Smoothing Control of Doubly-Fed Induction Generator Wind Turbine under Different Wind Conditions

Yuan Chang
School of Electrical & Information Engineering
University of Sydney
Sydney, Australia
e-mail: ycha1228@uni.sydney.edu.au

Kunkun Fu
School of Aerospace Engineering & Applied Mechanics
Tongji University
Shanghai, China
e-mail: stone_fkk@163.com

Abstract—Doubly-fed induction generator (DFIG) wind turbine has been widely used in wind energy industry due to its good energy capture performance, fine controllability and simple realization. In this paper, a mathematical model for the operation and control of a DFIG wind turbine was proposed. Battery storage device with a PID controller was connected to the grid side aiming at obtain a smooth power output of wind turbine under different wind conditions. The present model was numerically solved under different wind conditions, i.e. a constant wind, a sinusoidal-type wind and a step-type wind. The simulation results showed that DFIG wind turbine with a battery storage device could provide a much smoother power output at different wind conditions comparing with the conventional DFIG wind turbine. Furthermore, compared to other models, our model has some advantages such as less cost, easily manufacturing and maintenance and therefore can be used in wind energy industry.

Keywords-wind turbine; DFIG; smoothing control;battery storage device;PID controller

I. INTRODUCTION

In recent years, doubly-fed induction generator (DFIG) wind turbine has been extensively used in wind power industry due to its good energy capture performance, fine controllability and simple realization [1]. DFIG wind turbine is directly connected to the grid at the stator terminals to provide the power. In order to minimize the impact on the grid, it is of great importance to obtain a smooth power output from DFIG wind turbine using a control strategy.

A vast number of studies focused on the topics relating to smoothing control of DFIG wind turbine. For instance, Prabhugaonkar et al. [2] proposed a control strategy to enhance low voltage ride through capability of DFIG-based wind turbine. Wu et al. [3] investigated the improved control strategy for both the rotor side converter (RSC) and grid side converter (GSC) of a DFIG wind turbine system which improves the low voltage ride through capability. Mendis et al. [4-6] presented an energy management strategy for a wind dominated remote area power supply system. The battery storage was connected to the AC side of this system using a three phase inverter, and dummy load and main loads are included in their model. Ganti et al. [7] developed a new model for a grid-connected DFIG wind energy conversion system, and a battery energy storage system was used to reduce the power fluctuations. Recent studies such as Jiang et al. [8], Ibrahima et al. [9] and Sarrias et al. [10] employed the battery storage system to obtain a smooth power output for DFIG wind turbine, and the energy storage system was connected to the DC link of the back-to-back power converters.

Most of these models put battery energy storage to the side of the DC link of the back-to -back power converters. This kind of strategy increased the difficulty in manufacturing and maintenance. Some models used super capacitors as an energy storage system, which increased the cost of wind turbine because usually super capacitor is more expensive than the battery. Further, in practice, different wind conditions should be considered as input to investigate the response of the model.

In the present work, a new model for the operation and control of a DFIG wind turbine was developed. Battery storage system with a PID controller was connected to the grid side to achieve a smooth output of power. This kind of strategy makes it easy to manufacture and maintain. Using Matlab/simulink, the model was simulated under different wind condition to determine the power output. Further, output power by the present model was compared with that by the conventional DFIG wind turbine.

The paper is organized as follows. In the next section, we develop a detailed model for DFIG wind turbine connected to the grid, and the battery storage device is included in the model. Section 3 presents the results of the smooth output of DFIG wind turbine under different wind condition. The results are also compared with those by the conventional DFIG wind turbine. Finally, we conclude our work in Section 4.

II. MODELLING OF DFIG WIND TURBINE

Conventional DFIG wind turbine system consists of a wind turbine, a driving train, a wound rotor induction generator, a pitch angle control system, a rotor side converter and a grid side converter shown in Fig. 1.

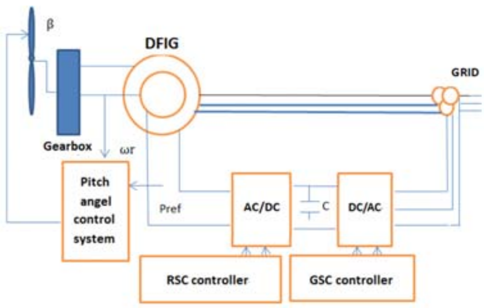

FIGURE 1: SCHEMATIC OF A BASIC DFIG WIND TURBINE SYSTEM

In this paper, we propose a DFIG wind turbine with battery storage device. Schematic of this model is illustrated in Fig. 2. This system includes a wind turbine, a driving train, a wound rotor induction generator, a pitch angle control system, a rotor side converter with controller, a grid side converter with controller and a battery storage device. The major objective of the rotor side controller is to control DFIG's rotor side voltage(V_{qr}, V_{dr}), whereas the grid side controller controls the grid side part voltage (V_{qs}, V_{ds}) and the common dc-link voltage. The battery storage device is connected on the grid side with a PID controller. The detailed configuration of this system is described as below.

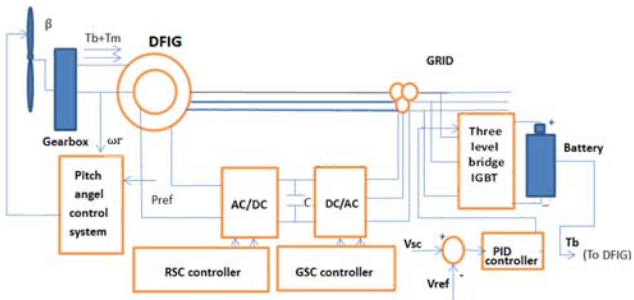

FIGURE 2: SCHEMATIC OF A DFIG WIND TURBINE SYSTEM WITH BATTERY STORAGE DEVICE

A. Modeling of Induction Generator

Based on the Kirchhoff's law, voltage equations and flux linkage of the wind turbine are obtained. The reference frame used here is synchronous q d reference frame [11]. The electric equations are shown as follows,

$$Vq_s = -R_s \times Iq_s + \omega_s \times \lambda d_s + \partial \lambda q_s \tag{1}$$

$$Vq_r = R_r \times Iq_r + (\omega_s - \omega_r) \times \lambda d_r + \partial \lambda q_r \tag{2}$$

$$Vd_s = -R_s \times Id_s - \omega_s \times \lambda q_s + \partial \lambda d_s \tag{3}$$

$$Vd_r = R_r \times Id_r - (\omega_s - \omega_r) \times \lambda q_r + \partial \lambda d_r \tag{4}$$

$$\lambda q_s = -L_s \times Iq_s + L_m \times Iq_r \tag{5}$$

$$\lambda d_s = -L_s \times Id_s + L_m \times Id_r \tag{6}$$

$$\lambda q_r = -L_m \times Iq_s + L_r \times Iq_r \tag{7}$$

$$\lambda d_r = -L_m \times Id_s + L_r \times Id_r \tag{8}$$

where the subscripts s represent quantities in the stator side and r represent quantities in the rotor side. λ is the flux linkage. V is the voltage. I is the current. R is the resistance. L is the self inductances. ω_s is the stator frequency related with the grid frequency.ω_r is the speed of the rotor. L_m is the mutual inductance.

The air gap torque and mechanical torque [11] are obtained as follows,

$$T_e = \frac{3P_p}{2}(\lambda d_s \times Iq_s - \lambda q_s \times Id_s) \tag{9}$$

$$T_m = \frac{P_m}{\omega_r} \tag{10}$$

where P_P is the number of pole pairs. P_m is the mechanical power.

B. Modeling of Battery Storage

In the present model, a nickel-metal-hydride type battery is employed. The discharge model and charge model of the battery are shown in equation (11) and equation (12) respectively [12].

$$f_1(it,i*,i,Exp) = E_0 - K \cdot \frac{Q}{Q-it} \cdot it + \text{Laplace}^{-1}\left(\frac{Exp(s)}{Sel(s)} \cdot 0\right) \tag{11}$$

$$f_2(it,i*,i,Exp) = E_0 - K \cdot \frac{Q}{|it|+0.1Q} \cdot i* - K \cdot \frac{Q}{Q-it} \cdot it + \text{Laplace}^{-1}\left(\frac{Exp(s)}{Sel(s)} \cdot \frac{1}{s}\right) \tag{12}$$

where E_0 is the voltage. *Exp(s)* denotes the exponential zone dynamics. K is the polarization resistance. Q is the maximum battery capacity. i* is low frequency current dynamics. i is the battery current. it denotes the extracted capacity. Sel(s) represents the mode of the battery, and Sel(s) = 0 during battery discharge, Sel(s) = 1 during battery charging.[12]

The battery is connected on the grid side and is controlled by a PID controller. When the Sel(s) reaches to zero, the battery provides the power to the grid. Whens Sel(s) is one, the battery is charging.

III. RESULTS AND DISCUSSION

In this section, DFIG wind turbine system described in Fig. 1 and Fig. 2 are simulated using Matlab/simulink. Three different wind conditions are used in the simulation to investigate the smoothing control effect of the present model and the conventional model under various wind conditions. A constant wind, a sinusoidal-type wind and a step-type wind are used as the wind conditions as shown in Fig. 3.

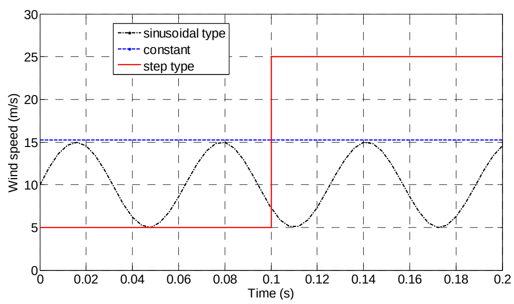

FIGURE 3: THREE DIFFERENT WIND CONDITIONS

A. Constant Wind

In the first case, the input of the model is a constant signal. The speed of the wind is 15.25 m/s, which is the average yearly wind speed in Sydney, Australia. The simulation time is 0.2 s. Fig. 4 shows the active power, reactive power of wind turbine, voltage of converter with time using the conventional wind turbine system. It can be seen that the active power and reactive power is not flat even though the RSC controller, GSC controller and pitch angle controller is used.

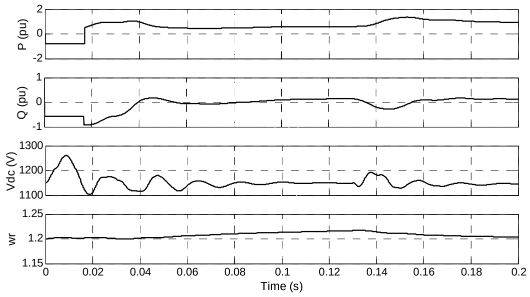

FIGURE 4: THE RESPONSE OF ACTIVE POWER, REACTIVE POWER, VOLTAGE AND ROTOR SPEED

Using the present model with the battery storage system, we obtain the active power, reactive power of wind turbine, voltage of converter with time by Matlab/simulink. We found that the active power and reactive power are much stable compared with those by the conventional wind turbine. As we mentioned before, the battery storage system is connected to the grid, and the converter is controlled by the PID controller. Hence, Vdc is not sensitive with the energy storage and release from the battery storage device. We also find that the reactive power is close to zero. If the reactive power is stable, the wind turbine system operates at a unity power factor and improves the stability of the energy. Also the rotor speed is almost a constant at around 1.2 pu rated.

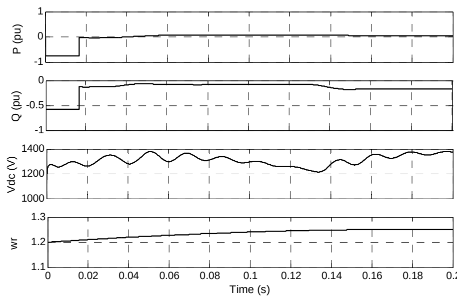

FIGURE 5: THE RESPONSE OF ACTIVE POWER, REACTIVE POWER, VOLTAGE AND ROTOR SPEED

B. *Sinusoidal-type Wind*

In the second case, the wind is modeled using a sinusoidal signal. The mean speed of the wind is set to 10 m/s. Amplitude of the wind is also 10 m/s. The simulation time is 0.2 s. Fig. 6 shows the active power, reactive power of wind turbine, voltage of converter with time using the conventional wind turbine system. In this case, the active power and reactive power is still not flat even though the RSC controller, GSC controller and pitch angle controller are considered.

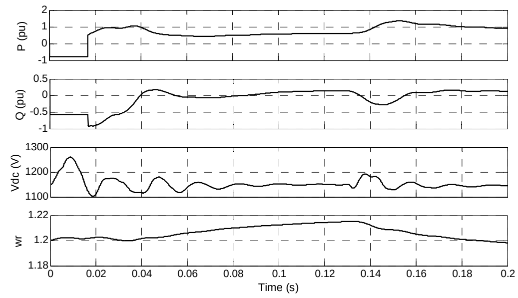

FIGURE 6: THE RESPONSE OF ACTIVE POWER, REACTIVE POWER, VOLTAGE AND ROTOR SPEED

We obtain the active power, reactive power of wind turbine, voltage of converter with time by Matlab/Simulink using the current model, and the result are shown in Fig. 7. We observe that the active power and reactive power is much stable compared with those by conventional wind turbine. As we mentioned in the section 2, the battery which is controlled by a PID controller is connected to the grid side. Due to the effect of battery storage device, the power output is much stable. And the speed of the rotor increases with the time.

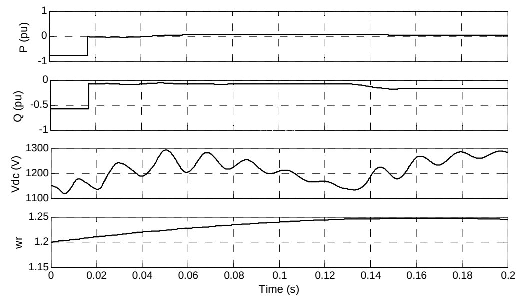

FIGURE 7: THE RESPONSE OF ACTIVE POWER, REACTIVE POWER, VOLTAGE AND ROTOR SPEED

C. *Step-type Wind*

In the third case, we consider an extreme situation that the wind suddenly increases. We use a step signal to model this case. The wind is set to 5 m/s at first. After 0.1s, the wind suddenly increases to 25 m/s, and keeps constant. The simulation time is 0.2 s. in Fig. 8, the active power, reactive power of wind turbine, voltage of converter with time is shown using the conventional wind turbine system. The simulation result shows that the active power and reactive power fluctuates, although the RSC controller, GSC controller and pitch angle controller is employed in this model.

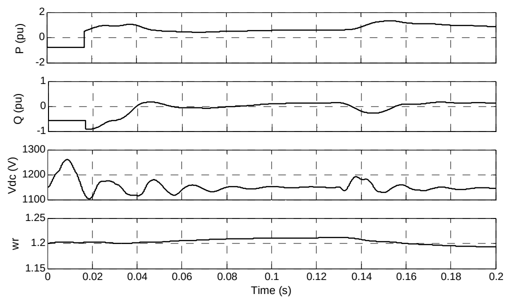

FIGURE 8: THE RESPONSE OF ACTIVE POWER, REACTIVE POWER, VOLTAGE AND ROTOR SPEED

Use the current model, active power, reactive power of wind turbine and voltage of converter are determined. The active power demand of the grid is around 10 kW at first and it reduces to around 1kW only after 0.06s.

The results show that the reactive power is close to zero. The rotor speed is almost constant of approximately 1.2 pu rated. Compared with the results of conventional wind turbine system, the active power, reactive power and voltage is much stable by the current model. Hence, the battery storage control device successfully obtains a smooth power output for the DFIG wind turbine.

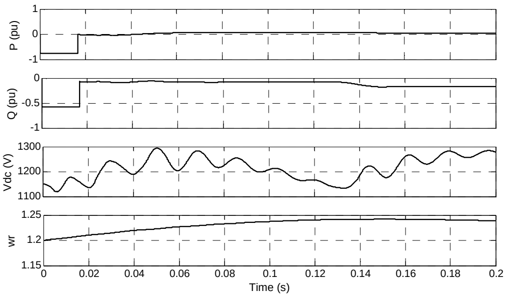

FIGURE 9: THE RESPONSE OF ACTIVE POWER, REACTIVE POWER, VOLTAGE AND ROTOR SPEED

IV. CONCLUSIONS

In this work, a model for the operation and control of a DFIG wind turbine integrating with battery storage devices has been developed, and the response of the model under different wind condition are obtained. The following conclusions can be drawn:

(1) Battery storage device was included in the present model and was connected to the grid side. PID controller was employed to estimate a smooth energy output.

(2) The present models determine a much smoother energy output compared with the conventional wind turbine model under various wind conditions.

(3) Compared to other models, our model has some advantages such as less cost, easily manufacturing and maintenance, and can be used in wind energy industry.

REFERENCES

[1] S. Muller, M. Deicke and R. W. De Doncker, "Doubly fed induction generator systems for wind turbines". Industry Applications Magazine, vol. 8(3), pp. 26-33, 2002.

[2] A. V. Prabhugaonka, D. S. Bankar and D. B. Talange, "Modeling and analysis of DFIG wind turbine". Journal of Engineering Research and Studies, vol. 3(2), pp. 72-76, 2012.

[3] Z. J. Wu, C. X. Zhu and M. Q. Hu, "Improved control strategy for DFIG wind turbines for low voltage ride through. Energies", 6, pp. 1181-1197, 2013.

[4] N. Mendis, K. M. Muttaqi and S. Perera, "Active power management of a super capacitor-battery hybrid energy storage system for standalone operation of DFIG based wind turbines". in: IAS : IEEE, pp. 1-8, 2012.

[5] N. Mendis, K. M. Muttaqi, S. Sayeef and S. Perera, "Autonomous operation of wind-battery hybrid power system with maximum power extraction capability". International Conference on Power System Technology, pp. 1-7, 2010.

[6] N. Mendis, K. M. Muttaqi and S. Perera, "Management of low- and high-frequency power components in demand-generation fluctuations of a DFIG-based wind-dominated RAPS system using hybrid energy storage". IEEE Transactions on Industry Applications, vol. 50(3), pp. 2258-2268, 2014.

[7] V. C. Ganti, B. Singh, S. K. Aggarwal and T. C. Kandpal, "DFIG-based wind power conversion with grid power leveling for reduced gusts". IEEE Transactions on Sustainable Energy, vol. 3(1), pp. 12-20, 2012.

[8] Z. H. Jiang and X. W. Yu, "Modeling and control of an integrated wind power generation and energy storage system". Power and Energy Society General Meeting, pp. 1-8, 2009.

[9] K. Ibrahima and C. Y. Zhao, "Modeling of wind energy conversion system using doubly fed induction generator equipped batteries energy storage system". Electric Utility Deregulation and Restructuring and Power Technologies, pp. 1780-1787, 2011.

[10] R. Sarrias, L. M. Fernandez, C. A. Garcia and F. Jurado, "Supervisory control system for DFIG wind turbine with energy storage system based on battery". International Conference on Power Engineering, Energy and Electrical Drives, pp. 1-6, 2011.

[11] L. Ran, J. R. Bumby, P. J. Tavner. "Use of turbine inertia for power smoothing of wind turbines with a DFIG". International Conference on Harmonics and Quality of Power. pp. 106-111, 2014

[12] "Matlab Documentation". 2011