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Aggregated dynamic model for wind farms with doubly fed induction generator wind turbines

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Abstract

As a result of increasing wind farms penetration in power systems, the wind farms begin to influence power system, and thus the modelling of wind farms has become an interesting research topic. Nowadays, doubly fed induction generator based on wind turbine is the most widely used technology for wind farms due to its main advantages such as high-energy efficiency and controllability, and improved power quality. When the impact of a wind farm on power systems is studied, the behavior of the wind farm at the point common coupling to grid can be represented by an equivalent model derived from the aggregation of wind turbines into an equivalent wind turbine, instead of the complete model including the modelling of all the wind turbines. In this paper, a new equivalent model of wind farms with doubly fed induction generator wind turbines is proposed to represent the collective response of the wind farm by one single equivalent wind turbine, even although the aggregated wind turbines operate receiving different incoming winds. The effectiveness of the equivalent model to represent the collective response of the wind farm is demonstrated by comparing the simulation results of equivalent and complete models both during normal operation and grid disturbances.

Keywords: Aggregated model; Doubly fed induction generator: Wind turbine; Wind farm

1. Introduction

Wind power is the world's fastest growing energy source with a growth at an annual rate in excess of 30% and a foreseeable penetration of 12% of global electricity demand by 2020 [1]. This important growth has been achieved by concentrating a large number of wind turbines in wind farms for a better exploitation of regions with good wind resources. As a result of increasing wind farms penetration in power systems, the wind farms begin to influence power system. This justifies the need for the development of suitable models of wind farms to be included in power systems simulation software in order to represent the behavior of grid-connected wind farms [2].

Doubly fed induction generator (DFIG) wind turbine has recently become the most widely used wind turbine for wind farms, since it presents noticeable advantages such as: the variable speed generation, 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].

The behavior of a wind farm with DFIG wind turbines can be simulated by a complete model including the modelling of all the wind turbines and the internal electrical network [4–6]. This model presents high-order if a wind farm with high number of wind turbines is simulated. In order to represent DFIG wind turbines without unnecessarily increasing the complete wind farm model, reduced models of wind turbines have been used [7–10]. In this paper, a reduced model of a DFIG wind turbine has been implemented by means of the third-order model of induction generator and modelling the power converter

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as two controlled sources, as usual for power system simulations [8,9].

The modelling and simulation of the complete model of a wind farm with high number of wind turbines suppose the use of a high-order model and a long computation time if all the wind turbines are modelled. In order to reduce the model order and computation time, equivalent models have been developed to represent the collective response of the wind farm at point common coupling (PCC) to grid. These models are based on aggregating wind turbines into an equivalent wind turbine. The authors of this paper performed a previous study about equivalent models of wind farms with fixed-speed wind turbines [11], whereas the work here presented is the extension of that work, but, in this case, concerning the wind farms with variable-speed wind turbines based on DFIG. In this paper, a review of state of art of the equivalent models of DFIG wind farms is performed and a new equivalent model is proposed to represent the whole wind farm by one single equivalent wind turbine.

The aggregation of wind turbines aimed at obtaining an equivalent model of wind farms depends on the study to be performed and the wind distribution in wind farm.

Hence, for large-scale power system simulations, the response of wind farms at PCC has been modelled by one single equivalent wind turbine, assuming a uniform wind speed distribution in the wind farm [12].

However, the wind farms usually present non-uniform wind distribution, and hence the wind distribution depends on the wind farm location. The wind farms located in smooth land or offshore present wind turbines placed in rows separated a minimum distance between three or five times rotor diameter at the same row, and five or nine times between the rows of wind turbines. Therefore, the wind turbines placed at the same rows present similar winds, whereas the wind incident on each row is different because of park effect or shadowing between the rows of wind turbines. The wind farms located in rough land (e.g., mountain ladder) or with wind turbines widely separated present wind turbines receiving different incoming winds. This implies that wind farms can present groups of wind turbines with similar incoming winds and wind turbines under different winds.

Equivalent models of DFIG wind farms have been used by aggregating wind turbines with identical wind into an equivalent wind turbine experiencing that wind [9,12]. These equivalent wind farms present so many equivalent wind turbines as groups of wind turbines with similar winds.

A model more reduced could be obtained if wind turbines receiving different incoming winds were aggregated into an equivalent wind turbine, since this would allow a wind farm to be represented by one single equivalent wind turbine. However, because of the differences between the output powers of the wind turbines operating under different incoming winds, this equivalent wind turbine must consider the wind incident on each individual wind turbine.

The aggregation of wind turbines receiving different incoming wind speeds has been considered in Ref. [13]. The equivalent model developed in that work is based on aggregating the electrical power of each individual wind turbine and using one voltage controller if the wind farm is equipped with a voltage controller. This equivalent model does not include the representation of the equivalent generation system or the converter.

In this paper, a new equivalent model of DFIG wind farms is proposed by aggregating all the wind turbines of a wind farm into one single equivalent wind turbine to represent the whole wind farm at PCC to grid, even though the wind turbines operate with different incoming winds. The equivalent model is based on using a dynamic simplified model of each individual wind turbine to approximate the generator mechanical torque according to the incoming wind. The generator mechanical torques of each individual wind turbines is aggregated and the resulting torque is applied to an equivalent generator system. This equivalent generation system is composed of the third-order model of induction generator and an equivalent converter in order to represent the dynamic response during power system simulations.

This paper is organized into the following sections. Section 2 describes the complete model of a DFIG wind farm, and Section 3 presents the equivalent models of the aggregated wind turbines and the internal electrical network. The effectiveness of the proposed equivalent model to represent the collective response of the wind farm with an important reduction of model size and computation time is illustrated in Section 4 by comparing the simulation results of equivalent and complete models both for normal operation and for grid disturbances. Finally, the conclusions are established in Section 5.

2. Complete wind farm model

A DFIG wind farm is composed of several DFIG wind turbines operating at an internal electrical network (lines and transformers) which enables the generated power to be delivered to grid, as depicted in Fig. 1.

DFIG wind turbines generate at low voltage (LV), and they are connected to the electrical network through a low/medium voltage (LV/MV) transformer and a medium voltage (MV) line for each wind turbine. A common MV line connects a group of wind turbines to the wind farm substation, where a medium/high voltage (MV/HV)

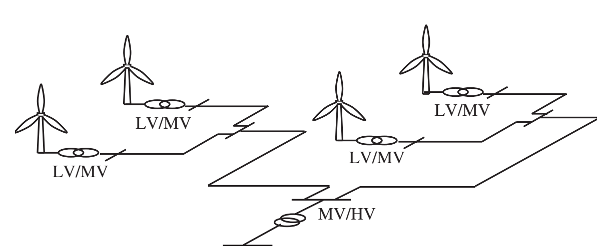

Fig. 1. DFIG wind farm.

transformer connects at high voltage (HV) the wind farm to grid.

The dynamic response of a DFIG wind farm can be represented by a complete model, in which all the wind turbines and the internal electrical network are modelled.

2.1. DFIG wind turbine

DFIG wind turbine includes a wound rotor induction generator connected to the wind turbine rotor through a gearbox. This generator presents the stator winding directly grid-coupled and a bidirectional power converter feeding the rotor winding, made up two back-to-back IGBT bridges based voltage source converters linked by a DC bus. This power converter decouples the electrical grid frequency and the mechanical rotor frequency, thus enabling variable speed wind turbine generation. The wind turbine rotor presents blade pitch angle control limiting the power and the rotational speed for high winds. Fig. 2 shows DFIG wind turbine configuration [3].

The DFIG wind turbine has been represented by the modelling of the rotor, drive train, induction generator, power converter and protection system.

The rotor model expresses the mechanical power extracted from the wind by the rotor, given as [14]

$$P_{\mathrm{w}} = \tfrac{1}{2}\rho A u^3 C_{\mathrm{p}}(\lambda, \theta) \tag{1}$$

where P_{w} (W) is the aerodynamic power, ρ (kg/m^3) the air density, A (m^2) the rotor disk area, R (m) the rotor radius, u (m/s) the wind speed, and C_{p} the power coefficient which is a function of the tip speed ratio λ (ratio between blade tip speed and wind speed) and θ the pitch angle of rotor blades.

The power extracted from the wind is maximized if the rotor speed is such that C_{p} is maximum, which occurs for a determined tip speed ratio. DFIG wind turbine operates controlling the rotor speed in order to maximize the output power in a wide range of wind speeds [3,9], according to the following optimal characteristic:

$$P_{\mathrm{opt}} = K_{\mathrm{opt}}\omega_{\mathrm{r}}^2, \tag{2}$$

where P_{opt} is the power which optimizes the efficiency of wind energy extracted from the wind and ω_{r} is the wind turbine rotor speed.

For above nominal winds, DFIG wind turbine uses blade pitch angle control to limit the energy extracted from the wind.

The drive train of DFIG wind turbine has been represented in this paper by the two masses model [15]:

$$T_{\mathrm{wt}} - T_{\mathrm{m}} = 2H_{\mathrm{r}}\frac{\mathrm{d}\omega_{\mathrm{r}}}{\mathrm{d}t}, \tag{3}$$

$$T_{\mathrm{m}} = D_{\mathrm{m}}(\omega_{\mathrm{r}} - \omega_{\mathrm{g}}) + K_{\mathrm{m}}\int(\omega_{\mathrm{r}} - \omega_{\mathrm{g}})\,\mathrm{d}t, \tag{4}$$

$$T_{\mathrm{m}} - T_{\mathrm{g}} = 2H_{\mathrm{g}}\frac{\mathrm{d}\omega_{\mathrm{g}}}{\mathrm{d}t}, \tag{5}$$

where T_{wt} is the mechanical torque from the wind turbine rotor shaft, T_{m} is the mechanical torque from the generator shaft, T_{g} is the generator electrical torque, H_{r} is the rotor inertia, H_{g} is the generator inertia, K_{m} and D_{m} are the stiffness and damping of mechanical coupling.

In this paper, the wound rotor induction generator has been represented by the third-order model, as usual for stability transient studies of power systems [16]. This model is obtained by neglecting the stator transients for the fifth order model of induction generator. It presents three differential equations [7,16]: two are electrical equations and the third equation is mechanical, given by Eq. (5). 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, which enables the decoupled control of active and reactive powers of DFIG [17]. The electrical differential equations are presented next, express per unit and using generator convention, which means that the currents are positive when flowing towards the grid and active and reactive powers are positive when fed into the grid.

$$\frac{\mathrm{d}e'_{\mathrm{d}}}{\mathrm{d}t} = -\frac{1}{T'_{\mathrm{o}}}(e'_{\mathrm{d}} - (X_{\mathrm{s}} - X'_{\mathrm{s}})i_{\mathrm{qs}}) + s\omega_{\mathrm{s}}e'_{\mathrm{q}} - \omega_{\mathrm{s}}\frac{L_{\mathrm{m}}}{L_{\sigma\mathrm{r}} + L_{\mathrm{m}}}u_{\mathrm{qr}}, \tag{6}$$

$$\frac{\mathrm{d}e'_{\mathrm{q}}}{\mathrm{d}t} = -\frac{1}{T'_{\mathrm{o}}}(e'_{\mathrm{q}} + (X_{\mathrm{s}} - X'_{\mathrm{s}})i_{\mathrm{ds}}) - s\omega_{\mathrm{s}}e'_{\mathrm{d}} + \omega_{\mathrm{s}}\frac{L_{\mathrm{m}}}{L_{\sigma\mathrm{r}} + L_{\mathrm{m}}}u_{\mathrm{dr}}. \tag{7}$$

$$T_{\mathrm{g}} = L_{\mathrm{m}}(i_{\mathrm{ds}}i_{\mathrm{qr}} - i_{\mathrm{qs}}i_{\mathrm{dr}}), \tag{8}$$

where u denotes voltage, i denotes current, indexes d and q, the direct and quadrature components, indexes s and r refers to stator and rotor, e'_{d} and e'_{q} are the internal voltage components of induction generator, ω_{s} is the synchronous

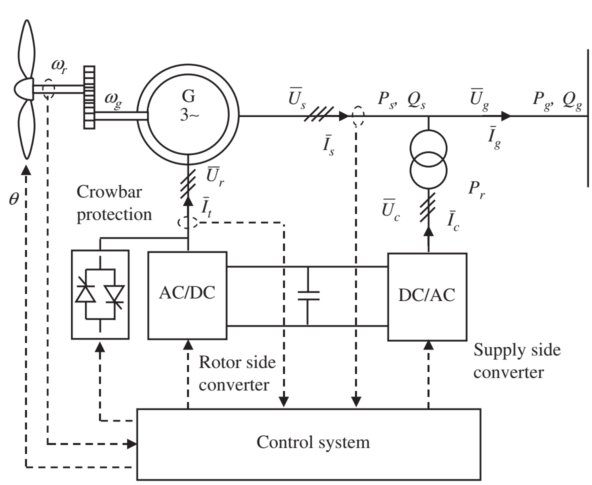

Fig. 2. DFIG wind turbine.

speed, s is the generator slip, T'_o is the transient open circuit time constant, X_s is the stator reactance and X'_s is the transient reactance, expressed as

$$T'_o = \frac{L_{\sigma r} + L_m}{R_r}, \quad X_s = \omega_s(L_{\sigma s} + L_m),$$
$$X'_s = X_s - \omega_s \frac{L_m^2}{L_{\sigma r} + L_m} \tag{9}$$

with R_s and R_r the stator and rotor resistances, $L_{\sigma s}$ and $L_{\sigma r}$ the stator and rotor leakages inductances and L_m the magnetizing inductance.

The power converter connected to rotor winding is composed of two converters linked by a DC bus [3,17]. A converter is connected to the rotor winding (rotor side converter) and another converter to grid (supply side converter). In this paper, it is assumed that these converters are considered ideals and the DC link voltage between the converters is constant, as usual for power system simulations [4–10]. This supposes the decoupling of the converters and only fundamental frequency components are taken into account.

The rotor side converter drives the wind turbine to obtain optimum power efficiency for below nominal winds, with active power limited to rated power for above nominal winds, and the desired reactive power. This converter enables the decoupled control of active and reactive powers by acting on rotor current components. Thus, the generation control of DFIG wind turbine can be performed by changing the rotor voltage components [3,9,17].

In this paper, the rotor side converter has been modelled by a current-controlled voltage source with the quadrature component of the rotor voltage u_{qr} controlling the rotor speed in order to optimize the active power and the direct component of the rotor voltage u_{dr} controlling the reactive power [3]. To determine the direct and quadrature components of the rotor voltage, the control system of the rotor side converter presents two controllers: the rotor speed and the reactive power controller.

The rotor speed controller (Fig. 3a) determines the quadrature component of the rotor voltage for the output power control [3]. This controller uses a power–speed curve like the one proposed in Ref. [18], which defines the reference output power according to the actual rotor speed, and thus the wind turbine can operate with variable speed maximizing the power extracted from the wind by tracking the maximum power coefficient for below nominal winds or with the output power limited to rated power for above nominal winds. Two control loops are used in this controller:

- An outer control loop regulates the active power, which defines the reference quadrature component of the rotor current.

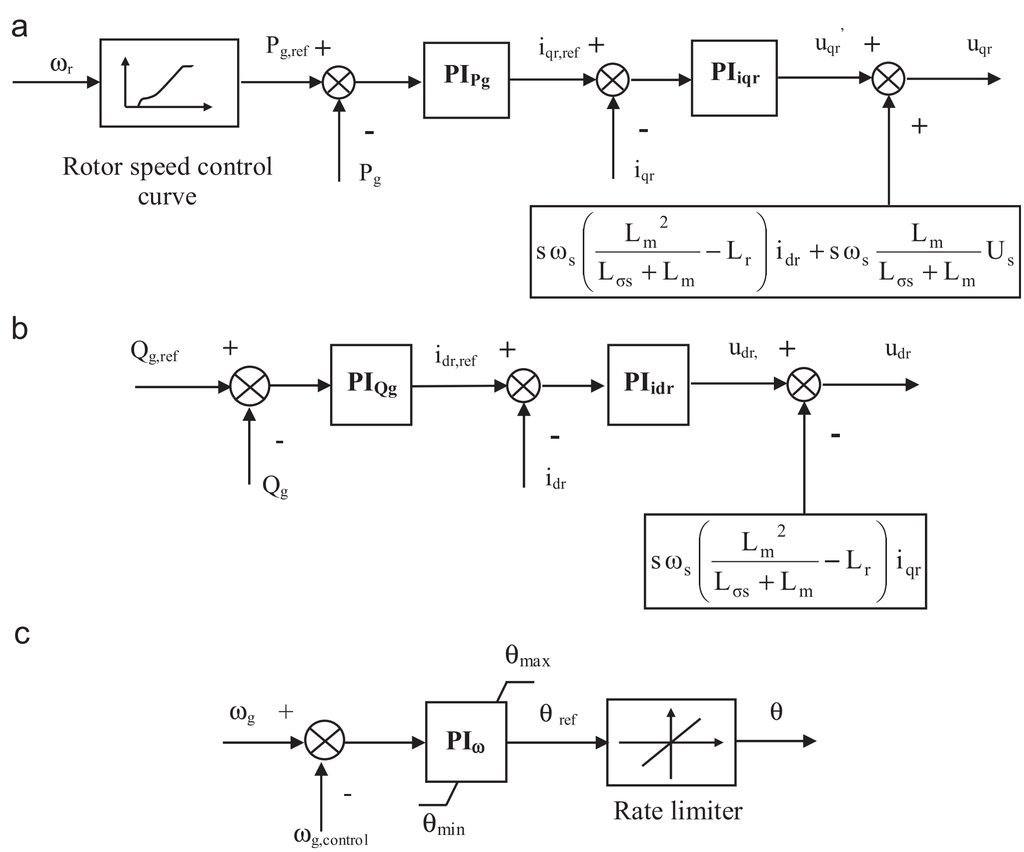

Fig. 3. Control system of DFIG wind turbine: (a) rotor speed controller, (b) blade pitch angle controller, and (c) reactive power controller.

- An inner control loop regulating the rotor current determines the quadrature component of the rotor voltage to be imposed to DFIG wind turbine.

The reactive power controller (Fig. 3b) determines the direct component of the rotor voltage which enables the wind turbine operation with the desired power factor [3]. This controller includes three control loops:

- An outer control loop regulating the reactive power which determines the reference direct component of the rotor current.
- An inner control loop regulating the rotor current defines the direct component of the rotor voltage.

The decoupled control of active and reactive power of DFIG wind turbine is achieved by using compensation terms for the components of the rotor voltage [17]. Thus, the voltage components applied to rotor side are determined from the described controllers and the compensation terms, expressed as

$$u_{dr} = u'_{dr} - s\omega_s\left(\frac{L_m^2}{L_{\sigma s} + L_m} - L_r\right)i_{qr}, \tag{10}$$

$$u_{qr} = u'_{qr} + s\omega_s\left(\frac{L_m^2}{L_{\sigma s} + L_m} - L_r\right)i_{dr} + s\omega_s\frac{L_m}{L_{\sigma s} + L_m}U_s, \tag{11}$$

where U_s is the magnitude of the wind turbine generation voltage.

DFIG wind turbine includes a blade pitch angle controller (Fig. 3c) 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 works with the output power limited to rated value for above nominal winds.

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 for 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 for above rated wind speed. The wind turbine operates with the power limited to its 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.

The supply side converter maintains the exchange power from the rotor circuit with the grid and operates with unity power factor [9]. Therefore DFIG wind turbine only delivers reactive power to grid by stator winding. This converter has been modelled by a controlled current source [9], where the direct and quadrature components of current source are calculated from the exchange power from the converter with the grid.

Considering the described generation system of DFIG wind turbine, the active power of DFIG can be divided between the stator and the rotor

$$P_s = u_{ds}i_{ds} + u_{qs}i_{qs}, \tag{12}$$

$$P_r = u_{dr}i_{dr} + u_{qr}i_{qr}. \tag{13}$$

The active and reactive powers of power converter delivered to grid are given by

$$P_c = P_r = u_{dc}i_{dc} + u_{qc}i_{qc}., \tag{14}$$

$$Q_c = 0. \tag{15}$$

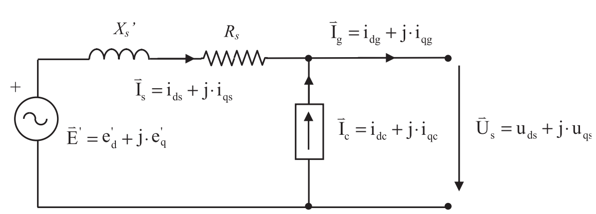

Fig. 4. Equivalent circuit of DFIG wind turbine.

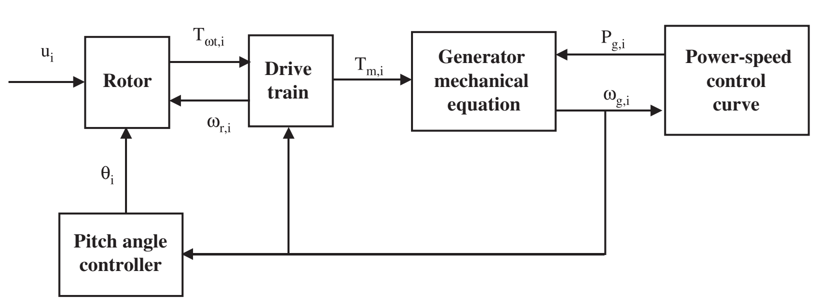

Fig. 5. Block diagram of the simplified model of each individual wind turbine (simplified wind turbine model) used in the equivalent wind turbine.

Therefore DFIG wind turbine delivers to grid the following active and reactive powers:

$$P_g = P_s + P_c, \quad (16)$$

$$Q_g = Q_s = u_{qs}i_{ds} - u_{ds}i_{qs}. \quad (17)$$

The generation system of DFIG wind turbine can be represented by the equivalent circuit shown in Fig. 4, which facilitates the incorporation of DFIG wind turbine model in power system simulations.

To limit the rotor voltage and current, and to protect the electronic devices used in the power converter, DFIG wind turbine presents a crowbar [9], which protects the rotor and power converter against over-current. The crowbar protection is an 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.

2.2. Internal electrical network

The internal electrical network of the wind farm has been modelled by the static model of electric lines and transformers, represented by constant impedance, as usual for power systems simulations [3–13].

3. Equivalent wind farm model

To represent the collective response of a DFIG wind farm for large power systems simulations with an important reduction of model order and computation time, an equivalent model of DFIG wind farms is proposed in this paper by aggregating all the wind turbines into an equivalent wind turbine operating at an equivalent internal electrical network.

3.1. Equivalent DFIG wind turbine

The usual way of reducing the wind farm model is based on aggregating identical wind turbines into an equivalent wind turbine operating at an equivalent network of the aggregated wind turbines, and thus achieving an equivalent model of the wind farm. The aggregation of wind turbines is mathematically exact when they receive the same wind and therefore generate the same output power. As a result of aggregating wind turbines, this equivalent wind turbine presents a rated power equal to the sum of rated power of aggregated wind turbines, and receives the same incoming wind of that one incident on the group of wind turbines. This implies that equivalent wind turbine presents the same model of the individual wind turbines, with the same equations, mechanical and electrical parameter per unit, and control parameters. The resulting equivalent wind farm presents so many equivalent wind turbines as wind turbines group with similar winds.

However, this equivalent wind turbine is not valid if wind turbines receiving different incoming winds are aggregated, since the operation conditions of each wind turbine are different. In this case, it must be regarded an equivalent wind turbine which considers the wind speed incident on each wind turbine.

In this paper, a new equivalent model of DFIG wind farms is proposed by aggregating all the wind turbines of a

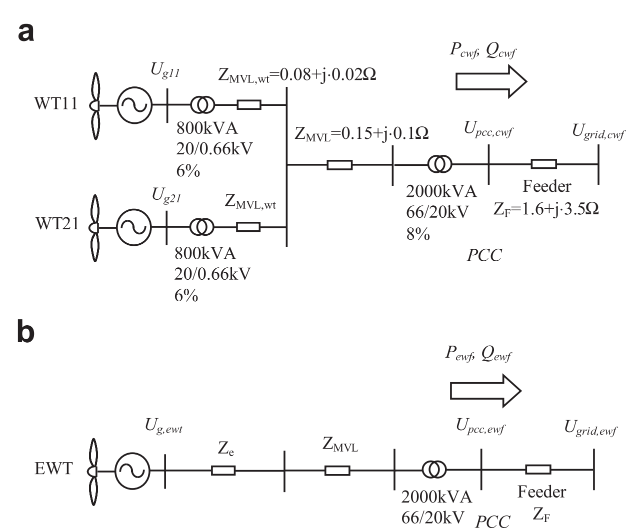

Fig. 7. Wind farms under consideration for steady-state simulations: (a) complete wind farm and (b) equivalent wind farm.

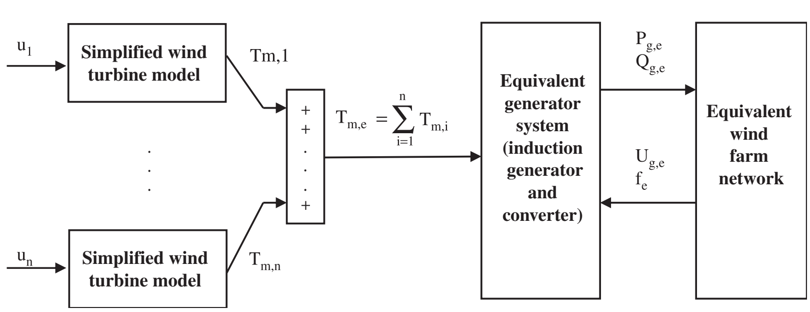

Fig. 6. Block diagram of the equivalent wind turbine model.

Table 1
DFIG wind turbine parameters

Parameter	Symbol	Value	Unit
Wind turbine			
Base power	S_B	660	kVA
Air density	ρ	1.12	kg/m^3
Rotor diameter	D	47	M
Gearbox ratio	$1{:}N$	1:52.5	p.u.
Rotor inertia	H_r	0.5	S
Shaft stiffness	K_m	0.35	p.u./rad
Shaft camping	D_m	5	p.u.
Generator			
Base power	S_B	660	kVA
Base voltage	U_B	660	V
Stator resistance	R_s	0.01	p.u.
Stator leakage reactance	$L_{\sigma s}$	0.04	p.u.
Rotor resistance	R_r	0.01	p.u.
Rotor leakage reactance	$L_{\sigma r}$	0.05	p.u.
Magnetizing reactance	L_m	2.9	p.u.
Generator inertia	H_g	2.5	S
Controllers			
PI_{Pg}	$K_{P,Pg}$	2.0	p.u.
	$K_{I,Pg}$	2.0	p.u./s
PI_{iqr}	$K_{P,iqr}$	0.5	p.u.
	$K_{I,iqr}$	0.5	p.u./s
PI_{Qg}	$K_{P,Qg}$	2.5	p.u.
	$K_{I,Qg}$	2.5	p.u./s
PI_{idr}	$K_{P,idr}$	0.2	p.u.
	$K_{I,idr}$	0.4	p.u./s
PI_{ω}	$K_{P,\omega}$	0.5	Deg
	$K_{I,\omega}$	0.2	deg/s

Table 2
Wind farm parameters

Internal network			
Base power	S_B	0.66	MVA
Base voltage	U_B	660	V
LV/MV transformers	LV/MV	20/0.66	kV
	S_T	800	kVA
	ε_{cc}	6	%
Wind turbine MV line impedance	$Z_{LMV,wt}$	$0.08+j\cdot 0.02$	p.u.
Wind turbine group MV line impedance	Z_{LMV}	$0.15+j\cdot 0.10$	p.u.
MV/HV transformer	MV/HV	66/20	kv
	S_T	5000	kVA
	ε_{cc}	8	%
External grid			
Base power	S_B	0.66	MVA
Short circuit power at PCC	S_{cc}	500	MVA
X/R ratio	X/R	20	p.u.

wind farm into one single equivalent wind turbine, and thus representing the whole wind farm at PCC to grid, even although the wind turbines operate receiving different incoming winds.

This equivalent wind turbine includes an aggregated model of the generation systems and a dynamic simplified model of each individual wind turbine approximating the operation points of each wind turbine according to the corresponding incoming wind speed. The equivalent wind turbine presents n-times the size of the individual wind turbines, 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 each individual wind turbine can operate with a different reactive power reference, the reactive power reference of equivalent wind turbine is equal to the sum of reactive power reference of the aggregated wind turbines.

A dynamic simplified model of each wind turbine is used to approximate the generator mechanical torque of each individual wind turbine according to the corresponding incoming wind speed. The simplified wind turbine model, depicted in Fig. 5, presents:

(i) The rotor model.
(ii) The drive train model.
(iii) The induction generator represented by the first order model, i.e., by the mechanical equation.
(iv) The rotor speed controller represented by the power–speed control curve.
(v) The blade pitch angle controller.

In this simplified wind turbine model, the combined model of the rotor and drive train determine the generator mechanical torque from the incoming wind, the generator speed and the blade pitch angle. The rotor speed controller uses the power-speed control curve to calculate the output power of the wind turbines from the generator speed. The generator speed is derived from the generator mechanical equation. The blade pitch angle controller computes the pitch angle that reduces the power extracted from the wind, when the generator speed goes up to the control speed.

The generator mechanical torques of the individual wind turbines, calculated from the procedure described above are aggregated and the resulting equivalent torque is applied to the equivalent generator system that is composed of an equivalent induction generator and power converter. This equivalent generator system has been represented by the same model of the individual wind turbines, given by the Eqs. (5)–(17) with the same mechanical and electrical parameters at per unit.

The control system of the equivalent wind turbine keeps the same rotor speed and reactive power controllers of the individual wind turbines and the same control parameters. The equivalent wind turbine does not include the blade pitch angle controller since the rotor model of equivalent wind turbine has been replaced by the simplified model of each wind turbine. The block diagram of the proposed equivalent wind turbine model is depicted in Fig. 6.

3.2. Equivalent internal electrical network

The equivalent wind turbine operates at an equivalent internal electrical network. If the two wind turbines for the

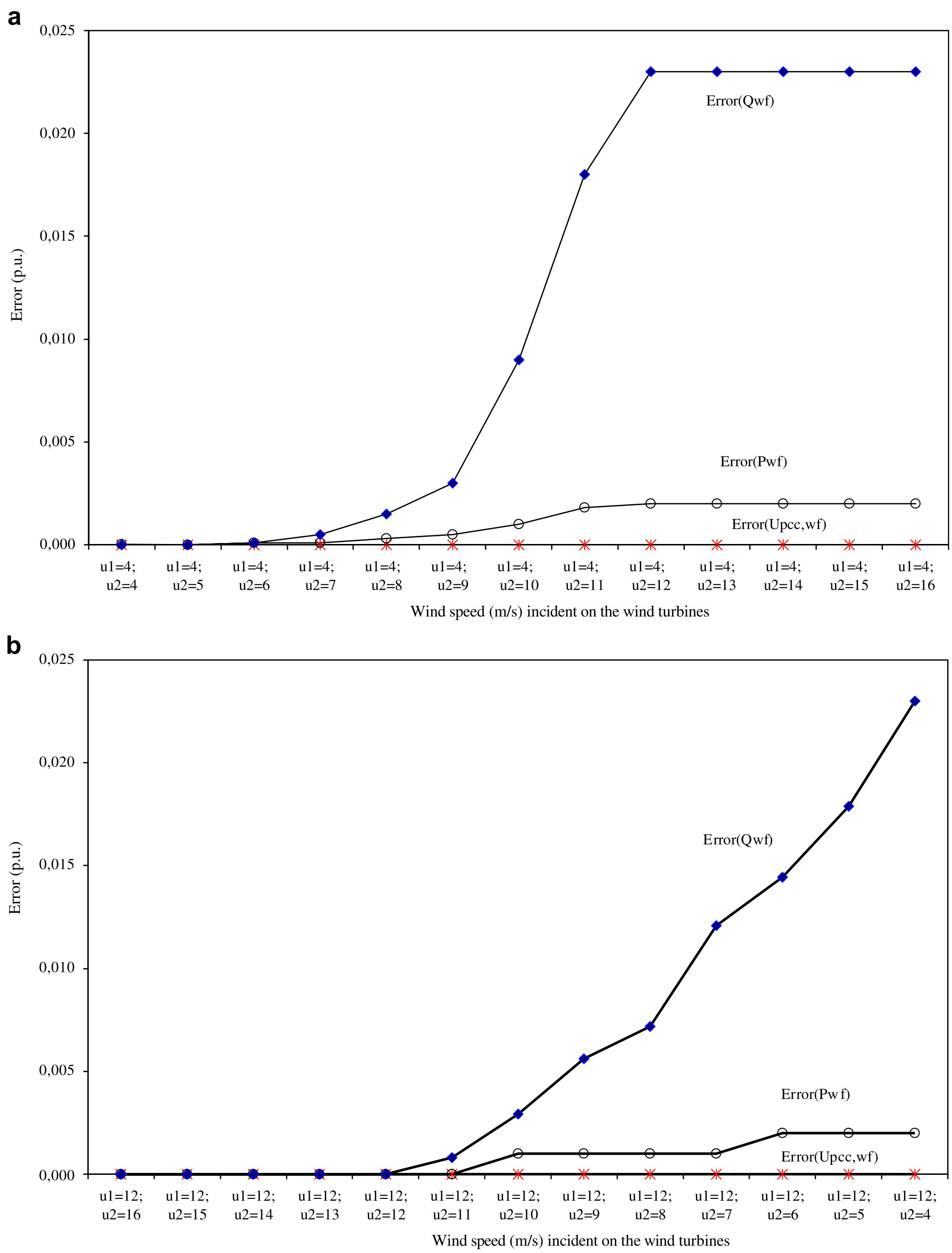

Fig. 8. Comparison of the steady-state response of the complete and equivalent wind farms.

complete wind farm depicted in Fig. 7a are aggregated into an equivalent wind turbine, the equivalent wind farm presents a configuration such as shown in Fig. 7b, where the common network of the aggregated wind turbines has been replaced by equivalent impedance.

This equivalent impedance has been calculated regarding that the short-circuit impedance of the equivalent wind farm must be equal to the short-circuit impedance of the complete wind farm. Hence, the impedance Z_e that appears in the equivalent wind farm shown in Fig. 7b can be calculated as

$$Z_e = Z_{awt} - \frac{Z_{wt}}{n}, \tag{18}$$

where Z_{awt} is the equivalent impedance for the common network of the aggregated wind turbines in the complete wind farm, Z_{wt} is the wind turbine impedance and n is the number of aggregated wind turbines.

4. Simulation results

The equivalent model of DFIG wind farm proposed in this paper has been verified by comparing the steady-state and dynamic responses of equivalent and complete wind farm models. These wind farm models have been implemented and simulated by using MATLAB/Simulink [19].

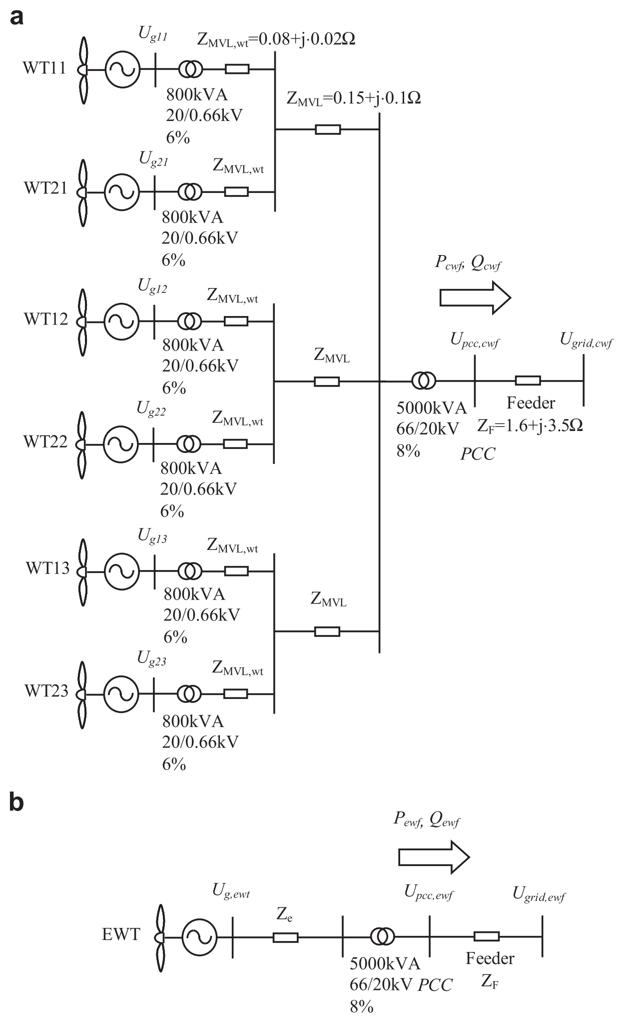

Fig. 9. Wind farm under consideration for dynamic simulations: (a) complete wind farm and (b) equivalent wind farm.

4.1. Steady-state simulations

Steady-state simulations using constant winds incident on the aggregated wind turbines have been run to evaluate the proposed equivalent model. These winds, although representing fictitious operation conditions for the wind turbines, are used to demonstrate the effectiveness of the proposed equivalent model when they approximate the steady-state response of aggregated wind turbines receiving any incoming winds.

The wind farm under consideration is composed of two DFIG wind turbines of 660 kW, 660 V each. Each wind turbine is connected to the internal electrical network through a transformer 20/0.66 kV and a MV line at 20 kV. A common MV line connects the group of wind turbines to the wind farm substation. The wind farm substation presents a transformer 66/20 kV coupling at 66 kV the wind farm to grid, as shown in Fig. 7a. DFIG wind turbine and wind farm parameters used in this work are presented in Tables 1 and 2, respectively. Fig. 7b shows the equivalent wind farm with one single equivalent wind turbine.

The equivalent wind farm model proposed in this work has been evaluated assuming different constant winds incident on the wind turbines and unity power factor for all the wind turbines (reactive power reference equals to zero).

The simulation results of the steady-state responses of complete and equivalent wind farms under different constant winds incident on the wind turbines are presented in Fig. 8. This figure shows the per unit differences between the responses of the complete and equivalent wind farms for variables such as the active and reactive powers, and the voltage at PCC of the wind farm to grid.

Fig. 8a shows the results assuming the wind turbine 1 operates with constant cut-in wind speed of 4 m/s and the wind turbine 2 operates with different wind speed from cut-in wind speed of 4 m/s to above nominal wind speed of 16 m/s (nominal wind speed of 12 m/s). Fig. 8b presents the results assuming the wind turbine 1 receives the nominal wind speed of 12 m/s and the incident wind on the wind turbine 2 varies from 16 to 4 m/s.

The results, depicted in Fig. 8, demonstrates that the aggregation of the generator mechanical torques of the individual wind turbines obtained from the simplified model and the use of an equivalent generation system allows a suitable approximation of the response of the aggregated wind turbines, even although the wind turbines operate receiving different winds. Therefore, the proposed equivalent model is valid for aggregating wind turbines experiencing any wind speed. These conclusions can be observed for the dynamic simulations performed next.

4.2. Dynamic simulations

The equivalent wind farm model has also been evaluated for dynamic simulations. In this case, two operation conditions have been considered: (1) normal operation (wind fluctuations in the wind farm); (2) grid disturbances (two voltage sags at wind farm PCC to grid).

The wind farm under consideration, shown in Fig. 9a, is composed of six DFIG wind turbines, organized into a network of three sections with two wind turbines for each section, according to the parameters included in Tables 1 and 2. A pair of indexes identify the wind turbines within the wind farm, where the second index denotes the number of the group and the first index is the number of the wind turbine within the group.

The equivalent wind farm presents one single equivalent wind turbine and the equivalent internal network depicted in Fig. 9b.

4.2.1. Case 1: normal operation

During normal operation, the wind farm operates under wind speed fluctuations. In this case, the wind farm has been simulated with different incoming winds between the groups of wind turbines, but similar winds for the wind turbines belonging to the same group, as shown in Fig. 10a. The group 1 and 2 of wind turbines operate with unity power factor during all the simulation, while the group 3 operates with unity power factor during half of simulation. For the rest of simulation, the group 3, which corresponds to the wind turbines with less generated power, generates the needs of reactive power to achieve the unity power factor at PCC.

The simulation of complete wind farm provides the operation conditions for the individual wind turbines depicted in Fig. 10b. In this figure, it has been represented the active and reactive powers of each wind turbine. It can be observed that the difference of the active power generation between the wind turbines due to the considered incoming winds, besides the increasing of the reactive power of the wind turbines group 3 (change of reference reactive power as a ramp of slope 0.1) in order to compensate the wind farm reactive power during the half of simulation.

Again, the evaluation of proposed equivalent wind farm model has been performed by comparing the responses of complete and equivalent wind farm. Hence, the variables used for the comparison are the wind farm active and reactive power (shown in Fig. 10c) and the generation voltage of each wind turbine and the voltage at wind farm PCC to grid (depicted in Fig. 10d).

The simulation results show a high correspondence between the response of complete and equivalent wind farms, with minimum discrepancies at the electrical variables (active and reactive powers and voltage) of the wind farm at PCC to grid. In addition, Fig. 10d can be observed that the equivalent wind turbine operates with a generation voltage that is intermediate to the generation voltage of the individual wind turbines.

4.2.2. *Case 2: grid disturbances*

The equivalent wind farm model has also been evaluated during grid disturbances. A voltage sag, or voltage dip, is a reduction (between 10% and 90%) of the voltage at a point in the electrical system with a duration of between one cycle and a few seconds [20]. Voltage sags are caused by motor starting, short circuits and fast reclosing of circuit breakers, and are one of the most common faults in power systems [21]. Therefore, a voltage sag at wind farm PCC caused by a remote fault is the grid disturbance used in order to evaluate the proposed model. Two voltage sags have been considered: (1) a voltage sag of 60% (implying that only 40% of the grid voltage remains) lasting for 100 ms; (2) a voltage sag of 20% (80% of grid voltage remains) lasting for 500 ms.

For both voltage sags, all the wind turbines have been simulated operating with unity power factor, and since the grid disturbances are much faster than wind speed

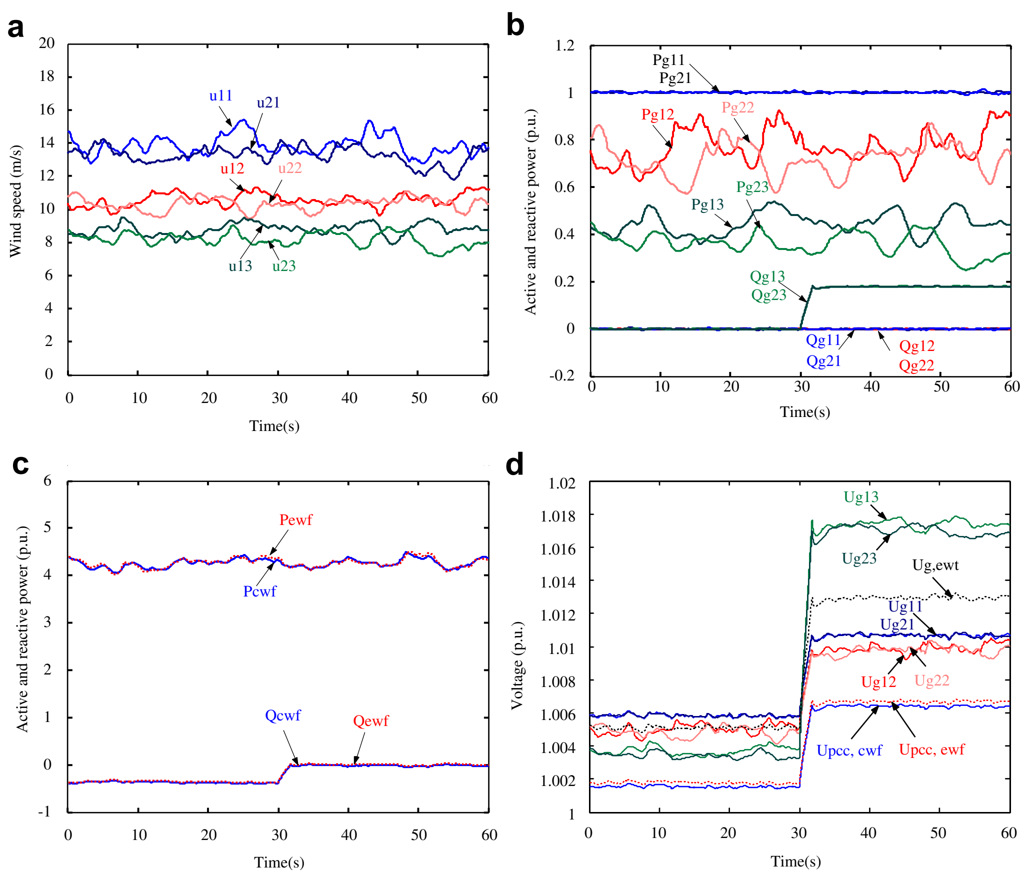

Fig. 10. Dynamic simulation results of complete and equivalent wind farm during normal operation (solid line corresponds to complete wind farm, and dotted line to equivalent wind farm): (a) wind speeds incident on the wind turbines, (b) active and reactive power of each individual wind turbine, (c) wind farm active and reactive powers at PCC, and (d) voltage at wind turbines generation nodes and PCC.

variations, the winds incident on the wind turbines have been assumed constant.

The simulation results of complete and equivalent wind farm during the grid disturbance are presented in Fig. 11. Figs. 11a and b show the simulation results for the collective response of the complete and equivalent wind farm during the voltage sag of 60%, 100 ms. For the voltage sag of 20%, 500 ms, the results are depicted in Fig. 11c and d.

Again, the results demonstrate the effectiveness of the equivalent wind farm model to approximate the collective response of the complete wind farm, even during grid disturbances.

Regarding the simulation time, a reduction of 92% is obtained by using the equivalent wind farm model instead of the complete wind farm model both for normal operation as well as for a grid disturbance.

Therefore, it can be concluded that the equivalent model proposed in this paper enables an accurate approximation of the collective response of the complete wind farm for power systems simulations, with an important reduction model order and the computation time.

5. Conclusions

In this paper, a new equivalent model of DFIG wind farms is proposed by aggregating all the wind turbines of a wind farm into one single equivalent wind turbine in order to represent the whole wind farm at PCC to grid, even though the wind turbines operate receiving different incoming winds.

The equivalent model is based on using a dynamic simplified model of each individual wind turbine to approximate the operation conditions of each one according to the corresponding incoming wind. Thus, this simplified model determines the generator mechanical torque of each individual wind turbine. The generator mechanical torques of the individual wind turbines are aggregated and the resulting torque is applied to an equivalent generator system. This makes the aggregation of wind turbines possible even under very different wind speed incident on the wind turbines.

The equivalent generator mechanical torque is applied to an equivalent generator system with a re-scaled power capacity generator and power converter, which presents the same per unit model of the individual wind turbines. The equivalent generator system has been modelled by the third-order model of induction generator and an equivalent converter, which facilities its incorporation in simulation software for dynamic power systems simulations.

The effectiveness of the equivalent model to represent the collective response of the wind farm response at PCC for power system simulations has been demonstrated through the performed simulations with an important reduction of model order and computation time.

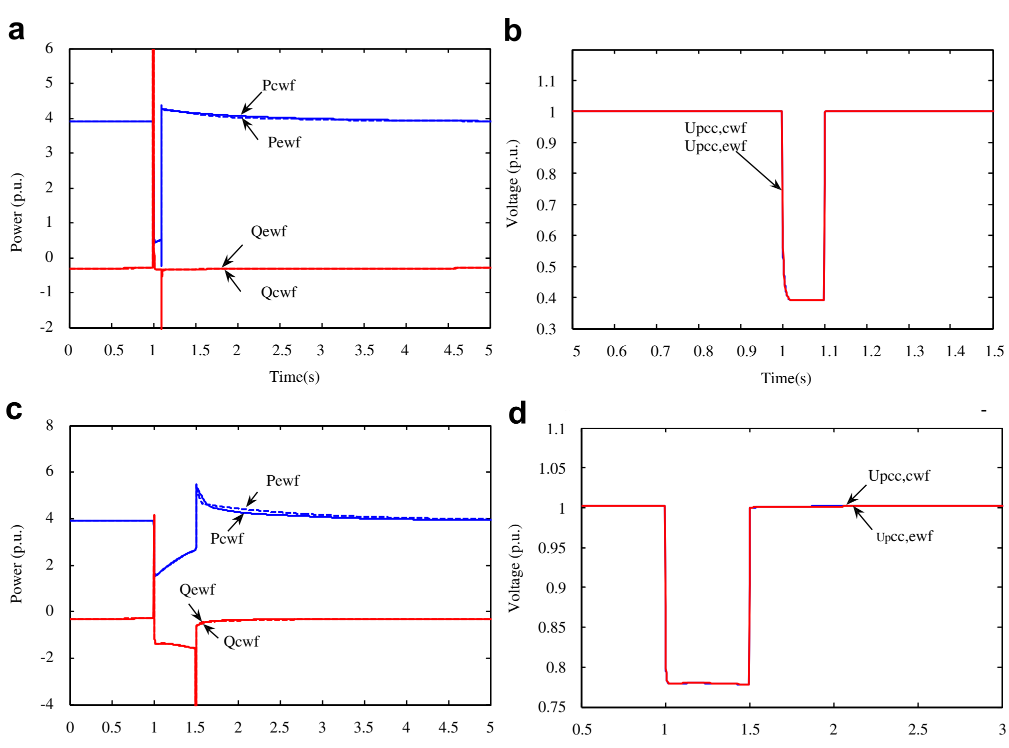

Fig. 11. Dynamic simulation results of complete and equivalent wind farm during grid disturbances (solid line corresponds to complete wind farm, and dotted line to equivalent wind farm): (a) wind farm active and reactive power at PCC for voltage sag of 60%, 100 ms; (b) voltage at PCC for voltage sag of 60%, 100 ms; (c) wind farm active and reactive power at PCC for voltage sag of 20%, 500 ms; and (d) voltage at PCC for voltage sag of 20%, 500 ms.

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