FREQUENCY SUPPORT BY VARIABLE SPEED WIND TURBINES IN THE POWER SYSTEM OF GRAN CANARIA

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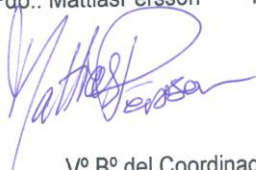
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ABSTRACT

The island of Gran Canaria is a small isolated power system that has a strong dependence on fossil fuels for electricity production. However, being the island in Spain with most wind power capacity, frequency regulation services do not take advantage of inertia support by wind turbines. Two extended inertia support methods by wind turbines (WTs), have been proposed to study the performance of WTs giving an extra active power support for a few seconds, and the evolution of the system frequency. A simple model of a primary regulation control loop for the power system of the island has been built, simulating a severe power imbalance. Both controls have managed to improve the frequency evolution of the system for a power loss of 25% of the load level with respect to its evolution without the inertia support from the WTs.

Key words: Wind Turbine (WT), Wind Power Ratio (WPR), Maximum Power Point Tracking (MPPT), frequency nadir, instant power support, inertia emulation

SUMMARY

This project analyses the power system of Gran Canaria, an isolated power system which is heavily dominated by fossil fuel technologies. Still, the island has the highest amount of installed wind power of its archipelago. Given the fact that wind does not participate in frequency regulation, the effect of implementing inertia support in variable wind speed turbines will be studied in order to allow their participation in primary regulation increasing temporarily their power output.

Firstly, the information of the main generation groups of the island and their participation in frequency regulation has been obtained. With this data, the models of these generation units have been built in Simulink.

Once the system was complete, the scenario for the simulation has been chosen at a moment of low load in the system with high wind power penetration. The information of the generation mixes has been obtained from the Spanish TSO. For the purpose of evaluating the effect of inertia support under severe conditions, the disturbance chosen was the loss of a large generation unit of 70 MW.

The results that have been obtained show that the inertia support techniques that were implemented, not only maintain the frequency stability of the system, but they are also capable of improving the temporary minimum frequency that the system reaches in the initial moments after the power imbalance. However, some other aspects such as the time to reach steady state after the disturbance worsen. It is therefore necessary to adjust the level of support of the turbines to adjust in the best possible way to the characteristics of each scenario.

Finally, additional simulations have been made in future case scenarios that will allow to grasp an idea on the effect of the frequency support by wind turbines in the near future, in which wind power is meant to increase. The results obtained are still favorable, and show the effect of increasing the proportion of wind power in the system on the response given by the turbines and the frequency evolution.

RESUMEN

En este proyecto se analiza el sistema eléctrico de la isla de Gran Canaria, un sistema aislado fuertemente dominado por tecnologías con combustibles fósiles. Aun así, la isla cuenta con la mayor cantidad de capacidad eólica instalada del archipiélago canario. Dado que esta tecnología no participa en la regulación de frecuencia, se estudiará el efecto de implementar técnicas de soporte de inercia en las turbinas eólicas de velocidad variable que permitan su participación en la regulación primaria a subir.

Primero se han obtenido los datos fundamentales de las principales tecnologías de generación y cómo participan en la regulación primaria. Para modelar el sistema se ha utilizado el software Simulink y se han construido los modelos de estos grupos.

Con el sistema completo, se ha elegido como escenario el momento de valle de un día con alta penetración eólica, para estudiar el impacto de los soportes de inercia a mayor escala. Como perturbación la pérdida de un grupo generador de 70 MW, que supone un 25% del nivel de carga del sistema.

Los resultados y las conclusiones que se han obtenido muestran que las técnicas de soporte de inercia que se ha implementado al control de las turbinas eólicas de velocidad variable, no sólo garantizan la estabilidad del sistema, sino que son capaces de mejorar aspectos la frecuencia mínima que se alcanza en los momentos iniciales al mismatch de potencia. Sin embargo, también se empeoran otros aspectos como la rapidez con la que se alcanza de nuevo el régimen permanente, y es necesario ajustar la cantidad de soporte que entrega la turbina para adaptarse de la mejor manera a cada escenario.

Además, se han realizado simulaciones que permitan obtener una idea del alcance del soporte de inercia en distintos escenarios futuros. Para diseñar estos casos, se ha tenido en cuenta la evolución de la tecnología eólica, que ha de aumentar en el futuro próximo. Los resultados obtenidos en estos escenarios siguen siendo favorables, y permiten ver la influencia de incrementar el porcentaje de penetración eólica en la generación sobre la respuesta de las turbinas y la respuesta que dan.

ACKNOWLEDGEMENTS

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1. INTRODUCTION

1.1   Background

The major energy sources in the world for electricity generation are coal, gas or oil. All of them share the fact that they pollute the atmosphere with greenhouse gases. In addition to this, running costs of these power plants are high and dependent on the availability of the fuel, which generally has to be imported.

With the overall increase in wind energy use around the world, Spain has experienced a boost at the beginning of the 21st century. It is the 4th country in installed capacity with 22882 MW (at the end of 2015), only below Germany, USA and China. In the year 2015, wind was the third most used technology supplying 19.1% of the total demand (just after nuclear and coal) [1]. Although the installation of new wind farms has decreased compared to the previous years, Spain has very favourable wind conditions, especially in the Canary Islands.

Despite these natural conditions, the archipelago is the fourth province of Spain with the least wind power capacity (only 177 MW at the end of 2015). Moreover, of the total demand for electricity in 2015; 4.9% was generated in wind farms, 91.7% came from fossil fuels and the rest from other minor renewables (solar) [1]. These statistics have been more or less the same in the last couple of years and show the sharp dependence on fossil fuels of the islands.

In order to reduce the dependence on the importation of foreign fuel, the Spanish Government decided to extend the deadline before which new wind farms will receive subsidies. This is expected to encourage more wind installations on the islands and reach the target of 450 MW on the archipelago [2].

There is a certain stability that the electric grid must have in order to have a secure and reliable energy supply system. Here is where frequency regulation has an important role to play. Currently, wind power does not participate in frequency regulation at any level. However, the development of variable speed wind turbines and the pitch controller have allowed them to gain great flexibility when decreasing their power output. On the other hand, more problems appear if the power supplied has to increase.

1.2   Power system of Gran Canaria

1.2.1   Thermal units

The electric power system in Gran Canaria is strongly dependent on fossil fuels, but still has the highest wind power penetration of the whole archipelago. Two thermal power plants (Jinamar and Barranco de Tirajana) are the main suppliers of electricity in the island. Their technologies and rated power are shown in Table 1 :

Table 1: Generation units in power plants of Jinámar and Bco Tirajana

Barranco de Tirajana				Jinamar	
Technology		Electrical Power (MW)		Technology	Electrical Power (MW)
Vapour turbine 1 (TV1)		80		Vapour turbine 1 (TV1)	33,2
Vapour turbine 2 (TV2)		80		Vapour turbine 2 (TV2)	40
Gas turbine 1 (TG1)		37		Vapour turbine 3 (TV3)	40
Gas turbine 2 (TG2)		37		Vapour turbine 4 (TV4)	60
Reheat 1	Gas turbine 1 (TG3)	70	210	Vapour turbine 5 (TV5)	60
	Gas turbine 2 (TG4)	70		Diesel 1 (D1)	12
	Vapour turbine (TV3)	70		Diesel 2 (D2)	12
Reheat 2	Gas turbine 1 (TG5)	70	210	Diesel 3 (D3)	12
	Gas turbine 2 (TG6)	70		Diesel 4 (D4)	24
	Vapour turbine (TV4)	70		Diesel 5 (D5)	24
Reheat 3	*Gas turbine 1 (TG7)*	*75*	*229*	Gas turbine 1 (TG1)	23,5
	Gas turbine 2 (TG8)	*75*		Gas turbine 2 (TG2)	37,5
	Vapour turbine (TV5)	*79*		Gas turbine 3 (TG3)	37,5
Total Power		**654** *(+229)*		**Total Power**	**415,7**

The data for this table has been elaborated from official documents of both power plants ([3] and [4]). The last reheat unit in Bco Tirajana is still not operational, hence it is not taken into account when adding to the total capacity of the plant. Gas-oil (for gas turbines) and fuel-oil (for vapour units) are the two primary energy sources on which these units run on.

1.2.1.1 Vapour turbines

Vapour (or steam) turbines generate electricity from a Rankine cycle. In this process, the fuel-oil is burnt in the combustion camera to vaporize water at high pressure. This steam will expand in the turbine, which is coupled to the generator to produce electricity. A higher level of detail for this process can be found in [5].

1.2.1.2 Gas turbines

Gas turbines use a Brayton cycle instead to produce electricity. In this cycle, the gas-oil is burnt in the combustion camera in the presence of air, also at high pressure. The gases then expand in the turbine producing mechanical energy that the generator converts to electricity. For more detailed information about this process see [5].

1.2.1.3 Reheat units

A reheat unit uses a combined cycle of both the Brayton and Rankine cycle of the gas and vapour turbines. Since the escaped gases of the Brayton cycle have a high temperature when they leave the gas turbine, they are used to heat up the water of the Rankine cycle. This makes the efficiency of combined cycle units higher than any of the other two cycles alone. Further information of combined cycle processes is present in [5].

The reheat groups in Gran Canaria are formed by two gas turbines and one vapour. They can work with one or two of the gas turbines alone in open cycle.

1.2.1.4 Diesel generators

Diesel generators are typically main generation units used in small isolated power systems. In the case of Gran Canaria, the majority of generation is carried out by the other bigger turbines described above as it is a big island. This technology consists of a diesel engine directly coupled to a generator.

1.2.2 Wind power in Gran Canaria

The island of Gran Canaria has the highest wind power penetration in the whole canary archipelago. The total installed capacity of 94.6 MW is distributed over 36 wind farms, with different turbine sizes and technologies as they have been built at different times.

AEE (Asociación de Eólica de España, the Spanish wind energy association) shows in its webpage the details of all the different wind farms in each region of Spain [2]. The size of the smallest wind turbine (WT) is a 90kW squirrel cage induction generator, while the biggest is a 5MW offshore Double Fed Induction Generator (DFIG) WT. With the exception of very few cases, all turbines are variable speed wind turbines (VSWTs).

At the end of 2015, a total of 97 MW of extra wind capacity was approved to be installed in Gran Canaria. These new wind farms will receive a specific retribution from the government in order to help re-boost the installation of wind power in the island [2].The location, rated power and other details of each wind farm are presented in [6] and [7].

1.3   Frequency control

In any power system, the frequency has to always be kept constant at its nominal value (50 Hz in Spain), within some allowed margins. This is important for a good quality electricity supply. For the frequency to be constant, then the active power balance in the system has to be verified at all times, following the equation defined in [8]:

$$\Delta P_G - \Delta P_L - D\Delta\omega = 2H_{sys}\frac{d\Delta\omega}{dt} \tag{1.1}$$

Where ΔP_G is the change in generated power in the system (in MW), ΔP_L is the change in the system load (in MW), D is the load damping constant (in %MW/%Hz), H_{sys} is the system inertia constant (in seconds), and $\Delta\omega$ is the change in the system frequency (in Hz).

The inertia constant is a ratio between the kinetic energy (of all generators) at nominal power and the total apparent power of the system. It determines how robust a system is; a higher inertia constant means a stronger system with lower frequency deviations. The definition of the inertia constant of a single generator is (obtained from [9]):

$$H = \frac{\frac{1}{2}J\omega_{base}^2}{S_{base}} \tag{1.2}$$

Where J is the moment of inertia of the generator, ω_{base} is its rated rotational speed (in rad/s) and S_{base} is its base apparent power (in VA).

The damping constant, D, is a natural property of all power systems that adjusts the load power according to the level of the frequency disturbance. This enables the system to reach a new equilibrium, correcting the power imbalance by itself; otherwise the frequency would grow or drop indefinitely.

There are two important factors to consider when analysing the response of the system to a frequency disturbance; the frequency change rate ($\frac{d\Delta\omega}{dt}$) and the steady state frequency deviation ($\Delta\omega_{ss}$). The frequency change rate will depend on the system inertia, and the steady state frequency deviation will be affected by the equivalent droop characteristic of the generators in the system.

The value of the frequency nadir (ω_{min}) is influenced by more factors; the size of the power imbalance, the amount of stored energy in the rotating masses of generators and their dynamic characteristics [10].

1.3.1   Primary regulation

Primary regulation is an automatic service that is offered by the speed governor of turbine groups, with the objective of rebalancing the power generation and load in the system after a mismatch. Most conventional units (thermal or hydro) have a governor that increases or decreases the flow area through the valves to vary the power output. The extensive details of operation procedures in primary regulation, including load shedding specifications are all present in [11].

Each generator has a droop characteristic R (in %Hz/%MW), which is represented in Figure 1, taken from [8]:
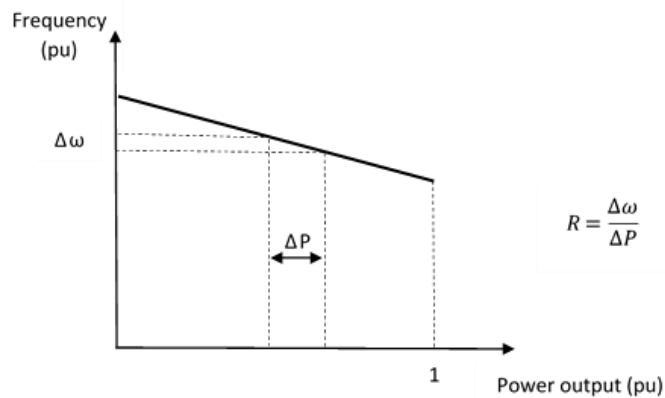
Figure 1: Ideal steady state characteristic of a governor with speed droop [8]

The primary regulation service usually acts within 30 seconds, and the R value of a generator has to be between 2% and 5% in pu of its own base power [11].

1.3.2 Secondary regulation

Secondary regulation is the next service frequency regulation, which restores the frequency of the system to its nominal value and restores the primary reserve so that it is ready to act again. The generators that participate in it change the reference set-point of their droop characteristic (ie: the curve in Figure 1 shifts to the right or to the left). In this way, they vary their power output accordingly, eliminating the steady state frequency error that resulted after the primary regulation took place.

Secondary regulation is an optional service offered by groups which have a power reserve. The power reserve required in each case is also automatically used (based on what the TSO determines), but it is a much slower service that acts between 30 seconds and 15 minutes [11].

1.3.3 Tertiary regulation

Tertiary regulation is a service used to restore the secondary reserve in the case of a new unexpected disturbance. It is manually operated and its time span can be from 15 minutes up to 2 hours [11].

1.4 Problem definition

The aim of this project is to analyse the possibility of wind turbines (WTs) using inertia support techniques to temporarily increase their active power output in order to participate in primary frequency regulation in the power system of Gran Canaria.

In addition, the effect of inertia support in the system frequency will also be studied in future scenarios with high levels of wind power penetration in the system.

The Power System will be represented in a Simulink model inspired in a typical frequency control block diagram, similar to the one shown in Figure 2 [8]:
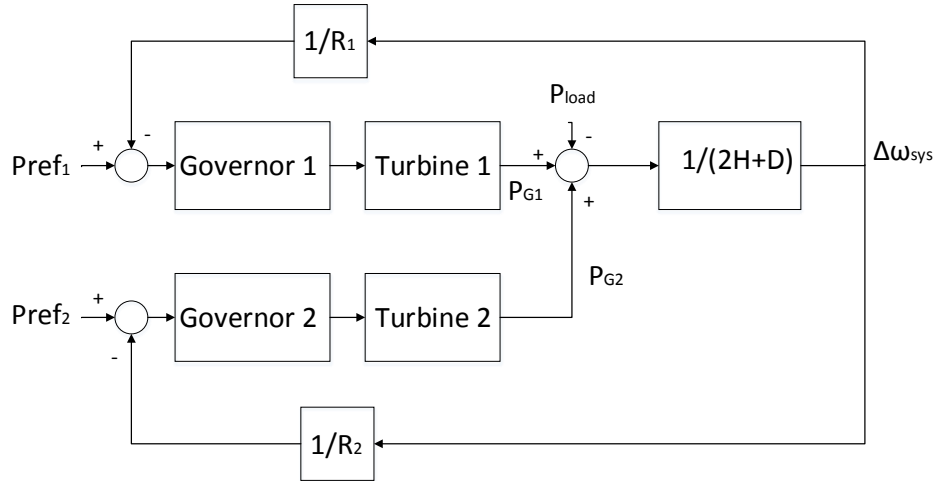

Figure 2: A schematic block diagram of a primary regulation control loop [8]

There will be 4 individual models of generators for each of the 4 different technologies shown in Table 1. The base power of each one will be the total sum of all the existing groups (from both power plants) for that technology. The same rule is applied for the model of the WT. The base powers of each generator are shown in Table 2:

Table 2: Generation units of the Simulink model

Technology	Base power (MW)
Reheat turbine	420 *(+229)*
Vapour turbine	393.2
Gas turbine	172.5
Diesel generator	84
Wind turbine	94.6 *(+97)*

The simplification of the system to only 5 different generators is valid because the power balance in a system and its inertia constant depend on the aggregate sum of all generator outputs. Therefore, frequency behavior of the system should be very similar to an equivalent model of a power system with all the separate but identically modelled units.

The study of future scenarios will be performed taking into account that both the reheat turbine and the WT will have an increased base power (added in grey).

1.5   Method

The potential of inertia support will be evaluated under a severe power imbalance to analyse pessimist scenarios. This will allow establishing the limits of the support. The power imbalance will be the tripping of a large vapour unit of 70 MW. To implement this in Simulink, the load power of the system will be increased by a step of 70 MW.

To complete the negative scenario for frequency regulation, the load level of the system has to be as low as possible: at night. With a low load level in the system, the power mismatch becomes more significant. Also, the system inertia is weakest at this moment of the day because there are more units not generating electricity that are disconnected. Hence they do not add to the system inertia.

Despite the fact that the number of DFIG WTs in Gran Canaria are not in majority, DFIG is a very flexible and extended technology. In addition, most of the wind farms in Gran Canaria have variable speed wind turbines (VSWTs). Therefore, the implementation of inertia support characteristics in other VSWTs, will be almost identical to that of a DFIG, with slightly different parameters and time constants.

During the last year 2015, the total generation structure of the island was distributed as shown in Figure 3:
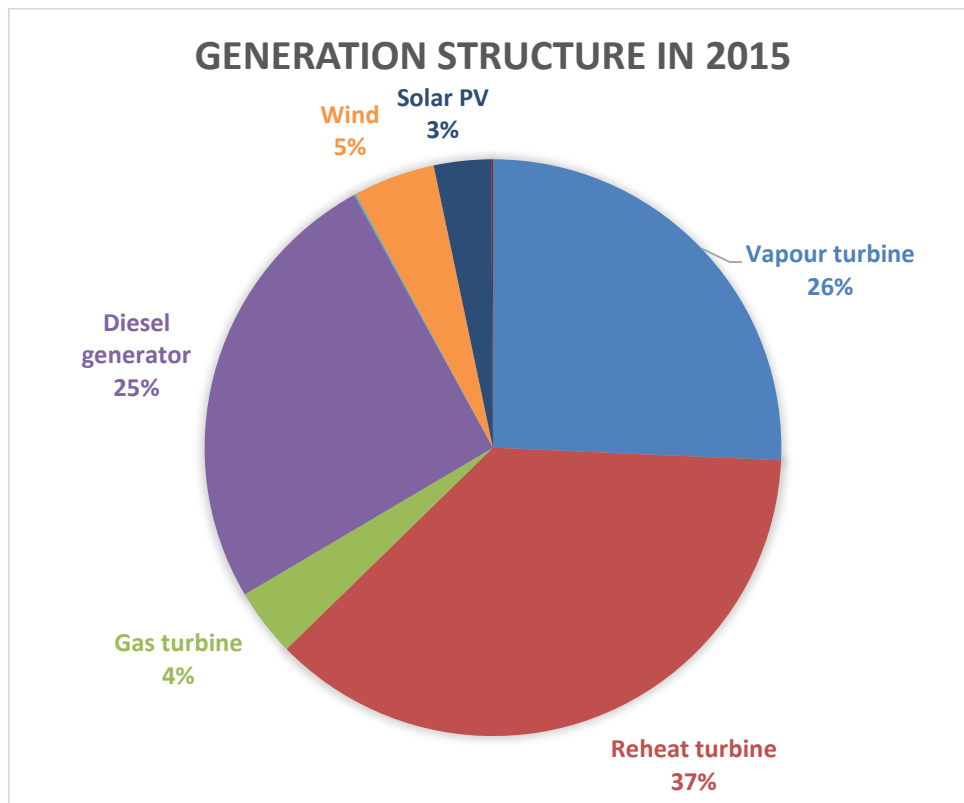

Figure 3: Generation structure in Gran Canaria in 2015 (constructed with data from REE)

Solar PV is the next generation unit in Gran Canaria with 3% of the yearly electricity supply, which is comparable to the contribution of wind and gas turbines. However, its participation is zero at night, so it will be neglected.

Finally, frequency regulation is dependent on active power balance, therefore, voltage and reactive power control are not relevant as long as they are kept within reasonable stability margins. This is the case when if the system is operates under normal conditions, and this condition will be fulfilled in the project, so all further mentions to "power" will refer exclusively to active power.

1.6   Effect of increasing wind power ratio

Wind power ratio (WPR) is the instant level of wind power in the system relative to the load level. It is defined as:

$$WPR\ (\%) = \frac{Wind\ power\ (MW)}{Load\ power\ (MW)} * 100\% \tag{1.3}$$

Increasing the level of WPR displaces responding generation units that contribute to the system inertia and primary regulation. This presents an interesting challenge when evaluating future cases with high WPR. The effect of WPR on the system frequency (with the same load level and power disturbance) is shown in Figure 4:
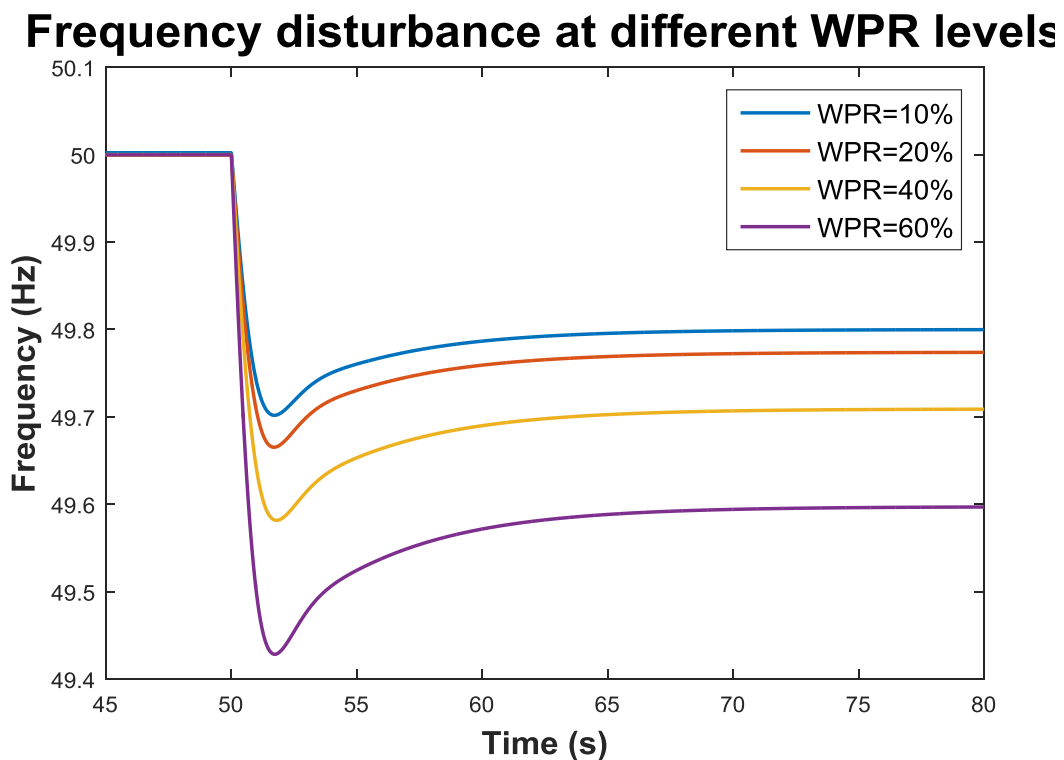
Figure 4: Frequency response at different levels of WPR

The graph shows how the system inertia is decreased, as the initial slope of the frequency drop gets sharper at each time. In addition, the response capability of the system has also been reduced as the steady state frequency is lower each time. In order to implement this effect in the model, these two parameters are calculated in the following way [12]:

$$H_{sys} = H_{sys}^{original}(1 - WPR)$$ (1.4)

$$R_{unit} = R_{unit}^{original}/(1 - WPR)$$ (1.5)

2. WIND TURBINE MODEL

2.1 Model of turbine used (GE DFIG 3.6MW).

The model of WT that will be implemented in Simulink is commercial variable speed wind turbine which is the one used in [13] and [14] (GE DFIG 3.6MW). The model has been implemented following the method of [12].

The mechanical power extracted from the wind by the turbine is given by the equation:

$$P_{mec} = \frac{1}{2}\rho A C_p(\lambda, \beta) v_{wind}^3 \tag{2.1}$$

Where ρ is the air density (1.19 kg/m^3 in this project), A is the swept area by the blades (in m^2), Cp(λ,β) is the power coefficient and v$_{wind}$ is the wind speed (m/s). The area of the WT is calculated as:

$$A = \pi R^2 \tag{2.2}$$

Being R the length of the blades (52 m).

2.1.1 Cp calculation

The power coefficient, C$_p$, is the efficiency of the WT, ie; the percentage of mechanical power that can successfully be extracted from the total wind power. The maximum theoretical C$_p$ value is approximately 0.59, as determined by Betz's law. For this turbine, its maximum value is around 0.49 which occurs at λ=8.7 (see Figure 5). One way of representing Cp(λ,β) is shown in (2.3) [14]:

$$C_p(\lambda, \beta) = \sum_{i=1}^{4}\sum_{j=1}^{4} \alpha_{ij}\beta^i\lambda^j \tag{2.3}$$

Where λ is the tip speed ratio (dimensionless) and β is the pitch angle (°). The value of the constants α$_{ij}$ are presented in [14][1]. λ is defined as:

$$\lambda = \frac{\omega R}{v_{wind}} \tag{2.4}$$

Where ω is the rotating speed of the blades (in rad/s).

The different operation points of the turbine are shown in Figure 5:

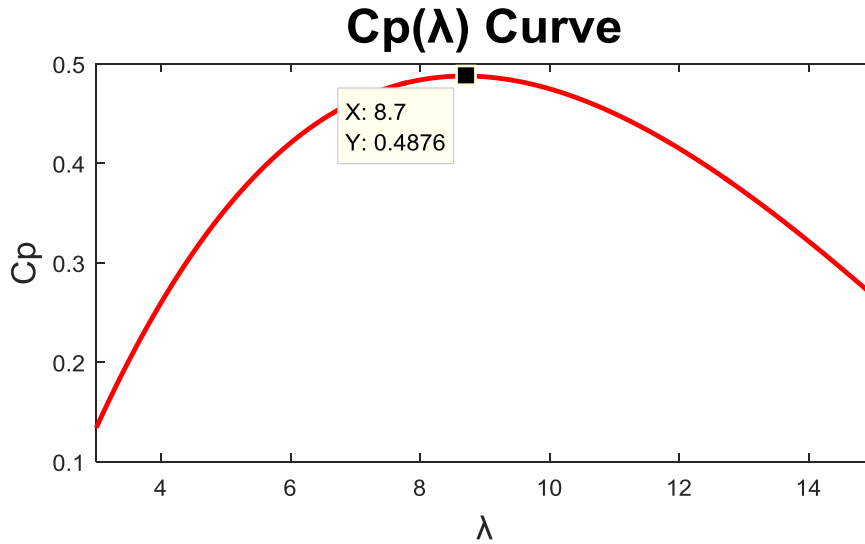[1] See section 4.3.3 Wind Power Model

Cp(λ) Curve

X: 8.7
Y: 0.4876

Figure 5: Cp values at different operation points of the WT

It is important to note that the formula offers a good approximation for values of λ between 3 and 15. For values of λ below 3, the algorithm calculates a negative value of C_p, so it is set to zero by default. This is not a problem since such at low value of λ (low WT speed), the minimum speed relay would disconnect the turbine.

2.1.2   Maximum Power Point Tracker

The WT has a control of the rotor speed that ensures that it is always at the optimal operation point. This control consists of a maximum power point tracking function (MPPT) that measures the electrical power of the WT and calculates the required reference speed that gives this power output:

$$\omega_{ref} = -0.67p_{e-meas}^2 + 1.42p_{e-meas} + 0.51 \tag{2.5}$$

Where all values are in per unit of P$_{base}$=3.6MW. The measured power output comes from a first order transfer function with a time constant of T$_{e-meas}$.

2.2   Simulink model

The full model of the turbine was implemented in Simulink as shown in [12]:
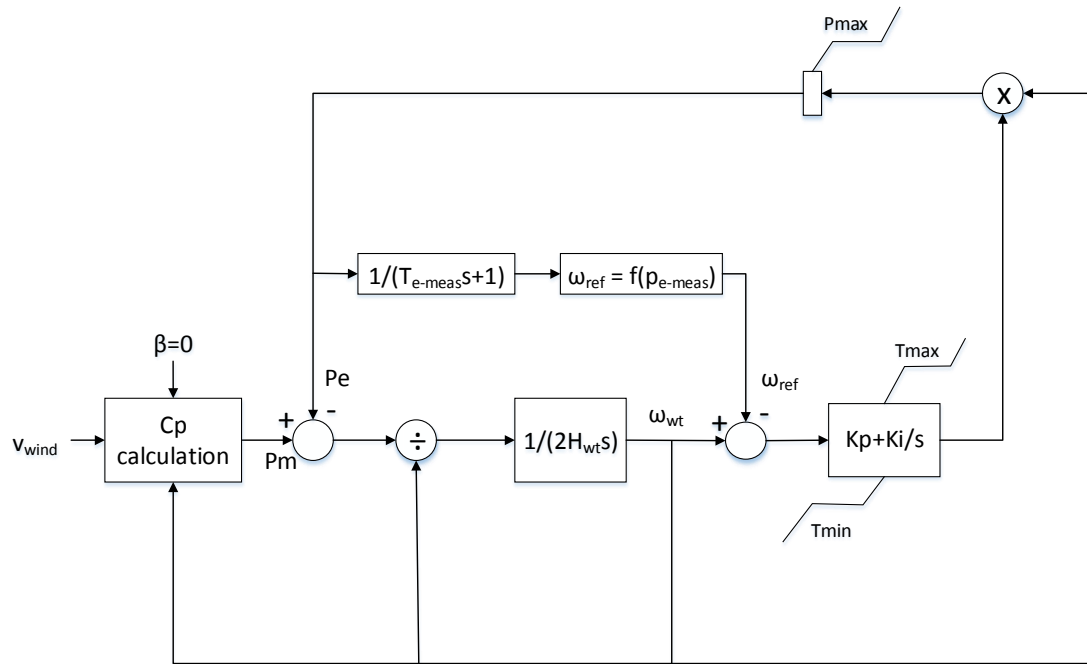
11

Figure 6: Wind turbine block diagram [12]

The mechanical power extracted by the WT is calculated inside the Cp calculation block that uses the algorithm described earlier. The parallel PI controller ensures a zero error in the speed by calculating the electrical torque of the WT. The value of all the parameters are given in Table 3:

Table 3: Parameters for WT model [12]

Parameter	Value
Kp	0.3
Ki	3
Te-meas	5s
Hwt	5.19s
Tmin	0
Tmax	0.833 pu
Pmax	1 pu

WTs can easily reduce their power output by increasing their pitch angle β to reduce the Cp and the effective swept area. Also, if the WT was working in underrated operation, reducing the pitch angle can increase the output of the WT. However, the objective of this project is to study inertia support techniques that can extract and an extra power from the WT. Therefore, the pitch controller is not included and β is always assumed to be zero so the WT is not spilling energy in this way.

2.2.1 Validation of the WT model

The model has been implemented and a simulation has been run to compare the values of mechanical power and rotor speed with the ones presented in [13] at different wind speeds. The results are shown in Figure 7:
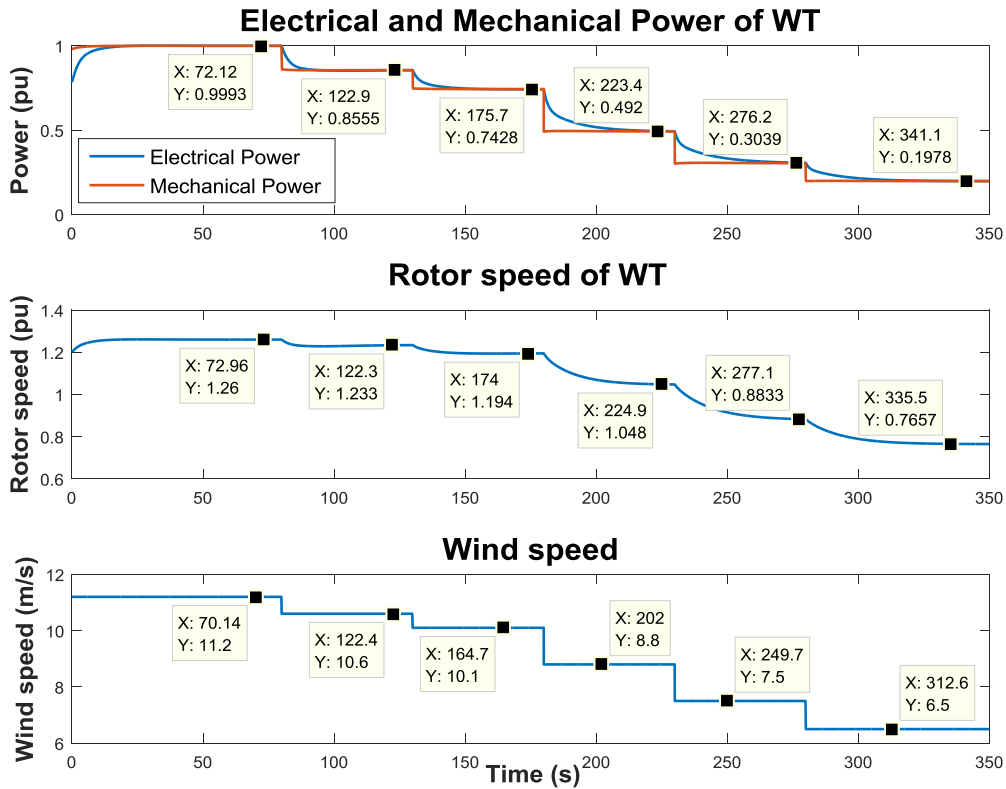

Figure 7: WT operation at different wind speeds

The behavior of the turbine is as expected; the steady state values of mechanical power and of the WT speed match those of [13]. For instant changes in wind speed, the mechanical power response also has to be instant as they are directly related. The electrical power and the speed of the WT have a slower response due to the inertia of the WT, the time constant Te-meas and the PI controller.

2.3 Inertia support techniques

In VSWTs, the rotor inertia (stored in the rotating mass of the blades) is decoupled from the grid due to the power electronic converters. In the case of a fixed speed WT, this inertia is already available, and therefore, FSWTs can provide a small inertial response [10].

There are different types of frequency support techniques with VSWTs which can be seen in [10]. In this project, two inertial support techniques are going to be implemented; Instant Power Support and Inertia Emulation.

These two supports, consist in extracting the kinetic energy of the rotating blades of the WT, which will translate into an additional power that is generated for some seconds. This is possible because the behavior of the WT verifies the equation:

$$T_{mec} - T_{elec} = J_{wt}\frac{d\omega}{dt}$$
(2.6)

Where T_{mec} is the mechanical torque caused by the wind blowing (in Nm), T_{elec} is the electrical torque of the generator (in Nm), J_{wt} is the moment of inertia of the wind turbine (in kgm^2), and $\frac{d\omega}{dt}$ is the derivative of the rotor speed of the WT (in rad/s^2).

As can be seen in (2.6), during the time for which the WT provides an extra electric power output, the rotor decelerates. In consequence, inertia supports can only be provided for some seconds, according to the minimum speed limit of the WT.

A detailed step by step explanation on how to obtain and implement each method can be seen in [10].

2.3.1   Inertia Emulation

This control consists in the VSWT "emulating" the hidden inertia of the WT that is not accessible for the grid. In the event of a disturbance in the system's frequency, the control will activate an extra power signal in the wind turbine.

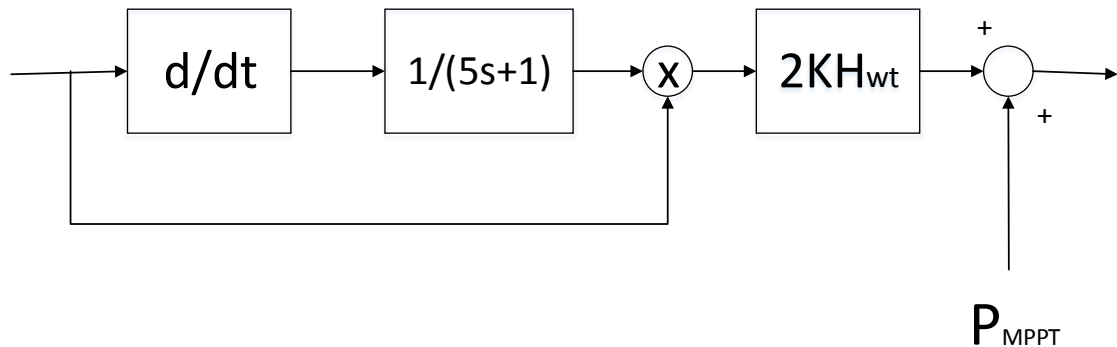The control is implemented in Simulink as shown in Figure 8:

Figure 8: Inertia emulation control in Simulink [10]

The extra power that is extracted and added to the MPPT power is defined as [12]:

$$P_{extra} = 2KH_{wt}\omega_{sys}\frac{d\omega_{sys}}{dt}$$
(2.7)

Where H_{wt} is the inertia constant of the wind turbine (in seconds) and ω_{sys} is the system's frequency (in pu). Note that the inertia emulation control acts "automatically", as soon as there is a frequency disturbance ($\frac{d\omega_{sys}}{dt} \neq 0$) big enough to be detected and trigger the signal. K is a gain that can be modified to tune the amount of power extracted.

2.3.2   Instant Power Support

In order to use the Instant Power Support strategy, the amount of kinetic energy that is going to be extracted has to be quantified and predefined.

There are many different patterns for the shape of the function explored in [13]. In this project, the chosen one is as shown in Figure 9:
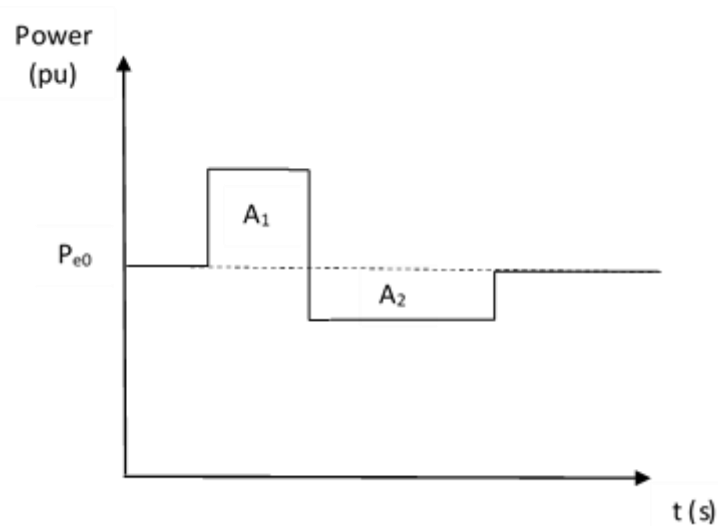
Figure 9: Instant Power Support Characteristic [12]

In the figure, P_{e0} is the pre-disturbance value of the power output of the WT (in pu). The areas A_1 and A_2 are the deceleration and re-acceleration areas respectively. While the WT is in operating in A_1, the WT turbine slows down; in order to return to the pre-disturbance operating point of the WT it is necessary to define A_2 ($A_1 = A_2$).

The maximum time for which this support can be provided (the gap of the A1) at different levels and wind speeds are provided in detail in [13].

3. MODEL OF POWER PLANTS

3.1 Thermal units

The models for the three different thermal units and their parameters have been obtained from [8][2]. The block diagrams share the same structure, as the gas and vapour turbine models are derived from the reheat block diagram.

3.1.1 Reheat turbine

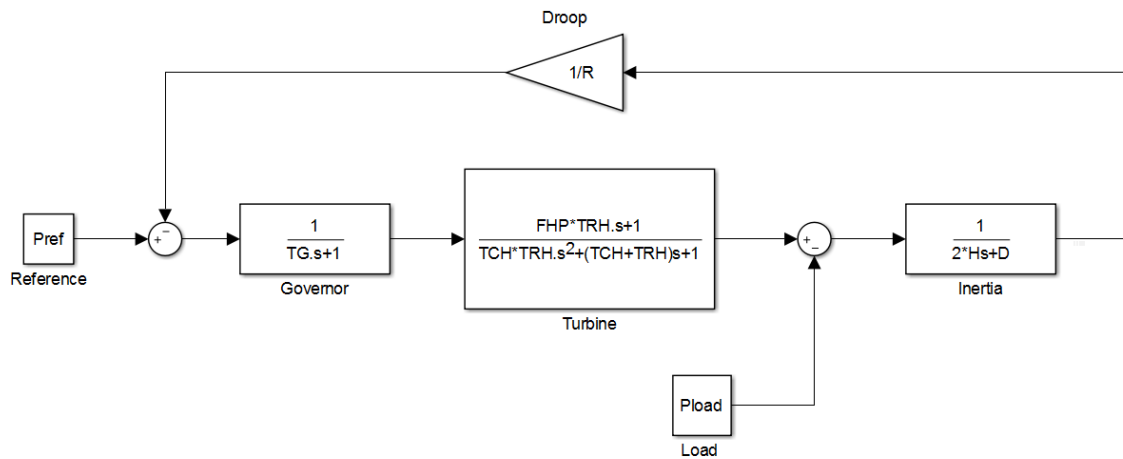A model of the reheat turbine in pu values, is presented in Figure 10:

Figure 10: Reheat turbine block diagram [8]

In the turbine transfer function, time constant T_{CH} of the control valve (CV) modulates the steam flow for load/frequency control during normal operation. The reheater time constant (T_{RH}) is present due to the amount of steam accumulated in the reheat camera. It is the reason why the response of reheat units is slower than conventional thermal units. F_{HP} is the fraction of the power, extracted from the high pressure gas turbine.

The inertia of the generator (H) and the power balance beween the load the output of the generator result in a frequency deviation (Δω) of this small power system (with only one generator). This frequency deviation is detected by the governor, whose droop characteristic (R) translates it into a power increase/decrease of the turbine.

The time constant of the governor, T_G, represents the delay of the governor since it detects the frequency error until the relays trigger the signal to change the valve position.

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[2] Block diagram models and parameter values are shown in page 598, for detailed analysis of different turbine and governing system types, see pages 418-448

3.1.2   Gas and vapour turbine

The model for both turbines is the same, and derived from the one of the reheat turbine. The block diagram is presented in [8]:
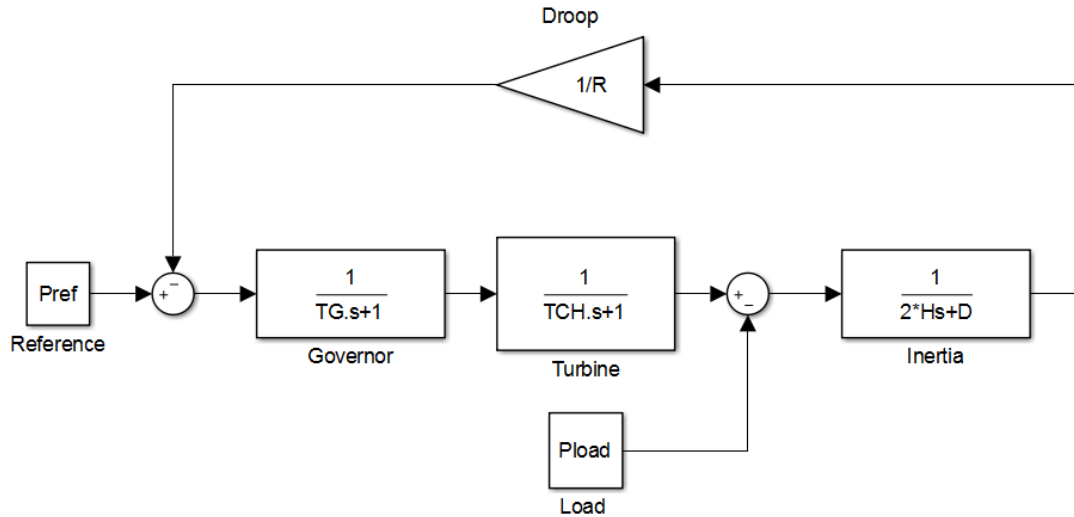
Figure 11: Block diagram of gas and vapour units [8]

Despite the fact that gas and vapour turbines are separate technologies with different cycles, their behavior and functioning in frequency regulation purposes has to be the same. Therefore, their models have been represented identically but separately in order to differentiate them easily in the simulations.

Their model is the same as the reheat turbine except for the simplification in the turbine transfer function, because there is no reheat camera. This makes the response of both units faster.

3.2   Diesel generator

The model of the diesel generator must have a similar behavior as those of the thermal units from [8]. A simple one was found in [15] and incorporated to this project, as illustrated in Figure 12:

Figure 12: Diesel engine block diagram [15]

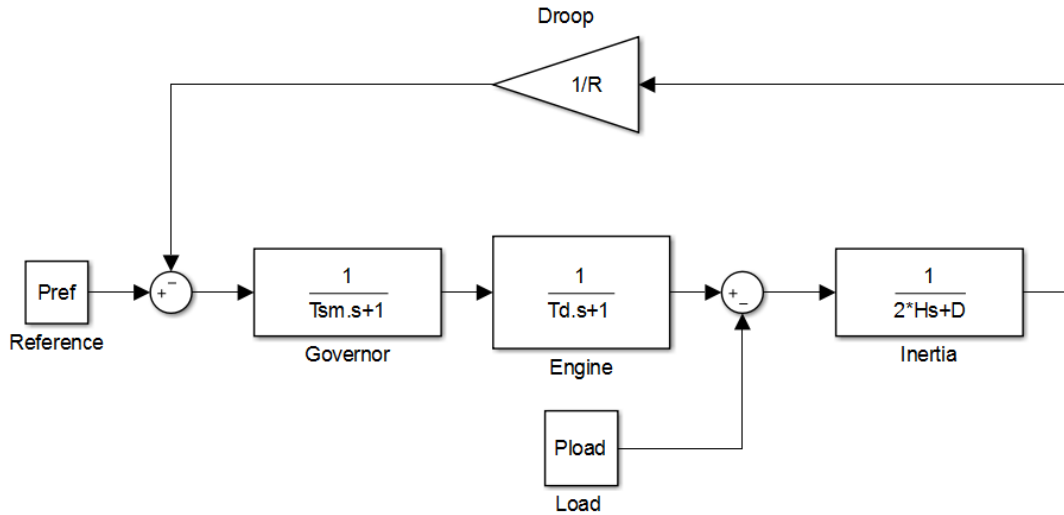The block diagram has the same structure as the models for the thermal units. The transfer function of the engine is a simple first order transfer with time constant T_d, which represents the delay of the motor. The time constant T_{sm} of the governor models the response of the servomechanism of the valve actuator. As always, R is the droop characteristic of the engine, and H is the inertia parameter of the generator.

The values of these parameters can be found in [15].

3.3   Complete system model

The 4 generator models and the WT model are connected together as it was specified in Figure 2, in Problem definition:

The parameter D is the load damping coefficient, which is set to D=1 as it has been seen in the literature [8]. The parameter H_{sys} is now the equivalent inertia of the system, which is calculated according to the equation [16]:

$$H_{Sys} = \frac{\sum_{i=0}^{n} H_i S_i}{S_{Sys}} \qquad (3.1)$$

Where H_i and S_i are the inertia constant and rated power of each generator. The rated powers of the generators are shown in Table 2. The value of S_{sys} is the sum of all the individual rated powers.

The power balance between the total generation and the system load results in a certain frequency deviation which is fed back to all the responding units to close the primary regulation loop. The frequency deviation is only fed back to the WT when the inertia emulation support is being performed.

4. SIMULATIONS & RESULTS

The data of the different instant generation mixes has been obtained from the Spanish TSO, [17]. These cases are at moments of the night, when the load level of the system is low and the wind power ratio (WPR) is high.

4.1 Assumptions

The system is assumed to be working in steady state equilibrium before the power disturbance. This is actually a common assumption as it is how power systems operate the majority of the time.

A further simplification that has been made is that wind speed is constant during the frequency event. Even though wind speed will normally vary and have many oscillations in a time span of 30 seconds, these are short and they are likely to oscillate around an average value of wind speed.
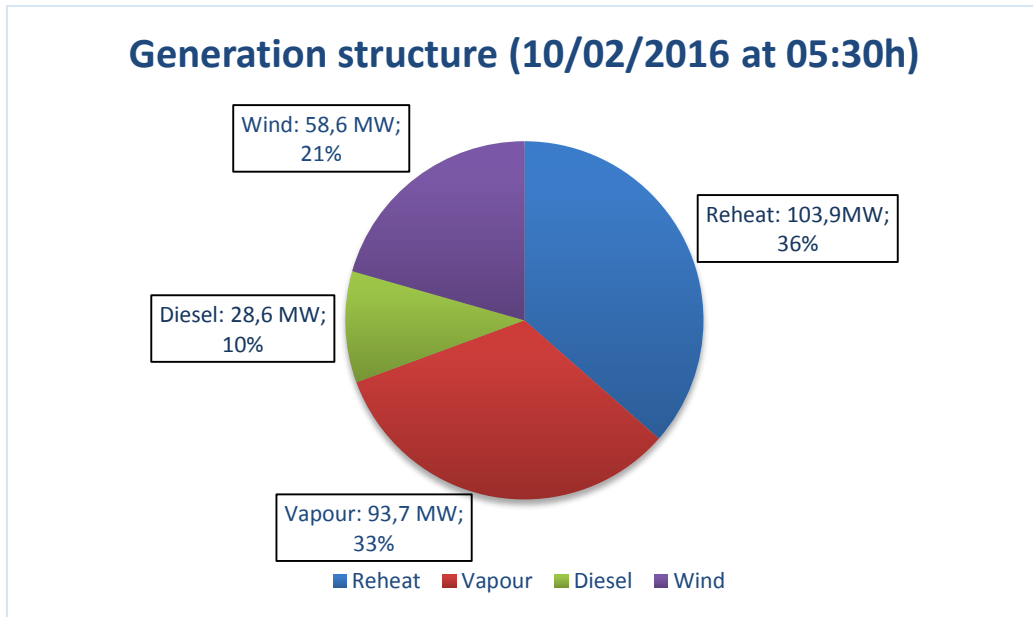
The impact of variable wind speed in the results would be oscillations in the power ouput and speed of the WT signals (which would be big or small depending on the size of the wind variations are). However, this issue is not a matter of concern for this project because the variability of wind speed is usually not the cause of a big frequency event.

In addition, since the frequency regulation is supposed to act within 30 seconds, the default deceleration time for the instant power support will be of 10 seconds. In order to smoothen the power step when switching to the re-acceleration area, the time length for this period will be 20 seconds, with a decreased step of half the value of the initial support (to keep both areas the same). In other words, if the WT gives a 5% extra power support for 10 seconds, it will give 2.5% less power than the reference value for 20 seconds in the re-acceleration area.

With respect to the inertia emulation support, the value of K will be tuned so that the turbine gives the same level of support as it does with the instant power support. To achieve this, both deceleration areas of the WT have to be equal (they will also both reach approximately the same minimum speed).

4.2 Case 1: Real case with WPR=20%

The data for the first case corresponds to the instant generation mix of the 10/02/2016 at 05:30h. The total amount of load in the system is 284.8 MW, and the technologies participating are shown in Figure 13:

Generation structure (10/02/2016 at 05:30h)

Wind: 58,6 MW; 21%

Reheat: 103,9MW; 36%

Diesel: 28,6 MW; 10%

Vapour: 93,7 MW; 33%

■ Reheat ■ Vapour ■ Diesel ■ Wind

Figure 13: Generation mix for case 1, data from [17]

It can be appreciated that the WPR is approximately 20% in this case. Also, the gas turbines are not generating any power, so they will be assumed to be disconnected, and not contributing to the system inertia or primary regulation. In this way, the system is weaker than if the turbine was rotating and adding to the inertia.

4.2.1 Case 1.1: Moderate level of support (5% instant support and K=15)

For this case, the wind speed is set constant to 9.5 m/s, which is required so that the output of the WT is 0.62 pu, which is then equivalent to 58.6 MW. Three cases are simulated: with no support from the WT, with a contribution of 5% instant power support and inertia emulation with K=15. The evolution of the system frequency for the three cases is compared and shown in Figure 14:
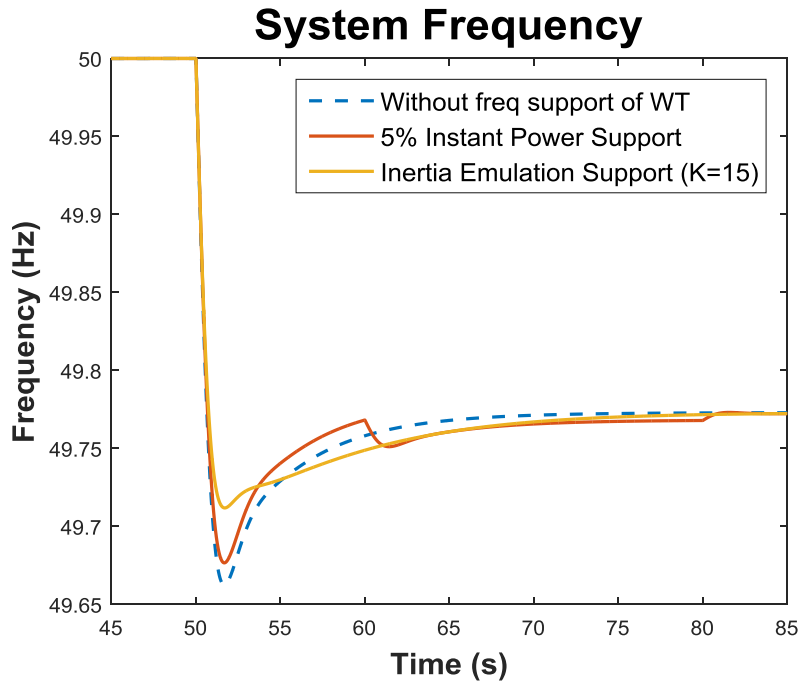
Figure 14: Frequency response for Case 1.1: Moderate level of support (5% instant support and K=15)

Table 4 shows the values of the frequency nadir reached in each case:

Table 4: Frequency nadir results for Case 1.1: Moderate level of support (5% instant support and K=15)

Type of support	Nadir value (Hz)
No support	49.66
Instant Power	49.68
Inertia Emulation	49.71

Both supports improve the frequency nadir of the system. The inertia emulation improves it by 0.05 Hz and the instant power support by 0.02 Hz. In addition, this last support throws a second frequency dip after the first 10 seconds of support have finished and the turbine enters in the re-acceleration area (decreasing its power output).

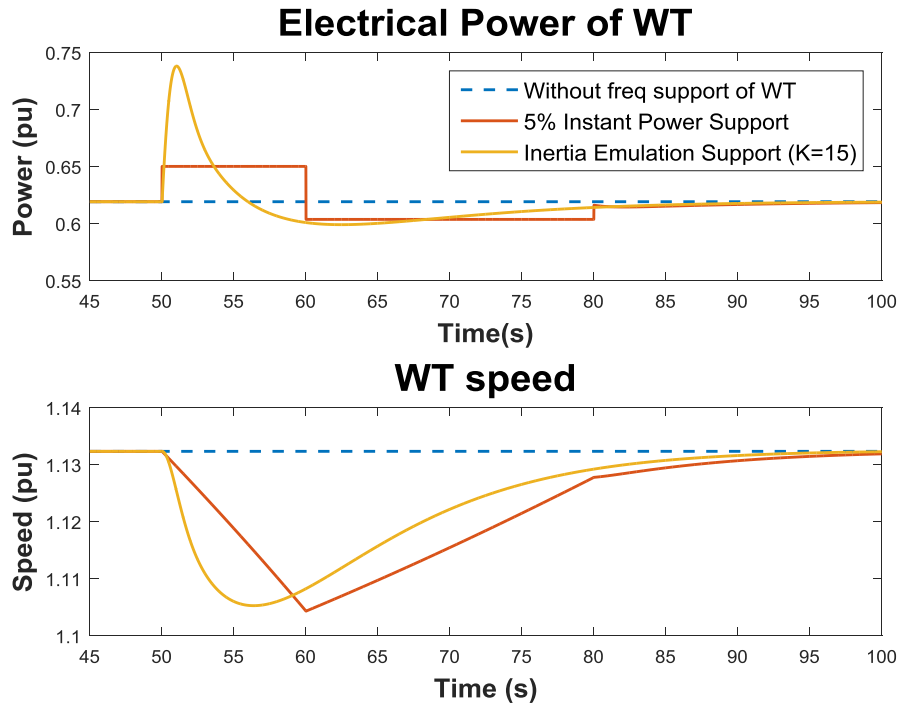In order analyse the behavior of the WT, Figure 15 is presented:

Figure 15: WT performance for Case 1.1: Moderate level of support (5% instant support and K=15)

It can be checked that both deceleration areas are the fairly equal by looking at the graphs and comparing them visually, and also the minimum speed of the rotor is more or less the same for both supports. However, in the case of the instant power support, the power and speed of the WT do not go back to the pre-disturbance operating point right after the support finishes, because both areas are not exactly the same. This makes the turbine finish adjusting itself for some extra seconds.

The power of the WT does not exceed the value of 1 pu, and the peak in the power curve in the inertia emulation case can be allowed for as long as the WT can extract kinetic energy from the rotor. When looking at the speed, the WT is far from hitting the minimum speed limit of 0.7 pu. This means that there is still a big margin of extra power that can be obtained before reaching the minimum speed.

4.2.2   Case 1.2: Higher level of support (10% instant support and K=30)

According to the results of the previous simulation, there is still a lot of kinetic energy in the turbine that has not been used for frequency support. Therefore, to try and improve even more the frequency evolution of the power system, the level of support has been doubled in this case: 10% active power support and K=30. The new frequency curve is shown in Figure 16:
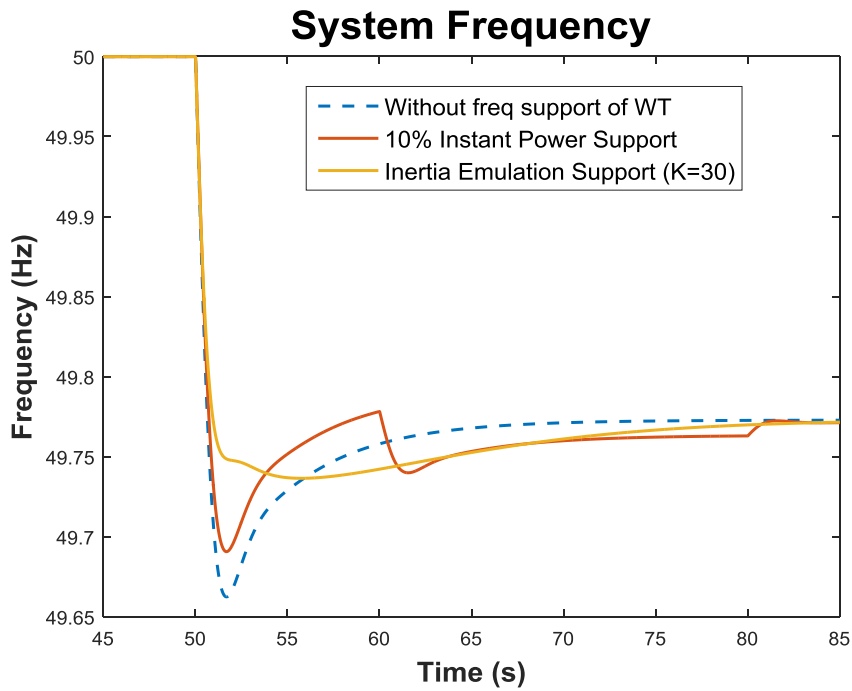
Figure 16: Frequency response for Case 1.2: Higher level of support (10% instant support and K=30)

A comparison between the results obtained in cases 1.1 and 1.2 is presented in Table 5:

Table 5: Comparison of results for Case 1: Real case with WPR=20%

Type of support	Nadir value (Hz)	
	Case 1.1	Case 1.2
No support	49.66	49.66
Instant Power	49.68	49.69
Inertia Emulation	49.71	49.74

Even though the inertia support is twice as big as before, the improvements with respect to the previous case are less noticeable. The frequency nadir for the instant support has improved by 0.01 Hz (0.02% increase) with respect to the previous instant support in Case 1.1.

Furthermore, the second frequency dip is much larger in this case because the power step between the deceleration and re-acceleration areas of the WT is larger. As for the inertia emulation support, the nadir also presents a small improvement of 0.03 Hz (0.06% increase), plus the response is much slower than before.

4.3   Case 2: Future scenarios with increasing WPR

With the new expected wind farms, the WPR in Gran Canaria could reach much higher values than 20% (which was the highest level found to this date). Also, the third reheat group of 229

MW (in Table 1) will be now assumed to be operative. The two possible future scenarios that will be analysed will be with 40% and 60% WPR, assuming the instant load to be 280 MW in both cases to test the inertia supports under more unfavorable conditions. The power imbalance in both cases is the same as it was previously; tripping of the 70 MW vapour unit.

The generation mixes, system inertia (H_{sys}) and wind speed for the cases with WPR=40% and WPR=60% are displayed in Table 6:

Table 6: Generation mix for Case 2: Future scenarios with increasing WPR

Technology	Power (MW)	
	WPR = 40%	WPR = 60%
Vapour	100	70
Reheat	68	46
Wind	112	164
Diesel	0	0
Gas	0	0
Parameters	**Value**	
H_{sys} (s)	3	2.07
Wind speed (m/s)	9.32	10.6

4.3.1 Case 2.1: 5% instant support and K=12

For both scenarios, the same disturbance and same level of support have been applied, and the plots of the evolution of the system frequency are presented below:
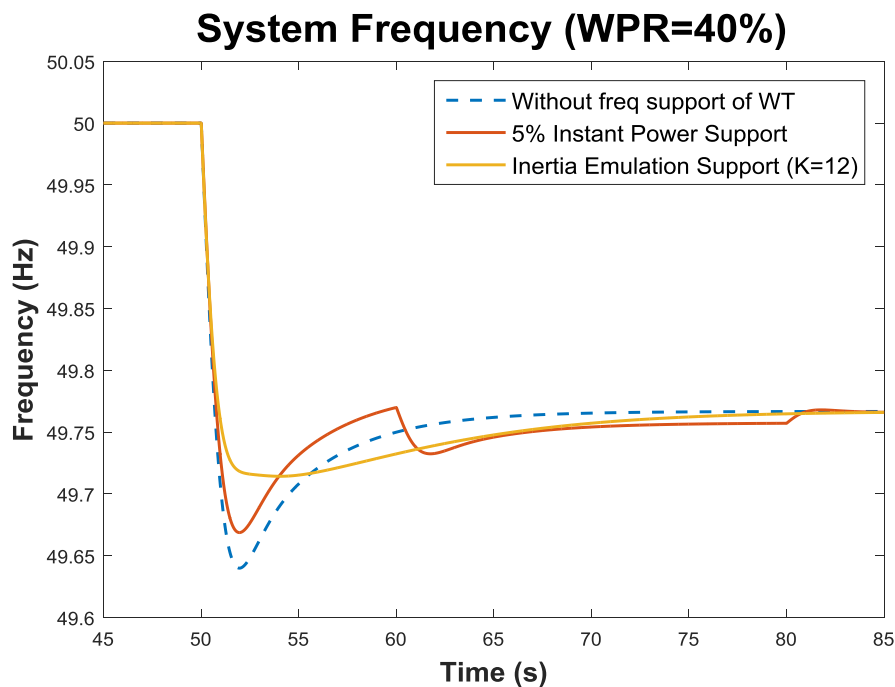

Figure 17: Frequency response for Case 2.1: 5% instant support and K=12 with WPR=40%

The case with 40% WPR (Figure 17) shows an improvement in the frequency nadir with both supports, although it is more noticeable with inertia emulation support again. However, the frequency nadir of the inertia emulation is slower as it can be seen that the minimum point of the curve is displaced to the right of the curve. Also, the second frequency dip caused by the instant power support is significant.
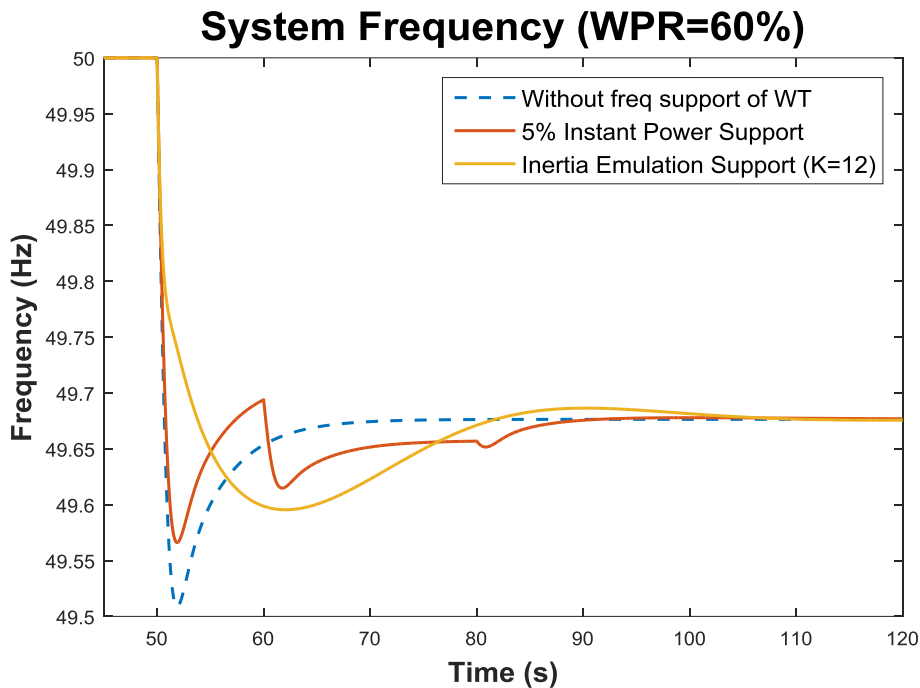

Figure 18: Frequency response for Case 2.1: 5% instant support and K=12 with 60% WPR

Figure 18, shows that the inertia emulation support has a slower response than in previous plots, as the frequency nadir is reached 10 seconds after the disturbance. Also, the instant support has a second dip which is almost as big as the first one. None of the responses reach the steady state frequency value 30 seconds after the disturbance (see Figure 17 and Figure 18). In the last case the response is particularly long.

The trend of results shows that as the WPR increases (keeping the level of inertia support constant), the emulation support slows the frequency response of the system and the instant support increases the second frequency dip.

4.3.2   Case 2.2: 2% instant support and K=7 with WPR=60%

The purpose of this case is to try to improve results obtained in Case 2.1 for the case of 60% WPR due to the symptoms it showed. This is done by reducing the extra power extracted from the WT and the results are shown in Figure 19:
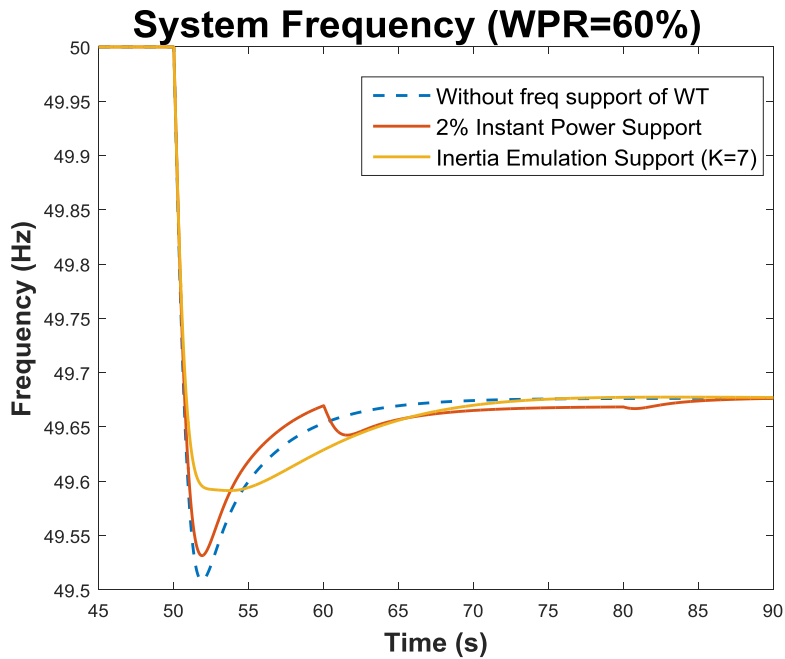
Figure 19: Frequency response for Case 2.2: 2% instant support and K=7 with WPR=60%

In this case, the inertia emulation support does reach the steady state value within 30 seconds. As for the instant power support, the second frequency dip has been improved, but the nadir is clearly lower than in the instant power support curve of Figure 18. The new figure shows that the reduction of the amount of support given by the WT results in a faster response of the frequency.

For the purpose of a clearer comparison between the two simulations at 60% WPR, the main differences between them are presented in Table 7:

Table 7: Comparison of results for Case 2: Future scenarios with increasing WPR

WPR=60%	Frequency nadir (Hz)	Approx. time to reach steady state (s)	Second frequency dip (Hz)
No support	49.51	20	-
5% instant support	49.57	40	49.62
Emulation (K=12)	49.6	45	-
2% instant support	49.53	35	49.64
Emulation (K=7)	49.59	25	-

In general, a higher amount of support given by the WT yields a better frequency nadir, when only comparing between the same types of support.

However, being too ambitious with the amount of extra power delivered by the WT compromises the fastness of the frequency response. If the target is too high, it takes longer to

stabilize at the final steady state value. Also, only in the case of the instant power support, the second dip can become significantly high compared to the original nadir.

To summarize, the results obtained for future scenarios with high WPR show that the best tuning of the supports might to reduce their contribution as the WPR increases. In this way, the frequency response of the system is better optimized and both for nadir, less time to reach steady state and a smaller second dip.

4.4   Analysis and limitations

4.4.1   Analysis

The results of the simulations show that there increasing the amount of support will improve the frequency nadir. Nonetheless, this might compromise the recovery time of the system frequency to its new steady state value and increase the second frequency dip in the case of the instant power support.

As a consequence, the optimal level of inertia support is different depending on the generation mix and the WPR, the inertia of the system, the wind speed and the parameters of the power system. For this reason, when comparing the same scenario with different adjustments of the supports, the best option can be subjective to preferring a faster response and smaller second dip or a better frequency nadir.

When choosing between inertia emulation and instant power support, each one has its own advantages and disadvantages over one another. In all the plots that have been presented, the emulation support has a better and more significant positive impact in the frequency nadir, improving it by a higher rate. In addition, it does not present the inconvenient second frequency dip, and hence, frequency reaches its steady state value earlier than with the instant power support.

However, the instant power support offers the advantage that the energy extracted from the turbine is predefined and can be quantified. Therefore, this technique is more manageable for the TSO in its plan of the daily demand and the primary reserves. On the other hand, the extra power from the emulation control is dependent on the system frequency, its derivative and the value given to K.

Moreover, if wind speed was assumed to be variable (as in a real situation), this would not affect the instant power support signal but it would influence the inertia emulation control. This is because the instant power support is defined independently of the operation point of the WT (disabling the maximum power point tracker).

4.4.2   Limitations

Because there is only one WT, the wind speeds have had to be assumed to be very high to match the generation mix. In the island, the wind farms are spread over different locations of the island and they will each have a different wind blowing. The amount of stored kinetic energy that can be extracted from the turbine at different wind speeds for instant supports lasting 10 seconds is shown in Figure 20:
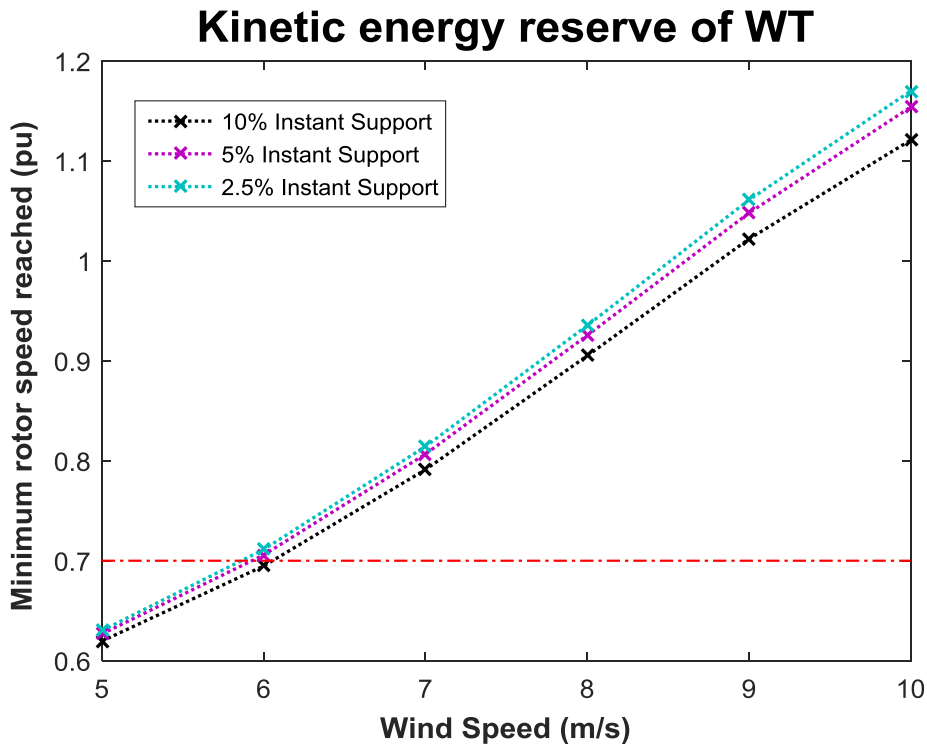

Figure 20: Extractable kinetic energy from WT at different wind levels

At each wind speed, the vertical distance from each marked point to the discontinuous line (representing the 0.7 pu minimum speed limit of the turbine) is a measure of the kinetic energy in the blades that has not been used. The WT can provide instant power support safely for wind speeds above 6 m/s. This condition is also valid for the inertia emulation support if the level of this support is adjusted to be the same as that of the instant power support, which is the case in the simulations that have been presented.

Also, the premise of constant wind speed would not be the real case. Usually, wind speed variations are random and a normal average rate of change of wind speed can be $1m/s^2$. If the wind speed is high and there is enough "kinetic energy reserve" (see Figure 20), the oscillations should not represent a big concern as they are not likely to slow the turbine down to 0.7 pu. On the other hand, at low wind speeds, the inertia supports are more likely to decelerate the turbine too much.

4.5   Final conclusions

All in all, the simulations of the real case with WPR=20% have been satisfactory. The results obtained show that the inertia support strategies can not only be safely implemented into primary regulation, but also improve the transient response of the system frequency.

Furthermore, the implementation of these support strategies when increasing the WPR to 40% and 60%, the system frequency keeps having a good response. However, these results are valid as long as the wind speed is sufficiently high (approximately at least at 6.5m/s as seen in Figure 20).

Lastly, for future work on this topic, it might be interesting to analyse whether if these inertia support techniques can help avoid load shedding due to minimum frequency. However, the minimum frequency obtained in the results was 49.51 Hz, and automatically programmed load shedding in Gran Canaria begins at 49.5 Hz [11]. Nevertheless, with more realistic assumptions (variable and lower wind speeds), the inertia support methods could have a real impact on this aspect.

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