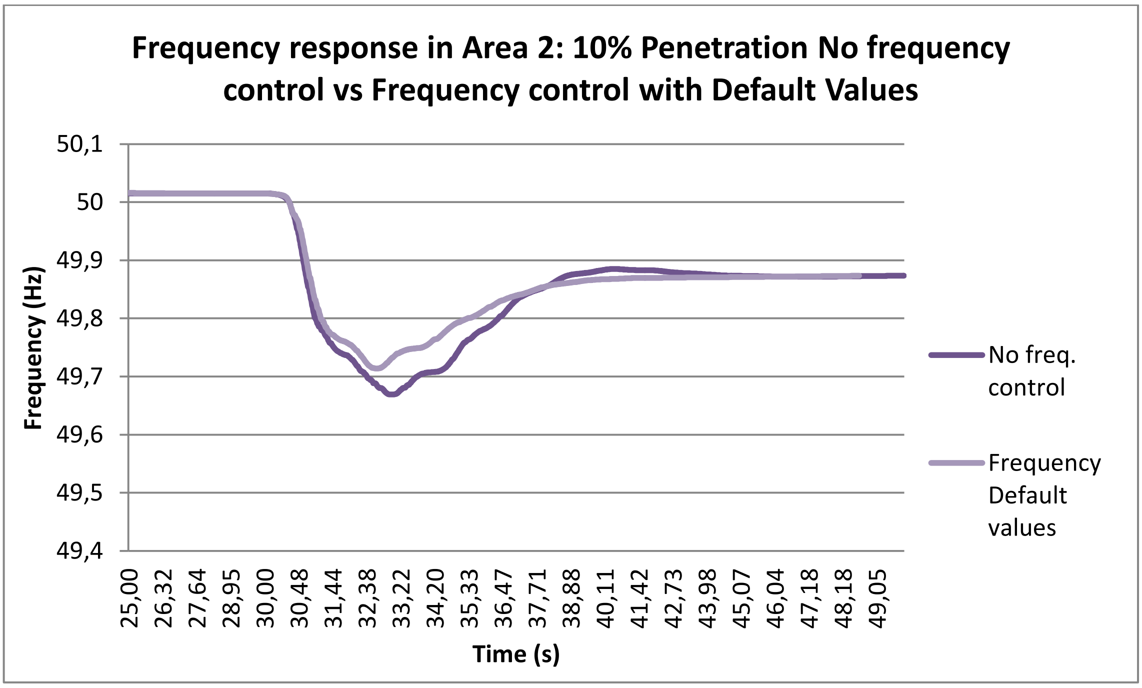


Figure 47 Frequency response in Area 1 and Area 2, 10% Penetration No frequency control vs Frequency control with Default Values

As expected with the Frequency control set at Default values we achieve a better Frequency Response in both areas. ROCOF decreases and NADIR increases due to the emulated inertia and the Droop Control. The inertia gives us a fast primary response, lowering the Rate of Change of Frequency and giving time to the Droop or slow primary control to increase the Power output leading to a decrease in the NADIR, minimum Frequency value achieved.

The oscillations we see in the Area 1 appear in all the scenarios simulated in this project. After studying the possibilities that may have led us to these oscillations we realized that the author of the simulation took as a reference the Kundur model.

The **kundur model** consists of 2 symmetrical areas linked together by two 230 kV lines of 220 km length. It was designed to study low-frequency electromechanical oscillations in large interconnected power systems.

Knowing that, we will proceed with the study taking into account that this simulation will have oscillations into the Area 1 due to the model the author took as reference.

POWER GENERATED BY THE WIND TURBINE

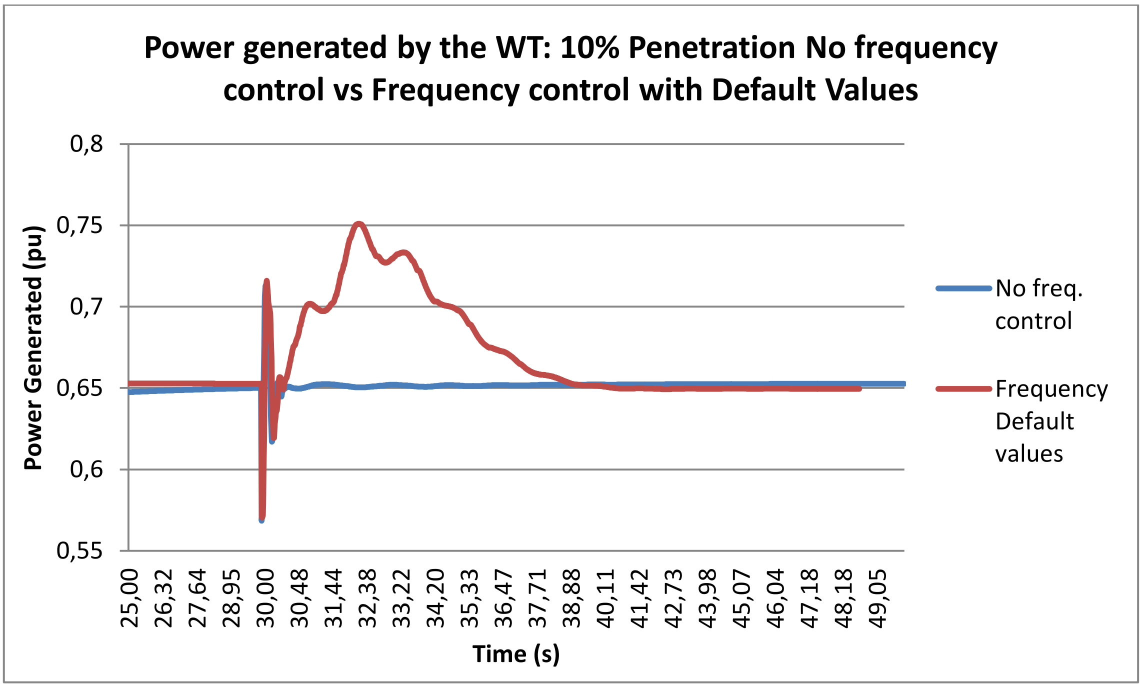


Figure 48 Power Generated by the Wind turbine, 10% Penetration No frequency control vs Frequency control with Default Values

Not having Frequency control means there is no emulated inertia and therefore the turbine cannot inject additional power. When there is a

Frequency Control available we are able to decelerate the machine and inject that kinetic energy stored in the rotating mass as electric power.

SPEED OF THE WIND TURBINE

It is important to notice, that the emulated inertia can only last a few seconds. We are decelerating the machine to take advantage of the energy of the rotating mass. If we decelerate the generator for a bigger period of time the machine will end up slowing down at a point it could be hard to recover or even worse, it can end up stopping completely. Both cases will be contributing to drop even more the frequency of the system.

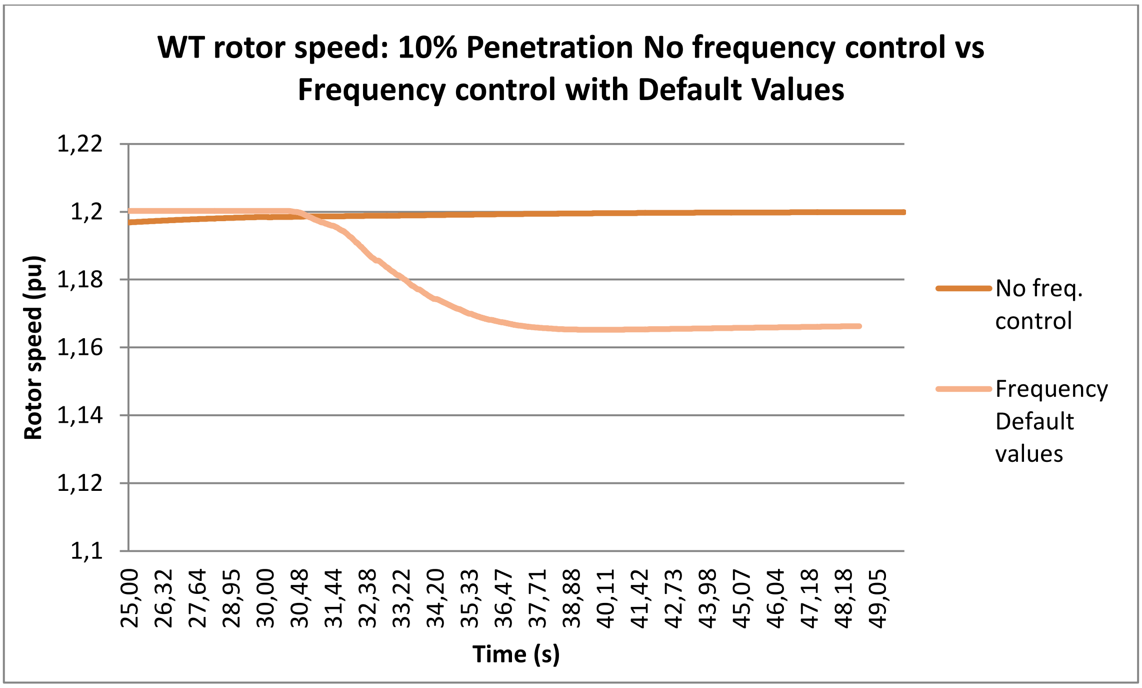


Figure 49 Wind turbine Rotor speed, 10% Penetration No frequency control vs Frequency control with Defaul Values

We can see in the Frequency control with Default values, that after the deceleration the power injected to the grid is lower than it was before the frequency drop. In this case it didn’t reach the critical points explained before.

WIND TURBINE ELECTROMAGNETIC TORQUE

The same happens with the electromagnetic torque, if there is Frequency Control that allow us to emulate inertia we can decelerate the machine when is needed, which means we are modifying the electromagnetic torque.

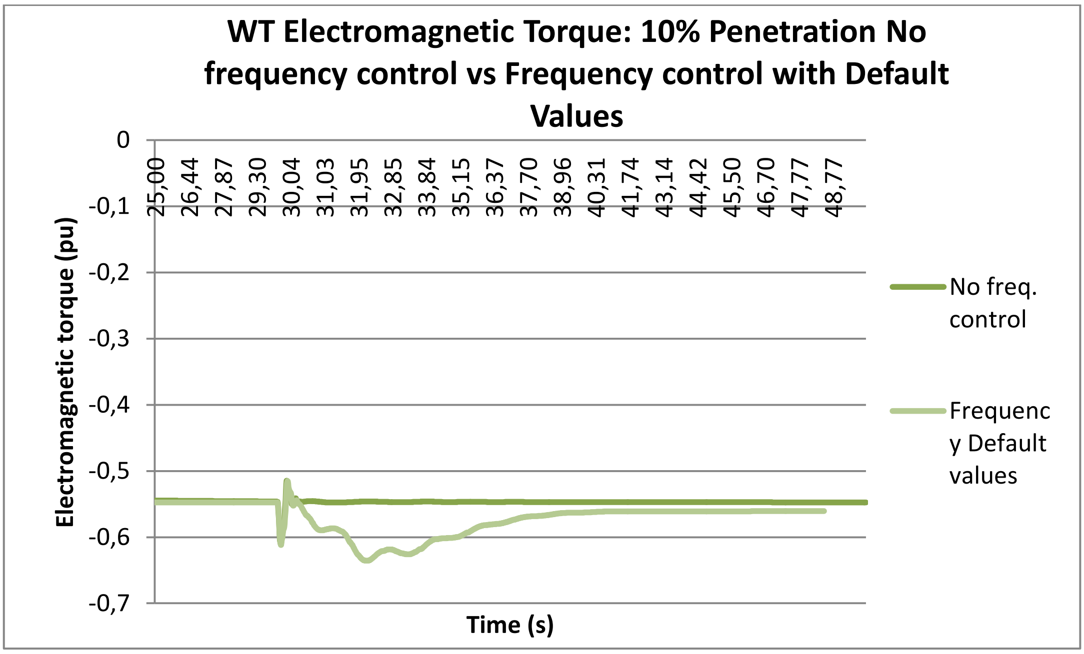


Figure 50 Wind Turbine Electromagnetic Torque, 10% Penetration No frequency control vs Frequency control with Defaul Values

4.2. CASE 2: COMPARISON OF 10% WIND ENERGY PENETRATION VS 30 % WIND ENERGY PENETRATION, DEFAULT WIND SPEED=12 m/s

We've seen how the system behaves in front of a frequency drop when the penetration of Wind Energy is a 10% of the total Generation, when there is Frequency control and when the Frequency Control is disabled.

The issue that is nowadays worrying experts is that renewable energy is gaining importance and the penetration of this new technologies is increasing. So it is important to also analyze the case of 30% Wind Energy Penetration and compare it with the case of lower Wind Energy Penetration explained previously.

4.2.1. COMPARISON OF NO FREQUENCY CONTROL OF 10% PENETRATION VS 30% PENETRATION

FREQUENCY RESPONSE

As expected, higher wind energy penetration with No Frequency Control available will lead to a decrease in the Frequency Response in both Area 1 and Area 2. This is because we are lowering the total stored inertia of the system.

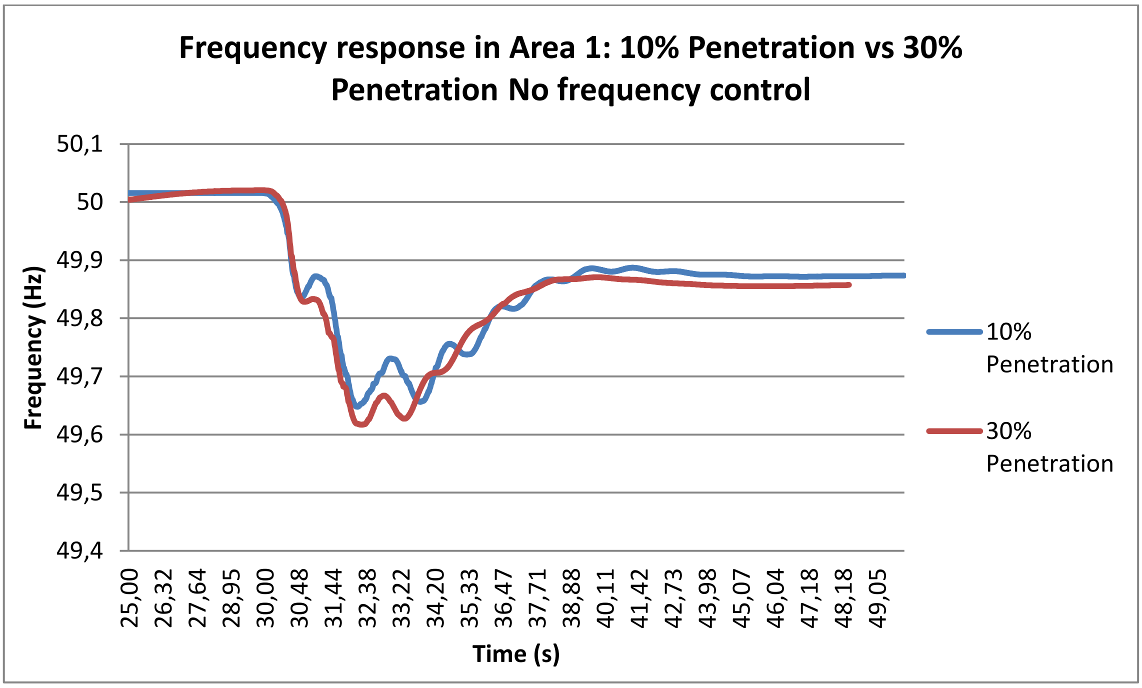


Figure 51 Frequency response in Area 1: 10% Penetration vs 30% Penetration No frequency control

ROCOF increases in the 30% Wind Energy Penetration case and NADIR values decrease, both are a clear example of the problem that high renewable energies penetration can cause if there is no Frequency Control available that can provide Frequency support to the grid.

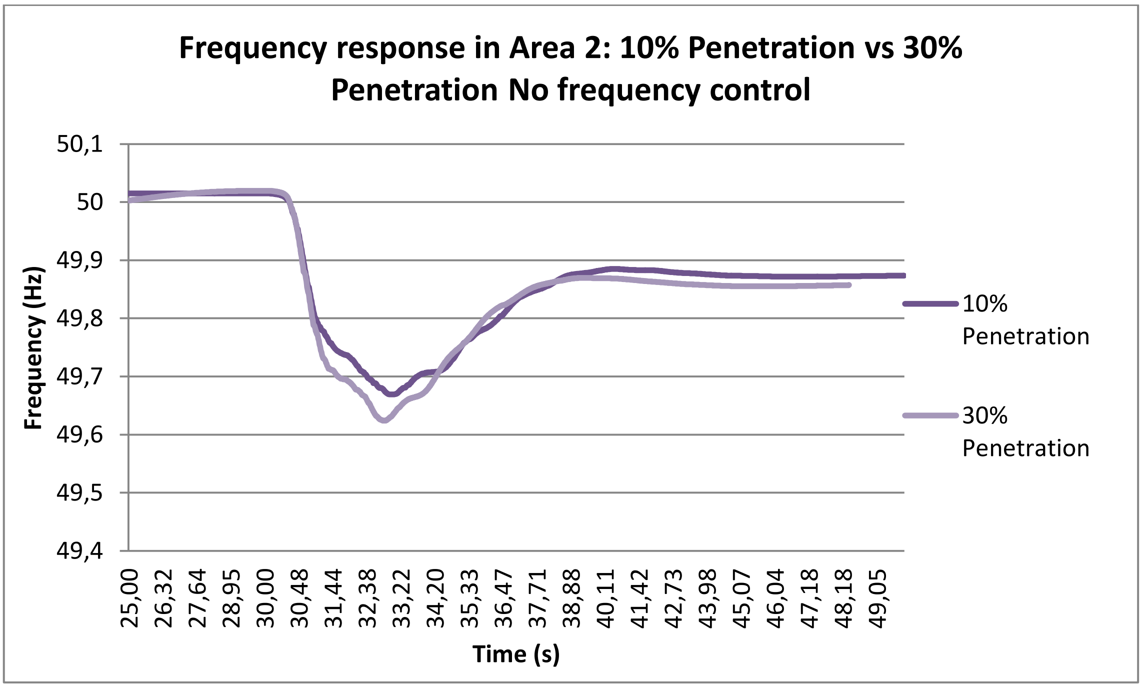


Figure 52 Frequency response in Area 2: 10% Penetration vs 30% Penetration No frequency control

POWER GENERATED BY THE WIND TURBINE

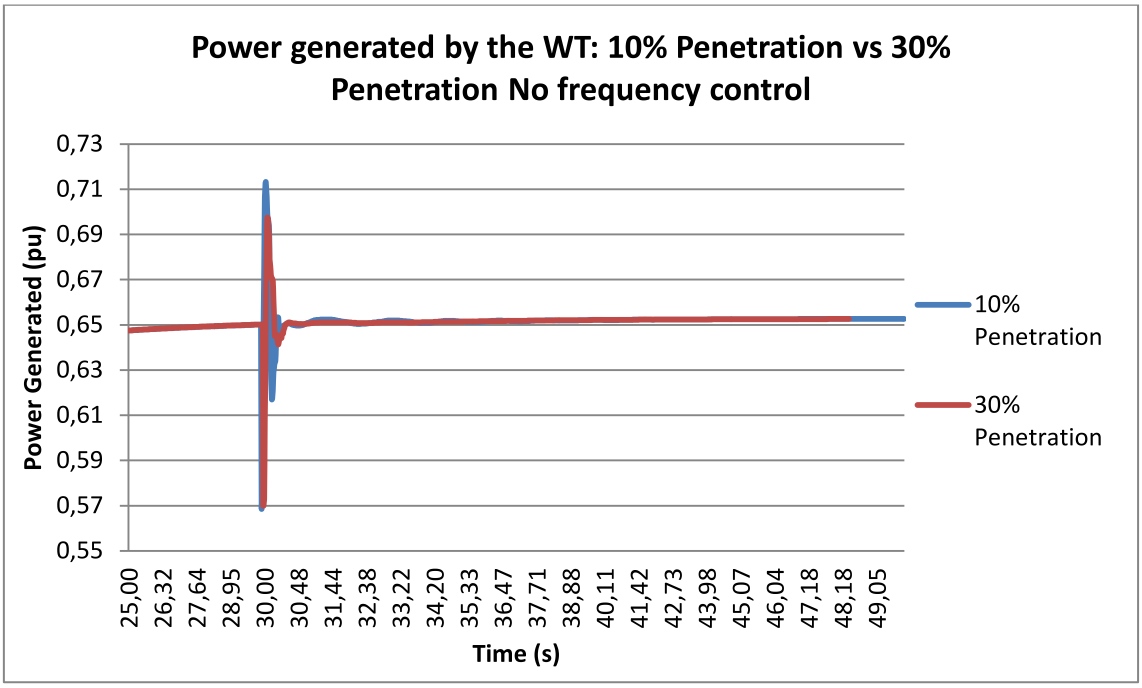


Figure 53 Power generated by the wind turbine: 10% Penetration vs 30% Penetration No frequency control

Although we see an oscillation in the 30 seconds mark, that could be due to the turbine detecting an unexpected event, no additional power is being injected to the grid as we can see at the rest of the period simulated.

SPEED OF THE WIND TURBINE

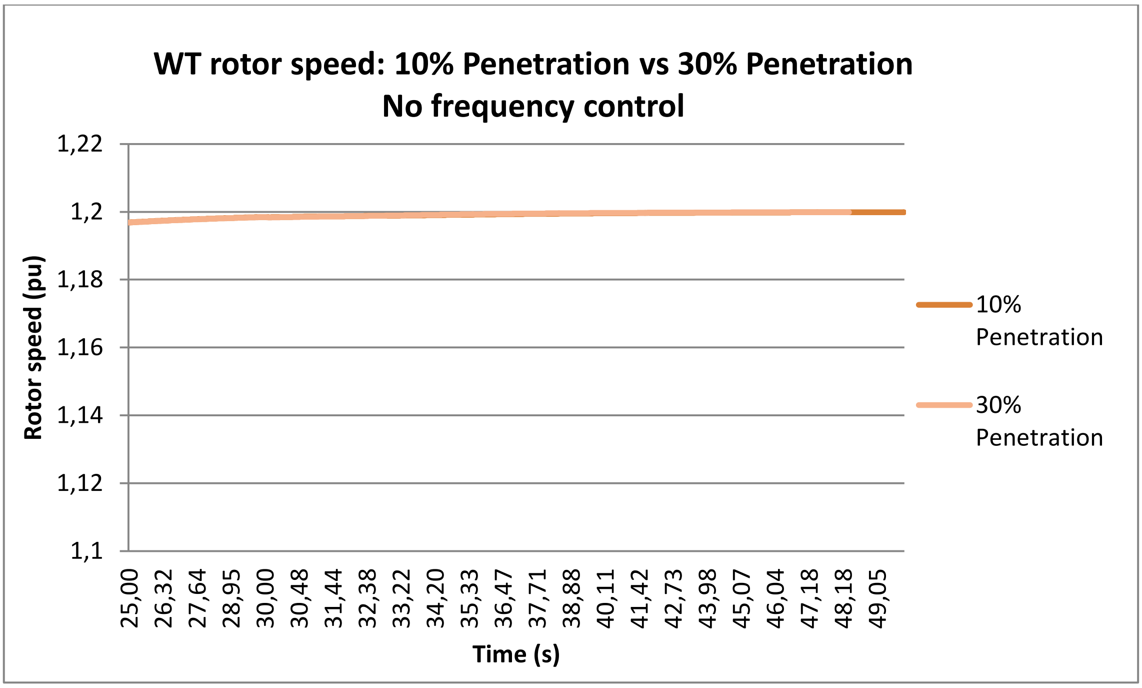


Figure 54 Wind Turbine rotor speed: 10% Penetration vs 30% Penetration No frequency control

Wind Turbine speed remains constant, there is no deceleration because there is no Frequency Control that can orders the machine to decelerate.

4.2.2. COMPARISON OF DEFAULT VALUES 10% PENETRATION VS 30% PENETRATION

FREQUENCY RESPONSE

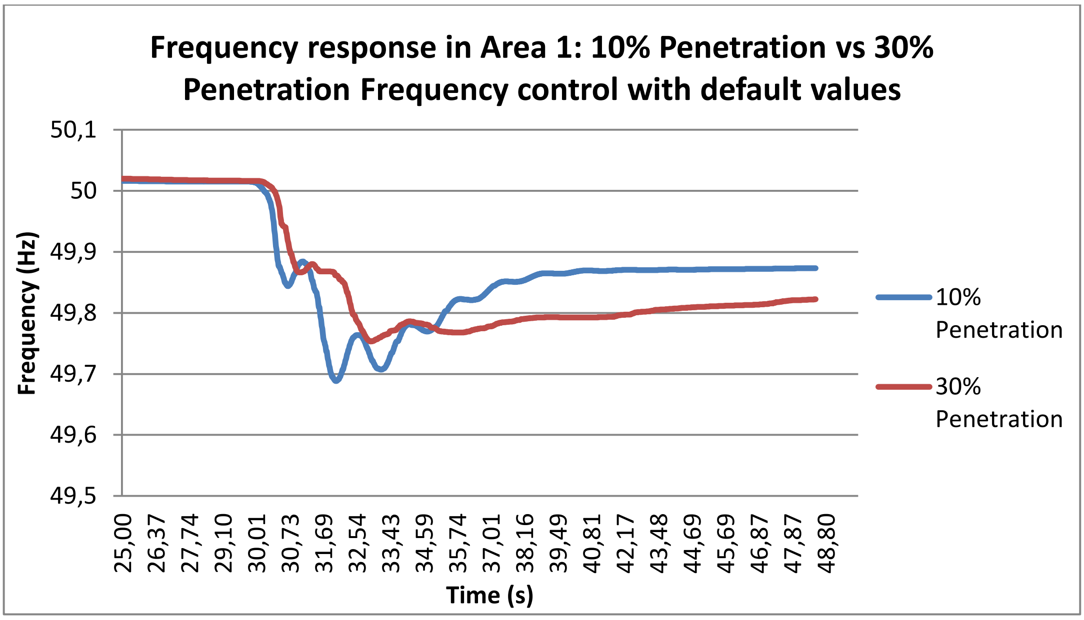


Figure 55 Frequency response in Area 1: 10% Penetration vs 30% Penetration Frequency control with default values

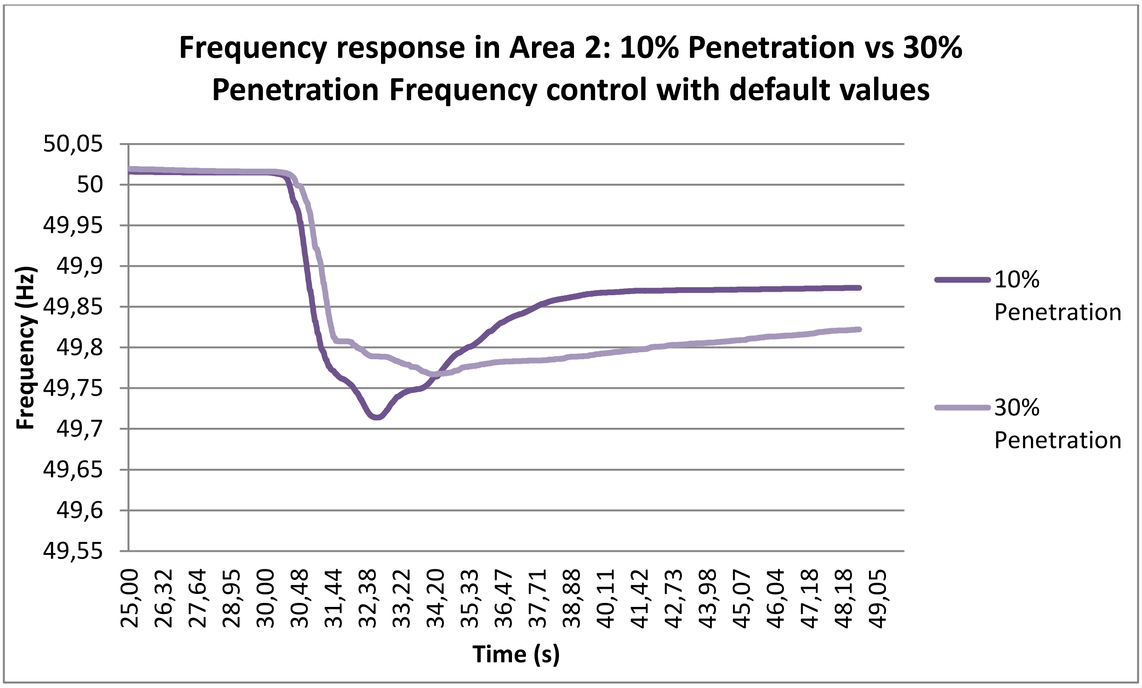


Figure 56 Frequency response in Area 2: 10% Penetration vs 30% Penetration Frequency control with default values

This new scenario, Frequency control with default values, shows us how for the 30% of Wind Energy Penetration the Frequency Response is much slower. This means, that the Rate of Change is slower giving time to the system to recover the frequency and avoiding lower NADIR values.

The frequency recovery is more stable than the one with the 10% Wind Energy Penetration.

POWER GENERATED BY THE WIND TURBINE

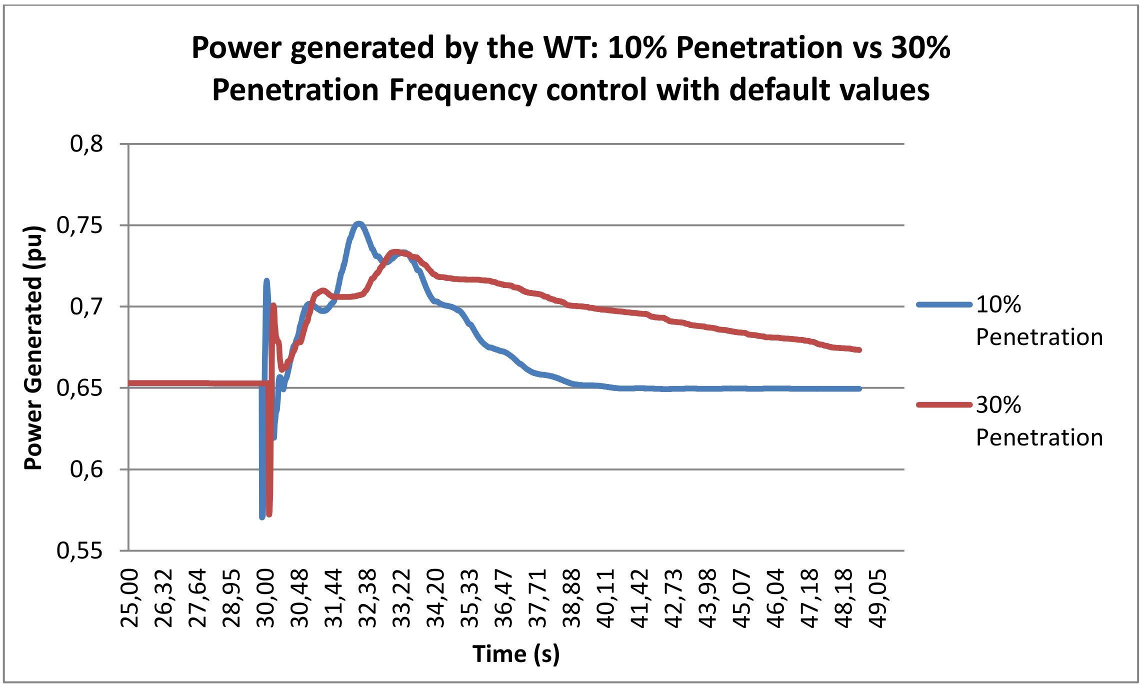


Figure 57 Power generated by the Wind Turbine: 10% Penetration vs 30% Penetration Frequency control with default values

Here we see more clearly, of the 30% case is giving a more stable response. The power is being injected gradually, we keep responding during a longer period of time.

SPEED OF THE WIND TURBINE

Rotor speed is related directly with power. If we inject power gradually means we are decelerating the machine also gradually.

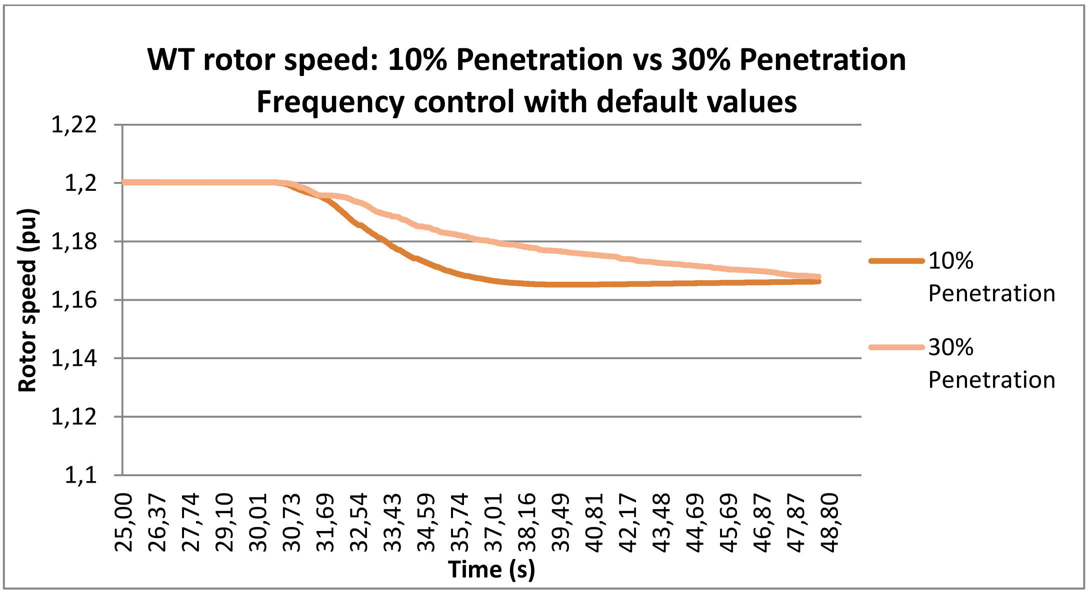


Figure 58 Wind Turbine rotor speed: 10% Penetration vs 30% Penetration Frequency control with default values

4.3. CASE 3: NADIR OF ALL WIND ENERGY PENETRATIONS, DEFAULT WIND SPEED=12 m/s

As said previously we simulated more than 60 cases for this project. To summarize the influence of the percentage of wind energy penetration into the systems frequency response we are going to study the NADIR for a scenario with No frequency control and for a scenario with Frequency Control Default.

4.3.1. NO FREQUENCY RESPONSE ALL PENETRATIONS:

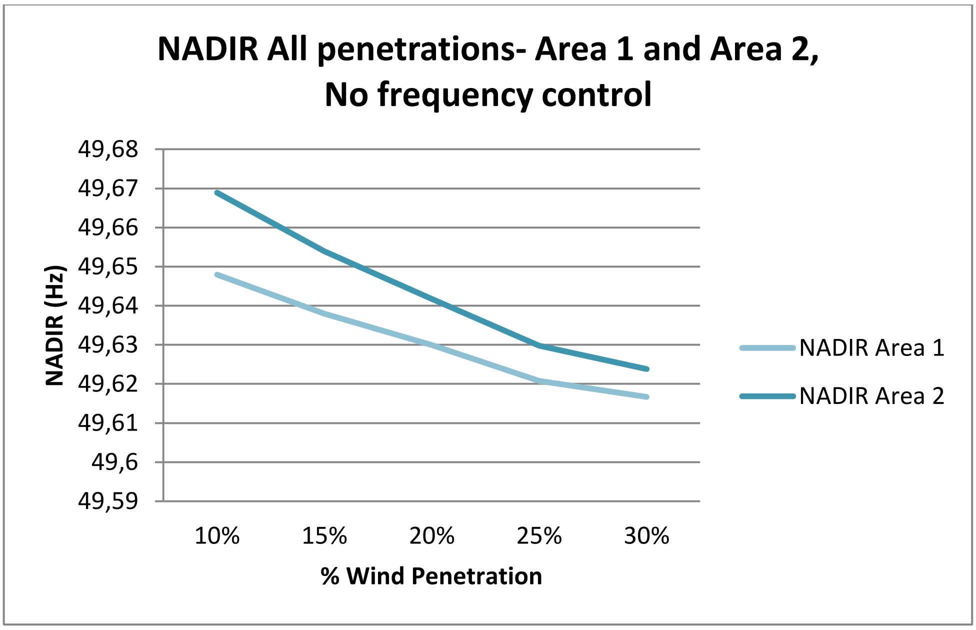


Figure 59 NADIR All Penetrations- Area 1 and Area 2, No frequency control

The NADIR tends to decrease while the penetration of Wind Energy increases. This is because Wind Turbines are partially decoupled and are not able to give frequency response if the controller is disabled.

As seen previously, the NADIR on the Area 2 is higher due to the frequency response of the Synchronous Machines.

4.3.2. FREQUENCY RESPONSE WITH DEFAULT VALUES ALL PENETRATIONS:

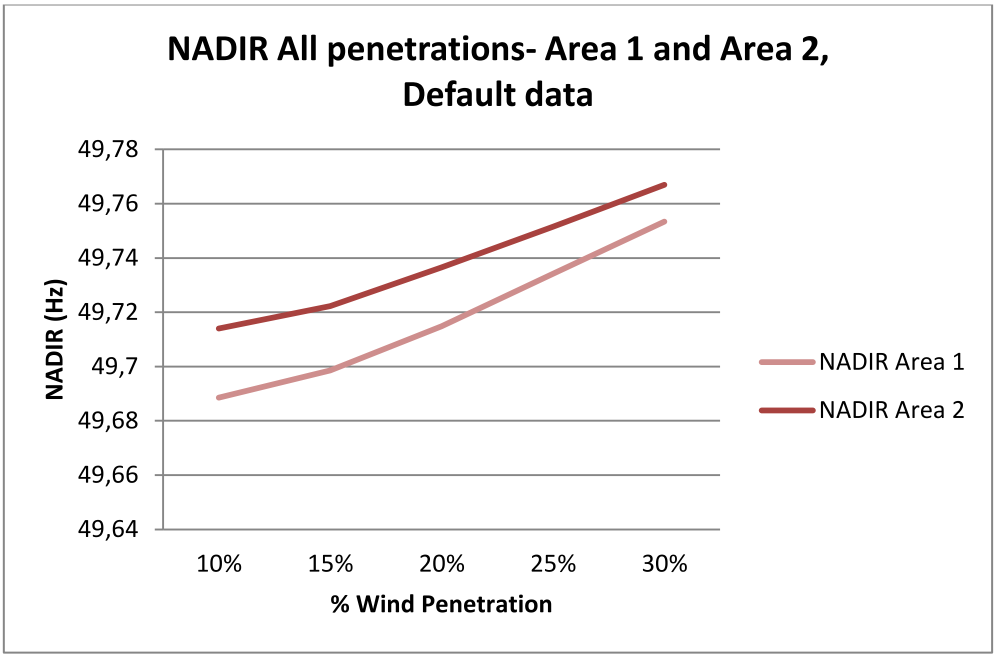


Figure 60 NADIR All Penetrations - Area 1 and Area 2, Frequency Control with Default data

In this case, we see all the opposite. The NADIR is higher when the penetration of Wind Energy is higher.

At first we thought it was because we were not working at the optimal point and we were using the overspeeding technique. The overspeeding technique consists in working at a higher rotor speed out of the optimal operation point, when there is a drop at the frequency of the system we can decelerate the machine and reach that optimum operational point, allowing us to emulate inertia and increase the power output all at once.

Nevertheless, after taking a look at the results of the different scenarios and comparing it with the turbine power characteristics we realized that it was because of the inertia emulation.

We will explain more deeply how the power characteristics work. See Case 6 where we modify the working wind speed.

4.4. CASE 4: 30% WIND ENERGY PENETRATION, INFLUENCE OF THE FREQUENCY CONTROL. DEFAULT WIND SPEED=12 m/s

By now we only studied two possibilities related to the frequency control parameters: No frequency control, values of inertia and Droop controls set to zero, and Frequency control with Default Values, H=5.04 and Droop=5%.

To see how the inertia control and the Droop control really influence the frequency response of the system we are going to study a scenario with default wind speed 12 m/s, 30% Wind Energy Penetration and different values for the inertia control constant and Droop control.

4.4.1. INERTIA CONTROL VALUES

The inertia control values will be changed to: **H= 0; H= 2; H=4; H= 6 and H= 10.** The droop control will be set at the default value of 5%, this way only the inertia will influence the frequency response.

FREQUENCY RESPONSE

Area 1: Wind Turbine Area and Area 2: Synchronous Machine

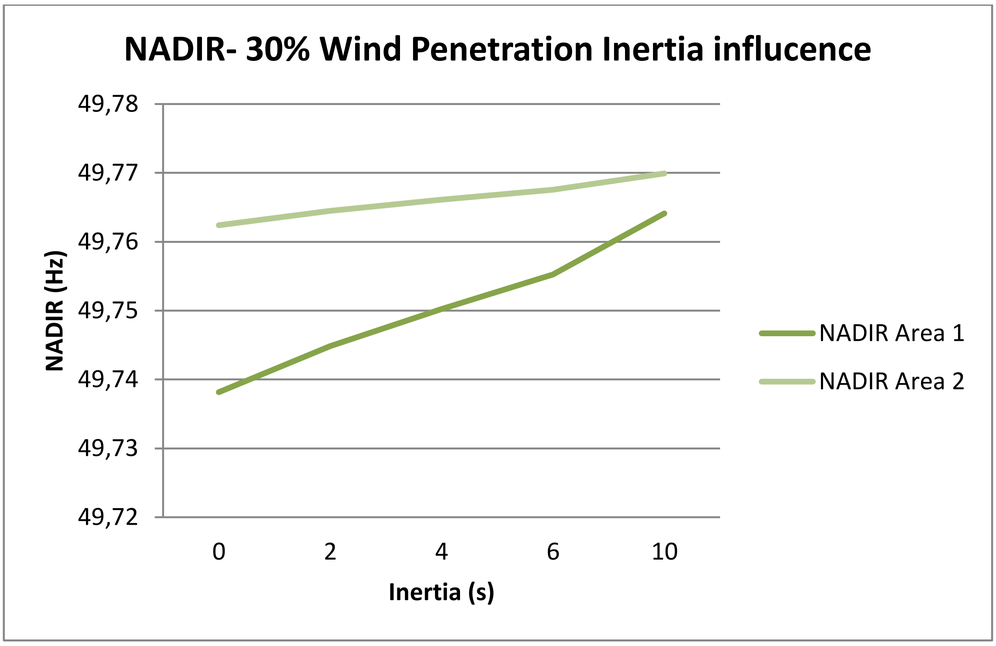


Figure 61 NADIR- 30% Wind Penetration Inertia influcence

Taking only into account the results for the NADIR the best Frequency Response will be the scenario in which the inertia control constant is 10. Focusing on the figure 61, H equal to 10 is the scenario where we obtain a higher minimum frequency value. It is certainly important to have the highest possible NADIR, because it would mean our frequency response, inertia and Droop, were able to avoid the frequency of the system to drop to lower values.

But in this case, it is crucial to also analyze the other graphs of frequency response, power injected and rotor speed. And see if this scenario is still the best option.

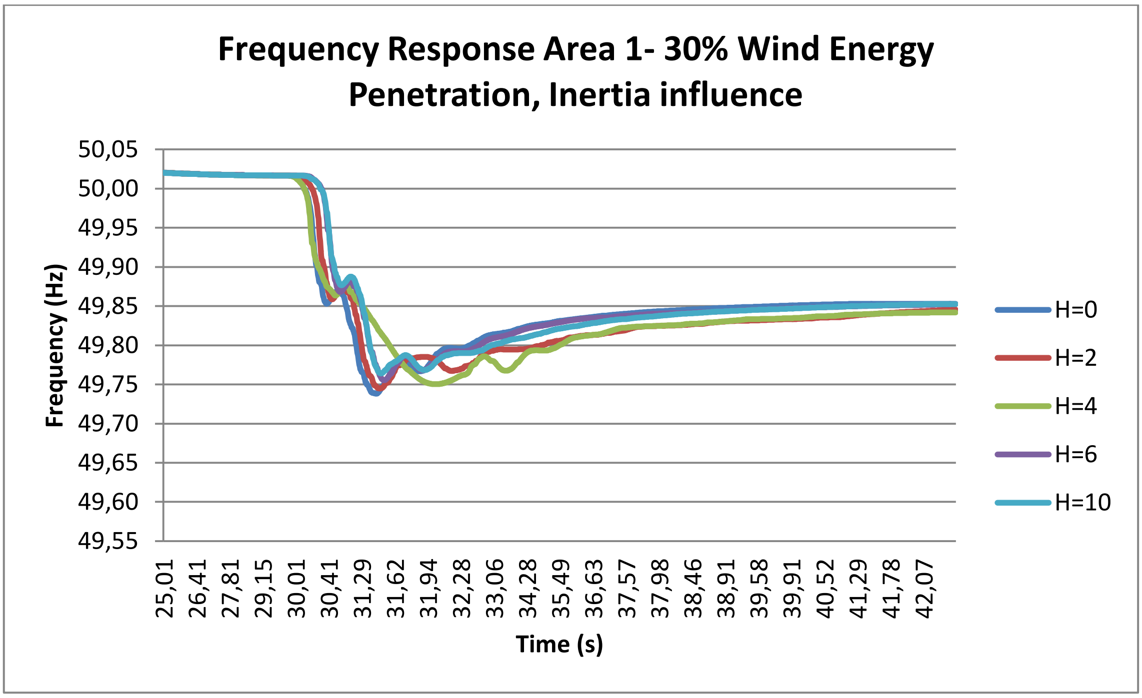


Figure 62 Frequency Response Area 1- 30% Wind Energy Penetration, Inertia influence

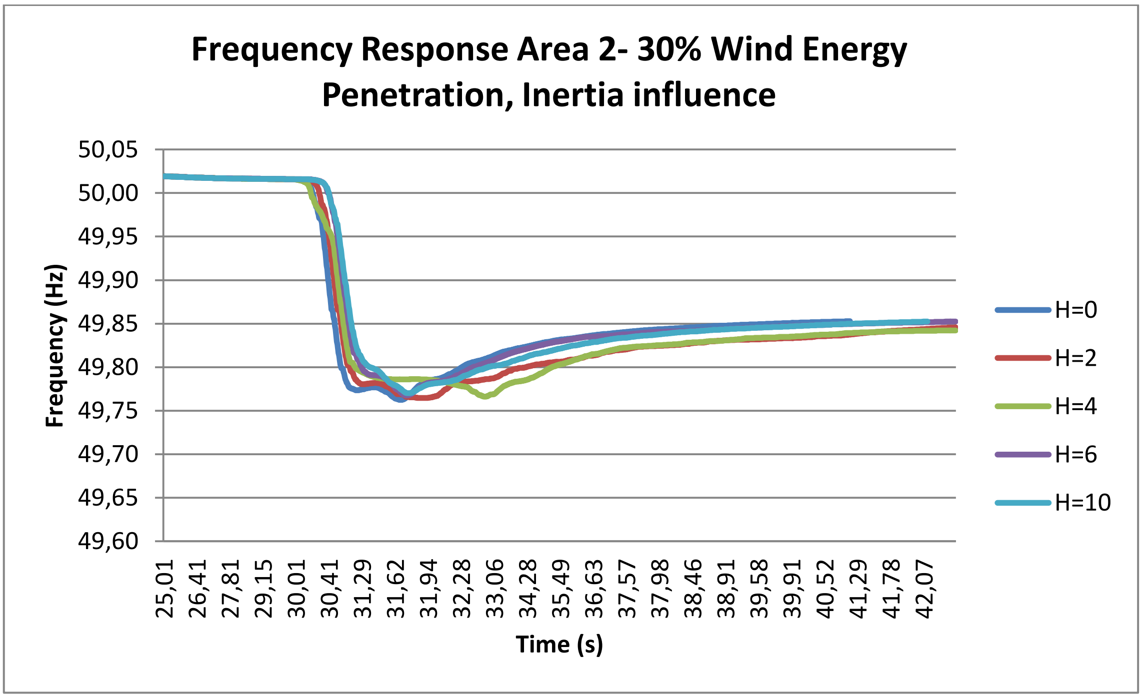


Figure 63 Frequency Response Area 2- 30% Wind Energy Penetration, Inertia influence

In the two Frequency Response figures, we can see not only the NADIR but also the ROCOF and the frequency recovery of the slow primary response and secondary response.

The scenario with constant inertia control of 4 has the lowest Rate of Change of Frequency. It takes 2 seconds to achieve NADIR, while the rest of the scenarios achieve their lower frequency values faster.

POWER GENERATED BY THE WIND TURBINE

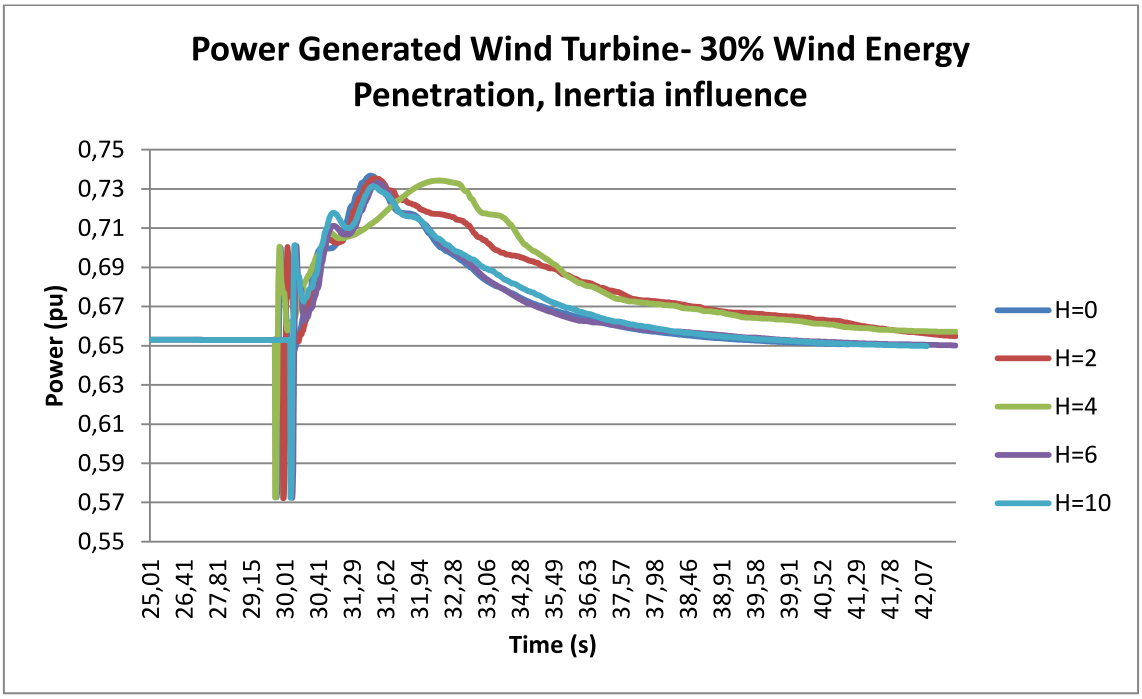


Figure 64 Power Generated Wind Turbine- 30% Wind Energy Penetration, Inertia influence

SPEED OF THE WIND TURBINE

If we take a look both at the speed of the rotor and at the power generated by the turbine we will see how the cases H=6 and H=10 are the ones that are more unstable.

They drop very quickly after only two seconds of simulation, while other scenarios can provide power during a longer period of time, reaching at the end the same power and rotor speed state.

This is because the inertia constant of the turbine is 5.04 and we are asking for an inertial response of 6 and 10 respectively. So the turbine forces itself to provide the maximum power possible and we end up with a more unstable and shorter frequency response.

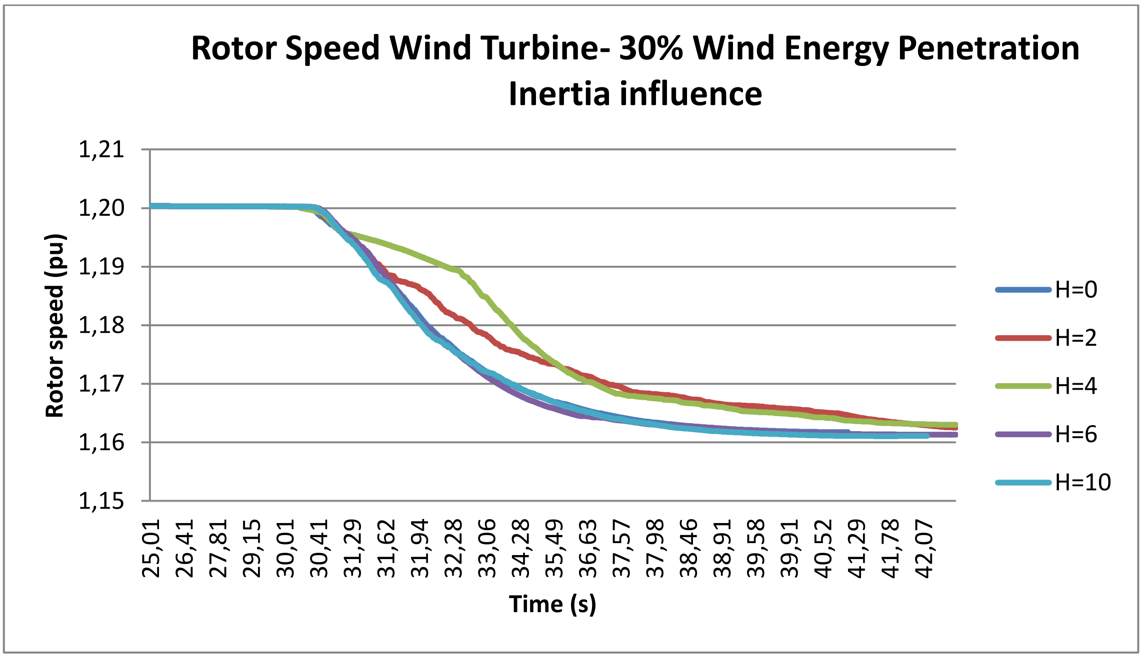


Figure 65 Rotor Speed Wind Turbine- 30% Wind Energy Penetration

4.4.2. DROOP CONTROL VALUES

The Droop control values will be changed to: **1%, 2%, 6% and 10%**. The inertia constant will be set at the default value of 5.04, this way only the Droop will influence the frequency response.

FREQUENCY RESPONSE

Area 1: Wind Turbine Area and Area 2: Synchronous Machine

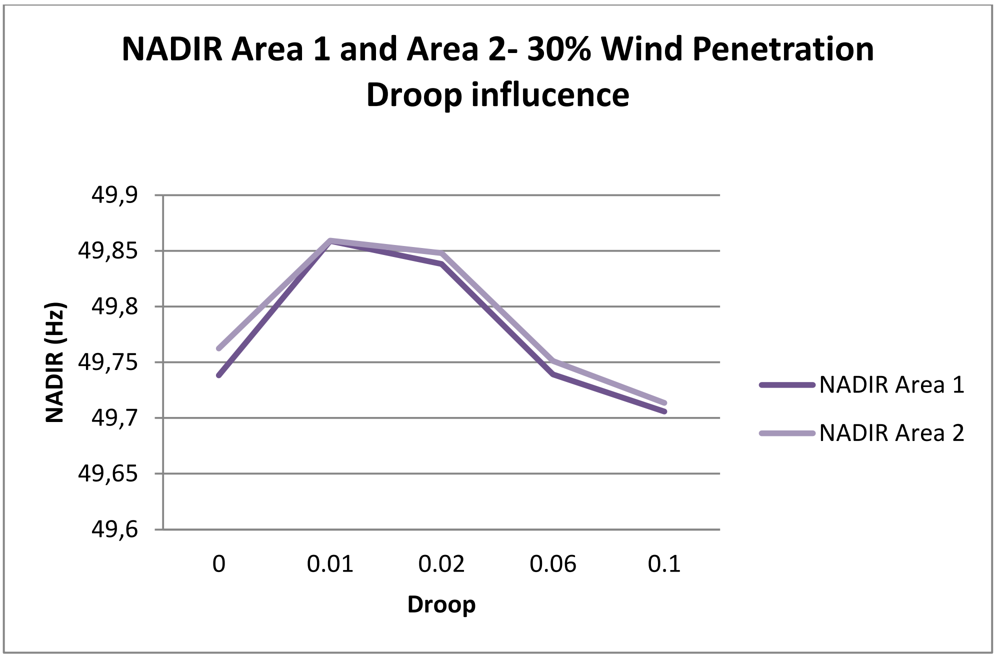


Figure 66 NADIR Area 1 and Area 2- 30% Wind Penetration Droop influcence

In this case and excluding the zero value which means we don't have Droop Control, it seems the most favorable values for a better frequency response are the lower Droop values.

As explained in the theoretical framework, a Droop control of for example 5% means that a 5% change in frequency will result in a 100% change in power output.

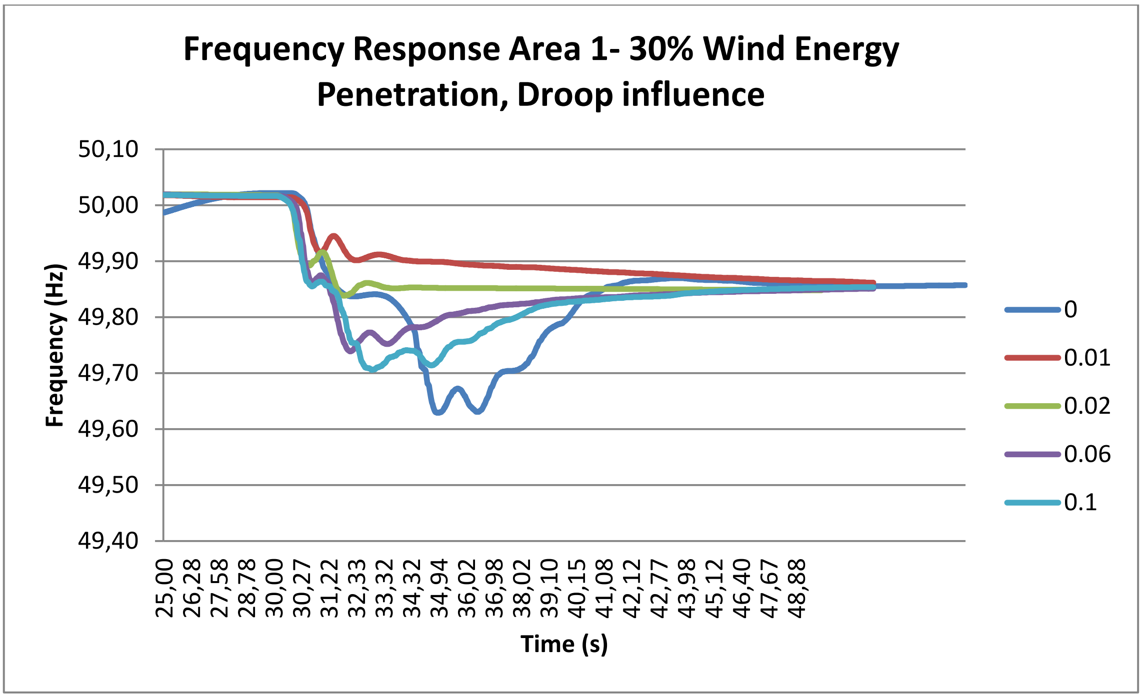


Figure 67 Frequency Response Area 1- 30% Wind Energy Penetration, Droop influence

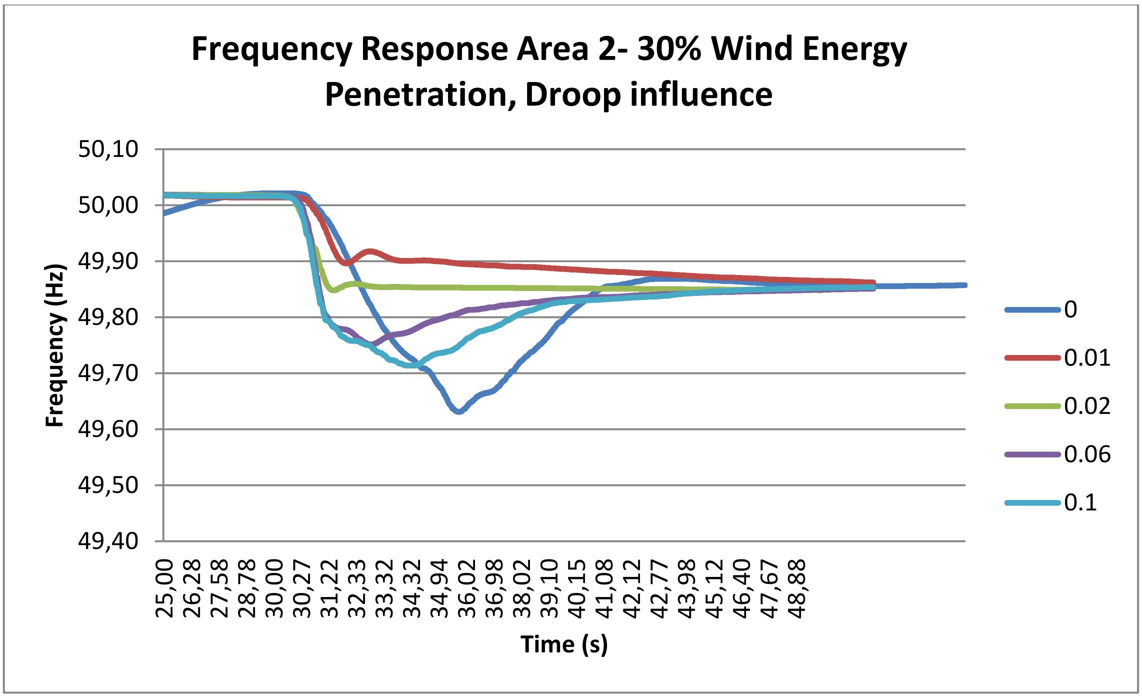


Figure 68 Frequency Response Area 2- 30% Wind Energy Penetration, Droop influence

The frequency response of the lower values for the Droop control also seem to be the better option. Not only was the NADIR higher, now we see how also the ROCOF has a lower value.

POWER GENERATED BY THE WIND TURBINE

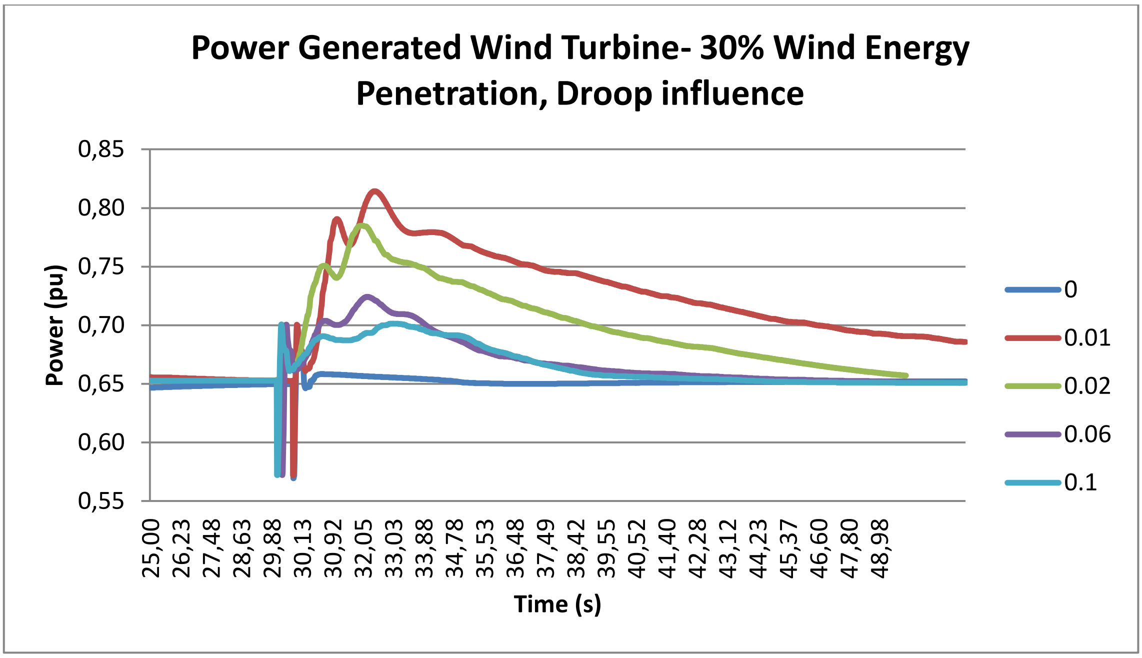


Figure 69 Power Generated Wind Turbine- 30% Wind Energy Penetration, Droop influence

SPEED OF THE WIND TURBINE

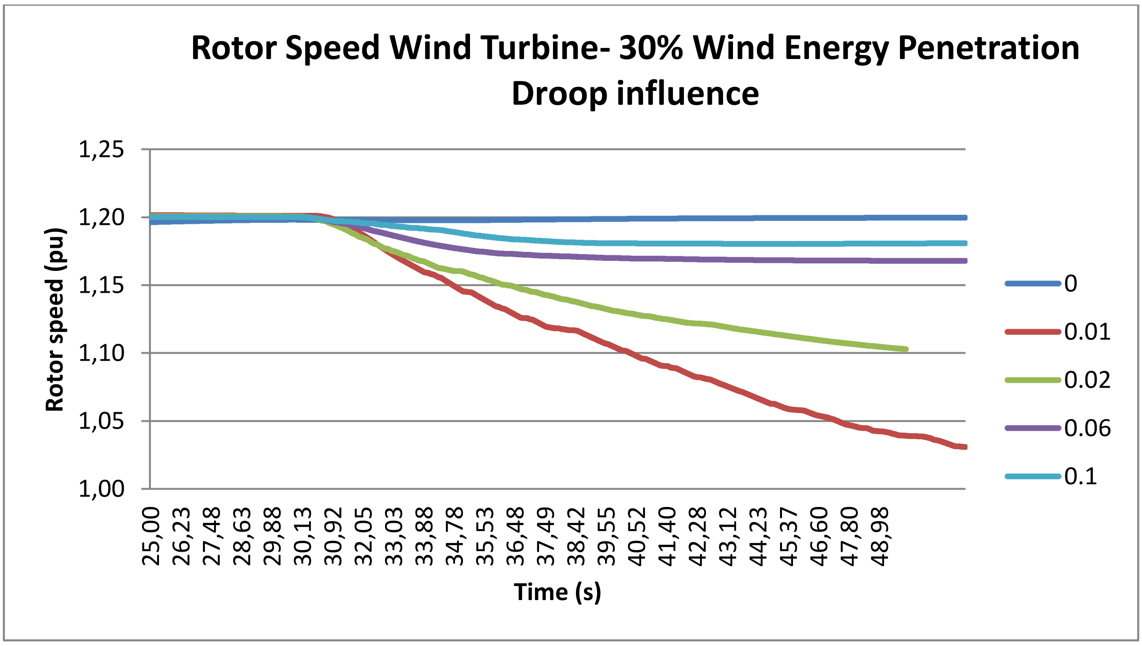


Figure 70 Rotor Speed Wind Turbine- 30% Wind Energy Penetration

The power generated by the turbine seem to be more stable for lower Droop control values, although the rotor speed decreases much more in this two cases.

4.5. CASE 5: NADIR OF ALL WIND ENERGY PENETRATIONS, FREQUENCY CONTROL PARAMETERS INFLUENCE. DEFAULT WIND SPEED=12 m/s

In order to see if the influence of both parameters, inertia control constant and Droop control, is the same for the rest of Wind Energy Penetrations we decided to analyze the NADIR:

4.5.1. INERTIA CONTROL VALUES

FREQUENCY RESPONSE

Area 1: Wind Turbine Area and Area 2: Synchronous Machine

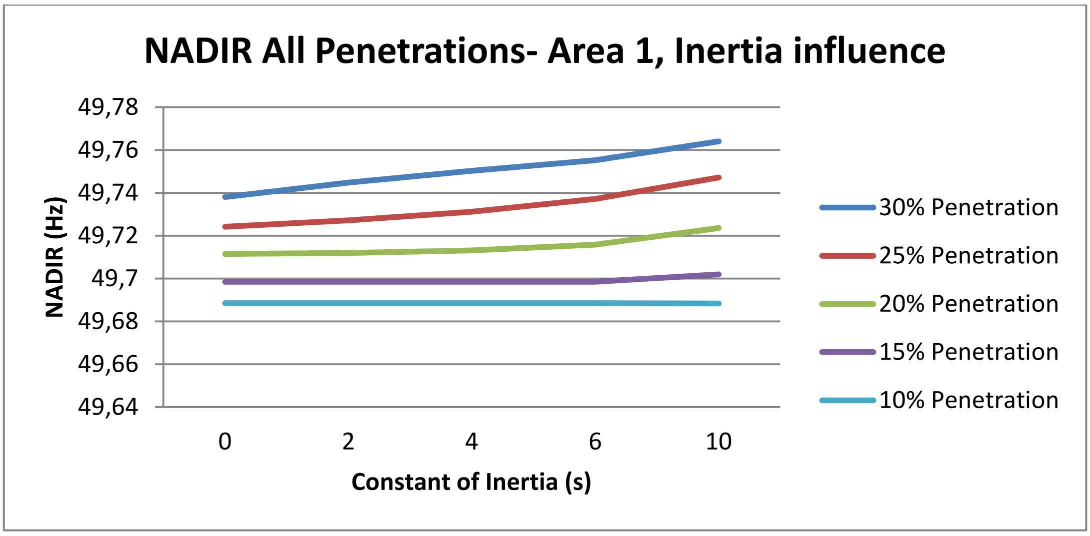


Figure 71 NADIR All Penetrations- Area 1, Inertia influence

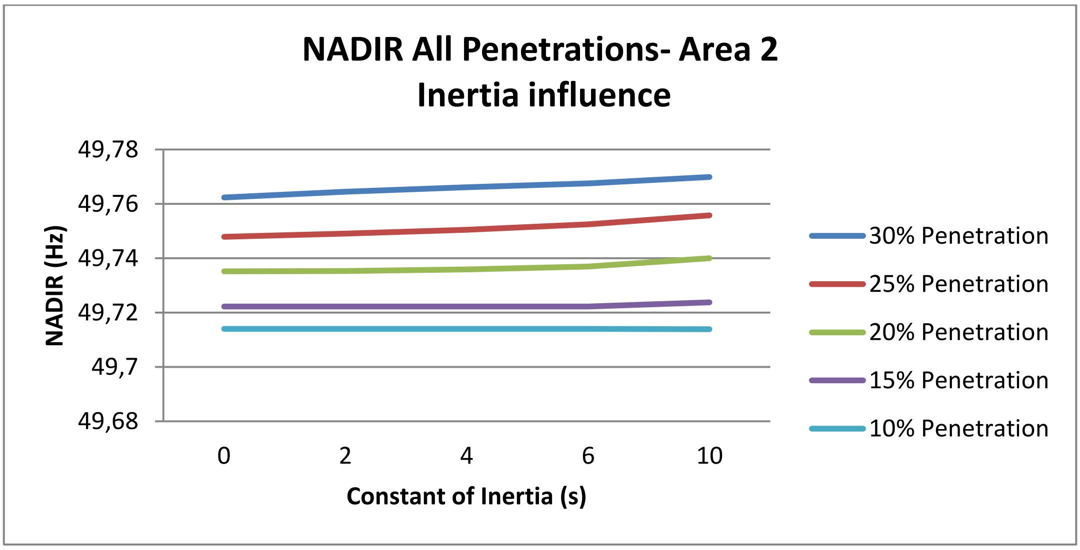


Figure 72 NADIR All Penetrations- Area 2, Inertia influence

4.5.2. DROOP CONTROL VALUES

FREQUENCY RESPONSE

Area 1: Wind Turbine Area and Area 2: Synchronous Machine

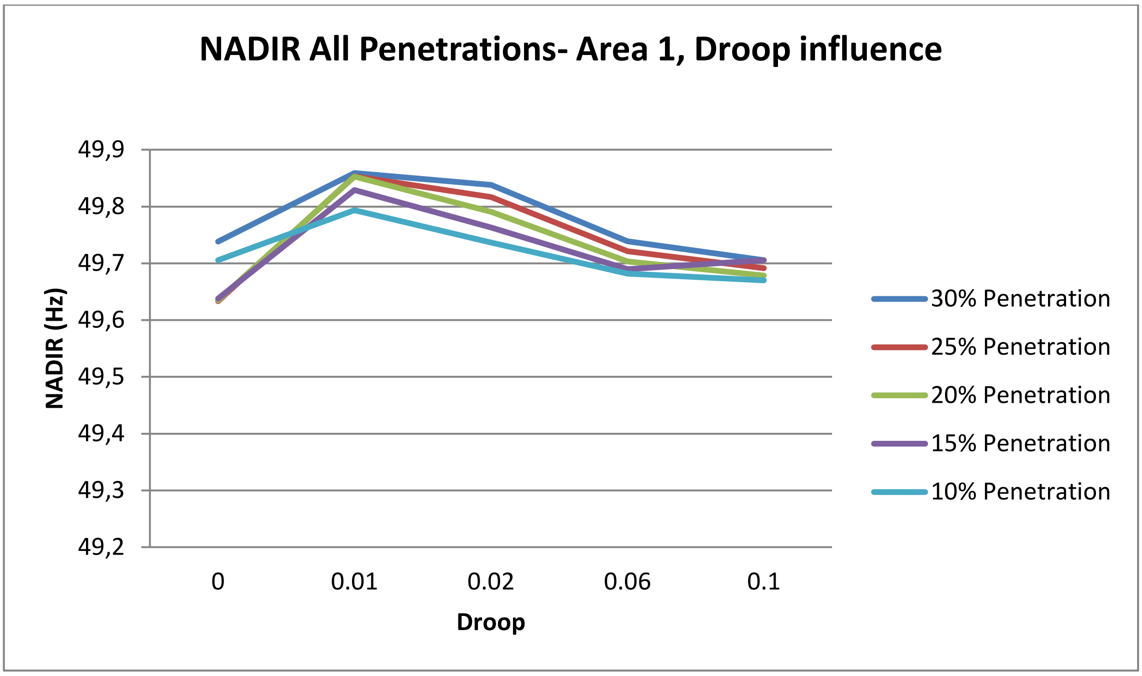


Figure 73 NADIR All Penetrations- Area 1, Droop influence

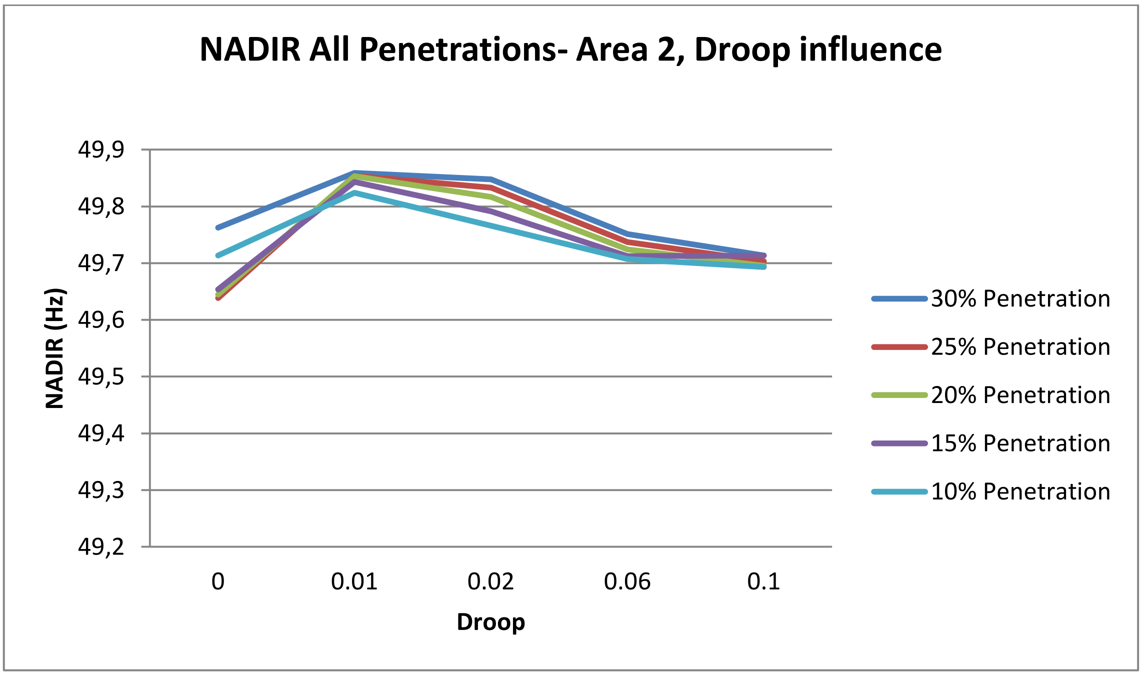


Figure 74 NADIR All Penetrations- Area 2, Droop influence

It is proved that the influence of both parameters has the same effect in all the Wind Energy Penetration Studied.

4.6. CASE 6: INFLUENCE OF THE WIND SPEED

In the theoretical framework we mentioned the wind speed influence in the Frequency Response of Wind Turbine.

Case 6 consists in varying the wind speed input of the Wind Power Plant to analyze the influence of this parameter on the results. We chose for this case to work with Default Values of Constant of Inertia and Droop Control and a Wind Penetration of 10%.

We are going to study 3 different wind speeds: 10 m/s, 15 m/s and 17 m/s.

To balance the demand with the generation we need to change the parameters related to the Power generated by the synchronous machines and the number of wind turbines. We decided to change only the Power generated by each turbine:

Wind speed of 10 m/s:

N=160; Pref2=0.59; Pref3=0.54; Pref4=0.54

Wind speed of 15 m/s:

N=160; Pref2=0.525; Pref3=0.50; Pref4=0.50

Wind speed of 17 m/s:

N=160; Pref2=0.515; Pref3=0.50; Pref4=0.50

4.6.1. VELOCIDAD 10 m/s

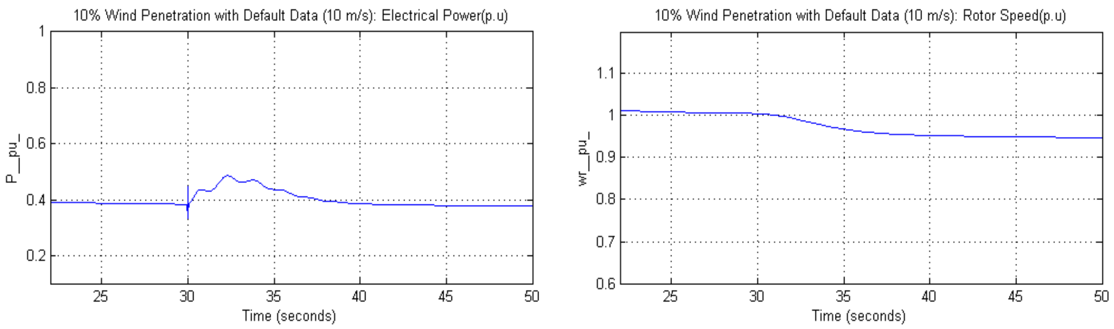


Figure 75 Power and Speed of the Wind Turbine with 10 m/s wind speed

In this first scenario we chose to work under the default wind speed of 12 m/s. The NADIR value for the Frequency Response Area 1 is 49,6740 Hz being the Default case value of 49,68 Hz; which means we are lowering our Frequency Response in terms of emulated inertia response.

Taking a look at the electrical power generated by the turbine we see how the values of the generation are much lower than the ones we had for default wind speed 12 m/s that were between 0.6 and 0.7 (pu).

The same happens for the rotor speed, we are now working at a rotor speed of 1 (pu), when at the default case we were most of the time working at 1.2 (pu).

Nevertheless, the behavior is similar, we start with a constant power output, the Frequency control detects a drop in the system frequency an demands extra generation. We decelerate the machine to emulate inertia and inject that extra power to the grid, and we end in a worse power operational point than before. This frequency response is only available during the emulated inertia, more or less 5 seconds; because the turbine is working at an operational point that there is no extra energy we can inject just the energy extracted from the emulated inertia. So the objective in this case is to not decelerate the machine up to a point that we cannot recover fast enough.

4.6.2. VELOCIDAD 15 m/s

In this second scenario the NADIR value of the Area 1 is 49,6723 Hz, a little bit lower than the previous case.

The power generated by the turbine not only is higher during all the simulation but after the emulated inertia we are even in a better power operational state, while the rotor speed is changing minimally.

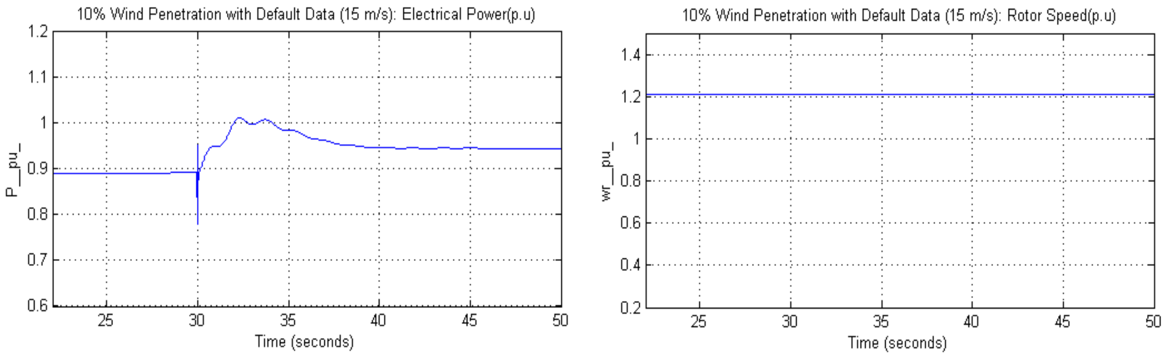


Figure 76 Power and Speed of the Wind Turbine with 15 m/s wind speed

4.6.3. VELOCIDAD 17 m/s

The same happens in this third scenario. We are not only able to emulate inertia; we can also produce more power than we were producing before the frequency drop, which is really positive for the frequency response of the system.

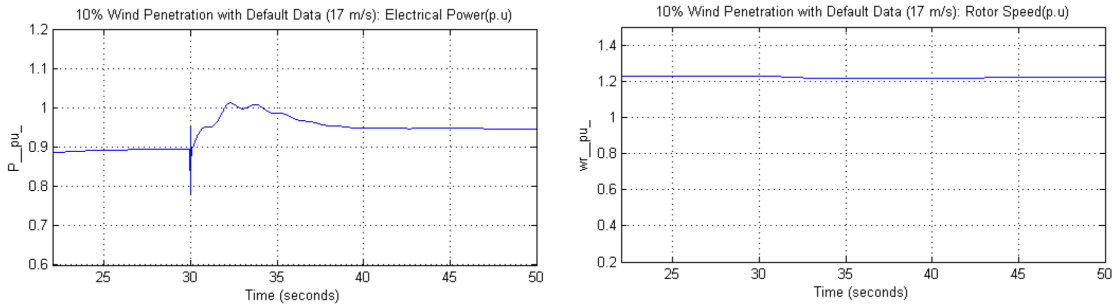


Figure 77 Power and Speed of the Wind Turbine with 17 m/s wind speed

Notice that in the case of 15 m/s and 17 m/s the rotor speed seem to remain constant, although there is an emulated inertia response that injects power during the fast primary response. This is due to the scale of the graph. The decrease on the rotor speed is so low that using the same scale as in the other examples we cannot appreciate the change.

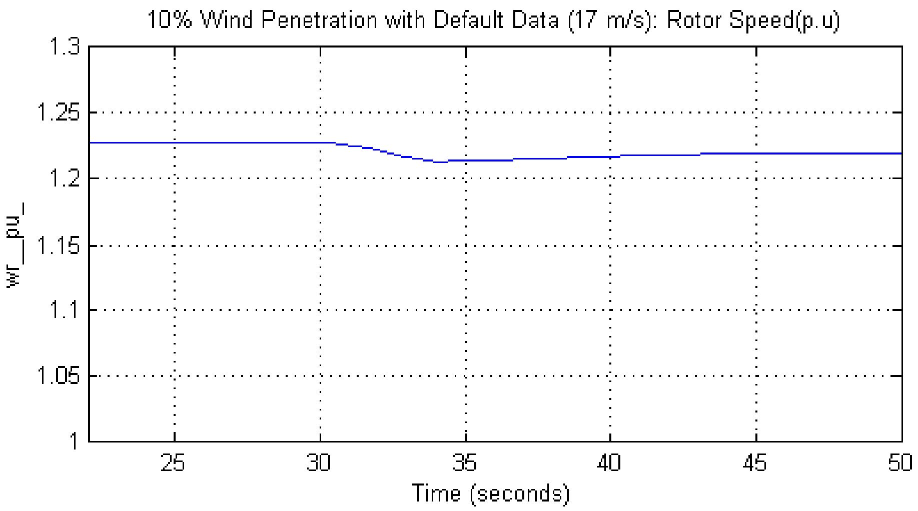


Figure 78 Close up of the wind turbine rotor speed wind speed 17 m/s

But as we see in Figure 81, the deceleration exists although is minimum.

The response to all these behaviors we can find it in the following figure, the Turbine Power Characteristics of the DFIG used in the simulation:

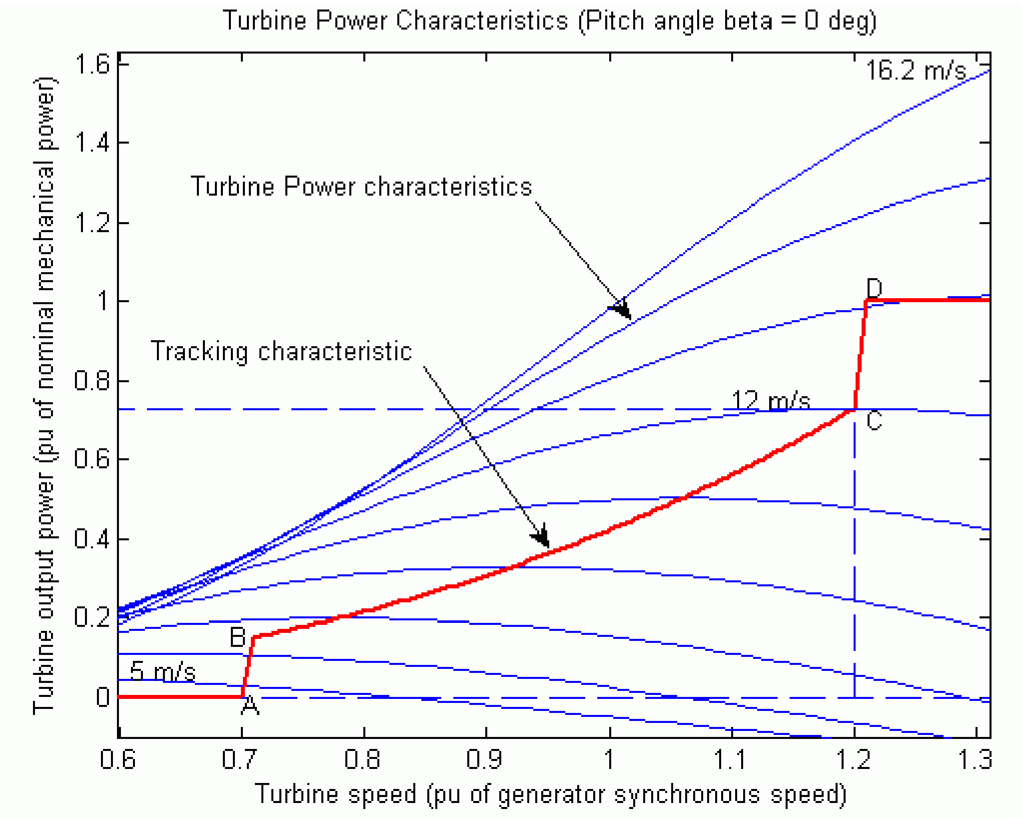


Figure 79 Turbine Power characteristics and Tracking Characteristics [16]

The power of the DFIG used for the simulation is controlled in order to follow the tracking characteristic (red line).

That tracking characteristic is defined by four points: A, B, C and D, which A correspond to the cut in wind speed and C to the rated wind speed.

So at 0 pitch angle, wind speed of 12 m/s is the rated speed. Below that wind speed our operational point will be place somewhere between point B and C.

For wind speed 10 m/s we will be working at a rotor speed of 1 pu and generating power of 0.4 pu. If we decelerate the machine working in this point, the speed and the power generated after the emulated inertia will be lower than initial state.

For the other two wind speeds that are above rated wind speed, 15 m/s and 17 m/s. We are working at a point in which the wind turbine is spilling away energy to generate at rated power. So at these two scenarios the wind turbines have a reserve of energy that can use to increase power. They decelerate to emulate inertia and at the same time use the pitch control to place their operational point at a higher state than the rated power. This allows the turbines to emulate inertia and gain power for the slow primary and secondary responses.

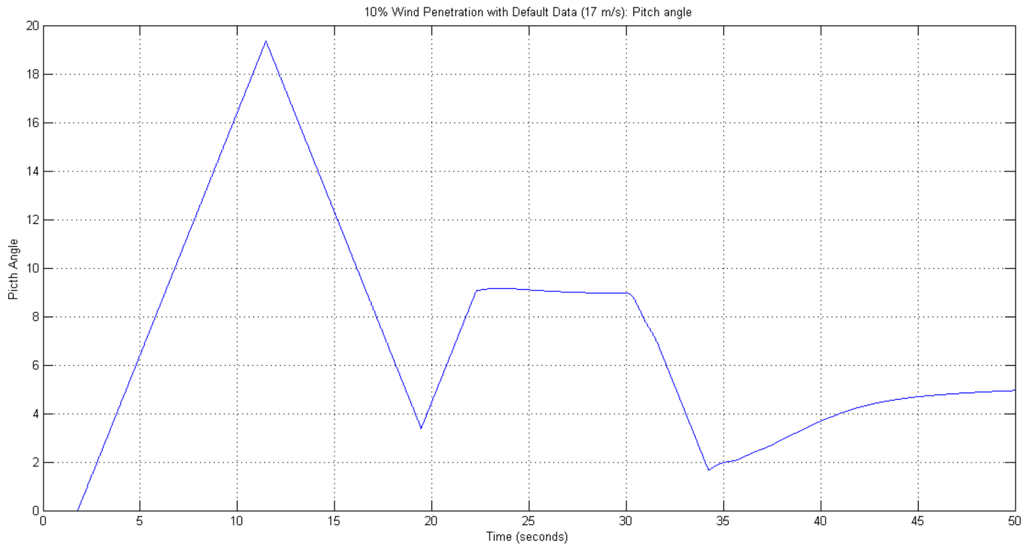


Figure 80 Pitch angle evolution 17 m/s

At figure 80 we can see how the pitch varies during the simulation due to the energy reserve that being above rated speed gives to the turbine.

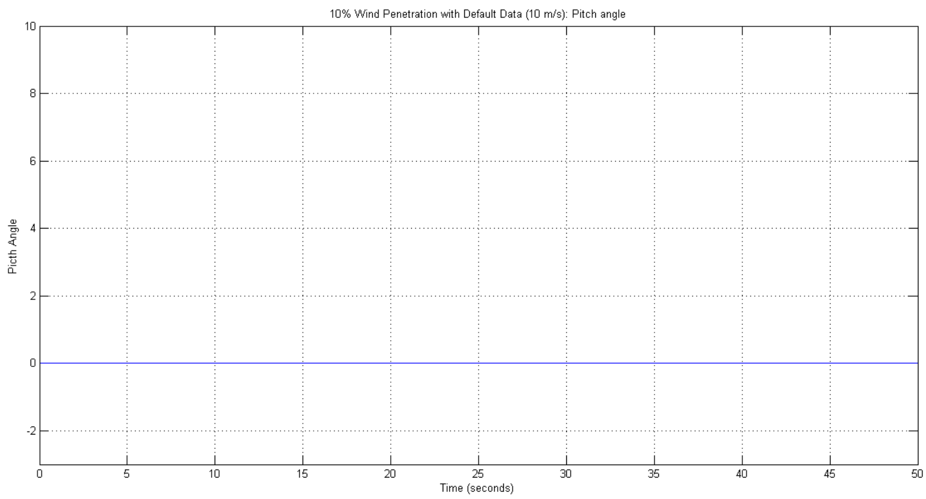


Figure 81 Pitch Angle evolution 10 m/s

At figure 81, we see the opposite example. No energy reserve, no pitch regulation needed. It remains at 0.

5. CONCLUSIONS

From the previous work we can extract the following conclusions:

- ✓ Renewable energy penetration will increase in the upcoming years. In this study we proved that the increase in energy penetration into the system without a Frequency control can lead to a worse frequency Response. Type 3, which are the most used wind turbines, and Type 4, which will be the most used technology in the future, cannot provide natural inertia response. By increasing the penetration we are lowering the inertia stored in the system. This leads to a higher ROCOF values and lower NADIR. Therefore, a Frequency control strategy is needed.

- ✓ Implementing a Frequency Control in the wind turbines, we observed an improvement on the Frequency Response of the system. We proved that the control placed at the converter, detects a frequency deviation and controls the generator in order to increase power. The generator decelerates so the kinetic energy stored in the rotating mass can be injected as electric power into the grid providing frequency support. In our case this process is known as emulated inertia.

- ✓ On the contrary, at the No Frequency Control scenarios the power and the rotor speed remain constant which means there is no Frequency response.

- ✓ We also proved that the reaction of the machine in front of the frequency drop after the control gives the order to decelerate depends on the Frequency Control values of inertia control and Droop control and on the Operational Point of the turbine:

Frequency control values of inertia and Droop

Setting the correct values for the Frequency Control parameters is crucial to obtain a good Frequency Response.
For the **inertia control constant** we saw that high values will lower the NADIR, but will not give a continued and stable frequency support. This is because the constant of inertia of the turbine was set at 5.04, we were asking for higher inertia to a machine that cannot provide it. This makes the machine to decelerate faster giving an unstable response.
So we conclude that higher inertia constant is positive only if the machine can provide it itself. The best value for the inertia control

constant in this case would be the same as the inertia constant of the machine, the default value of 5.04.

The **Droop control** values that resulted into a better frequency response are the lower ones. This means that a little deviation in the frequency would result in a 100% in generator output power. We have to take into account at which deviation we want the machine to change the output. We have good results with 1% and 2% but in reality the droop is around 3-5%, a bit higher values.

Operational point

If we are working at **higher wind speeds** than the rated wind speed, we have a reserve of energy that in normal operation we are losing. If there is a frequency drop we can use pitch control to achieve higher power production. We saw in this scenario that we can inject energy by emulating inertia decelerating minimally the turbine and reach a higher power generation point after the frequency drops being able to keep the support to the frequency of the system.

But wind is not a constant resource. So we can have wind speeds at rated speed, over rated speed or under the rated speed. As seen in the last scenario, the power characteristic curve will gives us the operational points depending on the wind speed and the speed of the rotor so we can have a hint of the behavior of the machine at any point.

For **lower wind speeds**, we saw that initially the machine was operating at lower power point and lower rotor speed then the default case. When the frequency drop at the 30 second mark the turbine provides emulated inertia and ends up in an even lower power generation and lower speed operational point. The frequency response in these cases will last only the few seconds that correspond only to the emulated inertia response.

At **rated wind speed**, we saw that the operational point after the emulated inertia remain almost the same.

- ✓ We conclude that Frequency Controls are crucial to the stability of the future power systems. Renewable energy technologies should be able to adapt to power system requirements so stability and security of supply can be provided to the final consumers.

6. FURTHER STUDIES

After finishing the project there are some lines of study that are still open and would be interesting for further studies:

- ✓ The oscillations seen in Area 1 can be reduced by adding a new control. This way we could analyze if the results are affected or not by these oscillations.

- ✓ It would be also interesting to implement a control for overspeeding and see how the Frequency Response of the system varies from our study.

- ✓ Increase the level of difficulty of this project by taking into account each and every wind turbine. We studied the Wind Power Plant as a unique turbine generating the total Power, which is a simplified way to study the behavior of the system. We could instead, implement a control that takes into account the wind speed and generating operational point of each wind turbine. So in case of a Frequency drop we are able to know which turbines can produce more power or which ones already are at their maximum capability.

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Acta d'Avaluació de Projecte

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9. ANNEX