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Comparative study on the performance of control systems for doubly fed induction generator (DFIG) wind turbines operating with power regulation

L.M. Fernandez [a], C.A. Garcia [a], F. Jurado [b,*]

[a] Department of Electrical Engineering, University of Cádiz, 11202 EPS Algeciras (Cádiz), Spain
[b] Department of Electrical Engineering, University of Jaén, 23700 EPS Linares (Jaén), Spain

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ABSTRACT

As a result of the increasing wind power penetration on power systems, the wind farms are today required to participate actively in grid operation by an appropriate generation control. This paper presents a comparative study on the performance of three control strategies for DFIG wind turbines. The study focuses on the regulation of the active and reactive power to a set point ordered by the wind farm control system. Two of them (control systems 1 and 2) are based on existing strategies, whereas the third control system (control system 3) presents a novel control strategy, which is actually a variation of the control system 2. The control strategies are evaluated through simulations of DFIG wind turbines, under normal operating conditions, integrated in a wind farm with centralized control system controlling the wind farm generation at the connection point and computing the power reference for each wind turbine according to a proportional distribution of the available power. The three control systems present similar performance when they operate with power optimization and power limitation strategies. However, the control system 3 with down power regulation presents a better response with respect to the reactive power production, achieving a higher available reactive power as compared with the other two. This is a very important aspect to maintain an appropriate voltage control at the wind farm bus.

1. Introduction

Nowadays, the most widely used wind turbine in wind farms is based on doubly fed induction generator (DFIG) due to noticeable advantages: the variable speed generation, the decoupled control of active and reactive powers, the reduction of mechanical stresses and acoustic noise, and the improvement of the power quality [1].

Until relatively recently, the wind farms equipped with DFIG wind turbines have commonly operated entirely delivering the available energy to the grid. Hence, the wind turbines have autonomously maximized the energy captured from the wind, without exceeding the generator limits and operating with the unity power factor (zero reactive power). However, the wind farms production has been voluntarily reduced by disconnecting wind turbines from the grid at special occasions, especially during low consumption periods and strong winds [2]. During these conditions, the system operators recommended the reduction of wind farm production in order to maintain the stability and reliability of the power systems with high wind power penetration.

The increase of wind power penetration on power systems has led to a gradual substitution of conventional power plants by the current wind farms. Therefore, the wind farms are today required to participate actively in the power system operation as conventional power plants. Thus, the power system operators have revised the grid connection requirements for wind turbines and wind farms [3–5], demanding an operational behavior with several control tasks similar to those of conventional power plants. One of these control tasks is the capability of generation control, both active and reactive powers of a wind turbine. In this case, the system operator defines the operating requirements to be followed by the wind farms ensuring a reliable and safe power system operation. The wind farms require therefore a centralized control system that computes the power references (active and reactive powers) for each wind turbine when trying to adjust the wind farm production in the connection point to the settings specified by the power system operator.

Most of the control strategies for DFIG wind turbines referred in literature [6–10] are based on producing the maximum power for the best conditions of economic exploitation, when all the produced energy can be delivered to the grid. In this case, the

* Corresponding author. Tel.: +34 953 648 518; fax: +34 953 648 586.
E-mail address: fjurado@ujaen.es (F. Jurado).

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Nomenclature

A	rotor area of the wind turbine (m^2).
e'	internal voltage of the induction generator (p.u).
H	inertia (s).
i	current (p.u.).
P	active power (p.u.).
Q	reactive power (p.u.).
R	resistance (p.u.).
s	slip.
T	torque (p.u.).
u	voltage (p.u.).
v	wind speed (m/s).
X	reactance (p.u.).
θ	pitch angle (deg.).
λ	tip speed ratio.
ρ	air density (kg/m^3).
ω	frequency (p.u.).

Indexes

c	converter
d, q	direct and quadrature components.
e	electrical.
g	generator.
m	mutual.
mec	mechanical.
r	rotor.
s	stator.
wt	wind turbine.
σ	leakage.

wind turbine operates with optimum power efficiency for a wide range of wind speeds, without exceeding the rated power and with the desired power factor or generation voltage.

However, as commented before, the wind turbines are today demanded to regulate both active and reactive powers according to the power set points ordered by the wind farm control system, which are defined considering the generation capability (related to the wind speed) and the grid power needs. Therefore, the present article focuses on the study of the control systems for DFIG wind turbines when regulating power.

The control of DFIG wind turbines operating with power regulation ordered by a centralized wind farm control system has been described in previous works [11–14]. Two control approaches can be distinguished in these works. The first approach, illustrated in [11], is based on controlling the active power with the blade pitch angle, the rotational speed by the quadrature component of rotor current, and the reactive power with the direct component of rotor current. The second approach, used in [12–14], is based on controlling the active power with the quadrature component of the rotor voltage, the rotational speed by the blade pitch angle and the reactive power with the direct component of the rotor voltage.

The main purpose of this work is to perform a comparative study of these control systems for DFIG wind turbines when regulating power, both the active and reactive powers, by means of simulations of DFIG wind turbines integrated in a wind farm with centralized control system. Furthermore, a novel control strategy is proposed in this work, whose performance is compared with the previous controls.

The paper is organized as follows. Section 2 describes the modeling of a DFIG wind turbine. Three control systems for DFIG wind turbines are explained in Section 3. The model and the control systems for DFIG wind turbines used in this work have been validated in Section 4 by comparison with the DFIG wind turbine model included in the Sim Power Systems library of MATLAB/Simulink®. Section 5 presents the wind farm control system that computes the power references for each wind turbine when the wind farm regulates its production to the settings ordered by the system operator. The performance of the wind turbine control systems is assessed and discussed in Section 6, and finally the conclusions are established.

2. DFIG wind turbine

DFIG wind turbine uses a wound rotor induction generator coupled to the wind turbine rotor through a gearbox. The wound rotor induction generator presents the stator winding coupled directly to the grid and a bidirectional power converter feeding the rotor winding. The power converter is made up of two back-to-back IGBT bridges linked by a dc bus. This power converter decouples the electrical grid frequency and the mechanical rotor frequency, enabling the variable speed generation. The wind turbine includes blade pitch angle control in order to limit the power extracted from the wind. Fig. 1 shows the DFIG wind turbine configuration.

2.1. Modelling assumptions

In this paper, the behavior of a DFIG wind turbine has been simulated by means of widely used models in the literature. The work focuses on comparing several control systems for grid-connected DFIG wind turbines when they regulate power. In this case, the characteristic frequencies of a grid-connected DFIG wind turbine are between 0.1 and 10 Hz. Therefore, fundamental frequency simulations (also known as electromechanical transient simulations) can be used to represent the dynamic response [6]. In this approach, only the fundamental frequency component of voltages and currents is taken into account and higher harmonics are neglected. This allows the use of a load flow representation of the power system. Furthermore, also some of the differential equations associated with generators are cancelled as well as short time constants, enabling the use of a larger time step. Simulation speed is increased substantially.

A quasi-static approach is used to describe the rotor. This means that an algebraic relation is assumed between the wind speed at hub height and the mechanical power extracted from the wind. More advanced methods, such as the blade element impulse method, require detailed knowledge of aerodynamics and of the wind turbine blade characteristics [15]. These data will often not be available and the impact on the control and grid interaction is assumed to be rather limited.

Regarding the drive train model, a two-mass model has been adopted in this work as the most commonly used [15]. In this model, one lumped mass accounts for the low-speed shaft (which includes hub and blades) and the other one accounts for the high-speed shaft (which includes the rotor of the generator).

In fundamental frequency simulations, the following assumptions are applied to the generator:

- Magnetic saturation is neglected.
- Flux distribution is sinusoidal.
- Any losses apart from copper losses are neglected.

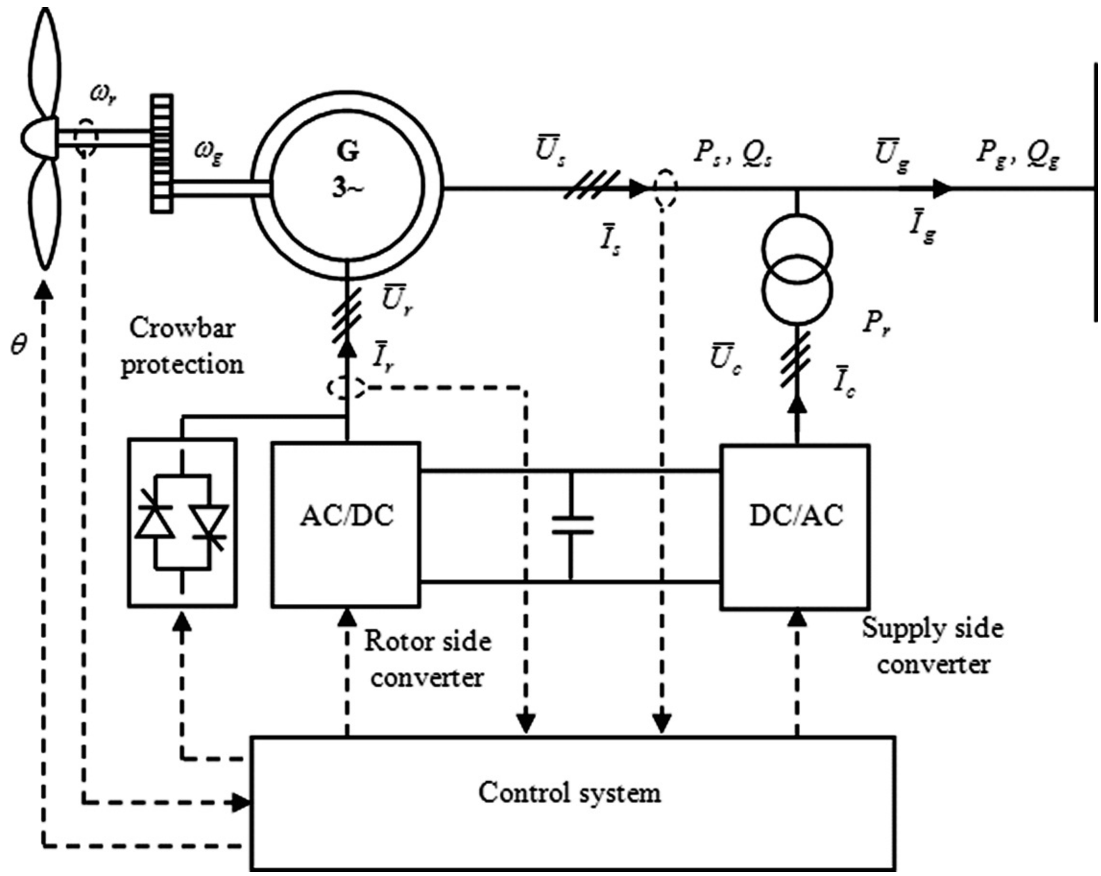

Fig. 1. DFIG wind turbine configuration.

- Stator voltages and currents are sinusoidal at the fundamental frequency.

Furthermore, the stator transients are neglected in fundamental frequency simulations, and therefore the behavior of the induction generator can be described with a third-order model instead of a fifth-order model.

Finally, as usual for fundamental frequency simulations where the internal dynamics of power converter are not of interest, the power converter is considered ideal. Therefore, the converters are modeled as voltage/current source and constant DC link voltage between the converters is assumed [6–14].

Both the fifth-order model of an induction generator and a more complex converter model are required for a correct representation of the wind turbine behavior during and after the voltage drops and short circuits. Hence, these models do not match the goal of the present work.

2.2. Modelling of DFIG wind turbine

DFIG wind turbine has been represented by a model consisting of the following subsystems: rotor, drive train, generation system and control system. A block diagram of the model and control system of a DFIG wind turbine is depicted in Fig. 2.

The rotor model expresses the mechanical power extracted from the wind, which is a function of the wind speed, the blade tip speed ratio and the blade pitch angle, as defined by the actuator disk theory [15].

$$P_{wt} = 1/2\rho A u^3 C_p(\lambda, \theta) \tag{1}$$

where P_{wt} is the mechanical power extracted by the wind turbine rotor, ρ is the air density, A is the area of the rotor disk, u is the wind speed and C_p is the power coefficient.

The power coefficient expresses the rotor aerodynamics as a function of both tip speed ratio λ and the pitch angle of the rotor blades θ. The tip speed ratio is defined as the ratio between the blade tip speed and the wind speed, expressed as

$$\lambda = \frac{\omega_r R}{u} \tag{2}$$

where ω_r is the rotor speed and R is the radius of the wind turbine rotor.

The power extracted from the wind is maximized when the rotor speed is such that the power coefficient is maximum, which occurs for a determined tip speed ratio. The control system of DFIG wind turbine assures the variable speed operation that maximizes the output power for a wide range of wind speeds, according to the optimum power extraction curve, given by

$$P_{opt} = K_{opt}\omega_r^2 \tag{3}$$

As the wind turbine limits the output power to the rated power of the generator for high winds, the power–speed curve is truncated to rated power. This power–speed curve serves as a dynamic reference for the control system of DFIG wind turbine. It assures the wind turbine operation with optimum power efficiency in winds below rated wind speeds and the rated power in winds above rated.

Fig. 3 illustrates the aerodynamic mechanical power–expressed by the Eq. (1)–, the optimum power extraction curve–according to the Eq. (3)–and the power–speed control curve for the DFIG wind turbine adopted in this work.

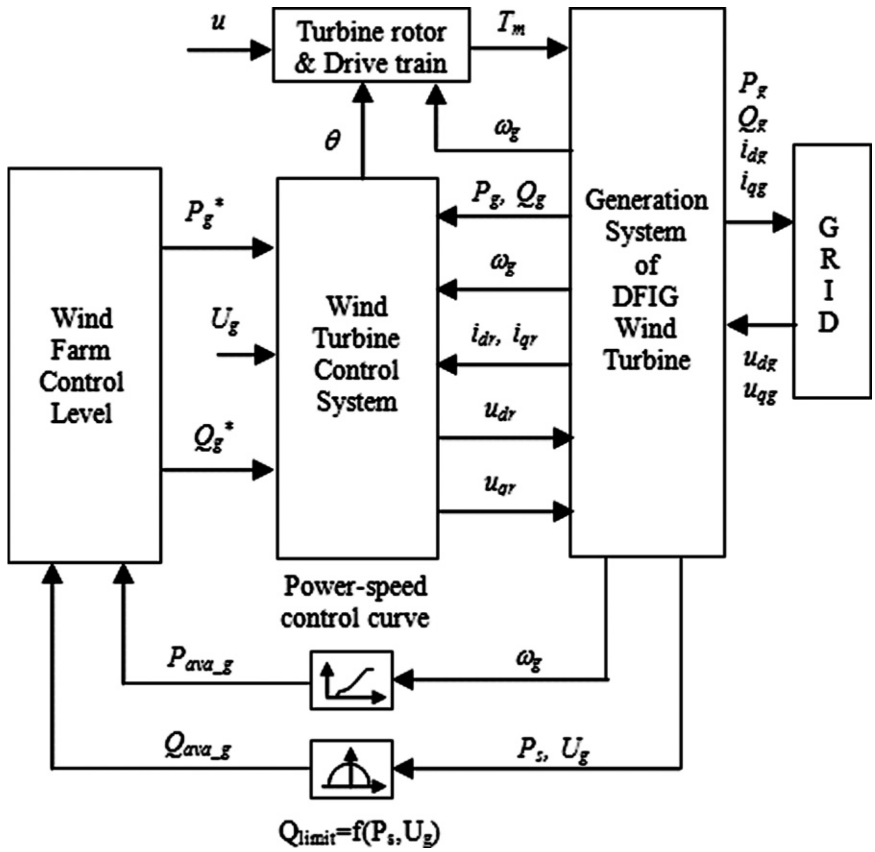

Fig. 2. Model and control system of a DFIG wind turbine.

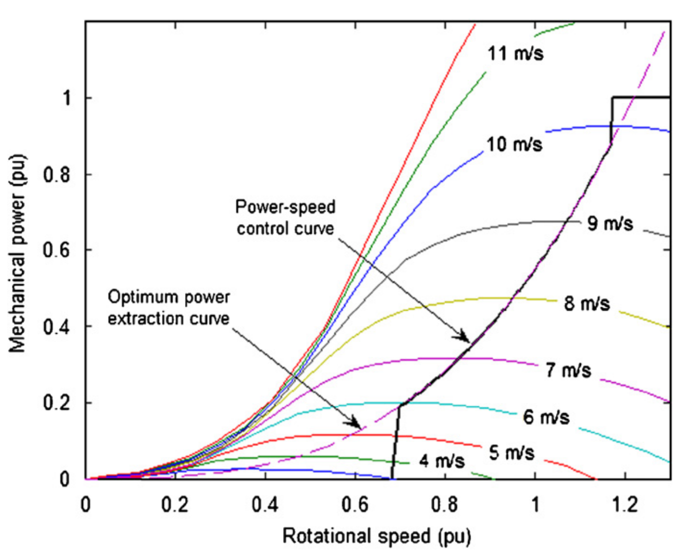

Fig. 3. Aerodynamic mechanical power, optimum power extraction curve and power–speed control curve.

The well-known two masses model has been used in the modeling of the drive train. This model is defined by the following equations:

$$T_{wt} - T_{mec} = 2H_r \frac{d\omega_r}{dt} \tag{4}$$

$$T_{mec} = D_{mec}(\omega_r - \omega_g) + K_{mec} \int (\omega_r - \omega_g)\, dt \tag{5}$$

$$T_{mec} - T_e = 2H_g \frac{d\omega_g}{dt} \tag{6}$$

where T_{wt} is the mechanical torque from the wind turbine rotor shaft, T_{mec} is the mechanical torque from the generator shaft, T_e is the generator electrical torque, and K_{mec} and D_{mec} are the stiffness and damping of mechanical coupling.

The generation system is composed of the induction generator and the power converter. As usual for power systems dynamics simulations, the induction generator has been modeled by the third-order model [16]. The model is expressed into a direct and quadrature reference frame rotating at synchronous speed with the position of the direct axis aligned with the maximum of the stator flux. This configuration enables the decoupled control of the active and reactive powers of DFIG.

$$\frac{de'_d}{dt} = -\frac{1}{T'_o}(e'_d - (X_s - X'_s)i_{qs}) + s\omega_s e'_q - \omega_s \frac{X_m}{X_r} u_{qr} \tag{7}$$

$$\frac{de'_q}{dt} = -\frac{1}{T'_o}(e'_q + (X_s - X'_s)i_{ds}) - s\omega_s e'_d + \omega_s \frac{X_m}{X_r} u_{dr} \tag{8}$$

$$u_{ds} = -R_s i_{ds} + X'_s i_{qs} + e'_d \tag{9}$$

$$u_{qs} = -R_s i_{qs} - X'_s i_{ds} + e'_q \tag{10}$$

$$T_e = \frac{X_m}{\omega_s}(i_{ds} i_{qr} - i_{qs} i_{dr}) \tag{11}$$

where u denotes voltage, i denotes current, indexes d and q are the direct and quadrature components, indexes s and r refer to stator and rotor, e'_d and e'_q are the internal voltage components of the induction generator and ω_s is the synchronous speed.

The stator reactance X_s, the stator transient reactance X'_s and the transient open circuit time constant T'_o are given by

$$T'_o = \frac{X_{\sigma r} + X_m}{\omega_s R_r} \tag{12}$$

$$X_s = (X_{\sigma s} + X_m) \tag{13}$$

$$X'_s = X_s - \frac{X_m^2}{X_{\sigma r} + X_m} \tag{14}$$

where R_s and R_r are the stator and rotor resistances, $X_{\sigma s}$ and $X_{\sigma r}$ the stator and rotor leakage reactances, and X_m the magnetizing reactance.

The bidirectional power converter connected to the rotor winding is composed of two converters linked by a dc bus [1,17]. In this paper, these converters are considered ideal and the DC link voltage between the converters is constant, as it is commonly used in power system simulations.

The rotor side converter drives the wind turbine to achieve the optimum power efficiency in winds below rated, to limit the output power to the rated value in winds above rated, or to adjust both the active and reactive powers to the power references when power regulation is demanded. This converter enables the decoupled control of active and reactive powers by acting on rotor current components. Thus, the generation control of a DFIG wind turbine can be performed by acting on the rotor voltage components [1,9,17]. The converter has been modeled as a current-controlled voltage source. Different ways to control this converter are explained in the next section.

The supply side converter maintains the exchange power from the rotor circuit to the grid and commonly operates with the unity power factor. In this case, DFIG wind turbine only delivers reactive power to the grid by the stator winding. This converter has been modeled as a controlled current source, where the direct and quadrature components of current source are calculated by the exchange power from the converter to the grid.

Further details on the DFIG modeling can be found in [18].

DFIG wind turbine delivers active power to the grid by both the stator and rotor winding, which can be calculated according to the following equations [1]:

$$P_m = (1 - s)P_s \tag{15}$$

$$P_r = -sP_s \tag{16}$$

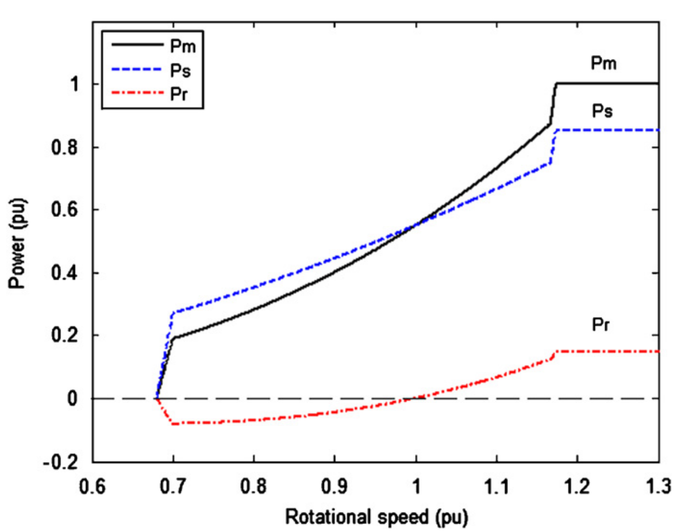

Fig. 4. Mechanical, stator and rotor powers versus rotational speed.

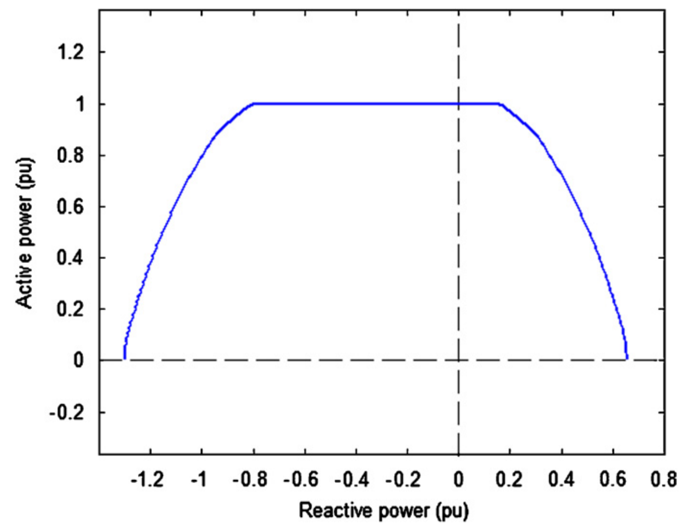

Fig. 5. Operating region of a DFIG wind turbine connected to an infinite bus.

where P_r is the rotor power, P_s is the stator power, P_m is the mechanical power and s is the slip speed.

The wind turbine considered in this work generates active power according to the power–speed curve shown in Fig. 4, where the capacity of delivering active power to the grid by both the stator and rotor winding can be observed.

However, the reactive power delivered to the grid is limited to restrictions imposed by the converter and expressed as rotor current limits to avoid an excessive heating of converters, rotor slip-rings and brushes [7]. The stator reactive power limits $Q_{s,lim}$ depend on the stator active power P_s, the stator voltage U_s and the maximum rotor current $I_{r,max}$ [7]:

$$Q_{s,lim} = -\frac{U_s^2}{X_s} \pm \sqrt{\left(\frac{X_m}{X_s} U_s I_{r,max}\right)^2 - P_s^2} \tag{17}$$

where X_s is the stator reactance and X_m is the magnetizing reactance of the induction generator.

The Eq. (17) expresses the maximum reactive power that can be rendered to the grid. Fig. 5 depicts the operating region Q–P for the considered DFIG wind turbine assuming the connection to an infinite bus.

3. Wind turbine control system

The aims of the control system of a DFIG wind turbine are the following:

- maximize the power extracted from the wind for a wide range of wind speeds (also known as power optimization),
- limit the output power to the rated power for high winds (power limitation),
- adjust both active and reactive powers to a set point ordered by the wind farm control system (power regulation) when trying to adjust the wind farm production to the settings specified by the power system operator.

In a DFIG wind turbine, this power control is performed by an appropriate control of the power converter and the blade pitch angle. Hence, to work effectively, the power converter must be controlled in collaboration with the blade pitch angle control. As explained before, the converter is controlled by acting on the direct and quadrature components of the rotor voltage. This allows the decoupled control of active and reactive powers.

However, DFIG wind turbine requires the blade pitch angle control to limit the power extracted from the wind for high winds (power limitation) or when the wind turbine is ordered to produce less than it is available (down power regulation).

Therefore, the control variables are the components of the rotor voltage and the blade pitch angle. Thus, the wind turbine control system is composed of a controller for each control variable. Two control approaches can be distinguished in previous works [11–14]. The first approach, illustrated in [11], is based on controlling the active power with the blade pitch angle, the rotational speed by the quadrature component of rotor current, and the reactive power with the direct component of rotor current. The second approach, used in [12–14], is based on controlling the active power with the quadrature component of the rotor voltage, the rotational speed by the blade pitch angle and the reactive power with the direct component of the rotor voltage. Wind turbines considered in [14] also include a control scheme to provide reserve power. This scheme has not been considered in this work.

As the purpose of this work is to perform a comparative study of these control systems, both control systems (denoted as control systems 1 and 2) have been illustrated. The control system 1 is based specifically on Ref. [11], whereas the control system 2 is based on Refs. [12,13]. Furthermore, a novel control system (control system 3), which is a variant of the control system 2, is presented.

For the reactive power control, the three control systems present the same controller, based on controlling the direct component of the rotor voltage u_{dr}. The u_{dr} controller determines the direct component of rotor voltage, enabling the wind turbine operation with the desired reactive power. It includes three control loops, as shown in Fig. 6. An outer control loop controls the reactive power and determines the generation voltage reference U_g^*. A subordinated voltage control loop defines the reference direct component of rotor current i_{dr}^* and assures that the generation voltage is maintained between the limits, while trying to reach the reactive power reference. An inner control loop regulates the i_{dr} current and defines the u'_{dr} voltage. To ensure a good tracking of this current, a compensation term is added to u'_{dr} [17].

Regarding the control of active power and generator speed, which has been performed by the quadrature component of the rotor voltage u_{qr} and the pitch angle θ, the control systems 1 and 2 present a different control scheme. The control Schemes 2 and 3 are similar, with certain differences that will be described below.

In the design of the active power control for the three control systems described below and both for the power optimization and power limitation strategies, it is assumed that whenever the wind turbine can deliver all the available energy to the grid, the active power set point will be set up to its rated value. Therefore, only when down power regulation is required by the wind farm control system, the power set point is changed to the reference value defined by the wind farm control system.

3.1. Control system 1

This control system presents the following characteristics: (1) the speed is controlled by acting on the quadrature component of the rotor voltage; (2) the active power is controlled by acting on the pitch angle. This control strategy is based on the one used in [11].

The u_{qr} controller (Fig. 7a) is a rotational speed controller. It controls the generator speed in order to maximize the power extracted from the wind (power optimization) without exceeding the rated power of the generator (power limitation) or to adjust the output power to the power set point ordered by the wind farm control system when a reduction of power is demanded (down power regulation). Two control loops are used in this controller. An outer control loop regulates the generator speed according to the reference value derived from the power–speed curve and it defines the reference quadrature component of the rotor current i_{qr}^*. An inner control loop regulates the i_{qr} current and sets the quadrature component of the rotor voltage u'_{qr}. A compensation term is added to u'_{qr} ensuring a good tracking of the current [17].

The pitch angle controller (Fig. 7b) acts as an active power controller, adjusting the pitch angle θ. Thus, the power coefficient and the power extracted from the wind are reduced. This controller keeps the blade pitch angle at its optimal value with power optimization strategy. Likewise, the controller enables the wind turbine to adjust the output power to a set point (rated power for high winds or the reference power required with down power regulation). When the output power goes up to the

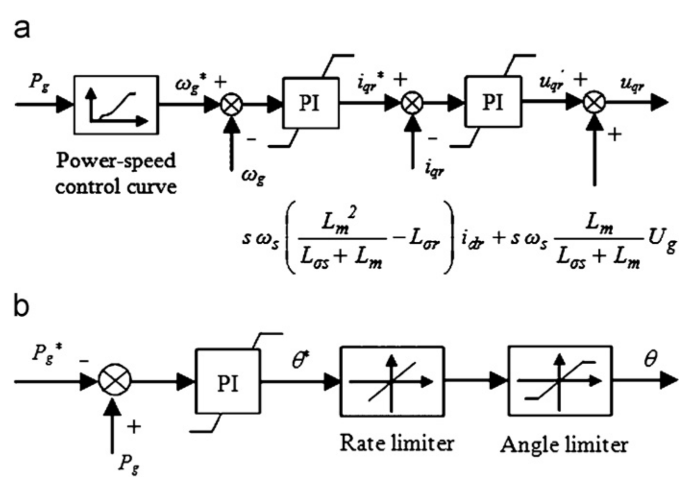

Fig. 7. Control system 1 for DFIG wind turbine: (a) u_{qr} controller (speed controller) and (b) pitch angle controller (active power controller).

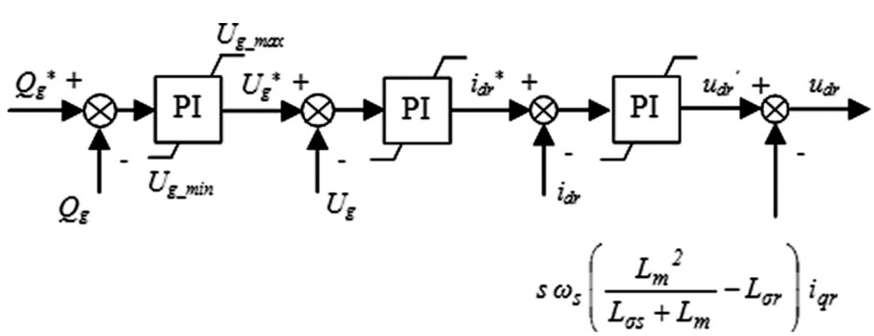

Fig. 6. u_{dr} controller (reactive power controller).

reference power, the controller acts adjusting the pitch angle and thus limiting the output power to the reference value. The controller includes the rate and angle limiters for the pitch angle movement.

The operating strategy of a DFIG wind turbine that uses this control system can be summarized as follows:

- *Power optimization strategy*: In this case, and as explained before, the active power set point for the wind turbine is set up at its rated value. In winds below rated, the blade pitch angle controller does not act and the pitch angle is kept at its optimal value. The u_{qr} controller controls the rotational speed, the tip speed ratio is kept at its optimal value, and thus the wind turbine operates maximizing the power extracted from the wind.
- *Power limitation strategy*: In this case, the active power set point for the wind turbine is set up at its rated value. In winds above rated, the pitch angle controller assures the rated power by acting on the pitch angle, and the u_{qr} controller keeps the generator speed at its rated value.
- *Down power regulation strategy*: When the wind turbine operates with down power regulation, the active power set point is reduced from the rated power to the reference value ordered by the wind farm control system. In this case, the blade pitch angle controller acts on the pitch blade to achieve the power set point. The u_{qr} controller adjusts the rotational speed to the reference value derived from the power–speed curve and the reference power.

3.2. Control system 2

In the second control system, (1) the active power is controlled by the quadrature component of the rotor voltage and (2) the speed control adjusts the rotational speed to a reference speed derived from the optimum power–speed curve by acting on the blade pitch angle. This control strategy is similar to the one adopted in [12,13], although with certain differences, as explained below.

The u_{qr} controller (Fig. 8a) is an active power controller that controls the output power by acting on the quadrature component of the rotor voltage. As described before, it is assumed that the wind turbine operates autonomously with power optimization and power limitation, receiving the rated power as a power set point from the wind farm control system. Therefore, this controller uses the actual rotational speed to define the reference power according to the power–speed curve. The controller adjusts the output power to the value derived from the power–speed curve and the actual rotational speed. It has the same control loops as the control system 1, however, in this case, the outer control loops regulates the active power. As a reference power for each wind turbine in [12,13], the wind farm control system sends out the available power of each wind turbine when it operates with power optimization, the rated power with power limitation and the power set point with down power regulation. In the wind turbine control system, the available power is derived from the power–speed control curve and sent out to the wind farm control system. Therefore, the active power controller adopted in [12,13] does not include the power–speed control curve to define the reference power, as it is proposed here.

The blade pitch angle controller (Fig. 8b) acts as a speed controller adjusting the pitch angle to reduce the power coefficient and the power extracted from the wind. In [12,13], the reference of the speed controller is generated from an 'optimum speed' look-up table as a function of the wind speed. However, the wind speed measured by the anemometer is not a good indication of the wind speed acting on the wind turbine rotor as a whole, and moreover, the measured wind speed is severely disturbed by the rotor wake, because the anemometer is located on the nacelle [6]. Due to difficulties derived from the accuracy of wind speed measurements, wind speed is not used as a control variable in the work described here. Therefore, the speed reference is generated from the optimum power–speed curve and the power reference. When the wind turbine operates with power optimization and power limitation strategies, the power reference is set up at the rated power and this controller acts limiting the rotational speed to the rated speed. In winds below rated and power optimization strategy, the generator speed is smaller than the rated speed, and thus the controller keeps the blade pitch angle at its optimal value. On the other hand, this controller acts on the blade pitch angle assuring the rated speed with power limitation strategy and winds above rated. With down power regulation, the rotational speed reference is derived from the power–speed curve and the reference power ordered by the wind farm control system, and the controller acts on the blade pitch angle assuring the rotational speed.

The operating strategy of a DFIG wind turbine with this control system is the following:

- *Power optimization strategy*: In this case, the u_{qr} controller adjusts the output power to the value derived from the power–speed curve and the actual rotational speed, maximizing the power extracted from the wind. As the generator speed is less than the rated speed, the blade pitch angle controller does not act and the pitch angle is kept at its optimal value,
- *Power limitation strategy*: The u_{qr} controller limits the output power to the rated power. Likewise, the pitch angle controller limits the rotational speed to the rated speed.
- *Down power regulation strategy*: In this case, the blade pitch angle controller keeps the rotational speed to the speed reference derived from the power–speed curve and the power reference. Moreover, the u_{qr} controller adjusts the output power to the set point generated from the power–speed curve and the actual rotational speed.

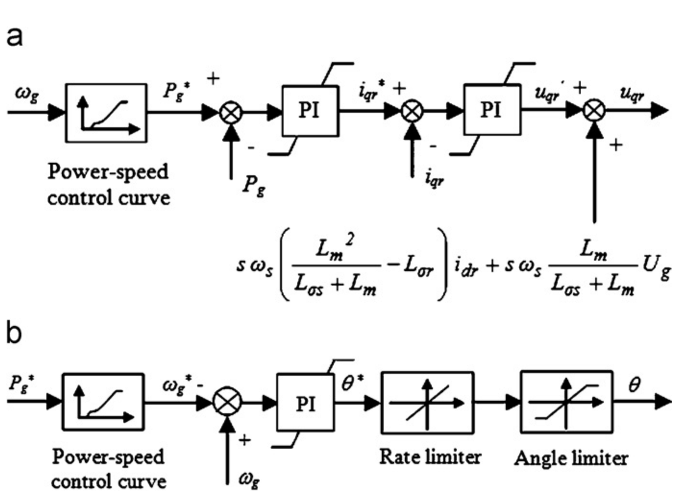

Fig. 8. Control system 2 for DFIG wind turbine: (a) u_{qr} controller (active power controller)and (b) pitch angle controller (speed controller).

3.3. Control system 3

Finally, the third control system presents a novel control strategy, which is a variant of the control system 2. This control

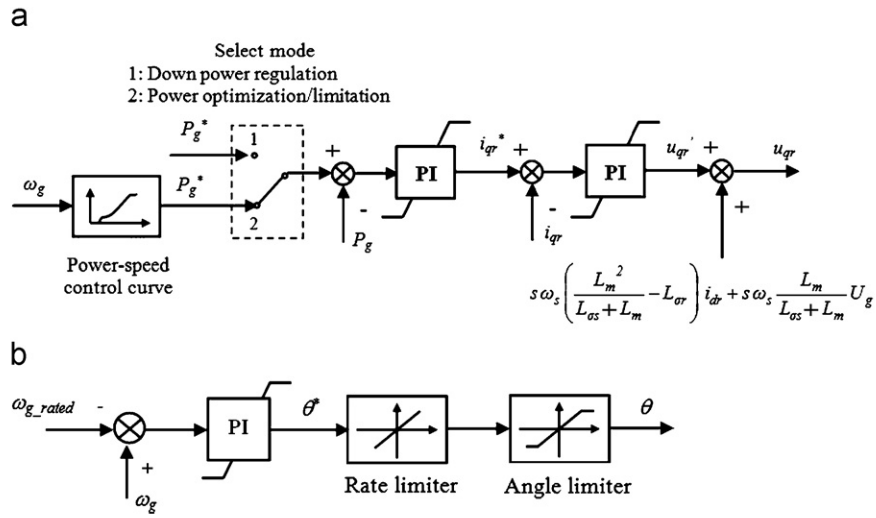

Fig. 9. Control system 3 for DFIG wind turbine: (a) u_{qr} controller (active power controller with a select mode) and (b) pitch angle controller (speed limiter).

has the following characteristics: (1) the active power control presents a select mode and acts on the quadrature component of the rotor voltage and (2) the speed control limits the rotational speed to the rated speed by acting on the blade pitch angle.

The u_{qr} controller (Fig. 9a) is an active power controller that controls the output power by acting on the quadrature component of the rotor voltage. This controller presents a select mode to choose the operating mode. Two operating modes can be selected: power optimization/limitation and down power regulation. In the power optimization/limitation mode, the controller uses the rotational speed to define the power reference from the power–speed curve. Thus, the wind turbine can operate with variable speed maximizing the power extracted from the wind in winds below rated or limiting the output power to rated power in winds above rated. In the down power regulation mode, the controller uses the value ordered by the wind farm control system as a power reference, instead of the power reference derived from the power–speed curve. This controller presents the same control loops as the control system 2.

The blade pitch angle controller (Fig. 9b) adjusts the pitch angle reducing the power coefficient and thus the power extracted from the wind, when the rotational speed increases up to the rated speed. The controller keeps the optimal pitch angle when the generator speed is less than the rated speed, and thus the wind turbine operates with optimum power efficiency. On the other hand, when the wind turbine operates with power limitation or down power regulation, this controller limits the rotational speed to the rated speed. Therefore, the blade pitch angle controller acts as a rotational speed limiter in any operating conditions.

The operating strategy of a DFIG wind turbine with this control system can be summarized as follows:

- *Power optimization strategy*: In this case, the blade pitch angle controller keeps the pitch angle at its optimal value, whereas the u_{qr} controller controls the output power, and thus the wind turbine operates maximizing the power extracted from the wind.
- *Power limitation strategy*: The u_{qr} controller assures the rated power and the pitch angle controller limits the rotational speed to the rated speed.
- *Down power regulation strategy*: In this case, the u_{qr} controller adjusts the output power to the set point ordered by the wind farm control system, whereas the blade pitch angle controller keeps the rotational speed at the rated speed.

4. Validation of the wind turbine model and control systems

The wind turbine model and control systems used in this work have been validated by comparison of the simulated responses with the one obtained by the built-in model for the DFIG wind turbine included in the SimPowerSystems library of MATLAB/Simulink®. This built-in model, developed by Hydro-Quebec Power System Simulation Laboratory, implements a phasor model for a DFIG wind turbine [19]. The DFIG wind turbine considered in this work presents a rated power of 2 MW and 690 V. Table 1 shows its parameters.

A wind speed sequence as depicted in Fig. 10a has been considered in the simulation. This wind fluctuates between 8 and 13 m/s. This sequence allows the evaluation of the wind turbine response in winds below and above the rated wind speed.

To evaluate the control systems, three wind turbines have been simulated in MATLAB/Simulink® environment. Each wind turbine is controlled by one of the proposed control systems. The wind turbines have been simulated operating without down power regulation and with the unity power factor (zero reactive power). Their responses are compared with the one obtained by the simulation of the built-in model included in SimPowerSystems. This comparison analysis is illustrated in Fig. 10, where the active and reactive power (Fig. 10b), the rotational speed (Fig. 10c), the pitch angle (Fig. 10d) are presented. When the responses are compared, the following conclusions can be inferred:

- The responses show a high degree of correspondence for all the variables shown.
- In winds below rated (less than 10.2 m/s), the wind turbine generates below rated power, it operates at variable speed and the pitch angle is kept at a minimum degree (0°).
- In winds above rated, the control system adjusts the output power to the rated power, limits the rotational speed to the rated speed and acts on the pitch angle limiting the power extracted from the wind. Furthermore, the wind turbine

Table 1
DFIG wind turbine parameters

Parameter	Symbol	Value	Unit
Wind turbine			
Base power	S_B	2.0	MVA
Rotor diameter	D	100	m
Gearbox ratio	1:N	1:89	p.u.
Rotor inertia	H_r	0.5	s
Shaft stiffness	K_m	0.35	p.u./rad
Shaft damping	D_m	5	p.u.
Generator			
Base power	S_B	2.0	MVA
Base voltage	U_B	690	V
Base frequency	ω_B	2 π 50	rad/s
Stator resistance	R_s	0.01	p.u.
Stator leakage reactance	$L_{\sigma s}$	0.10	p.u.
Rotor resistance	R_r	0.01	p.u.
Rotor leakage reactance	$L_{\sigma r}$	0.08	p.u.
Magnetizing reactance	L_m	3.0	p.u.
Generator inertia	H_g	2.5	s

operates with zero reactive power (unity power factor) during all the simulation.

As it can be observed, this comparison shows a high degree of correspondence between the responses obtained with the model and control systems used in this work and the SimPowerSystems model. Therefore, the model and control systems presented here can be considered suitable and valid to represent the wind turbine response.

5. Wind farm control system

The aim of the wind farm control system is to regulate in a centralized way the active and reactive powers injected by the whole wind farm into the grid (when the wind farm operates as a PQ node), or the active power and the voltage at the wind farm node (when it operates as a PV node). Hence, this control system computes the reference powers, both active and reactive powers, for each wind turbine.

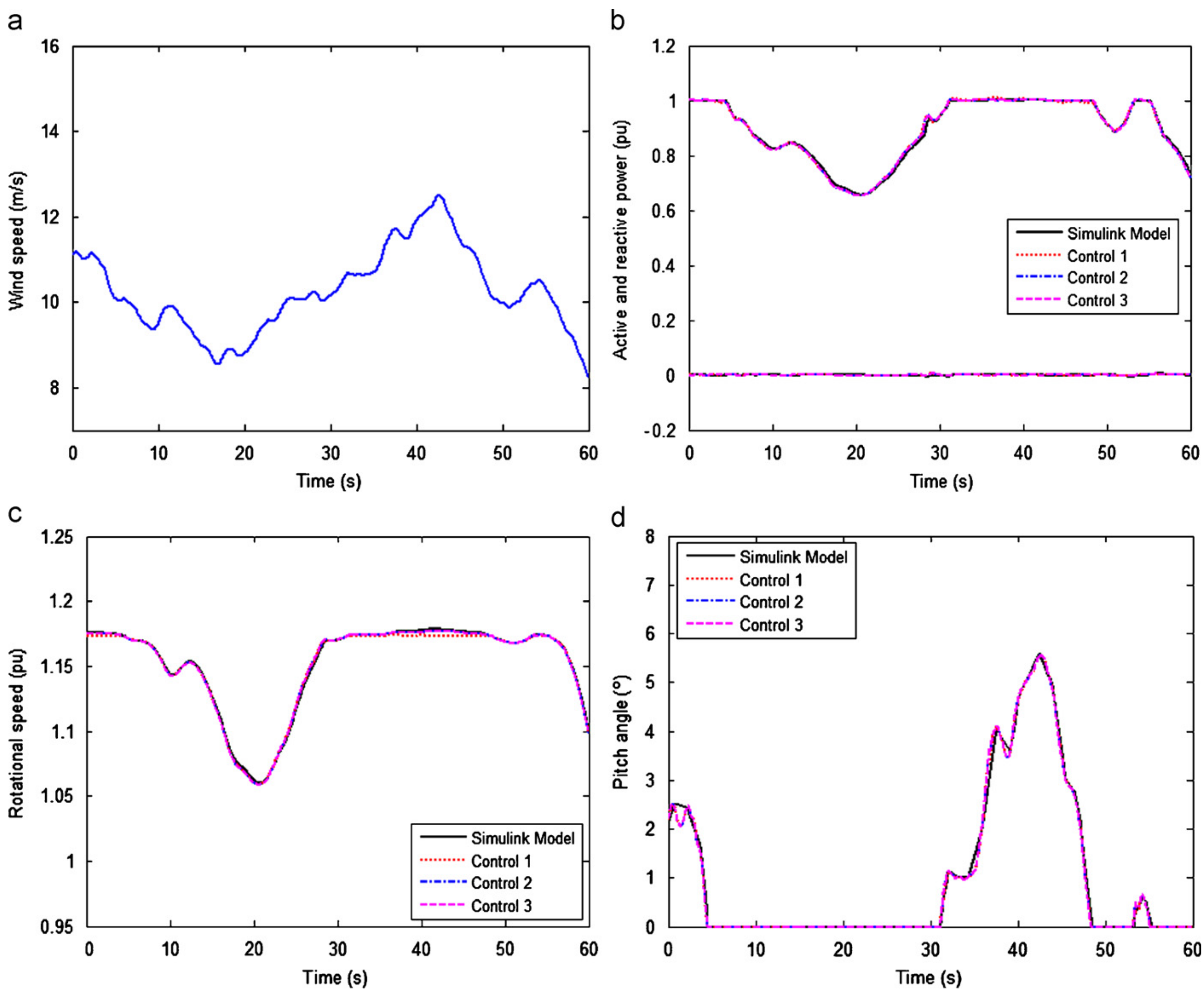

Fig. 10. Validation of the model and the control systems used in this work by comparison with the DFIG model wind turbine included in the SimPowerSystems library of MATLAB/Simulink: (a) wind speed, (b) active and reactive powers, (c) rotational speedand (c) pitch angle.

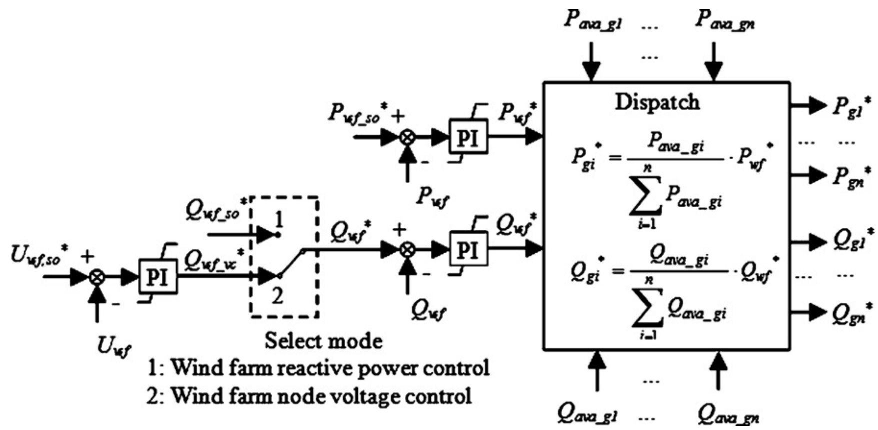

Fig. 11. Wind farm control system.

The wind farm control system presents: (1) a power controller that assures a correct wind farm production and (2) a dispatch control that distributes the wind farm generation between the wind turbines, and computes the active and reactive power references for each wind turbine. A block diagram of the wind farm control system is depicted in Fig. 11.

The wind farm power controller is composed of two separated control loops: one for the active power control and another for the reactive power control or the node voltage control. The active power control loop is based on a PI controller that assures the wind farm production according to the power set point ordered by the system operator $P_{wf}{}^*_{,so}$. This PI controller computes the active power error and sets up the power reference P^*_{wf} for the whole wind farm. Another control loop presents a select mode that enables the reactive power control or the node voltage control for the whole wind farm. When the wind farm operates as a PV node, the node voltage control tries to adjust the voltage at the wind farm node to the voltage reference ordered by system operator $U_{wf}{}^*_{,so}$. This control is performed by a PI controller that sets up the reactive power reference $Q_{wf}{}^*_{,vc}$ for the whole wind farm. The reactive power control, based on a PI controller, adjusts the reactive power to the power reference $Q^*_{wf,so}$ ordered by the system operator. This is done when the wind farm operates as a PQ node or a PV node, in which the power reference $Q^*_{wf,vc}$ is derived from the node voltage control. This PI controller sets up the power reference Q^*_{wf} for the whole wind farm.

The dispatch control receives the power references for the whole wind farm (P^*_{wf}, Q^*_{wf}) and computes the active and reactive power references for each wind turbine (P^*_{gi}, Q^*_{gi}). Different strategies for the dispatch function [12–14,20] have been used up to now. The simplest strategy is based on computing the same power references for each wind turbine [20]. Then, all the wind turbines generate the same active and reactive power. A more efficient strategy is proposed in [12,13], where the power references are defined from a proportional distribution of the available active and reactive powers. In [14], an optimized dispatch control strategy for optimizing the active and reactive power references in each wind turbine taking into account wind park internal losses is presented.

The dispatch control strategy used does not affect the performance of wind turbine control system. Thus, the strategy adopted in the present work has been the one based on a proportional distribution of the available active and reactive powers, since it is an efficient strategy and easy to implement. In this case, the power references for each wind turbine are calculated from

$$P^*_{gi} = \frac{P_{ava\_gi}}{\sum_{i=1}^{n} P_{ava\_gi}} P^*_{wf} \tag{18}$$

$$Q^*_{gi} = \frac{Q_{ava\_gi}}{\sum_{i=1}^{n} Q_{ava\_gi}} Q^*_{wf} \tag{19}$$

where P_{ava_gi} is the available active power for the *i*th wind turbine calculated from the power–speed control curve (shown in Fig. 3) and Q_{ava_gi} is the available reactive power for the *i*th wind turbine, computed from the Eq. (17).

It was assumed in this work that whenever the available energy (both for power optimization and power limitation) can be entirely delivered to the grid, the active power reference for the wind turbine is set up at its rated value. Therefore, only when down power regulation is required by the wind farm control system, the power reference is changed to the value defined from the dispatch control. Thus, if the wind turbine does not receive the power reference ordered by the wind farm control system, it could autonomously operate with power optimization or power limitation strategy, depending on the incoming wind. This operating scheme is used in [11]. In [12,13], the wind turbine requires constant sending out the power reference, ordered by the wind farm control system, in any operating conditions. Thus, the power reference is the available power when the wind turbine operates with power optimization strategy, the rated power with power optimization, and the power set point defined by the dispatch control with down power regulation.

6. Simulation results

This section focuses on evaluating the capability of the proposed control systems for power regulation of a DFIG wind turbine. It is evaluated when the available energy is entirely delivered to the grid by the wind turbine (both for power optimization and for power limitation), and when power regulation is required.

In this work, a wind farm consisting of three DFIG wind turbines has been considered. Fig. 12 illustrates the wind farm layout. DFIG wind turbines present a rated power of 2 MW and 690 V, as shown in Table 1. Each wind turbine is connected to the wind farm network through a transformer of 2.5 MVA, 20/0.69 kV. The wind farm connection to the grid is performed through a substation with a transformer of 8 MVA, 66/20 kV and a 10-km-long feeder.

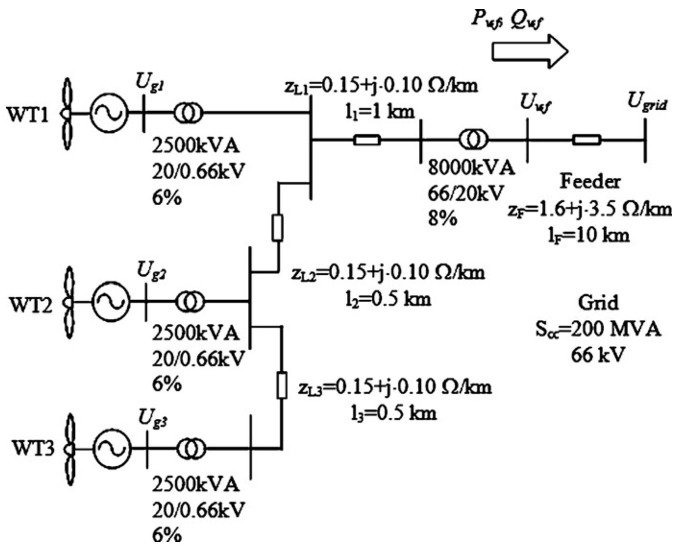

Fig. 12. Wind farm layout.

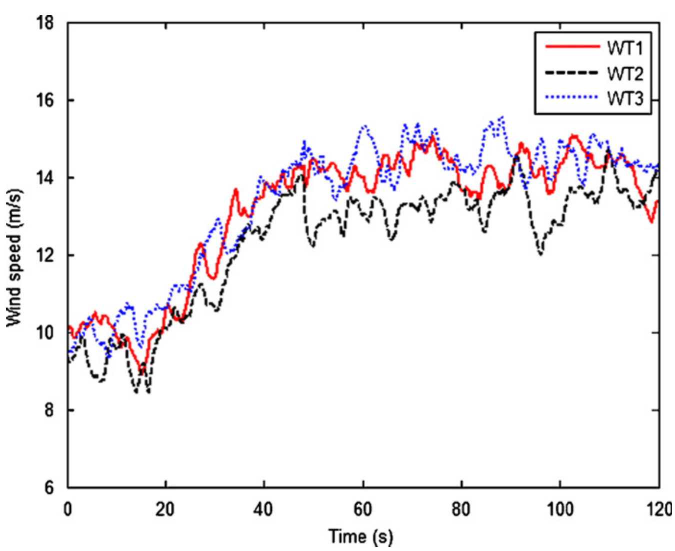

Fig. 13. Wind incident on the wind turbines.

Fig. 13 shows the wind speeds on the wind turbines considered in the simulations. These wind sequences correspond to winds below rated during the first thirty seconds and winds above rated during the rest of the simulation. This allows the evaluation of the wind turbine control systems in any operating conditions, with power optimization, power limitation or down power regulation strategies.

The performance of the control systems was assessed through two wind farm simulations:

(1) Wind farm operating as a PQ node, where the wind farm controls the active and reactive powers injected by the whole wind farm into the grid.
(2) Wind farm operating as a PV node, where the active power and the voltage at the wind farm node are controlled.

In order to compare the wind turbine control systems, three wind farms have been simulated. Each wind farm exhibits all the DFIG wind turbines controlled by one of the proposed control system.

Case 1: Wind farm operating as a PQ node. In this first case, the capabilities of wind turbine and the wind farm control systems to regulate the wind farm production (active and reactive powers) according to the power references ordered by the system operator have been tested.

The wind farm operates as follows:

- It produces the maximum possible output power injected to the grid during the first 60 s.
- At 60 s, the wind farm receives a 60% reduction of the active power reference by a slope of 0.1.
- The wind farm operates with the unity power factor during the first 80 s, whereas it generates the maximum reactive power for the rest of the simulation, with a slope of 0.1.

Fig. 14 illustrates the response of the three wind farms, where the active and reactive powers and the voltage at wind farm node are presented. As it can be seen, the simulation results show an adequate performance of the three wind turbine control systems, achieving the desired wind farm operation. However, it is worth mentioning that the wind farm with DFIG wind turbines commanded by the control system 3, generates more reactive power than the other wind farms when they operate maximizing the reactive power. This result that leads to a higher voltage at the wind farm node will be subsequently justified.

The performance of the three control systems is illustrated in Figs. 15 and 16, where only the response of the wind turbine 3, the furthest one from the wind farm substation, is represented.

As it can be observed in the results, while the wind turbine receives winds below rated (during the first twenty seconds), it generates below rated active power with variable rotational speed achieving optimum power efficiency. In this case, the wind turbine operates with a maximum power coefficient, and the pitch angle is kept at the optimal value.

DFIG wind turbine generates rated power between the twenty and sixty seconds, since the incoming wind exceeds the rated wind. In the control system 1, the pitch angle controller assures the rated power by acting on the pitch angle, and the u_{qr} controller keeps the rotational speed at the rated speed. Both for control systems 2 and 3, the u_{qr} controller adjusts the output power to the rated power and the pitch angle controller limits the rotational speed to the rated speed.

The variability from the incoming wind and the speed limitation on the pitch blade movement cause small variability on the output power for the wind turbine control system 1 and on the rotational speed for the control systems 2 and 3. The u_{qr} control, performed through the power converter, allows a perfect adjustment of the rated speed for the control system 1 and the rated active power for the control systems 2 and 3.

For the rest of the simulation, the wind turbine is able to generate the rated power since it experiences winds above rated. However, the wind turbine is ordered to reduce its output power to 0.4 p.u.(down power regulation). Notice that, although the control systems 1 and 2 achieve the same performance of the control variables, the wind turbine with control system 1 presents a higher variability on the response. In this case, the pitch angle controller acts on the pitch angle achieving the reference power and the u_{qr} controller adjusts the rotational speed to 0.899 p.u., which is derived from the power–speed curve according to the power reference. In control system 2, the u_{qr} controller adjusts the output power to the reference derived from the power–speed curve and the rotational speed, and the pitch angle controller adjusts the rotational speed to 0.899 p.u. derived from the power–speed curve and the power reference. Finally, in the control system 3, the u_{qr} controller adjusts the output power to

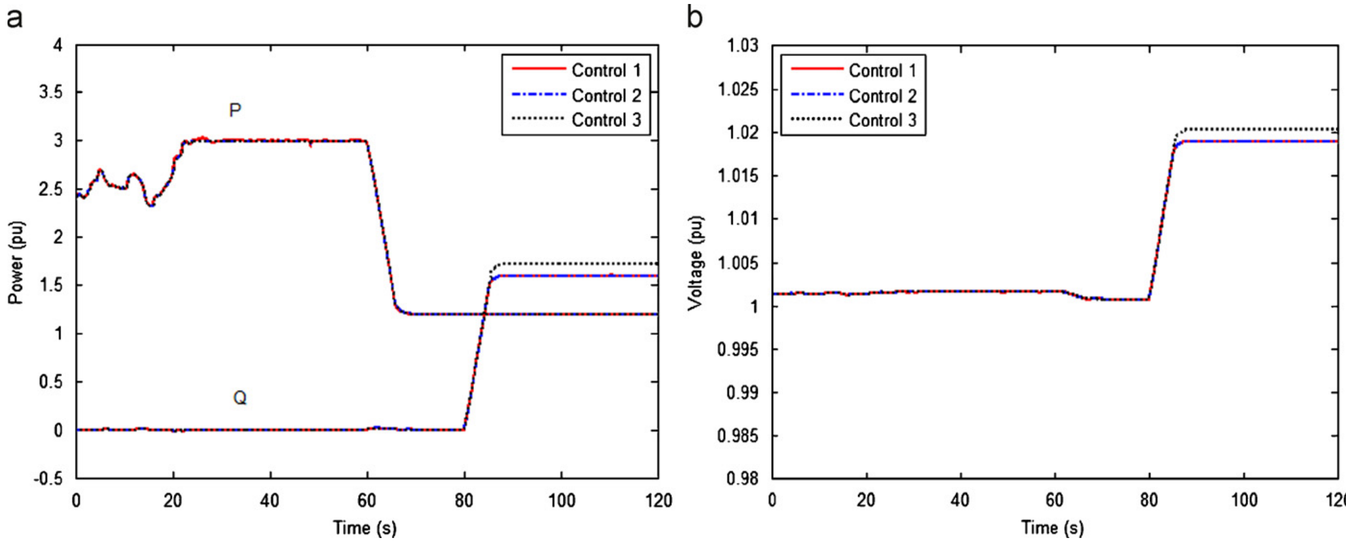

Fig. 14. Response of the wind farm operating as a PQ node: (a) Active and reactive powers and (b) voltage at wind farm node.

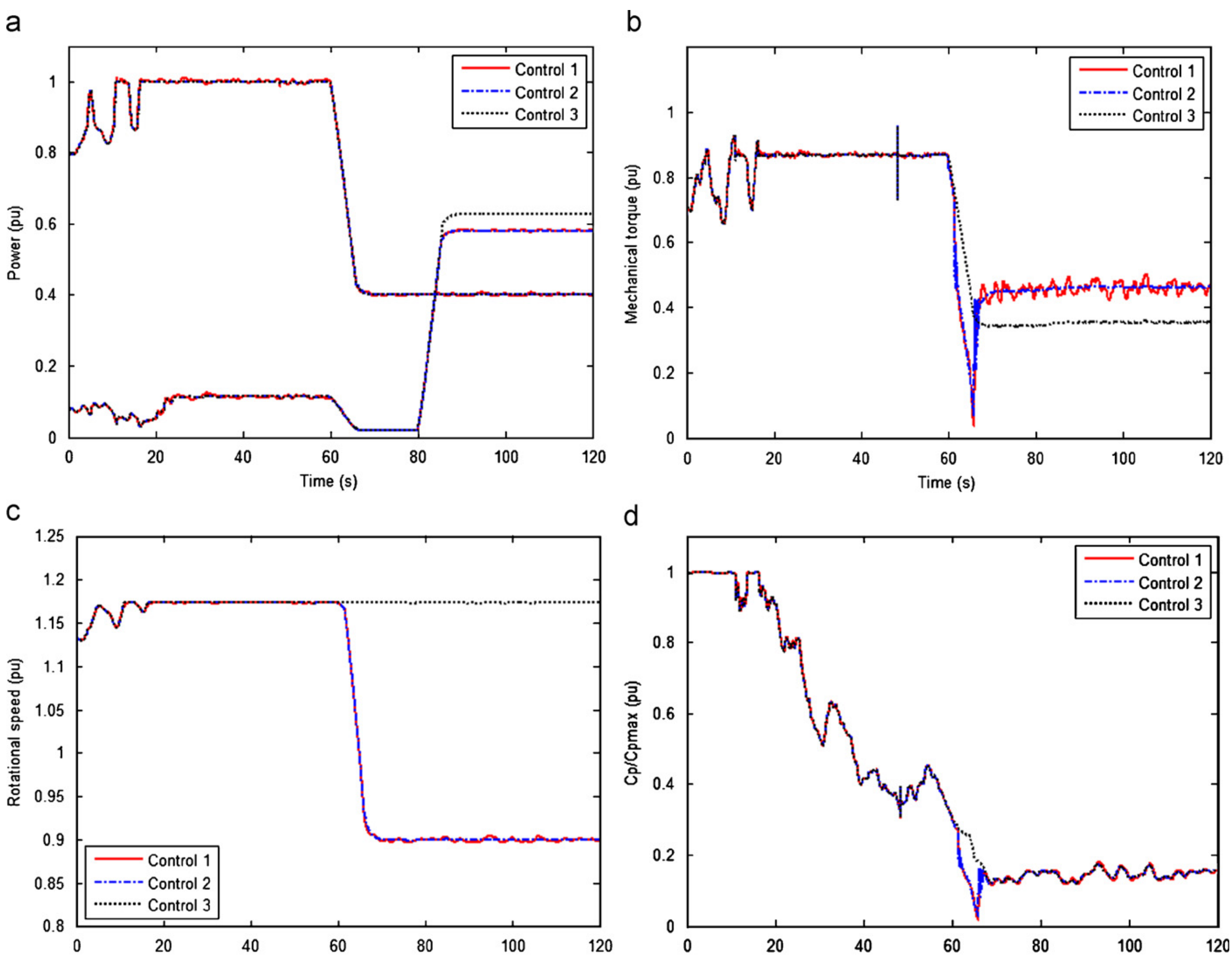

Fig. 15. Comparison of the wind turbine control systems through the response of the wind turbine 3 when the wind farm operates as a PQ node: (a) active and reactive powers, (b) mechanical torque, (c) rotational speed and (d) $c_p/c_{p,\max}$ relation.

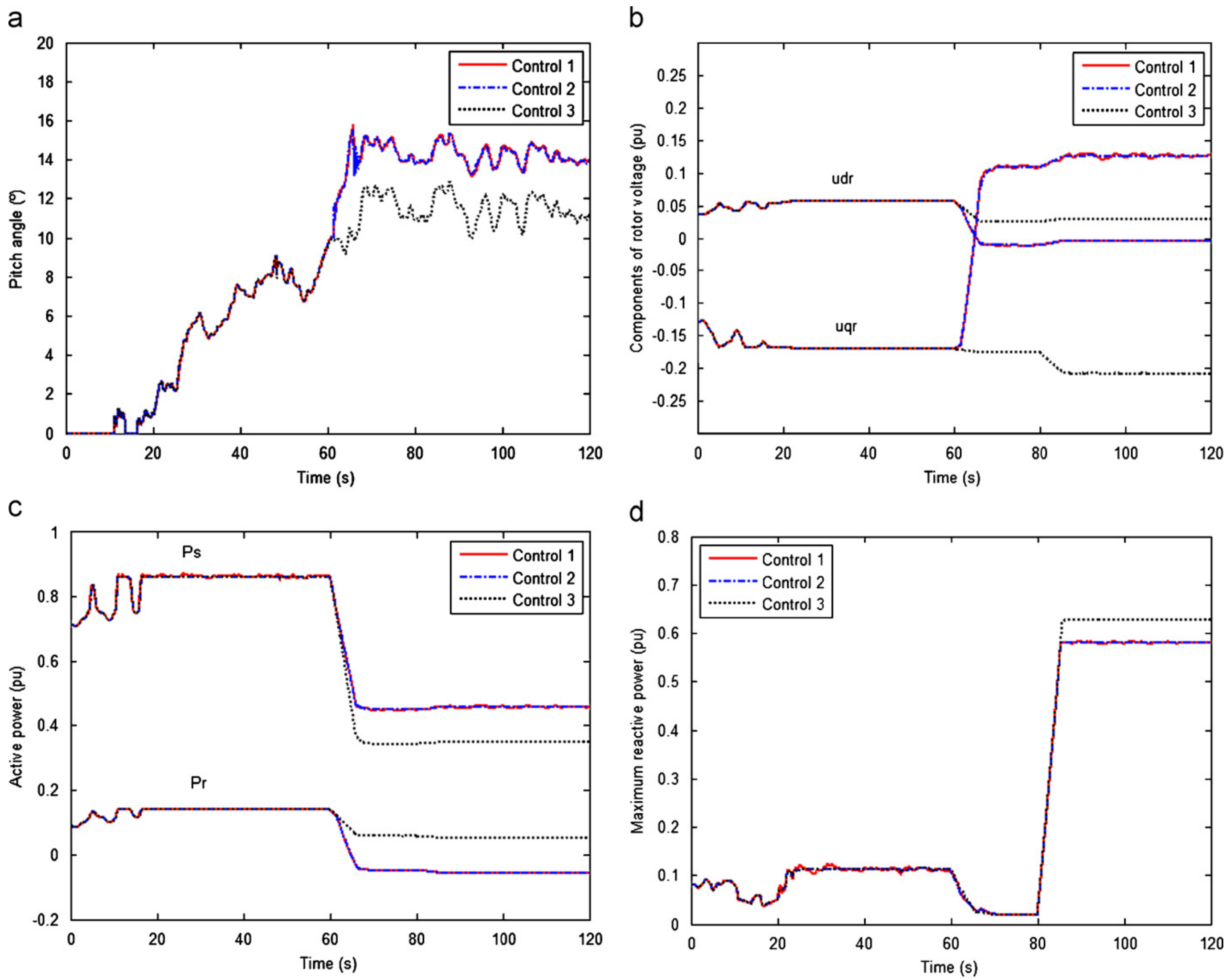

Fig. 16. Comparison of the wind turbine control systems through the response of the wind turbine 3 when the wind farm operates as a PQ node: (a) pitch angle, (b) direct and quadrature components of the rotor voltage, (c) stator and rotor active powers and (d) maximum reactive power.

the power reference ordered by the wind farm control system and the pitch angle controller keeps the rotational speed to a constant rated speed value.

Notice that the wind turbine with control systems 1 and 2 generate the reference power at below synchronous speed (0.899 p.u.), and therefore, the rotor winding consumes active power, as it can be deduced from the Eq. (16). On the other hand, the reference power for the control system 3 is achieved at the above synchronous speed. In this case, both the stator and rotor winding generate active power, as it can be derived from the Eq. (16).

With down power regulation, the wind turbines with control systems 1 and 2 generate at the same rotational speed, and thus the u_{qr} variable is controlled in the same way for both control systems. As the generation speed is different for control system 3, the wind turbine control system requires a different value of u_{qr}. Furthermore, the wind turbine commanded with control system 3 requires less pitch angle than the control systems 1 and 2, and as the rotational speed is higher, the tip ratio is different. This fact justifies the differences in the pitch angle, since the reduction of the power coefficient required is achieved from a different pitch angle.

When the wind farms operate with the unity power factor (during the first eighty seconds), each wind turbine adjusts the reactive power to the reference ordered by the wind farm control system. For the rest of the simulation, the wind turbine generates the maximum reactive power. It is worth to note that the reactive power and the direct component of the rotor voltage u_{dr} increase when the wind turbine changes its operating mode from the unity power factor to the maximum reactive power.

When the wind turbine operates without down power regulation (during the first sixty seconds of the performed simulation), the three control systems present the same performance for the u_{dr} control. Although it is worth mentioning a higher variability on the reactive power of the wind turbine commanded with the control system 1, due to the commented variability on the active power. For the remainder of the simulation, when down power regulation is required, the performance of the control systems 1 and 2 for the u_{dr} control are similar. However, they differ from the control system 3. In the operation with down power regulation, the wind turbines with control systems 1 and 2 operate at below synchronous speed, and therefore the stator winding generates power, while the rotor winding takes power from the grid. In the control system 3, the wind turbine operates at above synchronous speed, and both stator and rotor winding generate power. Hence, the wind turbine with control system 3 requires less stator power, and as the

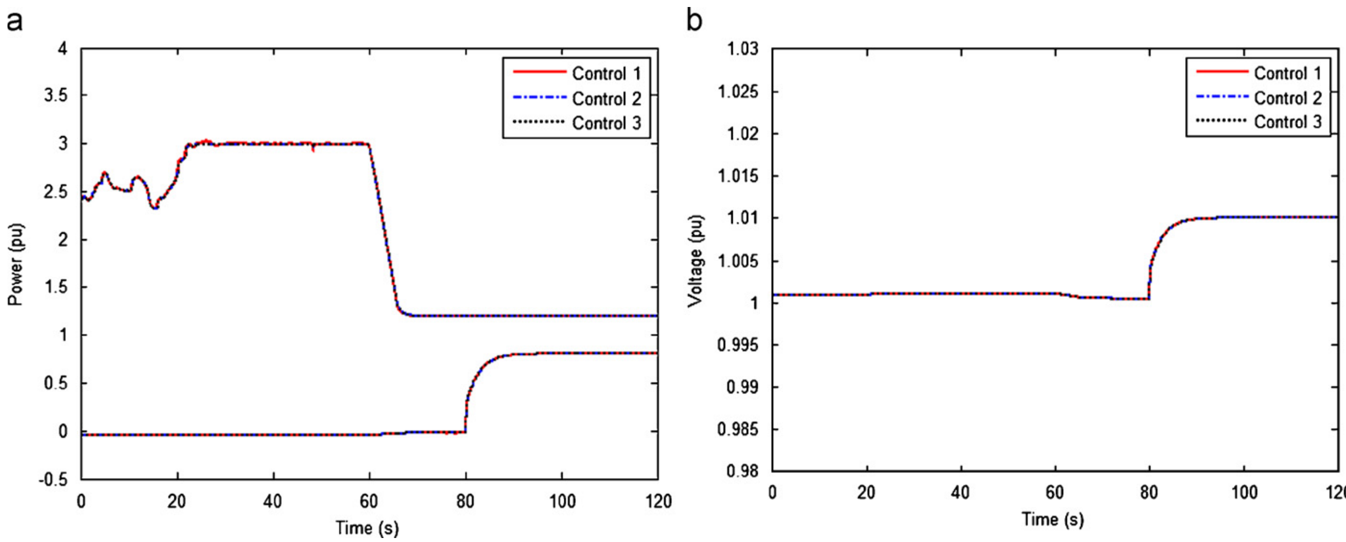

Fig. 17. Response of the wind farm operating as a PV node: (a) active and reactive powers and (b) voltage at wind farm node.

maximum reactive power depends on the stator power, this wind turbine is able to generate higher reactive power.

Case 2: Wind farm operating as a PV node. To evaluate the wind turbine and wind farm control systems when the wind farm production is regulated, a second case has been simulated. In this case, the active power and the voltage at the wind farm node are controlled according to the references ordered by the power system operator.

In the simulation performed, the wind farm operates with the same winds incident on the wind turbines and down power regulation, as the case 1. However, the voltage reference at the wind farm node is set to 1 p.u. during the first 80 s and to 1.01 p.u. for the rest of the simulation. In this simulation, the focus is on the performance of the wind farm control system at the wind farm node, and therefore, only the wind farm responses are presented. Fig. 17 illustrates the active and reactive power, and the voltage at the wind farm node.

Simulation results show a good performance of the proposed wind turbine and wind farm control systems to achieve the wind farm operation required, in this case, as a PV node.

7. Conclusions

The present paper presents a comparative study on the performance of three control strategies for DFIG wind turbines when they operate with power regulation, both active and reactive power to a set point ordered by the wind farm control system. The power control of a DFIG wind turbine is achieved by an appropriate control of the direct and quadrature components of the rotor voltage, performed through the power converter, in collaboration with the blade pitch angle control.

In this work, three possible ways to control these variables have been described. Two of them (control systems 1 and 2) are based on control systems existing strategies, whereas the third control system (control system 3) presents a novel control strategy, which is actually a variation of the control system 2. For the reactive power control, the three control systems present the same controller, based on controlling the direct component of the rotor voltage u_{dr}. Regarding the control of the active power and the generator speed, performed by the quadrature component of the rotor voltage u_{qr} and the pitch angle θ, the control systems 1 and 2 present a different control scheme, whereas the control Schemes 2 and 3 are similar although with certain differences. In the control system 1, the speed control is performed acting on the quadrature component of the rotor voltage, and the active power is controlled by the pitch angle. In the control system 2, the active power is controlled by the quadrature component of the rotor voltage, and the rotational speed is controlled to a speed reference derived from the power–speed curve control by acting on the pitch angle. In the control system 3, the active power is also controlled by the quadrature component of the rotor voltage. However, it presents a select mode to choose the operating mode (power optimization/limitation or down power regulation). In this case, the speed is limited to the rated speed by acting on the pitch angle.

The performance of the wind turbine control systems have been assessed through simulations of DFIG wind turbines, integrated in a wind farm with centralized control system. This wind farm control system computes the power references (active and reactive power), for each wind turbine, in order to regulate its production, following the references ordered by the power system operator. An efficient strategy has been adopted for the power reference distribution. It is based on a proportional distribution of the available active and reactive power. Three wind farms have been simulated operating as a PQ node and a PV node. Each wind farm exhibits all the DFIG wind turbines controlled by one of the proposed control system.

The simulation results illustrate the capability of the described control systems to control the power production, both active and reactive powers, of a DFIG wind turbine in any operating conditions. Without down power regulation, the control systems 2 and 3 present the same performance. When the wind turbine operates with power limitation, the output power generated with control system 1 presents small variability, due to the difficulty of the pitch controller to control the output power. With down power regulation, the control systems 1 and 2 have similar performance, since they generate the reference power at the same rotational speed. However, the performance of the control system 3 is different, since the wind turbine generates the reference power at the rated speed. Hence, the pitch angle required to reduce the power coefficient and the stator active power generated are less as compared with the other two controls. This implies a higher available reactive power, which is a very important aspect to maintain an appropriate voltage control at the wind farm bus. Therefore, as it can be deduced from the performance of the control systems in the simulation cases, the control system 3 achieves the best control strategy, as compared with the other two controls.

Acknowledgment

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