ESCUELA TÉCNICA SUPERIOR DE INGENIERÍA (ICAI)

GRADO EN INGENIERÍA ELECTROMECÁNICA

ESPECIALIDAD ELÉCTRICA

# FEASIBILITY ANALYSIS OF WIND POWER FOR FREQUENCY SUPPORT IN THE SPANISH ELECTRIC POWER SYSTEM


Autor: Nicolás Castillo Castejón

Director: Jimmy Ehnberg


Madrid

Junio 2016

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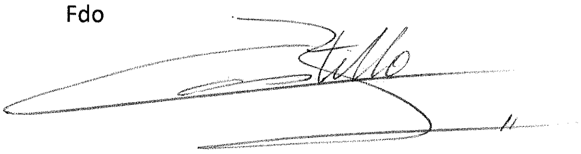

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## Abstract

One of the main characteristic of the Spanish power system is the strong dependency of foreign fossil fuels. The growth of renewable energy sources is an opportunity to become more energy self-sufficient. However, these renewable generation units cannot participate in frequency regulation as their power production depends of climatic conditions. Spain is the forth country with most installed wind power capacity but wind farms do not provide frequency support. A simple model of the Spanish power system has been built to simulate a frequency event in order to evaluate the contribution of wind power during primary regulation. During the power disturbance thermal units have been partially disconnected to recreate a possible scenario where these energy sources have been replaced by renewable power plants. Two different inertia support techniques have been applied providing an extra amount of power during the first seconds after the power imbalance. Both strategies have improved the frequency regulation even with thermal units disconnected, but these techniques also involve other problems.



**Index Terms:** Inertia support strategies, frequency regulation, Variable Speed Wind Turbines, lack of inertia.

# ESTUDIO DE VIABILIDAD DE SOPORTE DE FRECUENCIA POR ENERGÍA EÓLICA EN EL SISTEMA ELÉCTRICO ESPAÑOL

Autor: **Castillo Castejón, Nicolás Juan**

Director: Ehnberg, Jimmy

Entidad colaboradora: ICAI – Universidad Pontificia Comillas; Chalmers University of Technology

## RESUMEN DEL PROYECTO

### Introducción

En el sistema eléctrico español la regulación de frecuencia es llevada a cabo por fuentes de energía convencionales como el gas natural o el carbón. No obstante, España sufre una importante dependencia de combustibles fósiles extranjeros, lo que puede suponer un grave problema en un futuro próximo, bien por la escasez de estos recursos o por las consecuencias climáticas de su uso continuado.

El crecimiento de fuentes de energía renovables puede suponer una solución para esta dependencia, pero también genera otros problemas. No se puede controlar totalmente la producción de las plantas de energía renovable, por lo que no pueden ser utilizadas para regular la frecuencia. Por lo tanto un incremento de estas fuentes de energía en detrimento de las plantas de potencia convencionales, provocaría una reducción en la inercia del sistema y una pérdida de capacidad de respuesta ante desajustes entre la producción y la demanda.

Sin embargo, las turbinas eólicas de velocidad variable presentan cierta flexibilidad, siendo capaces de proveer una cantidad de potencia extra durante unos segundos. Esta característica permite que las turbinas eólicas contribuyan durante la regulación de frecuencia, pudiendo suponer un importante avance de cara a conseguir sistemas energéticos más sostenibles.

El objetivo de este proyecto consiste en evaluar la aportación de las turbinas eólicas durante un evento de frecuencia en el sistema eléctrico español (España es el cuarto país con más potencia eólica instalada) en situaciones de baja inercia, donde el sistema energético es más vulnerable a desajustes de potencia.

## Metodología

El sistema eléctrico español se ha modelado utilizando el software Simulink. Para simplificar el modelo y poder realizar una aproximación de las plantas de potencia, todas las centrales de generación de cada tecnología se han representado como una única unidad, con una potencia nominal igual a la suma de las potencias de todas las plantas individuales. Esto incluye también a las turbinas eólicas, que han sido representadas como una única turbina. El generador utilizado para representar las turbinas eólicas es un DFIG, debido a que la mayoría de turbinas del sistema eléctrico español utilizan este tipo de tecnología.

El modelo será usado para simular una desviación de frecuencia, provocada por un aumento repentino de la demanda de un 5%. El proyecto se centra en la respuesta primaria del sistema, por lo que se analizan los segundos posteriores al desajuste de potencia donde la regulación secundaria no entra en juego.

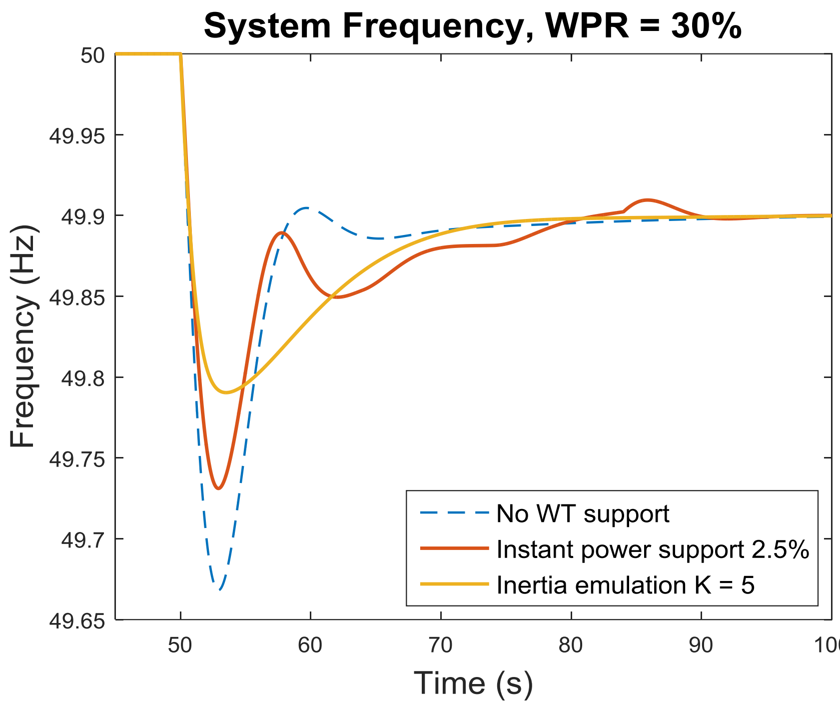
Para representar un escenario donde las plantas de potencia convencionales son reemplazadas se estudiarán diferentes casos donde las centrales de carbón y de gas hayan sido parcialmente desconectadas. También se estudiarán casos con diferentes velocidades de viento, para analizar situaciones donde la energía eólica tenga un mayor peso. Para simplificar las simulaciones la velocidad del viento es asumida constante durante todo el evento de frecuencia.

La potencia extra de las turbinas eólicas es obtenida a través de dos estrategias de control: ‘emulación de inercia’ y ‘soporte de potencia instantánea’. Ambas estrategias son comparadas para analizar las aportaciones positivas de cada una de ellas, así como las consecuencias negativas de su uso.

## Resultados

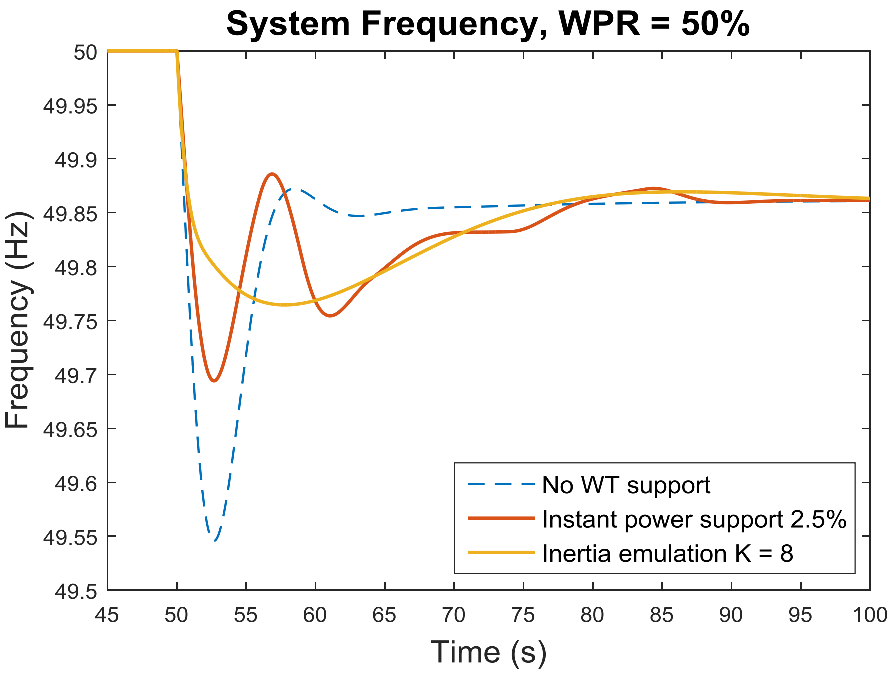
En total se han analizado cuatro escenarios, la evolución de la frecuencia del sistema en cada uno de los casos simulados se muestra a continuación:

Escenario A: Centrales de carbón desconectadas, WPR = 30%



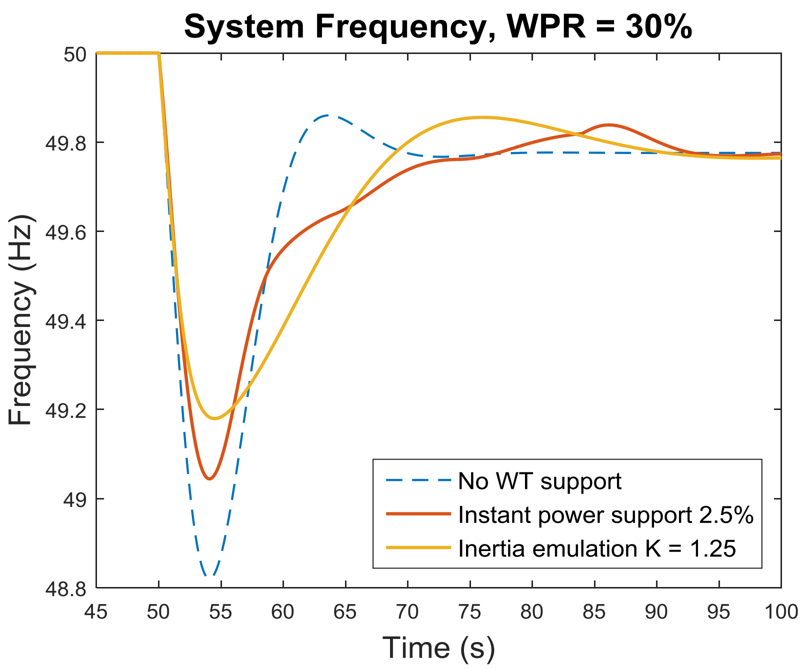

*Caída de frecuencia con diferentes estrategias.. Centrales de carbón desconectadas, WPR = 30%*

Escenario B: Centrales de carbón desconectadas, WPR = 50%



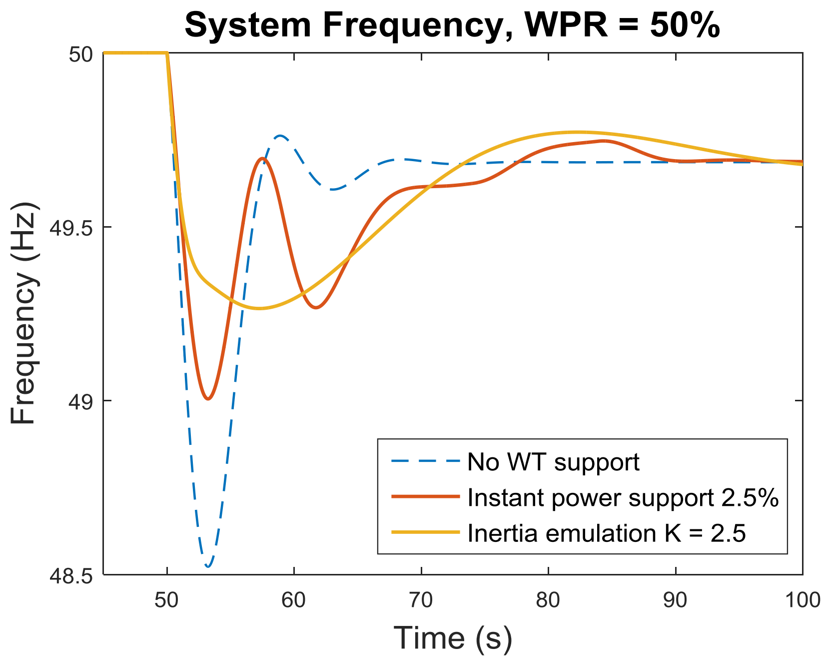

*Caída de frecuencia con diferentes estrategias.. Centrales de carbón desconectadas, WPR = 50%*

Escenario C: Centrales de gas y de carbón desconectadas, WPR = 30%




*Caída de frecuencia con diferentes estrategias.. Centrales de carbón y de gas desconectadas, WPR = 30%*

Escenario D: Centrales de gas y de carbón desconectadas, WPR = 50%




*Caída de frecuencia con diferentes estrategias.. Centrales de carbón y de gas desconectadas, WPR = 50%*

La principal aportación de las turbinas eólicas durante la regulación de frecuencia es una mejora significativa del nadir. Sin embargo, la implementación de estas estrategias tiene también consecuencias negativas.

El uso de la estrategia de 'soporte de potencia instantánea' provoca una segunda caída de frecuencia, que puede ser especialmente importante cuando la producción eólica es alta, sin embargo la velocidad de respuesta de la frecuencia suele ser aceptable. Por otro lado la estrategia de 'emulación de inercia' presenta una mayor mejora en el nadir, pero la frecuencia tarda más en estabilizarse por completo.

También es posible observar el efecto que produce en la frecuencia un WPR (porcentaje de generación eólica) elevado. El soporte de frecuencia por parte de las turbinas eólicas se vuelve menos efectivo, afectando negativamente a ambas estrategias.

## Conclusiones

Los estudios realizados muestran que en situaciones de baja inercia las turbinas eólicas pueden contribuir en la regulación de frecuencia, pudiendo llegar a obtener resultados satisfactorios.

Cuando el WPR es igual al 30%, ambas estrategias presentan buenos resultados, incluso cuando las centrales de gas también son desconectadas, aunque parece tratarse de la situación límite.

Cuando el WPR aumenta al 50%, únicamente la estrategia de 'soporte de potencia instantánea' parece tener un rendimiento ligeramente aceptable, pero cuando las centrales de gas son desconectadas ninguna estrategia puede hacer frente a la falta de inercia.

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Colaborating Entity: ICAI – Universidad Pontificia Comillas; Chalmers University of Technology

## SUMMARY OF THE PROJECT

### Introduction

In the Spanish power system frequency regulation is performed by conventional energy sources such as coal or natural gas. However, Spain suffers a strong energy dependence of foreign fossil fuels. This could be a problem in the near future due to the scarcity of these energy sources or due to the climatic impact of the power plants fired by these fuels.

The growth of renewable energy sources can be a solution for this dependence, but it also creates other problems. It is not possible to completely control the output power of these renewable power plants, so they cannot participate in frequency regulation. Moreover, an increase of these energy sources causes a reduction in the inertia of the system and a loss of response capability to mismatches between production and demand.

Nevertheless, variable speed wind turbines have some flexibility, being able to provide a certain amount of extra power for a few seconds. This feature allows wind turbines to participate in frequency regulation and it may represent and important advance in order to achieve more sustainable power systems.

The purpose of the project is to evaluate the contribution of wind turbines during a frequency deviation in the Spanish power system (Spain is the fourth country with most installed wind power capacity). The cases of study will represent scenarios with low inertia, where the power system is more vulnerable to power disturbances.

## Methodology

Spanish power system is modelled using the software Simulink. The power system has been simplified in order to represent an approximation of power plants of all energy sources. All the generators of each technology will be modelled as a single generation unit with a rated power equal to the sum of the powers of all single units. This also includes wind farms, which have been represented as a single wind turbine. The generator used to represent wind turbines is a DFIG, because it is a really common technology used for variable speed wind turbines in the Spanish power system.

The model will be used to simulate a frequency deviation caused by a sudden increase in demand of 5%. The main concern of the project is the primary response of the power system, so only the first seconds after the disturbance are analyzed (secondary regulation is not taken into account).

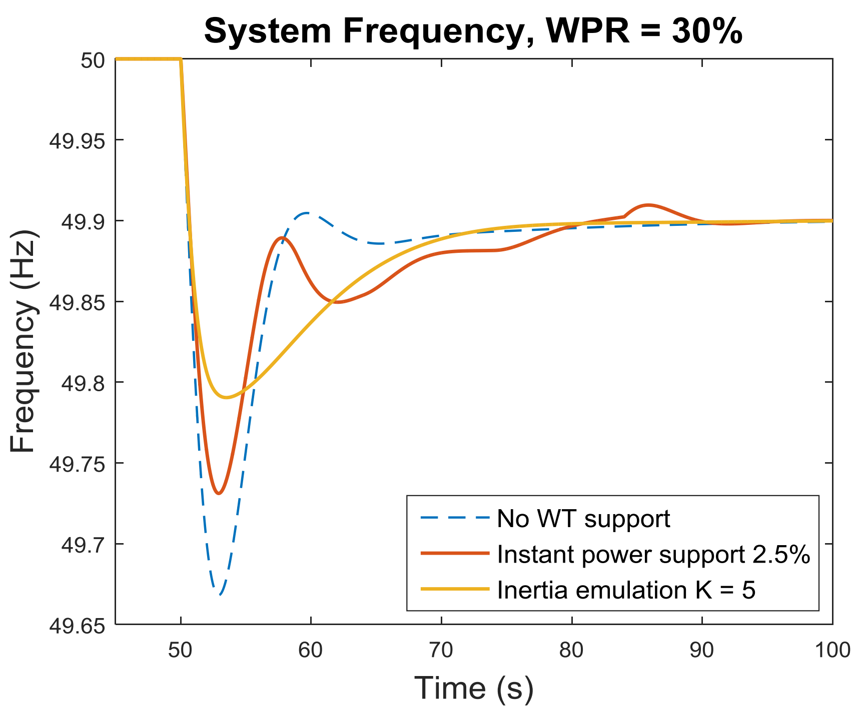
To represent a scenario where conventional power plants are replaced, different cases where coal and natural gas have been partially disconnected will be analyzed. Cases with different wind speeds will also be studied, in order to analyze situations where the wind power ratio (WPR) is high. To simplify the simulations wind speed is assumed constant during the whole frequency event.

The extra power provided by wind turbines is released throughout two control strategies: 'inertia emulation support' and 'instant power support'. Both strategies are compared in order to evaluate the positive contributions of each, as well as the negative consequences of their use.

## Results

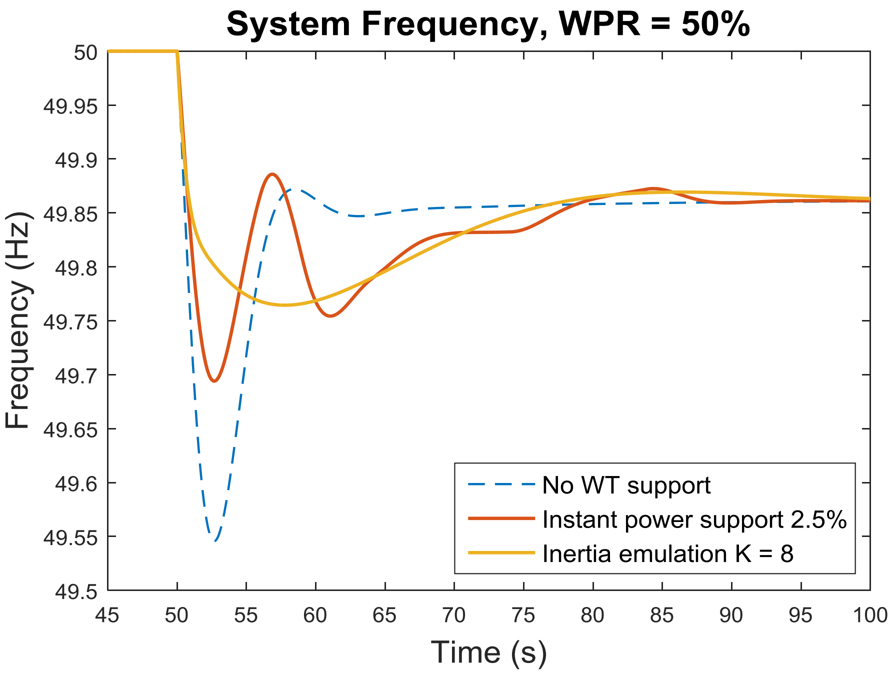
Finally, there are four scenarios of study. The behaviour of system frequency in each of the simulated cases is shown below:

Scenario A: Without coal power plants, WPR = 30%



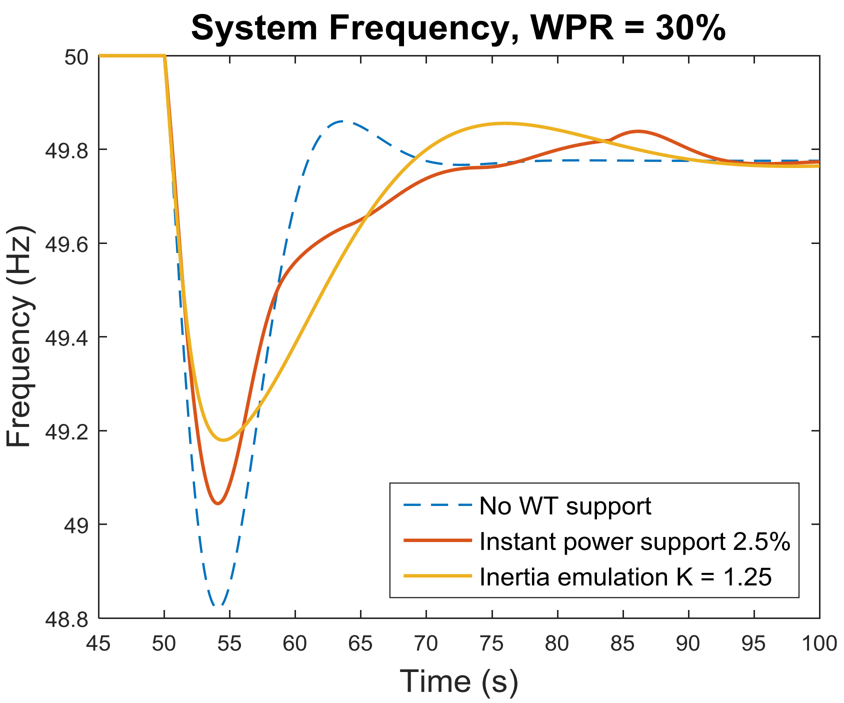

*Frequency nadir for different strategies. Hydro and reheat units operating, WPR = 30%*

Scenario B: Without coal power plants, WPR = 50%



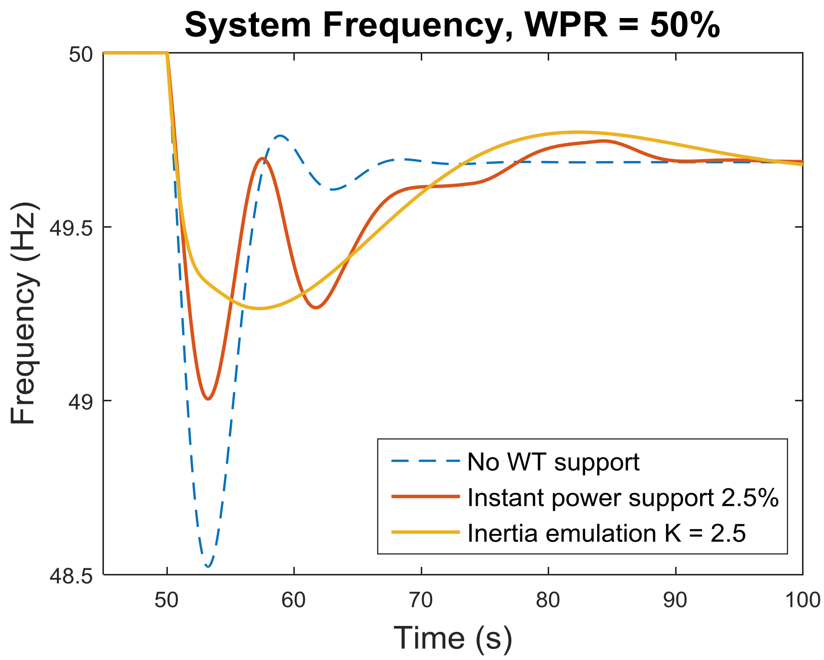

*Frequency nadir for different strategies. Hydro and reheat units operating, WPR = 50%*

Scenario C: Without coal and gas power plants, WPR = 30%




*Frequency nadir for different strategies. Hydro unit operating, WPR = 30%*

Scenario D: Without coal and gas power plants, WPR = 50%




*Frequency nadir for different strategies. Hydro unit operating, WPR = 50%*

The main contribution of frequency support by wind turbines is the improvement of the nadir. Nevertheless, there are also negative consequences affecting the speed of response of the frequency.

The application of the 'instant power support strategy' causes a second frequency dip, which can be especially significant with high WPR, however the speed of response is acceptable. On the other hand, when the 'inertia emulation support strategy' is implemented the nadir improvement is better, but the frequency response is slower.

It is also possible to observe the negative effects of high WPR. The frequency support by wind turbines becomes less effective, negatively affecting both strategies.

## Conclusions

In conclusion, the studies have shown that frequency support can be improved without a part the thermal units due to wind power contribution.

When the WPR level is 30%, the results show a good performance with both strategies even when gas units are disconnected but it looks to be the limit situation.

When the WPR level increases to 50% only instant power support presents a performance that can be considered acceptable (limit situation) when the gas units are working. Without these units wind turbines support cannot face the lack of inertia.

# Acknowledgements

I wish to express my sincere gratitude to all people from Chalmers University of Technology who have helped me, without whom I would not be able to finish this project. Especially Mattias Persson and Jimmy Ehnberg, for their patient guidance and advices.

Besides, I would like to thank my family. They have been by my side in the good and bad moments and I have never been alone even in distance these last four years.

Finally I wish to thank Maria for helping me to become a better person.

## Table of contents

## Table of figures

# 1. Introduction

## 1.1. Background and motivation

The major energy sources used to generate electricity are oil, natural gas and coal. The sum of the three represents over 48% of total power production in the European Union at the end of 2014 [1]. This leads to problems such as $CO_2$ emissions, fuel costs or lack of sources. In order to face all these problems, the development of renewable power production is growing in the EU [2].

Wind power is one of the most significant renewable energy sources in the European Union, reaching 10% of total power consumption [1]. Germany and Spain are the countries with the most installed wind power capacity currently. Specifically in Spain, wind power production represents 20% of the total power generation with almost 23 GW installed at 2014 [3].

Because of the energy dependence of Spain on fossil fuels used to fire the power plants, these are imported. However, renewable energy sources could be a solution for this problem, especially wind power. Wind conditions are favourable in Spain, allowing the installation of large wind farms in different regions of the country. At the end of 2014, wind power was the second technology with most installed power capacity [3]. Other renewable energy sources such as solar, hydro or biomass also have an important role in the Spanish power system.

The growth of these renewable sources poses a risk to the operation of the system due to its intermittent behaviour. The frequency in the electric grid must remain within strict limits to secure the quality in the electric supply. In order to ensure frequency stability it is necessary to control the balance between generation and demand. Frequency control is performed by the main power generation sources because they can change their power output to adapt to disturbances in the system quickly.

Currently, wind power is not involved in frequency regulation because it is difficult to control the power generation of a wind turbine. The main problem is wind variability, but with the development of variable wind speed turbines (VSWT), new wind farms have won flexibility to control their output power. These new wind turbines can reduce their output power due to the operation of a pitch controller. However, they cannot increase their production unless the turbines are already working in derated operation, not at the optimal angle. Moreover, the implementation of power support strategies makes possible the extraction of an extra power from wind turbines during a power imbalance.

## 1.2. Purpose

The main purpose of this thesis is to determine if it is possible for wind power to contribute to frequency support in Spain in scenarios with low inertia.

## 2. Method and problem definition

The power system in Spain will be simplified in order to represent an approximation of the power plants of all the energy sources. All the generators of each technology will be modelled as a single generation unit, using the software Simulink. This representation involves problems because climatic conditions vary depending on the region and there are power plants of the same technology with different characteristics. These generation units will be modelled according to the features of the largest power plants of each technology.

Wind farms will be represented as only one wind turbine. The value of the wind speed will be set in order to match it with the real wind power generation. The generator used to represent the wind farms will be a Doubly Fed Inductor Generator (DFIG) which is a really common technology used for Variable Speed Wind Turbines (VSWTs). This technology is the most used but there are different types of turbines too. Due to the small number of non DFIG wind farms, a general VSWT model is implemented.

The wind speed is assumed to be constant during the power disturbance and the frequency support process. Normally wind speed varies many times in a short period and it causes small oscillations in the output power of the turbine. These oscillations will not be taken into account in order to simplify the model as the wind turbine will be working at a stable operation point. Moreover, the system frequency will be working at steady state equilibrium before the power disturbance.

The Spanish power system is connected to French, Portuguese and Moroccan grids but each system must be able to regulate itself. In this report the Spanish grid has been treated as an independent power system and all international power exchanges are reflected in the model as a part of the load. The generation units that do not participate in frequency support (nuclear, solar, biomass, etc.) will be represented as a single generator too. Nuclear power plants do not perform frequency regulation but they provide inertia to the system.

Spain has two archipelagos (Balearic and Canary) but their frequency regulation is completely independent of the mainland system. There is only an exchange of energy between the peninsula and the Balearic Islands which will be included as part of the load.

In order to simplify the Simulink model, important elements of a real grid such as transmission lines or transformers will not be represented. As only large frequency disturbances will be considered. This means that losses of these elements are neglected. Reactive power losses are not taken into account because this project is focused on system frequency and it depends of the active power flow, the voltage levels in the model are not studied.

The load level will represent a typical low demand in the power system of Spain. A sudden load change will simulate the trip of a large power plant (around 1100 MW), that means an increase of the demand of 5%. The main concern of this project is the primary response of the power system so only the first 40 seconds after the disturbance are analyzed (secondary regulation is not taken into account).

In order to represent an approximation of a scenario where the thermal units have been partially replaced, the coal power plants will be disconnected. In this scenario the power disturbance will be simulated to evaluate the contribution of wind farms to frequency regulation. In a worst case scenario the gas power plants could be also disconnected.

# 3. Frequency control

## 3.1. Frequency regulation

Frequency stability is the capability of a power system to handle a power imbalance in order to maintain a constant steady frequency. In short, a power system is considered to be stable when all synchronous machines work at the same frequency (50Hz in Spain). The system stability can be altered by different phenomena, such as faults in generators, sudden changes in demand, etc. Disturbances may cause several problems such as loss of network elements, generation losses or instability [4]. It could be said that a disturbance occurs when normal system operating parameters are altered.

Balance between production and demand is achieved by control systems, which regulate the generation units in order to provide always the required power. If the balance between production and demand is changed the frequency will vary: increasing if there is an excess of generation or decreasing if demand exceeds power production. This process is known as 'frequency regulation'.

System frequency deviation of a power system when a power mismatch occurs is explained in [5] through the following equation

$$\Delta P_G - \Delta P_L - D\Delta\omega = 2H\frac{d\Delta\omega}{dt} \qquad (3.1)$$

Where $\Delta P_G$ is the change of generated power in MW, $\Delta P_L$ is the change of load power in MW, D is the load damping constant in $\frac{\%MW}{\%Hz}$, H is the system inertia constant in seconds and $\Delta\omega$ is the frequency deviation in Hz.

This inertia constant is the ratio between the kinetic energy of a generator at its nominal power and the total power of the system. It determines how much a power imbalance affects the system frequency. A large inertia constant means lower frequency deviations. In [5] the inertia is defined as

$$H = \frac{1}{2}\frac{J\omega_{BASE}^2}{S_{BASE}} \qquad (3.2)$$

Where J is the inertia moment of the generator, $\omega_{BASE}$ is the base rated rotational speed in rad/s and $S_{BASE}$ id the base apparent power in VA.

The damping constant, D, represents a natural property of all power system. Due to this the load level is adjusted according to the frequency deviation level, facilitating the system to find a new frequency equilibrium [5].

As the electrical frequency depends on active power balance of the power system, frequency regulation is also known as power regulation or frequency-power regulation. The frequency of an electrical system is equal in all nodes when the system is in steady state. In order to study the frequency-power control same frequency is assumed for the entire system. Therefore, frequency control is an issue addressed globally.

The generated power of each power plant must also meet other requirements in addition to frequency control, requirements related primarily to the operation of the electricity market. These commitments are associated to the production of each power plant and to the power exchange between neighbouring areas [6]. Due to the extension of modern power systems and the large number of institutions involved in their operation, power systems are divided into interconnected areas to facilitate technical and economic management. Energy exchanges between these areas are scheduled in advance, and each area must have sufficient energy reserves to address imbalances between production and demand [6].

### 3.1.1. Primary regulation

The objective of the primary regulation is to automatically correct the instantaneous imbalances between production and consumption. During this process the generators change their output power in order to adapt to mismatches. Turbines have a governor that is responsible for controlling the valves in response to frequency variations. In order to connect several generation units to perform this process, it is necessary to include a droop characteristic, R, to the speed governor. This characteristic will determine the ratio of frequency deviation to change the power output of each generator, as illustrated in Figure 1, taken from [5]. The droop characteristic of the generation units will share the load variation between the generators, in order to face the imbalance together.

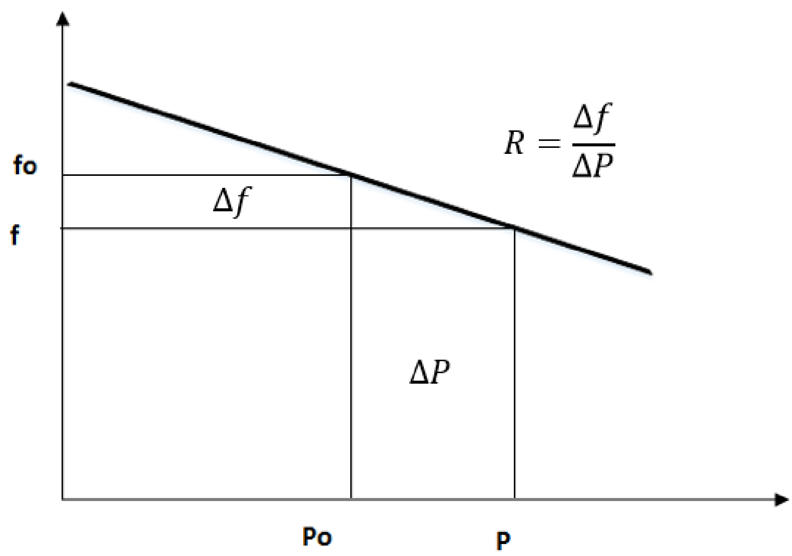



*Figure 1: Ideal steady-state characteristic of a speed-droop governor [5].*

### 3.1.2. Secondary and tertiary regulation

After primary regulation the power imbalance is fixed through inertia support and droop response of the generation units. However, the frequency of the system is offset from the reference. Furthermore, the variation of output power in the generators is determined by their droop characteristic, so the scheduled power flows between areas will not be met.

Secondary regulation repairs both problems. To perform this process successfully, generation units need to have energy reserves to compensate the variations of the load. During tertiary regulation these energy reserves are restored and the system returns to operate under normal conditions [5].

## 3.2. Inertia support

As explained in Section 3.1, a power imbalance will cause a frequency deviation. If the demand is larger than the power generation the frequency will drop. In [7] it is explained that for a frequency event, there are three security keys that must be controlled in order to ensure safety operation of the system. These are the minimum frequency point (known as nadir), the frequency change rate ($\frac{df_{sys}}{dt}$) and the steady state frequency deviation. These indices are affected by power disturbances, the inertia of the generators, the number of units with droop characteristic, etc.

Directly coupled generators can provide an amount of kinetic energy which is released just after a frequency variation occurs. This first response along primary frequency control are responsible for stabilizing the system frequency after a power imbalance. The speed of this process depends on the inertia constant of the generators. This constant reflects the ability of generation plants to respond to a power imbalance quickly [8].

As mentioned above, wind power has a major role in many power systems. Despite this, the stored kinetic energy of wind turbines cannot be fully exploited yet. VSWTs normally operate at the Maximum Power Point Tracking (MPPT) so they store no power reserves which can be released during frequency events [7].

Different inertia support strategies are explained in [7]. The application of them allow the extraction of a part of the kinetic energy stored in the rotating mass and in the blades of the wind turbine. The two support techniques applied in this thesis are the instant power support and the inertia emulation support.

### 3.2.1. Instant power support

With this support strategy it is possible to release a predefined amount of extra power throughout a simple control function. When a frequency deviation occurs, the normal power control of the turbine can be bypassed to introduce the instant power support control, in order to inject part of the kinetic energy of the turbine. Figure 2 shows the predefined pattern of the power control function.

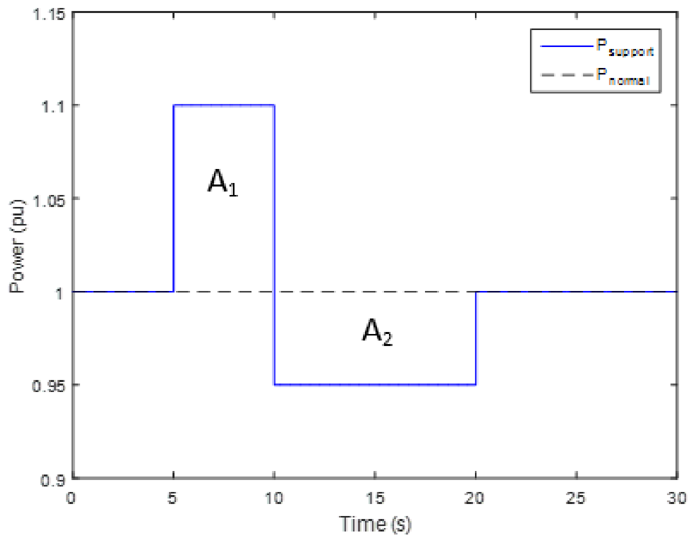



*Figure 2: Output power pattern for instant power support strategy [9].*

The extra power released improves the frequency stability the first seconds, causing a reduction of rotor speed. After this 'deceleration area', $A_1$, another power step is applied forcing the turbine to accelerate (the re-acceleration area $A_2$). The energy equilibrium must be met ($A_1 = A_2$) so the acceleration and deceleration times are selected in order to balance both power regions. Usually the deceleration time is longer in order to reduce the stress on the rest of the power system. After this process the normal control function of the wind turbine is switched on again [7].

The instant power support signal used in this model is a modification of the one shown in [7]. The new signal provides the same power areas but this new model supply more power during the first seconds in order to improve the frequency nadir. The step from the deceleration part to the acceleration part is replaced by a ramp, which reduces the power change when the re-acceleration area starts. Figure 3 shows the new implemented signal.

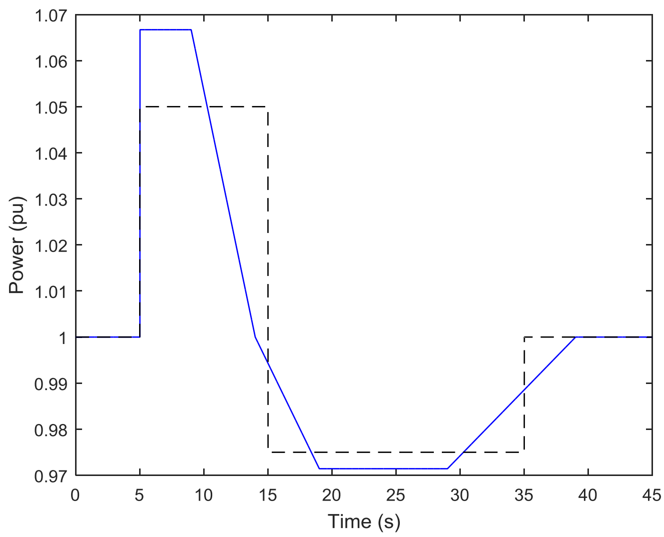



*Figure 3: Alternative pattern for instant power support strategy.*

### 3.2.2. Inertia emulation support

Using this strategy an extra amount of power can be achieved by implementing an inertial controller. Figure 4 shows this control function which is added to the electrical power output, providing power support during frequency deviations.

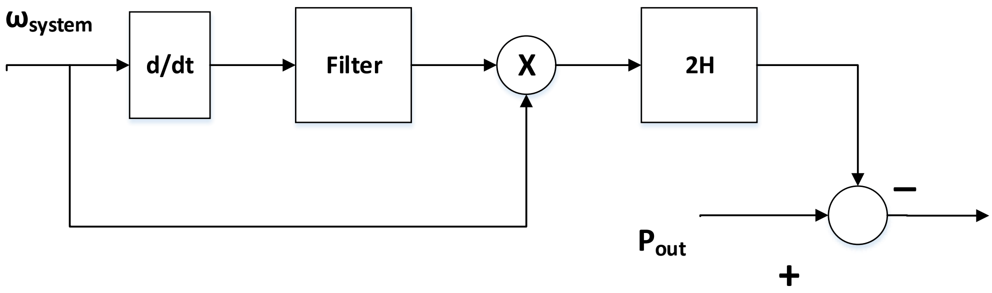



*Figure 4: Inertia emulation support block diagram [7]*

The amount of extra power is defined by the following equation, taken from [7].

$$P_{extra} = 2KH_{wt}\omega_{sys}\frac{d\omega_{sys}}{dt} \quad (3.3)$$

Where $H_{wt}$ is the inertia constant of the wind turbine in seconds and $\omega_{sys}$ is the rotational speed of the system in pu. The amount of extra power will vary depending on frequency drop, so the constant K is chosen in order to regulate released amount of power [7].

## 3.3.Grid code

As previously mentioned, during the primary regulation process the output power of the responding units vary in order to fix power disturbances. However, the increase of renewable power plants causes a loss of droop response capability in the power system because these generation units cannot control their output power easily. Due to this, a proper grid integration of these power plants is required to ensure the safety operation of the Spanish power system.

The variability of wind speed requires the development of grid integration standards in order to protect the frequency stability of the power system. It is possible to control the output power of the VSWTs throughout the strategies mentioned in Section 3.2, but this control is limited.

### 3.3.1. Spanish Grid Code characteristics

Renewable energy units have a main role in the Spanish electric power system, especially wind power [3]. It is also expected that the contribution of wind power plants increases in the short and medium term [10]. In order to ensure a safety performance, the Spanish grid code establishes safety frequency margins shown in Table 1 (the requirements related to the voltage and reactive power are not observable in the table, all the information is explained in detail in [11]).

*Table 1: Frequency safety margins of the Spanish Grid Code [11].*

| | **Upper limit** | **Lower limit** |
|---|---|---|
| **Frequency** | 51.5 Hz | 48 |
| | | 48 > f > 47.5 Hz *(for 3 sec.)* |
| **Derivative of the frequency,** $\frac{df_{sys}}{dt}$ | 2 Hz/s | -2 Hz/s |

# 4. High wind power penetration

## 4.1. Introduction

The term Wind Power Penetration Ratio (WPR) indicates the share of wind energy in a power system compared with the other technologies. The WPR is increasing in most of the electric power systems because wind power is replacing more robust power plants. Wind farms are more sensitive than usual thermal plants to frequency deviations due to lack of inertia. Therefore, a large WPR could imply a risk to system frequency stability.

$$WPR = \frac{Total\ amount\ of\ wind\ energy\ produced\ (MW)}{Total\ power\ demand\ (MW)} \cdot 100\% \tag{4.1}$$

## 4.2. Increasing WPR

The inertia of the system and the droop characteristic of the generation units are directly affected by the WPR. This relation is explained in [9] and [8]. It can be expressed as follows.

$$H_{unit}^{final} = H_{unit}^{initial}(1 - WPR) \tag{4.2}$$

$$R^{final} = \frac{R^{initial}}{1 - WPR} \tag{4.3}$$

Figure 5 shows the behaviour of the system frequency during a power disturbance for different values of WPR.

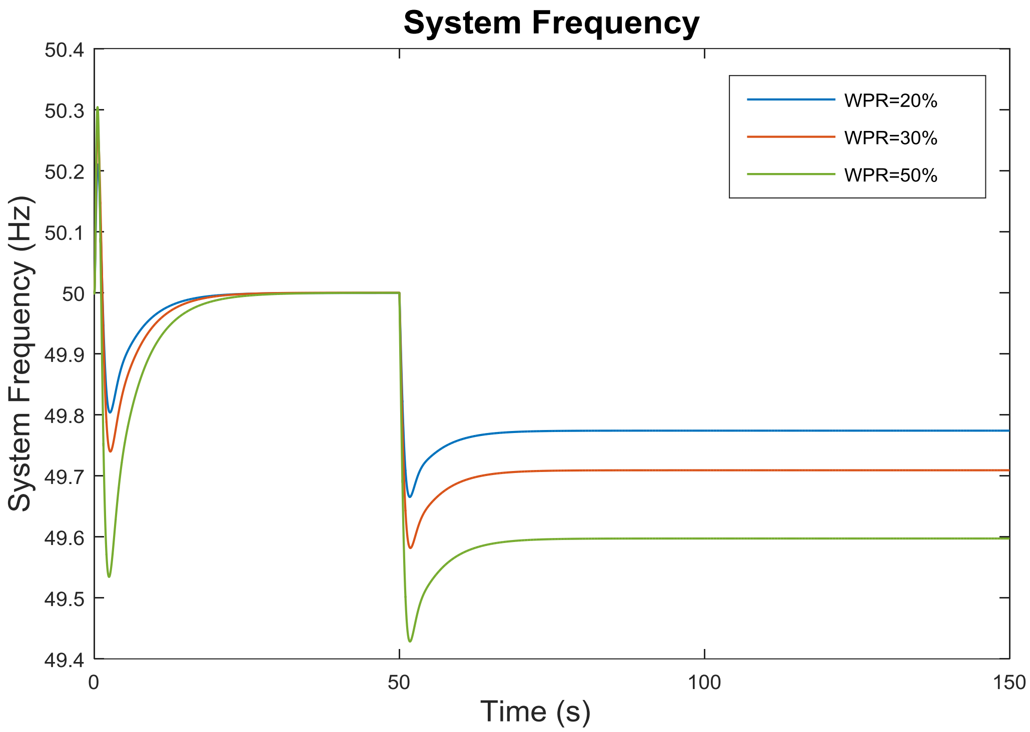



*Figure 5: Frequency response to power step for different values of WPR*

It can be seen that a high value of WPR causes a worse nadir, a larger frequency deviation and a higher derivative of frequency.

# 5. Characteristics of Spanish power system

## 5.1. Introduction

The Spanish electric power system has undergone a lot of changes over the last three decades, due to an economic and demographic expansion. All these changes represent a major growth for the electricity and energy sectors. Major advances have been made in terms of quantity, the demand has doubled its value and the installed power capacity has nearly tripled in that period [12].

The generation structure of the power system of Spain has changed too. A generation mix based on hydro, coal and nuclear power plants has given way to another generation mix where renewable and combined cycle power plants have an important role [12]. Furthermore, the Spanish electric power system has progressed in terms of quality; system security and the reliability of the transmission network have increased [12].

This section describes the main features of the Spanish electric power system and its operation.

## 5.2. Power plants

In this section it is briefly explained the situation of each technology during the last years. At the end of 2014, the installed power capacity of the Spanish power system was 102262MW [3]. Figure 6 shows the installed capacity by technologies.

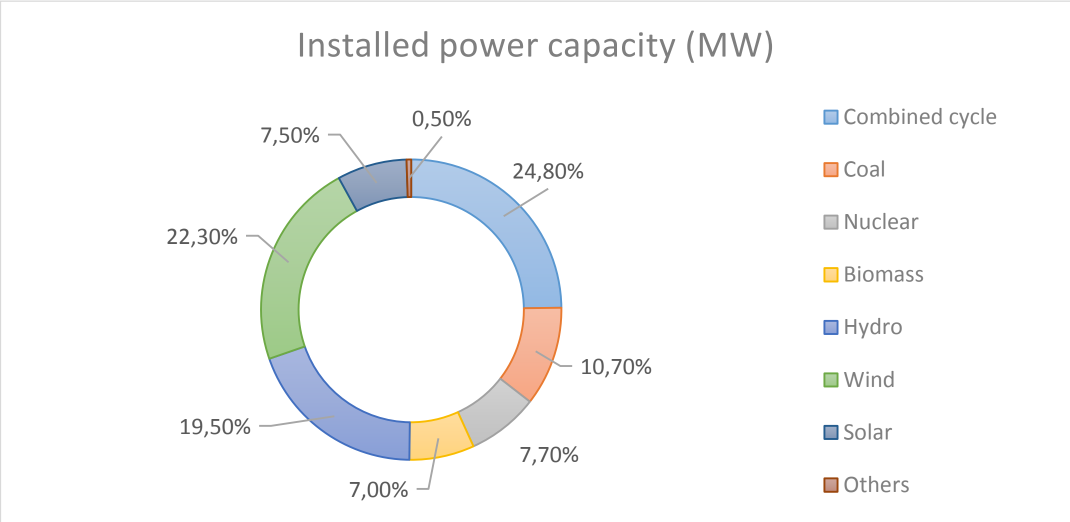



*Figure 6: Installed power capacity in Spain at the end of 2014 by technologies [3].*

### 5.2.1. Gas plants

Natural gas is the fossil fuel that has experienced greater growth in Spain in the last decades, however, national production is practically null. Spain gets natural gas from eleven different countries through imports and community trades [12].

Natural gas is used as fuel in more than thirty combined cycle plants in Spain. In these types of power plants, gas is fired to heat up air at high pressure. This air is compressed and it passes through a gas turbine in order to convert the mechanical power of the spinning blades of the turbine into electrical power (Brayton cycle). The heat of this first combustion is also used to heat up water vapour in order to produce electrical power using a conventional vapour turbine (Rankine cycle) [5]. The sum of the installed power capacity of these gas plants is 25361 MW, accounting for 24.8% of the total installed power of the Spanish power system at the end of 2014 [3].

The main advantages of using gas plants instead of conventional thermal plants fuelled by coal are a higher efficiency, a reduction of $CO_2$ emissions, etc. One of the main characteristic of these power plants is their flexibility. They can provide a fast droop response to power imbalances, being a crucial element in the primary and secondary regulation [3].

### 5.2.2. Coal plants

There are coal reserves in north of Spain. However, they are not sufficient to supply the required amount of coal and it is still required to import this fuel. The power capacity of these plants has remained almost constant over the last two decades; while a large amount of combined cycle power plants fired by gas have been installed [12].

There were over twenty coal power plants installed in Spain at the end of 2014 [3]. These plants consist of a conventional water vapour cycle where coal is fired to heat up and evaporate water at high pressure before it passes through a turbine with a coupled generator. Before the coal can be heated up in the furnace, it has to be processed. Furthermore, storage systems must be installed in the power plants to stock the coal. These systems are not required in the combined cycle plants as gas can be conducted to the combustion tank directly from the pipeline [5]. The total installed power capacity of all coal power plants is 10942 MW, representing 10.7% of the total installed power capacity at the end of 2014 [3].

Coal power plants have a faster droop response to power imbalances than hydro and reheat (combined cycle) units. This technology is used in frequency control, being the most used technology during 2014 for primary regulation [3].

### 5.2.3. Nuclear plants

The production of nuclear energy in Spain has remained stable over the last two decades, although some plants have begun a process of dismantling. [12].

There are seven nuclear plants in Spain and the installed power capacity of these units reaches 7894.8MW, 7.3% of total capacity at the end of 2014 [3].

Nuclear power plants always maintain their generation constant because maintenance conditions and the high cost of changing their output power. This is the main reason why nuclear power plants do not participate in frequency regulation directly, as their generators have great inertia, affecting the total inertia of the system. The main role of nuclear power plants is to cover the demand.

### 5.2.4. Hydro plants

Hydro power plants have had a major role in the power system of Spain during the last three decades. Hydro power has traditionally had the highest installed capacity of the Spanish power system. But currently it is the third technology with more installed power, after wind and combined cycle power plants [12].

In these power plants the water of the river flows through a turbine that is coupled to an electric generator. There are different types of hydro power plants, depending of the river flow. If it is not sufficiently constant, the construction of a dam is required in order to accumulate enough amount of water flowing through the turbine even during dry seasons [5].

There is another type of hydro power plant (pumping stations) where two dams are installed. These power plants operate as usual hydro units when the load is maximum, but when the load is low (and the electricity is cheaper) they pump the water up in order to resell the electricity when it is more profitable. There are several hydro power plants operating at six basins of different rivers in Spain. The total installed power of this technology accounts for 19.5% (19941 MW) of the total Spanish installed capacity at the end of 2014 [3].

Hydro units also have droop characteristic, so they participate in frequency control (primary and secondary regulation), being the most used technology for secondary regulation during 2014 [3].

### 5.2.5. Wind farms

At 1984, the first wind farm of the Spanish power system was built in Catalonia, with a power of 120kW [13]. After 30 years, the installed capacity reaches 22804 MW, representing 22.3% of the total installed power and becoming the second technology with more installed capacity in Spain at the end of 2014 [3]. Spain is the fourth country with more wind installed power in the world, behind China, United Stated and Germany [14].

There are almost 1000 wind farms spread all over Spain. Most of them are located in the centre of the mainland. However, favourable wind conditions also allow the installation of several wind farms in almost all the Spanish regions. Table 2 shows the installed wind power capacity and the number of wind farms in each region of Spain.

*Table 2: Installed wind power capacity in Spain by region [15].*

| Region | Installed power capacity at the end of 2014 (MW) | Number of wind farms |
|---|---|---|
| **Castilla y León** | 5561 | 241 |
| **Castilla-La Mancha** | 3807 | 139 |
| **Andalucía** | 3338 | 153 |
| **Galicia** | 3328 | 161 |
| **Aragón** | 1893 | 87 |
| **Cataluña** | 1269 | 47 |
| **Comunidad Valenciana** | 1189 | 38 |
| **Navarra** | 1004 | 49 |
| **Asturias** | 518 | 21 |
| **La Rioja** | 447 | 14 |
| **Murcia** | 262 | 14 |
| **País Vasco** | 153 | 7 |
| **Cantabria** | 38 | 4 |
| **Total** | **22807** | **975** |

The main manufacturers of Spanish wind turbines are Gamesa and Vestas. They have installed 52.2 and 17.8% of the total number of wind farms respectively. All the wind farms have been modelled as a single DFIG wind turbine. The 82% of the wind farms located in Castilla y León (the region with most installed wind power capacity) are DFIG and they account for over 84% of the installed wind power in this region [15].

### 5.2.6. Solar and biomass

In the solar power plants the electricity is produced using the Sun radiation or the light energy. Sun radiation is used to heat up a fluid in order to produce electricity through a conventional thermal cycle, and the light energy is converted into electricity by photovoltaic panels. The sum of these power plants accounts for 7% of the total installed capacity in Spain (7160 MW) at the end of 2014 [3].

In the biomass power plants organic wasted is fired through thermochemical processes in order to heat up a fluid and produce electricity through a conventional thermal cycle. The installed capacity of this technology in Spain accounts for 7.5% (7670 MW) of the total installed power at the end of 2014 [3].

Both technologies represent a large percentage of the installed capacity of the Spanish power system, but it is not possible to control their output power. In short, they are used to cover the demand.

## 5.3. Frequency evaluation

Spanish power system operates as an organized production market combining free competition in power generation with the duty to provide a supply that meets the required safety criteria and demand. The institution responsible for controlling and regulating the system is the Transmission-line System Operator (TSO). Its operation focuses on three types of actions [6]:

- Management of technical constraints, caused by power system.
- Management of complementary services to ensure the quality and safety of the power-frequency control (secondary and tertiary regulation).
- Deviation management to solve at real time power mismatches (primary regulation).

### 5.3.1. Operation of the system

Each generator technology has different characteristics. Thus, it is necessary to combine the different units to optimize the operation of the system. Figure 7 shows the coverage of demand by technologies during 2014 [3].

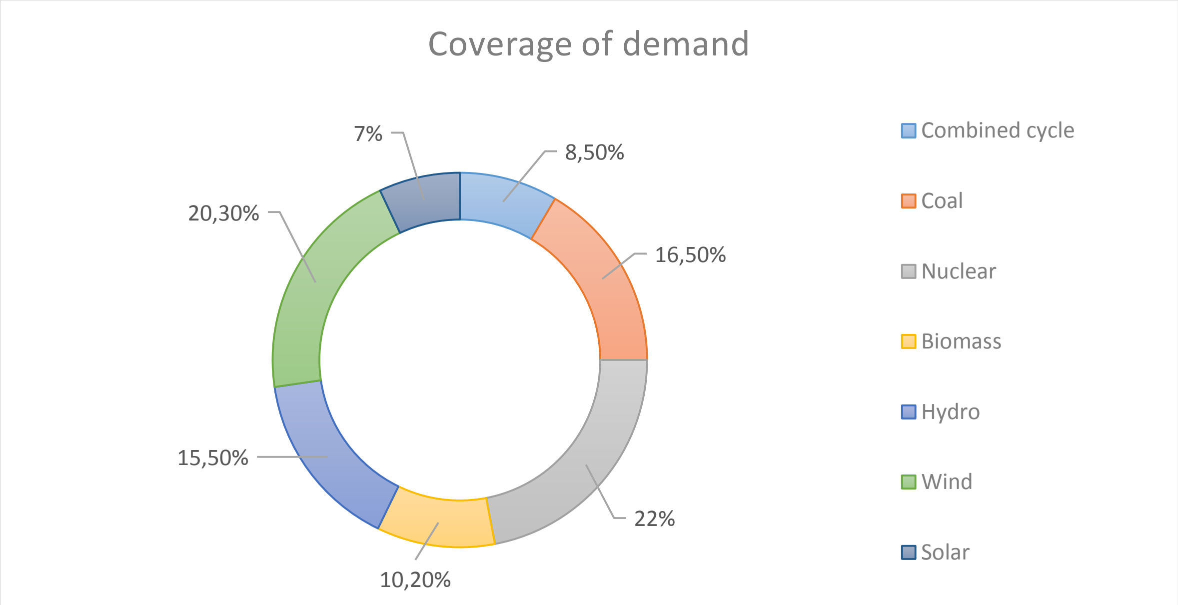



*Figure 7: Coverage of demand in Spain during 2014 by technologies [3].*

As shown in Figure 7 the demand is covered mainly by renewable sources as wind power and by nuclear power. The main reason is explained in section 5.2, nuclear plants cannot vary their output power quickly and the renewable sources such as solar cannot control their production because they depend on climatic conditions.

Coal, gas and hydro plants are the technologies used to perform the frequency-power control. When a frequency deviation occurs these units vary their output power to fix the power imbalance (primary regulation).  The units with droop characteristic must meet different criteria to participate in primary regulation, as explained in [11].

## 5.4. Inertia characteristics

Table 3 presents the typical values of the generation units, according to [16]

*Table 3: Typical inertia constants of generation units [16].*

| Generation type | Inertia constant H (s) |
|---|---|
| Thermal | 3-7 |
| Combined cycle | 7-8 |
| Nuclear | 5-8 |
| Hydro | 2-4 |

### 5.4.1. Inertia of the system

The inertia constant of the system is calculated using the following formula, taken from [17]

$$H_{System} = \frac{\sum_{i=0}^{n} H_n S_n}{S_{System}} \qquad (5.1)$$

Where, $H_n$ is the inertia constant of each technology in seconds, $S_n$ is the installed power of each generation unit in MW and $S_{System}$ is the total installed capacity of the power system in MW.

The inertia of all the power plants is affected by the WPR as explained in section 4.2.

# 6. Modelling

## 6.1. Wind turbine

The turbine of the model is an adaptation of a VSWT (GE 3.6 MW) developed in [18], [9] and [8]. The objective is to represent an approximation of the behaviour of a wind turbine (in this case several wind farms), which is part of a power system during a power imbalance. The objective is to evaluate the frequency, so that the model used is the One-mass model, as recommended by [8].

The design parameters of the turbine have been defined based on [9]. The main input is the wind speed, being the electrical power the main output. The equation that defines the mechanical power (in Watts) extracted by the turbine from the wind is:

$$Pmech = \frac{1}{2}\rho A C_p(\lambda, \beta) v_{wind}^3 \tag{6.1}$$

Where, ρ is the air density in kg/m3, A is the area swept by the rotor blades in $m^2$, $v_{wind}$ is the wind speed in m/sec, and $C_p$ is the power coefficient.

The power coefficient $C_p$ determines the amount of power that can be extracted (turbine efficiency) from the wind. It is calculated through the function taken from [18][1].

$$C_p(\lambda, \beta) = \sum_{i=0}^{4}\sum_{j=0}^{4} \alpha_{i,j}\beta^i\lambda^j \tag{6.2}$$

[1] See Annex A of [8] for α values.

Where β is the pitch angle in degrees and λ is the ratio (dimensionless) of the rotor blade tip speed ($w_t$) and the wind speed ($v_{wind}$):

$$\lambda = R\frac{w_t}{v_{wind}} \tag{6.3}$$

Where R is the radius of the turbine in m. See [9] for parameters of the WT.

Increasing the pitch angle reduces the power coefficient, so it is a way to control the output power. In order to simplify the model the value of β has been set to zero because in the simulations of this project it is not necessary to reduce the wind power. In this case the maximum value of Cp is around 0.52. Figure 8 shows the behaviour of Cp when β is zero.

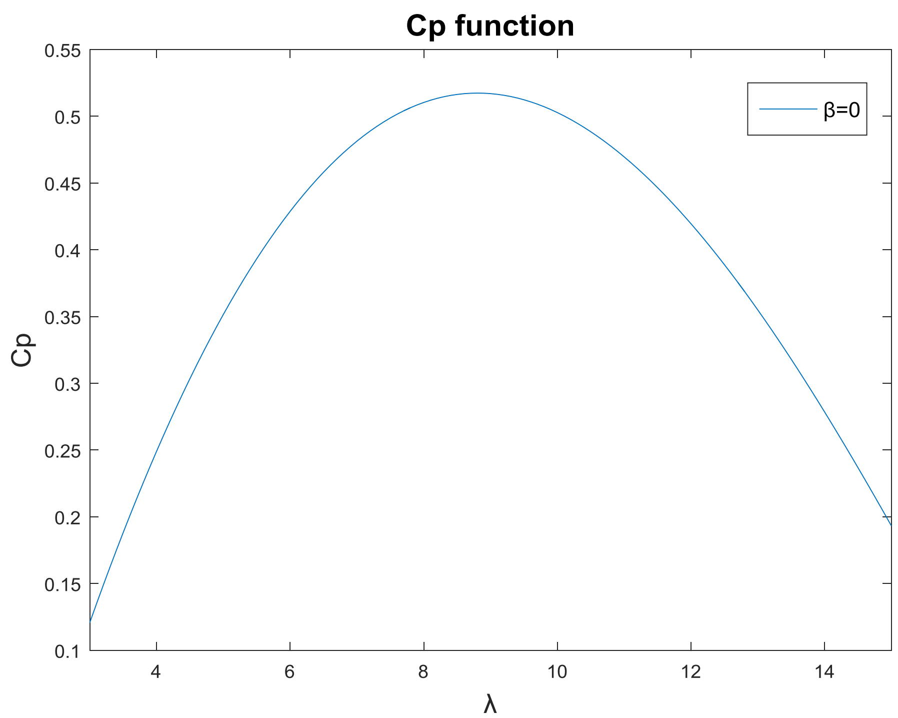



*Figure 8: Power coefficient for different values of λ and β = 0*

The algorithm used to calculate the value of $C_p$, does not provide proper approximations for values of λ below 3, where the calculated values of $C_p$ are negative. Thus, the value of λ has been limited from 3 to 15. However, it is not a problem because at low values of λ, the rotor speed would hit the minimum value of 0.7 pu, and the turbine would be automatically disconnected.

To maximize the power output the turbine speed must match the reference speed. This reference is intended in order to reach the MPPT and it is calculated using the measured electrical power, according to [9].

$$w_{ref} = -0.67P_{ef}^2 + 1.42P_{ef} + 0.51 \tag{6.4}$$

Where $P_{ef}$ is the measured electrical power in pu ($P_{BASE}$ = 3.6 MW), after passing through a first order transfer function with a time constant $T_f$ of 5 seconds.

Figure 9 shows the Simulink block diagram of the WT.

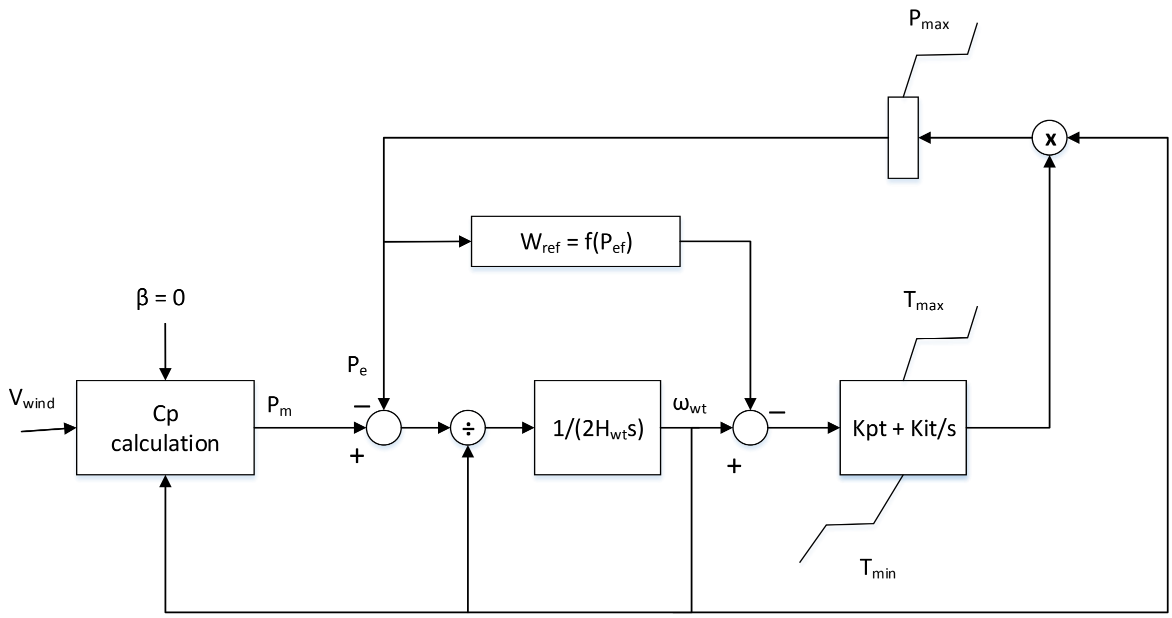



*Figure 9: Block diagram of VSWT [18], [8]*

A PI controller is implemented in order to ensure a zero error in the speed and to calculate the electrical torque of the WT.

The frequency deviation of the system is calculated using the following formula

$$T_m - T_e = 2H_{wt}\frac{d\omega}{dt} \tag{6.5}$$

Where $T_m$ is the mechanical torque caused by the wind in pu, $T_e$ is the electrical torque of the generator in pu, $H_{wt}$ is the inertia constant of the WT in seconds and $\frac{d\omega}{dt}$ is the derivative of the frequency which represents the frequency change when the electrical and the mechanical torques do not match.

The parameters of the model are shown in Table 4.

*Table 4: Parameters of VSWT*

| **Parameters** | **Value** |
|---|---|
| Kpt | 3 |
| Kit | 0.3 |
| Tf | 5 s |
| Hwt | 5.19 |
| Tmin | 0 |
| Tmax | 8.33 |
| Pmax | 1 |

Figure 10 show the behaviour of the electrical and the mechanical power for different wind speeds.

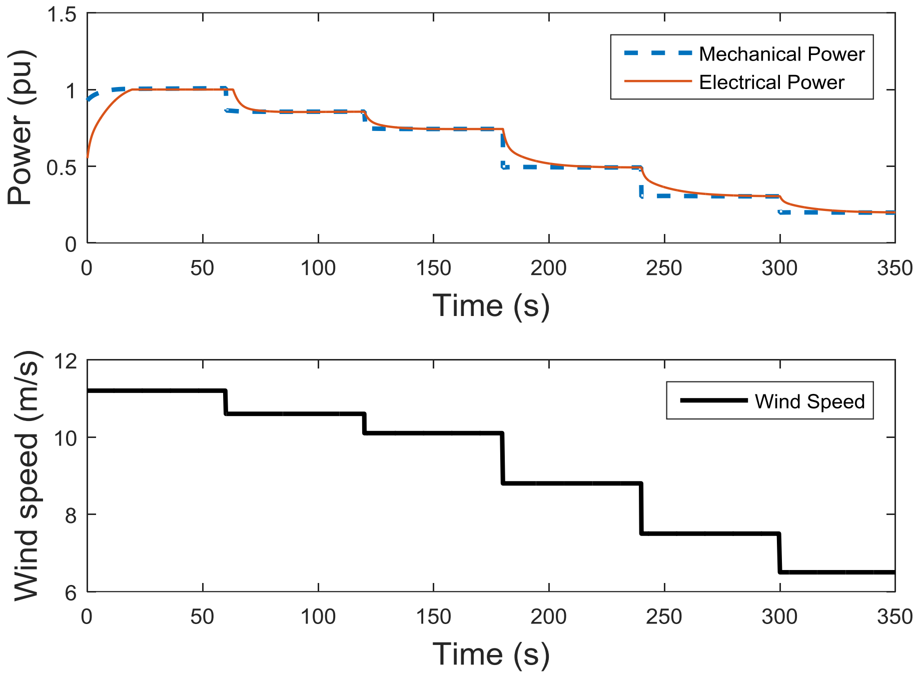



*Figure 10: Power response of WT for different wind speeds*

The different power values match with the reference values shown in [9]. Therefore, the model works as expected. It can be seen in the figure that the mechanical power has an instant response to wind speed changes. Otherwise, the electrical power needs a certain time to reach the operation value due to the inertia of the WT, the PI controller and the time constant $T_f$.

## 6.2. Responding units

The Simulink models of the different responding units are taken from those explained in [5]. All of them have the same structure, where the represented elements are the speed governor, turbine, droop characteristic and generator.

The speed governor block provides the primary speed control function as it is a representation of the gate position controller. The mechanical power is measured from the turbine block output. The difference between the mechanical power and the load power is the input of the generator block, which provides the frequency deviation (see formula 3.1 from Section 3.1). The loop is closed with the droop characteristic block, which determines the amount of extra power that generation units provide when a frequency deviation occurs.

A basic structure of a generation unit is detailed explained in [5].

### 6.2.1. Hydro unit

The hydro unit has been modelled in accordance with [5][2]. Due to water inertia, just after a change in gate position the power variation will be opposite to that desired. This problem is emulated adding a large transient droop, as a rate feedback, which also ensures a stable control performance. In the model this compensation is represented as a block between the turbine and the generator blocks. The result is a speed governor with a high droop for fast speed deviations and with a normal low droop for steady state [5].

[2] A detailed description of block diagrams and functional operation is shown in [5], p. 599-600 and p. 394-418 respectively

The block diagram is shown in Figure 12 and the parameters are observables in Table 5.

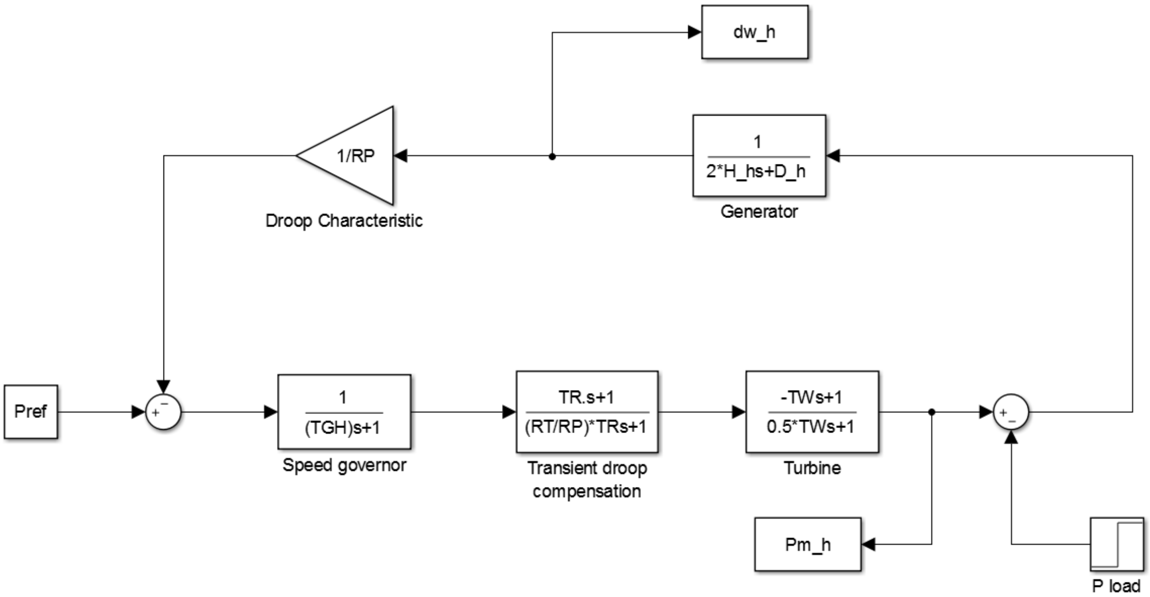



*Figure 11: Block diagram for the hydro unit [5].*

*Table 5: Parameters for the Hydro unit[5].*

| Parameter | Value |
|---|---|
| $R_H$ | 0.05 |
| $T_{GH}$ | 0.2 s |
| $T_W$ | 1.0 s |
| $R_P$ | 0.05 |
| $R_T$ | 0.38 |
| $T_R$ | 5.0 s |
| $D_h$ | 1.0 |
| $H_h$ | 3.0 |

### 6.2.2. Reheat and thermal units

The thermal unit is based on a conventional cycle power plant fired by coal while the reheat unit is based on a combined cycle power plant fired by natural gas. Both units have been modelled in accordance with [5][3].

In these cases there are no peculiarities as water inertia of the hydro unit, so governing requirements are simpler. The block diagrams of Figures 13 and 14 include the representation of speed governor, turbine and load control. Both models are identical except for the turbine block. Parameters for both models are observable in Tables 6 and 7.

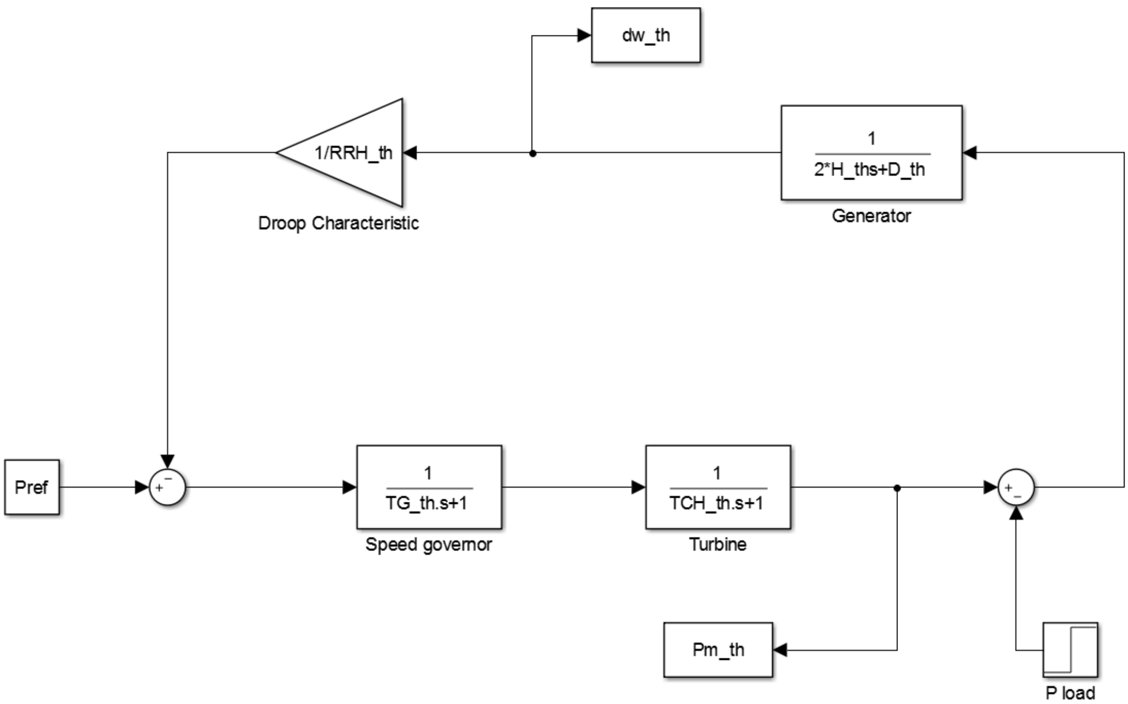



*Figure 12: Block diagram for the thermal unit [5].*

[3]A detailed description of block diagrams and functional operation is shown in [5], p. 598-600 and p. 424-448 respectively

*Table 6: Parameters for thermal unit [5].*

| Parameter | Value |
|---|---|
| $R_{RH}$ | 0.05 |
| $T_G$ | 0.2 s |
| $T_{CH}$ | 0.3 s |
| $D_{th}$ | 1.0 |
| $H_{th}$ | 3.0 |

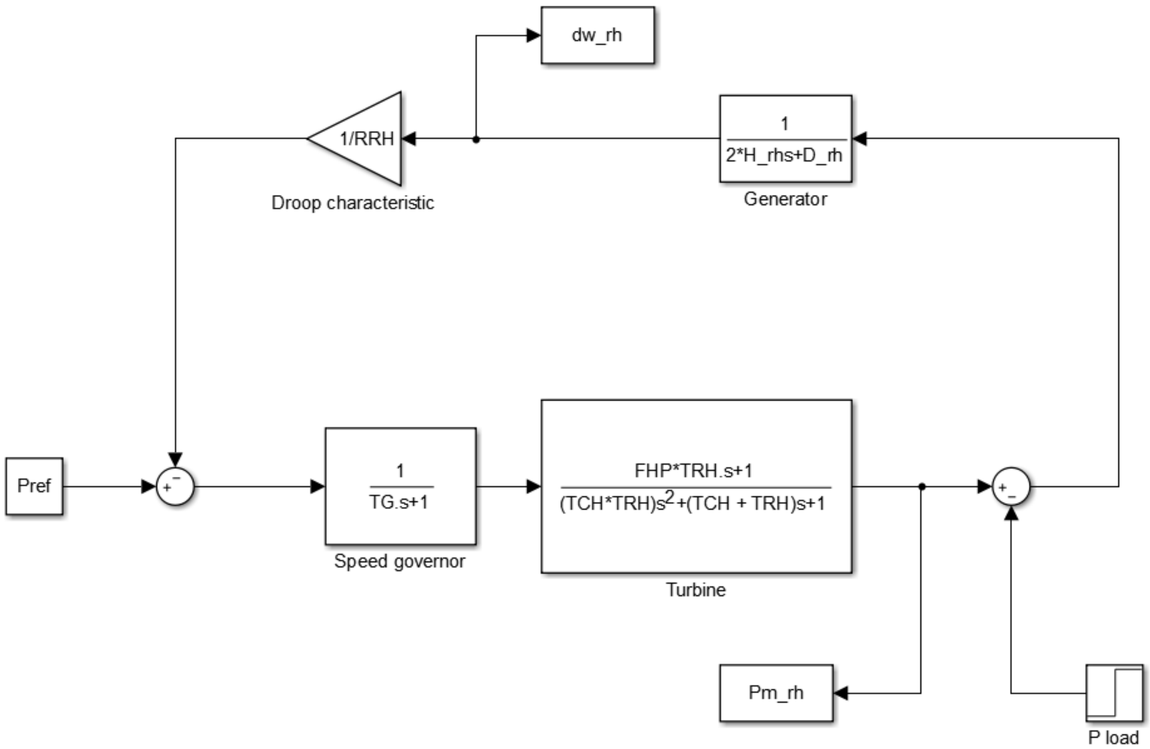



*Figure 13: Block diagram of the reheat unit [5].*

*Table 7: Parameters for reheat unit [5].*

| Parameter | Value |
|---|---|
| $R_{RH}$ | 0.05 |
| $T_G$ | 0.2 s |
| $F_{HP}$ | 0.3 |
| $T_{RH}$ | 7.0 s |
| $T_{CH}$ | 0.3 s |
| $D_{rh}$ | 1.0 |
| $H_{rh}$ | 3.0 |

### 6.2.3. Load and other generators

A power imbalance in the power system is modelled as a load step. This increase has similar size as the largest generator in the Spanish power system (in this case a nuclear power plant of 1100 MW). Power imbalance is fixed, through the droop control, by a power increase from responding units.

Non-responding units are represented as only a part of the inertia constant, as they cannot participate directly in frequency support. The output power of these units is included in the load, reducing the demand.

## 6.3. Validation of the model

Figure 14 shows the droop response of the responding units to a load increase of 1 pu. This matches with the result shown in [5], so the units are operating as expected.

It can be seen that the thermal unit has the fastest droop response and it is also possible to appreciate the effect of water inertia in the hydro response.

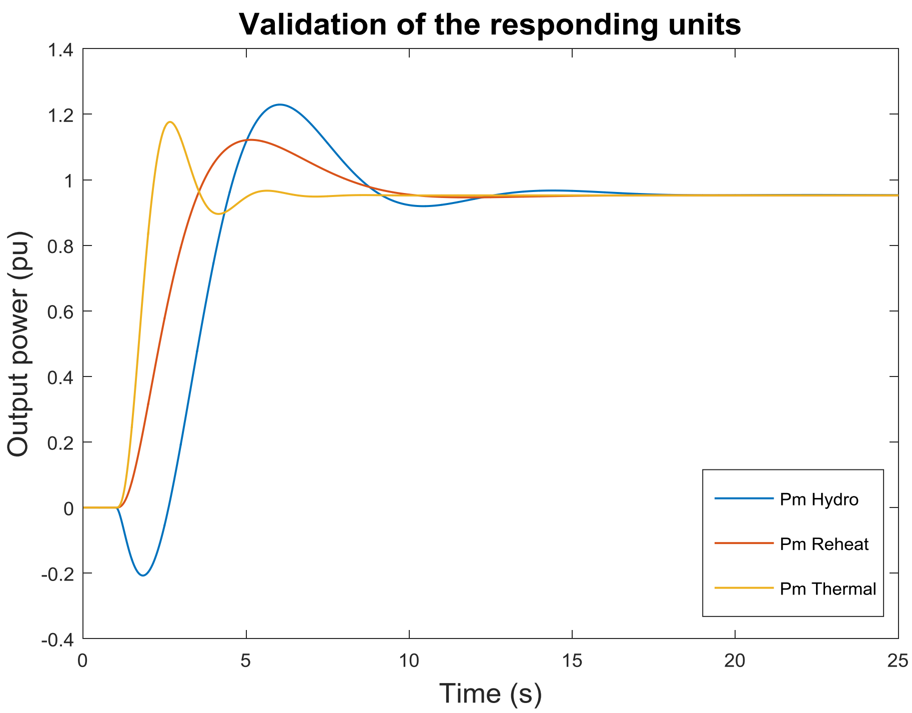



*Figure 14: Power response of responding units to a sudden increase in the load*

## 6.4.System block diagram

All the generators of the power plants are represented as only one generator, with an equivalent inertia constant (see section 5.4.1). The system generator input is the error between generation and consumption, so the generation units and the load are connected throughout a power balance. A change in the generator speed is equivalent to a change in system frequency [5]. After a power imbalance, the load increase is equally shared between the units due to their droop characteristics. The value of the damping constant of the system is set to 1, as it is a typical value shown in [5].

Figure 15 shows a representation of the system block diagram.

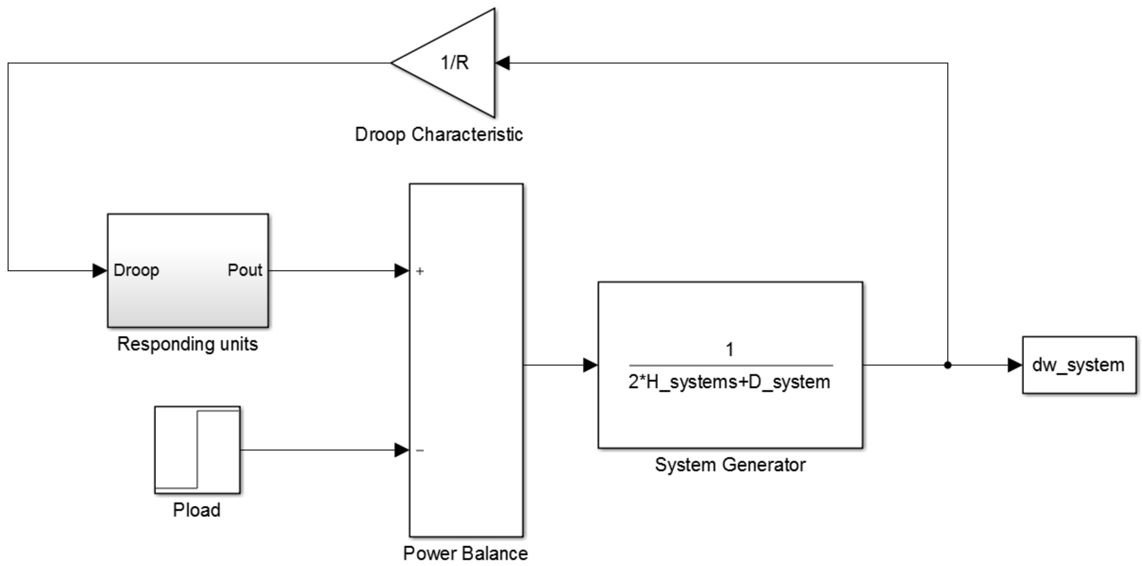



*Figure 15: Block diagram of the power system*

# 7. Simulation results

## 7.1. Introduction

The aim of the project is to evaluate if it is possible to perform frequency support by WT when the contribution of the thermal units is reduced. The simulation can represent an approximation of a future scenario where the wind power replaces partially these responding units. The main problem is to face the lack of inertia and droop response capability and to deal with high WPR levels.

In the first moment, only the coal power plants will be disconnected, as they produce more $CO_2$ emissions and they are less efficient than the combined cycle power plants. In this scenario the power imbalance is supplied by the hydro and the reheat units.

In the next simulations, the reheat unit will be also cut off. This scenario will simulate a generation structure where the frequency support is performed completely by renewable energy sources.

The WPR will also increase, from 30% to 50%, in order to simulate the worst case scenario. The extra power provided by the wind turbines will be released using the wind support strategies explained in Section 3.2, and the performance of each strategy will be compared. The wind speed is assumed to be constant during the frequency event.

## 7.2. Reducing number of responding units

The loss of thermal units implies two main consequences, a reduction in the system inertia and in the speed of response after a power imbalance.

The load variation is equally shared between the responding units due to the droop characteristic of each generator. Therefore, if the number of generators with this characteristic is reduced, the load variation is shared between fewer units, making the droop response slower.

Figure 16 shows this response after a load increase of 5%. The graphs show the behaviour of the system with and without the thermal units.

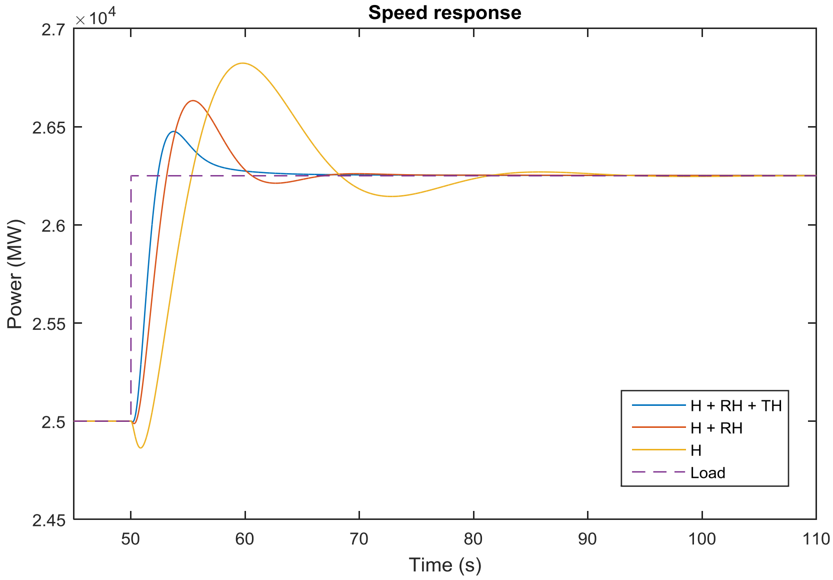



*Figure 16: Droop response of different combination of responding units to a load step of 5%*

The negative effects are observable, being the system with only the hydro generator as a responding unit the worst case scenario. In this case the power variation is faced completely by the hydro unit.

## 7.3.Simulation parameters

The load level is set to 25000 MW, as it could be a typical low demand value in the Spanish power system [3]. This demand will be common for all simulations such as a load change of 5%. This means an increase of 1250 MW, which represents the loss of the largest generator of the power system.

Table 8 shows the load level for all the scenarios.

*Table 8: Demand values and load step*

| | **WPR = 30%** | | **WPR = 50%** | |
|---|---|---|---|---|
| | H + RH | H | H + RH | H |
| **Demand** | 25000 MW | 25000 MW | 25000 MW | 25000 MW |
| **Load increase** | 1250 MW (5%) | 1250 MW (5%) | 1250 MW (5%) | 1250 MW (5%) |

There are many freedom degrees in order to choose the different parameters used for the wind support strategies.

The instant power support can cause an over frequency if wind power production is high and the load level is small. In order to avoid this problem, the extra power delivered will increase a 2.5% of the reference value during the deceleration period. This period is limited to 9 seconds and the normal control function is switched on again after 25 seconds.

In order to compare the results of both strategies, the amount of extra power provided by both of them must be similar. The value of the constant K of the inertia emulation support will be set to meet this requirement. As explained in Section 3.2.2, the amount of extra power of the inertia emulation support depends of the derivative of the frequency. So the value of K will be affected by the variations in the inertia of the system, the WPR value and the droop response. Table 9 shows the parameters of both WT support strategies.

*Table 9: Parameters for wind power support strategies*

| | WPR = 30% | | WPR = 50% | |
|---|---|---|---|---|
| | H + RH | H | H + RH | H |
| **Instant power increase** | 2.5% | 2.5% | 2.5% | 2.5% |
| **Inertia emulation K** | 5 | 1.25 | 8 | 2.5 |

## 7.4. Analysis and discussion of results

### 7.4.1. Scenario A: Hydro and Reheat units, WPR = 30%

The generation structure of this scenario is shown in Table 10.

*Table 10: Generation structure, hydro and reheat units operating, WPR = 30%*

| | Output power (MW) | |
|---|---|---|
| **Hydro** | 3000 | 12% |
| **Reheat** | 2000 | 8% |
| **Wind** | 7500 | 30% |
| **Non-responding units** | 12500 | 50% |
| **Total** | 25000 | |

This generation mix provides a system inertia constant of 1.9 seconds. The wind speed required to produce 7500 MW of wind power is 7.7 m/s.

Figure 17 shows the system frequency response of the three simulated cases.

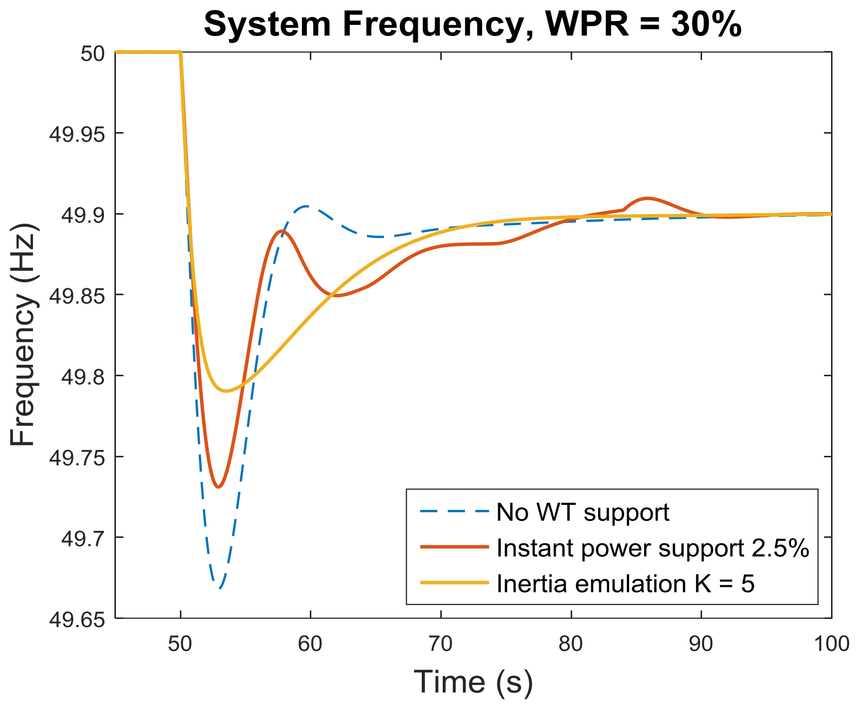



*Figure 17: Frequency nadir for different strategies. Hydro and reheat units operating, WPR = 30%*

The nadir presents an improvement with both support strategies. It can be seen that with the inertia emulation strategy the nadir is better and the frequency stabilizes in an acceptable time period. When the instant power support is applied, the nadir improves too, but the stabilization time is longer. With this strategy, the jump from the deceleration part to the re-acceleration part causes a second frequency dip. The new pattern designed reduces this effect, but it is still observable.

An approached view of the frequency drop during the first seconds is shown in Figure 18. The nadir improvement is presented in Table 11.

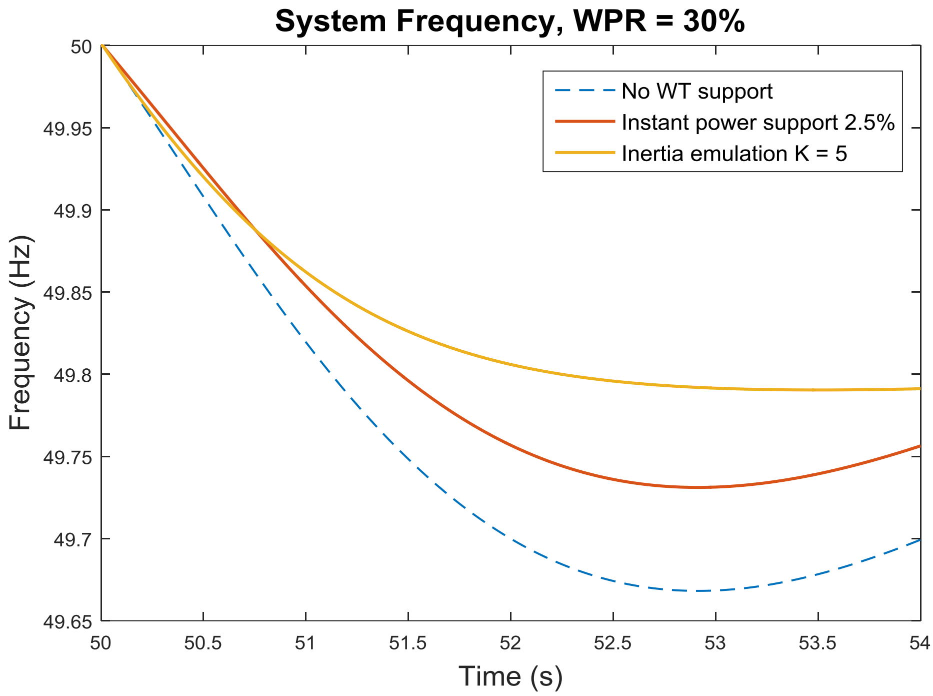



*Figure 18: Enhanced view of nadir for different strategies. Hydro and reheat units operating, WPR = 30%*

*Table 11: Nadir improvement, hydro and reheat units operating, WPR = 30%*

| | **Nadir** | **Improvement** |
|---|---|---|
| **No WT support** | 49.67 Hz | - |
| **Instant power support** | 49.73 Hz | 0.06 Hz |
| **Inertia emulation support** | 49.79 Hz | 0.12 Hz |

The evolution of the output power of the turbine and the rotor speed are shown in Figure 19.

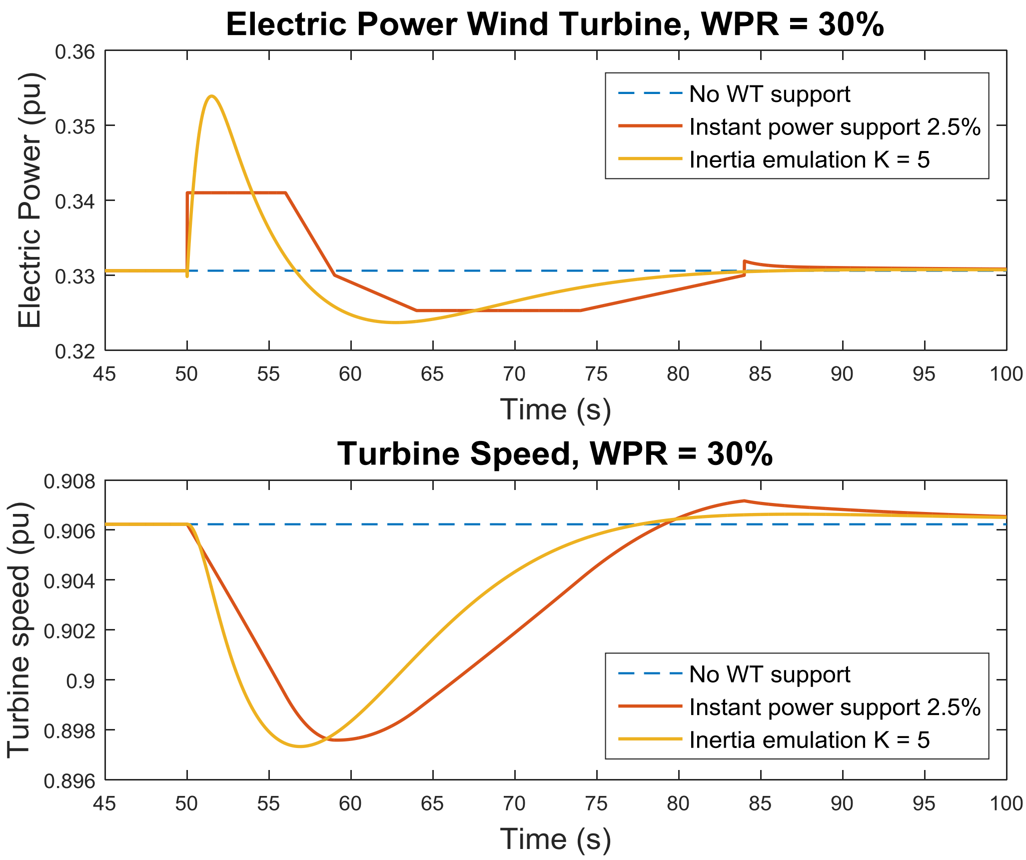



*Figure 19: Deceleration and re-acceleration areas and rotor speed. Hydro and reheat units operating, WPR = 30%*

It can be seen that both deceleration areas look similar, but the peak value of the released power by the inertia emulation support is higher. It explains the better nadir reached with this strategy. When the re-acceleration area is over, the turbine requires of a few extra seconds to stabilize because the power balance between areas is not perfect. The minimum rotor speed is far from hitting the minimum allowed speed of 0.7 pu, so it would be possible to extract more power before the WT snaps off.

Figure 20 shows the power response of the responding units after the load step.

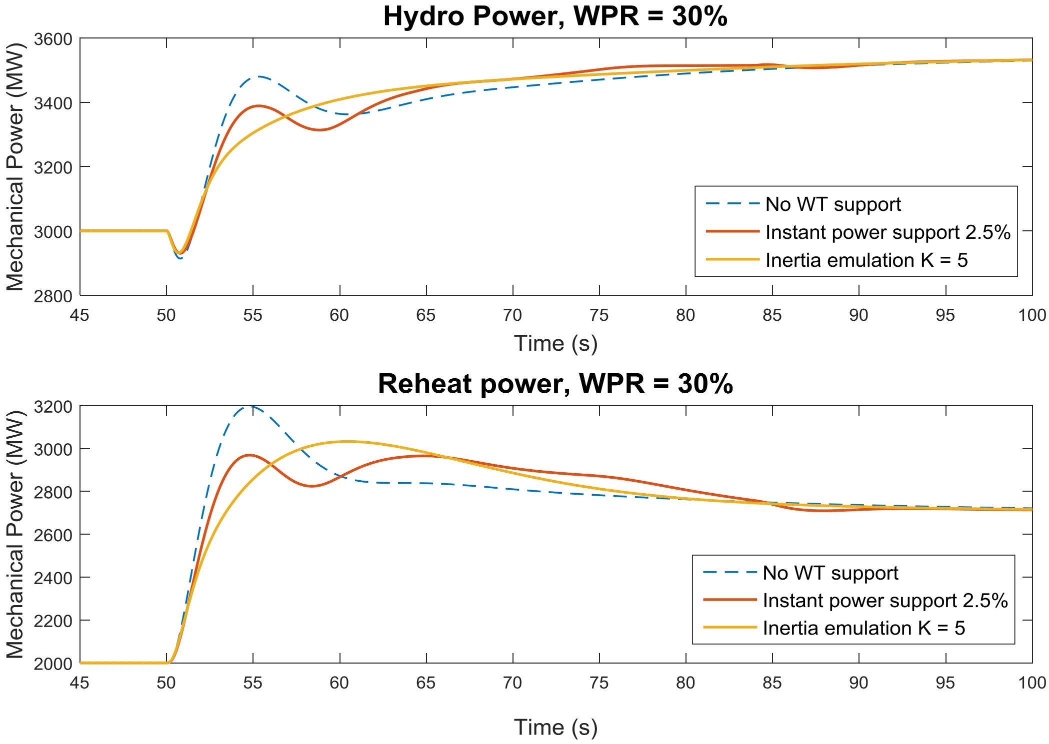



*Figure 20: Droop response of hydro and reheat units, WPR = 30%*

### 7.4.2. Scenario B: Hydro and Reheat units, WPR = 50%

In this scenario the wind power production increase a 20%, supplying the half of the demand. The other units reduce their power production, as shown in Table 12.

*Table 12: Generation structure, hydro and reheat units operating, WPR = 50%*

| | **Output power (MW)** | |
|---|---|---|
| **Hydro** | 1750 | 7% |
| **Reheat** | 750 | 3% |
| **Wind** | 12500 | 50% |
| **Non-responding units** | 10000 | 40% |
| **Total** | 25000 | |

The increase in the WPR is produced by an increase in the wind speed. In this scenario the wind speed is 9.1 m/s. An increase in the WPR implies a reduction in the system inertia, as explained in Section 4.1. In this scenario the system inertia is 1.4 seconds.

In Figure 21 frequency response for different strategies are shown.

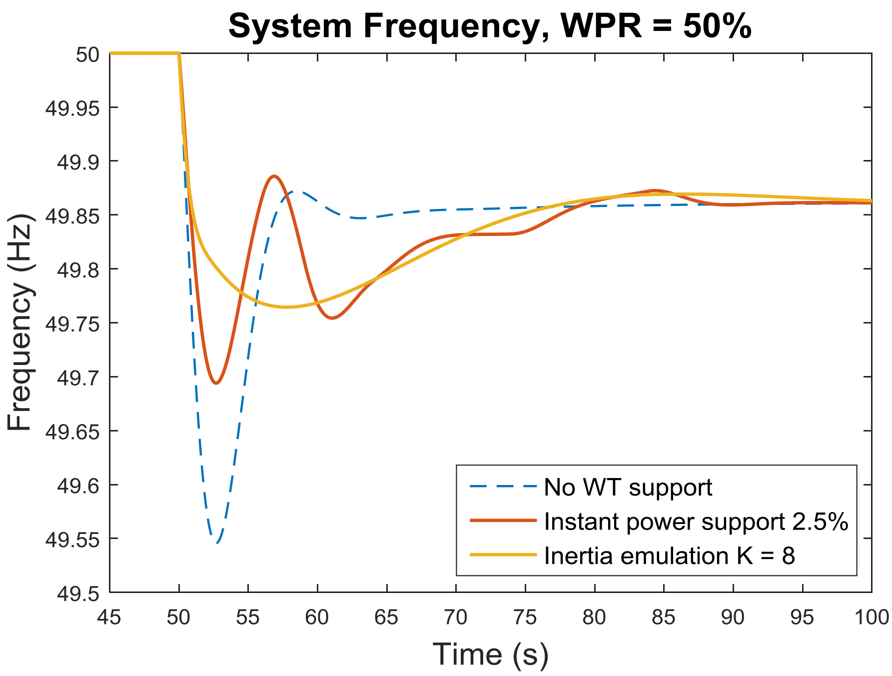



*Figure 21: Frequency nadir for different strategies. Hydro and reheat units operating, WPR = 50%*

The negative consequences caused by the higher WPR can be appreciated. The nadir improves because of the extra power delivered during the first seconds after the load increase. But the lack of inertia and the increase of WPR produce different problems for each strategy. The inertia emulation support presents a better nadir but the frequency needs more time to stabilize. On the other hand, when the instant power support is applied the frequency stabilizes faster. The main problem with this strategy is the second frequency dip. When the WPR is too high this second nadir can become even worse than the first one. The new pattern cannot avoid this problem.

The improvement of the nadir is measured in Table 13, and a better view of the first seconds after the step is shown in Figure 22.

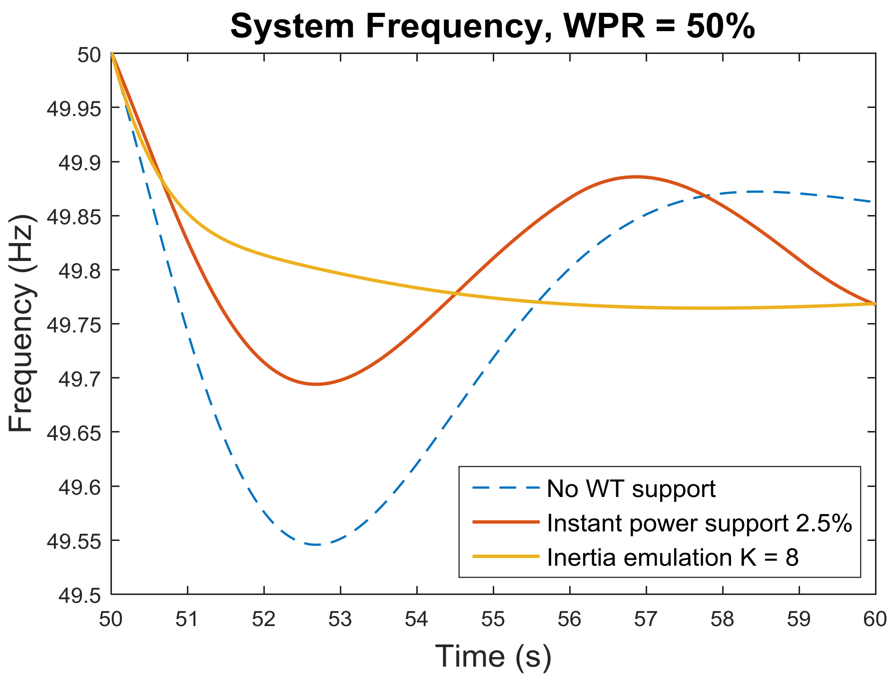



*Figure 22: Enhanced view of nadir for different strategies. Hydro and reheat units operating, WPR = 50%*

*Table 13: Nadir improvement, hydro and reheat units operating, WPR = 50%*

| | Nadir | Improvement |
|---|---|---|
| **No WT support** | 49.55 Hz | - |
| **Instant power support** | 49.69 Hz | 0.14 Hz |
| **Inertia emulation support** | 49.76 Hz | 0.21 Hz |

The evolution of the output power of the turbine and the rotor speed are shown in Figure 23.

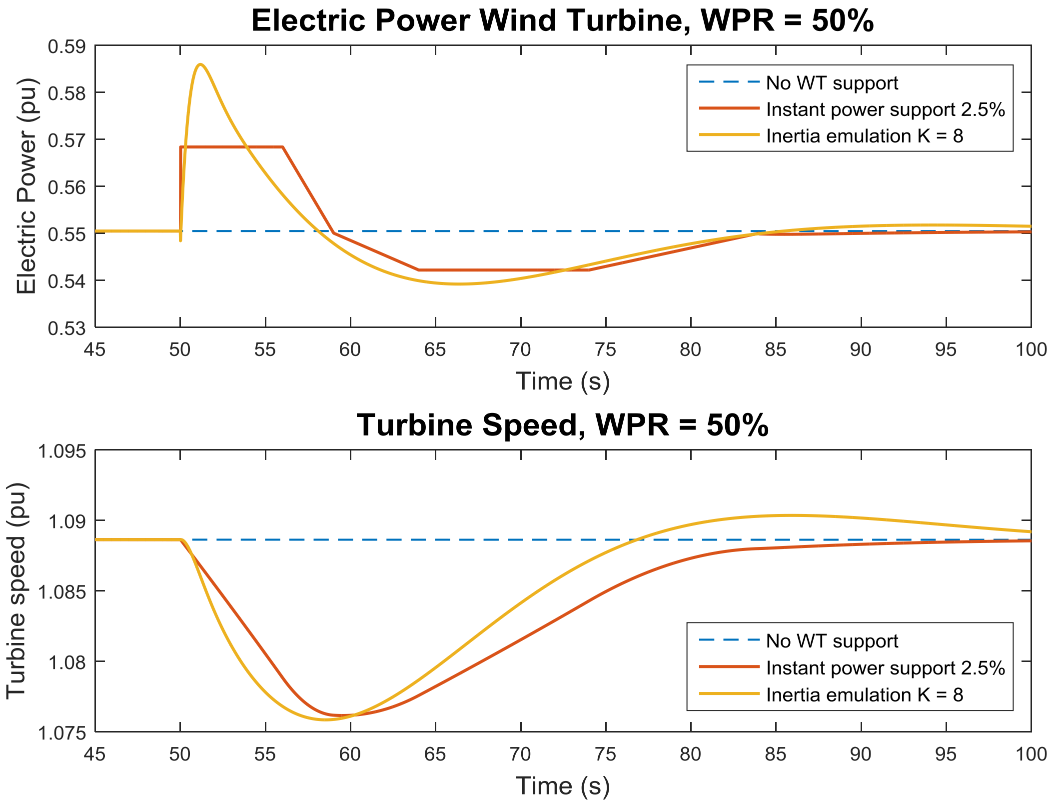



*Figure 23: Deceleration and re-acceleration areas and rotor speed. Hydro and reheat units operating, WPR = 50%*

In this case the speed error is larger with the inertia emulation support. The WPR affects the power balance of this strategy, making the frequency response slower. The deceleration areas of both strategies look to be similar, as the minimum speed in both cases is almost the same. The minimum wind speed remains always above the minimum allowed.

Figure 24 shows the power response of the responding units after the load step.

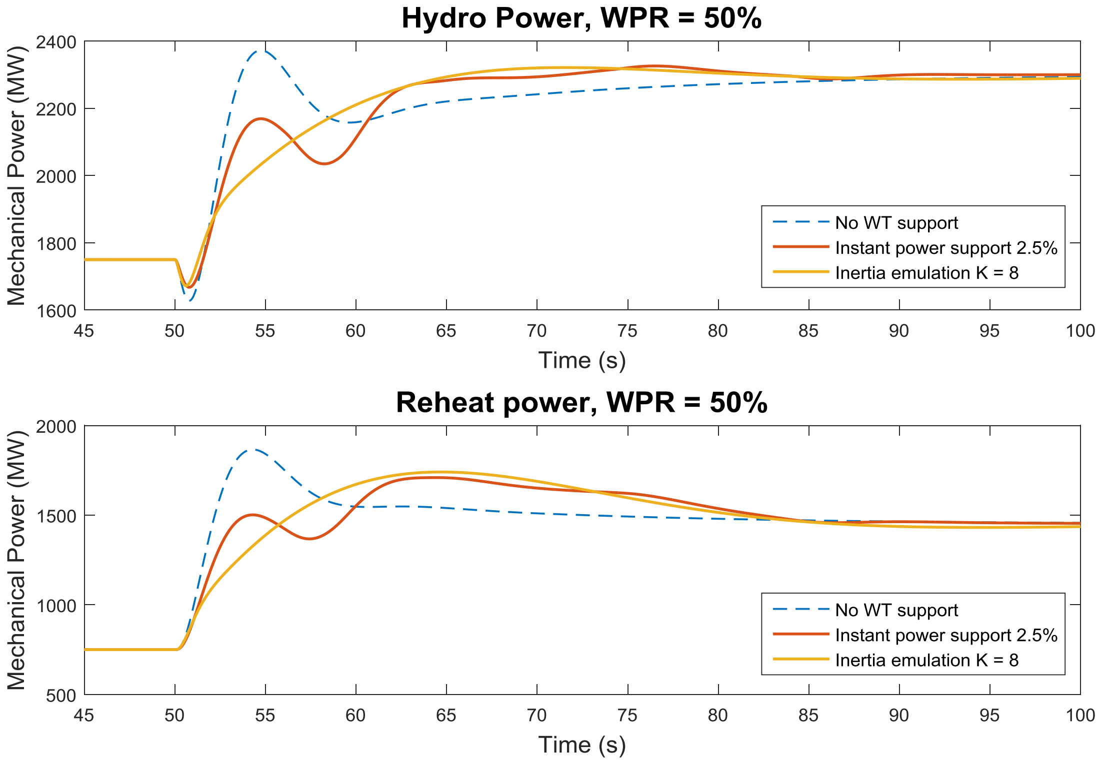



*Figure 24: Droop response of hydro and reheat units, WPR = 50%*

### 7.4.3. Scenario C: Hydro unit, WPR = 30%

For the next two scenarios the reheat unit is also cut off. The generation mix for this case is shown in Table 14.

*Table 14: Generation structure with the hydro unit operating, WPR = 30%*

| | Output power (MW) | |
|---|---|---|
| **Hydro** | 5000 | 20% |
| **Wind** | 7500 | 30% |
| **Non-responding units** | 12500 | 50% |
| **Total** | 25000 | |

In this scenario the wind speed is also 7.7 m/s and the only difference with the scenario A is the disconnection of the reheat unit. The inertia of the system is 1.4 seconds.

The evolution of the system frequency is shown in Figure 25.

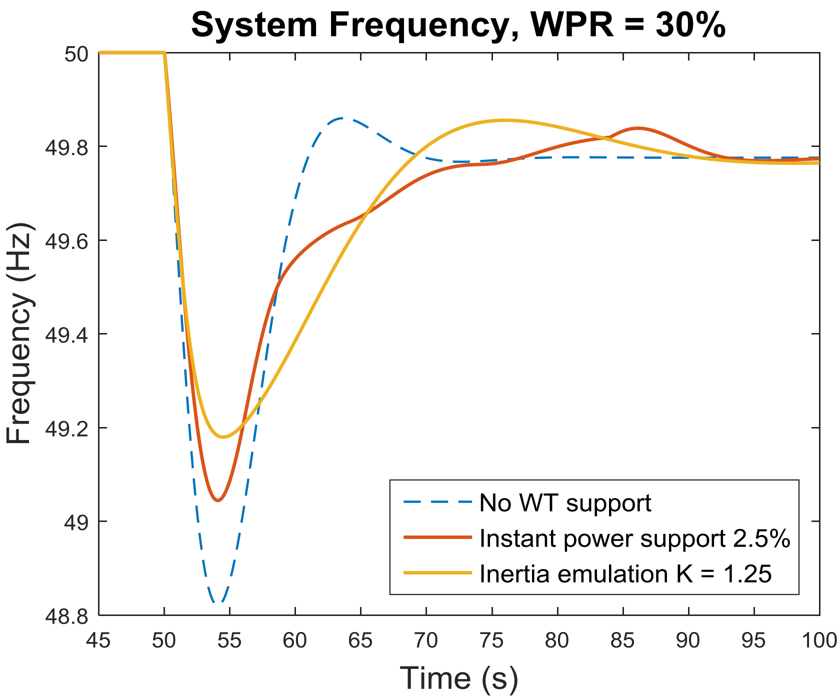



*Figure 25: Frequency nadir for different strategies. Hydro unit operating, WPR = 30%*

The loss of another responding unit means a reduction in the power reserves, a loss of droop response capability. The frequency drops more than 1 Hz without applying any WT support strategies. The inertia emulation support presents the best nadir and both strategies have similar speed of response. The improvement with both strategies is noticeable and the general performance looks acceptable.

Table 15 shows the nadir improvement. A better view of the frequency drop is observable in Figure 26.

*Table 15: Nadir improvement, hydro unit operating, WPR = 30%*

| | Nadir | Improvement |
|---|---|---|
| **No WT support** | 48.82 Hz | - |
| **Instant power support** | 49.04 Hz | 0.22 Hz |
| **Inertia emulation support** | 49.18 Hz | 0.36 Hz |

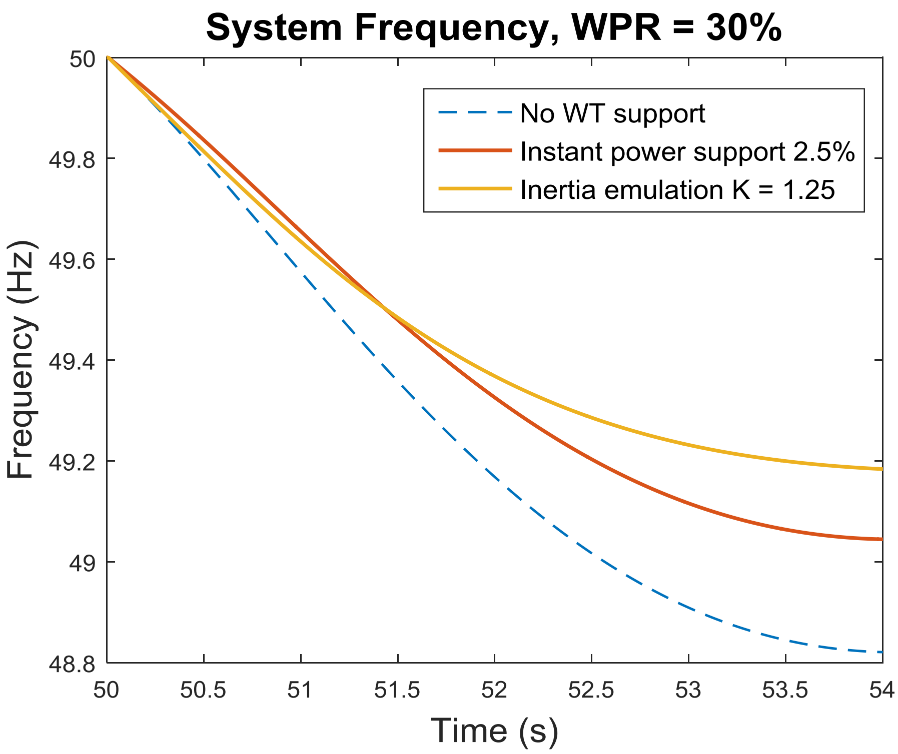



*Figure 26: Enhanced view of nadir for different strategies. Hydro unit operating, WPR = 30%*

The evolution of the output power and the rotor speed of the turbine is presented in Figure 27.

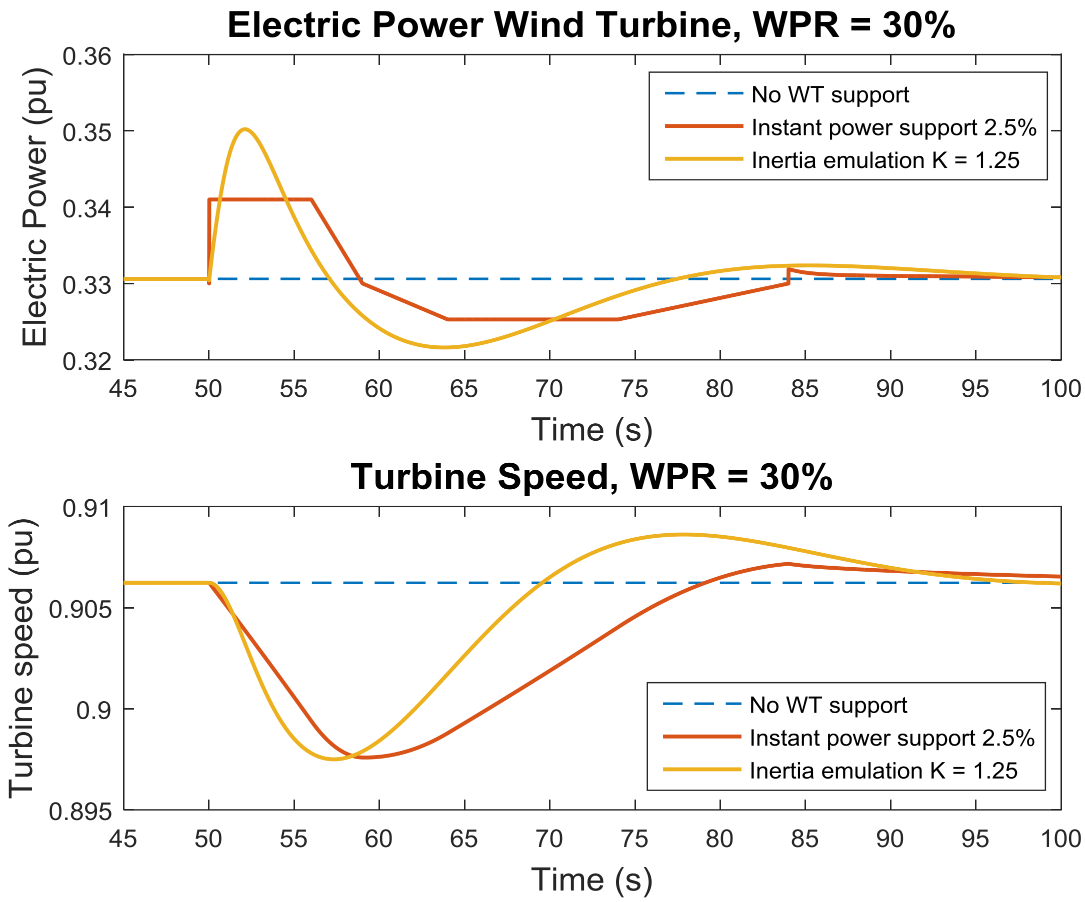



*Figure 27: Deceleration and re-acceleration areas and rotor speed. Hydro unit operating, WPR = 30%*

The amount of delivered power is similar in both graphs, and the minimum speed is over the limit. In this case the power imbalance is not really effective, especially when the inertia emulation is used. When this strategy is operating the speed error after the re-acceleration area is important, causing a slower response.

The power response of the hydro unit is show in Figure 28.

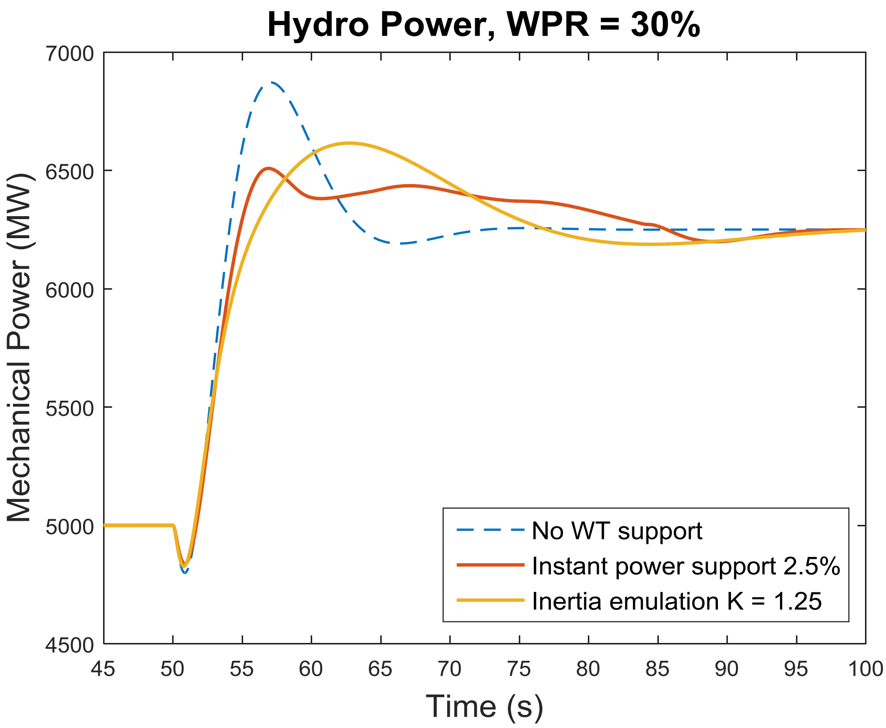



*Figure 28: Droop response of hydro unit, WPR = 30%*

### 7.4.4. Scenario D: Hydro unit, WPR = 50%

In this scenario the wind power production increase to 50%, meaning a reduction of the contribution of the other units. Table 16 shows the generation mix of this case.

*Table 16: Generation structure, hydro unit operating, WPR = 50%*

| | Output power (MW) | |
|---|---|---|
| **Hydro** | 2500 | 10% |
| **Wind** | 12500 | 50% |
| **Non-responding units** | 10000 | 40% |
| **Total** | 25000 | |

The wind speed is set to 9.1 m/s again. This is the worst case scenario, where the thermal units do not provide inertia to the system and the WPR is the highest. The inertia constant of the system has a value of 0.9 seconds.

Figure 29 shows the frequency deviation during the frequency event.

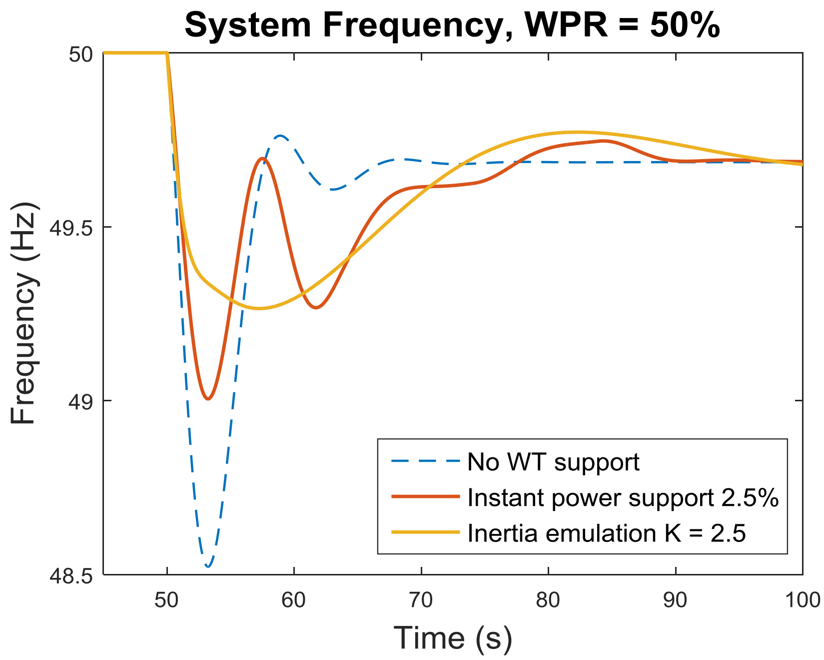



*Figure 29: Frequency nadir for different strategies. Hydro unit operating, WPR = 50%*

Due to the lack of inertia this is the worst case scenario for the nadir. When the inertia emulation support is connected the nadir is strongly reduced. Despite of this, the speed of response is slow because of the high WPR and the lack of inertia, needing more than 50 seconds to stabilize. The instant power support provides a better speed of response but the second frequency dip is important. In terms of quality it does not have an acceptable performance.

The nadir values are observable in Table 17, while an approached view of the first seconds after de step is shown in Figure 30.

*Table 17: Nadir improvement, hydro unit operating, WPR = 50%*

| | Nadir | Improvement |
|---|---|---|
| **No WT support** | 48.52 Hz | - |
| **Instant power support** | 49.01 Hz | 0.49 Hz |
| **Inertia emulation support** | 49.26 Hz | 0.74 Hz |

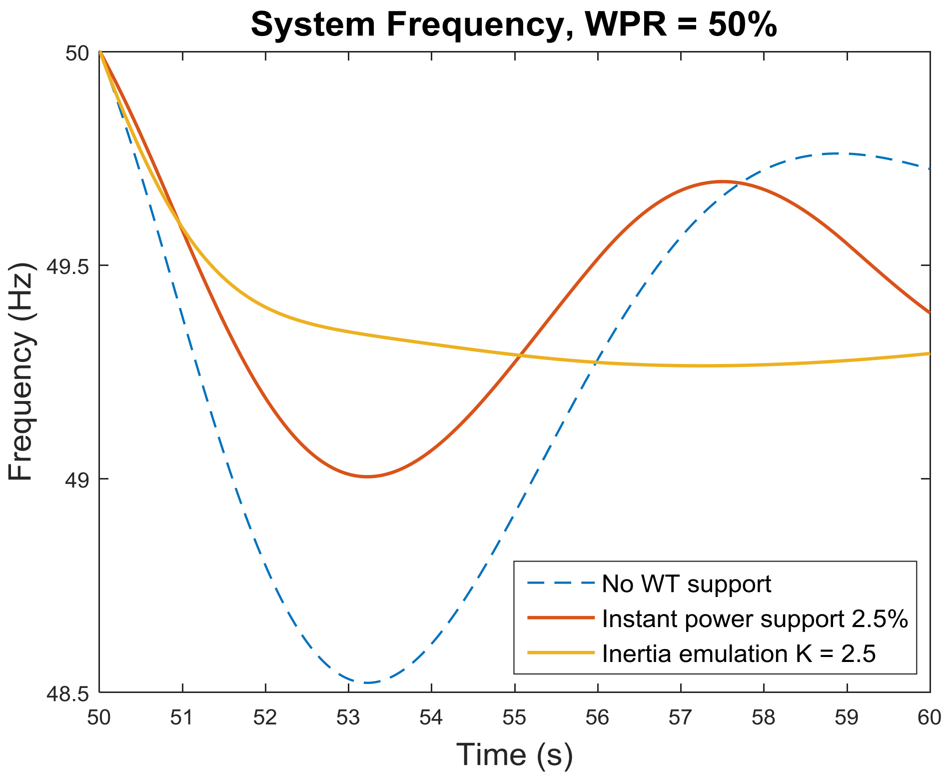



*Figure 30: Enhanced view of nadir for, different strategies. Hydro unit operating, WPR = 50%*

Figure 31 shows the output power and the rotor speed of the wind turbine.

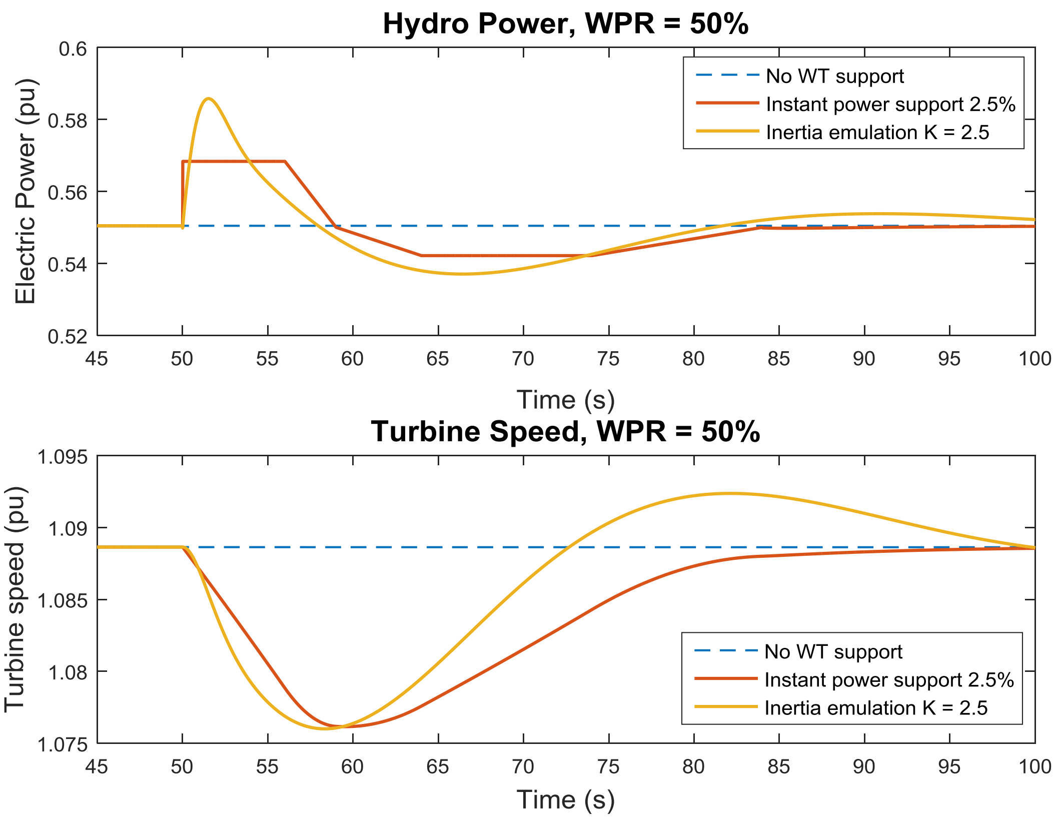



*Figure 31: Deceleration and re-acceleration areas and rotor speed. Hydro unit operating, WPR = 50%*

The power balance is more effective when the operating strategy is the instant power support. It explains the faster response. The inertia emulation support can deliver a larger extra power at the beginning, but it causes a large speed error.

The power response of the hydro unit can be seen in Figure 32.

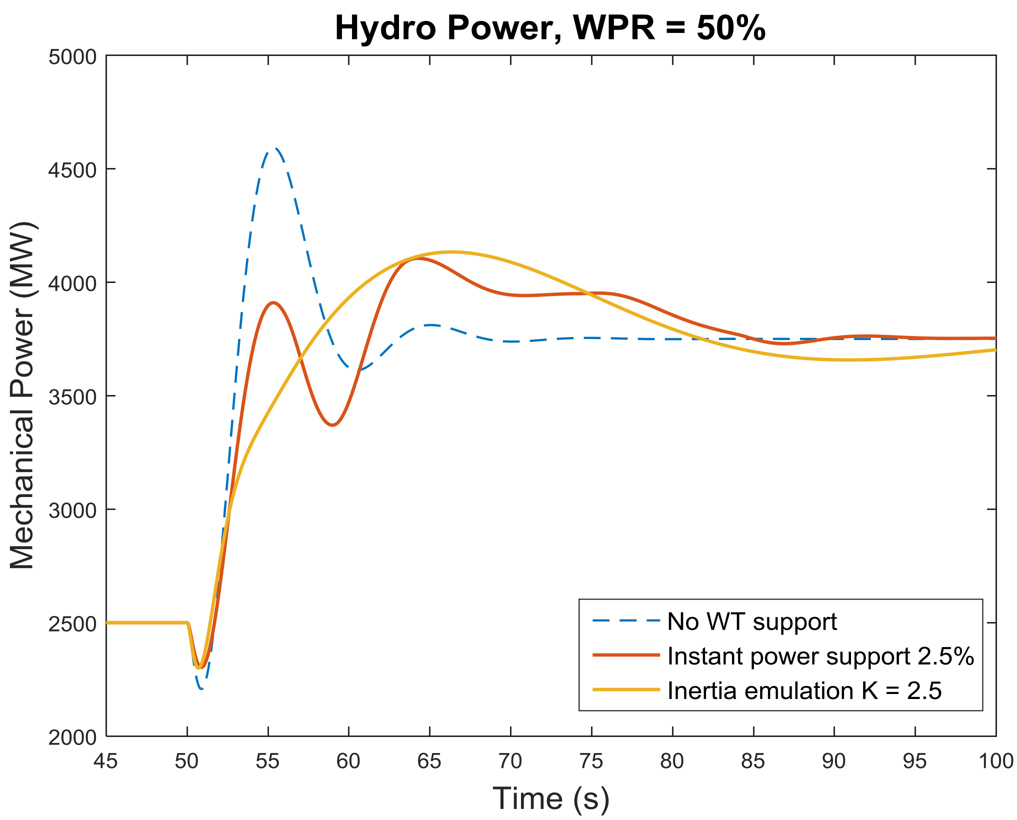



*Figure 32: Droop response of hydro unit, WPR = 50%*

# 8. Discussion and limitations

## 8.1. Discussion

The results show that the main contribution of frequency support by WT is the improvement of the nadir. Nevertheless, there are also negative consequences affecting the speed of response. Depending of the support strategy applied these negative effects might be different.

When the inertia emulation support is implemented the nadir improvement is generally more significant. The peak value of the extra power released during the deceleration area is higher, providing the same amount of power in a shorter time. Nonetheless, the re-acceleration period must be longer in order to carry out the power balance of the areas and it is not really effective when the inertia is low. The time to reach the steady state frequency is especially longer at high WPR levels.

Normally the nadir improvement is lower when the instant power support is operating. This strategy allows controlling the exact size of the deceleration and re-acceleration areas, improving the power balance between them. The required time to reach the new frequency value after the disturbance is shorter, even when the WPR is high. However, when the re-acceleration area starts, the power step between areas causes a second frequency dip. This ‘second nadir’ is especially significant when the WT is producing a large amount of power. This effect can be reduced changing the pattern of the control signal, but it cannot be completely fixed.

Both strategies present different advantages and disadvantages for each scenario.

When the WPR is 30% the inertia emulation support provides a better performance. The nadir improvement is better and the speed of response is acceptable, even when the reheat unit is disconnected.

Instead, the duration of the power areas of instant power support causes a slower response. Otherwise, this strategy also presents an acceptable performance even in situations of lack of thermal droop response.

If the WPR increases to 50% different problems appears when the WT support strategies are connected. The speed of response of inertia emulation support becomes slower because the power balance is automatically done and it is not effective. The frequency needs too much time to stabilize even if the reheat unit is working.

On the other hand, a lower nadir improvement is achieved by using instant power support, but the speed of response is good. The main problem of this strategy is the second frequency dip, very significant when the reheat unit is not operating. With high WPR this is the only strategy that presents a performance that can be considered slightly acceptable, in Scenario B.

In addition, the instant power support can provide a constant power control signal even if the wind speed is not constant, as in reality. With a good wind forecast it could be possible to design a pattern which adapts to wind variations. Instead, the extra power released by inertia emulation support is affected by wind speed and its performance could be less effective.

## 8.2. Limitations

The WT of the model represents an approximation of several wind farms. The wind speed used in the simulation is the average speed required to produce the desired amount of power. Nevertheless, in a real scenario the wind speed of the different wind farms would be different.

During the operation of the WT support strategies the turbine is decelerated in order to work below the MPPT. However, in the simulations the rotor speed never hits the minimum speed allowed of 0.7 pu as the average wind speed used is high enough. In reality some of these turbines may be working at a low wind speed and they might not be able to provide an extra power during power disturbances.

Moreover, it is not entirely fair to compare the strategies in similar scenarios because both of them have different features. For each scenario the instant power support pattern can be redesigned in order to offer the best performance. Also the value of K can be adapted for each frequency deviation. Nonetheless, it is a good way to compare their behaviours and how each strategy provides different contribution.

# 9. Conclusions and future work

In conclusion, the studies have shown that frequency support can be improved without a part of the thermal units due to wind power contribution.

For the simulations with a WPR level of 30%, the results show a good performance with both strategies when the reheat unit is working, especially with inertia emulation support. When this unit is disconnected the performance of both strategies is acceptable but it looks to be the limit situation.

If the WPR is high (50%) only instant power support presents a performance that can be considered slightly acceptable (limit situation). When the reheat unit is also cut off, WT support cannot face the lack of inertia.

An interesting way to continue this thesis would be to implement a pitch controller in the WT, in order to expand the flexibility of the model. This could be combined with the study of strategies that optimize more WT support, in order to consider more realistic scenarios. A further study of the Spanish Grid Code could be done in order to implement more precise results. It would also be interesting to analyse the economic impact of WT support strategies, in order to realize the cost of using this technology.

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