Steady-State Analysis of Permanent Magnet Synchronous Generator with Uncertain Wind Speed

Vikas Kumar Sharma and Lata Gidwani

Abstract This paper represents a platform for steady-state analysis of permanent Magnet Synchronous Generator (PMSG) based on uncertain wind speed. To evaluate the system performance such as torque, speed, current, voltage, and power of PMSG with considering the uncertain wind speed. This system consists of a wind speed model, wind turbine model, and PMSG model. The proposed wind speed model is put forward that could reflect the natural wind speed characteristics. The wind speed for wind turbine is used as an input, so that it captures the optimal power of wind and generates mechanical torque for PMSG. Mathematical analysis is used to demonstrate the efficacy of the model in d*q*-synchronous rotating reference frame of the generator. The steady-state analysis of the proposed PMSG uncertain wind speed model is evaluated with MATLAB/Simulink software.

Keywords Steady-state analysis · Permanent magnet synchronous generator (PMSG) · Uncertain wind speed · Wind turbine

1 Introduction

In the end of the twentieth century, it was nautical that the environment is getting polluted due to excess production of CO_2 and other similar elements. Advancement in the field of generation technology, countries all over the world are looking for green and clean generation sources. Renewable energy sources, especially wind generation is considered as the possible solution for this requirement [1]. Wind energy is the easily available source of nonrenewable source of energy. It is an indirect form of solar energy. The kinetic energy produced by the wind turbine is used to generate electrical energy. As by the use of wind energy, the carbon discharge also reduces. Among the entire energy source, wind energy is having maximum share because of low cost and less space requirement for the equipment installation [2].

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At present, generators for wind turbines is PMSG and induction generators which includes squirrel cage and wound rotor. Wind turbines with low power rating are of mainly PMSG and squirrel cage induction-type generators. These are often used because these are found suitable in terms of cost and reliability induction generators [3].

The main function of wind energy conversion system is that it extracts energy from the blade of the hub and transfer to the rotor of generator via a gearbox. We generally use PMSG because of its efficiency and in this, we have no need of gearbox. Elimination of gearbox is the main advantage of PMSG which are interfaced with voltage source converter [4].

Synchronous generator excitation is provided through permanent magnet with high energy. Because of relatively large number of poles, the permanent magnet construction would enable reduction in black iron and stator yoke. Nowadays, development of low speed and innovative synchronous machine, especially with permanent magnet excitation has received attention all over the world [5]. Permanent magnets could be considered as a potential solution for the excitation of synchronous generators. This would replace the excitation winding of synchronous generators. Hence, it reduces magnet price while improving the magnetic material characteristic [6]. Nowadays, variable speed turbine system is interfaced with electronics equipment and by doing this, we extracted maximum power with the control system. PMSG-based wind turbines are suitable in wind energy conversion system because of self-excitation property. These could operate at acceptable power factor and efficiency while offering economical solutions [7]. Steady-state model is formed considering PMSG, wind speed model ,and wind turbine. In wind turbine, rotor blades catch the wind energy and then, this is transferred to synchronous generator. PMSG converts mechanical energy into electrical energy. In steady-state analysis, wind generator is connected to load (see Fig. 1).

In this regard, this paper puts forward in detail modeling and steady-state analysis of PMSG-based wind turbine system and their control. The rest of the paper is structured as the detail mathematical modeling of wind speed, wind turbine, and PMSG are presented in Sect. 2. In Sect. 3, PMSG based with uncertain wind speed model simulation is discussed and conclusions are described in Sect. 4.

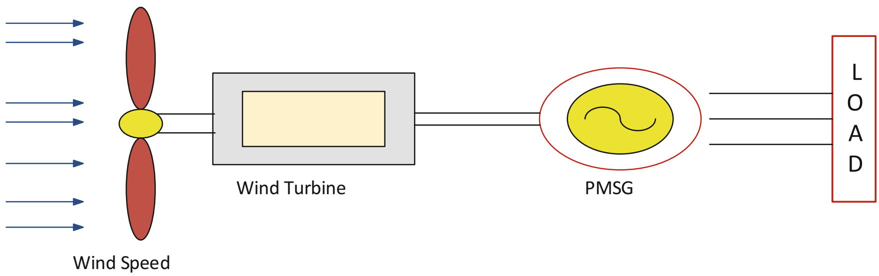

Fig. 1 Steady-state model of PMSG based wind power system

2 Mathematical Model of System

2.1 Mathematical Modeling of Uncertain Wind

The simulation of the uncertain wind in the MATLAB without wind can be done by mathematical model of wind speed. Here, this wind speed signal has four components, i.e., the basic speed of wind (V_B), a fluctuating wind speed (V_N) that describes a steady increase in wind speed, gust component (V_G), and a gradient wind component (V_R). The uncertain wind speed is sum of these components.

$$V_w(t) = V_B(t) + V_N(t) + V_G(t) + V_R(t) \quad (1)$$

2.1.1 Basic Wind Speed

It reflects the variation of mean wind speed during the whole process of wind turbines and also determines the size of rated power to the system. The basic systems find the change in mean speed of wind and determine size of rated wind turbine.

$$V_B = 0.1 + 0.824 N_W^{1.505} \quad (2)$$

where V_B is the basic wind speed of n-tire wind in m/s, N_W is the series of wind.

2.1.2 Fluctuating Wind Speed

To describe the random behaviors of wind and change of the speed at different heights and at different attitudes, the simulation of fluctuating wind is done. When the atmosphere is quiet or it is stable, the fluctuating wind can be considered as a stationary random process with sample at one point for a long time observation.

$$V_N = \frac{1}{\Delta t} \int_{t1}^{t2} V_W \mathrm{d}t = 0 \quad (3)$$

2.1.3 Gust of Wind

It tells us about characteristics of unexpected change in wind speed, i.e., wind speed with cosine characteristics with time. It is used to access the dynamic characteristics in the case of large wind speed change. It is the ratio of gust wind speed and average wind speed. It also related to turbulence intensity. It is given as

$$g(t) = 1 + 0.42\varepsilon u \ln \frac{3600}{t} \tag{4}$$

2.1.4 Gradient Wind

The gradient change characteristics of wind speed are a function of wind speed. It is used to describe the increase and decrease in the magnitude of wind speed.

$$V_R = \begin{matrix} 0 & 0 < T < t_{1r} \\ & V_{ramp} t_{1r} \leq T < r \\ & R_{max} t_{2r} < T \leq t_{2r} + t_r \end{matrix} \tag{5}$$

2.2 *Mathematical Modeling of Wind Turbine*

The mechanical power output of the wind turbine is given as

$$P_{wind} = \frac{1}{2} C_p(\lambda, \beta) \pi r^2 \rho_{air} V_W^3 \tag{6}$$

where ρ is the air density (kg/m^3), rotor radius of blades (m) is r, and V_W is the uncertain wind speed (m/s) C_p is the performance coefficient of the wind turbine. Which λ is the tip speed ratio, and the performance coefficient C_p is calculated by [8].

$$C_p = C_1 \left(C_2 \frac{1}{\alpha} - C_3 \beta - C_4 \beta^x - C_5 \right) e^{-C_6 \frac{1}{\alpha}} \tag{7}$$

β is function of pitch angle of rotor blades (in degree) when β is equal to zero, The tip speed ratio is defined as

$$\lambda = \frac{\omega_a r}{V_w} \tag{8}$$

where w_a is the rotor angular velocity (rad/sec) of the wind turbine generator. The output of wind turbine mechanical torque is defined as

$$T_{mech} = \frac{0.5 C_p \pi r^2 \rho_{air} V_w^3}{\omega_a} \tag{9}$$

2.3 Mathematical Modeling of PMSG

The dynamic model of PMSG is developed in dq rotating reference frame. The direct axis and quadrature axis voltage equation of generator is defined as

$$V_{\rm d} = -R_{\rm s} i_{\rm d} - L_{\rm d} \frac{{\rm d}i_{\rm d}}{{\rm d}t} + \omega_{\rm e} L_{\rm q} i_{\rm q} \tag{10}$$

$$V_{\rm q} = -R_{\rm s} i_{\rm q} - L_{\rm q} \frac{{\rm d}i_{\rm q}}{{\rm d}t} - \omega_{\rm e} L_{\rm d} i_{\rm d} + \omega_{\rm e} \mu_{\rm g} \tag{11}$$

where $\mu_{\rm g}$ the permanent flux of generator is, $\omega_{\rm e}$ is the electrical speed rotor in rad/s of the generator. The electromagnetic torque of generator is defined as

$$T_{\rm elect} = \frac{3}{4} P \left[\mu_{\rm g} + \left(L_{\rm d} - L_{\rm q} \right) i_{\rm d} \right] i_{\rm q} \tag{12}$$

3 Simulation Result and Discussion

The simulation is carried out to demonstrate the effectiveness of modeling of wind turbine and PMSG. Figure 2 shows simulation model implemented in Sim Power System of the Mat Lab to analyze the performance of the PMSG based wind power system operation in steady-state mode. It is operated with load to determine the dynamic performance of the model. Table 1 provides simulation parameter of wind turbine and generator. The steady-state analysis of system has been carried out with uncertain wind speed. When system reaches at steady state, mechanical torque is equal to electrical torque and rotor angular speed becomes stable.

Figure 3 shows the uncertain wind output generated by the wind speed model. In this output the wind speed varies from 7 to 12 m/s in the duration of 0–1 s.

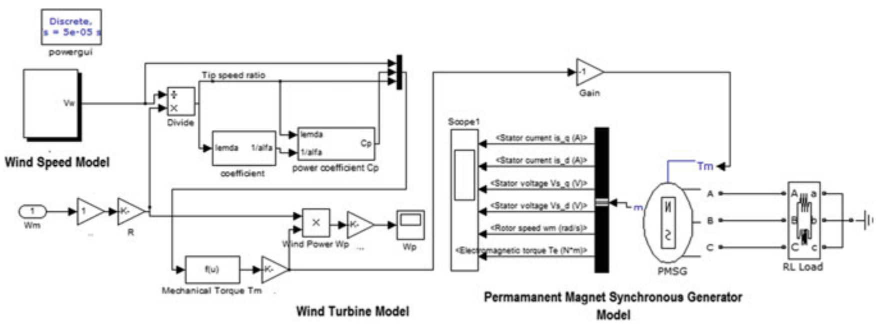

Fig. 2 Simulink modal of PMSG based wind power system

Table 1 PMSG parameter and wind turbine specification

Parameter	Value
Rated generated power (P)	2 MW
Stator resistance (R_s)	0.7305 m Ω
Stator d-axis inductance (L_d)	1.21 mH
Stator q-axis inductance (L_q)	2.31 mH
Permanent magnet flux (μ_g)	6.61 Wb
Equivalent inertia (J_{eq})	10,000 kg m^2
Number of pole pairs	30
Rotor radius of blades (r)	38 m

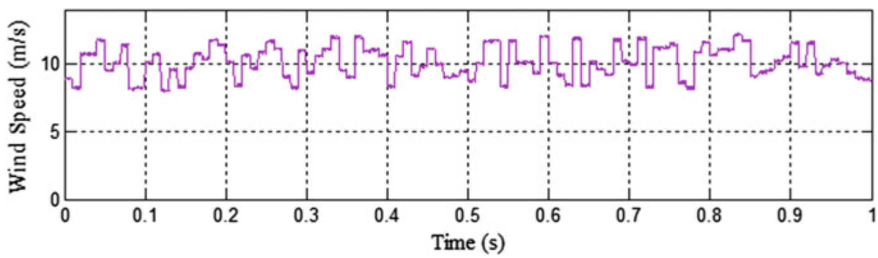

Fig. 3 Uncertain wind speed

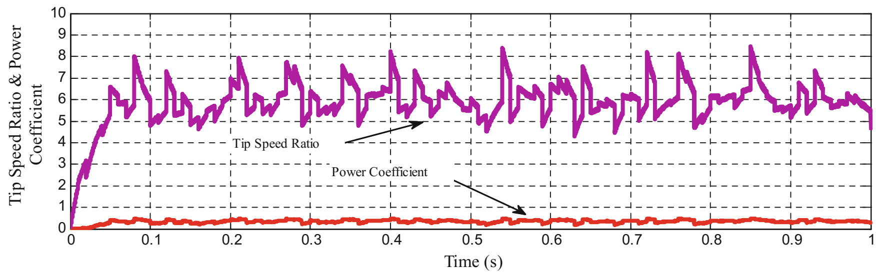

Fig. 4 Coefficient of power and TSR of wind turbine

It provides the uncertain wind input to wind turbine model. In Fig. 4, power coefficient of the wind turbine is maintained at 0.3–0.45 and in this, duration tip speed ratio is maintained 5–8 as per wind speed. Figure 5 show gives the steady-state conditions of wind turbine, so that mechanical torque equal to electrical torque. Figure 6 shows rotor speed of the generator. Figure 7 shows generated electrical power by the PMSG are gradually changed. Figures 8 and 9 shows the three-phase output voltage of PMSG is the line to line voltage and current. In the steady state, the entire performance variables include current, voltage, and power which are kept at their rated value.

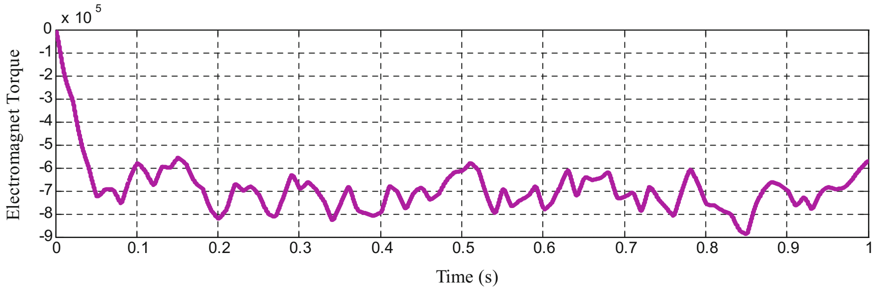

Fig. 5 Electromagnet torque developed by PMSG

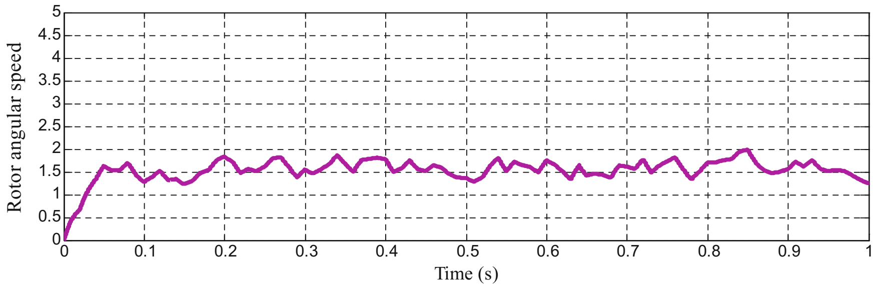

Fig. 6 Rotor angular speed of PMSG

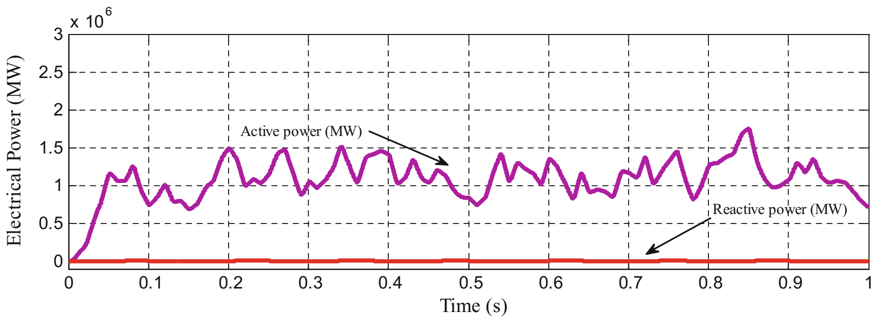

Fig. 7 Electrical power generated by PMSG

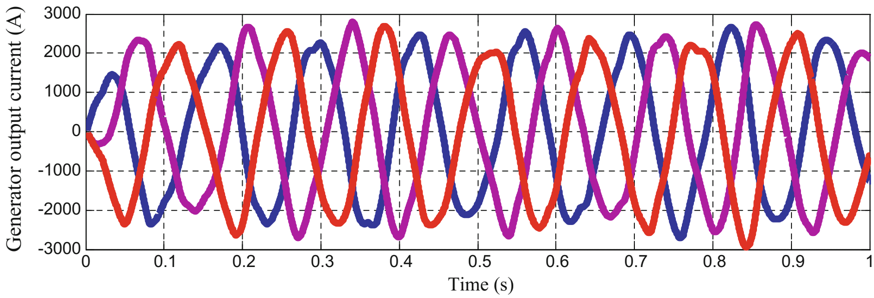

Fig. 8 Three phase output current of PMSG

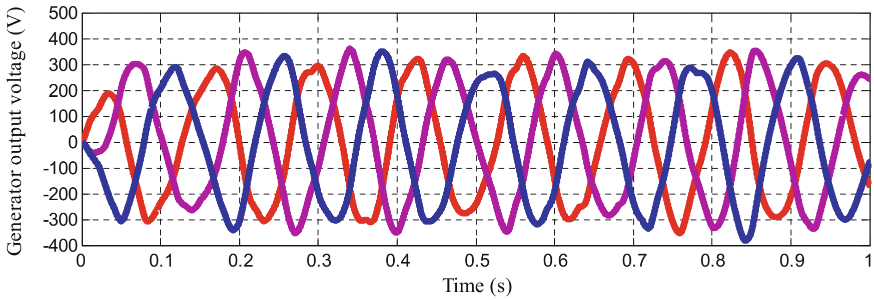

Fig. 9 Three phase output voltage of PMSG

4 Conclusion

This paper presents detail modeling and steady-state analysis of PMSG with uncertain wind speed system. The proposed model includes PMSG model, wind speed model, and wind turbine model. The proposed model is designed and implemented the MATLAB/Simulink platform. The efficacy of the proposed designed model is validated by building the dynamic model of the PMSG with uncertain system. Wind speed model quantifies the uncertain and randomness of wind speed. PMSG model is implemented with dq synchronous rotating reference frame and analysis is carried out for the steady-state mode. Simulation results verify the robustness and legitimacy of the implemented model in terms of quantification of uncertain wind speed while offering the parameters within the required limits. This model has the potential to provide a foundation for efficient quantification of uncertain wind speed.

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