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Simulation for Pitch Angle Control Strategies of a Grid-Connected Wind Turbine System on MATLAB/Simulink

Kyoung-Soo Ro* · Joon-Ho Choi

Abstract

This paper presents a pitch angle controller of a grid-connected wind turbine system for extracting maximum power from wind and implements a modeling and simulation of the wind turbine system on MATLAB/Simulink. It discusses the maximum power control algorithm for the wind turbine and presents, in a graphical form, the relationship of wind turbine output, rotor speed, and power coefficient with wind speed when the wind turbine is operated under the maximum power control algorithm. The objective of pitch angle control is to extract maximum power from wind and is achieved by regulating the blade pitch angle during above-rated wind speeds in order to bypass excessive energy in the wind. Case studies demonstrate that the pitch angle control is carried out to achieve maximum power extraction during above-rated wind speeds and effectiveness of the proposed controller would be satisfactory.

Key Words : Wind Turbine System, Maximum Power Extraction, Pitch Angle Control, Simulink

1. Introduction

In recent years, a wind turbine system is getting a great attention as an environmentally benign technology since it becomes cost- competitive compared to the conventional power generations. The wind turbine system can be categorized by the types of generators used, power control methods, constant or variable speed operation, and methods of interconnecting to the grid. Since wind energy does not vary constantly and its output is proportional to the cube of wind speed, the generated wind power fluctuates. If the capacity factor of wind turbine generators in a power system increases, evaluation of their impact on power system dynamics needs to be accompanied.

Many research results have been reported on the control of wind turbine generators. High-voltage dc link based on voltage-source converters, which supply a weak ac network for power produced from an offshore wind farm, is discussed in [1]. The link keeps the ac voltage fluctuations at an acceptable level with the control system based on adaptive fuzzy controllers. Since many wind turbine generators are grouped together in wind

* Main author : Department of Electrical Engineering at Dongguk University
Tel : +82-2-2260-3346, Fax : +82-2-2260-3346
E-mail : ksro@dgu.ac.kr
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turbine generators are grouped together in wind parks, modeling fixed-speed wind turbine generators in a wind park for transient stability studies has beeen proposed [2]. Compared with fixed speed operation, variable speed operation of wind turbines provides about 15[%] higher energy yield in spite of cost addition. Intelligent maximum power extraction algorithm for inverter-based variable-speed wind turbine generators [3] and a general model for representing of variable-speed wind turbines for power system dynamic simulation [4] are presented. Recently development of doubly-fed induction generators for wind turbine gets increased interest since they have better characteristics such as reduced inverter cost, improved system efficiency, and power-factor control with lower cost [5-7]. Operation of variable-speed wind turbines with pitch control is presented in [8]. Variable speed control has been added to pitch-angle controlled design in order to improve the performance of the system, but the claim that the target power is proportional to the cube of rotor speed is not correct when a pitch angle control is adopted. Reducing output power fluctuation of wind turbine generators for all operating regions by pitch angle control is proposed [9]. It uses a control strategy based on the average wind speed and standard deviation of wind speed.

This paper focuses on a pitch angle controller design and modeling of a grid-connected wind turbine system including induction generators on MATLAB/Simulink. It discusses the maximum power control algorithm for the wind turbine and presents, in a graphical form, the relationship of wind turbine output, rotor speed, and power coefficient with wind speed when the wind turbine is operated under the maximum power control algorithm. A pitch angle controller is introduced to extract maximum power from wind and it is achieved by efficiently regulating the blade pitch angle during above-rated wind speeds in order to bypass excessive energy in the wind. Case studies are going to demonstrate that the pitch angle control is carried out to achieve maximum power extraction during above-rated wind speeds.

2. Aerodynamic characteristics

The energy conversion in a wind turbine can be described by the nonlinear equation of (1).

$$P_m = \frac{1}{2}\rho A v^3 C_p(\lambda, \beta) \tag{1}$$

where $P_m[W]$ is the power captured from wind by the wind turbine, $\rho[kg/m^3]$ is the air density, $A[m^2]$ is the cross-sectional area of the wind turbine rotor, $v[m/\sec]$ is the wind speed, C_p is the power coefficient of the wind turbine, and β is the pitch angle of the rotor blade. And λ is the tip-speed ratio, which is defined by the following equation.

$$\lambda = \frac{\omega_m R}{v} \tag{2}$$

where $\omega_m[rad/\sec]$ is the rotational speed of the rotor, and $R[m]$ is the radius of the rotor blades.

The power captured by the wind turbine depends highly on C_p for a given wind speed, and the relationship of C_p with λ represents output characteristics of the wind turbine. Fig. 1 illustrates an example of $C_p-\lambda$ characteristic curves for different pitch angles, and the curves were drawn using the following equation [10]

$$C_p = 0.4654\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{\frac{-20.24}{\lambda_i}} \tag{3}$$

where

$$\frac{1}{\lambda_i}=\frac{1}{\lambda+0.08\beta}-\frac{0.035}{\beta^3+1} \quad (4)$$

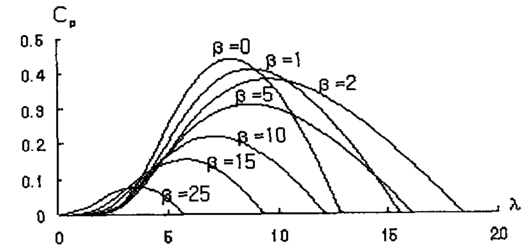

Fig. 1. Characteristic curves of a wind turbine for different pitch angles

The figure shows power coefficient changes with tip-speed ratio variations for a specified pitch angle and there is one λ value for which the corresponding C_p value is maximized. When the pitch angle increases, the C_p value is reduced, but overall trend of the curve is maintained.

3. Optimal algorithm for wind turbine control

In practice, there exist limits on the wind turbine operation for wind speed variations due to the system's mechanical or electrical limitations. This gives rise to the rotor speed control requirement in order to capture maximum available wind power as well as to protect the rotor and generator facilities from mechanically or electrically overloading at high wind speeds. With taking these limitations into account, Fig. 2 shows the speed control requirement without having the pitch angle adjustments involved.

The figure displays the relationships between the rotor power, the turbine rotating speed, and the power coefficient and the wind speed, where vci is the cut-in wind speed, vs is the wind speed at which the rotor speed reaches to its maximum, vr is the rated wind speed, and vco is the cut-out wind speed.

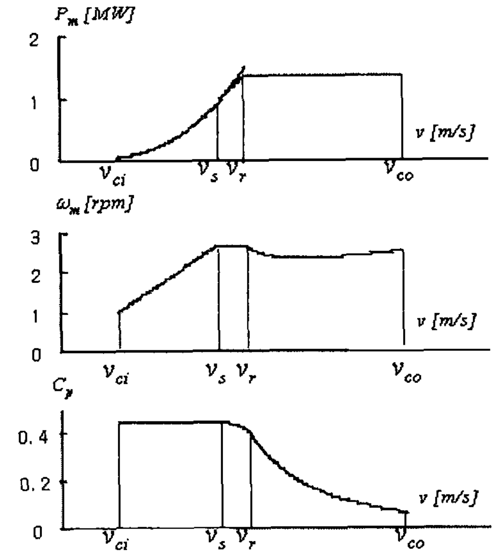

Fig. 2. Operational modes of a wind turbine considering limitations

The speed control requirement contains three regions such as maximum C_p region, constant speed region, and constant power region when the speed limit reaches earlier than the power limit; otherwise, the speed control would require two regions without the constant speed region.

In the constant maximum C_p region, the rotor speed is controlled with the variations of wind speed in order to operate at the constant maximum C_p value, which corresponds to the constant tip-speed ratio. As a consequence, the rotor power increases with the cube of the wind speed whereas the turbine speed changes linearly proportional to the wind speed.

When high winds make the turbine speed reach to the speed limit, the wind turbine is controlled to keep the turbine speed from varying. The C_p value is not maximized any more, thus decreasing slowly and the rotor power increases at a lower rate than that in the constant maximum C_P region.

When the wind speed belongs to the constant power region, the wind turbine is controlled to keep the rotor power constant by lowering the rotor speed. The constant power requirement can also be achieved by adjusting the pitch angle of the blades to shed the power captured by the wind turbine, but this effect is not represented in the figure.

4. System Modeling

Fig. 3 shows the block diagram of the wind turbine system with a loop of pitch angle controller. Characteristic data about the wind turbine system used in this work are given in Table 1.

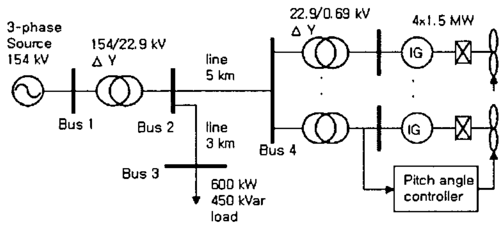

Fig. 3. Configuration of a grid-connected wind turbine system

Table 1. Data of wind turbine system

Wind turbine rating	1.5[MW]
Max. power coefficient	0.41
Radius of rotor	32[m]
Cut-in wind speed	4[m/s]
Rated wind speed	13[m/s]
Cut-out wind speed	24[m/s]
Air density	1.05[kg/m³]

The Simulink model of Fig. 3 is depicted in Fig. 4 and that for the drive train of the wind turbine system is in Fig. 5. The generator model used is a three-phase squirrel-cage induction machine that is provided in Simulink library. The induction machine can be operated as a generator when it is rotated beyond the synchronous speed.

The purpose of the pitch angle controller is to maintain the rated power during above-rated wind speeds by adjusting the pitch angle of the rotor blades. Adjusting the blade pitch angle provides fast variation of the turbine power by capturing less power from wind during above-rated wind speeds. Fig. 6 illustrates a model for such a pitch angle controller. This mechanism can be accomplished by an electro-mechanical actuator.

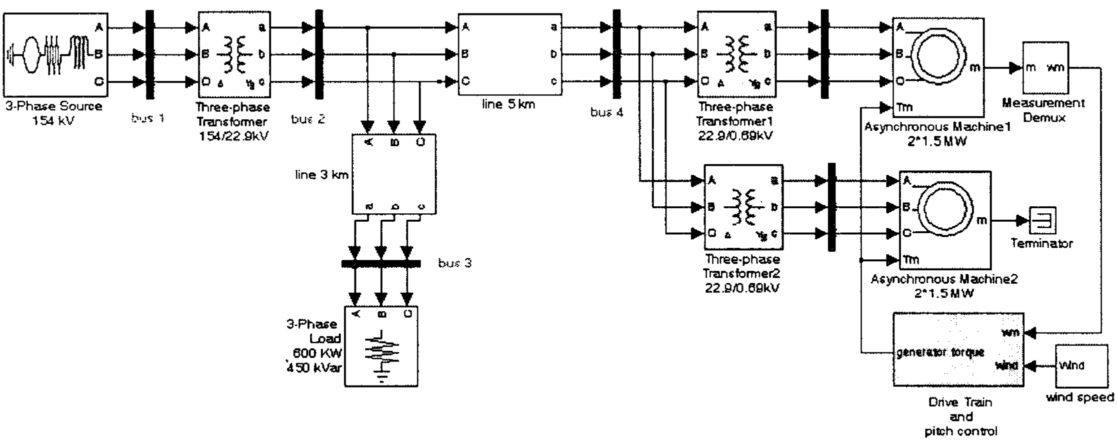

Fig. 4 Simulink model of a grid-connected wind turbine system

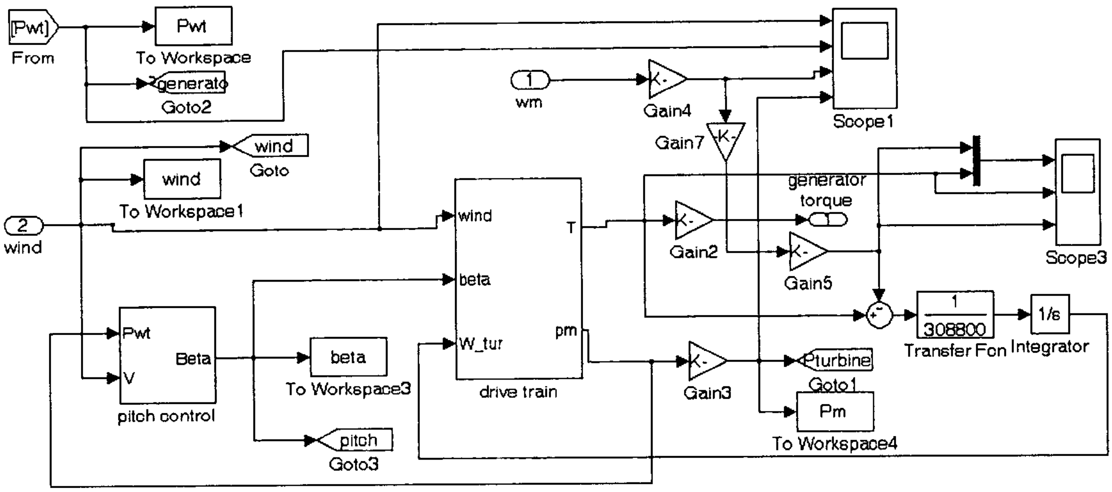

Fig. 5. Simulink model for the drive train and pitch control

5. Simulation and Discussions

This section verifies the performance of the proposed controllers by looking into the responses of the closed-loop wind turbine system to a wind speed variation. Randomly varying wind speed variation is illustrated in Fig. 7, where the wind speeds are above the rated from 3 to 25 second.

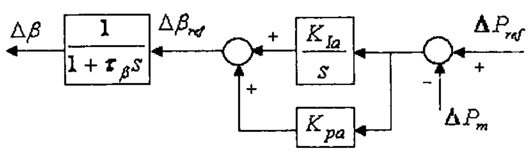

Fig. 6. Model for pitch angle control

The wind speeds in Fig. 7 are used to evaluate the performance of the wind turbine system having the pitch angle controller. For continuously varying wind speeds, the power output of the wind turbine generator will be changing accordingly. Variations of generator rotational speed, electrical torque of generator, pitch angle, generator terminal voltage, and active/reactive power for generator and grid are illustrated from Fig. 8 to Fig. 13, respectively.

According to those figures, the above variables are kept around the rated values at wind speeds above the rated due to the pitch angle controller. On the other hand, at wind speeds below the rated, those variables follow obviously the trend of the wind speeds.

Fig. 8 shows the generator's rotational speed variations with respect to wind speeds and its narrow variations above 1 pu illustrates the constant-speed operation of the wind turbine system. Fig. 9 illustrates the variations of generator's electrical torque. It displays negative values for generation operation of induction machines. Fig. 10 shows the variation of the generator terminal voltage, which is less than 1 pu during the wind speeds above the rated since the generator demands more reactive power. Rated constant power operation at wind speeds above the rated is achieved to bypass excessive energy in the wind by regulating the blade pitch angle, and the variations of the blade pitch angle are shown in Fig. 11.

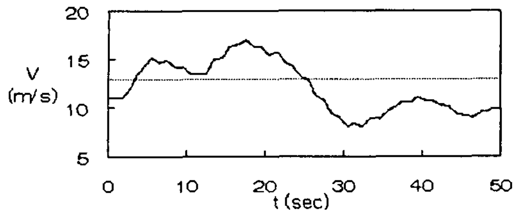

Fig. 7. Wind speed variation

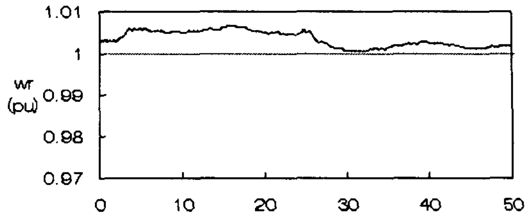

Fig. 8. Generator rotational speed

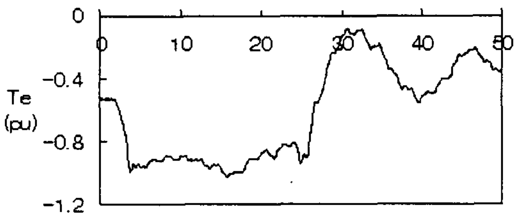

Fig. 9. Electrical torque of generator

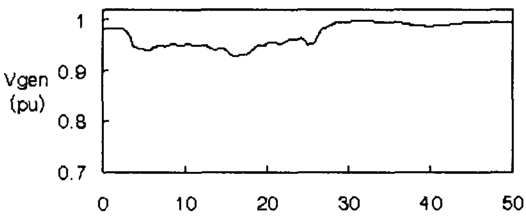

Fig. 10. Generator terminal voltage

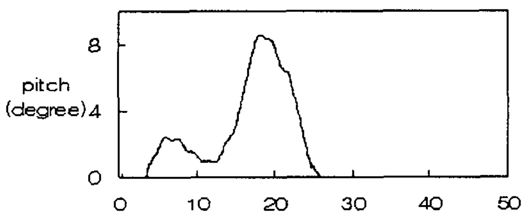

Fig. 11. Pitch angle variation

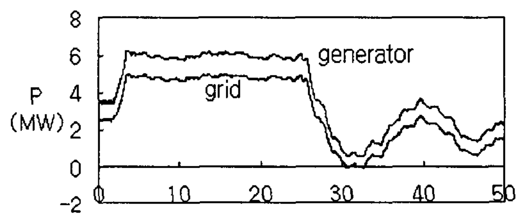

Fig. 12. Active power of generator and grid

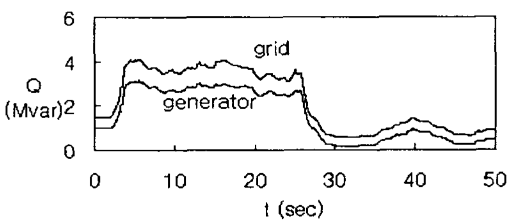

Fig. 13. Reactive power of generator and grid

Fig. 12 shows the variations of active power of the generator and grid. The figure represents that the generator output power is kept nearly constant during higher wind speeds and follows the trend of the wind speeds at the other regions. The difference values between the two curves represent the 600[kW] load at bus 3. Fig. 13 illustrates the variations of reactive power of the generator and grid. Reactive powers at grid side are larger than those at the generator terminal since the grid should supply reactive power to both the generator and 450kVar load at bus 3.

6. Conclusion

This paper presented a pitch angle controller of a grid-connected wind turbine system for extracting maximum power from wind and implemented a modeling and simulation of the wind turbine system on MATLAB/Simulink. It discussed the maximum power control algorithm for the wind turbine and presented, in a graphical form, the relationship of wind turbine output, rotor speed, and power coefficient with wind speed when the wind turbine is operated under the maximum power control algorithm. A pitch angle controller was introduced to extract maximum power from wind and it was achieved by efficiently regulating the blade pitch angle during above-rated wind speeds in order to bypass excessive energy in the wind. Simulation results demonstrated that the generation output power is maintained nearly constant at rated value and the effectiveness of the proposed controller would be satisfactory.

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◇ Biography ◇

Kyoung-Soo Ro

He obtained B.S. and M.S. degrees from Seoul National University, Seoul in 1985 and 1987, respectively. He received his Ph.D degree at the Virginia Polytechnic Institute and State University, Blacksburg, Virginia in 1997. He was a Visiting Professor at Arizona State University, Tempe, Arizona in 2005. He is currently an Associate Professor with Department of Electrical Engineering at Dongguk University, Seoul. His main areas of interest are renewable energy (wind power and photovoltaics) applications to power system and power industry deregulation.

Joon-Ho Choi

He received the B.S., M.S., and Ph.D. degrees in electrical engineering from Soongsil University, Seoul, Korea, in 1996, 1998, and 2002, respectively. Currently, he is an Assistant Professor with Chonnam National University, Gwangju, Korea. He was a Postdoctoral Fellow at the School of Electrical Engineering and Computer Science, Seoul National University, Seoul, Kora, in 2003. His research interests include operation and integration strategies of distributed generation and distribution automation systems.