Effect of Stochastic Wind Loads on Wind Turbine

Pradya Prempraneerach*, Wirachai Roynarin, Terdkiat Limpeteeprakarn
Department of Mechanical Engineering, Faculty of Engineering
Rajamangala University of Technology Thanyaburi
ppradya@gmail.com, wirachairoynarin@yahoo.com, terdkiat@rmutt.ac.th

Abstract—In the presence of wind turbulence and temperature variation, electrical power produced by wind turbine is very difficult to predict in advance. The uncertainty of captured energy from wind speed fluctuation is investigated to estimate the probability of electrical energy, supplying to the grid. Therefore, this paper presents the stochastic modeling of wind loads and modeling of wind turbine using a permanent magnet generator along with pitch-angle and speed controls. Stochastic wind velocity can be simulated as a gaussian random process according to a specified power spectral density. The model of wind turbine consists of the permanent magnet generator represented in the dq-synchronous rotating reference frame, drive train, variable speed control using a simplified vector control technique, and pitch-angle control. With this control structure, the wind turbine can operate near its optimum tip-speed ratio. The complexity of the proposed wind turbine model, constructed using Matlab/Simulink, is kept to a minimum such that the captured and generated power can be considered from a statistical perspective within a short simulation time.

1. INTRODUCTION

As a demand of energy consumption increases rapidly and an environmental concern on carbon dioxide emissions from fossil fuel grows every year, many countries turn to renewable energy from Biomass, Solar, Geothermal, Hydro, and Wind Energy. By the end of 2020, Britain projects to increase its renewable energy usage from 1.3 percent (in 2005) to 15 percent [6], which is comparable to energy generated from 20,000 2MW wind turbines. This will reduce carbon emission by 16 percent, the largest reduction rate predicted in the European countries. Typically, a 2 megawatt (2MW) wind turbine can produce electrical energy worth £500,000 per year [4]. However, according to Britain's government statistics, on average the 2MW wind turbine supplies only 0.54MW to the grid due to an uncertainty in wind energy.

At present, two main types of the wind turbine, used in wind farms, are fixed speed [1] and variable speed wind turbines [8]. Previously, fixed speed wind turbines using induction generators provide low efficiency and poor power quality. As a technology advance, variable speed wind turbines combining with either doubly fed induction generators (DFIGs) or permanent magnet synchronous generators (PMSGs) optimize the operating efficiency by adjusting blade angle to maintain optimum tip speed ratio for a wide wind speed range. Thus, the PMSG with variable-speed control is a main focus in this study.

The purpose of this paper is to investigate the performance of the stand-alone wind turbine on generating electrical energy subjected to the stochastic wind load. First, the wind turbine modeling, consisting of the aerodynamic wind load, stochastic wind turbulence, PMSG, drive train, and speed- and pitch angle-controllers, is explained in detail in Section 2. Second, an operation of the wind turbine can be examined from dynamic responses of both electrical and mechanical subcomponents in Section 3. Lastly, when the perturbation of stochastic wind load, modeled as the gaussian random process, is applied to the turbine blade, we can examine a variation of electrical frequency and generated electrical power or power quality before supplying to the grid.

2. SYSTEM MODELING OF WIND TURBINE

The 2MW wind turbine with PMSG generally connects to the AC grid through an AC back-to-back converter, which is function as a Voltage Source Converter (VSC) [8] that allows to optimize the generator's speed with respect to the fluctuation of wind velocity. The aerodynamic wind model is described as a lumped nonlinear relation depending on wind velocity square. Random processes of the wind speed variation around a nominal or mean wind speed are then expressed as a sum of narrow-band multiple-frequencies with the magnitude proportional to the power spectral density. The PMSG is modeled in a dq-synchronous rotating reference frame such that a speed control, similar to the vector control, can be applicable. A 41 m long turbine blade is coupled to the PMSG through a gearbox with a gear ratio (N_g) of 77. The pitch-angle control helps to maintain the extracted wind power not to be above a generator's rated power. Figure 1 exhibits a Matlab/Simulink model of the variable speed wind turbine using the PMSG with the pitch-angle control, implemented in this study. Appendix provides all parameters of each component, modified from [8].

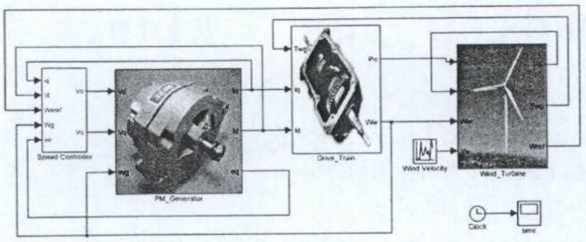

Fig.1 Matlab/Simulink model of the variable speed wind turbine using the PMSG with the pitch-angle control.

2.1 *Aerodynamic Model*

The extracted power of the wind turbine can produce a lumped aerodynamic torque, which proportional to wind velocity (V_w) square, given below

$$T_w = \frac{1}{2\gamma} \rho \pi R^3 V_w^2 C_p(\theta, \gamma). \tag{1}$$

Where ρ is the air density, R is the turbine blade length and C_p is power coefficient, expressed in equation (2). The C_p can be expressed as a function of a turbine pitch angle (θ) and a tip speed ratio ($\gamma = \omega_w R / V_w$), illustrated in Figure 2 for θ ∈ [2,26] degrees. The ω_w is a turbine blade rotational speed.

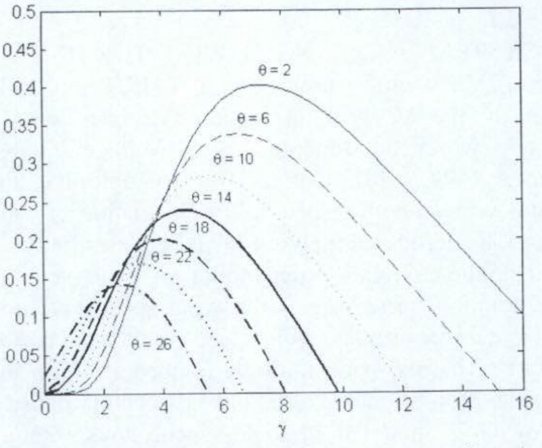

Fig.2 Power Coefficient, $C_p(\gamma,\theta)$, curve as a function of the tip speed ratio (γ) and blade pitch angle (θ), using in a wind power calculation.

$$C_p(\theta, \gamma) = 0.22\left(\frac{116}{\beta} - 0.4\theta - 5\right) e^{-\frac{12.5}{\beta}} \tag{2}$$

where

$$\beta = \left(\frac{1}{\gamma + 0.08\theta} - \frac{0.035}{\theta^3 + 1}\right)^{-1} \tag{3}$$

Then, the extracted mechanical power from wind can be described as $P_w = T_w \omega_w$.

2.2 *Wind Turbulence Model*

To generate a stochastic time-domain model of wind turbulence, the wind speed is approximated as a multi-frequency finite summation. The magnitude of wind velocity time history is constructed from a portion of narrow-band power spectral density (PSD). According to a NASA summary of atmospheric environment [7], the PSD of atmospheric turbulence, as shown in Figure 3, can be formulated as the following.

$$S_j(\omega_j) = \frac{12.3 \overline{V}_w h \left[\ln(10/z_0 + 1) \cdot \ln(h/z_0 + 1)\right]^{-1}}{1 + 192\left[h\omega_j \ln(10/z_0 + 1)/\overline{V}_w \ln(h/z_0 + 1)\right]^{5/3}} \tag{4}$$

The time-domain simulation of the wind speed around a nominal or mean wind velocity ($\overline{V}_w$) can be constructed from a finite summation of sine and cosine terms, shown below

$$V_w = \overline{V}_w + \sum_{j=1}^{n} \left(A_j \sin(\omega_j t) + B_j \cos(\omega_j t)\right), \tag{5}$$

where

$A_j = \sqrt{\frac{1}{2} S_j \Delta\omega_j} \sin\phi_j$, $B_j = \sqrt{\frac{1}{2} S_j \Delta\omega_j} \cos\phi_j$, and

ϕ_j is a uniform random phase varying between 0 and 2π. Combining the stochastic wind speed, in equation (5), with aerodynamic torque, in equation (1), can produce the uncertainty in wind loads.

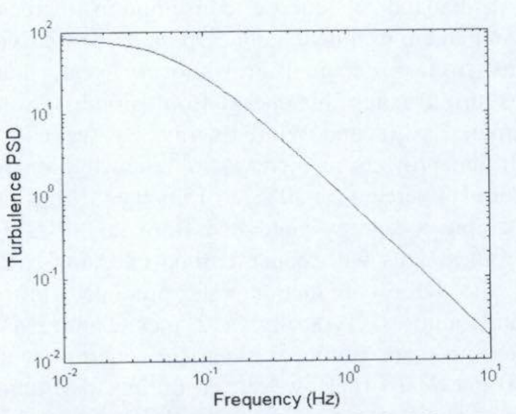

Fig.3 Power Spectral Density (PSD) of atmospheric turbulence

2.3 *Generator and Drive Train Model*

The variation in complexity of generator models depends on the study objective, ranging from a first-order model [2], a third-order model [3,8], and a fifth-order model [1,5]. In this study, we emphasize only on an interaction between the AC grid and the drive train, thus a one-lumped mass rotational inertia (J_{eq}) of the high-speed generator shaft and the low-speed turbine shaft is computational efficient and sufficient to capture system dynamics. Furthermore, the third-order PMSG model in the dq-synchronous reference frame, where the q axis leads the d axis by 90°, can adequately and accurately capture the generated electrical power (P_e). The dynamical PMSG model, represented by dq-currents as state variables, is given in equation (6) below.

$$\begin{aligned}\frac{di_d}{dt} &= -\frac{R_a}{L_d} i_d + \omega_e \frac{L_q}{L_d} i_q + \frac{1}{L_d} u_d, \\ \frac{di_q}{dt} &= -\frac{R_a}{L_q} i_q - \omega_e \left(\frac{L_d}{L_q} i_d + \frac{1}{L_q} \lambda_0 \right) + \frac{1}{L_q} u_q\end{aligned} \qquad (6)$$

where R_a is the armature resistance and (L_q,L_d) are the generator inductances in q- and d-axis. In this case, L_q=L_d for a simplification. The ω_e is the electrical rotational speed, which is related to the mechanical angular speed of rotor (ω_g) by $\omega_e = P \cdot \omega_g$. P is a number of generator pole. The (u_q,u_d) are the VSC voltage and λ_0 is the magnetic flux of stator permanent magnet. Counter electric potentials in the d-q frame (e_q,e_d), used in the speed control, are ($\omega_e\lambda_0$,0) respectively. Then, angular rotor speed and position can be derived from the following equations,

$$\begin{aligned}\frac{d\omega_g}{dt} &= \left(T_e - T_{w\_g} - B_m \omega_g\right) / J_{eq}, \\ \frac{d\alpha_g}{dt} &= \omega_g\end{aligned} \qquad (7)$$

where T_e and T_{w_g} are consequently the electromagnetic torque, described in equation (8), and the reduced mechanical torque from wind power, given by $T_{w\_g} = T_w/N_g$. B_m is the generator mechanical damping.

$$T_e = \frac{3}{2} P\left(\left(L_d - L_q\right) i_d i_q + i_q \lambda_0\right) = \frac{3}{2} P i_q \lambda_0 \,. \qquad (8)$$

The electrical power can be calculated from $P_e = T_e \omega_e$.

2.4 Speed and Pitch-Angle Control

According to [8], two control objectives of this variable speed wind turbine are (1) to maximize the extracted wind power by adjusting the turbine blade angle so that a maximum C_p can be obtained in light wind and (2) to maintain the generator output power at the rated power in strong wind by regulating u_q and u_d. A combination of the speed control and pitch-angle control is required to fulfill these control concepts. The pitch-angle control acts as a power limitation using a power feedback through a proportional-integral (PI) control and using a feed-forward wind velocity to adjust the turbine blade angle accordingly. Figure 4 shows a block diagram of this controller implementation. We assume $P_{eref} = P_w$ and neglect power loss associated with the gearbox. In the case of strong wind, above the rated wind speed (V_{rated}), the power coefficient decreases as the generator speed and tip speed ratio increase. On the other hand, this controller is inactivated and the turbine blade is fixed at 2 degrees when the wind velocity is below V_{rated}.

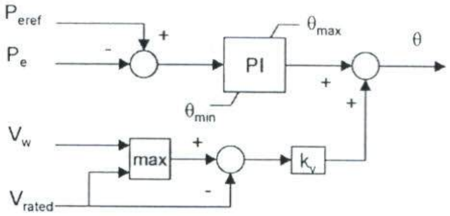

Fig.4 A block diagram of the pitch-angle control scheme.

The variable speed control regulates the generator's speed corresponding to the wind speed variation. Because of no reactive power transfer between the generator and machine side power converter, the vector control can be easily implemented for controlling the speed of PMSG, represented in the dq-synchronous reference frame. With an inner loop of a dq-current feedback with independent PI controllers, the u_d and u_q can be controlled. The i_{dref} is fixed at zero, but the i_{qref} is computed from velocity feedback ($\Delta\omega = \omega_{eref} - \omega_e$) passing through the PI control. The reference speed, ω_{eref}, is computed as the following: $\omega_{eref} = V_w \gamma N_g P / R$. In the generator's equation (6), the $\omega_e L_q i_q$ and $\omega_e L_d i_d$ terms must be feed forward to compensate for these cross-coupling terms. The variable speed controller, as shown in the leftmost block of Figure 1, can be implemented as a block diagram in Figure 5.

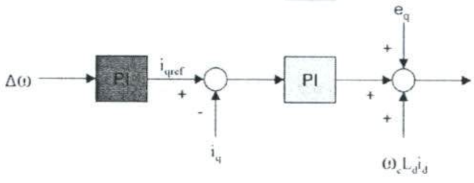

Fig.5 A block diagram of the variable speed control scheme.

3. SIMULATION RESULTS

First, the deterministic model of the variable speed wind turbine with PMSG, developed in Matlab/Simulink as shown in Figure 1, is tested with a sudden increase of the wind velocity from 8 m/s to 14 m/s. Deterministic responses of all important variables are plotted in Figure 6. Initially, with wind speed of 8 m/s, θ is kept constant at 2 degrees, which yields maximum values of C_p =0.4 and γ=8. When the wind speed suddenly increases to 14 m/s at 5 seconds, the pitch-angle controller spontaneously increases θ to 26 degrees and reduces the C_p value to around 0.1 at the same time. And the speed controller gradually increases the q- and d-axis VSC voltage, resulting in a slow acceleration of the generator speed. In the steady state regime, the pitch-angle controller adjusts the θ to 15 degrees such that the generated electrical power output, P_e, is limited to the rated power output of the 2MW PMSG. Note that a negative value of P_e indicates that it is the generated power.

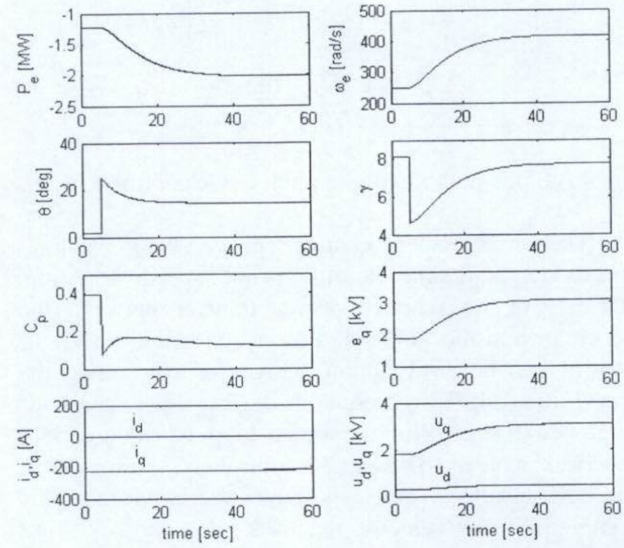

Fig.6 (Left Column): Deterministic responses of electrical energy (P_e), turbine pitch angle (θ), power coefficient (C_p), dq-axis current (i_d,i_q) from top to bottom rows; (Right Column): Deterministic responses of electrical rotational speed (ω_e), tip speed ratio (γ), q-axis counter electric potential (e_q), and dq-axis voltage (u_d,u_q) from top to bottom rows.

Second, when the wind speed becomes a gaussian random process, fluctuating around a mean value of 8 m/s, as shown in the topleft of Figure 8, the pitch-angle controller is non-actuated or the θ is kept constant at 2 degrees. As a result of the wind speed variation, the tip speed ratio and power coefficient are directly excited with the same frequency. On the other hand, the speed controller tries to maintain the generator speed around 250 rad/sec by regulating the q- and d-axis VSC voltages accordingly. The electrical power output varies between 1 and 1.5 MW. The probability density function, PDF, of V_w and P_e are illustrated in Figure 8. The PDF of V_w with its mean value around 8 m/s confirms that the V_w variation is a gaussian random process. Similarly, the PDF of P_e is closely approximated the gaussian distribution with a concentrated peak around 1.2 MW as well.

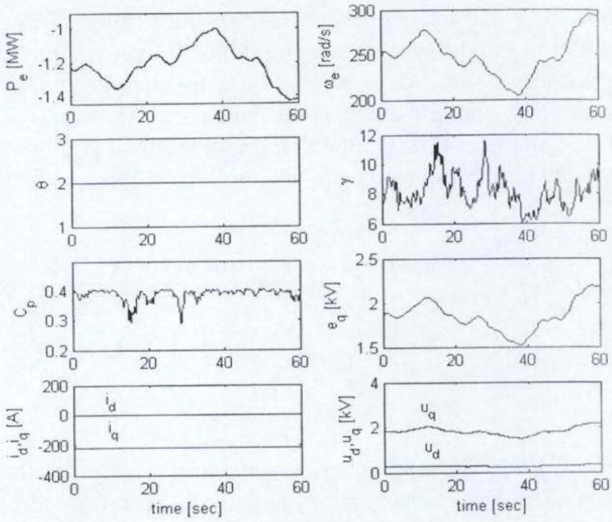

Fig.7 (Left Column): Stochastic responses of P_e, θ, C_p, i_d,i_q from top to bottom rows; (Right Column): Stochastic responses of ω_e, γ, e_q, and u_d,u_q from top to bottom rows.

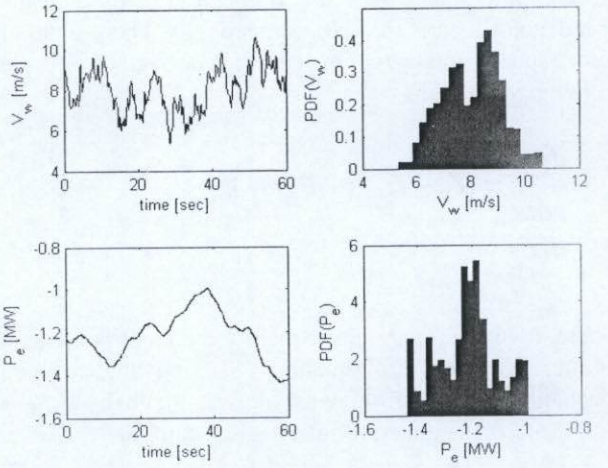

Fig.8 (Left Column): Stochastic wind speed and fluctuation of the generated electrical power from top to bottom rows; (Right Column): Their corresponding probability density function, PDF, of V_w and P_e from top to bottom rows.

4. SUMMARY

Using the model of the variable speed and pitch angle wind turbine using PMSG with the pitch-angle control, developed and implemented in Matlab/Simulink, the deterministic dynamic responses of both electrical and mechanical subcomponents can be predicted with a reasonable accuracy. The model complexity is sufficient to capture the interaction between electrical power output and aerodynamic wind power and to perform the computation efficiently. In addition, the probability of each variable, particularly the generated electrical power and frequency, can be employed to estimate the variation in the wind turbine performance and power quality before connecting to the grid, when stochastic wind turbulence excites the turbine blade.

5. ACKNOWLEDGEMENT

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