



MODELING AND SIMULATION OF WIND TURBINE FOR PARTIAL LOAD OPERATION

M. Y. Halyani¹, H. M. S. Firdaus¹, M. S. Azizi², A. Tajul³ and R. F. Farhana⁴

¹Faculty of Engineering Technology, Universiti Teknikal Malaysia Melaka, Durian Tunggal, Melaka, Malaysia

²Ranaco Education and Training Institute, Kawasan Perindustrian Jakar, Kemaman, Terengganu, Malaysia

³Mechanical Section, UniKL MSI, Kulim Hi-Tech Park, Kulim, Kedah, Malaysia

⁴Mechanical Engineering Department, Armag Oil & Gas Academy, Jalan Jeti Pulau Kapas, Marang, Terengganu, Malaysia

E-Mail: halyani@utem.edu.my

ABSTRACT

The purpose of this research is mainly to model a wind turbine with doubly fed induction generator (DFIG) and to investigate its behavior in partial load operation using computer simulation. System behavior analysis and simulation are two particular approaches applied in this research. The wind turbine model is developed whereby the behavior of its main components is described by mathematical model and transformed in simulation model in MATLAB/Simulink. The simulation model is carried out in partial load operation at a wind speed of 9 m/s. The physical quantities including generator speed, torque and electrical power output are measured and evaluated. By using variable speed generator, a wind turbine model with optimum power generation at wind speed between 4 m/s to 13 m/s is created. This research shows that if mathematical models represent the wind turbine accurately, then the proposed model can be used to observe the dynamic behavior of wind turbine precisely, efficiently and inexpensively. The simulation result is expected to be a reference for extending the knowledge of dynamic behavior of wind turbines and optimize the performance of future large-scale wind turbine systems.

Keywords: system behavior analysis, mathematical model, variable speed generator, optimum power generation.

INTRODUCTION

Alongside photovoltaic and combined heat and power system, wind turbines are used as an alternative to conventional large-scale power plants because wind power is clean and renewable. For these reasons, wind power can help to protect environment and control spikes in fossil fuel price. A modern wind turbine consists of essential components such as hub, tower, nacelle and rotor blade. The foundation is the anchor of the wind turbine in the earthly realm. It is required to hold a tall and slender plant. The foundation of the tower is embedded. It is the largest and heaviest component of a wind turbine. Location of the plant determines the height of the tower. Normally, the towers are built at a height of 40 m to 130 m (Paul, 2004). The higher the tower, the higher the energy output of a wind turbine as the wind speed increases with height.

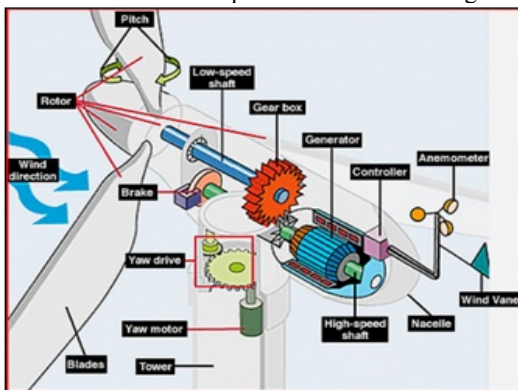


Figure-1. Components of Nacelle.

On the tower, there is nacelle which consists of the components such as drive train (low speed shaft, gearbox, generator, and brake), yaw motor and controller as shown by Figure-1 (Wiser *et al.* 2011). The rotor is mounted on the nacelle. It consists of hub and three blades, the main components in capturing the energy of the wind and converts it into rotational energy. In modern wind turbines, blade adjustment is controlled in the rotor. The pitch is also known as pitch control. Rotor speed and thus the performance of the wind turbine is limited by pitch regulation (Muljadi and Butterfield, 1999).

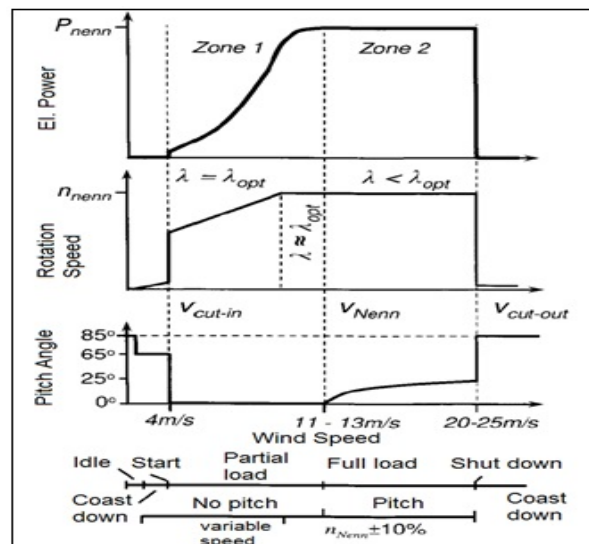


Figure-2. Operating range of variable speed, pitch controlled wind turbine.



There are four operation modes in wind turbine. One of them is partial load operation. For partial load operation, the range of wind speed is between 4 m/s and 13 m/s while the pitch angle is 0° as shown by Figure-2 (Gasch and Tvele, 2011).

Dynamic behavior analysis of wind turbine system in partial load operation is important in order to obtain the maximum power output generation at below synchronous and synchronous generator speed. Hence, a modern wind turbine was modelled and simulated to investigate its behavior in partial load operation. This paper is organized as follows: the first section describes the wind turbine components. Then, a detailed model of rotor, mechanical drive train and DFIG is presented. Finally, simulation results of the complete wind turbine model are evaluated.

WIND TURBINE COMPONENTS

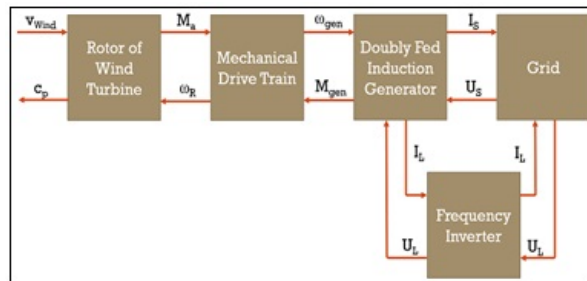


Figure-3. Wind turbine components.

Wind power plant is broken down into its component parts as shown by Figure-3. Major components of the system namely the rotor of wind turbine, mechanical drive train and DFIG are analyzed. The system behavior of the individual parts is described by a model. This model is first represented mathematically in the form of differential equations. Then, the mathematical model is implemented in the simulation model in the form of block diagrams. This simulation model is used later on the computer to simulate the behavior of the system.

At the "rotor of wind turbine", the kinetic wind energy is converted into rotational energy. Aerodynamic behavior of this part model is described. The mechanical behavior of the system is represented by two-mass model and one-mass model in the "mechanical drive train". Field orientation principle is explained in the "doubly fed induction generator". Using this principle, the behavior of this partial model can be patterned. In this paper, the frequency inverter is not discussed in details.

After final assembly of the part model, the simulations are carried out. First, the sub-model of the DFIG is checked by the simulations in three operation modes (Firdaus *et al.* 2015). If no errors occur, then the overall model of the wind turbine is simulated. The simulation of overall model is carried out in partial load operation. The simulation results are then interpreted.

MODELLING OF WIND TURBINE

Rotor of wind turbine

At the beginning, it is examined how much energy can be produced from the wind. It is then determined how much energy a wind turbine can extract from the wind. Important factors that are used for modeling the aerodynamic performance of a wind turbine is introduced and explained. Thereafter, the model of the rotor of wind turbine is illustrated.

Wind energy is the kinetic energy of moving air masses. The kinetic energy E_{kin} of an air mass ($m = \rho_{Luf} * V$), that moves at the speed v_{wind} can be expressed as:

$$E_{kin} = \frac{1}{2} * \rho_{Luf} * V * v_{wind}^2 \quad (1)$$

For the standard atmosphere (air temperature 15°C and atmospheric pressure 1013.25 hPa), the air density is 1.225 kg/m^3 . The wind power P_{wind} is obtained from the derivative of the kinetic energy with respect to time (Burton *et al.* 2011). A small time period is considered, in which the air particles flow through the distance $s_w = v_{wind} * \Delta t$. The distance is multiplied by the area of the wind turbine rotor and results a volume of $\Delta V = A * v_{wind} * \Delta t$. During the period, air particles drives the wind turbine. The wind power is:

$$P_{wind} = \frac{E_{kin}}{\Delta t} = \frac{1}{2} * \rho_{Luf} * A * v_{wind}^3 \quad (2)$$

The kinetic energy of moving air masses is converted into rotational energy by the braking of the air masses at the rotor of the wind turbine as shown by Figure-4 (Winkelmeier, 2006). However, the kinetic energy from wind cannot be fully converted by the rotor.

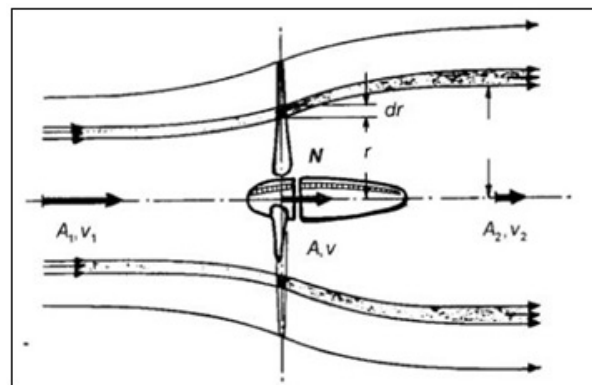


Figure-4. Power extraction principle of wind turbine.

From Figure-4, it can be determined that the wind speed before entering the rotor of the wind turbine is greater than the wind speed after ($v_1 > v_2$). The surface after the wind turbine A_2 is greater than the area in front A_1 because the air flow must be continuous. Since the



mass of the air is constant, the amount of the power taken from the wind depends on the difference of the wind speeds in front of and behind the rotor. This results in the power taken from the wind

$$P_R = \frac{dE}{dt} = \frac{1}{2} * \frac{dm}{dt} * (v_1^2 - v_2^2) \quad (3)$$

If the wind speed $v_1 = v_2$, no power can be extracted. On the other hand, if the air mass in the rotor surface A are completely braked, no power can be extracted due to the blockage of the flow conduit ($\frac{dm}{dt} = 0; v_2 = 0$). Between the two extreme cases there is an optimum of the low power extraction.

According to Betz's Law (Carriveau, 2011), a wind turbine can convert theoretical maximum of 59.3 % the kinetic energy of wind into rotational energy.

$$P_R = c_p * P_{wind} = c_p * \frac{1}{2} * \rho_{Luft} * \pi * R^2 * v_{wind}^3 \quad (4)$$

The maximum power coefficient $c_{p,Betz}$

$$c_{p,Betz} = \frac{16}{27} \approx 0.593 \quad (5)$$

The power coefficient depends on the tip speed ratio λ and the pitch angle β (the rotation of the rotor blade to the hub). The formula for the tip speed ratio is:

$$\lambda = \frac{\omega_R * R}{v_{wind}} = \frac{2\pi * n_R * R}{v_{wind}} \quad (6)$$

From the equation (4), it can be determined that the extracted power from the rotor increases with the cube of wind speed. In other words: If the wind speed is 3 m/s, the rotor power increases by a factor of 27. So the selection of a "windy" location for a wind power plant is very important. The rotor power also increases with the square of rotor radius. This means that the larger the rotor radius, the greater is the usable wind power. The torque, which is developed by the rotor can be determined using the angular velocity and rotor power.

$$M_a = \frac{P_R}{\omega_R} = \frac{1}{\omega_R} * c_p(\lambda, \beta) * \frac{1}{2} * \rho_{Luft} * \pi * R^2 * v_{wind}^3 \quad (7)$$

By inserting the moment coefficient $c_m(\lambda, \beta) = c_p / \lambda$ results (Sadowski, 2007):

$$M_a = c_m * M_{wind} = c_m(\lambda, \beta) * \frac{1}{2} * \rho_{Luft} * \pi * R^3 * v_{wind}^2 \quad (8)$$

Figure-5 shows the block diagram for the stationary model of rotor. The model contains equations (6) and (8). In this model, the values for the trend of the power coefficient c_p are entered in a table in Simulink. The corresponding values are obtained from (Schemel *et al.* 2002). The trend of power coefficient is used instead of the trend of moment.

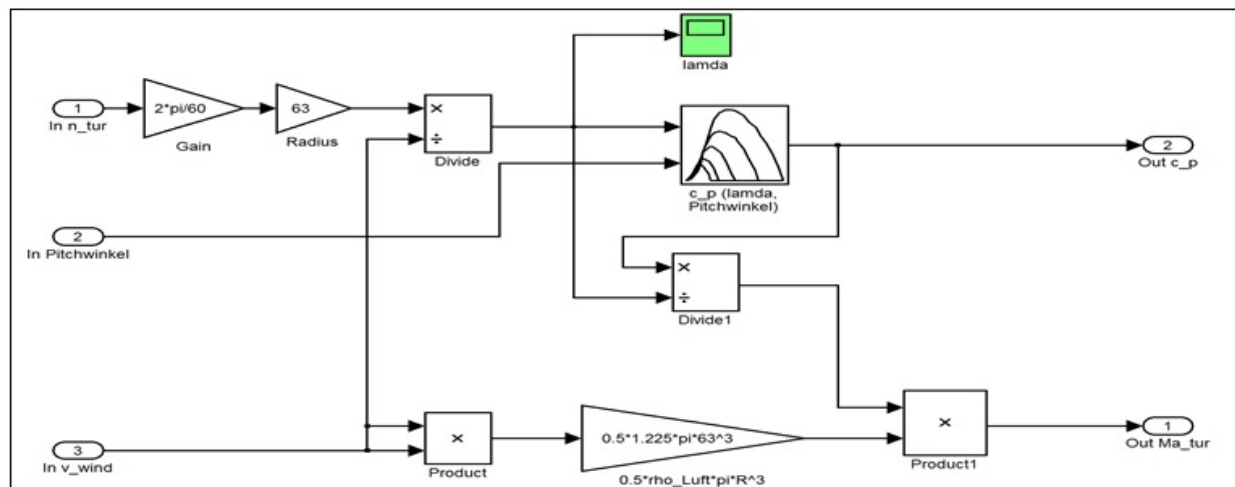


Figure-5. Stationary model of rotor for wind turbine.

Mechanical drive train

The second model of the wind turbine is a mechanical drive train. The mechanical drive train usually consists of the following components: rotor, shaft, gearbox and generator. In mechanical drive train, there is coupling of the aerodynamic-mechanical (primary) energy conversion with the mechanical-electrical (secondary)

conversion. The partial model is first described as a two-mass model (see Figure 6). Simple description of the subsystem is described later by one-mass model (Muyeen *et. al.*, 2009), (Boukhezzar and Siguerdidjane, 2011).



Two-mass model

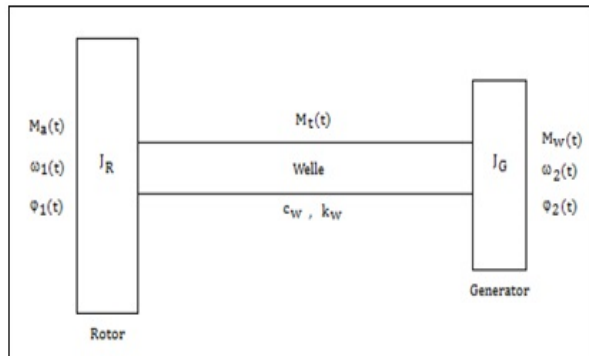


Figure-6. Two-mass model.

To describe the mechanical behavior of a wind turbine, the complex original system is mapped to a simpler model. This model is dual-mass model, which consists of two rotating masses to a shaft. The moment of inertia of the rotor is set at least four to five times the generator. The gear is assumed to be frictionless and floating ground. In addition, the inertial mass of the connecting shaft is neglected because the moment of inertia of the shaft is much smaller than the moment of inertia of the rotor and generator. The momentum theorem is applied to get the equation of motion of the two-mass model. In the following equations of motion, the transmission ratio of gear $i_G = 1$ is considered. Buoyant force, which is converted into a drive torque M_a , is generated by the aerodynamics of the rotor blades. The difference between the drive torque and the shaft torque results an accelerating torque on the rotor:

$$J_R \cdot \frac{d\omega_1}{dt} = M_a - M_{welle} \quad (9)$$

ω_1 refers to the angular velocity of the rotor where the rotor shaft rotates and J_R refers to the moment of inertia of the rotor. The generator shaft is driven by the rotor. A section modulus forms at the generator. By the difference from the shaft torque and section modulus the generator rotor is accelerated with the moment of inertia. This results in

$$J_G \cdot \frac{d\omega_2}{dt} = M_{welle} - M_w \quad (10)$$

The shaft is mathematically described as spring-damper system with the spring constant c_w and the damping constant k_w (Steinhart, 2011). Hereby the equation for the shaft torque is established.

$$M_{welle} = M_t - M_D = c_w \cdot (\varphi_1 - \varphi_2) + k_w \cdot (\omega_1 - \omega_2) \quad (11)$$

One-mass model

The partial model of the mechanical drive train can be described as a one-mass model (see Figure 7) if there is no relative movement between the two shaft ends ($\omega_1 = \omega_2$). The ratio of the transmission is taken into account and is described as:

$$i_G = \frac{\omega_2}{\omega_1} = \frac{M_R}{M_G} \quad (12)$$

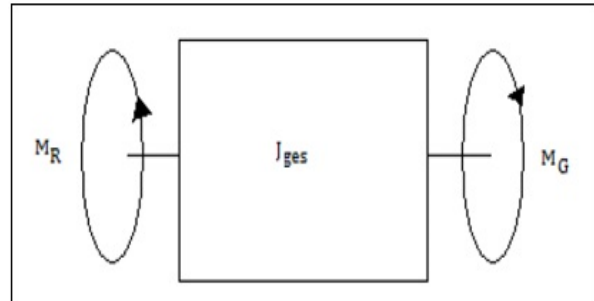


Figure-7. One-mass model.

The moment of inertia of the rotor J_R must be added to the generator side to calculate the total moment of inertia J_{ges} . With the following equation, the moment of inertia of the rotor can be determined related to the generator side J_R' :

$$J_R' = \frac{\omega_1^2}{\omega_2^2} \cdot J_R = \frac{1}{i_G^2} \cdot J_R \quad (13)$$

By adding up the moment of inertia of the rotor and generator results conclusively the total moment of inertia.

The equation of motion for the one-mass model is:

$$\frac{d\omega_2}{dt} = \frac{M_R' - M_G}{J_{ges}} \quad (14)$$

All parameters in the equation of motion are transformed on the generator side. The block diagram of the mechanical drive train is illustrated in Figure 8. If the drive torque of the wind turbine is greater than the torque of the generator, the system is started up with an acceleration. When the drive torque of the wind turbine is less than the torque of the generator, the system is slowed down. If the drive torque of the wind turbine is equal to the torque of the generator, the system will rotate at a constant speed.

$$M_b = M_{a_tur} - M_{w_gen} = J_{ges} \cdot \frac{d\omega}{dt} \quad (15)$$

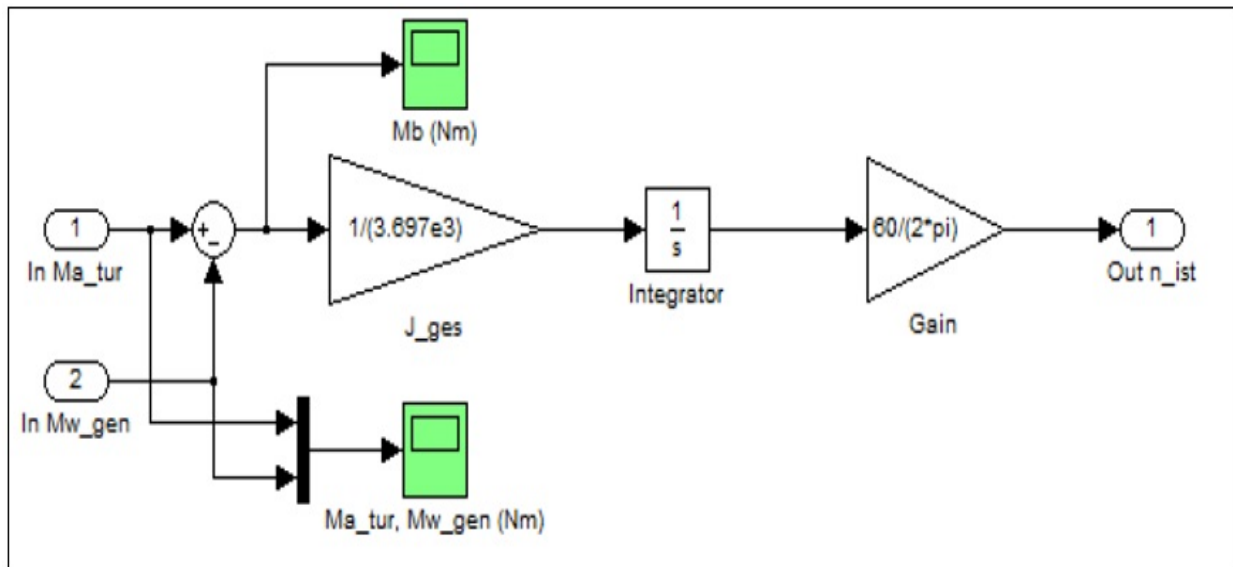


Figure-8. Model of mechanical drive train.

Doubly fed induction generator

Figure-9 shows the performance characteristic diagram of a wind turbine (Beckert, 2008). To extract the maximum performance at different wind speeds, the rotor speed of the wind turbine must be adjusted. For this purpose, a variable-speed generator principle is needed. In this research, doubly fed induction generator is used. In addition to the wide range of speeds, the doubly fed induction generator also offers the advantage, which in the generator mode, the active and reactive power are

independent from each other and completely decouple from the rotational speed where rotor current components can be controlled (Beckert, 2008). In this case, with appropriate operation management not only the efficiency can be increased, but also a neutral, even capacitive operation of the wind turbine is possible (Sinelnikova, 2005). For the dynamic active and reactive power regulation, the principle of field orientation is applied (Firdaus *et al.* 2015).

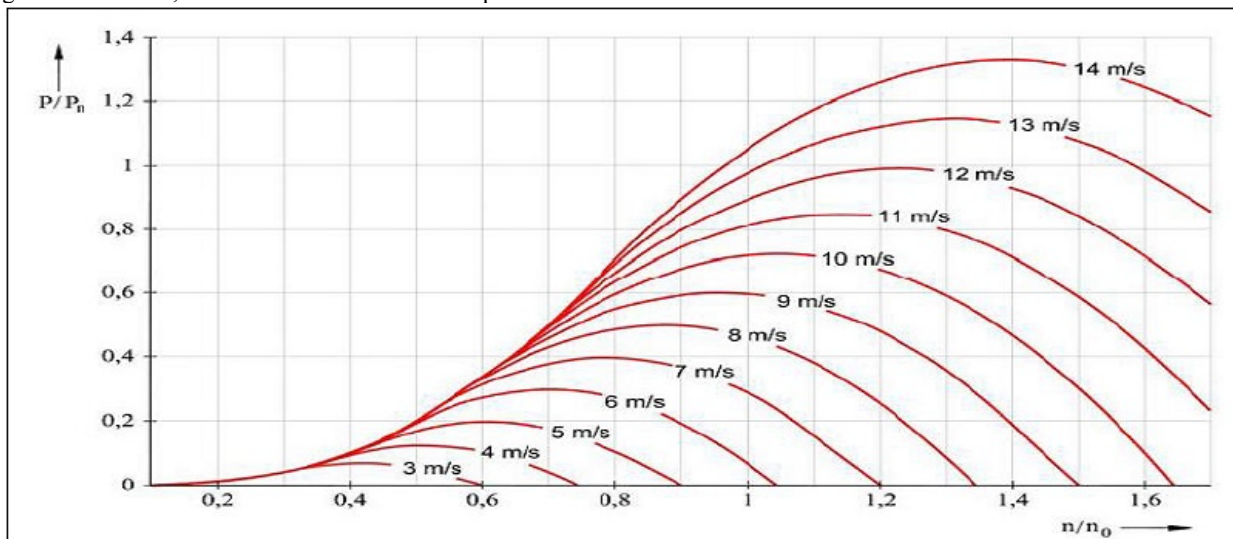


Figure-9. Performance characteristics of wind turbine.

SIMULATION RESULTS OF WIND TURBINE

After the simulation of the part model, the overall model of the wind turbine in the partial load operation is simulated. For simulation of the wind turbine, it is

assumed that the wind speed is constant and the torque of generator is preset as set point value. The behavior of the system is visualized and analyzed through simulation.

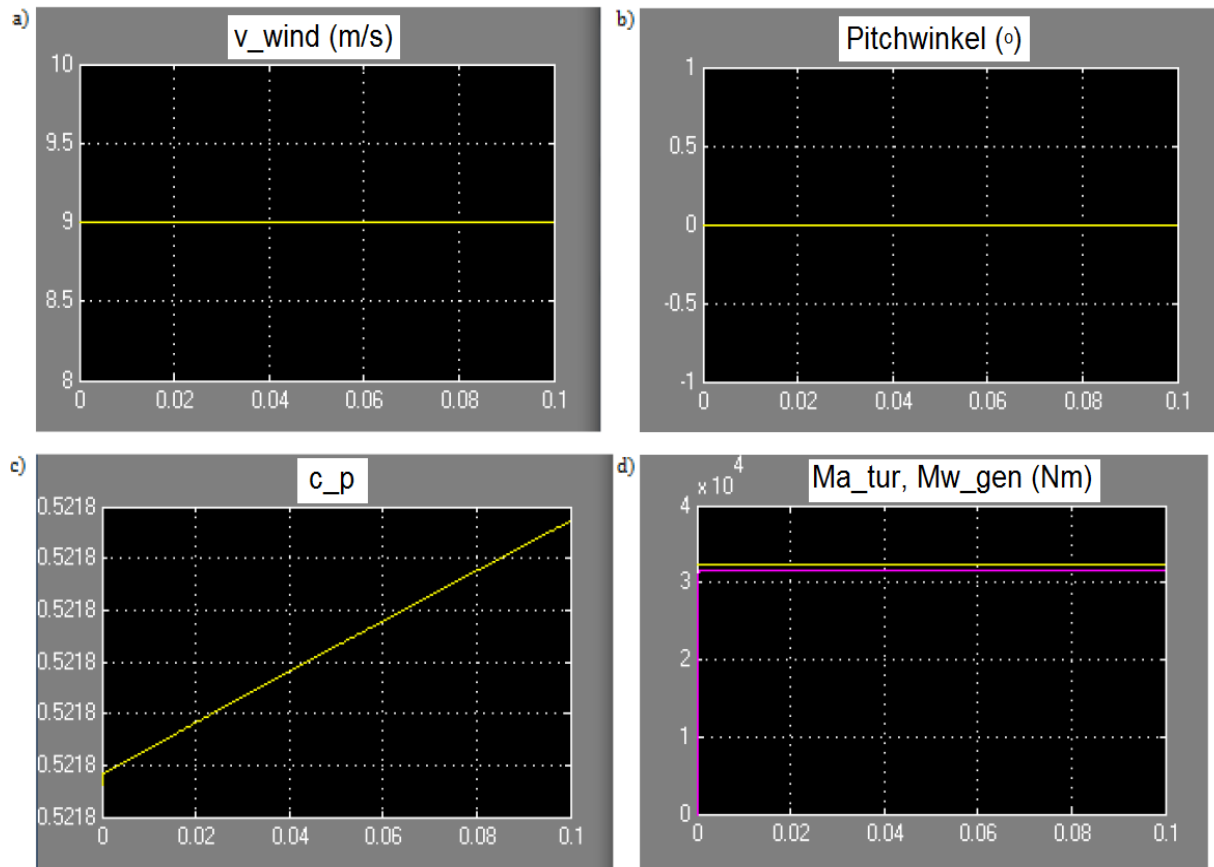


Figure-10. a-d: Behavior of wind turbine for partial load operation.

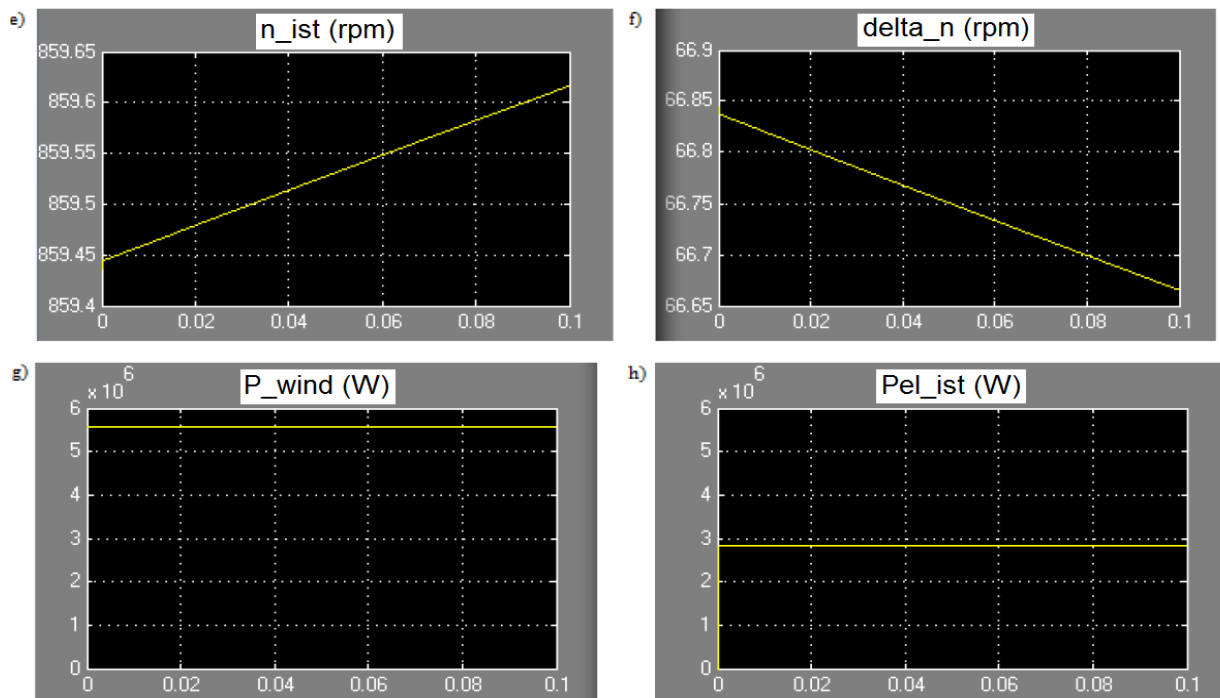


Figure-10. e-h: Behavior of wind turbine for partial load operation.



Discussions

Figure-10 shows the simulation results of the wind turbine for partial load operation. It can be seen that the rotor of the wind turbine at a wind speed of 9 m/s produces a high drive torque. This drive torque is 32.2 kNm. In this case, the system must be driven synchronously until the torque of the generator reaches the value of rotor torque as shown by Figure 10d. Mechanical power is then converted to electrical power by generator. The electric power of the generator is the product of torque and speed ($P_{el_ist} = M_{w_gen} * \frac{2\pi}{60} * n_{ist}$).

Figure-10e shows a positive slope of the speed characteristic. This means that the system is running at a speed up. If the speed of the system is equal to the desired speed, the plant will produce an optimal power output. For optimal power yield, the system must be operated as close to the optimum tip speed ratio ($\lambda_{opt} = 7$). At a constant wind speed, the rotor speed needs to be adjusted while the pitch angle is kept constant ($\beta = 0^\circ$).

Figure-11 provides the torque-speed characteristics of a wind turbine with a doubly fed induction generator (Specovius, 2009). By adjusting the rotational speed, the system can produce the optimum power at any wind speed.

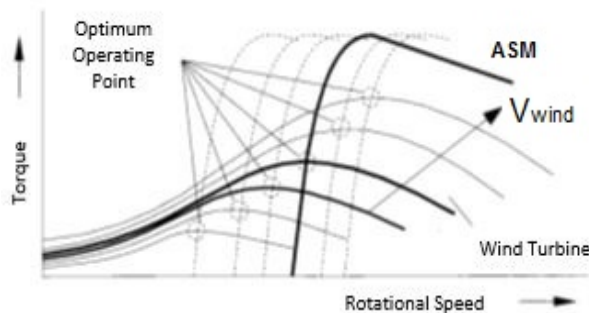


Figure-11. Torque-speed characteristics of wind turbine with doubly fed induction generator.

Limitation and suggestion

The proposed model of wind turbine is suitable for moderate wind speed application whereby the wind speed range is between 4 m/s and 13 m/s. Further study can be made to create a model for full load operation whereby the wind speed is between 13 m/s and 25 m/s. This research was not focused on the dynamic behavior of frequency inverter which the behavior of DFIG can be analyzed if faults occur on grid line.

CONCLUSIONS

The modeling and simulation of a wind turbine with doubly fed induction generator is presented in this paper. The simulation of the system in partial load operation is carried out to study the behavior of the wind turbine system at wind speed range between 4 m/s and 13

m/s. Prior to simulation, the real wind power plant is built using block diagram in MATLAB/Simulink. The behavior of key components of the wind turbine such as rotor, mechanical drive train and DFIG is described mathematically in the form of differential equations. Using these equations, a simulation model is constructed.

By simulation, the behavior of the wind turbine in partial load operation can be visualized. This research has successfully shown that using Matlab/Simulink, modeling, simulation and monitoring of wind turbine can be implemented as it is suitable in modeling wind turbine for partial load operation.

ACKNOWLEDGEMENTS

The team would like to thank Universiti Teknikal Malaysia Melaka (UTeM) for sponsoring conference fee and Prof. Dr.-Ing. Peter Hussels for his advice and guidance towards finishing this research.

LIST OF SYMBOLS

β / <i>Pitchwinkel</i>	Pitch angle
λ, λ_{opt}	Tip speed ratio, optimal tip speed ratio
φ_1, φ_2	Shaft position angle at rotor, shaft position angle at generator
$\rho_{Luft} / \rho_{ho_Luft}$	Air density
$\omega_R / \omega_1, \omega_2$	Angular velocity of rotor, angular velocity of generator
Δt	Time segment
A, A_1, A_2	Area of rotor, area before rotor, area after rotor
c_w	Spring constant
$c_p / c_{_p}, c_{p,Betz}, c_m$	Power coefficient, power coefficient of Betz's Law, moment coefficient
δ_{n_n}	Difference between nominal and actual value of generator speed
E_{kin}	Kinetic energy
i_G	Transmission ratio of gear
J_R, J_G, J_{ges}	Moment of inertia of rotor, moment of inertia of generator rotor, moment of inertia of complete system
k_w	Damper constant
m	Air mass
M_a / M_{a_tur}	Rotor drive torque
M_t, M_w, M_R	Torsional moment, section modulus, rotor torque
M_{welle}, M_D	Shaft torque, damping torque
$M_G / M_{w_gen}, M_b$	Generator torque, accelerating torque
M_{wind}	Wind torque
$n_R / n_{_tur}$	Rotor speed
n_{Nenn}	Nominal rotation speed
P_R	Rotor power
P_{el_ist}	Actual value of electrical power
$P_{wind} / P_{_wind}$	Wind power



R	Rotor radius
s_w	Distance
V	Volume
v_{wind} / v_{wind}	Wind speed
v_1, v_2	Wind speed before rotor, wind speed after rotor

REFERENCES

- [1] Beckert, U., (2008). Doppelt-gepeiste Asynchronmaschine als drehzahlvariabler Windenergiegenerator und ihre feldorientierte Regelung, Skriptum für Nichtelectrotechniker, TU Bergakademie Freiberg.
- [2] Boukhezzer, B. and Siguerdidjane, H., (2011). Nonlinear Control of a Variable-Speed Wind Turbine Using a Two-Mass Model, IEEE Transaction on Energy Conversion, Vol. 26, No. 1, pp. 149-162.
- [3] Burton, T., Jenkins, N., Sharpe, D. and Bossanyi, E., (2011). Wind Energy Handbook, 2nd Edition, John Wiley and Sons Ltd, United Kingdom.
- [4] Cariveau, R., (2011). Fundamental and Advanced Topics in Wind Power, InTech Publisher.
- [5] Firdaus, H.M.S., Halyani, M.Y., Ahmad, E.Z., Norain, I., and Zulfattah, Z.M., (2015). Modeling and Simulation of Doubly Fed Induction Generator for Wind Turbine, Engineering Technology International Conference, Kuta, Bali, Indonesia.
- [6] Muljadi, E. and Butterfield, C.P., (1999). Pitch-Controlled Variable-Speed Wind Turbine Generation, 1999 IEEE Industry Applications Society Annual Meeting, pp. 1-8.
- [7] Mueen, S.M., Tamura, J. and Murata, T., (2009). Stability Augmentation of a Grid-Connected Wind Farm, Springer Publishing Company.
- [8] Paul, G., (2004). Wind Power: Renewable Energy for Home, Farm and Business, Chelsea Green Publishing Company.
- [9] Gasch, R. and Tewe, J., (2011). Windkraftanlagen: Grundlagen, Entwurf, Planung und Betrieb, 7th Edition, Vieweg and Teubner, Wiesbaden.
- [10] Sadowski, T., (2007). Einsatz des Vienna – Stromrichter als Gleichrichter in Windkraftanlagen, Dissertation, TU Berlin.
- [11] Schemel, C., Ulrich, M., Hesse, J., Schoenborn, I., Jansen, M. and Schettler, R., (2002). Windkraftanlagen II WS 2001/02 – Offshore-Windpark in der Nordsee, Thesis Report.
- [12] Sinelnikova, E., (2005). Design und optimale Betriebsführung doppelt gespeister Asynchrongeneratoren für die regenerative Energieerzeugung, Dissertation, TU Chemnitz.
- [13] Specovius, J., (2009). Grundkurs Leistungselektronik: Bauelemente, Schaltungen und Systeme, 3. Auflage, Vieweg and Teubner, Wiesbaden.
- [14] Steinhart, H., (2011). Dynamik Elektrischer Antriebe W/S 2011/2012, Skript. Hochschule Aalen.
- [15] Winkelmeier, M.H., (2006). Energiesysteme – Windenergie: 02 – Bauformen und Aerodynamik von Windkraftanlagen, WS 2005/06.
- [16] Wiser, R.Z., Yang, M., Hand, O., Hohmeyer, D., Infield, P.H., Jensen, V., Nikolaev, M., O'Malley, G. and Sinden, A., (2011). Wind Energy, In IPCC Special Report on Renewable Energy Sources and Climate Change Mitigation, Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.