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Full Order Model of Doubly-fed Wind Generator and Simplified Methods

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Abstract

Based on the control principle of the doubly-fed inductor wind power generator (DFIG for short), this article establishes the full order model, including the converter control model and the control sysem of balde angle, the correctness of the model is verified by hybrid real-time simulation and the electromagnetic numerical simulation, and the model realizes whole operation running characteristic control. In addition, this article puts forward simplified methods of DFIG model innovatively and establishes two different degrees of simplification models with equivalence of the converter model and the generator model respectively. The results by comparing the operating performance of each model under the same operating condition, show that, the two simplified models have high accuracy, and speed up the simulation efficiency effectively, which is suitable for the study of large-scale wind power generation in power system.

Keywords: *DFIG, whole operation, full order model, simplified model, converter and generator*

1. Introduction

The doubly-fed wind power generator (DFIG) can not only realize variable speed constant frequency running, but also can realize decoupling control of active and reactive power. So in recent years, DFIG has occupies a large proportion in wind power development and the research has become a hotspot. Wind turbines is a nonlinear, strong coupling, multi-variable complex energy conversion system of multiple time scales, crossing multiple disciplines such as the aerodynamics, materials, machinery, electric power, electronics, control and so on. So, wind turbines modeling is a hot spot in current research. Each subsystem of wind turbines has different dynamic behavior and its time scale difference is very big. As a complete system, to describe the detailed stady and dynamic characteristics of each subsystem, it must take different time scale characteristics into account, but, the full order model which can describe the detailed characteristics is of large amount of calculation and the computation time is long, making it difficult to meet the needs of some occasions. Therefore, it's of important research significance of adopting of a certain simplification model.

The study of wind power generation system is relatively mature and domestic, and foreign scholars on DFIG mostly focus on the modeling and performance analysis [1-3], low voltage ride through [2], asymmetric control stratedy [5-9] and the influence of integrated to grid system of wind generator and so on.

General simplification methods of asynchronous generator model have the following kinds, adopting decline of order models [10-12] in the case of approximation, a reduced order model using singular perturbation theory [13] and a linear dynamic asynchronous machine model which used for studying the mechanical torque ripple [14]. But a linear dynamic model is only applicable on the condition of sine mechanical wave; a reduced order model based on the singular perturbation theory focuses on the study of the motor itself, which is better to modeling simplify.

This paper establishes the full order model based on the complete mathematical model, including the aerodynamic part model (model of wind turbine model and transmission system), generator model, the converter model (including machine side converter, MSC and the grid side converter model, GSC) and the variable blade angle control system model, then puts forwards the control strategy of each unit. The converter control strategy is implemented in the synchronous rotating coordinate system using the vector control technology. This paper

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demonstrates the validity of the full order model by hybrid real-time simulation RTDS, and implements the whole condition (above rated wind speed, and below the rated wind speed) of the running.

In addition, for the purpose of studying the characteristics of large-scale wind power generation in power system, this paper puts forward new simplifying method according to the DFIG model. The author gets two different degrees of simplified models by simplify the converter model and the generator model respectively. Taking a 1.5MW DFIG unit as an example, this paper compares the operating characteristics of the full order model and calculation time of the two simplified models with the full order model, to verify the validity of the simplified method and the applicability to the study of large-scale wind power grid.

2. The Full Order Model of DFIG for the Whole Operation Conditions

2.1. The full order model of DFIG

The full order DFIG model includes the aerodynamics, wind speed, shaft system, generator, converter model with its control system, and the control system of pitch angle.

a) Aerodynamic Model

Wind machine will convert the wind energy into mechanical energy. According to the aerodynamic characteristics, the output mechanical power can be described as:

$$P_m = \frac{1}{2}\rho S v^3 C_p = \frac{\pi}{8}\rho D^2 v^3 C_p \quad (1)$$

In The formula, ρ is for air density, S is for swept area of impeller, D is for the diameter of impeller, v is the actual wind speed through wind turbines, C_p is the wind energy utilization coefficient which reflects the absorption efficiency of wind power, and it's a function of the tip speed ratio and pitch angle.

b) Model of Shaft System

Shafting model can be built as one mass model and two-mass model. In the process of system simulation, the two models are in common, the corresponding equation is as below:

$$\begin{cases} T_{wtr} = J'_{wtr}\dfrac{d\omega_{wtr}}{dt} + D_{tg}(\omega_{wtr} - \omega_{gen}) + k_{tg}(\theta_{wtr} - \theta_{gen}) \\ -T_{gen} = J_{gen}\dfrac{d\omega_{gen}}{dt} + D_{tg}(\omega_{gen} - \omega_{wtr}) + k_{tg}(\theta_{gen} - \theta_{wtr}) \end{cases} \quad (2)$$

In The formula, T_{wtr} is wind turbine torque, J'_{wtr} is inertia constant of the wind turbine, ω_{wtr} is the wind turbine rotational speed, θ_{wtr} is rotation of the wind turbine, T_{gen} is electromagnetic torque of the genetaor, J_{gen} is inertia constant of the generator, ω_{gen} is the speed of the generator, D_{tg} is the damping coefficient of the shaft, k_{tg} is rigid coefficient of the axis of rotation. When ignoring the damping coefficient and stiffness coefficient of the shaft, assumptions, namely, $D_{tg} = 0, k_{tg} = 0$, then the traditional one mass model can be obtained as formula (3).

$$T_{wtr} - T_{gen} = J_{one}\frac{d\omega_{gen}}{dt} \quad (3)$$

c) Generator Model

Generator model is described in two-phase synchronous rotating coordinate system shown in formula (4).

$$\begin{cases} u_{sd} = R_s i_{sd} + p\psi_{sd} - \omega_1 \psi_{sq} \\ u_{sq} = R_s i_{sq} + p\psi_{sq} + \omega_1 \psi_{sd} \\ u_{rd} = R_r i_{rd} + p\psi_{rd} - \omega_s \psi_{rq} \\ u_{rq} = R_r i_{rq} + p\psi_{rq} + \omega_s \psi_{rd} \end{cases} \quad \begin{cases} \psi_{sd} = L_s i_{sd} + L_m i_{rd} \\ \psi_{sq} = L_s i_{sq} + L_m i_{rq} \\ \psi_{rd} = L_r i_{rd} + L_m i_{sd} \\ \psi_{rq} = L_r i_{rq} + L_m i_{sq} \end{cases} \tag{4}$$

The formula is for voltage equation and flux equation; The subscript 's' is for stator, 'r' is for rotor, 'dq' is for dq axis component respectively; R is for resistance and L is for inductance, ω is rotor speed.

d) Converter Model

GSC and MSC of DFIG often uses two-level PWM inverter, this paper takes GSC converter model for example for describing them. The GSC converter model in the two-phase synchronous rotating coordinate system shown in formula (5).

$$\begin{cases} e_{gd} = R_g i_{gd} + L_g \dfrac{di_{gd}}{dt} + \omega_1 L_g i_{gq} + V_{gd} \\ e_{gq} = R_g i_{gq} + L_g \dfrac{di_{gq}}{dt} - \omega_1 L_g i_{gd} + V_{gq} \\ C \dfrac{dV_{dc}}{dt} = S_d i_{gd} + S_q i_{gq} - i_{load} \end{cases} \tag{5}$$

In the formula, e_{gd} and e_{gq} is the dq axis grid voltage, i_{gd} and i_{gq} is the dq axis current into the converter, V_{gd} and V_{gq} is the ac voltage of the converter side, S_d and S_q is the switching function of the power electronic switching function.

2.2. Control Strategy of DFIG

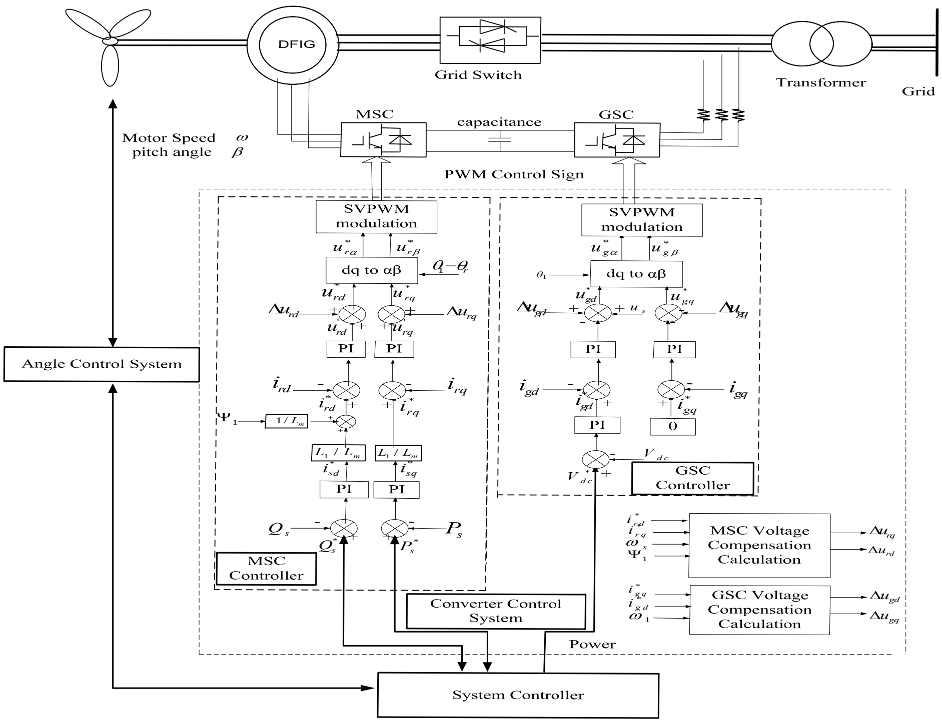


Figure 1. Full Order DFIG Model

DFIG control system includes the converter control system and pitch angle control system, and the converter control system can be divided into GSC control system and MSC control system [15]. The system controller gives the instructions for the yaw structure and the back-to-back converter control system. The control block diagram of full order model is shown in Figure 1.

a) GSC Controller Strategy

The main control objective of GSC controller is to ensure the DC bus voltage constant and to realize the power factor control. The GSC modulation voltage commands $u_{s\alpha}^*$ and $u_{s\beta}^*$ are got from the closed-loop of active current component i_{gd}^* (obtained by closed-loop of DC bus voltage) and the reactive current component ($i_{gq}^* = 0$, usually for unit power factor control), then get the GSC all drive pulses through the SVPWM modulation technology.

b) MSC Controller Strategy

The main control objective of MSC is to realize the maximum power tracking (MPPT for short). The MSC modulation voltage commands $u_{r\alpha}^*$ and $u_{r\beta}^*$ are got from the outer closed-loop of power and the inner closed-loop of current, then get the GSC all drive pulses through the SVPWM modulation technology. The active power instruction P_s^* is got from the MPPT controller which is in the system controller and the reactive power instruction Q_s^* is designed for the power factor (general set as 0 or decided by the wind park management system).

Variables in the full order model control block diagram are defined as follows: the subscript's' is for stator, 'r' is for rotor, 'g' is for the grid side, 'dq' is for dq axis component respectively, such as i_{rq} said for rotor axial current component; superscript * said instruction calculated value, such as i_{rq}^* is for q axis component of the rotor current instruction value, other variables are by parity of reasoning.

c) Control system of Pitch angle

Control system of pitch angle provides different angle of yaw in different operating stage. If the wind speed is below the rated wind speed, the angle of yaw maintains the best pitch angle a constant for tracking the maximum wind power, usually as 0; if the wind speed is above the rated wind speed, the pitch-controlled system will adjust the blade pitch angle according to a given power, to ensure that the generator output power within the scope of the permit. The control block diagram of the angle control model is shown in Figure 2.

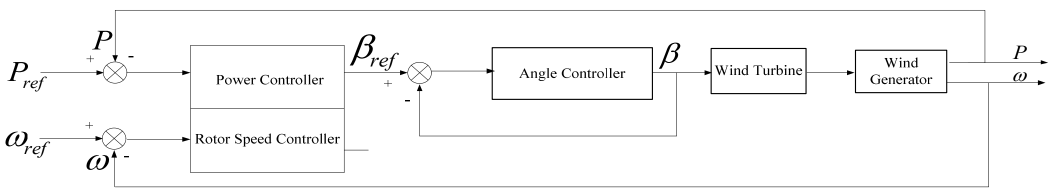


Figure 2. Angle Control Model

3. Simplified Method of DFIG Model

3.1. Simplified Model Ⅰ and its Realization Method

Simplified model Ⅰ reserves the control system of pitch angle, and simplifies the full order model by using a controllable power source instead of converter, omitting the process of SVPWM modulation. The concrete realization method: put the three-phase ac voltage u_{ra}^*, u_{rb}^*, u_{rc}^* (getting from the MSC modulation voltage command $u_{r\alpha}^*$ and $u_{r\beta}^*$ after transformation of coordinates) into the controllable voltage source, to provide the excitation voltage for rotor; With the same method, put the three-phase ac voltage u_{ga}^*, u_{gb}^*, u_{gc}^* (getting from the GSC modulation voltage command $u_{g\alpha}^{*}$ and $u_{g\beta}^{*}$ after transformation of coordinates) into the controllable voltage source, to provide the power to the grid after the line impedance. The complete control block diagram is shown in Figure 3.

The simplified model Ⅰ simplifies the high frequency process of power electronics switches, which meaning that the MSC and GSC systems are equivalent to a controlled voltage source to provide rotor excitation voltage for DFIG and the grid side voltage of the converter. Therefore, in the simplified model Ⅰ, DFIG still provides power to grid by two channels such as the full order model, one is the output of the stator side, and the other one is provided by the output of the equivalent power converter. The proposed model □guarantee the effectiveness of the simplification, also greatly reduces the complexity of the model.

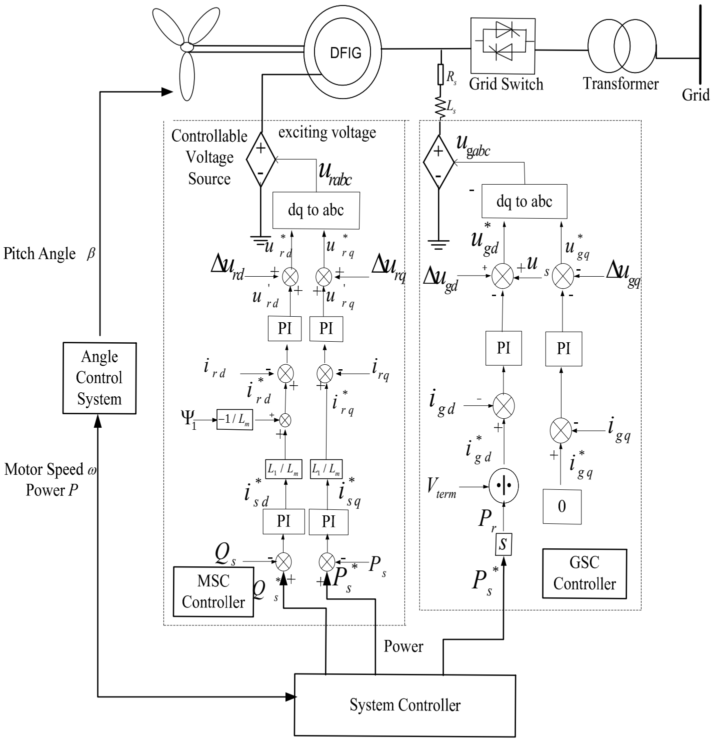


Figure 3. Simplified DFIG Model Ⅰ

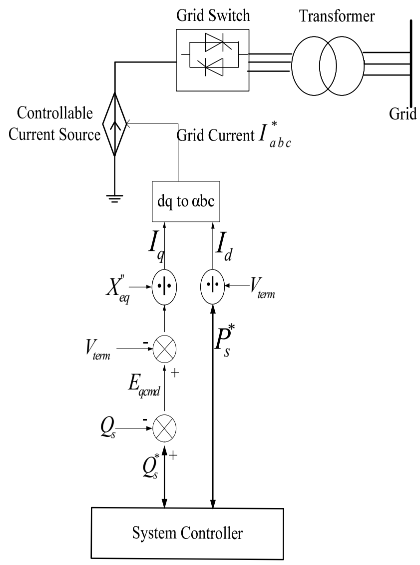


Figure 4. Simplified DFIG Model Ⅱ

3.2. Simplified Model Ⅱ and its Realization Method

In the simplified model Ⅱ, the generator part is simplified by ignoring electromagnetic dynamic process of the converter and generator to some extent. The model Ⅱ uses the equivalent algebraic computing controllable current source instead of the generator – convert model, to equal to the current inject to the grid. The concrete realization method: put the active current I_d (which is got from the active power instruction after divided by the grid voltage) and the reactive current I_q (which is got from the closed-loop of the reactive power together with the motor transient electric potential) into the controllable current source after transformation of coordinates. The complex control block diagram is shown in Figure 4.

Compared with the whole order model and simplified model Ⅰ, simplified model equivalents the genetator to a second order controlled current source which omitting the converter model. Therefore, in the simplified model Ⅱ, DFIG provides power to grid only by one channel, which is consists of the output of the stator and the GSC. So, the simplified model Ⅱ ignores the electromagnetic transient process and retains the mechanical and electrical properties, greatly saving the computation time and the amount of calculation, improving the calculation speed.

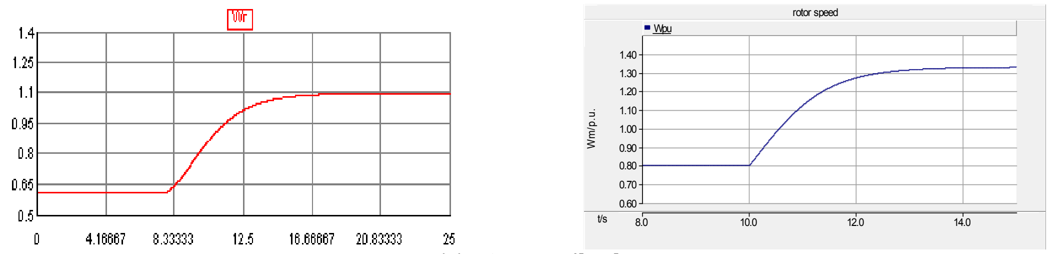
4. Comparisons of Performance of Full Order Model and Simplified Models

4.1. Operation Characteristic of the Full Order Model

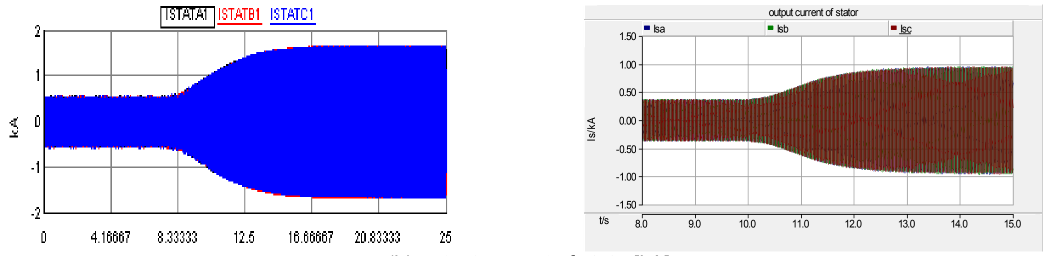
4.1.1 Operation Characteristic of the Full Order Model under the Rated Wind Speed

Based on the DFIG hybrid simulation system, this paper compares the hybrid real-time simulation results of actual physical controller with PSCAD electromagnetic numerical simulation results, to verify the correctness of the electromagnetic numerical simulation model.

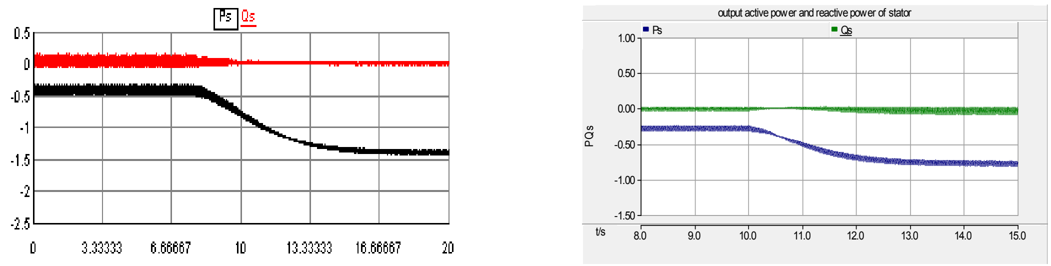
This paper uses the 1.5MW DFIG, under the same operation condition that the wind speed steps to 10 m/s from 6 m/s at 10s. The simulation results are shown in Figure 5, in which the left results are for RTDS, and the right results are for PSCAD.



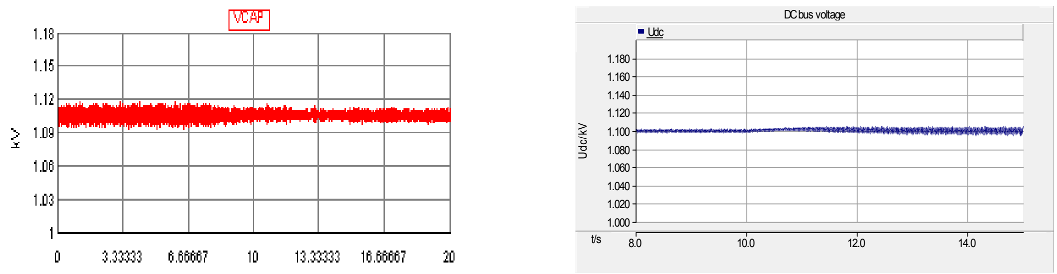
(a) rotor speed[p.u]



(b) output current of stator[kA]



(c) output active power and reactive power of stator[MW, Mvar]



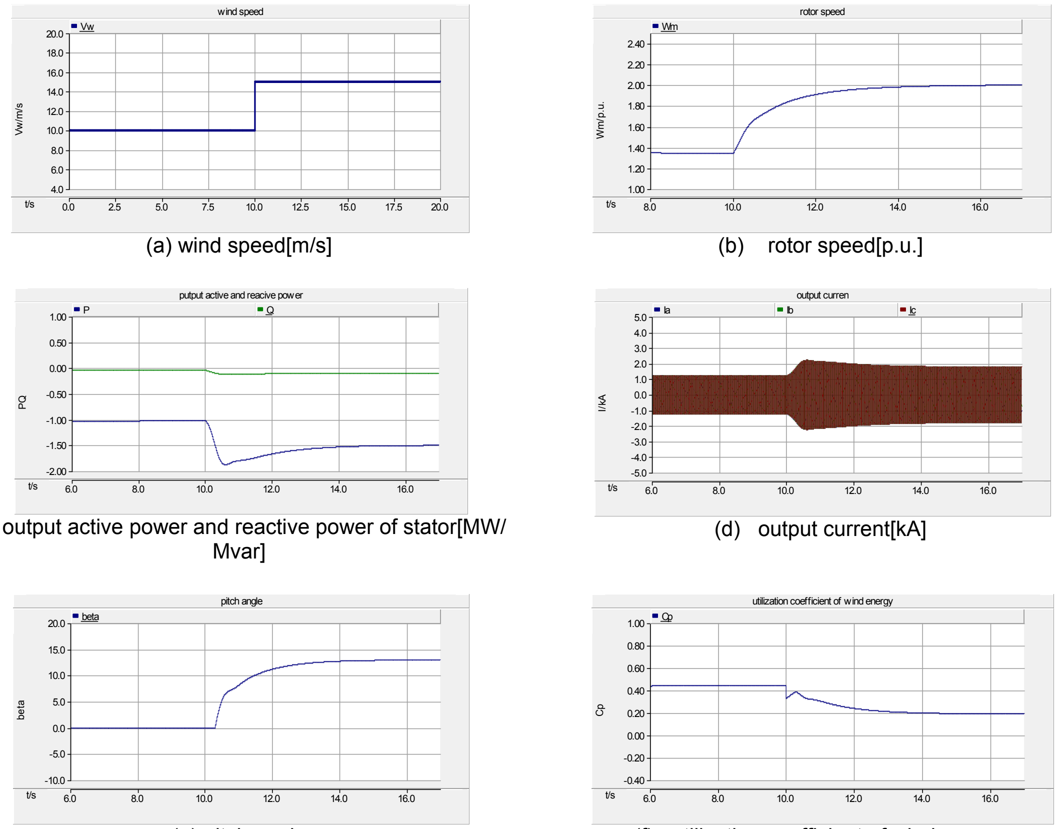
(d) voltage of DC bus[kV]

Figure 5. Comparison of the Operational Characteristics of the Full Order Model of PSCAD and RTDS Under the Rated Wind Speed

By comparing the simulation results of PSCAD model with RTDS real-time simulation model, it shows that under the step speed, these two models achieve good consistency, thus verified the correct of the PSCAD full order model.

4.1.2 Operation Characteristic of the Full Order Model Over the Rated Wind Speed

The simulation results of DFIG when the wind speed step to 15m/s from 6m/s are shown in Figure 6.



(a) wind speed[m/s] (b) rotor speed[p.u.]

(c) output active power and reactive power of stator[MW/Mvar] (d) output current[kA]

(e) pitch angle (f) utilization coefficient of wind energy

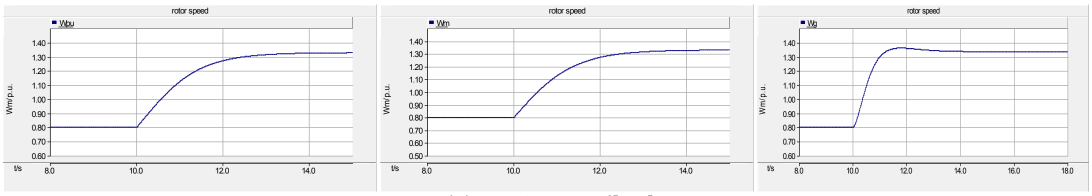
Figure 6. Operational Characteristics of the Full Order Model Under Rated Wind Speed

As shown in Figure 6, when the wind speed is over the rated speed, the control system of pitch angle will adjust the pitch angle, as shown in Figure 6(e), to reduce the swept area of the impeller, which will reduce the utilization coefficient of wind energy, as shown in Figure 6(f), ensuring that the output power will restrictions around the rated power.

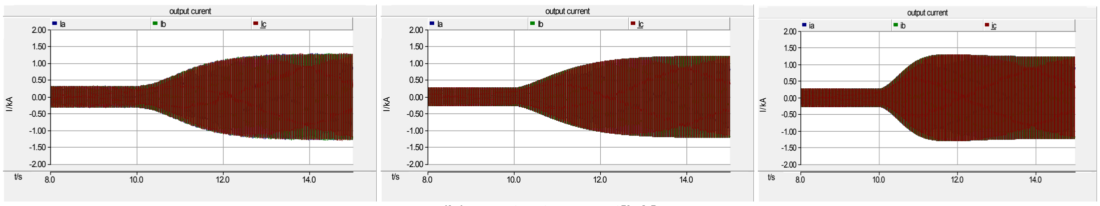
4.2. Comparison of Operational Characteristics

4.2.1. Comparision of Operation Characteristics under the Step Wind Speed

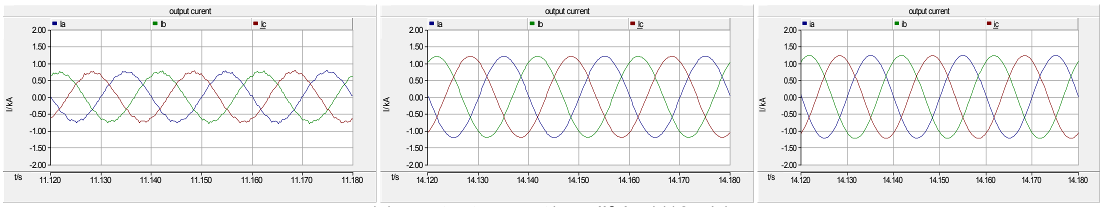
Under the same operation condition that the wind speed steps to 10m/s from 6m/s at 10s, the simulation results based on PSCAD/EMTDC of the performance characteristics of the full model and simplified models are shown in Figure 6 below, the left for the full order model, the intermediate for the simplified model Ⅰ, the right for the simplified model Ⅱ.



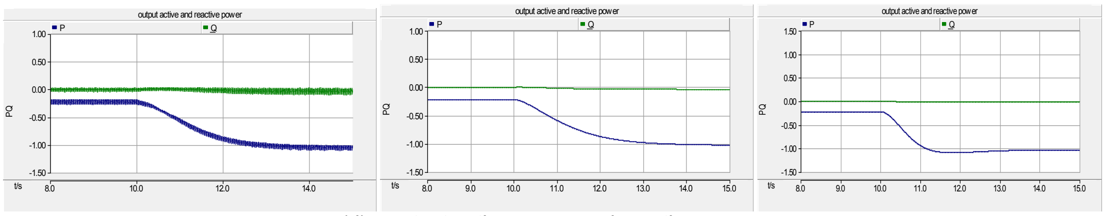
(a) motor speed[p.u]



(b) output current[kA]



(c) output current(amplifying)(10m/s)



(d) output active power and reactive power

Figure 6. Comparison of the Operational Characteristics of the Full Order Model and the Two Simplified Models

The comparisons of the steady state (for large wind speed as 10m/s) output characteristics both of the simplified models are shown in the following Table 1.

Table 1. Steady-state Output of the Two Simplified Models

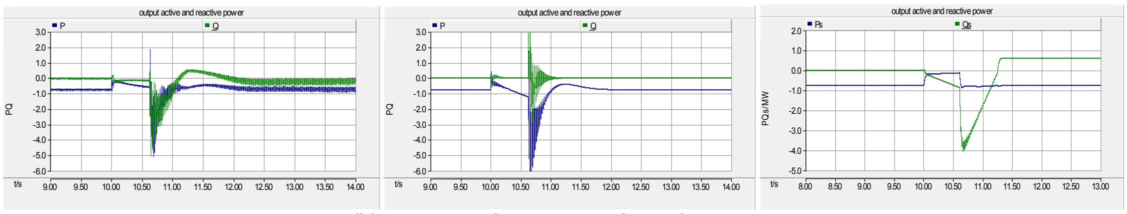
	Simplified model Ⅰ	Simplified model Ⅱ	error
Roter speed [p.u].	0.8022-1.3382	0.8011-1.3368	0.0011-0.0014
virtual value of current Injected to grid [kA]	0.1866-0.8567	0.1870-0.8672	0.0004-0.0105
Ouput active power[MW]	0.2230-1.025	0.2339-1.037	0.0109-0.012

As shown in Figure 6, the operational features of the two simplified models show good consistency as a whole result, both achieving the control targets that tracking of the maximum wind power, decoupling control of the active and reactive power, and variable-speed constant-frequency control. As shown in Table 1, the motor speed and output current and power have good consistency under the step wind speed, and the error both of them show slightly difference, verifying the validity of the simplified method.

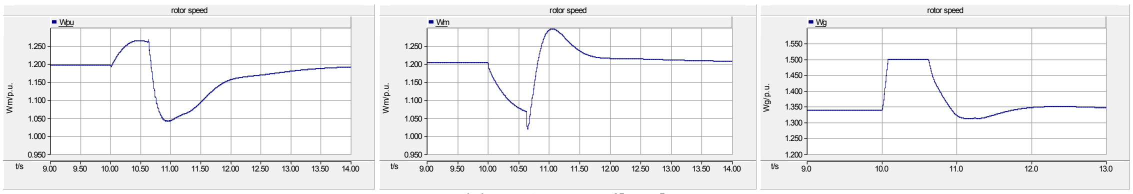
4.2.2.. Comparision of Operation Characteristics under Symmetrical Drop of Grid Voltage

Under the same operation condition that grid voltage drop to 20% at 10s symmerrically for 625ms, the simulation results of the full model and simplified models are shown in Figure 7 below, the left for the full order model, the intermediate for the simplified model Ⅰ, the right for the simplified model Ⅱ.

(a) output current[kA]



(b) output active power and reactive power



(c) rotor speed[p.u.]

Figure 7. Comparison of the Operational Characteristics of the Full Order Model and the Two Simplified Models

As shown in Figure 7, the simplified models and the full order model have the same change trend when the grid voltage drop symmetrily, escepilly the simolified model Ⅰ has higher consistency with the full order model; but, the simplified model Ⅱ has some little difference because of simplification of the genetator, leading to it cann't reflect the damping and electronmagnetic characteristic.

4.3. Comparison of the Simulation Efficiency

The simulation time step of the full order model should be short because of the existence of power electronics device — switching frequency is about several thousand Hz; however, the simulation time step can be longer because of omitting the detailed converter model.

This paper makes the comparison in the same simulation time step, such as 20us and 2us. The simulation schedule is shown in Table 2.

Table 2. The Calculation Schedule of the Full Order Model and Simplified Models

		1acc	1sim Ⅰ	1sim Ⅱ
Simulation time step	20us	4 min	1 min	15 s
	2us	23 min	7 min	2 min
		3acc	3sim Ⅰ	3sim Ⅱ
Simulation time step	20us	28' min	2 min	24 s
	2us	114 min	18 min	4 min

Note: 'acc' namely full order model; 'sim Ⅰ' namely simplified model Ⅰ; 'sim Ⅱ'namely the simplified model Ⅱ. The all results are statisted on the same computer configuration conditions.

As shown in Table 2 that, under the same simulation step, computation time is significantly shortened in the simplified model than the full order model, especially in the simplified model Ⅱ; but, the simulation time of the same degree of simplified model is not proportional to the with the extension of the number of the generator units. Therefore, it can adopt different degree of simplification model according to different research purpose when study the large-scale wind farm in system grid, to greatly improve the efficiency of simulation.

5. Conclusion

This paper puts forward two simplified DFIG models, and gets the following conclusions from the operation characteristics and simulation efficiency of the full order model and simpilified models:

a) Both of the simplified models which use controllable power source to equal to the detailed converter and generator model have good consistence with the full order DFIG model under the same operation condition, both the steady and dynamic charactristics.

b) Both of the simplified models can greatly shorten the simulation time, improving the efficiency which is applicable to large system simulation.

c) The simplified method of simplified model Ⅱ is also suitable for direct drive synchronous wind generation.

This paper proposes two simplified DFIG methods which can be used for system analysis. It is of important significance for the research and study of the impact on power grid of large-scale wind farm when access to system.

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