Proceedings of the Fifth IASTED International Conference
POWER AND ENERGY SYSTEMS
June 15-17, 2005, Benalmádena, Spain

EXPERIMENTAL VALIDATION OF ALGORITHMS TO INTEGRATE A VARIABLE SPEED WIND-TURBINE IN THE ELECTRICAL GRID

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ABSTRACT
This article presents the control algorithms that allow a variable speed wind turbine generator based on an asynchronous wound rotor machine, to contribute to the control of the frequency and voltage amplitude of the grid. Two different high level control techniques are proposed as solutions to control the frequency of the electrical grid by means of a variable wind speed turbine. It is also proposed, an electrical grid's voltage amplitude control by means of the asynchronous generator of the variable wind speed turbine.
Experimental results in a platform rig are presented validating satisfactorily proposed techniques in order to contribute to the control of the electrical grid.

KEY WORDS
Electric power generation, frequency control, power factor correction, wind power farms, machine control.

1. Introduction

The integration of renewable energy, particularly wind energy, in the electrical grid, accounts for an increasing proportion of the entire energy generated, currently evolving towards a 20% share.
Up until now no efforts have been made to integrate this type of energy with the electrical system's operations and control, but given the growth estimates, integration is essential as it now runs the risk of destabilizing the electrical system.
Today wind generators connected to the grid, work differently from traditional synchronous salient pole generators in conventional power stations. This type of generator interacts with the electrical system in a distinct way because of its different features.
When a large number of wind turbine generators connect to the system and replace a substantial number of conventional synchronous generators, they begin to effect different aspects of the system's behaviour, potentially leading to destabilization of the system. A particular case to bear in mind arises during periods of small loads and high wind speed; the relative wind energy contribution is greatest in these circumstances.

On the other hand, wind power generators are confronted with increasing standards from the grid operators (REE [1], E.ON [2], ELTRA [3]) in aspects as power quality, grid integration, control capacities, or voltage dips behaviours. Modern wind turbine technology allows these systems to not only produce energy but also fulfill the most demanding regulation requirements. An advanced control system facilitates the control of active and reactive power in modern wind energy parks, be it at the individual level (individual wind power generator) or in a coordinated way, which means the wind park operates as a conventional generation unit.
The following sections will analyze the different control algorithms that allow a wind turbine to individually influence system operations in terms of voltage and frequency control, where the wind turbine operates with active and reactive power references.
The wind turbine under analysis is based on a doubly fed induction generator (DFIG). The generator is controlled via the rotor with back to back converter. The results of experiments will be performed in an experimental rig detailed in [4].

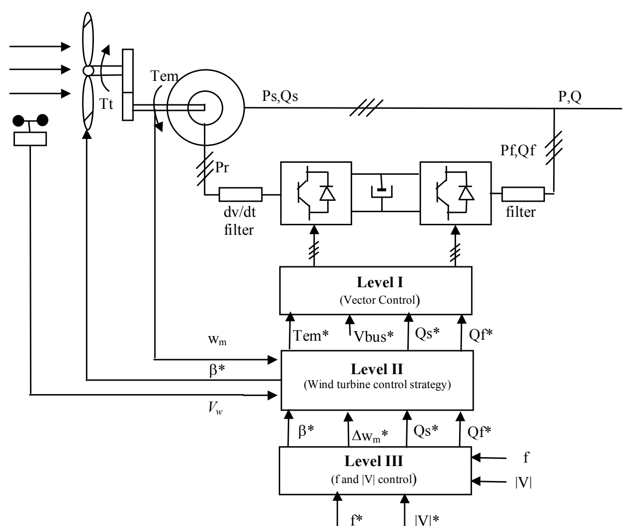

Fig. 1. Structure of the wind energy generation system

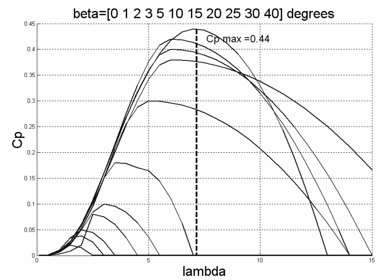

Fig. 2. Curves of Cp(λ,β).

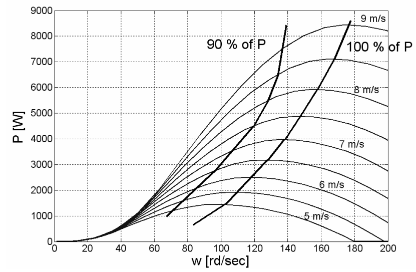

Fig. 3. Generated power vs speed at constant β.

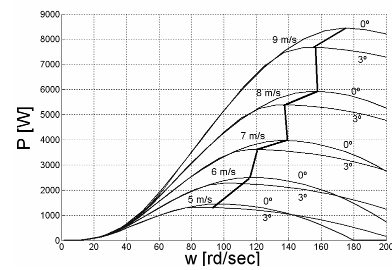

Fig. 4. Generated power for different pitch angles vs. speed.

2. Description of the control system

Control of the wind turbine generator occurs at three distinct levels, as seen in figure 1 [4].

Each control level performs different tasks: In level I, torque control, bus voltage control and reactive power control takes place, via vector control of each inverter.

In level II, the wind turbine control strategy is implemented.

Finally, in level III, higher level control takes place, to regulate grid voltage amplitude and frequency.

This document will study various control strategies for levels II and III.

3. Wind turbine power

By employing direct speed control [5] it is possible to control the power extracted from the wind via the wind turbine generator.

Varying the mechanical speed of the wind turbine Ω_t, it is possible to modify the tip speed ratio λ [6]:

$$\lambda = \frac{\Omega_t \cdot R}{V_w} \tag{1}$$

and the power coefficient $C_p = f(\lambda)$, so that the power generated will vary based on the value of λ according the next equation:

$$P = \frac{1}{2} \cdot \rho \cdot \pi \cdot R^2 \cdot V_w^{\ 3} \cdot C_p(\lambda, \beta) \tag{2}$$

Thus at optimal tip speed ratio ($\lambda_{optimum}$) operation condition, the power coefficient C_p will take its maximum value, so the power generation will be maximum for given wind conditions.

If different β values are chosen, the wind turbine operates at different C_p curves, yielding from equation (2), to different power extraction conditions, this fact is shown in fig 2.

From equation (2) and figure 2, by varying the speed of the wind turbine, power extraction is lower than optimal, in relation to particular wind conditions (figure 3).

The other option for controlling extracted energy from the wind consists in varying the pitch angle (β) of the blades, as shown in figure 2 and figure 4.

4. Control level III

The objective of control level III is to contribute to the control of the grid voltage, more specifically grid voltage amplitude and frequency. To achieve this, several control strategies are presented below.

4.1 Grid voltage frequency control

To control the frequency, in response to sudden changes in power demand, the wind turbine should be capable of reacting to said variations in power by varying the rotation speed, by varying pitch, or by a combination of both. Note that in order to provide this capacity, under normal operation, the wind turbine should operate below its optimum power extraction level, i.e. the wind turbine is deload [7].

Hence, when a power demand variation occurs the wind turbine should provide that power variation, as shown in the previous section, via a variation in the speed or in the pitch angle.

In the figure 5, whole control level III block diagram is shown. When a variation of the rotational speed is chosen, the control signal of the frequency regulator, is directly the variation of the speed needed to command, in order to get a variation in the generated power

When the other possibility is chosen to compensate the frequency of the grid, the structure of the control strategy is similar. In this case, the control signal of the frequency regulator directly generates the pitch angle reference, to compensate the variation in the power demand.

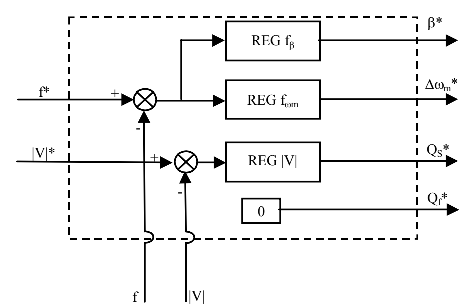

Fig. 5. Control level III block diagram.

4.2 Grid voltage amplitude control

On the other hand, it is possible to control grid voltage amplitude by varying the reactive power transmitted by the generator to the grid. From another point of view, varying the power factor of the grid, different voltage amplitudes may be achieved [8]. Using the proposed control diagram, shown in figure 1, the reactive power exchanged with the grid might be done, by the stator or by

the grid side converter, as both Q_s and Q_f, are electrical magnitudes controlled in control level I [4]. For convenience, voltage amplitude control has been implemented using stator reactive power, and the reactive power reference of the grid side converter has been set to zero.
Depending on the chosen frequency control strategy, pitch or speed variation reference, will not be taken into account in the next control level.

5. Control level II

Depending of desired performance of the wind turbine, several control level II strategies may be implemented. Some of those possible strategies are presented next.

5.1 Normal operation

In this case, the control objective is to extract maximum energy from the wind taking into account the speed limitations of the generator.

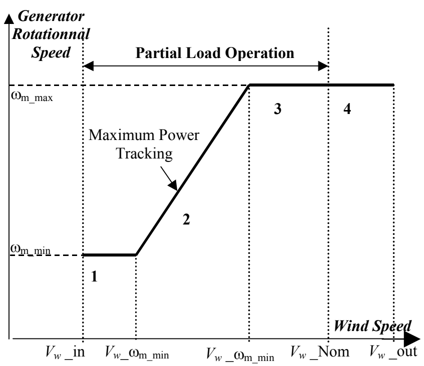

Fig 6. Operating curve.

Figure 6 shows the relationship between wind speed and mechanical speed in normal operation. Operating in this way, level III does not take part in the control of the grid frequency. Tip speed ratio is set to its optimum value at wind speeds from zone 2 in figure 6.

5.2 Power control with constant pitch (Zone 2)

In this case, power control takes place via variations in the rotation speed, while the pitch is kept constant.
Therefore, λ will take the required value, to satisfy the power demand at a given moment.

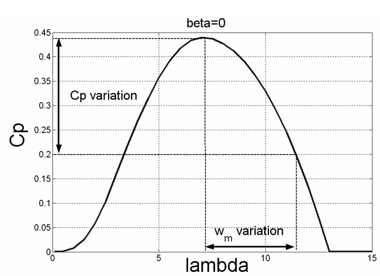

Fig. 7. Control level II $C_p(\lambda)$ curve, wind turbine deload with constant pitch strategy.

To deload the wind turbine, higher speed than the optimum is chosen, instead of lower speed, in order to store kinetic energy for power demands transients.

Control strategy block diagram is shown in the next figure, necessary speed variation reference is given by control level III, to satisfy power demand.

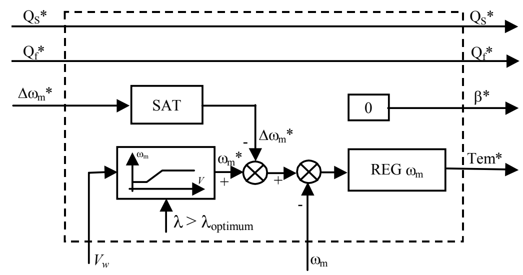

Fig. 8. Control level II block diagram, with constant pitch strategy.

With λ = 9.7, the following table shows the maximum power margins and required rotation speed margins, at different wind speeds.

V_w [m/s]	*P [p.u.]*		*ω_m[p.u.]*	
	Cp = 0.29 (λ=9.7)	*Cp_{max}=0.44 ($\lambda_{optimum}$=7.2)*	*Cp = 0.29 (λ=9.7)*	*Cp_{max}=0.44 ($\lambda_{optimum}$=7.2)*
6	*0.117 (1754 W)*	*0.176 (2647 W)*	*0.923 (145 rd/s)*	*0.681 (107 rd/s)*
7	*0.185 (2785 W)*	*0.2805 (4204 W)*	*1.07 (169 rd/s)*	*0.79 (125 rd/s)*
8	*0.277 (4158 W)*	*0.418 (6276 W)*	*1.23 (193rd/s)*	*0.91 (143 rd/s)*

Tab 1 Instances of power and speed for zone 2 operation (λ>$\lambda_{optimum}$)

Thus, for instance with wind of 7 m/s, the wind-turbine, in deload circumstances (C_p = 0.29), could handle a 0.0955 p.u. increase in power demand at most, thanks to a 0.28 p.u. decrease in rotational speed. On the other hand, if the power demand decreases, the power margin is greater.

5.3 Power control with variable pitch and constant speed

If we consider previous control technique, using pitch control may be advantageous, if the rotation speed remains constant. Hence now, the objective is to keep the wind turbine rotation speed constant, while the pitch is altered. The wind turbine works at a constant λ equal to $\lambda_{compromise}$.
This can be achieved maintaining constant tip speed ratio for different pitch angle values, as shown in next figure.

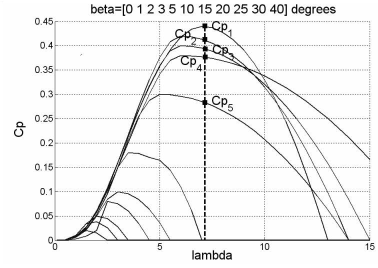

Fig. 9. Control level II Cp(λ,β) curve, , with variable pitch and constant speed strategy ($\lambda = \lambda_{compromise}$).

Note how the speed, by this control strategy, will remain constant if the wind speed does not change.

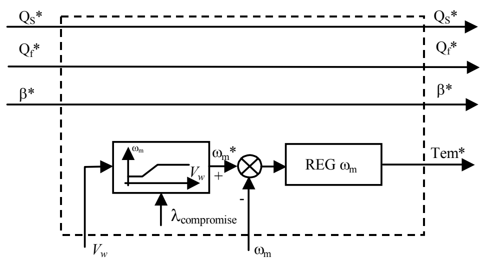

Fig. 10. Control level II block diagram, with variable pitch and constant speed strategy ($\lambda=\lambda_{compromise}$).

Selecting λ =7.2 (coincides with λ optimal of the maximum C_p curve), the rotation speed is kept constant, series of power figures are shown, at different angles of pitch and at different wind speeds.

V_w [m/s]	β[º]	C_p [λ=7.2]	ω_m [p.u.]	P [p.u.]
7	*0*	*0.4412*	*0.8* *(125.6 rd/s)*	*0.28* *(4204 W)*
7	*3*	*0.3435*	*0.8* *(125.6 rd/s)*	*0.218* *(3273 W)*
7	*5*	*0.2792*	*0.8* *(125.6 rd/s)*	*0.177* *(2661 W)*
10.5	*0*	*0.4412*	*1.2* *(188.4 rd/s)*	*0.946* *(14191 W)*
10.5	*3*	*0.3435*	*1.2* *(188.4 rd/s)*	*0.736* *(11048 W)*
10.5	*5*	*0.2792*	*1.2* *(188.4 rd/s)*	*0.598* *(8981W)*

Tab 2 Power and speed instances for zone 2 operation ($\lambda=\lambda_{compromise}$).

In this case, at 7 m/s constant wind speed, 0.103 p.u. power margin is achieved, by 5 degrees pitch angle variation at constant rotational speed. This margin is the biggest from two proposed strategies in present paper.

6. Experimental results.

For validation of the proposed algorithms, experimental results are carried out in a platform rig described in [4].
In both cases, a weak grid composed by a synchronous machine and a DFIG, driven by an emulated wind turbine are used. The synchronous machine contributes to the grid with approximately constant power generation.
The wind turbine undertakes the control of the grid voltage amplitude and frequency, when sudden load variation occurs, by means of the algorithms mentioned before. Since the experimental rig is closer to real behaviour of an electrical grid, than the simulation model, only experimental results will be shown in the present work.

6.1. Grid voltage frequency and amplitude variation without control

Next, the behaviour of the weak grid is going to be shown. When a load demand increment occurs in the grid, if no frequency control is being used, the frequency will decrease.
When both electrical machines where generating 5KW active power each, a sudden load increment of 3KW occurs.
Similar consequences may be deduced from the amplitude of the grid. In this case, no amplitude control has been implemented, and then in same conditions, the amplitude will decrease as the frequency does. This fact is shown, for the weak grid in figure 11.

6.2 Controlling grid voltage with constant pitch based algorithm.

In this section, frequency control based in speed variation at constant pitch is implemented in the platform rig, together with the voltage amplitude control.
The trial was carried out according to the following conditions: a constant wind speed of 7.8 m/s and a phase voltage reference of 280 V (peak value). Initial and final steady state conditions are summarized in table 3.

		Initial condition	Final condition
Synchronous generator	**P [p.u.]**	*0.153* *(2300 W)*	*0.153* *(2300 W)*
	Q [p.u.]	*-0.326* *(-4900 VAR)*	*-0.313* *(-4700VAR)*
Wound rotor generator	**P [p.u.]**	*0.166* *(2490 W)*	*0.286* *(4290 W)*
	Q [p.u.]	*0.326* *(4900 VAR)*	*0.313* *(4700VAR)*
	ωm[p.u.]	*1.2* *(187 rd/s)*	*0.99* *(155 rd/s)*
Load	**P [p.u.]**	*0.319* *(4785 W)*	*0.439* *(6585 W)*
	Q [p.u.]	*0*	*0*

Tab 3. Power balance in the isolated grid at constant pitch angle.

Experimental results are shown in figures 12 and 13. Frequency is compensated satisfactorily to the reference value 50 Hz. Amplitude control has been carried out as well, in this case, the reference was set to 280V.

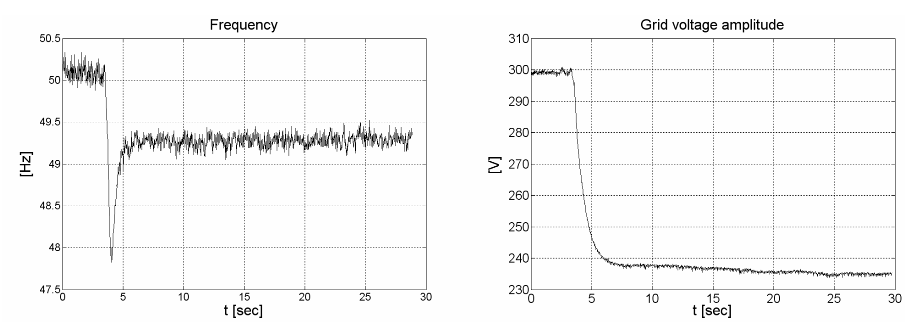

Fig. 11. Frequency and voltge variation without control.

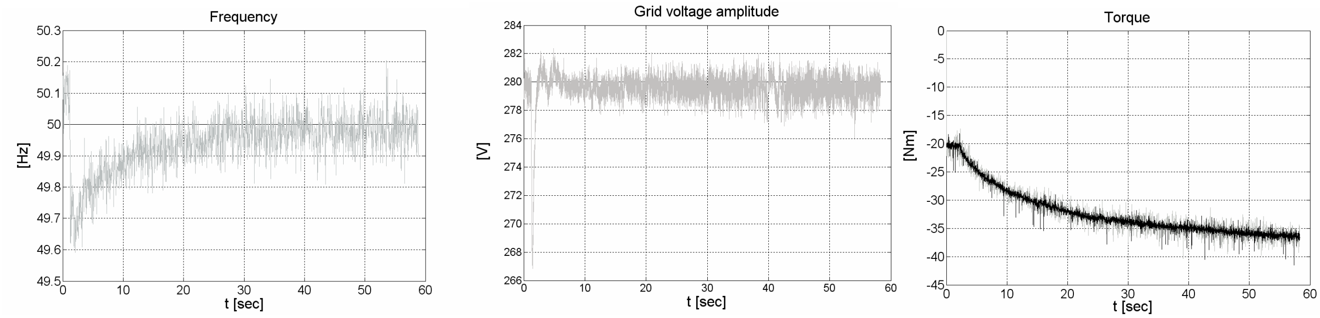

Fig. 12. Frequency, amplitude and torque variation at constant pitch angle.

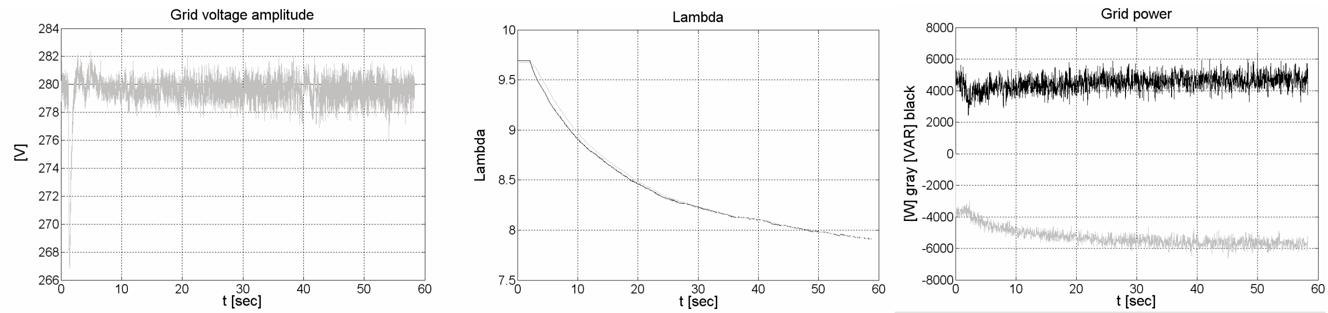

Fig. 13. Speed and lambda evolutions at constant pitch angle. Active (gray) and reactive (black) power interchanged with the grid by the DFIG

In order to compensate the frequency fall the DFIG must contribute with more power to the network, hence, it is necessary a speed decrement and lambda comes near to the optimal value, thus it will be possible to extract more power form the wind turbine.

As a consequence of working at higher power extraction value, the torque made by the generator is higher too.

Control strategy generates reactive and active power variations shown in figure 13.

Note that in the presented results, frequency compensation with this control technique takes 1 minute approximately.

6.3. Controlling grid with variable pitch and constant speed based algorithm.

In this section experimental results from the algorithm based in variable pitch and constant speed of the wind turbine are presented in figures 14 and 15. Together with it, amplitude control by means of reactive power is implemented too.

The experiment was carried out according to the following conditions: a constant wind speed of 9.7 m/s corresponding to a mechanical speed of 173.7 rad/s and a phase voltage reference of 300 V (peak value).

Initial and final steady state conditions are summarized in table 4.

The system is capable to control the frequency to the desired 50 Hz reference.

Increasing the wind turbine's power supplied to the grid compensates the frequency loss. For this purpose, the DFIG should supply the total power required, by means of the stator and rotor**.**

Note that a change in speed is not necessary to compensate the variation in power demand based on this control strategy. Under these conditions both the rotation speed of the blades as well as λ remain constant, given that the wind speed is constant.

The sudden increase in power is created by the control algorithm, varying the pitch angle (β).

		Initial condition	**Final condition**
Synchronous generator	**P [p.u.]**	*0.63 (9450 W)*	*0.63 (9450 W)*
	Q [p.u.]	*-0.28 (4200 VAR)*	*-0.28 (4200 VAR)*
Wound rotor generator	**P [p.u.]**	*0.14 (2100 W)*	*0.76 (11400 W)*
	Q [p.u.]	*0.28 (4200 VAR)*	*0.28 (4200 VAR)*
Load	**P [p.u.]**	*0.77 (11550 W)*	*1.39 (20850 W)*
	Q [p.u.]	*0*	*0*

Tab 4. Power balance in the isolated grid at variable pitch angle.

Thus, since the speed remains constant the torque variation of the wind turbine is approximately proportional to the active power.

The dynamic by which the compensation takes place, depends on the dynamics of the torque control and control of the pitch, which in general are quite fast. In the presented experiment, approximately 10 seconds are required to compensate the effect of load variation.

For this specific machine, the electric power losses are in the range of 1KW.

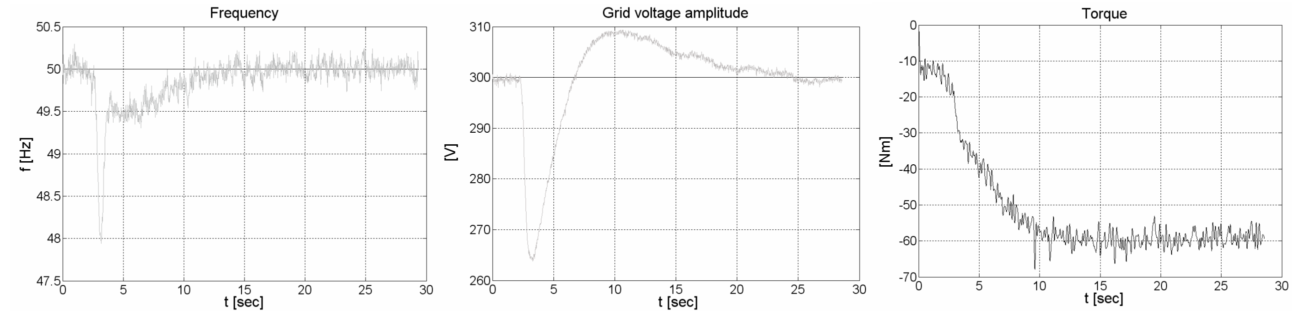

Fig. 14. Frequency, amplitude and torque variation at constant speed.

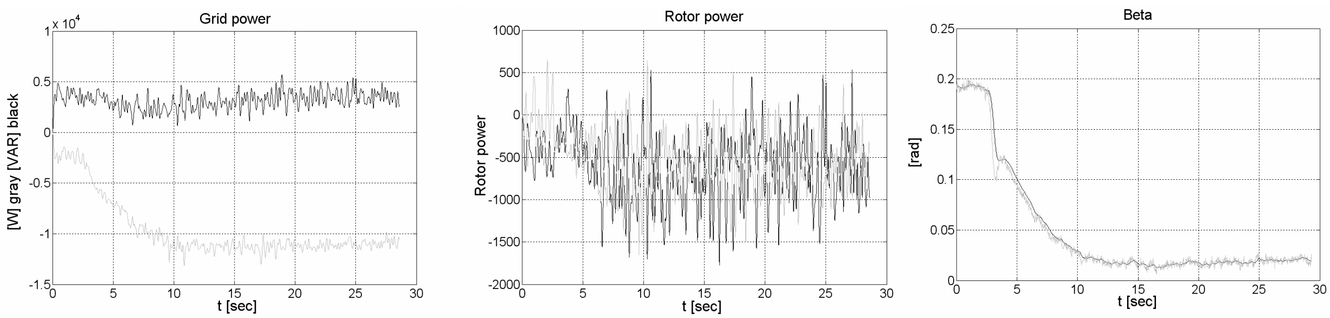

Fig. 15. Active (gray) and reactive (black) power interchanged with the grid, by the rotor and pitch variation.

The voltage amplitude reference (300 V) has been achieved.

Clearly, using a compensation of the frequency based in a variation of the speed of the wind turbine, if smooth power responses are required, the dynamic needs to be much slower than the one based on pitch variations.

7. Conclusion

Two different control techniques of high-level control have been proposed as solutions to controlling the electrical grid frequency, by means of a variable speed wind turbine.

An experimental result in an experimental rig has been presented, to validate two of those algorithms, satisfactorily.

In principle, both strategies produce similar results, but it is worth highlighting that the second strategy (pitch variation), in comparison to the first (speed variation), does not change the rotation speed of the wind turbine, whenever wind is constant.

This position is advantageous for the stability of the whole system, and because it gives bigger power compensation capacity of the wind turbine. Further more, the compensation dynamic is much faster, so this technique can be focused to applications that require quick power compensations.

Voltage amplitude control technique has proposed too, providing satisfactory results and capable of working together with frequency control.

Ancillary services provides by wind generators in aspects as voltage control, reactive power management, and frequency regulation, are possible. This fact will allow the integration of new wind plant power systems in the network.

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