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MODELING AND SIMULATION OF WIND POWER WITH PERMANENT MAGNET SYNCHRONOUS GENERATOR (PMSG)

Syafaruddin[1,*], Zaenab Muslimin[1], Fathul Razak Said[1]
Arnita Tri Ananda[1] and Satriani Latief[2]

[1]Department of Electrical Engineering
Universitas Hasanuddin
Jalan Perintis Kemerdekaan Km. 10 Tamalanrea, Makassar 90245, Indonesia
*Corresponding author: syafaruddin@unhas.ac.id

[2]Department of Architecture
Universitas Bosowa
Jalan Urip Sumoharjo Km. 4, Makassar 90231, Indonesia

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Abstract. *High dependency on fossil fuel can be reduced by utilizing renewable energy sources. One of the potential and promising energy sources is the wind power due to their abundant source in nature. In fact, the wind power technology is rapidly developing compared to other renewable energy sources due to the mature technology which can be seen from basic to advanced levels. Recently, the technology of generation of wind power is changed from families of induction generator to synchronous generator called permanent magnet synchronous generator (PMSG). This paper presents the modeling and simulation of permanent magnet synchronous generator using Matlab/Simulink model in order to understand its electrical behavior of model under wind speed variability. Several testing scenarios are performed including validation of output power based on wind speed and power coefficient to confirm the validity and accuracy of PMSG model.*

Keywords: Wind speed, DFIG, PMSG, Modeling and simulation, Wind power

1. **Introduction.** Wind power is the most rapid development and implementation of the renewable energy sources for power generation in the world. It has been increased about 30% in grid connection since the last decade. The motivation is mostly driven by the consistency target reduction of fossil fuel based power generation. The technology as well has reached the mature level denoted by high capacity of generation and its overall features can be competed with the conventional power generation. The advanced level of technology can be found in aerodynamic turbine and blade design, active and reactive power regulation for frequency and voltage control and generator types. As results, the output power from wind generation can be confirmed as smooth as hydro power generation.

In terms of generator development, there are doubly fed induction generator (DFIG) and permanent magnet synchronous generator (PMSG). DFIG is basically the latest developed conventional induction generator. It is well-known that the conventional induction generator can produce active power if the reactive power is available either by self-provision in internal machine by means of capacitor or absorbed from grid systems. The problems may come when the flexibility of power factor regulation is expected. To have more active participation in voltage and frequency control of wind power in grid connection, the induction generator might be automatically able to supply and absorb reactive power from the grid. In this respect, the doubly fed induction generators have capability to do so using automatic electronic control. As results, this generator may operate in lagging or leading power factor, smoother active power and more stabilized voltage connection. In comparison, the permanent magnet synchronous generators behave like the conventional synchronous generator where the active and reactive power is produced simultaneously. No gear box transmission in PMSG type is required to transfer from low speed, high torque in rotor turbine to high speed, low torque in rotor generator. The constant speed is provided by the compensation from the flux of permanent magnet. As results, the mechanism produces smooth torque and output power generation even under variable wind speed conditions.

The DFIG and PMSG are the most recently common technologies for wind power implementation worldwide. Nevertheless, there is still more open part of technology that needs to be improved. Besides the unbalanced voltage problem, DFIG still has many problems that need to be solved, for instance, stability analysis and reactive power compensation [1], grid fault [2] and optimal power tracking [3]. All efforts may bring the DFIG operation to reach the ultimate performance. Meanwhile, the PMSG has still many challenges in terms of finding solution regarding dynamic stability [4], provision of sophisticated control for grid connection [5] and flicker mitigation related to power quality [6], and so on. Many new proposed methods have been progressively achieved through modeling and simulation of wind turbine technology.

In terms of simulation, short time fault detection of DFIG and PMSG has been simulated with fault detection and isolation sensor design improvement characteristics combined with Kalman filter [7]. Meanwhile, the performance of DFIG under transient condition is simulated using symbolic-numeric computation (SNC) method compared with finite difference according to computational time cost [8]. Comprehensive simulation model for PMSG is proposed considering variable speed, two-mass rotor, different power converter topologies and filters [9]. All simulation efforts attempt to visualize the wind power technology more realistically and accurately for the latest development.

Meanwhile, a comprehensive dynamic model of direct-driven PMSG wind turbine is proposed using full scale converters and control scheme method as the simplification of state-space averaging technique [10]. The type of PMSG has potential in multi-pole design and no-gear construction with slow speed, brushless results in less maintenance, no excitation system, full control of wind power output and grid connection, fault ride-through and grid support. Another approach of modeling the PMSG for sensorless maximum power tracking control is proposed with diode-bridge for actual wind speed [11], maximum power control modeling of axial flux PMSG [12] and modeling and analysis of power smoothing with MPPT control [13]. In other approaches, the modeling of PMSG using voltage vector control is proposed for grid connected system based laboratory work [14]. Modeling and control of PMSG is proposed based on variable-speed wind turbine [15].

2. **Model Configuration of Permanent Magnet Synchronous Generator.** Modeling is very important in providing the fundamental knowledge for the wind power technology in order to come up with advanced design. We may understand the detailed aspects of turbine performance by looking for the output responses of modeling components. These outcomes are back-forward information and compromised for the ultimate turbine design and manufacture. The PMSG type can be viewed as conventional synchronous generator but the field excitation is provided from permanent magnet, not the dc coil excitation. Torque uniformity arises because the magnetic field generated from the induced currents in the three conductors of the armature winding is combined in such a way to resemble the magnetic field. The magnetic field of the stator emerged as rotating field and is stable with the same frequency of rotor when the rotor contains a single dipole magnetic field. Nevertheless, there were so many challenges of PMSG in wind power application, such as variability of wind speed, voltage and determining the optimal operating points. However, the advance in power electronics and control strategy implementation makes the output

voltage can be maintained stable, the machine architecture can be simplified and the wind power can be operated at the maximum power point.

Various types of permanent magnet generator synchronous (PMSG), namely: radial flux permanent magnet machine (RFPM), axial flux permanent magnet machine (AFPM) and transverse flux permanent magnet machine (TFPM) have been developed. RFPM engine produces a magnetic flux in the radial direction with permanent magnet which is also oriented radially. This type is the best choice for direct drive wind turbine. Meanwhile, AFPM machine is producing magnetic flux in the axial direction with a permanent magnet. It is available from low speed range and low power applications. In comparison, the TFPM produces magnetic flux perpendicular to the direction of rotation of the rotor. The construction of *permanent magnet synchronous generator* (PMSG) is simpler than other conventional synchronous generators for the reasons of dc excitation; slip ring and brush contact are not required. The magnetic flux density has high limited performance. The magneto motive force (mmf) torque vectorially continues to accumulate magnetic flux, resulting in high density of air gap magnetic flux.

The simulation is performed under Matlab/Simulink according to mathematical formulations. The main input of this modeling as shown in Figure 1 is the wind speed. The main control is related to speed generator control, and meanwhile pitch angle control regulates the angle between blade and wind speed direction (electrical model). The output of main controller is the torque of wind turbine. This torque is the input for two-mass drive train model (mechanical model). Then, the output of drive train is used as torque regulation and speed regulation of PMSG in order to produce three phase voltage including moment inertia of machine (measurement block).

The energy conversion in wind power starts from kinetic energy of wind to mechanic energy by blade turbine rotation. The rotor of turbine is coupled by generator to produce electrical energy. These conversion mechanisms should be in detail to represent system mathematical modeling. The mathematical equation of the wind power output (P_{wt}) in

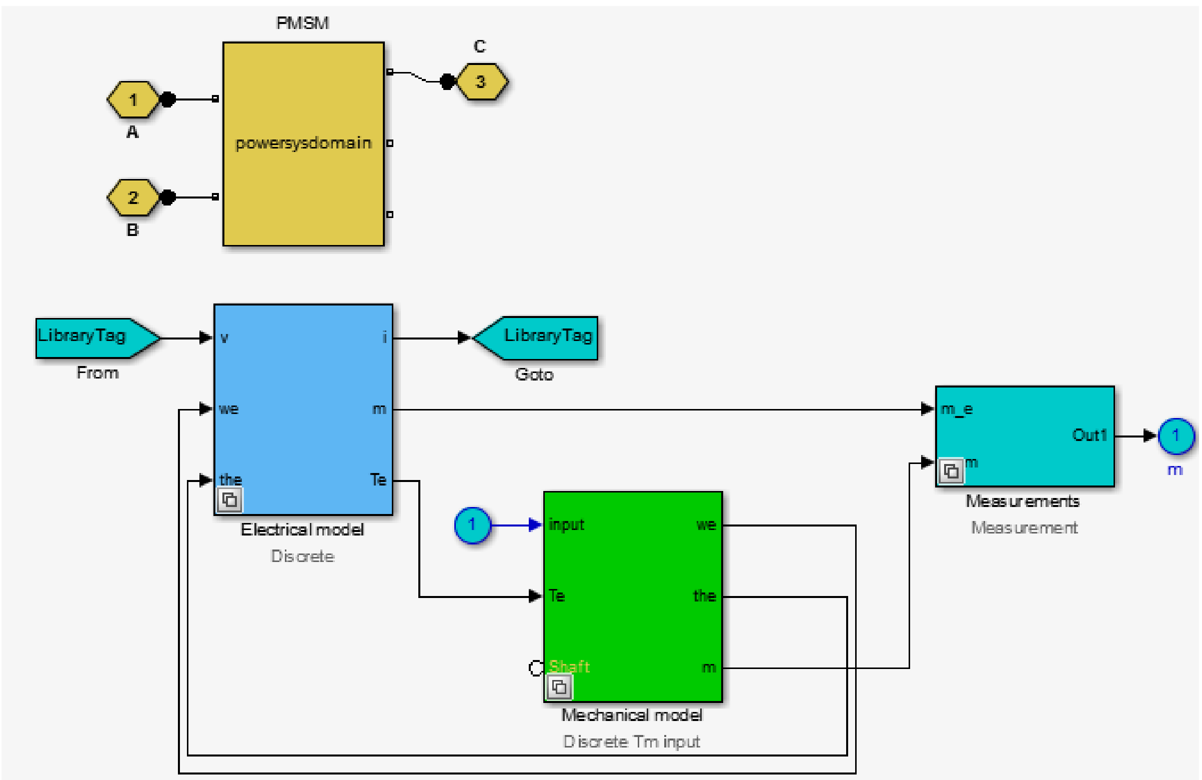

FIGURE 1. Simulation model of PMSG

Watt is given by:

$$P_{wt} = 0.5\rho C_p \pi R^2 V_w^3 \tag{1}$$

where ρ is the air mass density in kg/m^3, C_p is the power coefficient as the non-linear function between tip speed ratio (λ) and blade pitch angle (β), R is the blade radius in meter and V_w is the wind speed in m/s. The equation of power coefficient is presented as follows:

$$C_p(\lambda, \beta) = \frac{1}{2}\left(\Gamma - 0.022\beta^2 - 5.6\right) e^{-0.17\Gamma} \tag{2}$$

where the tip speed ratio is expressed as:

$$\lambda = \frac{\omega_{wt} R}{V_w} \tag{3}$$

and a constant (Γ) is defined as follows:

$$\Gamma = \frac{R}{\lambda}(2.2374) \tag{4}$$

In terms of two-mass drive train, the mathematical model is derived as simply kinematic converter for direct torque converter. The drive train can be represented with one-, two-, and three-mass models. The two-mass drive train is better than one-mass drive train for the reason of stability transient analysis. In this research, the two-mass drive train is considered where the torque is formed by the 2nd Newton's Law according to rotor angular speed equation for both turbine and generator. These equations are shown in (5) and (6), respectively.

$$\frac{d\omega_t}{dt} = \frac{1}{J_t}(T_t - T_{dt} - T_{at} - T_{ts}) \tag{5}$$

$$\frac{d\omega_g}{dt} = \frac{1}{J_g}(T_{ts} - T_{dg} - T_{ag} - T_g) \tag{6}$$

where J_t is the moment inertia of blade and hub, T_{dt} is the resistant torque at bearing of wind turbine, T_{at} is the resistant torque at hub and blade due to air flow viscosity, T_{ts} is the torque of rigidity, ω_g is the rotor angular speed of generator, J_g is the moment inertia of generator, T_{dg} is the resistant torque of bearing generator, and T_{ag} is the resistant torque due to air flow viscosity of generator.

Meanwhile, the modeling of generator output current and electromagnetic torque based on direct and quadrature axis are presented as follows:

$$\begin{aligned} \frac{di_d}{dt} &= \tfrac{1}{L_d} v_d - \tfrac{R}{L_d} i_d + \tfrac{L_q}{L_d} p\omega_r i_q \\ \frac{di_q}{dt} &= \tfrac{1}{L_q} v_q - \tfrac{R}{L_q} i_q - \tfrac{L_d}{L_q} p\omega_r i_d - \tfrac{\lambda p\omega_r}{L_q} \\ T_e &= 1.5p[\lambda i_q + (L_d - L_q) i_d i_q] \end{aligned} \tag{7}$$

where L_q, L_d are the quadrature and direct axis inductance, and R is the winding stator resistance; i_q, i_d are the quadrature and direct axis current; v_q and v_d are the quadrature and direct axis voltage; ω_r is rotor angular speed; λ is the flux linkage due to permanent magnet of rotor referred to stator side; p is the pole pairs and T_e is the electromagnetic torque.

3. **Simulation Results.** The proposed model requires validation before it runs for several scenarios of simulation. The important reference for the validation in this respect is the curve of wind power output according to the wind speed as shown in Figure 2. The cut-in wind speed is 3 m/s where the wind turbine starts producing output power linearly until reaching the rated wind speed at 14 m/s with the rated output power being about 6.1 kW. The rated output power is maintained until the wind speed reaches the cut-out speed of 25 m/s. For two regions before cut-in speed and after cut-out speed, the wind

turbine is not recommended to operate; therefore, sophisticated control is available for these operations. Wind speed lower than the cut-in speed makes the output power may not be enough to compensate the mechanical losses of turbine rotation mechanism, while the wind speed higher than cut-out speed tends to damage the electrical and mechanical process of the wind turbine. Another confirmation is obtained from the datasheet of *wind turbine permanent magnet generator* GL-PMG-5000 using our proposed model.

The wind speed is naturally varied from time to time. There are seasonal and diurnal variations that cause the output power production to fluctuate according to the value of wind speed. Under variable wind speed, our proposed dynamic model of PMSG still responds properly as in Figure 3 where the characteristic of output power -vs- wind speed follows the one in Figure 2. Consequently under this condition, the angular speed, rotor speed, electromagnetic and mechanical torques are timely changed. If the pitch angle control is applied, the fluctuation output power can be obtained much smoother as well as the output voltage and current variations.

The remaining testing for this model is to find the power coefficient (C_p) of wind turbine under condition of low wind speed, such as in the region of Makassar City, Indonesia. The wind speed profile in the region even being calculated in 100 m height is denoted with

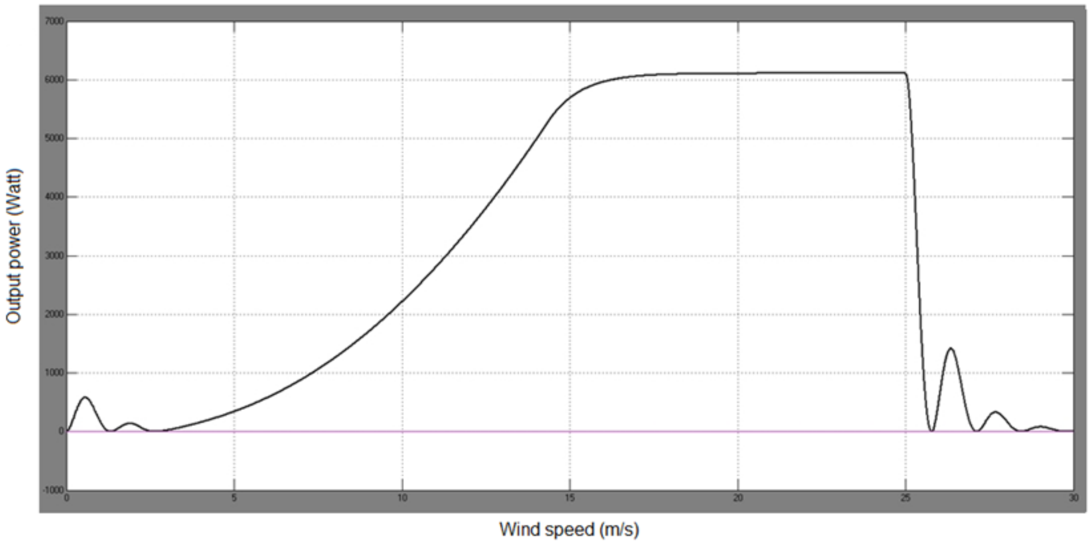

Figure 2. Characteristic of output power -vs- wind speed

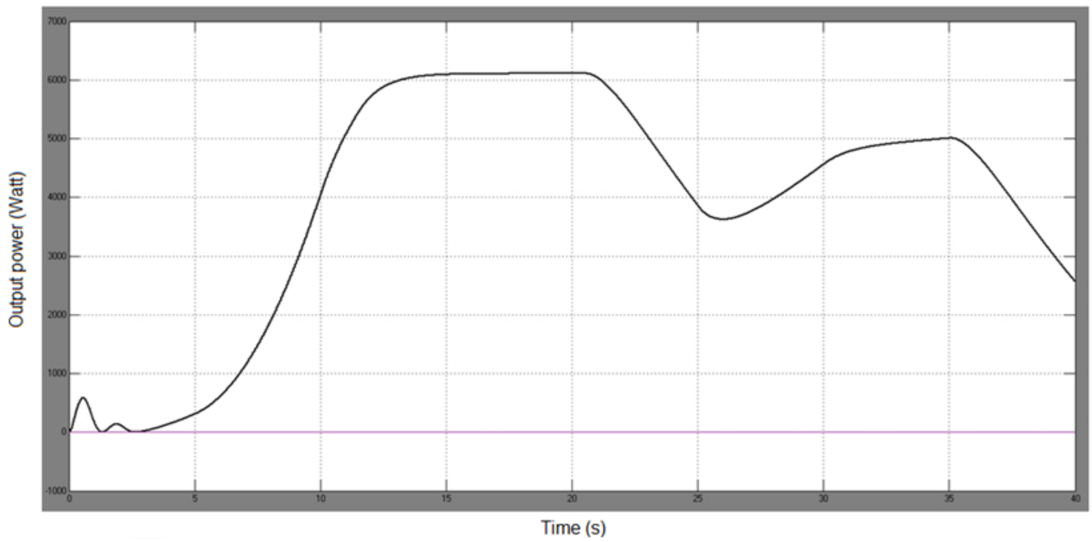

Figure 3. Output power fluctuation

Table 1. Monthly power coefficient (C_p) in Makassar city, Indonesia

Months	**Ideal Power (Watt)**	**Output Power (Watt)**	C_p
January	1188	710	0.500
February	256	140	0.545
March	76	0	0
April	76	0	0
May	76	0	0
June	1188	710	0.500
July	3260	1930	0.590
August	4867	2440	0.501
September	3260	1930	0.590
October	256	140	0.54
November	256	140	0.545
December	256	140	0.545

low wind speed which is averagely about 3 m/s from March to May. In the remaining months, the wind blow is quite ideal for wind turbine application where the wind speed is averagely about 9-10 m/s. It is well-known that the wind turbine is not operated under low wind speed and it is rotating if the wind speed is high. Regarding this knowledge, the power coefficient may indicate the performance of wind power. Ideally, the value of power coefficient is very close to the Betz limit (0.593) which indicates the maximum portion of wind energy can be transformed into useful energy by means of electrical energy. According to C_p measurement in the region as shown in Table 1, the C_p value can approach 0.59 when the wind speed in the linear region of wind turbine outputs power.

4. **Conclusions.** Recently, the development and implementation of wind turbine technology have reached the ultimate level where the generator technology has transformed from conventional induction generator into permanent magnet synchronous generator (PMSG). The PMSG technology was properly explained before the dynamic model and simulation were developed in Matlab/Simulink. The modeling covers the mechanical components, such as torque and angular speed and electrical components, such as the output voltage and current of generator. The two-mass drive train model is utilized as couple-connection between the rotor turbine and generator. The proposed model has been validated according to scenarios of wind speed variability, output power characteristics and power coefficient for the future actual implementation of PMSG wind turbine in Makassar city, Indonesia.

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