Evaluation of frequency response of variable speed wind farms for reducing stability problems in weak grids

J. Villena-Lapaz, A. Vigueras-Rodríguez, E. Gómez-Lázaro, A. Molina-García, J.A. Fuentes-Moreno

***Abstract*—Maintaining the frequency within certain limits in a power system is a basic operational requirement as many loads may be very sensitive to frequency deviations. Increasing wind penetration in the power grid may lead to stability problems in isolated systems, or systems with weak interconnections with surrounding areas. Modern wind farms are based on variable speed wind turbines where the rotor speed and the electrical frequency are not coupled, thus, these farms do not add inertia to the system. At certain levels of wind penetration, the system inertia may become critically small, and the system may get unstable. In this work, some frequency response capabilities are incorporated into a wind farm. A validated wind model, developed by the authors, is used to obtain the wind series which is used for the simulations. Typical models of conventional generation power plants are used to fulfill the system operation requirements.**

A. Introduction

The grid frequency is controlled by conventional power plants. The main goal of this control is to keep the frequency within specified limits depending on each Grid Code [1]. Conventional generators are usually equipped with so-called primary and secondary control, and the inertia of the rotating masses which are synchronously connected to the grid limits the rate of frequency change in case of an imbalance between generated and consumed power. Any power imbalance is catered by the generation by modifying their power input, and the system inertia limits the rate of change of frequency under power imbalances. The lower the system inertia, the higher the rate of frequency change when load or generation variations appear.

System inertia also plays an important role in the grid frequency control, as it limits the rate of frequency change under power imbalances. The lower the system inertia, the higher the rate of frequency change when load or generation variations appear. Under extreme levels of wind penetration, in power systems with weak interconections, it may appear a critical instability that makes the power balance difficult to maintain. In [2], this issue is analyzed for a bulk wind farm consisting of fixed-speed wind turbines, whose rotor speed is coupled to the grid. When operating under very high wind conditions, some of the turbines are disconnected because the wind surpasses the cut-off speed, and hence the total inertia of the system reduces considerably, producing instabilities that the conventional generators are not able to control.

When dealing with modern variable speed wind turbine generators, due to the electromechanical characteristics of these technologies, whose turbine speed is decoupled from the grid frequency [3], the stability requirements become more difficult to fulfill. The inertia contribution of wind turbines is much less than that of conventional power plants [3]–[5]. Besides, some variable speed wind turbines use back-to-back power electronic converters which create an electrical decoupling between the machine and the grid, leading to an even lower participation of wind generation to the system stored kinetic energy.

Some authors suggest that this drawback can be compensated by an adequate implementation of the machine control. In [6], [7] a power reserve is obtained following a power reference value lower than the maximum power which can be extracted from the wind, thus decreasing the turbine power efficiency. In [8], [9], a method to let variable-speed wind turbines emulate inertia and support primary frequency control using the kinetic energy stored in the rotating mass of the turbine blades is proposed. In [9], a power reserve with the help of pitch control when the wind generator works at a close-to-rated power is obtained.

Not only does the rising wind power penetration yield more challenges concerning the system stability due to the inertia reduction. The need for mainaining the apropriate amount of power reserves in order to assure the quality of the supply, also arises [10], [11]. On the other hand, to participate in reducing the impact of wind power fluctuations and wind turbines low inertia contribution to grid frequency control, demand-side actions may also have to be considered. In this regard, some authors analyze the posibility to manage, to some extent, the connection and disconnection of some loads [12]. In [13], a load controller is described to let the demand side participate in the primary frequency control within a system with high wind energy penetration.

In this work, a simple method for providing wind farms with frequency response capabilities is implemented and assessed under normal wind conditions.

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B. Model description

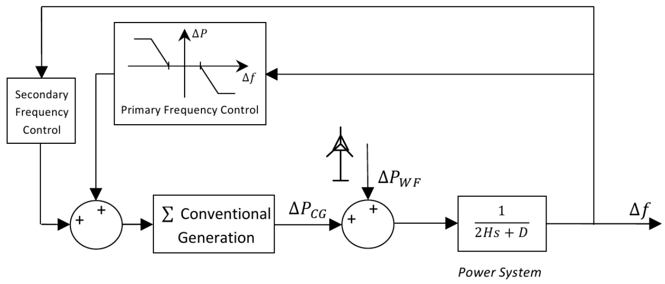

Fig. 1. General Scheme of the power system model. The wind farm is decoupled from the system frequency

1) General description: The power system model whose scheme is shown in Fig. 1, has been used. Under mechanical and electrical disturbances, the power system has been modeled from the torque balance equation for the generators:

$$\Delta P_{mec} - \Delta P_L = D\Delta f + 2H\frac{d\Delta f}{dt}, \tag{1}$$

where $\Delta P_{mec} - \Delta P_L$ represents the imbalance between power supply and demand in pu, Δf is the consequent variation of the grid frequency in pu, D is the damping coefficient in pu too, which models the variation in the electric power consumption with respect to speed changes and H, expressed in seconds, is the system inertia constant.

$H = \frac{1/2J\omega_0^2}{S_{base}}$, being J the moment of inertia of the rotating masses coupled to the grid, ω_0 the rotor nominal speed and S_{base} the total aparent power of the system, represents the total system inertia that supports the power imbalnces. In the case study, this equivalent inertia constant is given by:

$$H = \sum_{i=1}^{n} H_i \frac{S_i}{S_{sys}}, \tag{2}$$

where $H_i = \frac{W_i^k}{S_i}$ is the inertia constant of the i^{th} generator. W_i^k and S_i are the kinetic energy and nominal power of the i^{th} generator.

Additionally, frequency deviations are used as feedback signals for primary and secondary frequency control.

2) Generation model: The supply side consists of two conventional generators and a wind farm.

The conventional generators are a hydraulic plant and a two-stage thermal plant with reheating turbine, and participate both in primary and secondary control. The models depicted in Fig. 2 and 3 include the transfer functions for the two main elements of the generators: the primary energy–mechanical torque converter and the mechanical torque-electrical power converter.

The wind power production is based on the implementation of an aggregated power fluctuations model of a wind farm developed by some of the authors. These model was previously validated by comparing its results with real power fluctuations measured in Nysted Offshore Wind Farm. In order to assess the frequency response of a modern wind farm, a published model of a multi-megawatt commercial variable speed wind turbine (GE 3.6 MW) is used in this work, which is adopted

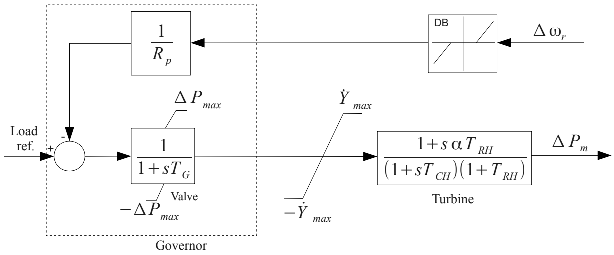

Fig. 2. Model of the thermal–plant

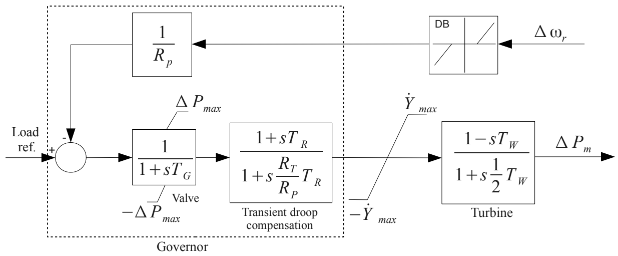

Fig. 3. Model of the hydro–plant

from [14] and shown in Fig. 4. Such model has been extended in order to include non optimal tip speed ratio effect and the kinetic rotational energy of rotor and blades, elements which are needed for providing frequency response in the system.

For the aim of this work, it is considered that the wind farm's influence on the system frequency is negligible, and the actual frequency control actions are performed by the conventional generators. Anyway, the frequency error along the simulations will be used to evaluate the behavior of the implemented frequency response loop in the wind turbine model.

3) Frequency response: The frequency response algorithm aims to temporarily change the power delivered to the system, by changing the wind farm's power reference (ΔP_{WF}). Such change in power reference is given by $\Delta P_{WF} = -K\Delta f$.

As it is shown in the paper, this strategy is limited by available rotational speed and by loss of power efficiency if tip speed ratio changes significantly.

C. Simulation and results

A mix of two conventional power plants (a thermal and a hydro units) and a wind farm has been considered.

For generating the wind speed series, an offshore location is considered. The simulator estimates the average wind power

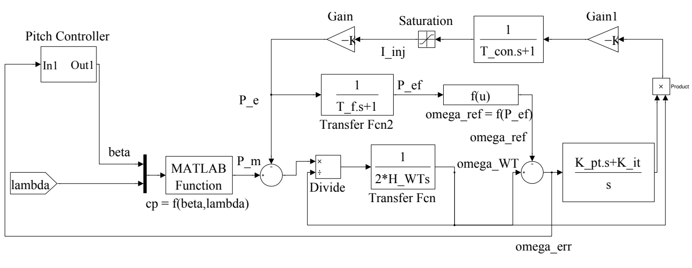

Fig. 4. Wind turbine model from [14].

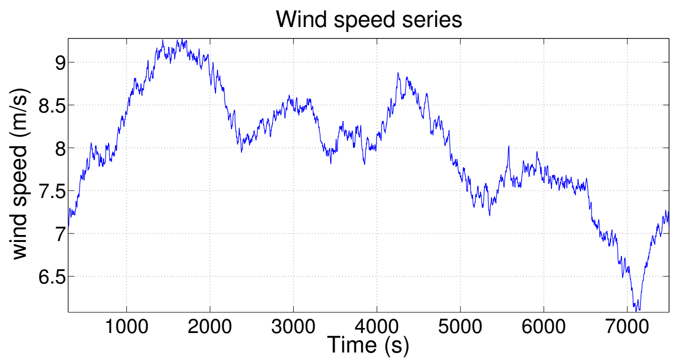

Fig. 5. Wind speed series in 2-hour time interval, expressed in m/s

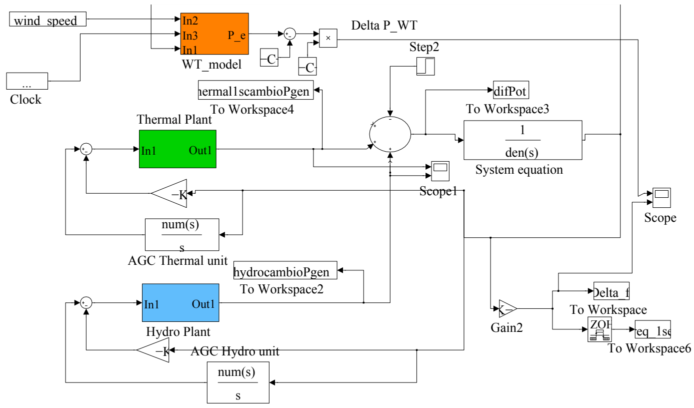

Fig. 6. Power system model in Simulink

within a wind farm with a certain distribution of wind turbines, which has to be specified. In this case, it consists of 10 rows with 2, 3.6 MW wind turbines each. The distance between columns is about 500 m, whereas rows are separated around 900 m. Several 2-hour time intervals of wind speed have been simulated for the proposed wind farm. From these data series, one of them has been used for the aim of the study –see Fig. 5– . The selected data series is relevant enough, as it represents a period with high fluctuations, and its average value is below, but close to, the rated, thus allowing the wind farm to produce over and under its nominal power when performing frequency response actions.

As mentioned above, the wind farm doesn't influence the system frequency. On the other hand, the frequency error is fed back to the wind turbine model, as shown in Fig. 6.

There are two inputs to the system: the wind speed series and a negative load step in $t = 400$ s. The conventional plants have been modeled to produce the difference between the wind power and the load, plus their participation in primary and secondary control.

The values of all parameters of the conventional power plant models used in this work are given in Table I and are obtained from [15], see Figs. 2 and 3. The selected inertia constants of thermal and hydro plants are $H_{thermal} = 4$ s and $H_{hydro} = 3$ s, respectively.

The aim is to study the implementation of the primary control loop on the wind farm model, as briefly described in subsection -B3. The algorithm must take into consideration

TABLE I
PARAMETERS FOR THE CONVENTIONAL GENERATORS MODELS

Parameter	Thermal plant	Hydro plant
DB	± 20 mHz	± 20 mHz
R_P	5 %	5 %
ΔP_{max}	0.05 pu	0.05 pu
$\dot{Y}_{max}$	0.05 pu/s	0.16 pu/s
$\dot{Y}_{min}$	-0.1 pu/s	-0.16 pu/s
α	0.3 pu	–
T_{RH}	7 s	–
T_{CH}	0.3 s	–
T_w	–	1 s
R_T	–	0.38 pu
H	4 s	3 s

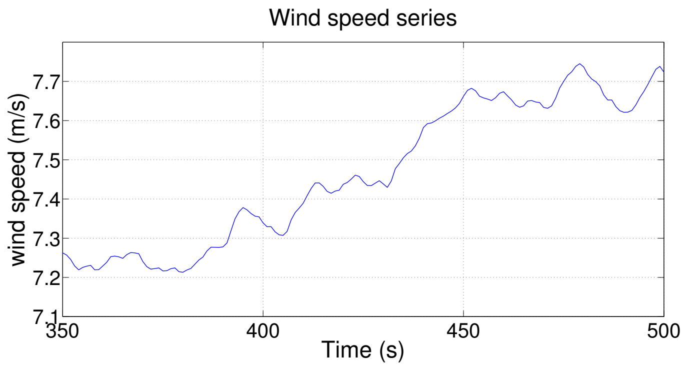

Fig. 7. wind speed (m/s) between $t = 350$ s and $t = 500$ s.

that the frequency response actions can only be carried out for a limited amount of time, given that the loss of wind farm's kinetic energy may reach unacceptable levels. In this way, according to different criteria as in [16], it is possible to chose some minimum rotational speed as a limit for the participation of the wind farm. Once this limit is reached, the wind farm emulated inertia loop must be disconected in order to recover its normal operation status. The lower the chosen speed limit, the more time the wind turbines will need to get back to their normal rotational speed. In the same way, a frequency fall followed by another one may lead to a significant loss of wind farm power production, and hence to a critical system inertia.

For this reason, it is interesting to consider a series of wind power data with important fluctuations over time, as that described before.

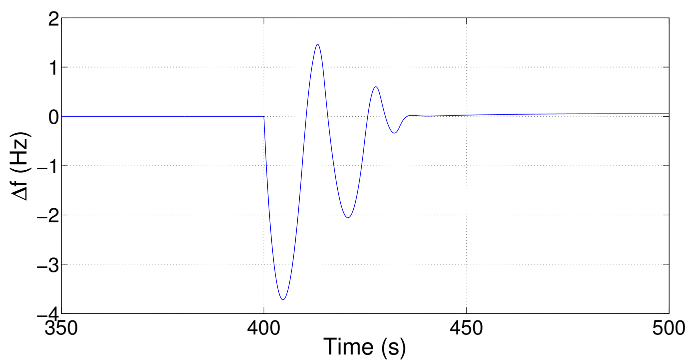

Fig. 8. Frequency excursions (Hz).

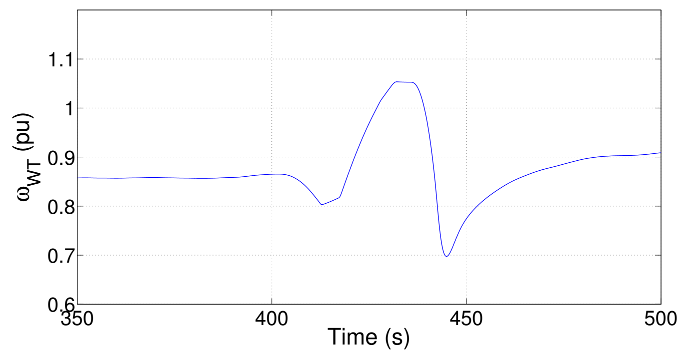

Fig. 9. Wind turbine speed (pu).

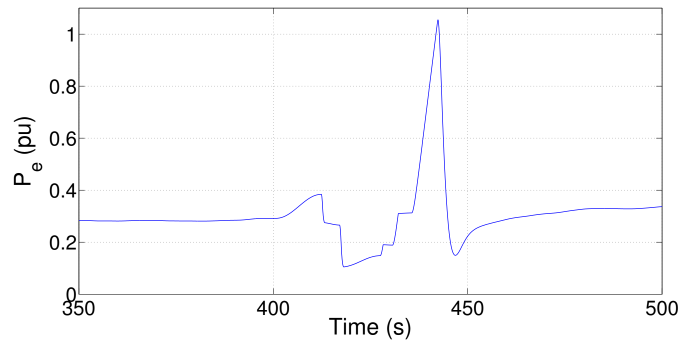

Fig. 10. Electric power delivered by the wind turbine (pu).

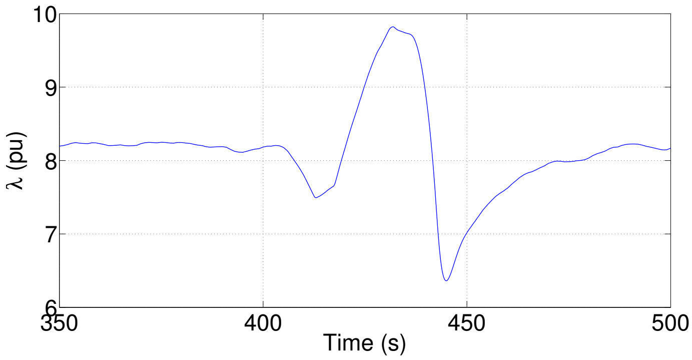

Fig. 11. λ coefficient (pu).

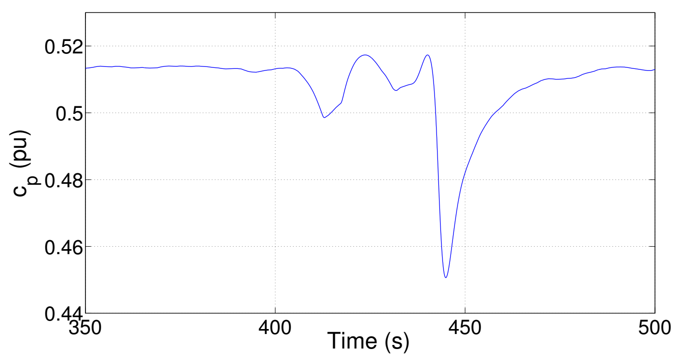

Fig. 12. Power coefficient c_p (pu).

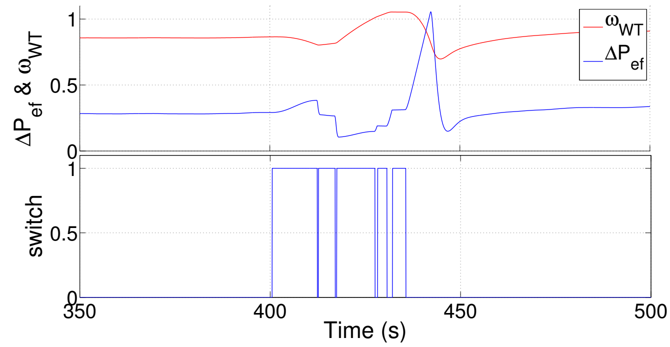

Fig. 13. Comparison of the reference power and the wind turbine rotor speed during the event. Beneath, the signal that switches on and off the control loop.

The active wind farm control gets active if $0.7 < \omega_{WT} < 1.2$ pu and $|\Delta f| > 0.1$ Hz.

As shown in Fig. 6, the output of the wind farm block is not considered for balancing the power. In order to provoque a significative power imbalance, a step of 0.2 pu takes place at $t = 400s$ from the demand side. It means, for instance, that a sudden connection of a big group of loads happens, or that a big generation unit switches off suddenly. As a consequence of this step, the system frequency falls down as well, as can be seen in Fig. 8, reaching a minimum excursion of -3 Hz, which is considerable. This large frequency excursion happens because the step introduced into the system is very deep –20% of the total power–. In order to restore the system frequency, the conventional plants' primary and secondary controls demand more power through their governors, augmenting their power production.

The wind farm sees the same frequency change, which is inside the control zone ($|\Delta f| > 0.1$ Hz) and the control loop turns on, delivering an extra active power –see Fig. 10–. To that end, it changes the reference value of the electric power, $P_{ef} = P_{ef0} + \Delta P_{ef}$, and inmediately the wind turbine rotor speed decreases –see Fig. 9. In fact, the extra active power that it is delivering is taken from its rotational kinetic energy. After a few seconds, the rotor speed reaches the minimum value set for the control, $\omega_{WT} = 0.7$ pu, and the control turns off. During the next seconds, although the frequency error continues in the control zone, the wind turbine needs to recover its normal operation speed.

Fig. 12 and 11 show the reaction of C_p and λ during the perturbation. In Fig. 13, the behavior of the wind turbine active control can be observed. After the frequency fall,the control gets active, given that $\omega_{WT} = 0.7$. While the control is active, the electric power delivered by the wind turbine keeps rising, until the moment in which Δf rises again, and when reaching the -0.1 Hz level, the control switches off. Since the frequency change is very fast, it again surpasses 0.1 Hz, and the control switches on. This process continues until the frequency is stabilized by the conventional generators.

D. Conclusions

In this work, an algorithm for providing active power support on variable speed wind turbines is implemented on a wind farm, simplified in a wind turbine model. Its behavior is evaluated under variable wind speed, and under a disturbance consisting in a load sudden conection. The control algorithm has been introduced in a 3.6 MW GE wind turbine model. The extra active power delivery when a frequency fall occurs has been tested, and show good results.

As the wind power has been considered negligible compared to the conventional generators that carry out the primary and secondary frequency control actions, in this work the tested wind farm active power control loop has not participated in this issue. It is expected for future works to consider the participation of the wind farms in the primary frequency control, according to the algorithm proposed here.

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