Primary Load-Frequency Control from Pitch-Controlled Wind Turbines

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***Abstract*—In this paper, an operating strategy is suggested for the participation of variable speed, variable pitch wind generators (VSVPWG) in primary load-frequency regulation through pitch-control. The proposed strategy is mathematically precise and neither direct wind measurement as a control input, nor any linearization of the system are required. The above suggested are independent of the specific type of the electric generator connected to the turbine and the only requirement is the expansion of the look-up tables of the aerodynamic characteristics of the rotor. The operating strategy is applied to a VSVPWG model developed in MATLAB-Simulink and connected to both a doubly-fed induction generator (DFIG) and a full-power converter synchronous generator (FPCSG). Indicative simulation results are shown, the effectiveness of the proposed control versus wind and set-point of power variations is validated, tuning issues are addressed and lastly a comparison is presented between the aforementioned technique and the method of over-speeding previously developed and published in the specific field of research.**

***Index Terms*--primary load-frequency control, de-loading, pitch-control, wind generator, wind turbine**

I. NOMENCLATURE

A	Swept area of the wind turbine
P	Wind power through an area equal to A
P_m	Power extracted from the wind by the turbine
C_P	Power coefficient
Λ	Tip speed ratio
Ω	Rotational speed
R	Radius
U_W	Wind-speed
β	Blade pitch angle
ρ	Air density
T	Torque
K	Stiffness coefficient
J	Moment of inertia
D	Damping coefficient
P_e	Electric power
v	Voltage (normalized value)
i	Current (normalized value)
λ	Flux-linkage (normalized value)
r	Resistance (normalized value)
l	Inductance (normalized value)
s	Rotor Slip

II. INTRODUCTION

THE greenhouse emissions have led the world organizations, the international policy makers and the local governments and administrations to the realization that the increase of the Renewable Energy Sources (RES) penetration in the power-producing portfolios, is possibly one of the most drastic strategies in their attempt to inverse the negative effects of the conventional carbon-based power generation [1]–[2]. However the increasing participation of wind generation in power systems has brought up interesting issues, concerning the quality of power and the potential services that this source can offer to the grids. On one side – referring to the power quality concerns – voltage drop, voltage fluctuation and flicker, harmonics emission and frequency interference, and on the other side – referring to the potential services – voltage control, over-frequency response and fault-ride-through capability are topics vastly addressed, cited and in most cases already incorporated in regulatory, connection and electromagnetic compatibility codes of most power grids as, for example, the IEC and the CENELEC standards.

Nevertheless, the participation of wind generation in load-frequency control has only lately become a serious concern under study [3] for a number of reasons. One of the major ones is that in terms of unit commitment the conventional power plants are engaged in covering the stochastic nature of the wind power by keeping spinning reserves to meet and face the variability of the wind [4]. These reserves, added to the ones kept for the rest of the grid-stability needs, could lead either to the reduction of the output power from some conventional power units to their technical minimums (sometimes meaning their actual shut-down) or to the disconnection of specific amounts of wind generation in the first place. Thus, the goal to increase RES penetration is either becoming too costly or overruled; facts that in the future highly deregulated power markets are unacceptable. In the direction to avoid the latter some services requiring spinning reserve could possibly be carried out by wind power and, thus, relieve the conventional generation from them. Load frequency response from wind generators, although only recently addressed, has been widely discussed and many control strategies have been proposed ranging from inertial frequency sup-

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port [5] up to actual increase/decrease of injected power responding to frequency variations [6]–[8].

In this paper a pitch-controlled strategy is presented, suggesting prior de-loading of the wind turbine through pitch-angle adjustment in order to meet under-frequency occurrences due to load increase or loss of power. Response to over-frequency cases is easily expandable. Unlike previous studies, a measurement of the wind-speed or a linearization of the rotor aerodynamics is not required in order to achieve precise power control since the methodology is mathematically accurate and only limited by the precision of the measurements and control of the actual wind generator, that said, pitch servo-motor, rotational speed average measurement, etc. Moreover utilization of wind-speed measurement as a control parameter is avoided since it is a stochastic, rapidly and continuously varying value and its measurement is not directly linked to the actual power produced by the wind turbine at any given moment.

In Section III the load frequency control is synoptically described.

In Section IV the principles of wind generation, the DFIG and the FPCSG are concisely presented in a manner that the suggested can be easily linked with and applied to them.

In Section V the proposed control strategy is described and analyzed in regards to the operational point below and above nominal values, the results of the indicative examples simulated are shown and relative observations are discussed.

In Section VI a comparison is discussed between the present and the previously cited over-speeding control strategy.

In Section VII the final conclusions are reached, suggestions and issues for further research and discussion are pointed out. An enhanced method is proposed for further consideration.

III. LOAD FREQUENCY CONTROL

The frequency of a power system is dependent on active power balance. As frequency is a common factor throughout the system, a change in active power demand at one point is reflected throughout the system by a change in frequency. Because there are many generators supplying power into the system, some means must be provided to allocate change in demand to the generators. A speed governor on each generating unit provides the primary frequency control function, while supplementary control originating at a central control centre allocates generation [9].

Primary frequency control occurs in the very first seconds after a change in power generation (or load demand) in a manner to respond to the frequency deviation from its nominal value and to an amount of participation given by the droop characteristic of each generating unit. Secondary frequency control acts in a supplementary way in order to bring frequency between the allowed limits and the participation of each generating unit is given by the integral gain on the frequency control. The above described are more clearly shown in Fig. 1.

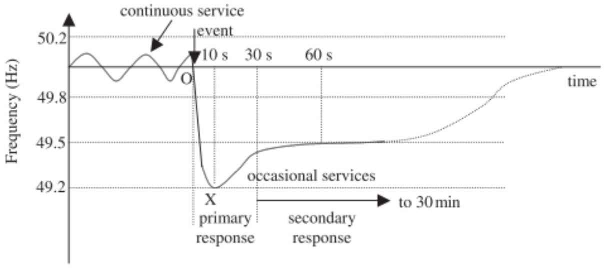

Fig. 1. Primary and secondary load-frequency response in power systems

IV. WIND GENERATION PRINCIPLES

A. Wind Power

The wind turbine can only extract a part of the wind's energy that passes through the blades area. The quotient:

$$C_P = \frac{P_m}{P} \tag{1}$$

is called Aerodynamic Power Coefficient C_P and can be expressed as a function of the tip speed ratio and the blade pitch angle, denoted as Λ and β respectively. Λ is the quotient:

$$\Lambda = \frac{\Omega_t \cdot R}{U_w} \tag{2}$$

where Ω_t is the rotational speed of the wind turbine expressed in rad/sec and U_w is the wind speed on the blades of the wind turbine in m/sec.

For the purpose of the analytical approach of the above referred complex relation, numerous arithmetical estimations have been developed and evaluated. A general function cited in [10] is the following:

$$C_P = c_1 \cdot \left(c_2 \cdot Z - c_3 \cdot \beta - c_4 \cdot \beta^x - c_5\right) \cdot e^{-c_6 Z} \tag{3}$$

where c_1–c_6 and x are coefficients dependent on the rotor type of the wind turbine, while Z is a parameter which is a function of β and Λ. In the framework of this study the following values have been assigned to c_1–c_6 as following from [6]: $c_1=0.22$, $c_2=116$, $c_3=0.4$, $c_4=0$, $c_5=5$ and $c_6=12.5$. From these assignments C_P, Z are defined as:

$$C_P = 0.22 \cdot \left(116 \cdot Z - 0.4 \cdot \beta - 5\right) \cdot e^{-12.5Z} \tag{4}$$

$$Z = \frac{1}{\Lambda + 0.08\beta} - \frac{0.035}{1+\beta^3} \tag{5}$$

The mechanical power that a given wind turbine extracts from the wind is equal to:

$$P_m = \frac{1}{2} \cdot \rho \cdot A \cdot U_w{}^3 \cdot C_P(\lambda, \beta) \tag{6}$$

In the framework of the current study a model of two masses will be used to model the drive train as from in the case of the DFIG wind turbine [10].

B. Control Strategy for Maximum Wind Power Extraction

For wind speed below rated value the generator realizes maximum power extraction from the wind through the maximization of C_p – hereafter $C_{p,opt}$. This is achieved by keeping β at its minimum value which in turn results in a fixed and optimum Λ – hereafter Λ_{opt}.

For wind speed above nominal value the generator operates in a way to limit the produced mechanical power to the nominal value of the wind generator. To achieve the above, the pitch angle is activated on Ω, keeping it at its nominal price, Ω_n. [10]

C. *Electrical Generators for Wind Power Applications*

Most common types of generators used in the conversion of mechanical wind power to electrical are the squirrel cage asynchronous generator, the DFIG and the synchronous generator. In the scope of the current study the DFIG and the FPCSG will be hereafter presented.

1) DFIG

The generator is grid-connected at the stator terminals, and also at the rotor through a back-to-back voltage source converter. This decouples the turbine's rotational speed from the grid frequency and also enables reactive power control.

The DFIG equations are transferred in the d-q frame through the Park transformation and are as following after normalization to nominal values and as also seen in [11]:

- Stator and Rotor equations:

$$\begin{aligned} \mathrm{v}_s &= -r_s \mathrm{i}_s - j\omega\lambda_s - \tfrac{p}{\omega_b}\lambda_s \\ \mathrm{v}_r &= r_r \mathrm{i}_r - js\omega\lambda_r - \tfrac{p}{\omega_b}\lambda_r \\ \lambda_s &= l_{ls}\mathrm{i}_s + l_{ms}\mathrm{i}_r \\ \lambda_r &= l_{lr}\mathrm{i}_r + l_{ms}\mathrm{i}_s \end{aligned} \tag{7}$$

- Electromagnetic Torque:

$$\tau_e = \lambda_{d,s} \cdot i_{q,s} - \lambda_{q,s} \cdot i_{d,s} \tag{8}$$

2) Full Power Converter Synchronous Generator

The direct drive synchronous generator is connected to the grid via a power electronics converter. Consequently the generator is fully decoupled from the grid. The grid-side converter is typically a voltage-source converter while the generator-side can be a voltage-source converter or simply a diode rectifier. The former case is assumed in this paper. The generator-side converter type generally affects the machine's degree of exploitation, and will not have any impact on the results presented. No damper windings are considered.

The FPCSG equations are transferred in the d-q frame through the Park transformation and are as following after normalization to nominal values and as also seen in [9]:

- Stator and Rotor equations:

$$\begin{aligned} \mathbf{v}_s &= -r_s \mathbf{i}_s - j\omega\lambda_s - \tfrac{p}{\omega_b}\lambda_s \\ v_{fd} &= r_f i_{fd} - \tfrac{p}{\omega_b}\lambda_{df} \\ \lambda_{sd} &= l_d i_{sd} - l_{md} i_{fd} \\ \lambda_{sq} &= l_q i_{sq} \\ \lambda_{fd} &= -l_{fd} i_{fd} + l_{md} i_s \end{aligned} \tag{9}$$

- Electromagnetic Torque:

$$\tau_e = \lambda_{d,s} \cdot i_{q,s} - \lambda_{q,s} \cdot i_{d,s} \tag{10}$$

In both machine cases the electrical control systems design is based on the method in [14].

V. PITCH-CONTROLLED DE-LOADING OPERATIONAL STRATEGY

In order for a wind generator to participate in primary load frequency control a spinning reserve must be kept. In the case of wind generation it is a spill of power or de-loading of the generator because it cannot be kept for later use but only wasted since it is not extracted from the wind at the specific time that it is available. A pitch-controlled strategy is hereby suggested for that reason.

A. *De-Loading Below Nominal Wind Speed*

For wind speed below nominal any amount of de-loading can be expressed as a percentage of the maximum available power that can be extracted from the wind at that point, e.g. if the maximum available wind power is 100 kW and 80 kW is the commission requested, then 20% is the de-loading at that point. That said and taking (6) into account, de-loading can be achieved by an equal percentage change of the $C_{p,opt}$. Provided that the Ω_t and Λ are given then β can be calculated from (4) and (5) in a way that C_p equals the desired percentage of $C_{p,opt}$.

In order to avoid both any direct wind speed measurement and linear approximations around the desired operating point, Λ is suggested to be kept at Λ_{opt}, thus maintaining the same relation between wind speed and Ω_t as in the maximum wind power extraction strategy. Therefore in order to de-load the wind generator by a certain amount, then, that amount expressed as a percentage of the maximum available power (and consequently as a percentage of $C_{p,opt}$) can be reached by increasing accordingly the blade pitch angle, β, as from the solution of the equation:

$$C_p(\Lambda_{opt}, \beta) = (100 - \mathrm{X})\% \cdot C_{p,\,opt}(\Lambda_{opt}, \beta_{min}) \tag{11}$$

where X% is the desired de-loading. Fig. 2 clearly shows the above described as an X% of power is spilled by setting the β from 0^o to β_1 ($> 0^o$).

Equation (11) can be either solved online or calculated offline and the corresponding look-up tables be produced. In both cases and given the current measurement of Ω_t, the

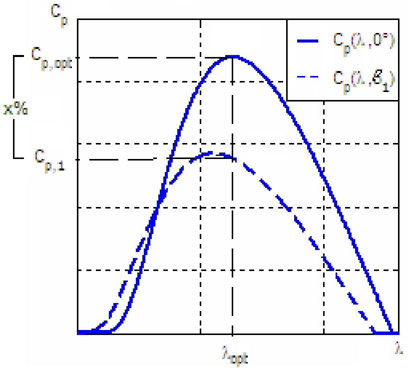

Fig. 2. Pitch-controlled reduction of C_P by X%

set-points of β will be provided to the mechanical part of the wind turbine and the electrical generator for various levels of the input de-loading requested.

B. *De-Loading Above Nominal Wind Speed*

As from the described in the previous paragraph, since the suggested strategy directs the use of Λ_{opt}, it is clear that at nominal wind speed, nominal Ω_t will have been reached. Therefore the pitch angle control of the Ω_t will be activated and its effect will be added to the de-loading set-point keeping Ω_t, at its nominal value and, thus, the power at the selected level of spill.

Any alteration of the desired de-loading will only require the extraction of electric power from the generator to be altered accordingly.

That said, if the electric generator is requested to spill a certain amount of electric power then the increase in Ω_t leads to an increase of β in order to reestablish nominal Ω_t, while on the same time mechanically de-loading the turbine.

C. *Model Overview, Stability Concerns and Examples*

The above suggested are depicted in the wind generator model in Fig. 3 where (11) is shown as $f(P_e, \omega_t) = \beta$. Although the blade pitch driven control of power production from wind generators has been previously proven stable as from [12], a clarification is offered. In Fig. 4 the Ω_t versus Power characteristics, both electrical P_e and P_m, are shown for the suggested control strategy and at an initial de-loaded operational point where $P_0 = P_{m,0} = P_{e,0}$.

If the rotor accelerates, the electrical decelerating torque must be greater than the mechanical accelerating in order the system to return to the initial stable operating point. That said, if $\Omega_1 > \Omega_0$, to reestablish stability: $T_{e1} > T_{m1}$. It is: $T_{e1} = \dfrac{P_{e1}}{\Omega_1}$ and $T_{m1} = \dfrac{P_{m1}}{\Omega_1}$. But $P_{e1} > P_{m1}$ Q.E.D.

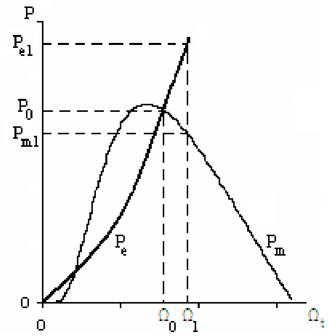

Fig. 4. Explanation of mechanical stability of suggested de-loading

In Fig. 5 and Fig. 6 the effect of the suggested control is presented for wind-speed below and above nominal value respectively. The lower lines in each figure represent the effect of a load increase when the wind generation is not participating in primary load-frequency control (LFC) and the upper lines the effect when wind generation is participating in primary LFC. Following, a number of indicative examples are shown. More specifically a single-bus power system is considered, consisting of a diesel generator, a wind turbine either connected to a DFIG or a FPCSG and a load.

Without LFC participation from the wind generators and only from the diesel generator, it is noticed that the DFIG supports the system inertially as this is also analyzed in [5] and therefore has a slightly less frequency dip than the system with the FPCSG.

With the participation of the wind generators in LFC the frequency dip is reduced and the permanent after-fault frequency is considerably increased.

Moreover in some additional simulations which have

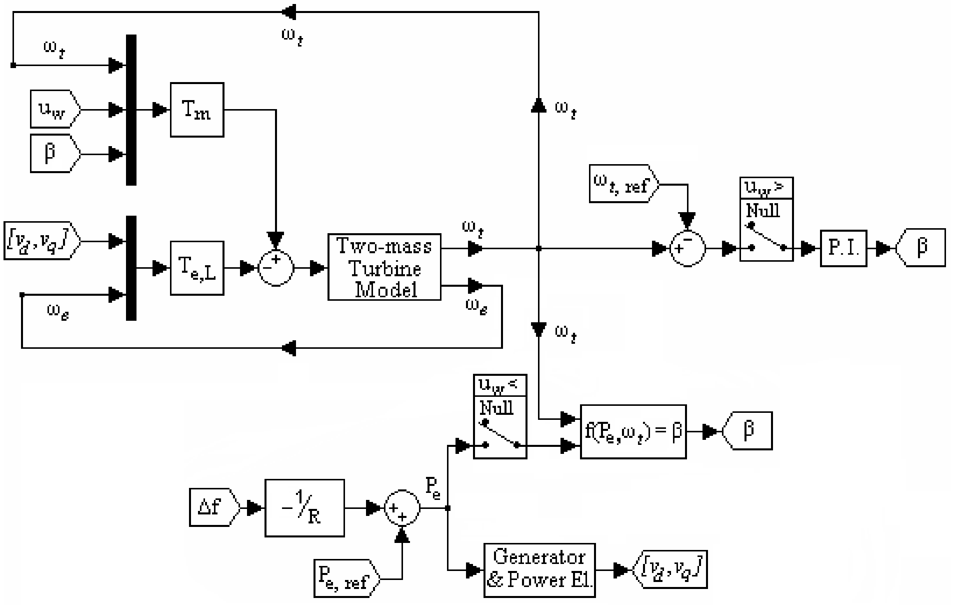

Fig. 3. The wind generator model for the suggested pitch-controlled de-loading and load-frequency participation strategy.

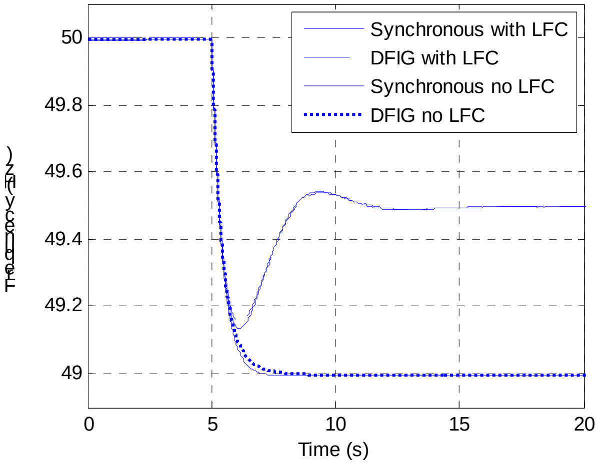

Fig. 5. Indicative example of load increase in a single bus system for wind speed below nominal value.

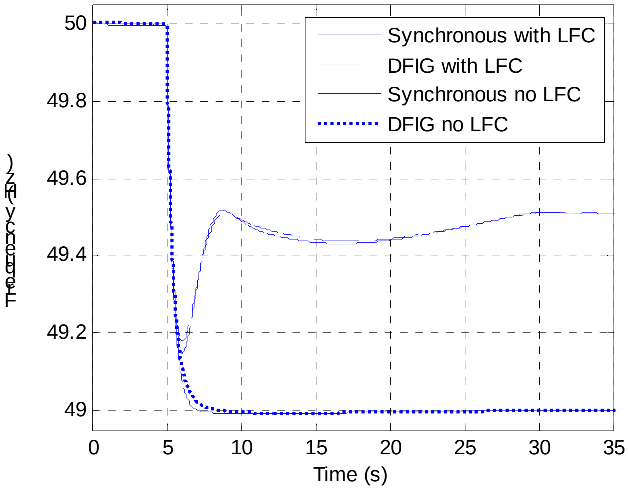

Fig. 6. Indicative example of load increase in a single bus system for wind speed above nominal value.

been conducted, given a reference set-point of absolute and per unit power it was proven that the wind generator reacts in a manner to maintain the set-point assigned. For the purpose of the last remark Fig. 7 shows how an absolute reference of power is maintained after an increase in the wind speed for a FPCSG.

VI. BLADE PITCH VERSUS ROTATIONAL SPEED DE-LOADING AND LOAD-FREQUENCY CONTROL

The Ω_t versus P_m characteristics for any given wind speed imply that, in order to de-load the wind turbine, instead of controlling β, Ω_t could be used instead in the manner of an initial over-speeding of the rotor(Fig. 7). Thus, in the case of an under-frequency event (shortage of power) the kinetic energy of the wind turbine will be reduced to increase the power output, while in case of an over-frequency (oversupply of power) the wind turbine's kinetic energy will be increased in order to reduce the power output. Subsequently, in the aforementioned cases the rotating mass of the wind turbine serves as a source or sink of power accordingly. [6].

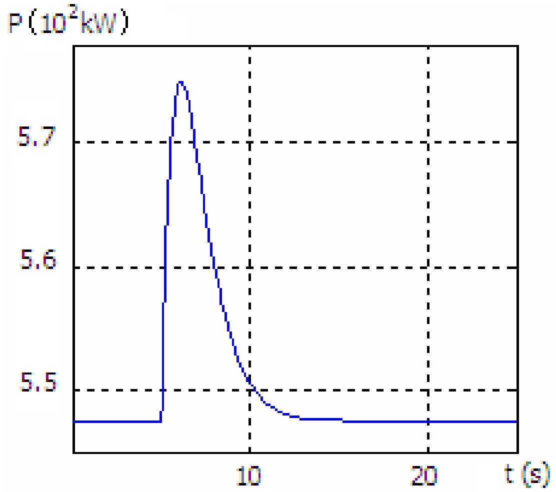

Fig. 7. Wind generator maintaining absolute power reference after wind-speed increase.

The above method is limited in application by both mechanical and electrical reasons. As a result, in wind speeds above nominal, de-loading only through over-speeding is not possible. Therefore any advantages reaped from this method would be in the low wind speed regime.

In terms of realization, the deterministic over-speeding de-loading control methods that have been proposed till now require wind speed measurement. However, the accuracy of a wind speed measurement is questionable. The complexity of the technique is a factor that should also be considered.

For the example used in Section V the two techniques are compared for wind speed below nominal and the results are shown in Fig. 9. As it was expected, the rotational speed control responds better than the pitch control, since the former does not require the extra time delay that the latter imposes because of the servo-motor which is realizing it.

VII. CONCLUSIONS AND FURTHER CONSIDERATIONS

In the current paper a complete control strategy is suggested for the participation of wind generation in primary

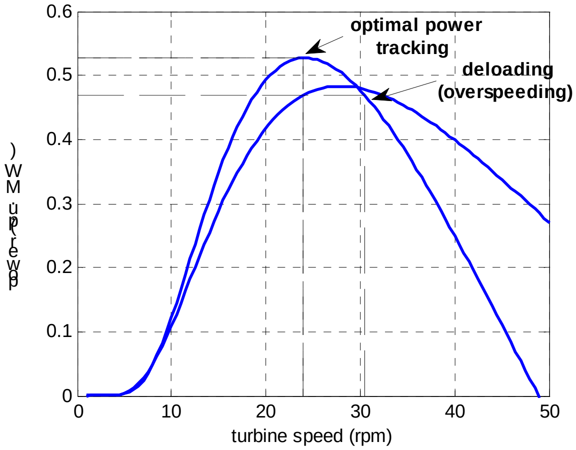

Fig. 8. Explanation of the over-speed de-loading control strategy

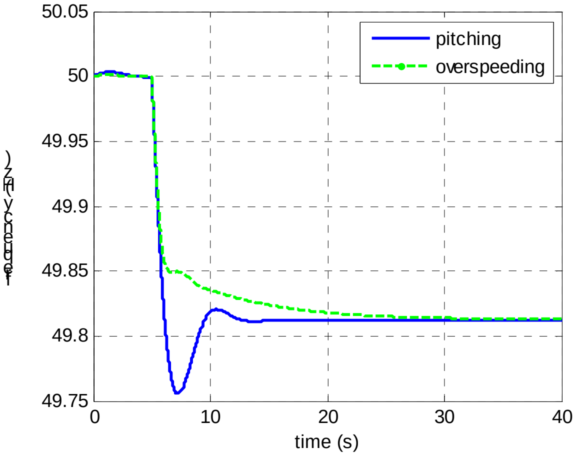

Fig. 9. Comparative of the response between pitch-controlled and rotational speed controlled strategies to a load increase for wind speed below nominal.

load-frequency response after prior de-loading of the wind turbine through pitch control. The use of the wind speed as a control parameter is avoided and the precision of the technique is only limited by the characteristics of the wind generator itself. The stability of the system is not endangered by the de-loading and the technique can be applied for wind speed both below and above nominal values.

Example simulations have shown that on one hand the contribution of wind generation to primary LFC through pitch control is positive in all cases although not as successful as the rotational speed control strategy for wind speed below nominal. Some further research on a combined control strategy between the aforementioned techniques should be considered.

However, the subject addressed should be thoroughly discussed taking into account the mechanical strains imposed by either strategy and further simulated in a large power network in order to monitor the interaction among all generating and regulating units.

VIII. APPENDIX

- *Wind Turbine and Drive Train* (as from [6], [10], [13])
  $R = 25$ m, $U_{w,n} = 12.4$ m/s, $P_n = 1$ MW,
  $\beta_{min} = 0^o$, Pitch Servo = 0.2 sec,
  Pitch Rate of Change Limit = 8^o/sec, Droop = 0.1,
  $J_{turbine} = 3 \cdot 10^6$ kg·m^2, $J_{generator} = 10^2$ kg·m^2,
  $K = 15 \cdot 10^6$ N·m/rad, $D = 5 \cdot 10^6$ N·m·sec/rad,
  r = 1:60 (only for the DFIG-based wind turbine).
- *DFIG* (in dq reference frame [11], values as from [14])
  $R_s = 2.20 \cdot 10^{-3}$ Ω, $R_r = 1.67 \cdot 10^{-3}$ Ω,
  $L_{ls} = 0.12$ mH, $L_{lr} = 0.05$ mH, $L_m = 2.90$ mH,
- *FPCSG* (in dq reference frame [9], values as from [13])
  $R_s = 28e\text{-}3$ Ω, $R_f = 8.6e\text{-}3$ Ω,
  $L_d = 5.8$ mH, $L_q = 3$ mH, $L_f = 6.3$ mH,
- *Diesel Generator* (as from [15])
  $P_n = 1$ MW, $K_2 = 1$, $\tau_2 = 0.05$ s, $\tau_1 = 0.02$ s,
  Droop = 0.1.
- *Power System*
  $H = 2.5$ s,
  No secondary LFC.

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X. BIOGRAPHIES

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