Wind turbine modelling and simulation using Matlab/SIMULINK

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Abstract. Malaysia is aiming to reduce the dependency on oil and gas by increasing the utilization of renewable energy. One of the promising renewable energy available is wind energy. Malaysia is located near the equator which is situated in a low wind speed region with an annual mean wind speed of 1.2-4.1 m/s. However, Malaysia also experiences two different monsoon seasons which is the southwest monsoon and the northeast monsoon. Wind speed during the southwest monsoon season can reach 7 m/s while the wind speed during the northeast monsoon can exceed 15 m/s. Limited researches and studies had been done to investigate the potentiality of wind energy in Sarawak, Malaysia. In this paper, modelling and simulation of different wind energy conversion system (WESC) using different generators operating under the same parameters will be carried out using MATLAB/SIMULINK to investigate the efficiency of the generators. PMSG has shown to be more efficient over SCIG and DFIG for lower wind speed although all of them eventually reaches the similar efficiency. Efficiency of SCIG, DFIG and PMSG for rated wind speed are 66.25%, 69.38% and 71.88% respectively.

1. Introduction

Wind turbine is used to convert the kinetic energy of the wind into mechanical energy that rotates the rotor blades which are connected to the low speed shaft. The mechanical energy will then be transmitted into the high speed shaft via a gearbox to generate electrical energy in the generator [1]. Horizontal axis wind turbine (HAWT) rotates at an axis parallel to the direction of the wind [2]. Wind power can be harvested as long as the blades are facing the direction of the wind. Besides, HAWT usually have taller tower which allows the turbine to face stronger wind as wind speed increase with heights. With variable pitch angle turbines, maximum extractable amount of wind energy is possible by increasing or reducing the blade’s pitch angle depending on the electricity generated. In this paper, modelling and simulation will be focusing on HAWT as they are more efficient.

The power, $P$ in the wind that can be extracted by a wind turbine are given by the formula:

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

where $\rho$ is the air density, $A$ is the surface area of the blade, $C_p$ is the power coefficient of the turbine and $v$ is the wind speed. Power coefficient of a turbine can be determined by using the formula:

$$C_p(\beta, \lambda) = c_1 \left( \frac{C_2}{x} - c_3 \beta - c_4 \right) e^{-\frac{C_5}{x}} + c_6 \lambda$$  (2)
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\[ z = \frac{1}{\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1 + \beta^3}} \]  \hspace{1cm} (3)

where \( c_1 = 0.5176, c_2 = 116, c_3 = 0.4, c_4 = 5, c_5 = 21, c_6 = 0.0068 \), \( \beta \) is the pitch angle for the blades and \( \lambda \) is the tip speed ratio.

Figure 1 shows the characteristic parameters of a wind turbine which is essential in choosing an appropriate turbine. Cut-in speed is the minimum wind speed required to overcome the friction of the turbine blades to rotate the blades. The rated speed is the minimum wind speed at which the turbine generate the rated power output. Rated power output is the maximum power generated by the generator without damaging the generator and batteries. Pitch angle adjustment of the blades limits the output power by varying the aerodynamic forces acting on the blades at higher wind speed [3]. Cut-out speed or furling speed is the maximum wind speed at which the generator will continue to generate electricity before shutting down to protect the turbine. Any wind speed above the cut-out speed will cause damage to the turbine and therefore the braking mechanism will be activated and shut down the turbine.

1.1. Components in a WECS

Wind energy conversion system as shown in Figure 2 can be divided into the blades, generator, power converter and controller. The turbine blades are responsible of converting the kinetic energy from the wind into mechanical power that rotates the turbine shaft. The mechanical power of the shaft is converted into electrical energy via the generator. Drivetrain is used to increase the rotational speed of the turbine shaft to power the generator. The converter and inverter will convert noisy AC power generated by the variable speed generator into clean and reliable AC power [5].

1.2. Wind Turbine

HAWT can be further classified into fixed speed wind turbine and variable speed wind turbine [7]. One of the fixed speed wind turbine utilizes squirrel cage induction generator (SCIG). The rotor of a fixed speed turbine remains constant regardless of the wind speed. It is determined by various parameters such as gear ratio, grid frequency and generator design. Tip speed ratio, \( \lambda \) can be determined using \( \lambda = \frac{R \cdot \omega_t}{v} \) where \( R \) is the turbine radius, \( \omega_t \) is the turbine speed and \( v \) is the wind speed. For a fixed speed wind turbine, the TSR will keep varying with the fluctuation of wind speed. This means the system will only able to achieve maximum efficiency at a certain wind speed as shown in Figure 3. SCIG is one of the
most commonly used generator since this type of generator can be connected directly to the grid as the generator’s frequency remains constant and same with the grid’s frequency throughout the operation [8]. The advantages of this type of generators are that this system is more simple, reliable and cheap but lack in power control, uncontrollable reactive power consumption and additional mechanical stresses on the turbine due to the fixed speed generator.

Doubly-fed induction generators and permanent magnet generators are commonly used variable speed generators. For this type of generators, the rotor speed will vary proportionally with the increasing wind speed and thus the TSR and performance will remain constant throughout the operation. This will ensure that maximum efficiency of the turbine can be obtained for a wide range of wind speed. Power converters are required due to the fluctuating rotor speed of the generators and frequency of the electricity generated [10]. This system has a higher power capture efficiency, improved power quality and reduction in mechanical stress as the rotation of the turbine blades rely on the magnitude of wind speed.

1.3. Generator

Electric generators can be further divided into asynchronous and synchronous generator. The main difference between the two is that asynchronous generators require the grid supply for excitation while synchronous generators do not require grid supply for the excitation of its winding. Gearbox is used to increase the low rotational speed of the turbine blades to a higher rotational speed of the rotor shaft to power the generator.

![Figure 3. Power Coefficient vs TSR for Wind Turbine. [9]](image)

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![Figure 4. Types of Generator in WESC [7]](image)

The three-phase stator windings of a squirrel cage induction generator (SCIG) can be connected directly to the utility grid by using a transformer [11]. The grid is responsible in providing the reactive
power required for the excitation of stator’s winding. The rotor of the generator will be accelerated up to synchronous speed based on the frequency of the grid. Slip is the difference between the rotational speed of the stator’s magnetic field and the rotor’s speed. Slip can be calculated by using $s = \frac{n_s - n_r}{n_s}$.

Negative slip means the generator is operating above the synchronous speed due to the wind power acting on the rotating blades. For SCIG which is a fixed speed turbine, the slip is very small, usually below 1%.

Figure 5. Squirrel Cage Induction Generator [12]

Doubly fed induction generator (DFIG) on the other hand is gaining more and more attention for applications in the range of megawatts of power [13]. This generator comprises of a three-phase stator windings and a three-phase rotor windings. Both the rotor and stator windings are connected to the grid where the rotor speed is adjusted by back to back converters. The grid will excites the rotor windings and the magnetic field of the rotor windings will rotates with the rotating blades. The rotating magnetic flux acting on the stator windings will results in the generation of alternating current. The rotating speed of the stator’s magnetic field relies on the rotor speed and the frequency of the grid. In order to maintain a consistant frequency of the generated current, it is necessary to condition the frequency of the grid signal acting on the rotor windings. Back to back converter consists of a machine side converter and a grid side converter with a DC voltage line between them.

Figure 6. Doubly Fed Induction Generator [14]

Synchronous generators require external excitation either by permanent magnet or via an external DC power source. Wound rotor synchronous generator (WRSG) uses DC current, brushes and slip rings for the excitation of rotor windings [15]. Extra maintenances are required to maintain the brushes and slip rings. On the other hand, permanent magnet synchronous generator (PMSG) is a better alternative to WRSG as it eliminates the need of brushes and slip rings. For PMSG, the excitation field of the rotor windings is created by the permanent magnet or electromagnets. Three-phase power is generated in the stator windings when the rotor is rotated by the wind turbine. Figure 7 shows the PMSG wind turbine model which is popular due to their simple design. By using permanent magnets, the commutators, slip rings and brushes of a WRSG can be eliminated which will greatly improve the reliability of the system, making it a better option compared to the WRSG. PMSG requires rectifier and inverter as it is a variable speed generator. The AC-DC-AC power converter will convert the fluctuating electrical power generated into fixed DC power and then back into AC power with fixed frequency and magnitude.
2. Methodology
Simulations for different WECS will be presented in this section. The wind speed for the simulation is simulated by the following blocks as shown in Figure 8. The wind speed will increase from 0m/s to 9m/s from t=1s to t=10s. It will then increase from 9m/s to 15m/s from t=15s. The wind speed will remain constant until t=30s. The purpose of this simulation is to study the behaviour of different types of generator, operating under zero wind speed, base wind speed which is 9m/s and wind speed above rated wind speed. The real power, reactive power, rotor speed, mechanical torque and pitch angle are recorded and analysed. Real power, rotor speed and pitch angle will be discussed in the following paper.

2.1. SCIG Wind Turbine
Figure 10 shows the SCIG wind turbine modelled using SIMULINK. The 1.5MW induction generator is connected directly to the power grid via a 575V/25kV and 25kV/120kV step-up transformer and a 30km transmission line. The wind turbine model in SIMULINK will be used to provide the mechanical torque required to drive the rotor of the generator. SCIG will convert the mechanical torque into electrical power and then fed it to the grid via the stator windings. VI-measurement blocks will record the voltage, current, active and reactive power.

2.2. DFIG Wind Turbine
The DFIG model in Figure 11 is similar to the SCIG model except that the rotor windings are connected to the grid via power converters and step-up transformers. The stator windings are connected directly to the grid via transformer. Reactive power require to energize the generator stator will be provided by the grid. Simulation of DFIG wind turbine is done with the addition of rectifier and inverter using universal bridge. Rectifier will convert the fluctuating electrical power generated into fixed DC power and the inverter will convert the DC power back into AC power. The rectifier control system controls the generator speed and the inverter control system controls the power transmitted to the grid.
2.3. **PMSG**

PMSG SIMULINK model in Figure 12 is also similar to the SCIG except that the generator do not require grid supply for the windings excitation. Power converters are required as PMSG is a variable speed wind turbine. Permanent magnets will excite the rotor windings while the stator windings will be connected directly to the grid via a rectifier, inverter, step up transformers and 30km transmission line.

### 3. Result and analysis

All of the data will be analysed in per unit (pu) for ease of comparison. Per unit is the ratio of the actual value obtained to the reference value or base value in the same unit. Analysis will be focused on power generated, rotor speed and pitch angle of the SCIG, DFIG and PMSG.

#### 3.1 Generated Power

Figure 13 shows the data obtained from the SIMULINK models on the power generated by SCIG, DFIG and PMSG. The behaviour of each generators with varying wind speed can be observed. High starting current of the SCIG can be noticed from \( t=0 \)s to \( t=1 \)s as SCIG is connected directly to the power grid without any power converter. This spike in the starting current will cause severe voltage disturbances to the grid and a soft starter is required to limit the high starting current of the generator. Both stator and rotor windings for DFIG are directly connected to the grid which allow for better control of active and reactive power. Parts of the output power of DFIG are controlled by the power converter. This reduces the fluctuation in the power generated and increased in the power control. It is also worth noting that both SCIG and DFIG draw reactive power from the power grid for winding excitation. The grid will supply three-phase AC power to the stator, creating a rotating magnetic field. When the rotor driven by the wind turbine rotates at a speed higher than the synchronous speed, power will be generated.
Standalone induction generator wind turbines are possible with the addition of capacitors or diesel generators to provide the required current for winding excitation. PMSG do not require external excitation as the magnet or electromagnet mounted on the stator will provide the excitation required.

![Figure 13. Simulation of Power Generation for Different Types of Generator](image)

3.2 Generator’s Efficiency

The efficiency of the generators shown in Figure 14 are obtained by using $\eta = \frac{\text{power}_{\text{out}}}{\text{power}_{\text{in}}}$.

$\text{Power}_{\text{in}}$ can be determined by calculating the power of the wind, $\text{Power}_{\text{in}} = \frac{1}{2} \cdot \rho \cdot A \cdot v^3$, where $\rho$ is the air density, $A$ is the rotor swept area and $v$ is the speed of wind. The efficiency of the generator are calculated until $t=15s$ as the pitch controller will be activated as the wind speed rises above the rated wind speed. Efficiency for $t=0s$ until $t=3s$ is neglected from the study as SCIG is experiencing a current spike as it is connected to the power grid directly without any soft starter. From $t=3s$ to $t=7s$, SCIG is consuming electricity from the grid for the winding excitation before the generator starts producing electricity and thus explaining the negative efficiency. PMSG can be observed to perform better under lower wind speed condition compared to SCIG and DFIG. Although all three generators eventually reach a similar efficiency, PMSG is more suitable for wind turbines application in Malaysia as it has better efficiency for lower wind speed and a lower cut-in speed.

![Figure 14: Efficiency of Generators](image)
3.3 Rotor Speed

Differences between fixed and variable speed generators can be seen from Figure 15. The rotor speed for SCIG, ranges from 0.9975pu and 1.0075pu is considered to be fixed speed. On the other hand, both DFIG and PMSG required additional power converter to condition the fluctuating frequency of the generated power to a fixed frequency appropriate for the grid. This increases the complexity and cost of the system. SCIG and DFIG required additional drivetrain to increase the rotor speed of the generator while PMSG can be driven directly by the turbine. TSR for a fixed speed generator fluctuates with wind speed as the rotor speed remain constant. This results in SCIG having lower efficiency and reliability as maximum efficiency can only be achieved at a certain wind speed. Fixed rotor speed results in additional mechanical stresses, fatigue and noises of the turbine and greatly reduce the reliability of the system.

4. Conclusion
SIMULINK model for SCIG, DFIG and PMSG wind turbine had been successfully simulated in this paper. SGIG turbine design is a lot simpler compared to variable speed wind turbine using DFIG and PMSG. However, variable speed generator has the advantages over fixed speed generator as they are more efficient and reliable. From the simulation done, PMSG has shown to be more efficient over SCIG and DFIG for lower wind speed although all of them eventually reaches the similar efficiency.

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References
[1] Saberi, Z., A. Fudholi, and K. Sopian, Fitting of Weibull Distribution Method to Analysis Wind Energy Potential at Kuala Terengganu, Malaysia. Journal of Advanced Research in Fluid Mechanics and Thermal Sciences, 2020. 69: p. 13-22.
[2] Yahyaoui, I. and A.S. Cantero, Chapter 16 - Modeling and Characterization of a Wind Turbine Emulator, in Advances in Renewable Energies and Power Technologies, I. Yahyaoui, Editor. 2018, Elsevier. p. 491-508.
[3] A.R, S., et al., Numerical study of effect of pitch angle on performance characteristics of a HAWT. Engineering Science and Technology, an International Journal, 2016. 19(1): p. 632-641.
[4] Katsigiannis, Y. and G. Stavrakakis, Estimation of wind energy production in various sites in Australia for different wind turbine classes: A comparative technical and economic assessment. Renewable Energy, 2014. 67.
[5] Islam, M.R., Y. Guo, and J.G. Zhu, *Power converters for wind turbines: Current and future development*. 2013. p. 559–571.

[6] Funabashi, T., *Chapter 1 - Introduction*, in *Integration of Distributed Energy Resources in Power Systems*, T. Funabashi, Editor. 2016, Academic Press. p. 1-14.

[7] Sumathi, S., L. Ashok Kumar, and P. Surekha, *Wind Energy Conversion Systems*, in *Solar PV and Wind Energy Conversion Systems: An Introduction to Theory, Modeling with MATLAB/SIMULINK, and the Role of Soft Computing Techniques*, S. Sumathi, L. Ashok Kumar, and P. Surekha, Editors. 2015, Springer International Publishing: Cham. p. 247-307.

[8] Mali, S., S. James, and I. Tank, *Improving Low Voltage Ride-through Capabilities for Grid Connected Wind Turbine Generator*. Energy Procedia, 2014. 54: p. 530-540.

[9] Laakam, M., D. Mehdi, and S. Lassaad, *Study of induction generator isolated mode*. International Journal of Research in Engineering & Advanced Technology IJARET, 2014. Vol. 2: p. pp. 1-14.

[10] Rawal, C.S. and A.M. Mulla, *An AC-AC converter for doubly fed induction generator driven By Wind Turbine*.

[11] Zou, Y., *Induction generator in wind power systems*, in *Induction Motors-Applications, Control and Fault Diagnostics*. 2015, IntechOpen.

[12] Shewale, A.J., A.R. Gagangras, and N.M. Lokhande, *Comparison of various Wind Turbine Generators*.

[13] Jadhav, H.T. and R. Roy, *A comprehensive review on the grid integration of doubly fed induction generator*. International Journal of Electrical Power & Energy Systems, 2013. 49: p. 8–18.

[14] Calderaro, V., et al., *Design and implementation of a fuzzy controller for wind generators performance optimisation*. 2007. 1-10.

[15] Esterhuizen, R., *Comparative Study between Synchronous Generator and Doubly-Fed Induction Generator in Wind Energy Conversion Systems*. 2019.