Participation of Doubly Fed Induction Wind Generators in System Frequency Regulation

R. G. de Almeida and J. A. Peças Lopes, *Senior Member, IEEE*

Abstract—**This paper proposes a control scheme which allows doubly fed induction wind generators (DFIWG) to participate effectively in system frequency regulation. In this control approach, wind generators operate according to a de-loaded optimum power extraction curve such that the active power provided by each wind turbine increases or decreases during a system frequency changes. The control strategy defined at the wind generator to supply primary frequency regulation capability exploits a combination of control of the static converters and pitch control, adjusting the rotor speed and the active power according to the de-loaded optimum power extraction curve. Results obtained in a small isolated system are presented to demonstrate the effectiveness of the approach.**

Index Terms — **Primary frequency control, dynamic behavior, wind generation.**

I. INTRODUCTION

F REQUENCY control is essential for a secure and stable operation of any power system. Nowadays, power systems are facing a large wind penetration increase which may lead to difficulties in frequency control. It is recognized that the presence of a large wind power penetration (either as embedded generation or in large wind parks) may lead to a reduction of power system frequency regulation capabilities, namely when wind generation do replace conventional synchronous units that supply the major portion of the active power consumed by the grid and are responsible for reestablishing the overall system frequency [1].

In fact a reduction of the number of synchronous units in operation implicates in reducing the system inertia (rotating mass) "seen" by the grid affecting significantly the overall frequency regulation and contributing to reduce system robustness regarding disturbances. Such problem is particularly delicate in isolated systems and requires further attention regarding the potential of wind parks to participate effectively in primary frequency regulation.

Recent technological developments regarding the increase of control capabilities of wind generators are allowing their participation in frequency control and thus providing an increase in robustness of operation in such systems enabling safe increase in wind power penetration.

In order to allow operating scenarios with large shares of wind power penetration, system operators, when revising their grid codes, are nowadays requiring frequency control capabilities to wind generation [2], which can be activated in specific conditions like during valley hours.

Considering this scenario, some researches have developed research regarding the possibility of using doubly fed induction wind generators (DFIWG) to contribute for primary frequency control [3]-[6]. Two types of control can be adopted to provide contributions for system frequency control:

a) *Inertial control;*

b) *Primary frequency control.*

Inertia control can be provided in a DFIWG through a supplementary inertia control loop, as described in [5], to reintroduce inertia response. The proposed method exploits the kinetic energy stored in the rotating mass of wind turbines, such that the additional amount of power supplied by wind generator to the grid is proportional to the derivative of the system frequency df_{sys}/dt. Nevertheless, the inertia control can be similar to the one usually used in synchronous generator as presented in [3] and [6]. In this case, the droop loop (characterized by a regulation R) is used to produce a change in the active power injected by the wind generator being proportional to the difference between the measured and the nominal system frequency ($\Delta f_{sys} = f_{sys\_meas} - f_{sys\_nom}$).

In [7] both frequency control schemes, described before, are exploited such that the droop loop is only activated when the grid frequency exceeds certain limits. When exploiting an inertia control mode the wind generator is, however, unable to participate effectively in the grid primary frequency regulation because it is not deloaded, i.e. there is not a margin for its output active power increase during large low frequency periods.

In [8], a primary frequency control strategy has then been developed, such that the DFIWG is able to provide a proportional frequency response, in terms of grid injected active power, exploiting a pitch angle controller. In this case, the active power injected by the wind generator is adjusted

J. A. Peças Lopes is with INESC Porto and Faculdade de Engenharia da Universidade do Porto (FEUP), Rua Roberto Frias 378, 4200-465 Porto, Portugal (e-mail: jpl@fe.up.pt).

Rogério G. de Almeida is with INESC Porto, Rua Roberto Frias 378, 4200-465 Porto, Portugal (e-mail:rgdalmeida@yahoo.com.br).
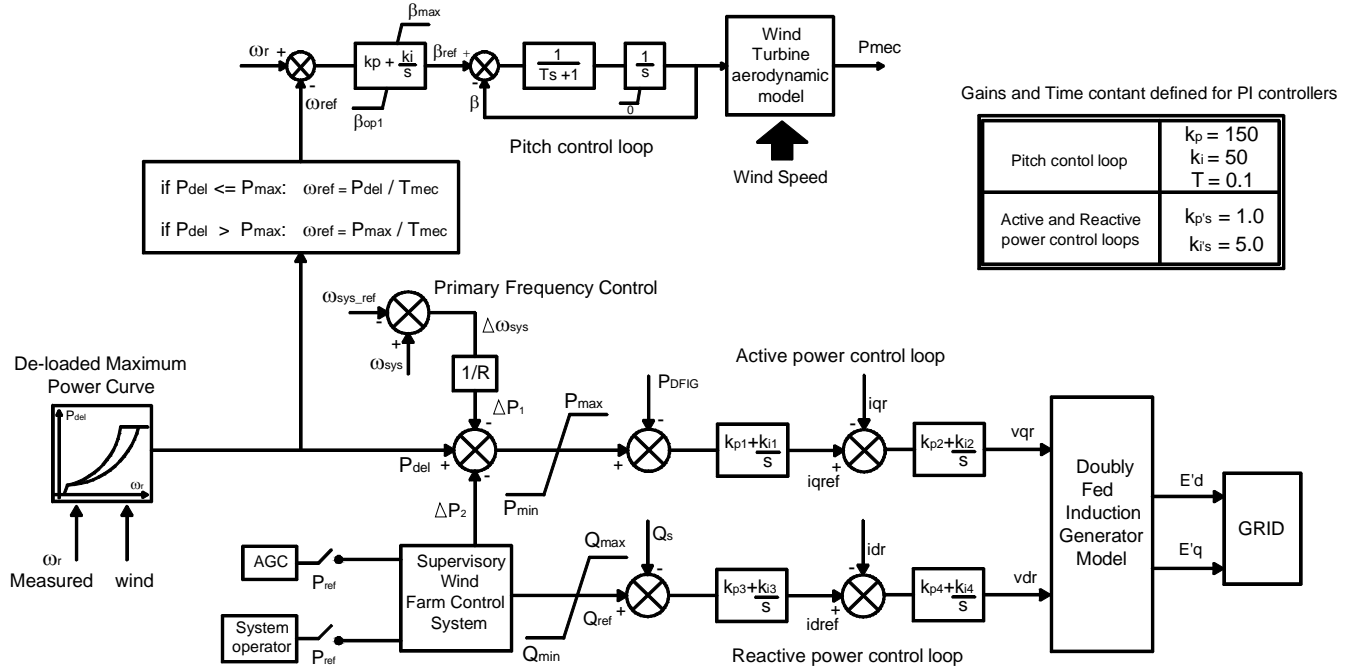
Fig. 1. Full control for DFIWG rotor-side converter.

through the regulation of the minimum pitch angle according to frequency variation (Δf_{sys}). The implementation of more sophisticated control schemes, seeking to control the rotational speed of the rotor, is suggested by these authors in order to improve the dynamic performance of the wind generator.

In the present paper a novel primary frequency control approach for a DFIWG is proposed such that, when a grid frequency excursion occurs, an active power injection takes place through the initial leading action of the rotor-side electronic converter of the wind generator, followed by the pitch control in order to adjust the mechanical power. This electrical power injection is defined from a proportional frequency regulation loop together with a power reference adjustment obtained from a deloaded power curve, such that a new equilibrium can be obtained when frequency changes occur. In this way, active power injected by the machine is kept on, while frequency deviation stands, therefore contributing for system primary frequency control. This approach (that includes a proportional integral control for pitch angle control) avoids the use of a mechanical characteristics look-up table, usually needed to identify the required pitch angle and reference speed that would lead to the required response. The pitch control is also responsible for limiting the mechanical power of the wind turbine during high wind speeds.

The effectiveness of this control approach was tested in a small isolated system, where wind generation plays an important role. Results from the dynamic response of the wind turbines and system frequency are discussed.

II. DESCRIPTION OF THE DEVELOPED CONTROL APPROACH

The full control approach adopted for the rotor-side converter of the DFIWG includes, as described in Fig. 1, the well known active and reactive power control loops [9], a primary frequency control loop responding to frequency changes (that defines the ΔP_1 set point in Fig. 1), a pitch control strategy and a control block associated to a external supervisory wind farm control system.

Through this external control block wind generators are required to respond to a request from the system operator, due to an AGC demand or because of operational reasons related with the need to control power flows in the network area. This request leads to an optimized adjustment of the output of each wind generator inside the wind park, to be calculated as described in [10], defining the ΔP_2 set point in Fig. 1.

In general, the wind generator is controlled by AC-DC-AC link converters, modeled as voltage and controlled current sources, respectively. The control scheme used to control the rotor-side converter (see Fig.1) consists of a d-q voltage regulator in which both output active and reactive powers of the machine are controlled through v_{qr} and v_{dr} components obtained from two separate sets of proportional-integral (PI) controllers. The PI controllers involve a cascade structure, in which the outside PI blocks are used to regulate the reference rotor currents (i_{qref} and i_{dref}), and the inner side PI blocks are used to regulate the v_{qr} and v_{dr} components, respectively. When using PI controllers, a careful gain tuning for different operation conditions is required. A trial and error adjustment was adopted in this research to identify these gains.

The grid-side converter, modeled as current source, is designed to control only the dc link voltage, taking into account the balance of the active power between rotor and the grid. The control algorithm implemented for this converter is explained in details in [6].
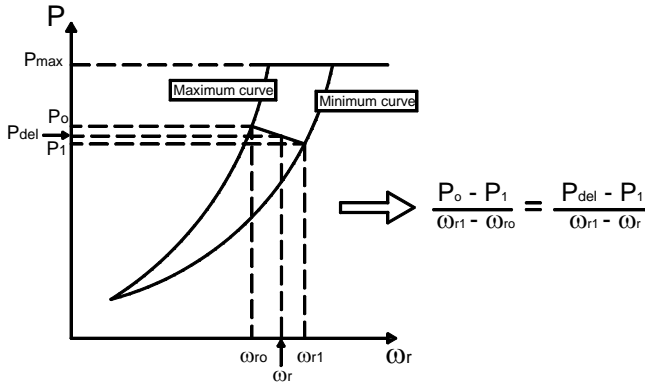
Fig. 2 Schematic diagram of deloaded optimal active power curve.

Through the rotor-side active power control loop, the wind turbine can be driven to operate with maximum power, once the reference active power input (P_{del}) used to the control system is obtained from a deloaded optimum power extraction curve, as depicted in Fig. 2. This reference power is also used to adjust the rotor speed through the pitch control loop.

The adoption of a power reference that uses a deloaded power extraction curve, as described in Fig. 2, allows the increase of active power generated by the wind generator when frequency decreases, as a result of a sudden load increase or loss of a large generation facility.

From Fig. 2, one can see that the power reference P_{del} can be defined as:

$$P_{del} = P_1 + \frac{P_o - P_1}{\omega_{r1} - \omega_{ro}}\left(\omega_{r1} - \omega_r\right) \qquad (1)$$

Where P_o and P_1 are the maximum and deloaded active powers for a given wind speed, respectively, being ω_{ro} and ω_{r1} the minimum and maximum rotor speeds referred to the generator side, respectively. Additional details concerning the deloaded optimal operating point of the variable-speed wind turbine can be obtained in [10].

The primary frequency control integrated into the rotor-side active power control loop is characterized by a droop loop that tries to emulate the proportional primary frequency control philosophy adopted in a conventional synchronous generator. This control strategy is completed by the pitch control, used simultaneously with the static converters, by adjusting the rotor speed referred to generator side, ω_{ref} according to the de-loaded maximum power curve and according to the operational conditions described in Fig 1.

III. SIMULATION RESULTS

The power system described in Fig. 3 was used to test the effectiveness of the proposed primary frequency control approach. In this system, 5 DFIWG (660 kW each), are installed in a wind park connected to an isolated grid, represented by a single bus with a synchronous thermal unit.
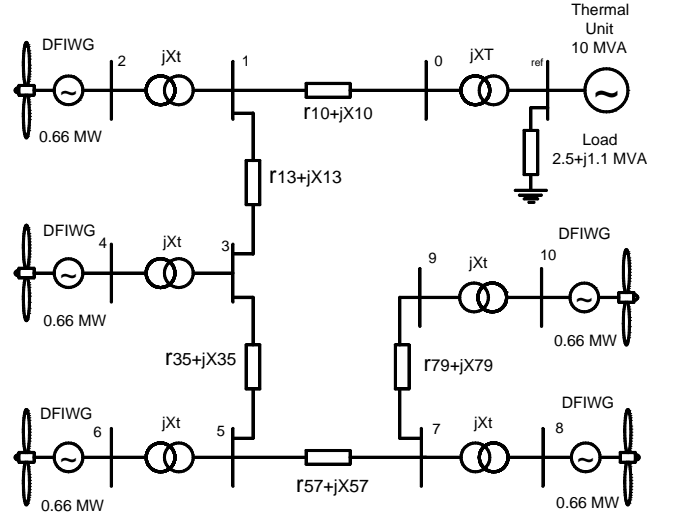

Fig. 3. Single line diagram of the system used for test purposes.

The thermal unit has a nominal capacity of 10 MVA, with an inertia constant H = 4s. Additional information concerning lines and transformers data of the small wind park, shown in Fig. 3, can be found in [10].

A single cage reduced order model without stator transients was adopted for the dynamic representation of the electrical part of the induction generator, as described in [11]-[13]. The thermal unit was modeled by a synchronous generator represented through a 4th order transient model, including also the automatic voltage regulator (IEEE type 1), an isochronous speed governor (with proportional and integral frequency control loops) and a simple first order model to describe the thermal turbine behavior, as presented in [11], [14] and [15]. The frequency droop of the governor is 4% (in the machine base). The integral control loop of this synchronous unit allows the system to recover frequency to its nominal value when load unbalance occurs. A dedicated dynamic simulation software package, using MATLAB®, was developed for this purpose.

A deload margin of 20% was adopted for each wind generator, providing in this way a 20% generation reserve. This deload margin is available in the all range of wind speed, as shown in Figure 4 (dotted line).

For simulations purpose, it was assumed that the wind speed was 12 m/s in all the wind generators. Because of an operator request, all wind generators are operating in the minimum optimum curve (dotted line in Fig. 4), which corresponds to 0,458 MW.

In order to evaluate the effectiveness of the primary frequency control approach described before, a change in load value was simulated at t = 35 s, such that it provokes a change in system frequency. The load connected in the reference bus, ($S_{Load} = 2.5 + j1.1$ MVA), was increased by 80%.

A 5% value (defined in the machine base) was adopted for the droop, R, of the primary frequency control loop of the wind generator, described in Fig. 1.
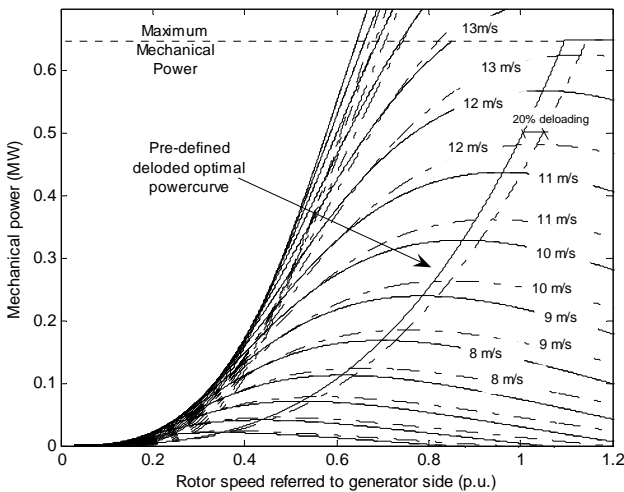
Fig. 4. Deloaded optimal power curve adopted for the DFIWG.

A. Results considering the synchronous generator (thermal unit) without integral control loop

In Fig. 5 the behavior of the grid frequency is presented for the cases where the DFWIG is participating in frequency control (dotted line) and when it is not participating in such control (full line). It can be clearly observed that the frequency excursion is smaller when the wind generators are participating in the grid frequency control. In this case it was assumed that the integral frequency control loop of the thermal unit was not operating, to show that wind generators were capable of picking up part of the load increase. This is similar to the initial periods that follow a system disturbance, where only primary frequency control operates, while expecting for AGC to correct the drift in frequency.

Figures 6, 7 and 8 describe the behavior of the active powers, rotor speeds and pitch angles of the DFIWG with and without primary frequency control, respectively.

During the grid frequency loss the active power of the wind generators increases fast while participating in frequency control, trying to compensate the system load increase. In this case, speed of the wind generators also decreases, following the deloaded power extraction curve, as shown in Fig. 7. Similarly pitch angles decrease in order to allow an increase in the mechanical power extracted from the wind turbine, as depicted in Fig. 8. This occurs due to the characteristics of the wind turbine performance curves (usually known as C_p x λ curves), where the power coefficient (C_p) increases (and thus the mechanical power) when the pitch angle decreases. More details about these characteristic curves can be found in [16].

The initial behavior of the active power and rotor speed of the DFIWG participating in frequency control is similar to the one that can be obtained with inertial control only, as described in [6]. If inertia control would be used, active power and rotor speeds would recover their initial values, after the initial transient, while with the new control approach these variables stabilize in a different value than the initial one.

From the observation of these plots one can conclude that when DFIWG participate in frequency control, system behavior is considerably better in terms of frequency excursions.
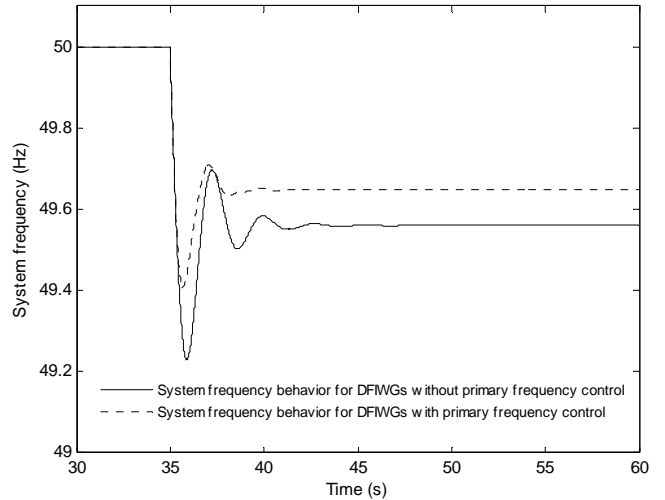

Fig. 5. Grid frequency behavior for wind generators with and without primary frequency control, considering the synchronous generator without integral control loop.
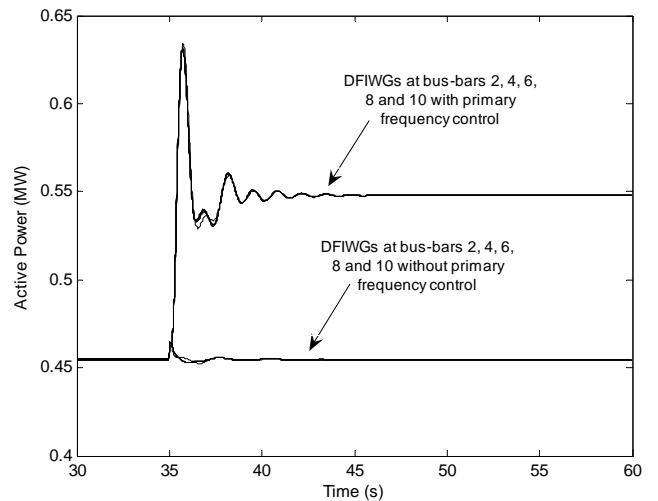

Fig. 6. Active powers behaviors of the wind generators with and without primary frequency control, considering the synchronous generator without integral control loop.
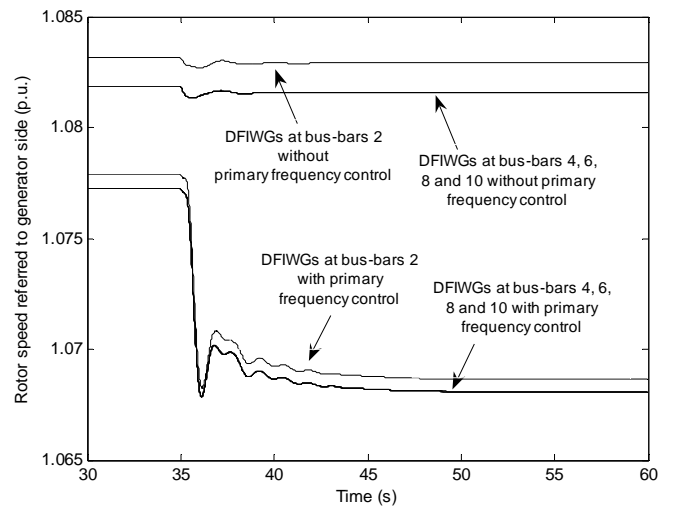

Fig. 7. Rotor speeds behaviors of the machines with and without primary frequency control considering, the synchronous generator without integral control loop.
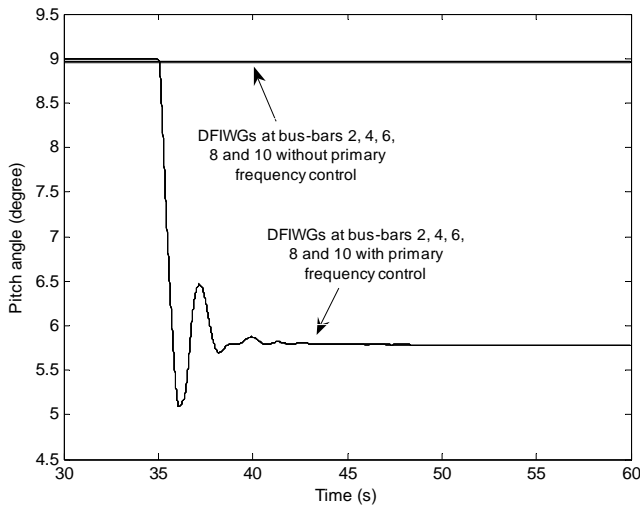
Fig. 8. Pitch angles behaviors of the wind generators with and without primary frequency control considering the synchronous generator without integral control loop.

B. Results considering the synchronous generator (thermal unit) with integral control loop.

Results regarding the presence of an integral control loop in the speed governor of the thermal unit are presented next, in order to highlight the behavior of the DFIWG in this case.

Grid frequency behavior for the cases with and without primary frequency control in the wind generators is shown in Fig. 9, while Figures 10, 11 and 12 show the behavior of the active powers, rotor speeds and pitch angles of the DFIWG. In this case frequency is brought to its nominal value because of the integral control action of the governor of the thermal unit.

In this case it was assumed that the integral control gain of the thermal unit has a value of 4.5 p.u. (in the system base power). Additional details of the speed governor with an integral control loop, as adopted in this research, can be found in [11].
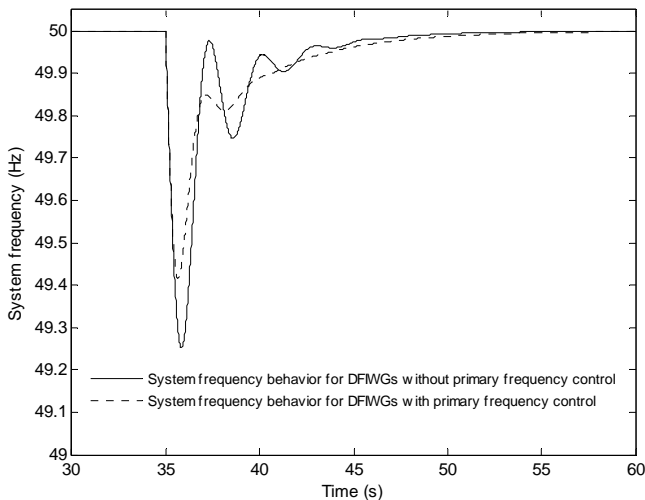

Fig. 9. System frequency behavior considering the wind generators with and without primary frequency control and the synchronous generator with frequency integral control loop.
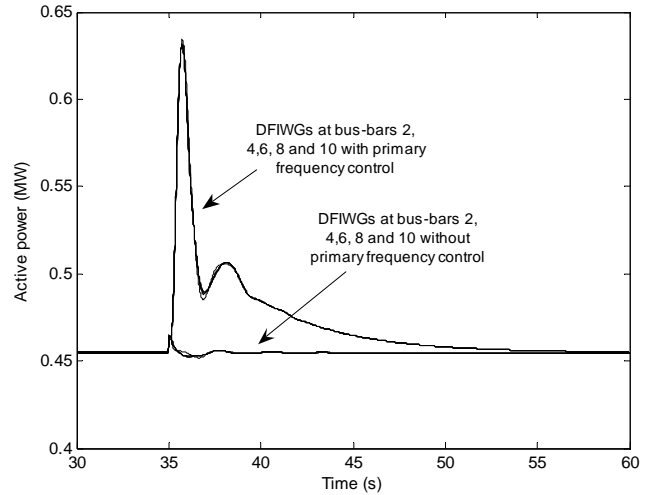

Fig. 10. Active power behaviors of wind generators with and without primary frequency control considering the synchronous generator with frequency integral control loop.
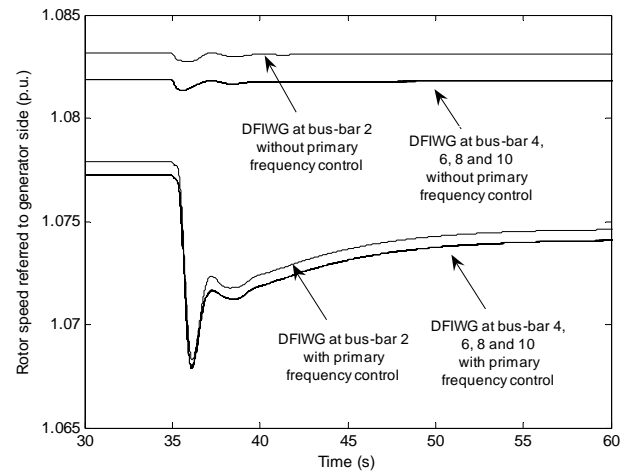

Fig. 11. Rotor speed behaviors of the machines with and without primary frequency control, considering the synchronous generator with frequency integral control loop.
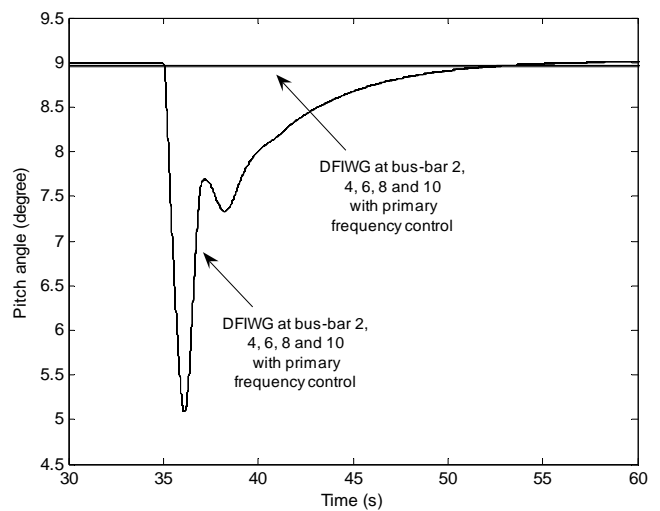

Fig. 12. Pitch angle behaviors of wind generators with and without primary frequency control considering the synchronous generator with frequency integral control loop.

When DFIWG do not participate in frequency control, only minor changes in active power outputs and rotor speed behaviors can be observed (Fig. 10 and 11), as a result of induced changes in the electrical torques of these units that result from changes in network voltages. The network voltage changes, which result from the load change, are also compensated at the wind generators level through the operation of local Q- U control loops of these units.

From these plots, one can conclude again that when DFIWG participate in the primary frequency control the frequency excursions are smaller and better damped due the fast operation of the static converter.

In the situation where frequency control is activated in the DFIWG and when grid frequency recovers, the active powers of these generators return to its previous values, although their electrical torques are different from the initial values, because their rotor speed is now less than initially (as shown in Fig. 11), due to the static converter control operation that drives the generator to a different deload margin. Electrical torques of the DFIWG changed because of the load increase that changed network conditions, namely bus voltages. In this case one must keep in mind that the Supervisory Wind Farm Control System was imposing, since the beginning of the simulation, a given $\Delta P_2 \neq 0$ (see Fig. 1), which imposes the initial active output power value to the machines.

IV. CONCLUSIONS

This paper evaluated the impact in an isolated system of having doubly fed induction wind generators participating in primary frequency control. The control strategy adopted consisted in emulating in the wind generator a proportional frequency response, controlling initially the static converter, and adopting a deload margin regarding the optimum power extraction curve. This control is followed by a pitch control that allows the generator to stabilize in a different operating point.

It was shown that the presence of wind generators operating with such a frequency control may contribute to increase system robustness, reducing frequency excursions following system disturbances. Such a control approach allows increasing wind power penetration in a system, with particular benefits for isolated systems.

Having in mind the increase in the penetration of wind generation in power systems, namely using DFIWG technology, such a control approach can play a key role in providing a frequency control ancillary service that helps supporting frequency when large disturbances occur. Such a service can be required when the power system is facing operating scenarios where conventional generation, charged of frequency control, has a smaller presence, like during load valley hours with large wind generation.

Since the deloading strategy, needed to provide effective system frequency control participation, is to be adopted only a few hours per year, the loss of annual revenues for wind park developers will be reduced. Such approach is always preferable to the disconnection of wind generators in specific

operational conditions, because of the lack of operational security in the system.

The coordination of the activation of the adoption of deload margins, definition of droop settings and other control parameters of the DFIWG in a large system should be performed through an hierarchical control approach, where the transmission system operator should send requests, to be transformed in control settings by the wind generation dispatch centers, that finally will interact with the wind parks and wind turbines in the field. Such conceptual approach involves a set of other problems, like the identification of the needed volume of deload margins for a given set of operating conditions in a system, which requires further research.

It is also important to point out that the control strategy described here can be transposed to synchronous variable speed wind generators, with some additional research effort, by including the frequency control concepts here described in the active power control loops of this unit type.

V. APPENDIX

A. Parameters:

Base values for the per-unit system conversion.
Base Power: 100 MVA
Base Voltages: 0.69 kV for low-voltage bus-bar, 15 kV for medium-voltage bus-bar and 63 kV for high voltage bus-bar.

B. Doubly Fed Induction Generator:

P_n (kW) = 660, V_n (V) = 690, R_s (p.u.) = 0.067, X_s(p.u.) = 0.03, R_r(p.u.) = 0.0058, X_r(p.u.) = 0.0506, X_m(p.u.) = 2.3161, ω_s(r.p.m) = 1500, No of poles = 4, rated slip generator = 2% , DC Voltage = 326.60 V, Capacitor = 284 μF.

C. Wind Turbine:

No. of blades = 3, Rotor diameter = 22 m, cut-in speed = 4 m/s, cut-off speed = 25 m/s, Atm. density = 1.225 Kg.m^{-3}, Inertia time constant = 4, Gear box ratio 1: 45

D. Transformers:

- *Wind Generator Rotor Transformer (200:690V): S_n (kVA) = 100, reactance = 9.5%; Wind Generator Stator Transformer (0.69:15 kV): S_n (kVA) = 750, reactance = 5%; Wind farm Transformer (15:63kV): S_n (MVA) = 3.75, reactance = 5%.*

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VI. BIOGRAPHIES

R. G. de Almeida received the B. Sc. Degree from Federal University of Pará – Brazil in 1996 and the M. Sc. degree from the same University in 1999. He has finished his PhD on power system dynamic impact analysis resulting from large scale renewable energy integration. The research was carried out at the Power System Unit of INESC Porto. His main interests are focused on power system dynamic analysis, electrical machines and power electronics**.**

J. A. Peças Lopes is an Associate Professor with Aggregation at the Dept. of EE of the Faculty of Engineering of University of Porto. He obtained an EE degree (5 years course) in 1981 from University of Porto and a PhD. degree also in EE from the same University in 1988. In 1996 he got an Aggregation degree. In 1989 he joined the staff of INESC as a senior researcher and he is presently Coordinator of the Power Systems Unit of INESC Porto and a senior member of the IEEE.