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Dynamic Modeling of Wind Farms with Fixed-Speed Wind Turbine Generators

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***Abstract*--A wind farm typically consists of a large number of individual wind turbine generators (WTGs) connected by an internal electrical network. To study the impact of wind farms on the dynamics of the power system, an important issue is to develop appropriate wind farm models to represent the dynamics of many individual WTGs. This paper presents various dynamic models, including a detailed model and three reduced-order equivalent models, of wind farms with fixed-speed WTGs. These models are developed and compared by simulation studies in the PSCAD/EMTDC environment under different wind velocity and fluctuation conditions as well as gird fault conditions. Concluding remarks are provided on how to choose an appropriate wind farm model for power system dynamic and transient studies.**

Index Terms--**Detailed model, equivalent model, fixed-speed wind turbine, squirrel-cage induction generator, wind farm**

I. Introduction

The worldwide concern about environmental pollution and the possible energy shortage has led to increasing interest in generation of renewable electrical energy. Wind energy generation is one way of electrical generation from renewable sources that uses wind turbine generators (WTGs) to convert the energy contained in flowing wind into electrical energy. Wind power has become the fastest growing energy source in the world and the leading source among various renewable energy sources in the power industry.

Because of the technology constraints, the size of individual WTGs is still limited to several megawatts. Therefore, a large wind farm typically consists of hundreds of individual WTGs running simultaneously. With the rapid increase in penetration of wind power in power systems, the dynamic influence of a large wind farm on power systems is becoming an important issue for integration and operation of wind farms. To study the influence of large wind farms on the dynamics of the associated power system, it is necessary to develop appropriate wind farm models to represent the dynamics and control of many individual WTGs.

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One of the WTG concepts, as shown in Fig. 1, is the fixed-speed wind turbine (FSWT) driving a directly grid-coupled squirrel-cage induction generator (SCIG). A gearbox is used to connect the low-speed wind turbine rotor shaft and the high-speed induction generator rotor shaft. The SCIG in this WTG concept can only operate within a narrow range of the rotational speed slightly above the synchronous speed. Because of these very small rotational speed variations, this type of WTG is considered to operate at fixed speed. The SCIG consumes reactive power and therefore is normally equipped with compensating capacitors for reactive compensation and improving the power factor.

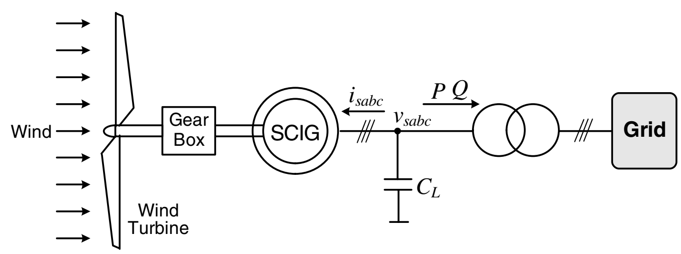

Fig. 1. Configuration of the fixed-speed wind turbine generator

The wind farms equipped with FSWTs are composed of a large number of wind turbines with directly grid connected SCIGs, compensating capacitors, and an internal electrical network (power lines or cables, transformers) that connects the wind farm to the gird. Different models have been developed to represent the dynamic behavior of wind farms with fixed-speed WTGs.

The dynamic behavior of wind farms is usually represented by a detailed model, in which the dynamics of each individual WTG and the internal electrical network are fully represented [1], [2]. Because a large wind farm normally consists of a large number of WTGs, this detailed model presents a high order model and requires excessive simulation time. The detailed model is therefore not suitable for studying the impact of the entire wind farm on the dynamic behavior of a large-scale power system.

To reduce the simulation time, the complexity of the wind farm model can be reduced by equivalent models. In [3]-[7], all the WTGs in the wind farm were aggregated into a single equivalent WTG operating on an equivalent internal electrical network, provided that the incoming wind velocity is identical or similar on all the wind turbines. If the incoming wind

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velocities vary across in the wind farm, reference [3] proposed to use an equivalent wind velocity to drive a single equivalent wind turbine aerodynamic model for aggregating all the wind turbines. This equivalent wind velocity is the average wind velocity across the wind farm. However, because of the cubic relationship between the wind velocity and the mechanical power that the wind turbine extracts from the wind, the wind velocity itself can not simply be added for wind turbine aggregation. A more reasonable approach is to aggregate the mechanical powers of all the wind turbines, while the mechanical power of each individual wind turbine is calculated using different incoming wind velocity values. This aggregated mechanical power is then applied to a single equivalent generator [5], [6]. Another idea is that the group of WTGs that experiences identical or similar wind velocity can be aggregated by an equivalent WTG, while the entire wind farm is represented by several equivalent WTGs receiving different winds [6]-[8].

This paper presents and compares various dynamic models of wind farms with stall-controlled fixed-speed WTGs. First, a detailed model is developed, in which the dynamics of each individual WTG is fully represented. Based on the individual WTG model and the wind velocity characteristics in the wind farm, three different equivalent models are developed to aggregate the WTGs in a wind farm in terms of the wind velocity conditions. These models are developed and compared by simulation studies in the PSCAD/EMTDC environment under different wind conditions as well as gird fault conditions. Some recommendations are provided for the choice of different wind farm models for power system dynamic and transient studies.

II. Dynamic Model of Individual WTG

As shown in Fig. 1, each individual WTG consists of a SCIG driven by a wind turbine through a mechanical shaft system and operates at a certain incoming wind velocity. A gearbox is used to connect the low-speed wind turbine shaft to the high-speed SCIG shaft. Compensating capacitors are added at the SCIG stator terminals to generate the magnetizing current for the SCIG. This section presents the mathematical model for each component of the WTG system, including the wind power (wind turbine aerodynamic) model, the mechanical shaft system model, the wind model and the SCIG model.

A. Wind Power Model

The aerodynamic model of a wind turbine can be characterized by the well-known C_P-λ-β curves [9]. C_P is the power coefficient, which is a function of both tip-speed-ratio λ and the blade pitch angle β. The tip-speed-ratio λ is defined by

$$\lambda = \frac{\omega_t R}{v_w} \tag{1}$$

where R is the blade length in m, ω_t is the wind turbine rotor speed in rad/s, and v_w is the wind velocity in m/s. The C_P-λ-β curves depend on the blade design and are provided by the wind turbine manufacturer.

Given the power coefficient C_P, the mechanical power that the wind turbine extracts from the wind is calculated by

$$P_m = \tfrac{1}{2}\rho A_r v_w^3 C_P(\lambda, \beta) \tag{2}$$

where ρ is the air density in kg/m^3, $A_r = \pi R^2$ in m^2 is the area swept by the rotor blades.

The wind turbine aerodynamic model and the wind power model are represented by a user-defined component in PSCAD/EMTDC.

B. Mechanical Shaft System Model

The shaft system of the WTG can be represented either by a two-mass system or by a single lumped-mass system [9], [10]. Since wind fluctuations cause considerable shaft oscillations and power fluctuations in fixed-speed WTGs, the two-mass shaft model should be used. In addition, in power system transient studies, since grid disturbances can cause significant shaft oscillations in WTGs, the WTG shaft system should also be represented by a two-mass model. In the two-mass model, separate masses are used to represent the low-speed turbine and the high-speed generator, and the connecting resilient shaft is modeled as a spring and a damper. The motion equations are then given by

$$2H_t p\omega_t = T_m - D_t\omega_t - D_{tg}(\omega_t - \omega_r) - T_{tg} \tag{3}$$

$$2H_g p\omega_r = T_{tg} + D_{tg}(\omega_t - \omega_r) - D_g\omega_r - T_e \tag{4}$$

$$pT_{tg} = K_{tg}(\omega_t - \omega_r) \tag{5}$$

where $p = d/dt$; ω_t and ω_r are the turbine and generator rotor speed, respectively; T_m and T_e are the mechanical torque applied to the turbine and the electrical torque of the generator, respectively; T_{tg} is an internal torque of the model; H_t and H_g are the inertia constants of the turbine and the generator, respectively; D_t and D_g are the damping coefficients of the turbine and the generator, respectively; D_{tg} is the damping coefficient of the flexible coupling (shaft) between the two masses; K_{tg} is the shaft stiffness.

The standard multi-mass component module in the PSCAD/EMTDC library is used to model the two-mass shaft system described by (3)-(5).

C. Wind Model

The wind model is a four-component model defined by [11]

$$v_w = v_{wM} + v_{wG} + v_{wR} + v_{wN} \tag{6}$$

where v_{wM} is the mean wind velocity in m/s, v_{wG} is the gust wind component in m/s, v_{wR} is the ramp wind component in m/s, and v_{wN} is the noise wind component in m/s. The last three terms in (6) represent the turbulent wind velocity components; among them v_{wG} and v_{wR} are deterministic turbulences while v_{wN} is the stochastic part to predict the occurrence of wind turbulence and the correlation of wind turbulence at different wind turbines in a wind farm. These four components provide reasonable flexibility for the study of one or a group of WTGs.

The mean wind velocity is a constant. This component is always assumed to be present in studies where the WTG is in service.

The gust wind velocity component is considered an essential component of wind velocity for dynamic studies and is described by

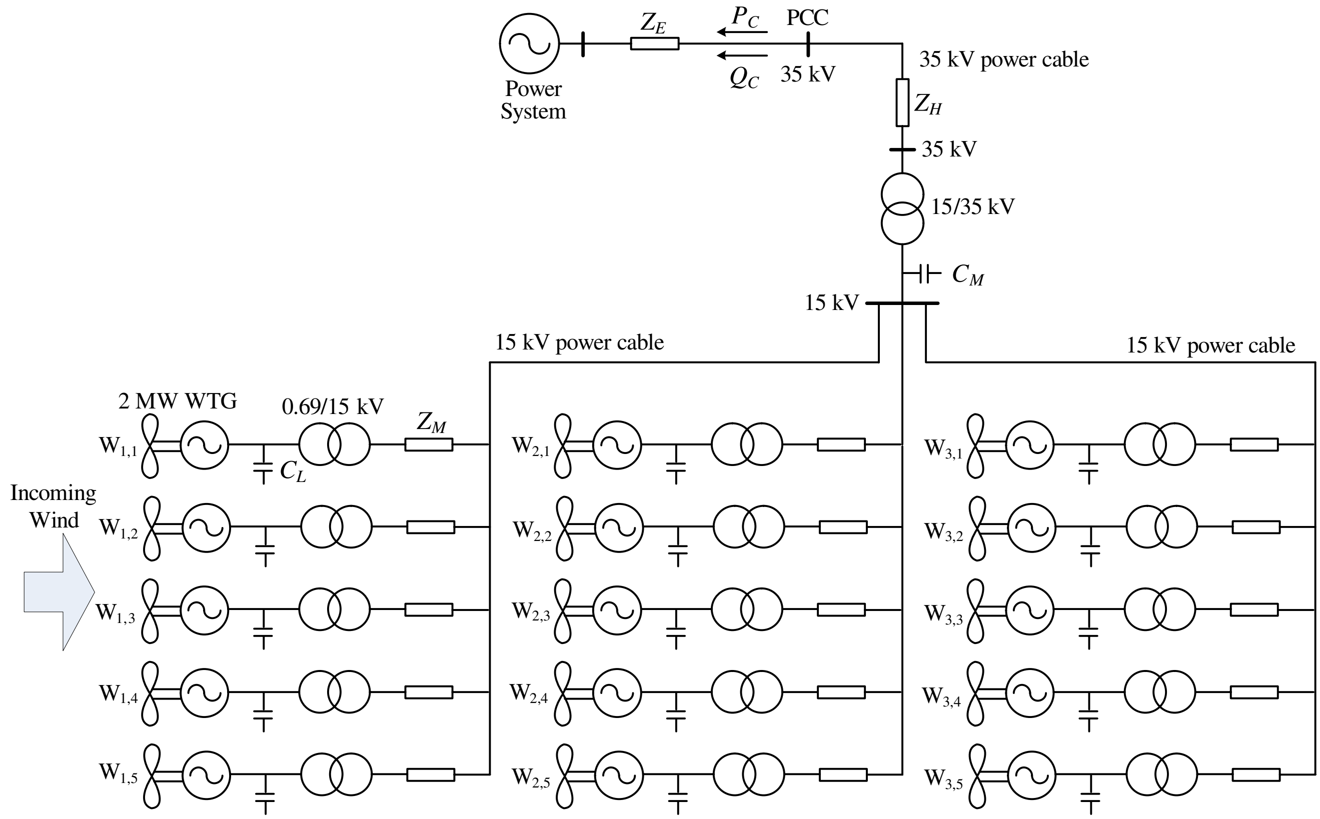


Fig. 2. Configuration of a wind farm with fixed-speed WTGs connected to a power network.

$$v_{wG} = \begin{cases} 0 & t < t_{1G} \\ \dfrac{V_{G\max}}{2}\left[1-\cos 2\pi\left(\dfrac{t-t_{1G}}{T_G}\right)\right] & t_{1G} < t < t_{1G}+T_G \\ 0 & t > t_{1G}+T_G \end{cases} \quad (7)$$

where V_{Gmax} is the gust peak in m/s, T_G is the gust period in s, and t_{1G} is the gust starting time in s.

The ramp wind velocity component is described by

$$v_{wR} = \begin{cases} 0 & t < t_{1R} \\ V_{R\max}\left(1-\dfrac{t-t_{2R}}{t_{1R}-t_{2R}}\right) & t_{1R} < t < t_{2R} \\ 0 & t > t_{2R} \end{cases} \quad (8)$$

where V_{Rmax} is the maximum ramp magnitude in m/s, t_{1R} is the ramp starting time in s, t_{2R} is the ramping stopping time in s and $t_{2R} > t_{1R}$. This component may be used to approximate a step change, by setting t_{2R} slightly larger than t_{1R}, or a slowly increasing wind velocity to study ramp tracking.

The last wind velocity component is the random noise component defined by

$$v_{wN} = 2\sum_{i=1}^{N}[S_V(\omega_i)\Delta\omega]^{1/2}\cos(\omega_i t+\varphi_i) \quad (9)$$

where N is the number of noise components, $\Delta\omega$ is the noise amplitude controlling parameter, $\omega_i = (i\text{-}0.5)\Delta\omega$, φ_i is a random variable with uniform probability density in the interval 0 to 2π and the function $S_V(\omega_i)$ is the spectral density function [11] defined by

$$S_V(\omega_i) = \frac{2K_N F^2 |\omega_i|}{\pi^2[1+(F\omega_i/\mu\pi)^2]^{4/3}} \quad (10)$$

where K_N is the surface drag coefficient, F is the turbulence scale, μ is the mean wind velocity in m/s at some reference height.

D. SCIG Model

The PSCAD/EMTDC software library provides the standard model of the SCIG, in which the double-squirrel-cage induction machine is represented by a standard seventh-order model in a dq reference frame [12].

III. Dynamic Models Of Wind Farm

Figure 2 shows the configuration of the wind farm used for this study. It consists of 15 fixed-speed WTGs of 2 MW power capacity each. The total installed power capacity of the wind farm is 30 MW. The wind farm is organized into an internal network consisting of three sections with five WTGs in each section. Each wind turbine is equipped with a no-load compensated SCIG, which is connected to the internal network through a 0.69/15 kV transformer. The HV terminals of all the transformers in each wind farm section are connected by a 15 kV sea/underground power cable. The entire wind farm is then connected to the power network at the point of common coupling (PCC) through a 15/35 kV transformer and a 15 km sea/underground power cable. The parameters of each WTG and the network components are given in the Appendix. Four different models of the wind farm are presented as follows in this section.

A. Detailed Model

In the detailed model, the dynamics of each individual WTG and the internal electrical network is fully represented, as shown in Fig. 2. The dynamic model of each individual WTG, including the wind power model, the mechanical shaft system model, the wind model and the SCIG model, has been presented in Section II.

B. Single WTG Equivalent Model

If the incoming wind velocities on all the wind turbines are identical or similar, then it can be assumed that the WTGs in the wind farm operate at the same operating point, namely, all the wind turbines and the SCIGs operate at the same rotational speed. Under this assumption, the entire wind farm can be simply represented by a single WTG equivalent model operating on an equivalent internal network, as shown in Fig. 3. Then the MVA-rating of the equivalent WTG is the sum of the MVA-rating of all the individual WTGs

$$S = \sum_{i=1}^{3}\sum_{j=1}^{5} S_{ij} \tag{11}$$

where S_{ij} is the MVA-rating of WTG no. j in the section no. i. The mathematical model of this equivalent WTG is exactly the same as each individual WTG described in Section II. If the MVA-rating of the equivalent WTG is used as the base value, then the per-unit values of the equivalent WTG parameters and the internal network parameters, including the equivalent wind turbine parameters, equivalent shaft system parameters, equivalent SCIG parameters, equivalent 0.69/15 kV transformer parameters, equivalent compensating capacitor $C_{L,e}$, and equivalent 15 kV cable impedance $Z_{M,e}$, are exactly the same as those for each individual WTG in Fig. 2.

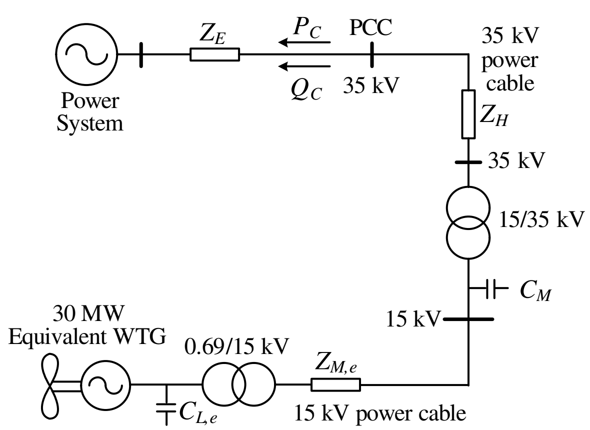


Fig. 3. Single WTG equivalent model of the wind farm.

C. Multiple Wind Turbines Driving Single SCIG Equivalent Model

If the incoming wind is incident on the wind farm with the direction shown in Fig. 2, then the wind turbines belonging to the same section usually experience similar winds. Because of shadowing between wind turbines and the turbulence within the wind farm, the wind turbines in different sections usually experience different incoming winds. Since the mechanical power that the wind turbine extracts from the wind is a cubic function of the wind velocity, the wind turbines that experience different winds generate different output powers and therefore cannot be aggregated into a single equivalent model. However, since the wind turbines in the same section experience similar winds, they can be aggregated by an equivalent wind turbine model with the power capacity of 10 MW.

On the other hand, the speed deviations between fixed-speed WTGs in a wind farm are small. Therefore, all the WTGs can be assumed operating at the same rotational speed. Under this assumption, the shaft systems and the SCIGs of all the WTGs can still be represented by a single equivalent shaft driving a single equivalent SCIG. The MVA-rating of the equivalent SCIG is calculated by (11).

Figure 4 shows the schematic diagram of the multiple wind turbines driving a single SCIG equivalent model. The input mechanical power of the single equivalent shaft and SCIG is calculated by

$$P_m = \sum_{i=1}^{3} P_{m,i} \tag{12}$$

where $P_{m,i}$ is the wind power extracted from the wind by each of the three equivalent wind turbines.

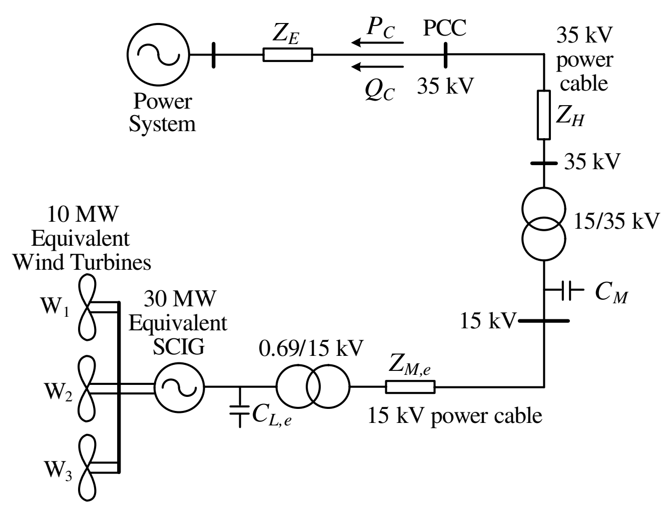


Fig. 4. Multiple wind turbines driving a single SCIG equivalent model of the wind farm.

D. Multiple WTGs Equivalent Model

With the same incoming wind conditions as in the previous Section C, if the effects of speed deviations between different WTGs cannot be neglected, then the entire wind farm can be represented by three equivalent WTGs as shown in Fig. 5. The MVA-rating of each equivalent WTG is the sum of the MVA-rating of all the individual WTG in one section, given by

$$S_i = \sum_{j=1}^{5} S_{i,j} \tag{13}$$

The mathematical model of each equivalent WTG is exactly the same as for each individual WTG described in Section II. Using the MVA-rating (13) as the base value, the parameters in per-unit value of each equivalent WTG are the same as those for each individual WTG.

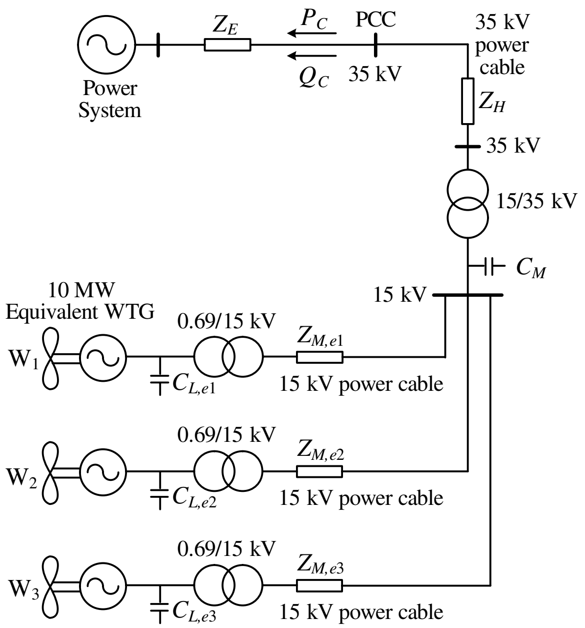


Fig. 5. Multiple WTGs equivalent model of the wind farm.

IV. Simulation Results

Simulation studies are carried out in this section to evaluate the dynamic responses of different equivalent wind farm models. These equivalent models are compared with the detailed wind farm model under different operating conditions: (1) wind fluctuations in the wind farm; (2) grid faults.

A. *Wind Fluctuations*

In the real wind farm, the wind velocity is always fluctuated. To compare the dynamic response of each equivalent model with the detailed model, three different wind fluctuation tests are applied to the wind farm: (1) identical wind velocity across the wind farm; (2) irregularly distributed wind in the wind farm with identical wind velocity across each wind turbine section; (3) irregularly distributed winds on all the wind turbines in the wind farm.

1) Identical Wind Velocity across the Wind Farm: In this test, all the wind turbines in the wind farm experience identical wind with the mean velocity of 11 m/s, as shown in Fig. 6(a). Under this condition, the single WTG equivalent model can be used. Figure 6(b)-(d) compares the active power, reactive power, and voltage magnitude at the PCC by using the single WTG equivalent model and the detailed model, respectively. These results clearly show that under identical wind velocity condition, the single WTG equivalent model provides the same accuracy as the detailed model. Therefore, the entire wind farm can be exactly represented by a simple single WTG equivalent.

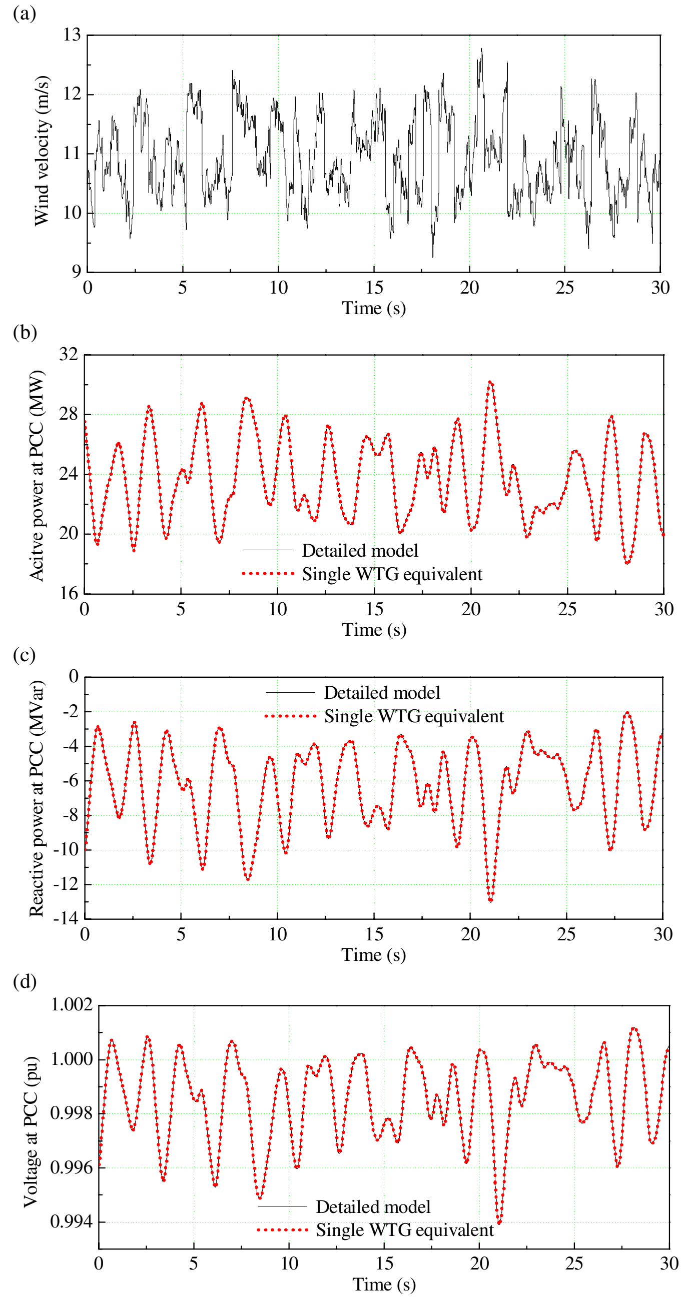


Fig. 6. Comparison of the detailed model and the single WTG equivalent model under wind fluctuations: identical wind velocity across the wind farm.

2) Irregularly Distributed Wind in the Wind Farm with Identical Wind Velocity across each Wind Turbine Section: If the incoming wind is incident on the wind farm with the direction shown in Fig. 2, then it is reasonable to assume that the wind turbines in the same section experience identical wind. However, because of shadowing between wind turbines and the turbulence within the wind farm, the wind velocities across different wind turbine sections are usually different. In the first test, the mean wind velocities across the wind turbine sections 1-3 are 12 m/s, 11 m/s and 10 m/s, respectively, as shown in Fig. 7(a). In this case, the wind variations between two adjacent wind turbine sections are small with the mean wind velocity difference of 2 m/s. Figure 7(b)-(d) compares the active power, reactive power, and voltage magnitude at the

PCC by using the detailed model, the multiple WTGs equivalent model, and the multiple wind turbines driving a single SCIG equivalent model. The multiple WTGs equivalent model provides the same accuracy as the detailed model since all the WTGs in the same section are running at the same operating point and therefore can be exactly represented by one equivalent WTG. Because of different wind velocities, the WTGs in different sections are running at different operating points with slightly different rotational speeds. As a result, compared to the multiple WTG equivalent model, the accuracy of the model that only uses a single SCIG equivalent degrades slightly but it is still accurate enough to represent the dynamics of the entire wind farm.

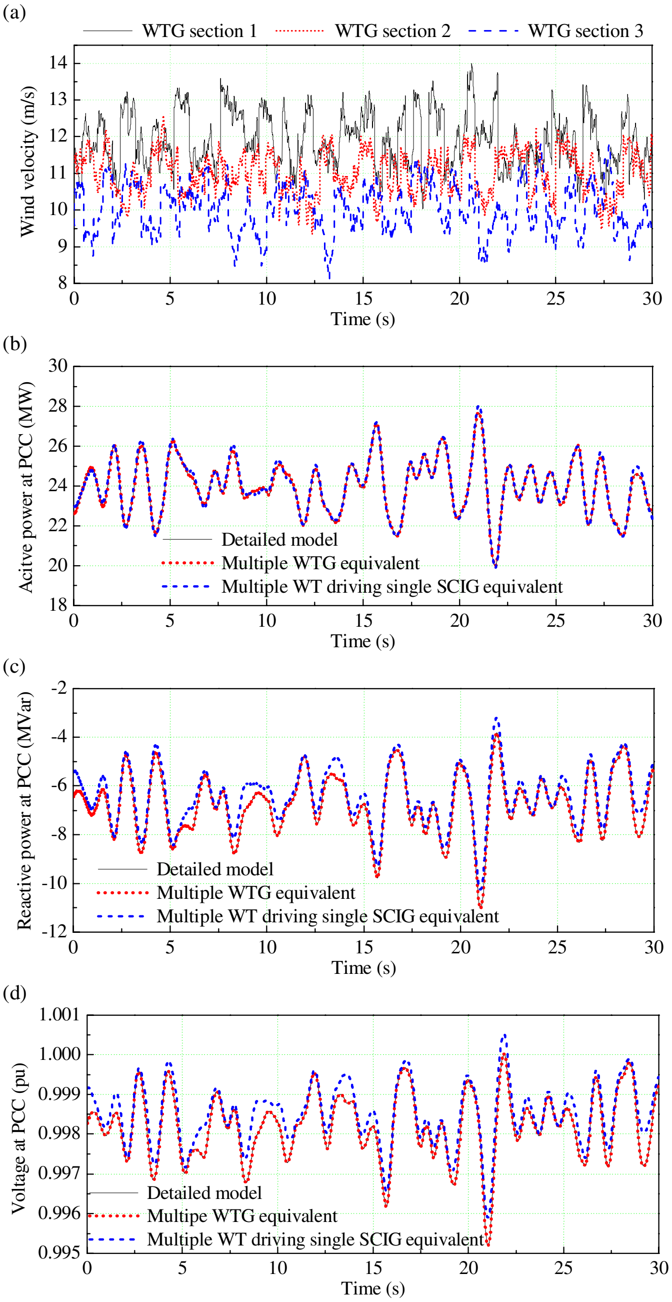
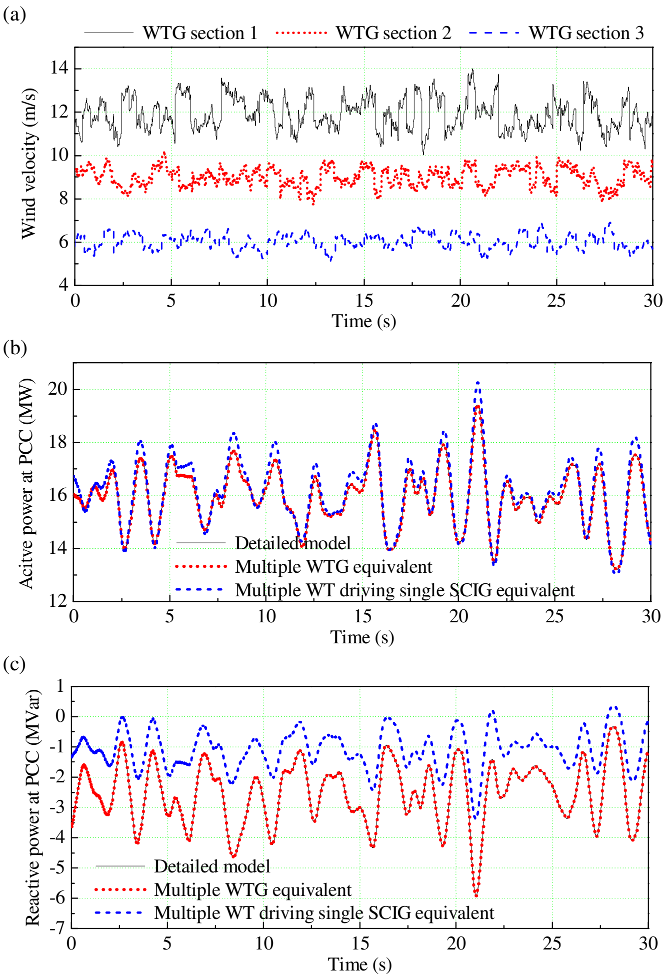


Fig. 7. Comparison of different models under wind fluctuations: identical wind velocity across each section but small wind variations between two adjacent sections.

In another test, the mean wind velocities across the wind turbine sections 1-3 are set at 12 m/s, 9 m/s and 6 m/s, respectively, as shown in Fig. 8(a). This represents the case that two adjacent wind turbine sections are experiencing large wind variations with the mean wind velocity difference of 3 m/s. The dynamic responses the active power, reactive power, and voltage magnitude at the PCC by using different models are compared in Fig. 8(b)-(d). Again, the multiple WTGs equivalent model provides good accuracy. Since only the wind turbines with the same or similar wind velocity are aggregated into the same wind turbine equivalent, the multiple wind turbines driving a single SCIG equivalent model provides good accuracy on the active power dynamics. However, due to the significant differences of the wind velocities, the WTGs in different sections are running at different rotational speeds and therefore have different terminal voltages. These voltage differences, however, are neglected in the single SCIG equivalent model. Since the reactive power of the SCIG depends on the active power and the voltage, the voltage deviations between the single equivalent SCIG and each individual SCIG result in the deviations of the reactive power at the PCC between the single SCIG equivalent model and the detailed model, which in turn results in the deviations of the PCC voltage between two models, as shown in Fig. 8 (c), (d).



(d)

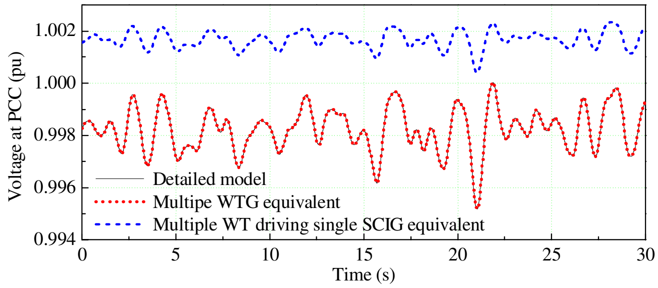


Fig. 8. Comparison of different models under wind fluctuations: identical wind velocity across each section but large wind variations between two adjacent sections.

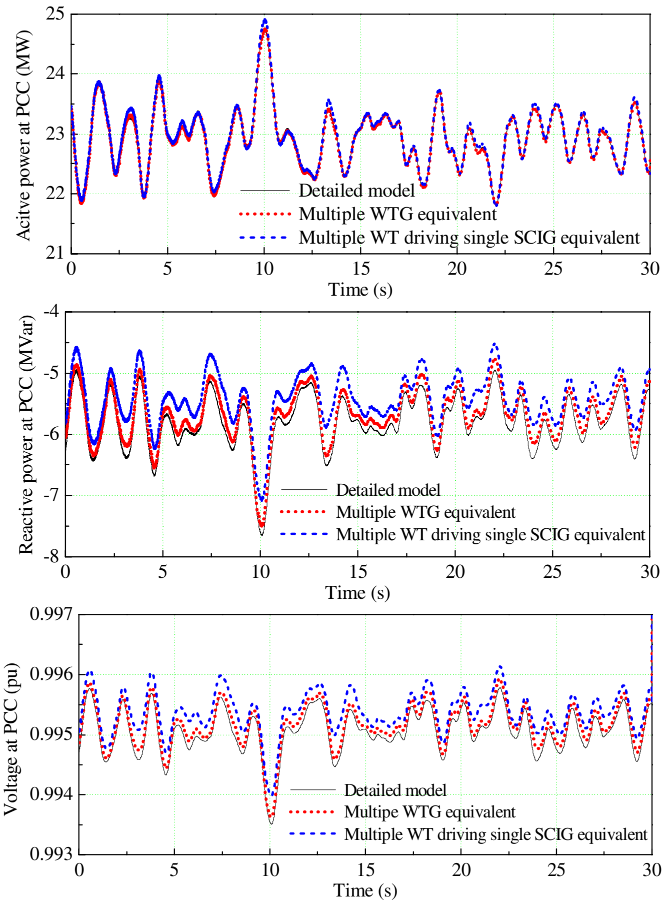


Fig. 9. Comparison of different models under wind fluctuations: irregularly distributed wind velocity on all the wind turbines in the wind farm.

3) Irregularly Distributed Wind on all the Wind Turbines in the Wind Farm: The is the most common case of the wind distribution in a wind farm. The wind velocities across the wind turbines in the same section are similar, but are reduced per section along the wind direction due to shadowing between wind turbines. In this test, the mean wind velocities across the first wind turbine in each of the three sections (i.e. $W_{1,1}$, $W_{2,2}$ and $W_{3,3}$ in Fig. 2) are 12 m/s, 11 m/s and 10 m/s, respectively, as shown in Fig. 7(a). The mean wind velocity across the rest four wind turbines in each section is reduced by 0.15 m/s per wind turbine. The average mean wind velocity across each section is used as the equivalent wind velocity for the corresponding equivalent wind turbine in both equivalent models, i.e., the multiple WTGs equivalent model and the multiple wind turbines driving a single SCIG equivalent model. Figure 9 compares the active power, the reactive power, and the voltage magnitude at the PCC by using different models. Both equivalent models provide good accuracy. As explained in the previous case of Fig. 8, both equivalent models provide higher accuracy of the active power dynamics than the reactive power and the voltage. Compared to the multiple WTGs equivalent model, the accuracy of the model that only uses a single SCIG equivalent degrades slightly.

B. Grid Faults

In order to evaluate the validity of different models for power system transient studies, a three-phase short circuit is applied at the PCC at t = 5 s and is clear in 150 ms. This test is applied at two different wind conditions.

1) Identical Wind Velocity across the Wind Farm: The wind condition in the wind farm is the same as in Fig. 6(a). Figure 10 compares the active power and the voltage magnitude at the PCC during the grid fault transient state by using the single WTG equivalent model and the detailed model, respectively. These results show that under identical wind velocity condition, the entire wind farm can be exactly represented by a simple single WTG equivalent model for transient studies.

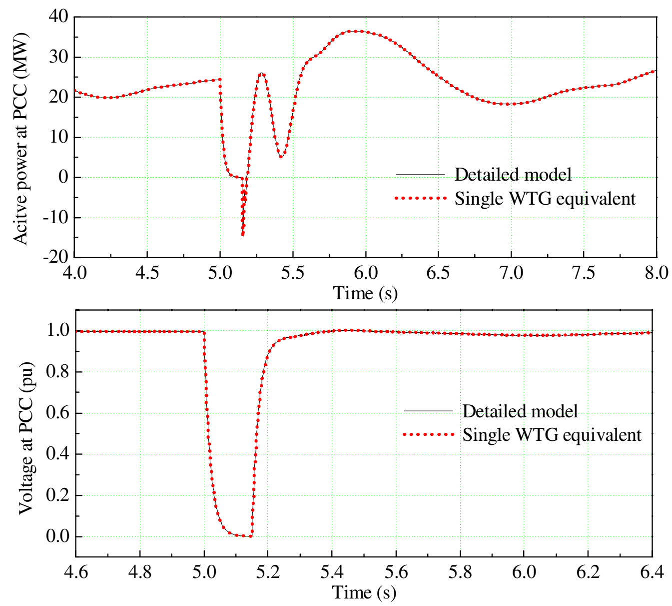


Fig. 10. Comparison of the detailed model and the single WTG equivalent model during grid faults: identical wind velocity across the wind farm.

2) Irregularly Distributed Wind on all the Wind Turbines in the Wind Farm: In this test, the wind distributions in the wind farm are the same as for the test in Fig. 9. Figure 11 compares the active power and the voltage magnitude at the PCC during the grid fault transient state by using the detailed model, the multiple WTGs equivalent model, and the multiple wind turbines driving a single SCIG equivalent model. These results show that under the most common wind condition, both equivalent models can be used for power system transient studies.

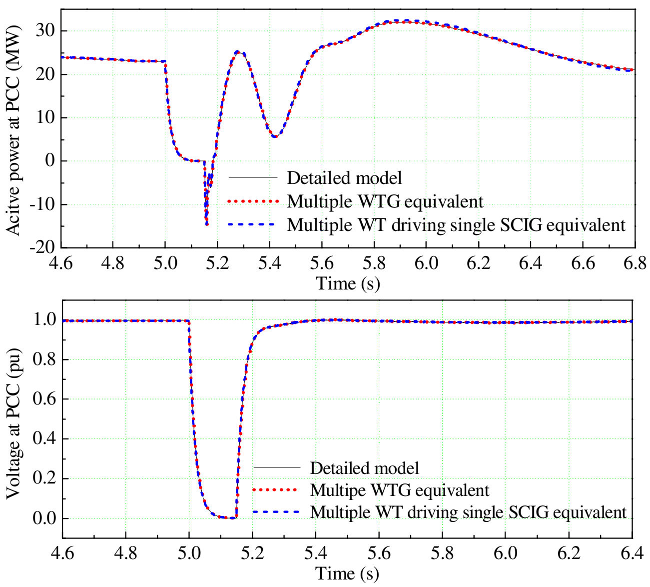


Fig. 11. Comparison of different models during grid faults: irregularly distributed wind velocity on all the wind turbines in the wind farm.

V. Conclusion

A grid-connected wind farm typically consists of a large number of individual wind turbine generators (WTGs) operating on an internal electrical network. To study the impact of large wind farms on the dynamic and transient behavior of the associated power system, an important issue is to develop appropriate wind farm models to represent the dynamics of many individual WTGs.

This paper presents various dynamic models of wind farms equipped with fixed-speed WTGs, including a detailed model, a single WTG equivalent model, a multiple WTGs equivalent model, and a multiple wind turbines driving a single SCIG equivalent model. These models are compared by simulation studies in the PSCAD/EMTDC environment under different wind velocity and fluctuation conditions as well as gird fault conditions. Results show that if the wind velocities across the entire wind farm are identical, the dynamics of the wind farm can be exactly represented by the simplest single WTG equivalent model. While if the wind distribution across the wind farm is irregular, both the multiple WTGs equivalent model and the multiple wind turbines driving a single SCIG equivalent model can be applied to represent the wind farm for power system dynamic and transient studies.

VI. Appendix

Wind turbine: rated capacity = 2 MW.

Mechanical shaft system (on 2 MW base): H_t = 4.3 s, H_g = 0.9 s, $D_t = D_g = 0$, D_{tg} = 1.5 pu, K_{tg} = 113 pu.

Squirrel-cage induction generator (on 2 MW, 690 V bases): rated power = 2 MW, rated stator voltage = 690 V, r_s = 0.048 pu, r_{r1} = 0.298 pu, r_{r2} = 0.018 pu, L_{ls} = 0.075 pu, L_{lr1} = 0.122 pu, L_{lr2} = 0.105 pu, L_m = 3.8 pu, base frequency f = 60 Hz.

0.69/15 kV transformer: MVA-rating = 2.7 MVA, leakage reactance = 0.03 pu, copper loss = 0.006 pu.

15/35 kV transformer: MVA-rating = 40 MVA, leakage reactance = 0.02 pu, copper loss = 0.005 pu.

Other parameters: compensating capacitor C_L = 2875 µF, C_M = 40 µF, $Z_M = 0.08 + j0.1\ \Omega$, $Z_H = 0.4 + j2\ \Omega$, $Z_E = 0.4 + j0.2\ \Omega$

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