REVIEW ON WIND TURBINE TECHNOLOGY AND CONTROL

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ABSTRACT: This paper provided a review on wind turbine technology and control. The technologies, differences, advantages and disadvantages of horizontal and vertical axis wind turbine structures were reported. The control strategies of wind turbine such as fixed speed and variable speed were also discussed along with the wind turbine distribution profile for both vertical and horizontal axis configuration. The aim is to cover the appropriate wind turbine structures and control strategies to be used in the certain area condition. Regardless similar wind speed distribution profile except the power coefficient, horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT) have different structures and control strategies. As a conclusion, HAWT structure is less suitable for urban area as compared to VAWT nevertheless is more appropriate for large-scale wind farm. For the control approach, variable speed wind turbine (VSWT) is more appropriate for high wind speed area due to its ability to achieve maximum efficiency as compared to a fixed speed wind turbine (VSWT).

KEYWORDS: *Vertical Axis Wind Turbine; Horizontal Axis Wind Turbine; Variable Speed; Fixed Speed*

1.0 INTRODUCTION

In European countries, research and development of wind turbine technology is rather encouraging [1]. However, in Southeast Asian continent, the development in wind turbine technology is rather slow. Few studies on evaluation of wind energy feasibility in Southeast Asian continent have been reported. For instance, wind turbine feasibility studies in Malaysia emphasize few regions with high wind speed. Mersing, Kota Bharu, Kuala Terengganu, Langkawi and Penang are listed as potential location for harversting wind energy [2]. In addition, Kota Belud, Kudat, Langkawi, Gebeng and Kerteh are the best wind sites with the range of 2450 to 3750 MWh/year [3]. In [4], Mersing was reported to have power density from 10 to 26 W/m² which verified it as a promising location for generating wind power. In addition, Temburong Island is a potential wind power harvesting location in Brunei [5]. Moreover, in Myanmar, 360.1 TWh/year wind energy available in high land area of Chin and Shan States, littoral area and west region [6] whereas 120 W/m² power density in Arakan, 125 W/m² in Pathien, 100 W/m² in Yangon, and 130 W/m² in Ye were recorded [7]. Besides, Indonesia has potential wind energy of 3 to 6 m/s [8]. These studies prove that Southeast Asian continent has potential in developing wind farm.

Previous studies [9–17] have recorded several advantages that lead to the increasing research and development activities involving wind turbine as well as it shortcomings. The main benefit of wind turbine technology is due to its ubiquitous energy resources. Wind turbine is also ecologically friendly as no greenhouse gas or heat emission being released into the atmosphere. Besides, it can be built on existing farms or ranches without disturbing the activities operating in that area because the wind turbine only requires a fraction of the land. Furthermore, servicing and repairing process of wind turbine can be performed individually without shutting down the whole wind farm. Apart from the advantages, the wind turbine records several shortcomings such as noise produced by the turbine's blade. Moreover, it might also causes aesthetic pollutant to the landscape. Furthermore, the spinning blade is dangerous to local wildlife as birds might be killed. To-date, technological improvement has reduced this problem. Besides, as the turbine is often installed in remote area, transmission lines are required to dispatch the electricity from the wind farm to the city that can incur high cost.

Wind turbine converts kinetic energy from the winds into electrical energy. The principle operation of wind turbine is the kinetic energy of the winds turn the rotor blades and produces mechanical rotational power. The main shaft connects the rotor to the generator. Then, the turning shaft will spin the generator that produces electricity [10], [18–23]. Main components of wind turbine are rotor, tower, foundation, and nacelle. The nacelle consists of generator, gearbox, and control and protection system [10, 18-19, 24]. The rotor consists of a hub, blades and pitch where the kinetic energy from the wind is aerodynamically converted into mechanical energy through shaft. The rotor is raised high in the air by the tower which connects to the foundation to find higher speed winds and maintain vibration within wind speed changes as well as to hold the nacelle. The foundation supports the entire wind turbine to ensure it is firmly fixed onto the ground or the roof. The generator is to convert mechanical energy into electrical energy. The gearbox is used to increase the rotor rotational speed towards the required generator rotational speed. The control and protection system acts as a safety feature to ensure that the turbine does not operate under stressed condition as it includes a braking system triggered by the higher wind speed signal by means of under excessive wind gust, such as the rotor stops. Wind turbine applies wind energy conversion system (WECS) which consists of a mechanical power control (MPC) side and electrical power control (EPC) side as shown in Figure 1. However, power converter is not required in a fixed speed wind turbine system as this configuration produces constant voltage and frequency. WECS are dependent on wind flow dynamics which are highly nonlinear, non-deterministic and have chaotic behavior. Besides, the most striking characteristic of wind flow that bothers control engineers is its variability. EPC side of the system demands maximum mechanical power from the MPC side despite wind intermittent and seasonal interference.

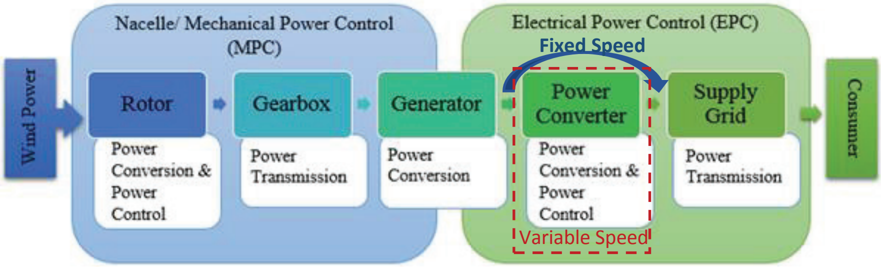

Figure 1: Wind energy conversion system (WECS)

Wind turbine can be categorized based on the structures and the control strategies which will be explained in section 2.0 and section 3.0. Section 4.0 describes distribution profile of wind turbine. This review aimed to cover appropriate wind turbine structures and control strategies to be used in certain locations subject to the area conditions.

2.0 WIND TURBINE STUCTURE

Wind turbines are commonly classified into horizontal axis wind turbines (HAWT) and vertical axis wind turbines (VAWT) as shown in Figure 2. The classification is made based on the structure and the rotor shaft orientation of such configuration [25]. The main rotor shaft, gearbox and generator of HAWT are placed on top of the tower with the main rotor shaft's orientation is parallel to the wind direction. In VAWT, the main rotor shaft which is perpendicular to the wind direction is located on top of the turbine while the gearbox and generator are located near the turbine foundation [10, 26–28].

VAWT is considered as a less viable alternative for distribution due to its efficacy [29]. According to aerodynamic and mechanical characteristic, VAWT can be classified into two categories namely drag-based Savonius and the lift-based Darrieus. The drag-based Savonius is the simplest form of wind turbine with two or three scoops. The drag concept causes it to move more when moving with the wind and less when moving againts the wind [30]. On the other hand, the lift-based Darrieus is powered by the airfoil's lifted forces which is actuated by a powered motor because it has no self-starting mechanism [30]. The structure of VAWT makes it more appropriate for urban application as the turbine allows it to accept wind from any direction [10, 25-26, 29, 31–33], produce less noise compared to HAWT [25-26, 29, 34], operate in low wind speed [29, 32], perform better in turbulent wind flow [25, 29, 34] and require less space [25]. On the other hand, the structure also gives advantage in maintenance process [25, 34]. The efficiency of the VAWT is depending on the control strategy that can be either fixed pitch or variable pitch. VAWT variable pitch has higher efficiency as compared to VAWT fixed pitch [29]. Furthermore, VAWT variable pitch is able to self-start during low wind speed while VAWT fixed pitch is unable to do [29].

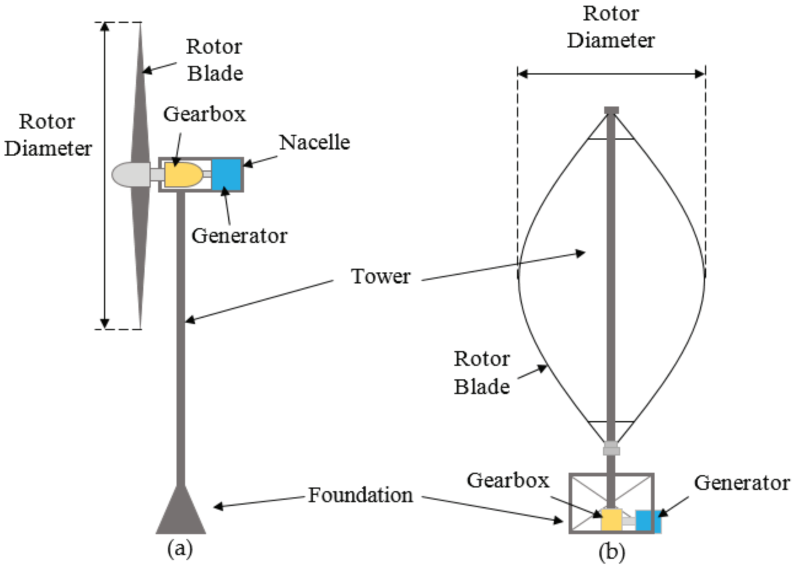

Figure 2: Types of wind turbine (a) Horizontal axis wind turbine (b) Vertical Axis Wind Turbine

Many researchers such as [10] and [35–37] are focusing on HAWT improvement due to the efficacy for large-scale production as compared to VAWT. Although HAWT has taller structure, the blades are attached to the center of gravity of the turbine which helps in stability. There are two types of HAWT; upwind wind turbine and downwind wind turbine. The rotor location of the upwind wind turbine is facing the wind while the downwind wind turbine is located on the downwind side (lee side) of the tower. Contrary to VAWT, HAWT requires yaw mechanism to assure that the rotor is facing towards wind consistently [38]. However, the movement produces undesirable noise. The yaw mechanism and tall tower helps the turbine to capture maximum wind power. However, HAWT is not suitable for urban area because of the noise emission and the structure that cause it difficult for installation and maintenance process [39].

3.0 WIND TURBINE CONTROL STRATEGIES

Fixed speed wind turbine (FSWT) is developed earlier than variable speed wind turbine [40]. In early development, FSWT system has been given more attention due to robustness, inexpensive and simple structure. FSWT does not need power converter as the generator is directly connected to the grid [19, 41]. As such, induction generator is utilized as the generating system for FSWT. Thus, FSWT uses aerodynamic power to control the system that varies from pitch control, stall control or active stall control. However, power fluctuation produced by the system cancels the cost reduction [41-42]. In a FSWT, the rotor speed remain constant for all wind speeds, thus producing poor power quality and increasing mechanical drive train load [19, 40–42]. However, as the size of turbine increases and due to wind intermittent, the inherent problems of the FSWT become more pronounced.

Variable speed wind turbine (VSWT) allows the rotor and wind speed to be matched with the aim of maintaining its optimum tip-speed ratio (TSR) for maximum efficiency [19, 43-44]. TSR is the ratio of the blade tip-speed and wind speed. However, the electrical power control system is more complex because power converter is required in between the generator and the grid that can cause power electronics losses and increase the installation cost [45]. The arrangement of power converter in VSWT can be categorized into partially rated power converter and full scale power converter. In wind turbine with partially rated power converter (dynamic slip-controlled wounded rotor induction generator and doubly fed induction generator) the generator stator is directly connected to the grid while the generator rotor is connected to the power converter, indicating only parts of the power produced are supplied into the power converter. Contrary to full scale power converter (synchronous generators and induction generators without rotor winding), the power converter is connected between the generator stator and the grid, hence, the total power produced is fed into the power converter. In modern WECS, studies in VSWT are blossoming. To-date, researchers produce VSWT control structure using linear parameter varying [46], linear parameter varying with anti-windup [47], sliding mode control [48], nonlinear static and dynamic state feedback controller [49], full state-feedback [50-51] and many more. Studies [43, 52] address the advantages of variable speed wind turbines such as the possibility to control the turbine rotor speed which helps in reducing drive train loads, hence, allowing the system to operate asymptotically to its optimum tip-speed ratio, increasing energy capture and maximizing energy generation.

Both FSWT and VSWT can be augmented with additional control strategies such as fixed pitch or variable pitch control. Variable pitch control allows the pitch angle to be remotely changed to ensure maximum wind energy is captured. The pitch control also helps in preventing wind turbine from being damaged by decreasing the turbine power coefficient when the wind speed is too high. However, the system is more complex and expensive especially when the size of wind turbine is larger.

4.0 WIND TURBINE DISTRIBUTION PROFILE

Regardless of the structure, the energy conversion of wind turbine depends on the turbine wind speed and swept area, A. The instantaneous power produced by the wind is the kinetic energy's rate of change and is expressed as $P_{wind} = \frac{1}{2}\rho A v^3$ where v is the wind speed, and ρ is the air density. The multiplication of power coefficient $C_p(\lambda,\beta)$ with the instantaneous wind power renders aero-dynamic power produced by the turbine. Mathematically, aero-dynamic power can be expressed as $P_m = P_{wind} C_p(\lambda,\beta)$. Note that $C_p(\lambda,\beta)$ is the rotor conversion efficiency in a function of tip-speed-ratio λ and the pitch angle, β. The power coefficient characteristic for various pitch angle, β is as shown in Figure 3 [53].

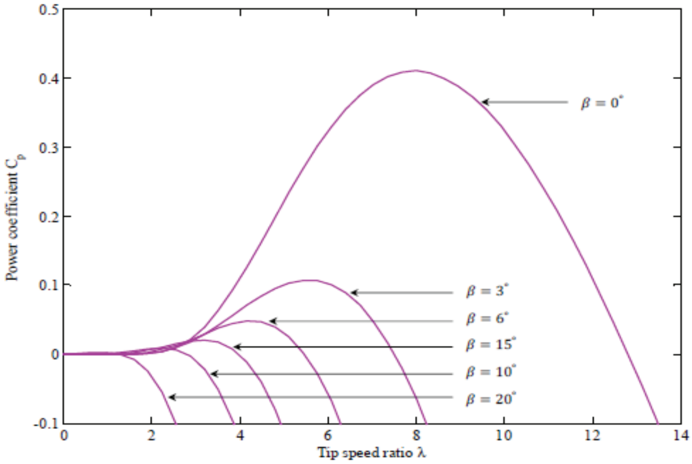

Figure 3: Power coefficient characteristic [53]

The tip-speed ratio is defined as the ratio of the blade tip speed and wind speed

$$\lambda = \frac{R\omega_r}{v} \tag{1}$$

where ω_r is the rotor speed. Power coefficient is often obtained by look-up table provided by turbine manufacturer [54]. However, in previous studies [22] and [55-56], the empirical power coefficient model can be represented as

$$C_p(\lambda,\beta) = 0.5\left(116\frac{1}{\varphi} - 0.4\varphi. \; -5\right)e^{-21\frac{1}{\varphi}} \tag{2}$$

where the function φ is given as

$$\frac{1}{\varphi} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1 + \beta^3} \tag{3}$$

For fixed-pitch system, the pitch angle, β is regulated at 0°. Maximum power coefficient that HAWT can achieve is 0.59 while VAWT can achieve power coefficient approaching 0.4 [38]. For variable-pitch system, the power coefficient varies due to the pitch angle of the blade. However, the maximum power coefficient is still limited to the value of Betz limit which is 0.59.

5.0 CONCLUSION

HAWT is not suitable for urban area as compared to VAWT because of the noise emission and the structure itself that causes difficulties in installation and maintenance process. However, the structure and efficacy of HAWT is appropriate for large-scale wind farm as compared to VAWT. Apart from the structure, the performance of the wind turbine also depends on the control strategies. FSWT is not applicable for high wind speed area as compared to VSWT. VSWT allows the rotor to be matched to the wind speed in order to achieve maximum efficiency. Regardless of the structure, the wind turbine distribution profiles for both HAWT and VAWT are similar except for the power coefficient. In future, appropriate wind turbine structure and control can be determined to develop wind farm in the potential wind energy region such as in the South East Asian continent.

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