Research Article

Equivalent Modeling of DFIG-Based Wind Power Plant Considering Crowbar Protection

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Crowbar conduction has an impact on the transient characteristics of a doubly fed induction generator (DFIG) in the short-circuit fault condition. But crowbar protection is seldom considered in the aggregation method for equivalent modeling of DFIG-based wind power plants (WPPs). In this paper, the relationship between the growth of postfault rotor current and the amplitude of the terminal voltage dip is studied by analyzing the rotor current characteristics of a DFIG during the fault process. Then, a terminal voltage dip criterion which can identify crowbar conduction is proposed. Considering the different grid connection structures for single DFIG and WPP, the criterion is revised and the crowbar conduction is judged depending on the revised criterion. Furthermore, an aggregation model of the WPP is established based on the division principle of crowbar conduction. Finally, the proposed equivalent WPP is simulated on a DlgSILENT PowerFactory platform and the results are compared with those of the traditional equivalent WPPs and the detailed WPP. The simulation results show the effectiveness of the method for equivalent modeling of DFIG-based WPP when crowbar protection is also taken into account.

1. Introduction

With the rapid development of wind power generation and power electronics, the doubly fed induction generator (DFIG) has recently become the most commonly used wind turbine in wind power plant (WPP) based on its characteristics of maximum power point tracking (MPPT) [1], decoupled control of active and reactive powers [2], the use of a power convertor with a rated power of 25% of total system power [3], and so forth. To investigate the effect of the ongoing changes in power systems due to the increasing penetration of wind power, a wide range of studies, from steady-state to transient, are necessary. A detailed WPP model, in which the dynamics of each wind turbine and the internal network are fully represented, is not suitable as it could significantly increase the order of the mathematical model of the power system to be solved and thus influence the overall simulation time. As a result, the equivalent WPP model is generally recommended for reflecting the collective response of the whole WPP on large power systems.

Equivalent WPPs using aggregated wind turbines are classified as either the single-machine representation or the multiple-machine representation [4]. In the first case, the actual WPP is modeled as a unique rescale wind turbine in the single-machine representation. Accordingly, this is rational when all wind turbines are operating in an identical condition, whereas that might not be the case in real-world system operation. Nowadays, in order to improve the conformity of the single-machine representation with the actual WPP, numerical identification methods for optimizing the parameters of equivalent models are applied. The optimized objects include the generator [5, 6], power convertor [7], and passive frequency-dependent network [8]. The fuzzy logic system is also utilized to compute the mechanical torque compensating factor, which is integrated into a single-machine aggregated WPP [9].

In the second case, study of the multiple-machine representation focuses on selecting reasonable clustering indices by quantifying and abstracting key features of wind turbines. The coherency method is presented in [10, 11] by

FIGURE 1: Schematic of DFIG generation system.

FIGURE 2: (a) PCC voltage of the DFIG model. (b) PCC output active power. (c) PCC output reactive power.

clustering wind turbines with similar wind speed. In [12], the wind direction is implemented. To represent the power loss on the collective network within the WPP, a method of calculating the equivalent impedance is introduced in [13].

Moreover, research work in [14] analyzes the impact of the line impedance on the diversity in the voltage profile of each wind turbine and describes a voltage-profile-based approach to develop multiple-machine aggregated WPP. In addition, a

FIGURE 3: Terminal voltage dip threshold of DFIG: (a) power factor = -0.95, (b) power factor = 1, and (c) power factor = 0.95.

FIGURE 4: Daisy-chain physical diagram of the WPP.

clustering index considering the influence of fault types on coherency is depicted in [15].

Compared with conventional power resources, wind resources are stochastic and fluctuating. Equivalent models of an actual WPP might change due to different operating conditions. Therefore, the actual application should be based on historical data for the specific WPP and establish a probabilistic equivalent WPP [13, 16, 17]. This makes the equivalent WPP very practical and easy to use.

On the basis of previous equivalent methods, the research hot-spot has gradually shifted to the validation and analysis of equivalent WPPs using field measurement data. The primary focus of reference [17] is to explain that the multiple-machine representation should take the diversity in protection conduction into account by investigating the discrepancies between the simulation results and the actual measurement. Perdana et al. [18] and Singh et al. [19] explore methods for validating the equivalent WPPs for SCIG-based and DFIG-based WPP, respectively. Meanwhile, reference [20] supports the fact that traditional clustering indices fail to cluster wind turbines when crowbar protection is enabled. Therefore, it is necessary to develop an equivalent method for modeling WPPs considering system protection.

This paper proposes a new equivalent method for modeling WPPs when the crowbar protection is taken into account. Based on the rotor current of the DFIG after an external three-phase short-circuit fault, the terminal voltage dip threshold is determined and from this it can be identified whether the crowbar protection is activated. Then, the threshold is revised based on the influence of the chain topology of the WPP. The revised terminal voltage dip threshold can be utilized to judge whether the crowbar is conducting. Furthermore, the equivalent WPP is established based on the division principle of crowbar conduction. Finally, the proposed equivalent WPP is simulated by the DigSILENT PowerFactory platform and the results are compared with those of traditional equivalent WPPs and the detailed WPP. The simulation results validate the effectiveness of the equivalent method for modeling DFIG-based WPP.

2. Postfault Rotor Current Transient Analysis of DFIG

2.1. Postfault Rotor Current Calculation. Using the motor conversion, the stator and rotor voltages and fluxes in a synchronously rotating d - q reference frame are given by

$$\begin{aligned} u_s &= R_s i_s + \frac{d\psi_s}{dt} + j\omega_1 \psi_s, \\ u_r &= R_r i_r + \frac{d\psi_r}{dt} + j\omega_s \psi_r, \\ \psi_s &= L_s i_s + L_m i_r, \\ \psi_r &= L_m i_s + L_r i_r, \end{aligned} \quad (1)$$

where u , i , and ψ represent voltage, current, and flux, respectively. R is the resistance, and L is the inductance. Subscripts s and r denote the stator and rotor quantities, respectively. L_m is the mutual inductance. ω_1 and ω_s are the synchronous speed and the slip speed, respectively.

One DFIG is connected to the infinite grid through a grounding transformer and a tertiary transformer, as shown in Figure 1. It is assumed that, at $t = t_0$, an external three-phase short-circuit fault occurs, and, as a result, the terminal voltage of the DFIG abruptly changes from the steady-state voltage u_{s0} to the remaining voltage u_{sk} . The solution of (1) for $t > t_0$ can be written as

$$\begin{aligned} \psi_s &= \frac{u_{sk}}{j\omega_1} + \left(\frac{u_{s0}}{j\omega_1} - \frac{u_{sk}}{j\omega_1} \right) e^{-j\omega_1 t} e^{-t/T_s}, \\ \psi_r &= \frac{u_r(0)}{j\omega_s + 1/T_r} - \frac{AR_r u_{sk}}{j\omega_1 (j\omega_s + 1/T_r)} \\ &\quad - \frac{AR_r (u_{s0} - u_{sk})}{j\omega_1 (-j\omega_r + 1/T_r - 1/T_s)} e^{-j\omega_1 t} e^{-t/T_s} \\ &\quad + C_1 e^{-j\omega_s t} e^{-t/T_r}, \end{aligned} \quad (2)$$

where $u_r(0)$ is the prefault rotor voltage. $T_s = (L_s L_r - L_m^2)/(L_r R_s)$ is the stator decay time constant. $T_r = (L_s L_r -$

TABLE 1: Model parameters.

Generator	Rater power/MW	2	Rated stator voltage/V	690
	Rated frequency/Hz	50	X_m/pu	3.5
	R_s/pu	0.01	X_s/pu	0.1
	$R_r (\text{pu})$	0.01	X_r/pu	0.1
Grounding transformer	S/MVA	2.5	$X_T/\%$	6
Tertiary transformer	S/MVA	150	$X_T/\%$	13.5
Crowbar protection	Maximum rotor current/pu	2	R_{cr}/pu	0.1
Overhead line				
LGJ-240/35	$r_0 (\Omega/\text{km})$	0.131	$x_0 (\Omega/\text{km})$	0.372
LGJ-300/220	$r_0 (\Omega/\text{km})$	0.107	$x_0 (\Omega/\text{km})$	0.414

$L_m^2)/(L_s R_r)$ is the rotor decay time constant. ω_r and C_1 represent the rotor electrical angular speed and the integral constant, respectively, and $A = -L_m/(L_s L_r - L_m^2)$.

When the DFIG operates in the stator voltage vector oriented control mode, $u_{sd} = U_s$, $u_{sq} = 0$. Thus, the relationship between the output powers, voltage, and current can be written as

$$\begin{aligned} P_s &= -\frac{3}{2} (u_{sd} i_{sd} + u_{sq} i_{sq}) = -\frac{3}{2} U_s i_{sd}, \\ Q_s &= -\frac{3}{2} (u_{sq} i_{sd} - u_{sd} i_{sq}) = \frac{3}{2} U_s i_{sq}, \end{aligned} \quad (3)$$

where $U_s = |u_{s0}|$ is the amplitude of the steady-state terminal voltage.

Based on (1) and (3), the prefault rotor voltage $u_r(0)$ can be described as

$$\begin{aligned} u_{rd}(0) &= \frac{2}{3} \frac{1}{\omega_1 L_m U_s} \left(R_r \omega_1 L_s P_s + R_s \omega_s L_r P_s \right. \\ &\quad \left. + \omega_1 \omega_s L_s L_r \sigma Q_s - R_s R_r Q_s + \frac{3}{2} \omega_s L_r U_s^2 \right), \\ u_{rq}(0) &= \frac{2}{3} \frac{1}{\omega_1 L_m U_s} \left(\omega_1 \omega_s L_s L_r \sigma P_s - R_s R_r P_s \right. \\ &\quad \left. - R_r \omega_1 L_s Q_s - R_s \omega_s L_r Q_s - \frac{3}{2} R_r U_s^2 \right), \end{aligned} \quad (4)$$

where $\sigma = 1 - L_m^2/(L_s L_r)$.

From (1), the rotor current i_r is derived as follows:

$$i_r = -\frac{L_m}{L_s L_r - L_m^2} \psi_s + \frac{L_s}{L_s L_r - L_m^2} \psi_r. \quad (5)$$

According to (2), (4), and (5), the dynamic representation for rotor current of the DFIG can be written as

$$\begin{aligned} i_r &= -\frac{L_m}{L_s L_r - L_m^2} \left[\frac{u_{sk}}{j\omega_1} + \left(\frac{u_{s0}}{j\omega_1} - \frac{u_{sk}}{j\omega_1} \right) e^{-j\omega_1 t} e^{-t/T_s} \right] \\ &\quad + \frac{L_s}{L_s L_r - L_m^2} \left[\frac{(2/3) (1/\omega_1 L_m U_s) (R_r \omega_1 L_s P_s + R_s \omega_s L_r P_s + \omega_1 \omega_s L_s L_r \sigma Q_s - R_s R_r Q_s + (3/2) \omega_s L_r U_s^2)}{j\omega_s + 1/T_r} \right. \\ &\quad \left. + \frac{j(2/3) (1/\omega_1 L_m U_s) (\omega_1 \omega_s L_s L_r \sigma P_s - R_s R_r P_s - R_r \omega_1 L_s Q_s - R_s \omega_s L_r Q_s - (3/2) R_r U_s^2)}{j\omega_s + 1/T_r} - \frac{A R_r u_{sk}}{j\omega_1 (j\omega_s + 1/T_r)} \right. \\ &\quad \left. - \frac{A R_r (u_{s0} - u_{sk})}{j\omega_1 (-j\omega_r + 1/T_r - 1/T_s)} e^{-j\omega_1 t} e^{-t/T_s} + C_1 e^{-j\omega_s t} e^{-t/T_r} \right] = f(R_s, L_s, R_r, L_r, L_m, P_s, Q_s, u_{sk}, u_{s0}, \omega_1, \omega_s, \omega_r). \end{aligned} \quad (6)$$

2.2. Timer Action Crowbar. The crowbar circuit used in this paper is formed of a three-phase rectifier, power resistor, and series IGBT switch [21]. The crowbar protection signal is triggered when the magnitude of the rotor current exceeds a threshold value set for crowbar protection insertion (2 pu)

and then remains engaged for a fixed time (50 ms). When the crowbar is released, rotor-side pulse width modulation (PWM) and rotor current PI control are immediately resumed. As shown in Figure 2, the DFIG wind turbine meets fault ride through requirements which refer to the capability

FIGURE 5: WPP network.

of generation plant to remain connected and dynamically stable and offer network support throughout a serious voltage disturbance [22].

2.3. Terminal Voltage Dip Threshold. According to (6), when the DFIG is connected to the infinite grid, the postfault rotor current is jointly determined by the generator parameters,

active and reactive power outputs, terminal voltage dip, steady-state terminal voltage, and generator speed. For the DFIG with the MPPT property, there is a corresponding relationship between the generator speed and the active power output. Thus, the influence of the generator speed on the rotor current can be included in the influence of the active power output. Once the generator parameters and the maximum rotor current for crowbar protection insertion are

TABLE 2: Wind data of each DFIG at 10.5 m/s, 0.5° wind.

DFIG	v/m·s ⁻¹
1(0)	10.50
1(1)	8.92
1(2)	8.38
1(3)	8.73
1(4)	8.18
1(5)	7.98
1(6)	7.92
1(7)	9.16
1(8)	8.59
1(9)	8.17
1(10)	8.04
2(0)	8.00
2(1)	7.99
2(2)	8.46
2(3)	8.25
2(4)	8.48
2(5)	8.46
2(6)	8.09
2(7)	8.00
2(8)	7.98
2(9)	8.46
2(10)	8.08
3(0)	10.50
3(1)	9.91
3(2)	8.57
3(3)	8.23
3(4)	8.14
3(5)	8.77
3(6)	8.11
3(7)	10.32
3(8)	8.85
3(9)	8.99
3(10)	8.66
4(0)	8.20
4(1)	7.99
4(2)	7.98
4(3)	7.97
4(4)	7.97
4(5)	7.97
4(6)	7.96
4(7)	7.96
4(8)	7.96
4(9)	7.96
4(10)	7.96
5(0)	10.50

TABLE 2: Continued.

DFIG	v/m·s ⁻¹
5(1)	8.74
5(2)	8.32
5(3)	8.15
5(4)	8.20
5(5)	8.84
5(6)	8.25
5(7)	8.16
5(8)	8.63
5(9)	8.78
5(10)	8.06
6(0)	9.04
6(1)	9.68
6(2)	8.61
6(3)	8.35
6(4)	8.06
6(5)	9.34
6(6)	9.02
6(7)	8.93
6(8)	8.28
6(9)	8.08
6(10)	8.01

fixed, the terminal voltage dip is the function of only the power outputs and the steady-state terminal voltage. As a result, the terminal voltage dip threshold can be quantified when the crowbar protection is just activated. Crowbar conduction occurs if the terminal voltage dip is lower than the terminal voltage drop threshold. Otherwise, the crowbar protection is not activated.

We select 0.1 MW as the power step length within the scope of the DFIG rated power and 0.01 pu as the voltage step length within the amplitude scope of steady-state terminal voltage 0.97–1.07 pu [22]. The terminal voltage dip changes through regulating the external short-circuit impedance and then finding out the terminal voltage dip threshold which makes the rotor current equal to the maximum rotor current for crowbar protection insertion. The terminal voltage dip thresholds of the DFIG whose power factor is -0.95 , 1 , and 0.95 , respectively, are presented in Figure 3. The DFIG parameters are specified in Table 1.

3. Dynamic Equivalence of the WPP

3.1. Effect of Collector Line Impedance on Terminal Voltage Dip Threshold. In order to reduce the power loss of a low-voltage circuit, it might be a better practice to connect multiple wind turbines to a middle-voltage bus using the daisy-chain structure within an actual WPP and then power in-feed to the external grid from the WPP through transmission lines. In the same feeder, owing to the convergence effect of output

TABLE 3: DF/G units with crowbar protection conduction.

Grounding impedance	Detailed WPP	Before revision		After revision	
		Right judgment	Wrong judgment	Right judgment	Wrong judgment
$Z_f = j5.5 \Omega$	1(0)-(1), 1(3)-(10), 2(0)-(10), 3(0)-(1), 3(7)-(10), 4(0)-(10), 5(0), 5(9), 6(0)-(10)	1(0), 1(7)-(10), 2(0)-(10), 3(0), 3(7), 3(9)-(10), 4(0)-(10), 5(0), 6(0)-(10)	1(1), 1(3)-(6), 3(1), 3(8) 5(9)	1(0)-(1), 1(3)-(10), 2(0)-(10), 3(0)-(1), 3(7)-(10), 4(0)-(10), 5(0), 5(9), 6(0)-(10)	1(2), 5(10)
$Z_f = j7 \Omega$	1(0), 2(0)-(10), 3(7), 4(0)-(10), 6(1), 6(5)-(10)	1(0), 2(0)-(10), 4(3)-(10), 6(5), 6(7), 6(9)-(10)	3(7), 4(0)-(2), 6(1), 6(6), 6(8)	1(0), 2(0)-(10), 3(7), 4(0)-(10), 6(1), 6(5)-(10)	None

TABLE 4: Wind data of each DFIG at 8.5 m/s, 174.5° wind.

DFIG	v/m·s ⁻¹
1(0)	6.36
1(1)	6.23
1(2)	7.44
1(3)	6.29
1(4)	6.93
1(5)	6.92
1(6)	7.45
1(7)	6.38
1(8)	6.40
1(9)	6.46
1(10)	6.99
2(0)	6.39
2(1)	7.64
2(2)	6.37
2(3)	6.37
2(4)	6.40
2(5)	6.65
2(6)	7.00
2(7)	6.50
2(8)	6.83
2(9)	8.50
2(10)	8.26
3(0)	6.39
3(1)	6.64
3(2)	7.11
3(3)	6.28
3(4)	7.05
3(5)	7.58
3(6)	6.79
3(7)	8.16
3(8)	6.58
3(9)	7.70
3(10)	6.36
4(0)	6.36
4(1)	6.36
4(2)	6.37
4(3)	6.37
4(4)	6.38
4(5)	6.39
4(6)	6.42
4(7)	6.49
4(8)	6.83
4(9)	8.50
4(10)	6.16
5(0)	6.40
5(1)	6.47

TABLE 4: Continued.

DFIG	v/m·s ⁻¹
5(2)	7.13
5(3)	6.36
5(4)	6.39
5(5)	6.49
5(6)	6.50
5(7)	7.86
5(8)	6.35
5(9)	6.39
5(10)	6.52
6(0)	7.72
6(1)	6.40
6(2)	7.21
6(3)	7.02
6(4)	8.14
6(5)	6.47
6(6)	6.39
6(7)	6.42
6(8)	6.49
6(9)	6.83
6(10)	8.50

current from other wind turbines, the voltage delta between a wind turbine and the middle-voltage bus has increased significantly, which is equivalent to increasing the electrical distance of the wind turbine to the middle-voltage bus.

Within the WPP, the differences in terminal voltages among the wind turbines are mainly caused by the different electrical distances from each wind turbine to the middle-voltage bus. Compared with the infinite grid connection structure for a single DFIG, in the WPP topology, the increasing effect of electrical distance between the wind turbine and the middle-voltage bus means the line impedance must not be ignored. At this time, the line impedance is jointed between the grounding transformer and the middle-voltage bus. Based on (6), if the impedance is incorporated into the generator stator side, the change in generator impedance parameters will have an impact on the rotor time constant, which will affect the relationship between the terminal voltage dip and rotor current. Therefore, the terminal voltage dip thresholds should be revised.

3.2. Terminal Voltage Dip Threshold Revision. In the same feeder, owing to the convergence of output currents among the wind turbines, the voltage drop has increased. In this paper, the virtual line impedance is introduced to characterize the equivalent electrical distance in the daisy-chain topological structure of the WPP.

TABLE 5: Equivalent accuracy of crowbar conduction and model error indices.

Operating conditions	Clustering index	Equivalent accuracy/%	Dynamic absolute error			Dynamic relative error		
			U/pu	P/MW	Q/Mvar	$U/\%$	$P/\%$	$Q/\%$
Figure 6(a)	Crowbar conduction	100.0	0.0004	0.08	0.12	0.07	0.65	1.44
	Incoming wind	77.3	0.0016	0.53	0.61	0.39	5.36	3.98
	Speed vector of generator	57.6	0.0061	0.67	2.32	1.42	6.32	25.87
Figure 6(b)	Crowbar conduction	100.0	0.0007	0.10	0.23	0.15	0.77	16.03
	Incoming wind	54.5	0.0046	0.73	1.78	1.13	6.39	27.44
	Speed vector of generator	47.0	0.0072	0.56	2.62	1.66	4.74	236.25
Figure 6(c)	Crowbar conduction	98.5	0.0012	0.35	0.50	0.22	2.46	3.78
	Incoming wind	72.7	0.0035	0.35	1.25	0.79	2.22	13.74
	Speed vector of generator	72.7	0.0045	0.57	1.78	0.95	3.59	16.72
Figure 7(a)	Crowbar conduction	98.5	0.0005	0.10	0.21	0.13	6.74	1.88
	Incoming wind	54.5	0.0044	0.81	1.55	1.21	74.75	21.31
	Speed vector of generator	53.0	0.0042	0.85	1.46	1.16	73.81	19.85
Figure 7(b)	Crowbar conduction	95.5	0.0006	0.22	0.22	0.14	7.23	3.97
	Incoming wind	50.0	0.0066	1.19	2.35	1.80	45.76	53.90
	Speed vector of generator	51.5	0.0064	1.22	2.26	1.74	45.51	50.70
Figure 7(c)	Crowbar conduction	100.0	0.0004	0.13	0.19	0.07	2.17	0.86
	Incoming wind	80.3	0.0006	0.18	0.20	0.08	3.50	0.97
	Speed vector of generator	78.8	0.0005	0.24	0.26	0.10	3.20	1.13

As shown in Figure 4, there are n DFIGs in one feeder, and the voltage drop ΔU_k that is between the wind turbine number k and the middle-voltage bus is

$$\Delta U_k = \frac{\sum_{j=k}^n (Z_j \sum_{i=1}^j S_i^*)}{\sqrt{3}U}, \quad (7)$$

where Z_j refers to the line impedance number j ; S_i^* is the conjugate value of apparent power of the wind turbine number i ; U is the voltage amplitude of the middle-voltage bus.

Based on the principle of equal voltage drop, the virtual line impedance $Z_{\text{eq-}k}$ which is between the wind turbine number k and the middle-voltage bus is

$$Z_{\text{eq-}k} = \frac{\sum_{j=k}^n (Z_j \sum_{i=1}^j S_i^*)}{S_k^*}. \quad (8)$$

In the infinite grid connection structure for a single DFIG, $Z_{\text{eq-}k}$ is jointed into the grounding transformer and the middle-voltage bus; then, the terminal voltage dip threshold is redetermined by means of the method in Section 2.3.

3.3. Clustering Principle of DFIGs. Based on the coherency-based method in the power system dynamic equivalence, crowbar conduction is selected as the clustering principle;

for example, DFIGs are divided into two groups: (1) crowbar conduction during the fault; (2) crowbar nonconduction during the fault. Depending on the abovementioned analysis, whether the crowbar protection is activated or not can be judged by comparing the postfault terminal voltage dip of the DFIG with its terminal voltage dip threshold.

4. Simulation Results

The developed equivalent WPP is tested by comparing its transient response with the traditional equivalent WPPs and the detailed WPP.

4.1. WPP Description. The network of the WPP is presented in Figure 5. The WPP is composed of one 35/220 kV transformer, six collector systems, and 0.69 kV DFIGs that are connected to the collector system through 0.69/35 kV grounding transformers. Each collector system has 11 DFIGs, and the interval between two DFIGs within the same collector system is 400 m. Model parameters are given in Table 1.

4.2. Validation of Clustering Index. The measured wind data of the 66 DFIGs are listed in Table 2. All DFIGs operate with a unity power factor. Three-phase short-circuit faults are applied at point A, as shown in Figure 4. Faults start at 0.1 s and last for 150 ms. Two case studies are performed for different short-circuit grounding impedance: (1) $Z_f =$

TABLE 6: The crowbar conditions of the detailed WPPs ($\checkmark$ stands for having a working crowbar).

DFIG	Figure 6(a)	Figure 6(b)	Figure 6(c)	Figure 7(a)	Figure 7(b)	Figure 7(c)	Figure 8
1(0)		✓	✓				✓
1(1)			✓				✓
1(2)							✓
1(3)			✓				✓
1(4)							✓
1(5)							✓
1(6)							✓
1(7)			✓				✓
1(8)			✓				✓
1(9)			✓		✓		✓
1(10)			✓		✓		✓
2(0)	✓	✓	✓	✓	✓		✓
2(1)	✓	✓	✓	✓	✓	✓	✓
2(2)		✓	✓	✓	✓		✓
2(3)	✓	✓	✓	✓	✓		✓
2(4)	✓	✓	✓	✓	✓		✓
2(5)	✓	✓	✓	✓	✓	✓	✓
2(6)	✓	✓	✓	✓	✓	✓	✓
2(7)	✓	✓	✓	✓	✓	✓	✓
2(8)	✓	✓	✓	✓	✓	✓	✓
2(9)	✓	✓	✓	✓	✓	✓	✓
2(10)	✓	✓	✓	✓	✓	✓	✓
3(0)			✓				
3(1)			✓				
3(2)							
3(3)							
3(4)							
3(5)							
3(6)							
3(7)		✓	✓				✓
3(8)			✓				
3(9)			✓				✓
3(10)			✓				✓
4(0)		✓	✓	✓	✓		✓
4(1)		✓	✓	✓	✓		✓
4(2)		✓	✓	✓	✓		✓
4(3)		✓	✓	✓	✓		✓
4(4)		✓	✓	✓	✓		✓
4(5)		✓	✓	✓	✓		✓
4(6)	✓	✓	✓	✓	✓		✓
4(7)	✓	✓	✓	✓	✓		✓
4(8)	✓	✓	✓	✓	✓	✓	✓
4(9)	✓	✓	✓	✓	✓	✓	✓

TABLE 6: Continued.

DFIG	Figure 6(a)	Figure 6(b)	Figure 6(c)	Figure 7(a)	Figure 7(b)	Figure 7(c)	Figure 8
4(10)	√	√	√	√	√	√	√
5(0)			√				
5(1)							
5(2)							
5(3)							
5(4)							
5(5)							
5(6)							
5(7)							
5(8)							
5(9)			√				
5(10)							
6(0)			√		√		
6(1)		√	√				
6(2)			√		√		
6(3)			√		√		
6(4)			√		√	√	
6(5)		√	√		√		
6(6)		√	√		√		
6(7)		√	√	√	√		
6(8)		√	√	√	√		
6(9)		√	√	√	√		
6(10)		√	√	√	√	√	

TABLE 7: Equivalent accuracy of crowbar conduction and model error indices.

Clustering index	Equivalent accuracy/%	Dynamic absolute error			Dynamic relative error		
		U/pu	P/MW	Q/Mvar	$U/\%$	$P/\%$	$Q/\%$
Crowbar conduction	98.5	0.0014	0.17	0.55	0.29	1.34	11.06
Incoming wind	56.1	0.0057	0.48	1.89	1.41	3.61	41.82
Speed vector of generator	56.1	0.0055	0.43	1.82	1.38	3.24	39.86
Reactive-power level	89.4	0.0061	0.28	1.22	1.32	2.44	57.48

$j5.5 \Omega$; (2) $Z_f = j7 \Omega$; therefore, the voltage of the 35 kV bus decreases to 53.7% and 55.7% of its nominal value. The postfault terminal voltage of the DFIG is compared with its terminal voltage dip threshold before revision and after revision, respectively, thus judging the DFIG whose crowbar protection is activated. Then, based on the simulation results of the detailed WPP, the correctness of the abovementioned judgment is tested, and the statistical results are listed in Table 3.

As can be seen from Table 3, when $Z_f = j5.5 \Omega$ and $Z_f = j7 \Omega$, based on the terminal voltage dip threshold before revision, the numbers of wrong judgments of crowbar conduction are eight and seven, respectively; based on the

terminal voltage dip threshold after revision, the numbers of wrong judgments of crowbar conduction are reduced to two and zero, respectively. The accuracy of the judgment of crowbar protection conduction can be significantly improved by using the terminal voltage dip threshold after revision.

4.3. Transient Response. The detailed WPP and the equivalent WPPs are modeled on the DIgSILENT PowerFactory platform. The detailed WPP consists of the 66 DFIGs, collection systems, grounding transformers, and a main transformer. Three-phase short-circuit faults are applied at point A, as shown in Figure 5. Faults start at 0.1 s and last for 150 ms.

FIGURE 6: U , P , and Q of the WPPs at 10.5 m/s, 0.5° wind: (a) power factor = -0.95 , (b) power factor = 1 , and (c) power factor = 0.95 . The three equivalent WPPs built based on crowbar conduction, incoming wind, and speed vector of generator are in red dash, blue dot, and magenta dash dot, respectively, and the detailed WPP is in black solid.

Compared with the simulation results of the detailed WPP, error indicators are defined as follows:

$$\begin{aligned} E_a &= \frac{1}{n} \sum_{i=1}^n |Y_{fi}(k) - Y_i(k)|, \\ E_r &= \frac{1}{n} \sum_{i=1}^n \left| \frac{Y_{fi}(k) - Y_i(k)}{Y_i(k)} \right|, \end{aligned} \quad (9)$$

where $Y_i(k)$ and $Y_{fi}(k)$ are the output variables of the complete collector system for the equivalent WPPs and the detailed WPP, respectively, and n stands for the number of DFIGs within the WPP.

4.3.1. The Same Power Factor within WPP. All DFIGs operate with the same power factor, and two case studies are performed for different incoming winds: (1) 10.5 m/s, 0.5° ;

(2) 8.5 m/s, 174.5° . Based on wake effects, the incoming winds of each DFIG are listed in Tables 2 and 4, respectively. Three different reactive-power levels of DFIG, for example, the maximum production (0.95), unity power factor, and maximum consumption (-0.95), are used for the cases. Figures 6 and 7 illustrate the behavior of the voltages, active and reactive powers of the complete collector system for the three equivalent WPPs, and the detailed WPP following the application of a three-phase short-circuit fault.

The equivalent accuracy of the equivalent WPPs compared to the detailed WPP about the crowbar protection conduction and error indices are listed in Table 5. During the fault, whether the crowbar protection is triggered or not decides the reactive power supporting ability of the DFIG to the power grid, thereby affecting the depth of the voltage dip and the active power output of the WPP. The equivalent WPP

FIGURE 7: U , P , and Q of the WPPs at 10.5 m/s, 0.5° wind: (a) power factor = -0.95 , (b) power factor = 1 , and (c) power factor = 0.95 . The three equivalent WPPs built based on crowbar conduction, incoming wind, and speed vector of generator are in red dash, blue dot, and magenta dash dot, respectively, and the detailed WPP is in black solid.

built by this paper is more similar to the detailed WPP, due to its higher equivalent accuracy for crowbar conduction.

The crowbar conditions of the detailed WPPs are listed in Table 6. It should be noted that the DFIG might lose its capability to control the generator after crowbar conduction; thus, a DFIG whose generator speed is lower than the synchronous speed operates in the motor state. From fault elimination to crowbar protection resection, with the grid voltage recovery, a DFIG operating in the motor state will consume more active power, causing the active power at the complete collector system for the WPP to appear with a larger negative value. The equivalent WPP built by this paper can also accurately reflect this situation.

4.3.2. Different Power Factors among WPP Feeders. The incoming wind of the WPP is 10.5 m/s, 0.5° . Based on wake

effects, the incoming winds of each DFIG are listed in Table 2. The power factors of the DFIGs in feeders 1-2, 3-4, and 5-6 are -0.95 , 1 , and 0.95 , respectively. Three-phase short-circuit faults are applied at point A, as shown in Figure 5. Faults start at 0.1 s and last for 150 ms. Figure 8 shows the behavior of the active and reactive powers at the complete collector system for the equivalent WPPs and the detailed WPP following the application of a three-phase short-circuit fault. The crowbar condition of the detailed WPP is listed in Table 6. The equivalent accuracy of the equivalent WPPs compared to the detailed WPP about the crowbar protection conduction and error indices are listed in Table 7.

When the DFIGs operate with different power factors within the WPP, the traditional equivalent method will divide the DFIGs which have the same reactive-power level into groups. But the simulation results of the detailed WPP

FIGURE 8: U , P , and Q of the WPPs. The four equivalent WPPs built based on crowbar conduction, incoming wind, speed vector of generator, and reactive-power level are in red dash, blue dot, magenta dash dot, and green dash dot, respectively, and the detailed WPP is in black solid.

indicate that the crowbar conduction of DFIGs with the same power factor is not completely consistent.

5. Conclusions

After the fault, the crowbar conduction of the DFIG is related to the depth of the terminal voltage dip. This paper simplifies the judgment criterion of crowbar conduction as the terminal voltage dip threshold, which is convenient to calculate and makes it easy to identify the crowbar conduction.

Considering the influence of the connection line impedance within the same collector system on the terminal voltage dip threshold, the virtual line impedance is introduced to characterize the equivalent electrical distance from the DFIG to the medium-voltage bus. The equivalent accuracy of crowbar conduction discrimination is improved by revising the terminal voltage dip threshold.

The equivalent WPP established based on the division principle of crowbar conduction is verified, showing that it can more accurately reflect the external characteristics of the WPP.

Appendix

See Tables 1, 2, 4, and 6.

Competing Interests

The authors declare that there is no conflict of interests regarding the publication of this paper.

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