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Equivalent models of wind farms by using aggregated wind turbines and equivalent winds

L.M. Fernández [a,*], C.A. García [a,1], J.R. Saenz [a,2], F. Jurado [b,3]

[a] Department of Electrical Engineering, EPS Algeciras, University of Cádiz, Avda. Ramón Puyol, s/n. 11202 Algeciras, Cádiz, Spain
[b] Department of Electrical Engineering, EPS Linares, University of Jaén, C/ Alfonso X, n° 28. 23700 Linares, Jaén, Spain

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ABSTRACT

As a result of the increasing wind farms penetration on power systems, the wind farms begin to influence power system, and therefore the modeling of wind farms has become an interesting research topic. In this paper, new equivalent models of wind farms equipped with wind turbines based on squirrel-cage induction generators and doubly-fed induction generators are proposed to represent the collective behavior on large power systems simulations, instead of using a complete model of wind farms where all the wind turbines are modeled. The models proposed here are based on aggregating wind turbines into an equivalent wind turbine which receives an equivalent wind of the ones incident on the aggregated wind turbines. The equivalent wind turbine presents re-scaled power capacity and the same complete model as the individual wind turbines, which supposes the main feature of the present equivalent models. Two equivalent winds are evaluated in this work: (1) the average wind from the ones incident on the aggregated wind turbines with similar winds, and (2) an equivalent incoming wind derived from the power curve and the wind incident on each wind turbine. The effectiveness of the equivalent models to represent the collective response of the wind farm at the point of common coupling to grid is demonstrated by comparison with the wind farm response obtained from the detailed model during power system dynamic simulations, such as wind fluctuations and a grid disturbance. The present models can be used for grid integration studies of large power system with an important reduction of the model order and the computation time.

1. Introduction

Wind power is the world's fastest growing energy source with a growing at an annual rate in excess of 30% and a foreseeable penetration 12% of global electricity demand by 2020 [1]. As a result of the increasing wind power penetration on power systems, the wind farms begin to influence power system. This justifies the development of adequate wind farms models to be included in power systems simulation software in order to represent the behavior of wind farms, evaluate their influence and improve the planning and exploitation of electrical networks [2].

The two most widely used wind generation systems used in wind farms are based on induction generators [3]: (1) squirrel-cage induction generators (SCIG) directly connected to grid with power-factor-correction capacitors; and (2) doubly-fed induction generators (DFIG) with wound rotor induction generator and back-to-back power converter connected to the rotor winding. Hence, this work deals with the development of equivalent models for wind farms equipped with these wind turbines.

Modeling of wind farms depends on the purpose of investigations to be performed. For investigations of the internal behavior of wind turbines within a wind farm, it is required the wind farms to be modeled by a detailed model. It includes the modeling of all the wind turbines and the wind farm electrical network, such as performed for wind farms with SCIG in [4–6] and with DFIG in [7,8]. It can be also used to represent the collective response of a wind farm during transient stability studies of large-scale power systems. In such a case, when a wind farm with large number of wind turbines is modeled, it is obtained a high order model and therefore the simulation requires relatively large computation time. To reduce the complexity of the wind farm model during simulations of a large power system, equivalent models of wind farms have been developed to simulate the collective response of wind farms on large power systems.

One of the most used equivalent models of wind farms is based on aggregating wind turbines experiencing identical incoming

* Corresponding author. Tel.: +34 956 02 81 66; fax: +34 956 02 80 01.
E-mail addresses: luis.fernandez@uca.es (L.M. Fernández), carlosandres.garcia@uca.es (C.A. García), joseramon.saenz@uca.es (J.R. Saenz), fjurado@ujaen.es (F. Jurado).
[1] Tel.: +34 956 02 80 18; fax: +34 956 02 80 01.
[2] Tel.: +34 956 01 57 34; fax: +34 956 01 57 34.
[3] Tel.: +34 953 64 85 18; fax: +34 953 64 85 86.

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winds into an equivalent wind turbine. It presents re-scaled power capacity and operates at an equivalent wind farm network. This equivalent turbine receives the same wind as the wind incident on the group of wind turbines [9–12]. Applying this aggregation method, it is obtained an equivalent wind farm with so many equivalent wind turbines as groups of turbines with identical winds. However, there are many wind farms with wind turbines experiencing different winds, where the aggregation of wind turbines with identical winds is not possible, and therefore, a new aggregation method must be used. In such a case, the differences in the incoming winds lead to output power deviations among the aggregated wind turbines, and therefore the wind incident on each wind turbine should be considered in the aggregation method.

The aggregated models of wind farms with wind turbines experiencing different incoming wind speeds developed until now [13–15] are based on using a dynamic simplified model of each individual wind turbine that receives the corresponding incoming wind speed. Equivalent models for SCIG and DFIG wind turbines are proposed in [13]. For SCIG wind turbines, the dynamic simplified model calculates the mechanical power of each individual wind turbine. For DFIG wind turbines, the dynamic simplified model computes the active and reactive powers of each aggregated wind turbine. The powers of the individual wind turbines are aggregated to calculate the wind farm production. Therefore, it is not used an equivalent wind turbine with the same model as the individual wind turbines. This fact leads to differences between the collective responses of the wind farm obtained from the detailed and equivalent models, as it can be observed in the results shown in [13].

In the work [14] for SCIG wind farm and in [15] for DFIG wind farms, the equivalent models are also based on a dynamic simplified model of each individual wind turbine. However, it is used in this case an equivalent generation system with the same model as the individual wind turbines. The dynamic simplified model approximates the generator mechanical torque, instead of the powers as performed in [13]. The generator mechanical torques of the individual wind turbines are aggregated and the resulting torque is applied to an equivalent generation system. To represent the dynamic response during power system simulations, this equivalent generation system is composed of the third-order model of the induction generator and an equivalent compensating capacitor with variable reactance for SCIG wind turbines [14] and an equivalent converter for DFIG wind turbines [15]. This approach achieves a better approximation of the collective response of wind farm as compared with the results shown in [13].

New equivalent models of wind farms with SCIG and DFIG wind turbines are presented in this paper. The equivalent wind turbine proposed here presents the same model as the individual wind turbines, not only for the generation system but for the complete model, including the turbine, drive train and generation system. It has re-scaled power capacity and receives an equivalent wind of the ones incident on the turbines. Two equivalent winds are considered: (1) the average wind of the ones incident on the aggregated wind turbines, and (2) an equivalent incoming wind derived from the power curve and the wind incident on each wind turbine. Therefore, it is not required a dynamic simplified model of each individual wind turbine, as used in previous works [13–15]. This approach allows a reduction of the equivalent model order as compared with works [14,15], since it presents less differential equations. The effectiveness of the proposed equivalent models to represent the collective response of the wind farm at the point of common coupling to grid is demonstrated by comparison with the wind farm response obtained from the detailed model during power system dynamic simulations, such as wind fluctuations and a grid disturbance.

2. Wind farms equipped with wind turbines based on induction generator

Depending on the generation system, the wind farms equipped with wind turbines based on induction generator can be classified in: (1) SCIG wind farms or fixed speed wind farms and (2) DFIG wind farms or variable-speed wind farms.

SCIG wind turbine (Fig. 1a) presents a squirrel-cage induction generator connected directly to the grid and coupled to the wind turbine rotor through a gearbox. This generator presents very small rotational speed variations, because the only speed variations that can occur are changes in the rotor slip, so that these wind turbines are considered to operate at fixed speed. In order to limit the power extracted from the wind for high winds, the wind turbine rotor limits the power extracted from the wind using the stall effect (stall regulated wind turbine) or controlling the blade pitch angle (pitch regulated wind turbine). A SCIG consumes reactive power, so that capacitors are added to generate the induction generator magnetizing current, thus improving the power factor of the system.

DFIG wind turbine (Fig. 1b) uses a wound rotor induction generator coupled to the wind turbine rotor through a gearbox. This generator presents the stator winding connected directly to the grid and a bidirectional frequency converter feeding the rotor winding. It is made up of two back-to-back Insulated Gate Bipolar Transistor (IGBT) bridges linked by a direct current (DC) bus. This converter decouples the electrical grid frequency and the mechanical rotor frequency and thus enabling variable-speed generation of the wind turbine. The wind turbine rotor presents blade pitch angle control in order to limit the power and the rotational speed for high winds. Furthermore DFIG presents noticeable advantages such as the decoupled control of active and reactive powers, the reduction of mechanical stresses and acoustic noise, the improvement of power quality, and the use of a power converter with a rated power 25% of total system power.

3. Detailed models of wind farms

A wind farm can be modeled by a detailed model, which includes the modeling of all the wind turbines and the internal electrical network of the wind farm. To represent the behavior of the wind farm during power system simulations without increasing unnecessarily the detailed model order and simulation time, reduced models of the wind turbines, both SCIG and DFIG, and the electrical network of the wind farm have been developed. The reduced models described below are based on widely used models in the literature.

3.1. Detailed model of SCIG wind turbines

Stall controlled SCIG wind turbines has been considered in this work since they are the most widely used fixed speed wind turbines in wind farms. They can be represented by the modeling of rotor, drive train and generation system with generator and power-factor-correction capacitors.

3.1.1. Rotor model

The rotor model [16,17] expresses the power extracted from the wind as

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

with P_{wt} the power extracted from the wind (W), ρ the air density (kg/m^3), A the rotor disk area (m^2), v the wind speed (m/s) and C_p the power coefficient that is a function of the tip speed ratio

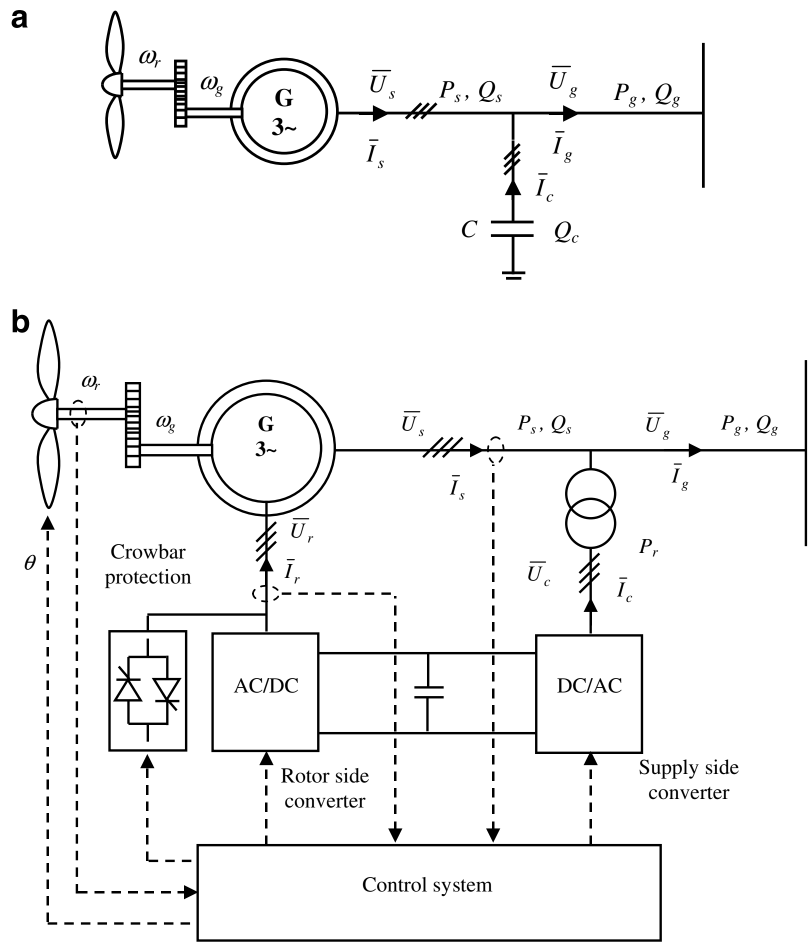

Fig. 1. Wind turbine configuration: (a) SCIG and (b) DFIG.

λ and the pitch angle of rotor blades θ. For stall controlled SCIG wind turbines, C_p is a function of only λ, since θ stays fixed in these turbines.

3.1.2. Drive train model

The drive train of the SCIG wind turbines is represented by the two masses model [16]:

$$T_{wt} - T_{mec} = 2H_r \frac{d\omega_r}{dt} \quad (2)$$

$$T_{mec} = D_{mec}(\omega_r - \omega_g) + K_{mec} \int (\omega_r - \omega_g)dt \quad (3)$$

$$T_{mec} - T_e = 2H_g \frac{d\omega_g}{dt} \quad (4)$$

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, K_{mec} and D_{mec} are the stiffness and damping of mechanical coupling.

3.1.3. Generation system

The dynamic behavior of a SCIG has been represented by the third-order model of the induction machine, as usual for power systems simulations [18]. The electrical equations of a SCIG, expressed in direct*(d)*-quadrature*(q)* coordinate reference frame rotating at synchronous speed ω_s are the following:

$$\frac{de'_d}{dt} = -\frac{1}{T'_o} \cdot (e'_d - (X_s - X'_s) \cdot i_{qs}) + s \cdot \omega_s \cdot e'_q \quad (5)$$

$$\frac{de'_q}{dt} = -\frac{1}{T'_o} \cdot (e'_q + (X_s - X'_s) \cdot i_{ds}) - s \cdot \omega_s \cdot e'_d \quad (6)$$

$$T_e = \frac{1}{\omega_s} \cdot (e'_d \cdot i_{ds} + e'_q \cdot i_{qs}) \quad (7)$$

The third differential equation is the generator mechanical equation, included in the drive train model.

SCIG uses local power-factor-correction capacitors to provide the induction generator magnetizing current. Therefore, the current injected by a SCIG wind turbine at the generation node is given by

$$i_{dg} = i_{ds} + i_{dc} = i_{ds} + \frac{1}{X_c} \cdot u_{qg} \quad (8)$$

$$i_{qg} = i_{qs} + i_{qc} = i_{qs} - \frac{1}{X_c} \cdot u_{dg} \quad (9)$$

where X_c is the reactance of the power-factor-correction capacitors, i_{dc} and i_{qc} are the current components of the capacitors, u_{dg} and u_{qg} are the voltage components at the generation node of the wind turbine.

The generation system model for a SCIG wind turbine can be modeled by the equivalent circuit shown in Fig. 2.

3.2. Detailed model of DFIG wind turbines

The detailed model of a DFIG wind turbine considered in this paper includes the following models: rotor, generation system with generator and converters, and control system.

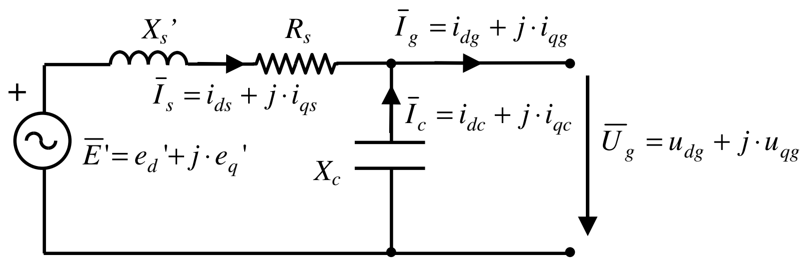

Fig. 2. Equivalent circuit of a SCIG wind turbine.

3.2.1. Rotor model

The rotor of a DFIG wind turbine presents the same model as a SCIG wind turbine. However, the DFIG wind turbine includes blade pitch angle control in order to limit the power extracted and the rotational speed for high winds. Therefore, the rotor model is described by Eq. (1).

3.2.2. Drive train

Again, the drive train model of a DFIG wind turbine is described by the same equations as SCIG wind turbine, Eqs. (2)–(4).

3.2.3. Generation system

The wound rotor induction generator of a DFIG wind turbine has been represented by the third-order induction machine model, expressed in d–q coordinate reference frame rotating at synchronous speed with the position of the d-axis aligned to the maximum of the stator flux. This transformation allows the independent control of active and reactive power of a DFIG wind turbine [19]. The modeling of the generation system of a DFIG is expressed by [18]

$$\frac{de_d'}{dt} = -\frac{1}{T_o'} \cdot (e_d' - (X_s - X_s') \cdot i_{qs}) + s \cdot \omega_s \cdot e_q' - \omega_s \cdot \frac{X_m}{X_r} \cdot u_{qr} \tag{10}$$

$$\frac{de_q'}{dt} = -\frac{1}{T_o'} \cdot (e_q' + (X_s - X_s') \cdot i_{ds}) - s \cdot \omega_s \cdot e_d' + \omega_s \cdot \frac{X_m}{X_r} \cdot u_{dr} \tag{11}$$

$$T_e = \frac{X_m}{\omega_s} \cdot (i_{ds} \cdot i_{qr} - i_{qs} \cdot i_{dr}) \tag{12}$$

The bidirectional frequency converter is made up of two back-to-back IGBT bridges linked by a DC bus. A converter is connected to the rotor winding (rotor side converter) and another converter to grid (supply side converter) [20]. The rotor side converter controls the rotor voltage, and thus the wind turbine can operate with optimum efficiency below nominal winds or with the output power limited to rated power above nominal winds and with the desired power factor. The supply side converter maintains the exchange power from the rotor circuit to the grid and operates at unity power factor. It is assumed in this paper that these converters are considered ideals and the DC link voltage between the converters is constant, as usual for power system simulations [21–24]. This supposes the decoupling of the converters and only fundamental frequency components are taken into account.

The rotor side converter is modeled as a controlled voltage source with the q-axis rotor voltage u_{qr} controlling the rotor speed and d-axis rotor voltage u_{dr} controlling the reactive power. The supply side converter is represented by a controlled current source, which provides the exchange of active power from the rotor circuit to the grid with unity power factor. The DFIG generation system can be represented by the equivalent circuit shown in Fig. 3.

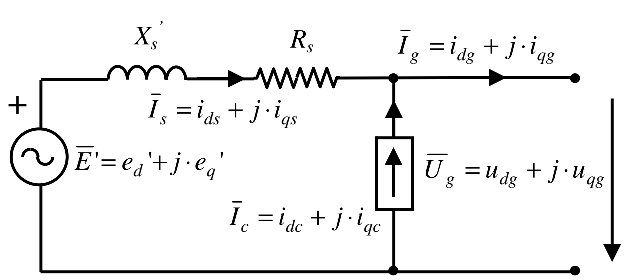

Fig. 3. Equivalent circuit of a DFIG wind turbine.

3.2.4. Control system

The control system of a DFIG wind turbine is composed of three controllers: rotor speed, blade pitch angle and reactive power controller.

The rotor speed controller (Fig. 4a) computes the quadrature component of the rotor voltage for the output power control [19]. This controller uses a power–speed curve as the one proposed in [25], which defines the reference output power according to the actual rotor speed. Thus, the wind turbine can operate with variable-speed below nominal winds maximizing the power extracted from the wind or limiting the output power to rated power above nominal winds.

The reactive power controller (Fig. 4b) computes the direct component of the rotor voltage, which enables the wind turbine operation with the desired power factor [19]. This controller includes a subordinated voltage controller, which maintains the generation voltage between the limits when trying to reach the reactive power reference. However the reactive power delivered to grid is limited to restrictions imposed by the power electronics converters connected to the rotor winding and expressed by rotor currents limits in order to avoid an excessive heat of converters, rotor slip-rings and brushes [8].

The limited stator reactive power $Q_{s,lim}$ depends on the stator active power P_s, the stator voltage U_s and the maximum rotor current $I_{r,max}$, expressed as [8]

$$Q_{s,lim} = -\frac{U_s^2}{X_s} \pm \sqrt{\left(\frac{X_m}{X_s} \cdot U_s \cdot I_{r,\max}\right)^2 - P_s^2} \tag{13}$$

Because DFIG wind turbine only delivers reactive power to grid by the stator winding, the maximum value for the reactive power reference that can be imposed to the reactive power controller is the limited stator reactive power, calculated according to Eq. (13).

DFIG wind turbine includes a blade pitch angle controller (Fig. 4c) to reduce the power coefficient and thus the power extracted from the wind, when the generator speed goes up to the control speed. This controller prevents high generator speed, when the wind turbine operates with the output power limited to rated value above nominal winds. The control scheme shown in Fig. 4c includes the actuator with pitch angle saturation and rate limiter.

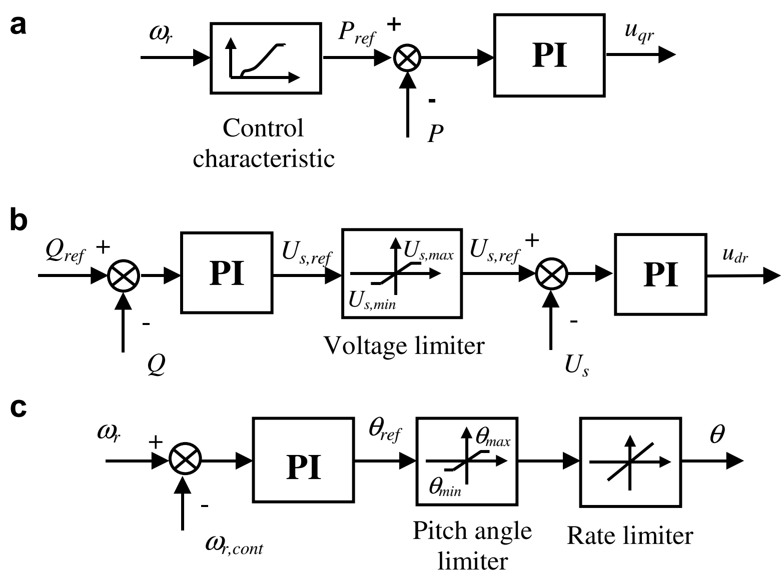

Fig. 4. Controllers of a DFIG wind turbine: (a) rotor speed controller, (b) reactive power controller and (c) blade pitch angle controller.

To work effectively, the power converter must be controlled in collaboration with the wind turbine pitch control. The wind turbine control is based on the following control strategies:

1. *Power optimization below rated wind speed.* In this case, the wind turbine generates the optimum power corresponding to the maximum power coefficient. The blade pitch angle controller keeps the pitch angle to its optimal, whereas the tip speed ratio is driven to its optimal value by the rotor speed controller acting on the rotor speed/generator torque.
2. *Power limitation above rated wind speed.* The wind turbine operates with the power limited to the rated value. In this case, the rotor speed controller assures the rated power by acting on the rotor voltage, whereas the blade pitch angle keeps the generator speed limited to the control value by acting on the pitch angle.

3.2.5. Protection system

To limit the rotor voltage and current, and to protect the electronic devices used in the power converter, DFIG wind turbine presents a crowbar [23], which protects the rotor and power converter against over-current. The crowbar protection is external rotor impedance, coupled via the slip-rings to the generator rotor instead of the converter. When a grid disturbance occurs and the control system detects a rotor current value above the current protection limit, the rotor side converter is disabled and bypassed by the crowbar protection. Therefore, DFIG is turned into squirrel-cage induction generator, and the independent controllability of active and reactive power gets lost.

3.3. Wind farm electrical network

The wind farm electrical network is modeled by the static model of electric lines and transformers, represented by constant impedance, as usual for power systems simulations [18].

4. Validation of the wind turbine models

The models of SCIG and DFIG wind turbines used in this work have been validated by comparison with the responses simulated from the built-in models for SCIG and DFIG wind turbines included in the SimPowerSystems library of MATLAB/Simulink®. These built-in models, developed by Hydro-Quebec Power System Simulation Laboratory, implement phasor models of both SCIG and DFIG wind turbine [26]. In this work, a 350 kW SCIG wind turbine and a 660 kW DFIG wind turbine have been modeled. Appendix 2 shows their parameters. Both models described in this work and the SimPowerSystems models have been simulated in MATLAB/Simulink environment [27] and their responses have been compared.

A wind speed sequence as depicted in Fig. 5a was used for the simulation of both SCIG and DFIG wind turbine. This wind fluctuates between 8 and 13 m/s. It corresponds to below nominal wind for SCIG wind turbine, and wind between below and above nominal wind for DFIG wind turbine.

Wind turbines were simulated assuming the connection to an infinite bus, without compensating capacitors in the SCIG wind turbine, and with unity power factor (zero reactive power) for the DFIG wind turbine.

Fig. 5 illustrates the results obtained from the simulation. For both SCIG and DFIG wind turbine, the active and reactive powers (Fig. 5b), and the generator speed (Fig. 5c) are presented. Fig. 5d shows the pitch angle of the DFIG wind turbine.

When the responses are compared, a high degree of correspondence for all the variables shown can be observed. SCIG wind turbine generates below rated power and consumes reactive power. Below nominal winds (less than 11.8 m/s), DFIG wind turbine generates below rated power at variable-speed and the pitch angle is kept at minimum degree (0°). Above nominal winds, the control system of DFIG wind turbine adjusts the output power to the rated power, limits the rotational speed to the control speed and acts on the pitch angle limiting the power extracted from the wind. Furthermore, the wind turbine 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 models used in this work and the SimPowerSystems models. Therefore, the models presented here can be considered suitable and valid to represent the response of both SCIG and DFIG wind turbines.

5. Equivalent models of wind farms

Equivalent models of wind farms with SCIG and DFIG are proposed in this paper, which are based on aggregating wind turbines

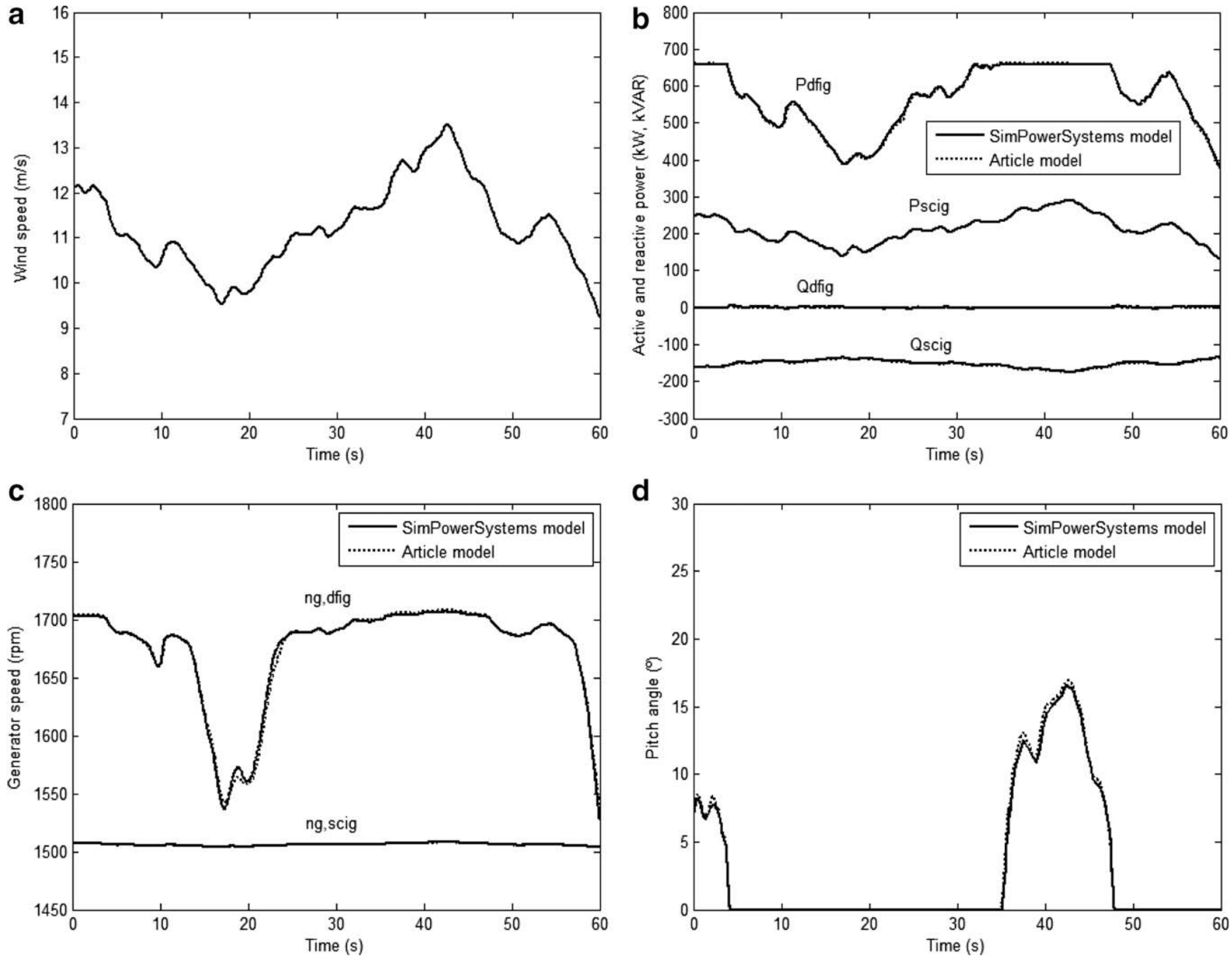

Fig. 5. Validation of the models described in this work by comparison with the wind turbine models included in the SimPowerSystems library of MATLAB/Simulink: (a) wind speed; (b) active and reactive powers; (c) generator speed; and (d) pitch angle of the DFIG wind turbine.

into an equivalent wind turbine with re-scaled power capacity. It presents the same complete model as the individual wind turbines and receives an equivalent wind from the ones incident on the turbines. These equivalent models are described next.

5.1. Equivalent winds

The wind distribution in wind farms depends on the wind farm location. For wind farms located in smooth land or offshore, the wind turbines are placed in rows. The wind turbines placed at the same rows present similar winds, whereas the incoming winds between rows are different because of shadowing among the rows of wind turbines. The wind farms located in rough land (mountain ladder) or with wind turbines widely separated present wind turbines with different incoming wind. Therefore, there are some wind farms with groups of wind turbines receiving similar incoming winds and other wind farms with all the wind turbines experiencing different winds.

Actually one of the most widely used equivalent wind farm models is based on the aggregation of wind turbines with identical incoming winds into an equivalent wind turbine which receives an equivalent wind equals to the wind incident on the group of the wind turbines. For wind turbines experiencing similar incoming winds (small differences in wind speed), it is proposed in this paper to use the average wind from the ones incident on the aggregated wind turbines as equivalent wind incident on the equivalent turbine.

$$v_{eq} = \frac{1}{n} \cdot \sum_{j=1}^{n} v_j \tag{14}$$

where v_{eq} is the wind incident on the equivalent wind turbine, v_j is the wind incident on an individual wind turbine, j index corresponds to each individual wind turbine and e index refers to equivalent wind turbine and n is the number of aggregated wind turbines.

The described equivalent wind farms present so many equivalent wind turbines as groups of wind turbines with similar winds.

As a result of the differences in the generation of the wind turbines experiencing different incoming winds, the aggregation of these wind turbines requires an equivalent wind turbine that considers the wind speed incident on each wind turbine. In this paper, this equivalent model is based on using an equivalent wind turbine with re-scaled power capacity that receives an equivalent wind of the ones incident on the turbines. This equivalent wind is derived from the power curve of the wind turbine, according to the following procedure:

1. An approximation of the power that generates each wind turbine P_j is derived from the power curve of the wind turbine according to the incoming wind.

$$P_j^{wt} = PC_{wt}(v_j) \tag{15}$$

where PC_{wt} is the function which represents the power curve of the wind turbine and super-index wt represents the value in p.u., expressed in the individual wind turbine base.
2. The sum of power that generates each wind turbine is the equivalent power P_{eq},

$$P_{eq}^{wt} = \sum_{j=1}^{n} P_j^{wt} \tag{16}$$

3. The power curve of the equivalent wind turbine PC_{ewt} is obtained from the sum of the powers of the individual wind turbines for each incoming wind speed. The resulting power curve expressed in the equivalent wind turbine base is the same as the individual wind turbines,

$$P_{eq}^{ewt} = PC_{ewt}(v_{eq}) \tag{17}$$

$$PC_{ewt} = PC_{wt} \tag{18}$$

where super-index ewt represents the value in p.u. expressed in the equivalent wind turbine base.
4. The equivalent wind is derived from the inverse function of the power curve of the equivalent wind turbine PC_{ew}^{-1} and the power of the equivalent wind turbine, obtained from Eq. (16) and expressed in the equivalent base.

$$v_{eq} = PC_{ewt}^{-1}(P_{eq}^{ewt}) \tag{19}$$

5. If all the aggregated DFIG wind turbines experience above nominal winds, the equivalent wind is the average wind, since the power curve is limited to rated power and therefore any above nominal wind could be solution for Eq. (19).

$$T_{mec,eq}^{wt} = \sum_{j=1}^{n} T_{mec,j}^{wt} = n \cdot T_{mec,j}^{wt} \tag{21}$$

The generator mechanical torque of an individual wind turbine is calculated from the same model for the rotor and drive train as any individual wind turbine, Eqs. (1)–(3) with identical parameters.

When the equivalent generator mechanical torque is expressed in the equivalent wind turbine base, this value is equal to the generator mechanical torque of an individual wind turbine expressed in its base,

$$T_{mec,eq}^{ewt} = T_{mec,j}^{wt} \tag{22}$$

The aggregation of the generation system for SCIG wind turbines, represented by their equivalent circuit (Fig. 2), implies that the equivalent induction generator presents the same model as an individual wind turbine, represented by Eqs (4)–(7) with the same mechanical and electrical parameters in p.u.

Applying the aggregation to power-factor-correction capacitors, it is obtained an equivalent capacitor with the same reactance in p.u. as an individual wind turbine. However the use of this capacitor with constant reactance would provoke errors in the approximation of the reactive power for the aggregated wind turbines, since the reactive power for a SCIG wind turbine depends on the active power and the generation voltage and these variables differ in each wind turbine when the incoming winds are different. A better approximation for the reactive power can be obtained by an equivalent capacitor with variable reactance, which provides the difference in the reactive power between the aggregated wind turbines and the equivalent wind turbine without capacitor. The procedure to calculate the equivalent capacitor is described next.

1. A approximation to the reactive power Q_j of each individual wind turbine is obtained from the steady-state model of the induction generator (shown in Fig. 6), the electrical power $P_{e,j}$ and the generation voltage $U_{g,j}$ according to the following expression:

$$Q_j = U_{g,j}^2 \cdot \frac{X_c - X_m}{X_c \cdot X_m} + (X_{\sigma s} + X_{\sigma r}) \cdot \frac{U_{g,j}^2 + 2 \cdot (R_r + R_s) \cdot P_{e,j}}{2 \cdot ((R_r + R_s)^2 + (X_{\sigma s} + X_{\sigma r})^2)} - (X_{\sigma s} + X_{\sigma r}) \cdot \frac{\sqrt{(U_{g,j}^2 + 2 \cdot (R_r + R_s) \cdot P_{e,j})^2 - 4 \cdot P_{e,j}^2 \cdot ((R_r + R_s)^2 + (X_{\sigma s} + X_{\sigma r})^2)}}{2 \cdot ((R_r + R_s)^2 + (X_{\sigma s} + X_{\sigma r})^2)} \tag{23}$$

5.2. Equivalent wind turbine for SCIG wind turbines

The equivalent wind turbine from the aggregation of SCIG wind turbines presents re-scaled power capacity, and therefore the rated power is equals to the sum of rated power of aggregated wind turbines,

$$S_{eq} = \sum_{j=1}^{n} S_j = n \cdot S_j \tag{20}$$

This equivalent wind turbine receives the equivalent wind as incoming wind. The use of a single equivalent wind incident on the equivalent wind turbine implies that all the aggregated wind turbines experience the equivalent wind as incoming wind and therefore all they develop the same generator mechanical torque. Therefore, the equivalent generator mechanical torque is n times the torque of an individual wind turbine when the values in p.u. are expressed in the individual wind turbine base,

The electrical power of each wind turbine is derived from the power curve (shown in Fig. 7 for the SCIG wind turbine considered in this work) and the incoming wind. The generation voltage of each wind turbine $U_{g,j}$ is approximated from the gen-

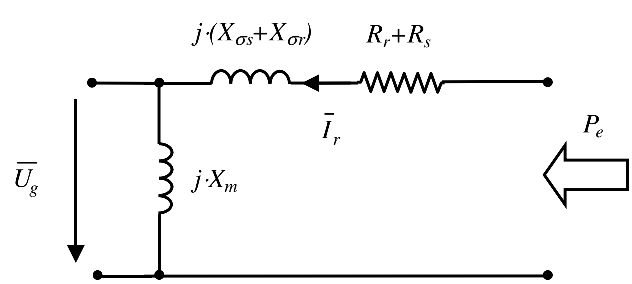

Fig. 6. Steady-state model of an induction generator.

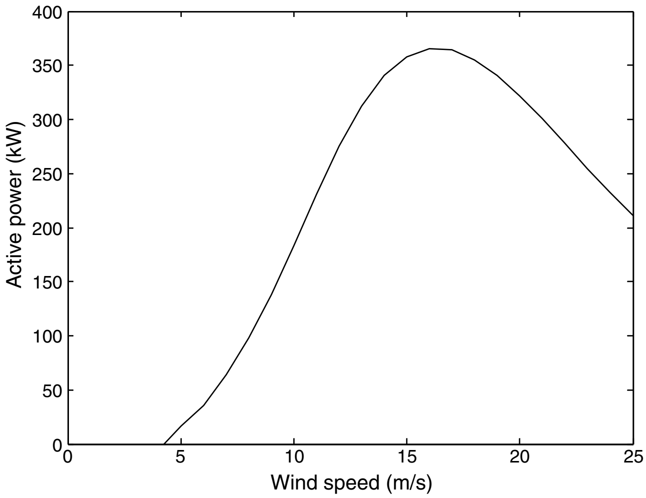

Fig. 7. Power curve of a SCIG wind turbine.

eration voltage of the equivalent wind turbine $U_{g,eq}$ operating in the equivalent wind farm network.

2. The reactive power of the aggregated wind turbines Q_{awt} is equal to the sum of the reactive powers of each wind turbine:

$$Q_{awt} = \sum_{j=1}^{n} Q_j \tag{24}$$

3. The reactive power of the equivalent wind turbine without power-factor-correction capacitors $Q_{eq,wc}$ is obtained from the steady-state model of the equivalent generator without capacitors.

$$Q_{eq,wc} = \frac{U_{g,eq}^2}{X_{m,eq}} + (X_{\sigma s,eq} + X_{\sigma r,eq}) \cdot \frac{U_{g,eq}^2 + 2 \cdot (R_{r,eq} + R_{s,eq}) \cdot P_{eq}}{2 \cdot ((R_{r,eq} + R_{s,eq})^2 + (X_{\sigma s,eq} + X_{\sigma r,eq})^2)} - (X_{\sigma s,e} + X_{\sigma r,e}) \cdot \cdot \frac{\sqrt{(U_{g,eq}^2 + 2 \cdot (R_{r,eq} + R_{s,eq}) \cdot P_{eq})^2 - 4 \cdot P_{eq}^2 \cdot ((R_{r,eq} + R_{s,eq})^2 + (X_{\sigma s,eq} + X_{\sigma r,eq})^2)}}{2 \cdot ((R_{r,eq} + R_{s,eq})^2 + (X_{\sigma s,eq} + X_{\sigma r,eq})^2)} \tag{25}$$

4. The variable reactance of the capacitor is calculated as

$$X_{c,eq} = \frac{U_{g,eq}^2}{Q_{awt} - Q_{eq,wc}} \tag{26}$$

A scheme of the equivalent wind turbine model for SCIG wind turbines is shown in Fig. 8.

5.3. Equivalent wind turbine for DFIG wind turbines

The equivalent wind turbine for aggregated DFIG wind turbines presents re-scaled power capacity and therefore its rated power is equal to n times the rated power of the individual wind turbines, where n is the number of aggregated wind turbines. Assuming that each individual wind turbine can operate with a different reference reactive power, the reference reactive power of the equivalent wind turbine is equal to the sum of the reference reactive power of the aggregated wind turbines:

$$S_{eq} = \sum_{j=1}^{n} S_j = n \cdot S_j \tag{27}$$

$$Q_{ref,eq} = \sum_{j=1}^{n} Q_{ref,j} \tag{28}$$

A wind farm control level computes the commanded reactive power Q_{com} for each wind turbine. As commented before, the reactive power of a DFIG wind turbine is limited (Fig. 9 shows the generation P_s–Q_s limit curve for the DFIG wind turbine considered in this paper), and therefore the reference reactive power Q_{ref} for each wind turbine can differ from the reactive power Q_{com} demanded by the wind farm control level. The maximum reactive power of a DFIG wind turbine has been calculated from Eq. (13), the stator active power and the generation voltage of each wind turbine. The stator active power is calculated from the power curve (Fig. 10 depicts the power curve for the DFIG wind turbine used in this work) and the incoming wind. The generation voltage of each wind turbine is approximated from the generation voltage of equivalent wind turbine.

Again, this equivalent wind turbine receives an equivalent incoming wind, which is used with the rotor and drive train model of an individual wind turbine in order to compute its generator mechanical torque. To calculate the equivalent generator mechanical torque with this method, it is assumed that all the aggregated wind turbines experience the equivalent wind as incoming wind, therefore all they develop the same generator mechanical torque. This torque, expressed in the individual wind turbine base, coincides with the generator torque of the equivalent wind turbine when it is expressed in the equivalent base.

Furthermore, the equivalent wind turbine includes the same model as an individual wind turbine for the generation system (induction generator and frequency converter), the control scheme and the controllers (rotor speed, reactive power and pitch angle controller) and the protection system. A scheme of the equivalent wind turbine model for aggregated DFIG wind turbines is depicted in Fig. 11.

5.4. Equivalent internal electrical network in the wind farm

The equivalent wind turbine operates at an equivalent internal electrical network. Then the common network of the aggregated wind turbines is replaced by equivalent impedance. This equivalent impedance is calculated assuming that the short-circuit impedance of the equivalent wind farm must be equal to the short-circuit impedance of the complete wind farm.

6. Simulation results

The equivalent models described in this paper have been verified by the comparison of steady-state and dynamic responses of the complete and equivalent wind farm models. They have been implemented and simulated in MATLAB/Simulink® environment.

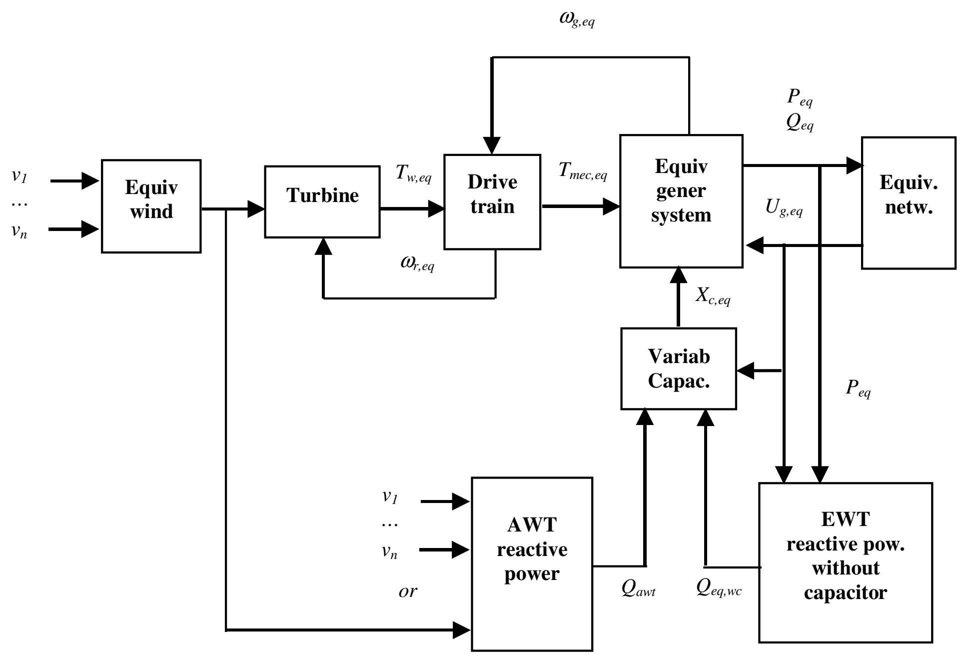

Fig. 8. Equivalent wind turbine model for SCIG wind turbines.

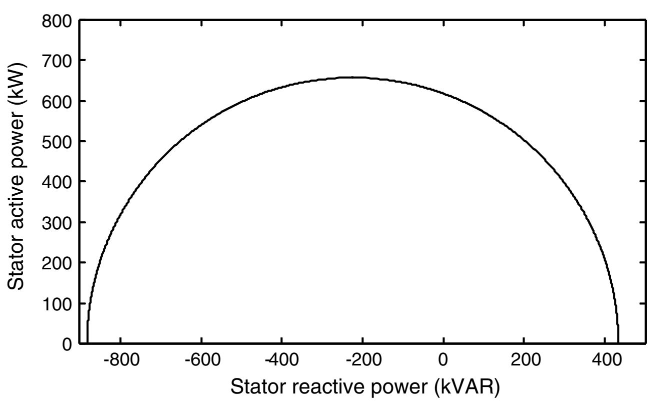

Fig. 9. Generation P_s–Q_s limit curve of DFIG wind turbine.

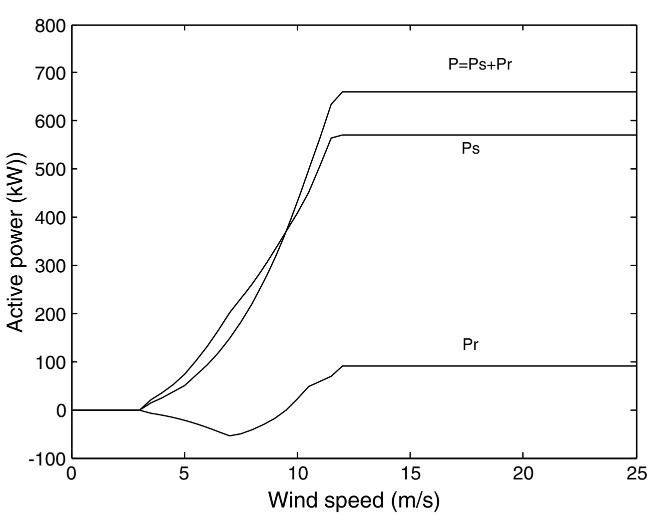

Fig. 10. Power curve of a DFIG wind turbine.

6.1. Steady-state simulations

Steady-state simulations have been run in order to establish the application limits of the equivalent models according to the wind speed incident on the aggregated wind turbines.

It has been considered a wind farm of two SCIG wind turbines and another of two DFIG wind turbines. The response of the detailed models of these wind farms have been compared with the ones obtained from the equivalent wind farms. This equivalent farm has been represented by a single equivalent wind turbine receiving the equivalent winds proposed in this paper.

To cover the greater part of possible cases of aggregation of wind turbines, the wind farms have been simulated with the first wind turbine experiencing three different constant wind speed (cut-in, nominal and intermediate wind speed, between cut-in and nominal wind) and the second wind turbine with different constant wind speed from cut-in to cut-off wind speed for each one of the winds considered in the first wind turbine. DFIG wind farm has been simulated assuming that all the wind turbines generate the maximum reactive power, which supposes the more unfavorable case for the equivalent models.

The simulation results demonstrate that the equivalent wind turbines with average winds are valid when the winds incident on the aggregated wind turbines are similar (differences in wind speeds less than 2 m/s) and when all the aggregated DFIG wind turbines receives above nominal winds since the control system assures the rated power. On the other hand, the equivalent wind turbines with equivalent wind obtained from the power curve are valid with any wind speed incident on the aggregated wind turbines, both SCIG and DFIG wind turbines, although the DFIG wind turbines generate the maximum reactive power. Next, these application limits can be observed in the dynamic simulations performed.

6.2. Dynamic simulations

The equivalent models have also been evaluated during dynamic simulations. In this case, two operation conditions have

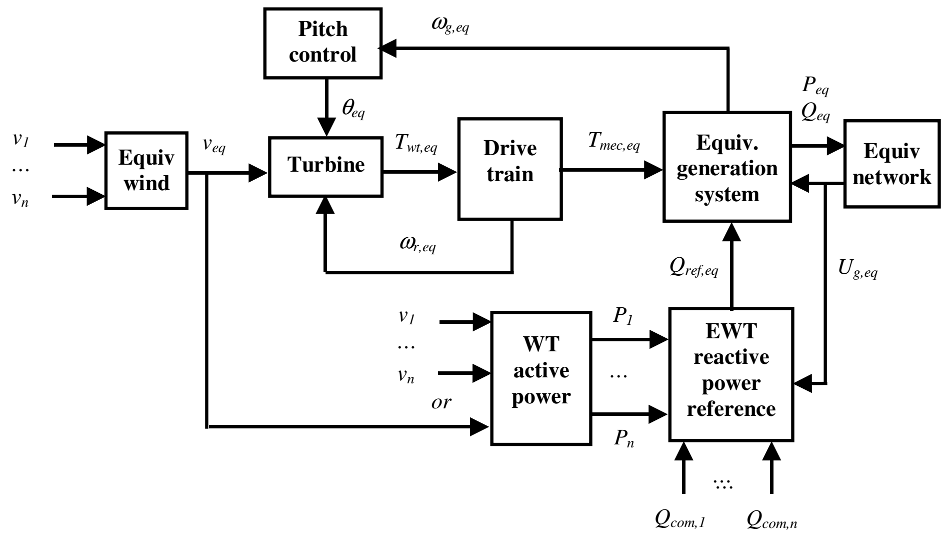

Fig. 11. Equivalent wind turbine model for DFIG wind turbines.

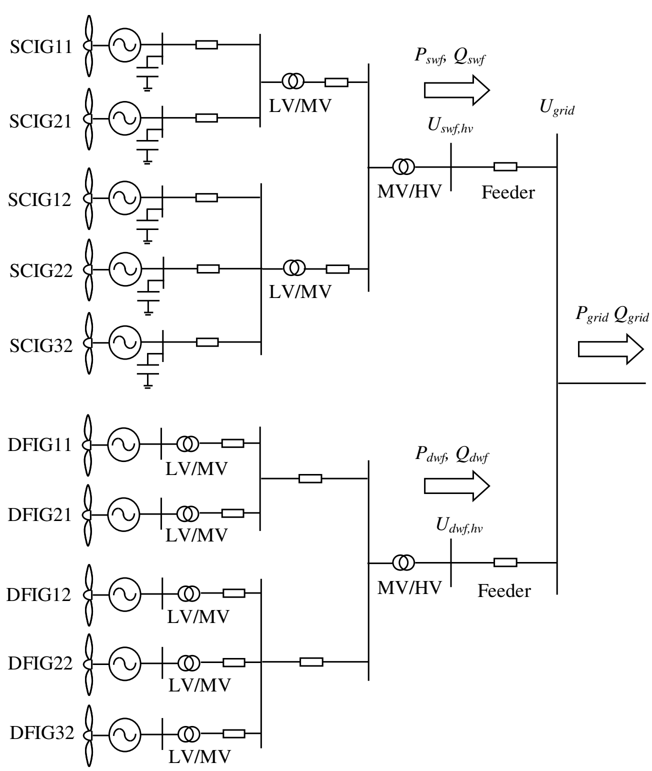

Fig. 12. Complete wind farms.

been considered: (1) normal operation (wind fluctuations in the wind farm) and (2) a grid disturbance (a short-circuit fault at the point common coupling of the wind farms to grid).

Two wind farms have been considered during the dynamic simulations, one with SCIG wind turbines and another with DFIG wind turbines, connected to the point common coupling (PCC) to grid by a feeder as depicted in Fig. 12.

Each wind farm presents five wind turbines, organized into a network of two sections with two and three wind turbines, respectively. SCIG wind farm is composed of wind turbines of 350 kW, 660 V and compensating capacitors each. DFIG wind farm uses wind turbines of 660 kW, 660 V each. A pair of indexes has been used to identify the wind turbines within the wind farm, where the second index denotes the number of the group and the first index refers the number of wind turbine within the group.

Two equivalent wind farms models have been considered. The first one presents an equivalent wind turbine for each group of wind turbines with similar winds, which receives the average wind of the aggregated wind turbines as incoming wind (Fig. 13a). The second one uses an equivalent wind turbine for each wind farm, which receives the equivalent wind obtained from power curve as incoming wind (Fig. 13b).

Case 1: Wind fluctuations. In this case, the wind farms have been simulated during wind speed fluctuations. It has been considered the same wind speeds incident on the wind turbines, both for SCIG and DFIG wind farms (Fig. 14). The first group of wind turbines receives close nominal winds for SCIG wind turbines and above nominal winds for DFIG wind turbines. The second group of wind turbines experiences below nominal winds, but with differences in winds less than 2 m/s between the wind turbines of the same group.

In the performed simulation, SCIG wind turbines operate with compensating capacitors for half rated power. DFIG wind turbines operate with unit power factor during 30 s and generate the maximum reactive power for the rest of simulation.

The simulation of complete wind farm provides the operating conditions for the individual wind turbines depicted in Fig. 15 for SCIG wind farm and in Fig. 16 for DFIG wind farm. These figures show the active and reactive powers of each wind turbine. It can be observed the difference in the active power generation among the wind turbines due to the incoming winds, and the operation of the DFIG wind turbines with unit power factor during the half of the simulation and with maximum reactive power for the rest of simulation.

The evaluation of the equivalent models has been performed by comparing the response of the complete and equivalent wind farms. The comparison variables are the active and reactive power of each wind farm and the total power at PCC of the wind farms to grid (shown in Fig. 17), and the voltage at PCC of each wind farm and at PCC of the wind farms to grid (depicted in Fig. 18). It has been used in these figures solid lines for the response of complete wind farms, dashed lines for the equivalent wind farms with equivalent wind turbines and average winds as equivalent winds, and dotted lines for the equivalent wind farms using equivalent winds derived from the power curve.

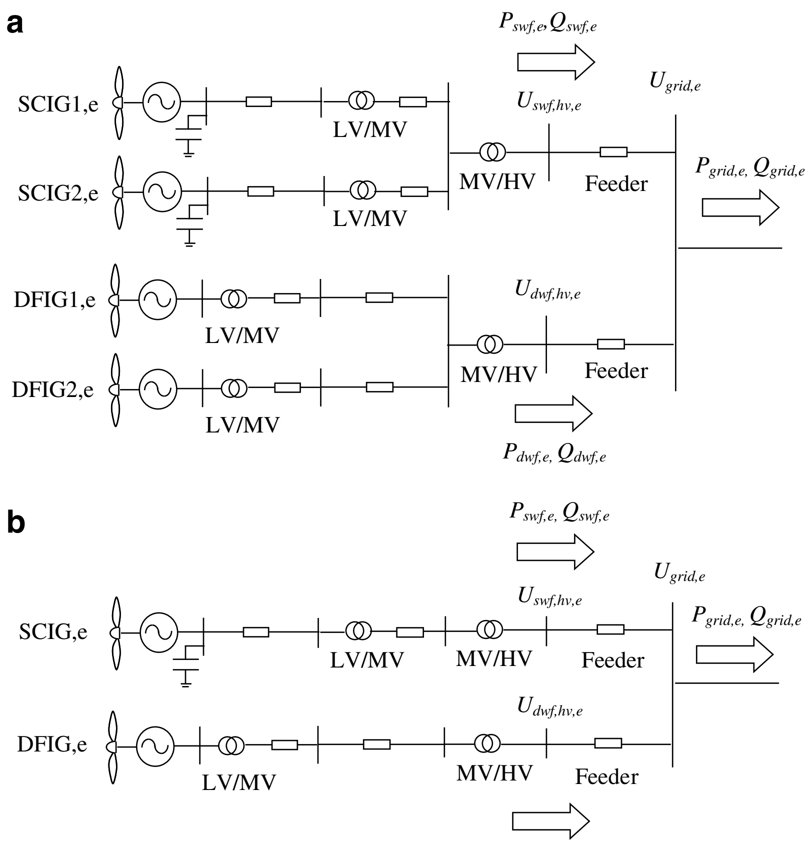

Fig. 13. Equivalent wind farms with equivalent wind turbines by using: (a) average winds and (b) equivalent winds obtained from the power curve.

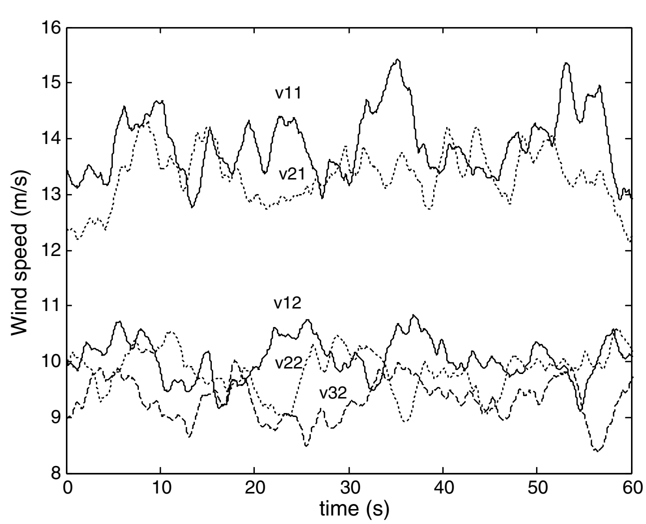

Fig. 14. Wind speed incident on the wind turbines of SCIG and DFIG wind farms.

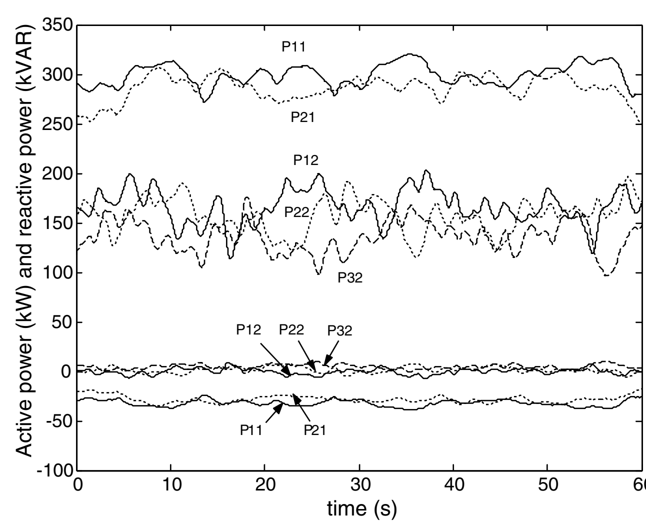

Fig. 15. Active and reactive power of SCIG wind turbines.

Analyzing the simulation results, it can be concluded that the present models allow an accurate approximation of the dynamic response of the wind farms operating with different winds incident on the wind turbines, although the DFIG wind turbines generate the maximum reactive power.

Case 2: A grid disturbance. The equivalent models have been also evaluated during a grid disturbance. In this case, it has been considered a short-circuit fault at PCC of wind farms to grid at $t = 1$ s with a duration of 100 ms, and after the fault the voltage starts to recover. Because the grid disturbances are much faster than wind speed variations, the wind speeds have been assumed constant.

Again the simulation results (Figs. 19 and 20) show a high correspondence between the response of the complete and equivalent wind farms, in this case, during a short-circuit fault.

Regarding the simulation time, an approximate reduction of 75% is obtained for the equivalent wind farm of Fig. 13a with respect to the complete wind farm and of 96% for the equivalent

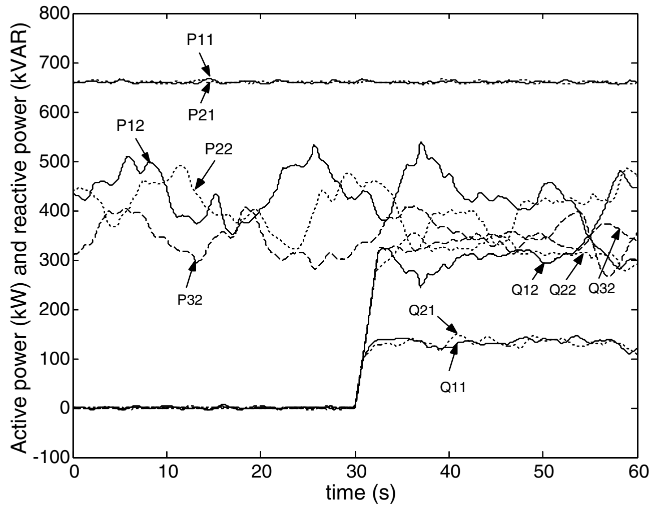

Fig. 16. Active and reactive power of DFIG wind turbines.

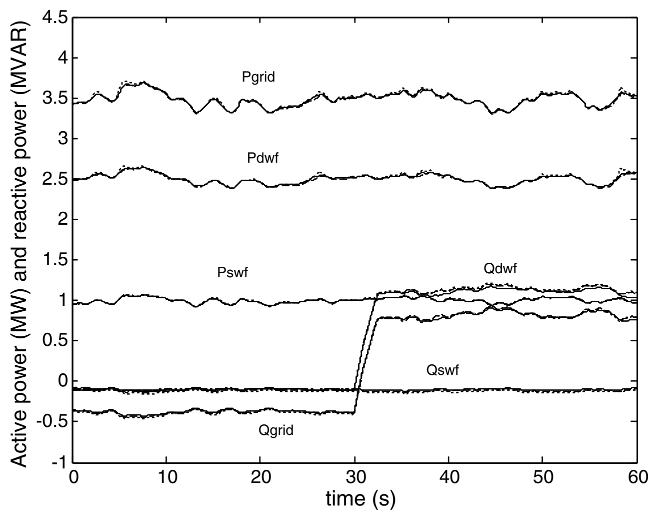

Fig. 17. Active and reactive power of each wind farm and at PCC of the wind farms to grid during wind fluctuations.

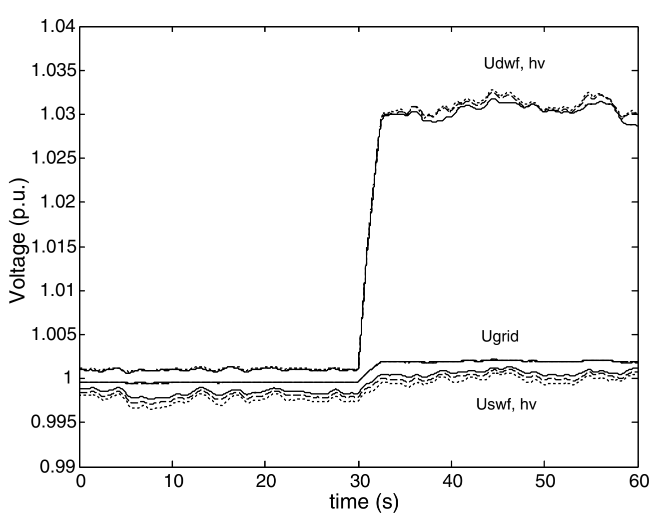

Fig. 18. Voltage at PCC of each wind farm and at PCC of the wind farms to grid during wind fluctuations.

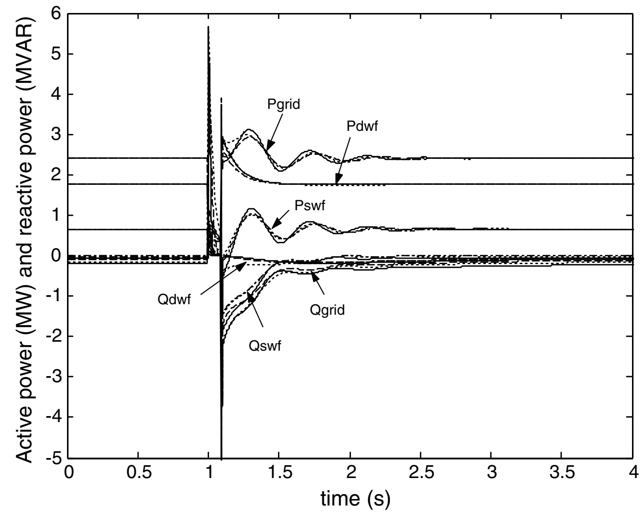

Fig. 19. Active and reactive power of each wind farm and at PCC of wind farms to grid during a short-circuit fault at PCC.

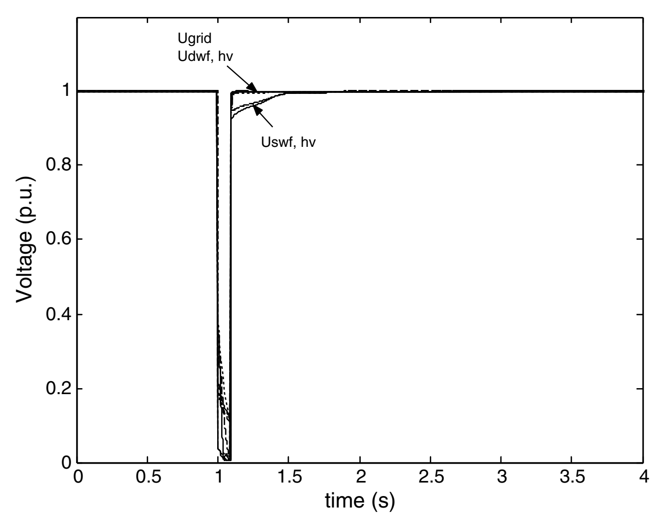

Fig. 20. Voltage at PCC of each wind farm and at PCC of wind farms to grid during a short-circuit fault at PCC.

wind farm of Fig. 13b, both for the wind fluctuations as well as for the grid disturbance.

6.3. Discussion

In this section, the present equivalent models are compared with the ones used in previous works [13–15] for wind turbines experiencing different incoming wind speeds.

The equivalent models proposed in [13] are based on a dynamic simplified model of each wind turbine, which approximate the powers generated. These powers are aggregated to compute the wind farm production. Therefore it is not used an equivalent wind turbine with the same model as the individual wind turbines. This approach leads to differences between the collective responses of wind farm obtained from the detailed and equivalent models, as it can be observed in results shown in [13]. These differences are mainly due to the simplifications applied in deriving the equivalent models.

In the case of the works [14,15], the equivalent wind turbine includes an equivalent model of the generation system, which presents the same model as the individual wind turbines. The turbine and drive train of the equivalent wind turbine are replaced by a dynamic simplified model of each individual wind turbine, which computes the generator mechanical torque. The equivalent generator torque, which is applied to the equivalent generation system, is calculated as sum of the individual generator torques. The simplified model for SCIG wind turbines proposed in [14], and for DFIG wind turbines used in [15] presents two differential equations for each individual wind turbine. In the case of SCIG wind turbines, the simplified model consists of the rotor and drive train models, and the steady-state generator electrical torque. For DFIG wind turbines, it is composed of the rotor and drive train models, the induction generator represented by the first-order model (the mechanical equation), the rotor speed controller represented by the power–speed control curve, and the blade pitch angle controller. Therefore, the equivalent wind turbine model presents $2n-2$ more differential equations than the individual wind turbine model, where n is the number of aggregated wind turbines into the equivalent turbine. As it can be observed in the results shown in [14,15], this approach achieves a better approximation of the collective response of wind farm as compared with results shown in [13].

As commented before, the equivalent wind turbines proposed in this work present the same model as the individual wind turbines, not only for the generation system but also for the complete model, including the turbine, drive train and generation system. It has re-scaled power capacity and receives an equivalent wind of the ones incident on the turbines. Therefore, it is not required a dynamic simplified model of each individual wind turbine, as used in previous works [13–15]. Thus, the equivalent wind turbine model presents the same number of differential equations as the individual wind turbine model. As it can be observed from the simulation results, the present equivalent models achieve similar results to the ones obtained with the equivalent models described in [14,15]. However, this approach allows a reduction of the equivalent model order and therefore, the computation time is reduced as compared with the previous works [14,15].

7. Conclusions

In this paper, new equivalent models of wind farms equipped with SCIG and DFIG wind turbines are proposed in order to represent the collective behavior on large power systems simulations, instead of using the complete model of wind farms where all the wind turbines are modeled. The main feature of these models is the aggregation of wind turbines into an equivalent wind turbine with re-scaled power capacity. This equivalent turbine receives a wind, which is the equivalent of ones incident on the aggregated wind turbines. Unlike the equivalent models developed until now, the equivalent wind turbine presents the same complete model (turbine, drive train and generation system models) as the individual wind turbines. Steady-state and dynamics simulations were performed to illustrate the effectiveness of the present equivalent models. The results analysis demonstrates that the equivalent wind turbine with the average wind obtained from the aggregated wind turbines must be used for wind turbines with similar winds (differences in wind speeds less than 2 m/s) or when all the aggregated DFIG wind turbines receives above nominal winds. The equivalent wind turbine with the equivalent wind obtained from the power curve supposes the best way of reducing the model order and the simulation time, enabling the aggregation of all the wind turbines of wind farm into a single equivalent wind turbine. This approach achieves an adequate approximation of the collective response of the wind farm during power system dynamic simulations, such as wind fluctuations and a grid disturbance.

Appendix A

Nomenclature	
A	rotor area of wind turbine (m^2)
C	coefficient (p.u.)
D	shaft damping (p.u.)
e'	internal voltage of induction generator (p.u.)
H	inertia (s)
i	current (p.u.)
K	shaft stiffness (p.u.)
n	number of aggregated wind turbines
P	active power (p.u) or (W) [indicated in text]
Q	reactive power (p.u.)
R	resistance (p.u.)
s	slip (p.u.)
S	rated power (MVA)
T	torque (p.u.)
u	voltage (p.u.)
v	wind speed (m/s)
X	reactance (p.u.)
θ	pitch angle (deg.)
ρ	air density (kg/m^3)
ω	frequency (p.u.)
capital letter	space vector modulus of voltage or current (p.u.).
small letter	instantaneous voltage or current component (p.u.).
Indexes	
awt	aggregated wind turbines
com	commanded value
d	direct component
dwf	doubly-fed induction generator wind farm
e	electrical
eq	equivalent
ewt	equivalent wind turbine
g	generator
j	number of wind turbine
k	number of wind turbines group
lim	limited value
m	mutual
mec	mechanical
q	quadrature component
r	rotor
ref	reference value
s	stator
swf	squirrel-cage induction generator wind farm
wt	wind turbine
σ	leakage

A.1. Parameters

A.1.1. SCIG wind turbine

Rated power: 350 kW, rated voltage: 660 V, A = 2903.33 m^2, H_r = 5 p.u., gear box ratio: 1:44.5, K_{mec} = 100 p.u., D_{mec} = 10 p.u., H_g = 0.5 p.u. R_s = 0.00571 p.u., $R_r' = 0.00612$ p.u., $X\sigma_s$ = 0.00690 p.u., $X\sigma_r' = 0.18781$ p.u., X_m = 2.78 p.u., X_c = 2.5 p.u.

A.1.2. DFIG wind turbine

Rated power: 660 kW, rated voltage: 660 V, A = 6939.77 m^2, gear box ratio: 1:52.5, H = 3 p.u. R_s = 0.01p.u., R_r' = 0.01 .u., $X\sigma_s$ = 0.04 p.u., $X\sigma_r$' = 0.05p.u., X_m = 2.9 p.u.

A.1.3. Wind farms electrical network

LV/MV transformers: SCIG group 1 (800 kVA, 20/0.66 kV, ε_{cc} = 6%); SCIG group 2 (1250 kVA, 20/0.66 kV, ε_{cc} = 6.5%); DFIG (800 kVA, 20/0.66 kV, ε_{cc} = 6%).

MV/HV transformers: SCIG (2500 kVA, 66/20 kV, ε_{cc} = 8%); DFIG (4000 kVA, 66/20 kV, ε_{cc} = 8.5%).

Electrical lines: LV lines of SCIGs and MV lines of DFIGs: r = 0.4 Ω/km, x = 0.1 Ω/km, length = 200 m; MV lines of wind turbines groups: r = 0.15 Ω/km, x = 0.1 Ω/km, length = 0.5 km (group 1), 1.5 km (group 2).

Feeder: SCIG (r = 0.16 Ω/km, x = 0.35 Ω/km, length = 10 km); DFIG (r = 0.2 Ω/km, x = 0.4 Ω/km, length = 20 km).

Grid: Short circuit power at PCC: 500 MVA. X/R ratio: 20.

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