ISSN: 2186-8476, ISSN: 2186-8468 Print
Vol. 1. No. 3. September 2012

COMPARATIVE ANALYSIS OF SMALL-SCALE WIND TURBINE DESIGN FOR THE LOW RATE WIND SPEED

Ali Musyafa

Department of Engineering Physics, Faculty of Industrial Technology,
Sepuluh Nopember Institute of Technology, Surabaya of Indonesia
INDONESIA.
musyafa@ep.its.ac.id

ABSTRACT

This paper reports developments and tests of simulation and a prototype for wind turbine with blade diameter of 2 m, with three blades of airfoil NREL S83n. Crucial problem in implementation of small scale wind turbine for low wind speed regimes (i.e. 3.8-7.5 ms^{-1}, like in most areas in Indonesia), is to determine the position of pitch angle of turbine blade. The right position of blades' pitch angle may produce maximum mechanical power, wich means also maximum electrical power. The proof of concept experiments were done by considering pre-determined dimension, type and diameter of blade, as well a range of angular velocity and power produced. The prototype of turbine was exposed to variation of wind speed flow, and stepwise variation of blades's pitch angle was set through PC, with angular step of 5^0 for range of angle 0-90 degrees. Optimal pitch angle 0f 15± 5 degree was obtain, with a maximum value of Cp=0.54 for a prototype and 0,59 for simulation.

Keywords: pitch angle, wind turbine, mechanical energy, electrical power.

INTRODUCTION

Indonesia as a tropical country with low wind speeds (2.8-7.5 m / s) has 1.4 MW wind turbine installations, and in 2011 a new plant is built in South Sulawesi and Aceh Bulukumba consist of 0.5 MW and 10 MW respectively. However, the majority of the installed wind turbines in Indonesia are from other countries, as a result there is a great dependency of the components from other countries. Therefore, it is needed to develop local wind turbine either by LAPAN, BPPT, colleges, or the general public [1-2-3].Wind energy conversion systems (WECS) consists of wind turbines, generators, power electronics, network systems and control systems. Small scale of WECS is wind turbines with <10 kW capacities, this turbine is suitable for low-speed wind farms such as Indonesia. The important part of SKEA is the wind turbine. In this part, the wind kinetic energy will be transformed into mechanical energy and then converted into electrical energy. Fluctuation in the wind kinetic energy value was often influenced by the wind speed changes and the type of air. Wind turbine mechanical energy production value is parallel with the wind kinetic energy input [4-5]. Maximum mechanical power production of wind turbines can be attained by increasing the angle of wind turbine rotational speed. Wind turbine mechanical power production depends on several variables of wind turbines, such as power coefficient (Cp), which depends on the value of (λ, θ). λ is the tip speed ratio (TSR) that cost = ωR / V), the value of R constant wind turbines, meanwhile the fluctuation of V value depend on the condition of the wind field, ω is the angular velocity of the wind turbine correlated to a blade angle position. Hence, the most influence variable of mechanical power production of wind turbines is the blade angle position other quantities which influence over mechanical power production is the type of blade and blade number, but its value is constant after the system was designed [6].

The wind turbine performance can be monitored, if a prototype wind turbine is outfitted with a computer-based electronic monitoring system. Here, major scales such as V, ω and θ are likely to be monitored. To obtain these quantities, wind turbine is outfitted with a sensing rotary encoder for sensing turbine rotational speed. Furthermore, this rotation data is processed by processor, and then it is displayed and recorded in real time by the PC. The variations of blade angle position changes can be set via PC, so the blade angle position changes can be done in every single step 5^o quickly and precisely [7-8]. From these experiments, all data related to head position blade angle changes, wind speed and the speed will be processed to obtain the relation between the wind power and the turbine mechanical power output. The maximum power production values are obtained when the blade angle is in a particular position and then this value is used as a reference for developing the turbine and the design of control systems. This study focuses are to find and trace the position angle blade wind turbine that can produce maximum mechanical power.

MATERIAL AND METHOD

A wind power production by a wind turbine can be expressed through a kinetics wind energy equation using equation (1) and (2) [13].

$$U = \frac{1}{2} m v_w^2 = \frac{1}{2} (\rho_{air} A_r x) v_w^2 \quad (1)$$

$$P = \frac{dU}{dt} = \frac{1}{2} \rho_{air} A_r v_w^2 \frac{dx}{dt} = \frac{1}{2} \rho_{air} A_r v_w^3 \quad (2)$$

Where U is a kinetic energy (Joule), ρ_{air} is air density (kg/m^2), A_r is a sweeping blade area (m^2), v_w is a wind speed (m/s), and P is wind turbine power (watt). Kinetics energy is converted into rotational energy or wind turbine power. When the wind passed through the blade, a wind velocity profile can be illustrated using a contour tube as in Fig. 1.

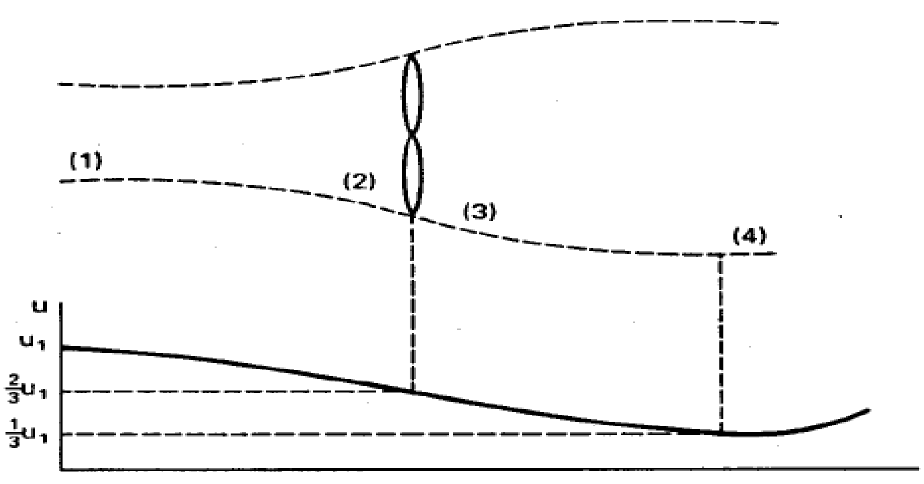

Figure 1: Velocity Profile in the Wind Turbine Area

There are four points to be considered as in Fig. 1. The velocity profile and its relation to the sweeping blade area are given below:

$$v_2 = v_3 = \frac{2}{3} v_1 \quad (3.a)$$

$$v_4 = \frac{1}{3} v_1 \quad (3.b)$$

$$A_2 = A_3 = \frac{3}{2} A_1 \quad (3.c)$$

$$A_4 = 3A_1 \quad (3.d)$$

Equation (4) can be used to calculate the extraction of wind power. The power can be calculated by comparing the wind power before and after the blade:

$$P = P_1 - P_4 = \frac{1}{2}\rho_{air}\left(A_1 v_1^3 - A_4 v_4^3\right) = \frac{1}{2}\rho_{air}\left(\frac{8}{9} A_1 v_1^3\right) \quad (4)$$

$$P = \frac{1}{2}\rho_{air}\left[\frac{8}{9}\left(\frac{2}{3} A_2 v_1^3\right)\right] = \frac{1}{2}\rho_{air}\left(\frac{16}{27} A_2 v_1^3\right) \quad (5)$$

A substitution eq. (5) into eq. (4), and substitution the value of A, it can be obtained a constant of 16/27 = 0.59. This value is known as a Betz coefficient [14]. This coefficient shows a maximum efficiency of wind turbine or it is called a power coefficient (Cp). It is known that wind power production is also effected by the Cp. The bigger Cp can produce the bigger wind power production. The expression of extracted wind power also can be written as in eq. (6).

$$P = \frac{1}{2}\rho_{air} C_p A_r v_w^3 \quad (6)$$

Cp also can be determined in a simple way based on P_1 and P_4 as in eq. (7)

$$Cp = \frac{P_4 - P_1}{P_1} \quad . \quad (7)$$

Tip speed ratio is the ratio between the rotational speeds of the blade tip to wind speed. Blade tip speed is obtained by multiplying the rotor angular velocity (rad / s) with the radius of the rotor. This value is then compared with the wind speed in zone 1. R is the radius of the rotor and the RPS is the rotation per second.

$$TSR = \frac{2\pi\pi.R.RP}{V} \quad (8)$$

A design of wind turbine is consists of three blades, a gear blade, motor servo, a generator and others supporting components. The blade is designed based on an air foil contour standard of NREL S833, S835 and S834. This blade type is chosen with a consideration of its easiness of fabrication process. The blade has a length of 100 cm and a thickness of 18 %, 15 % and 21% t/C. It is made of fiber material. A gear box is fabricated based on a specification of the motor servo. The gear box can achieve a movement resolution of 5^o. The fabricated wind turbine parameters are shown in Table 1.

Table 1. Specification of the Wind Turbine Prototype

Rotor Blade
Span = 85 cm Blade = 3 Airfoil = non-uniform NREL → S835 (root), S833 (primary), S834 (tip) Tapered, no-twist. Blade Shaft = Stainless Steel, ø 10 mm, l = 15 cm Material = Fiberglass
Pitch Setting
Motor Servo = GWS Servo S125-1T/2BB/F 360 Deg Driver = Microcontroller ATMega8535L Angle rotation = 360^o Power Suplay = 6 V Torque = 6.60 kg/cmB Gear box = Nylon, 1:1.25
Rotary Sensor
Rotary Encoder = Relative, 20 slate, ø 40 mm Photo Interrupter = Sharp GP1S53, 5 mm gap, IR (Tx) Phototransistor (Rx)
Center Plate & Hub Cover
Center Plate → t = 20 mm, ø 28 cm Material = Poly Vinyl Chloride (PVC) Grey Hub Cover → Material = Fiberglass
Rotor Shaft
Stainless Steel, ø 15 mm, t = 2 mm, l = 55 cm Shaft holder = bearing NTN 6203LU
Rotary Connector
Carbon Brush Holder = Bosch and Black Dekker Carbon Brush = Makita

The fabricated wind turbine is equipped with monitoring software based on Visual Basic and a serial port interface for data communication. This software is used to control and to show the position of the pitch angle of the wind turbine blade. The measurement data can be presented in real time to indicate all of the necessary information. Monitoring system is also equipped with recording data system based on Microsoft Office-Excel integrated with the Visual Basic. Therefore, all of measurement process for the wind turbine can be accessed in real time and online. In this paper, wind speed data for experiment taken for a period of 100 seconds, in a steady state for the variation of wind speed 3-8 m/s. It indicates that the most of wind speed is in the range of 3-6 m/s. Therefore, it is necessary to design a wind turbine with an operational wind speed within this range.

Method of Development Wind Turbines with a Simulation

Design optimization of wind turbine parameters (Cp) and (P), constructed through the wind turbine system model operation as shown in Figure 1. Betz theory using the hypothesis, that the fluid used in the experiments have constant air pressure, air velocity and has an ideal air, the system is illustrated in a vague boundary. Betz model illustrated by equation 9. As follows:

$$P = \rho.\, Q \left[\frac{V1^2}{2} - \frac{V3^2}{2} \right] \;;\; F = \rho.\, Q\, (V_1 - V_3);\; \rho = ct,\;\; and\;\; p = ct. \qquad (9)$$

The maximum power coefficient is approached by the equation 9, with the associated order Constanta to obtain the value of 'an' optimum:

$$a_{opt} = 16/27 = 0{,}593 \qquad (10)$$

The change of the power coefficient calculated by the equation (10), then plotted and shown in Figure 2. By performing simulations with the program package Mat lab, the obtained maximum value of Cp = 59.3%, the value describes the value of the maximum wind kinetic energy that can be extracted by a wind turbine for a wind speed axial output state whose value is worth a third of the value of wind speed input or V3 = 1/3 V1, By following the continuity equation, the Betz theory into equation 11.

$$Q = V_1 \,.\, A_1 = V2.\, A_2 = V_3.\, A_3\,, \qquad (11)$$

These conditions are practically acceptable and is called the Betz theory approach. Wind energy conversion process can be illustrated further by the TSR constant, which is the ratio of the tangential (ωR) with winds of velocity, and then written in equation (12). Wind turbines can operate when the TSR (λ) changes from the borders of the maximum power coefficient (Cp).

$$\lambda = \omega R \,/\, V_1 \qquad (12)$$

Wind turbine power optimization method, is associated with a variable wind speed associated with the position of blade pitch angle, the wind turbine will have a maximum power coefficient is described by functions that depend on pitch angle and tip speed ratio is shown by equations (13-14).

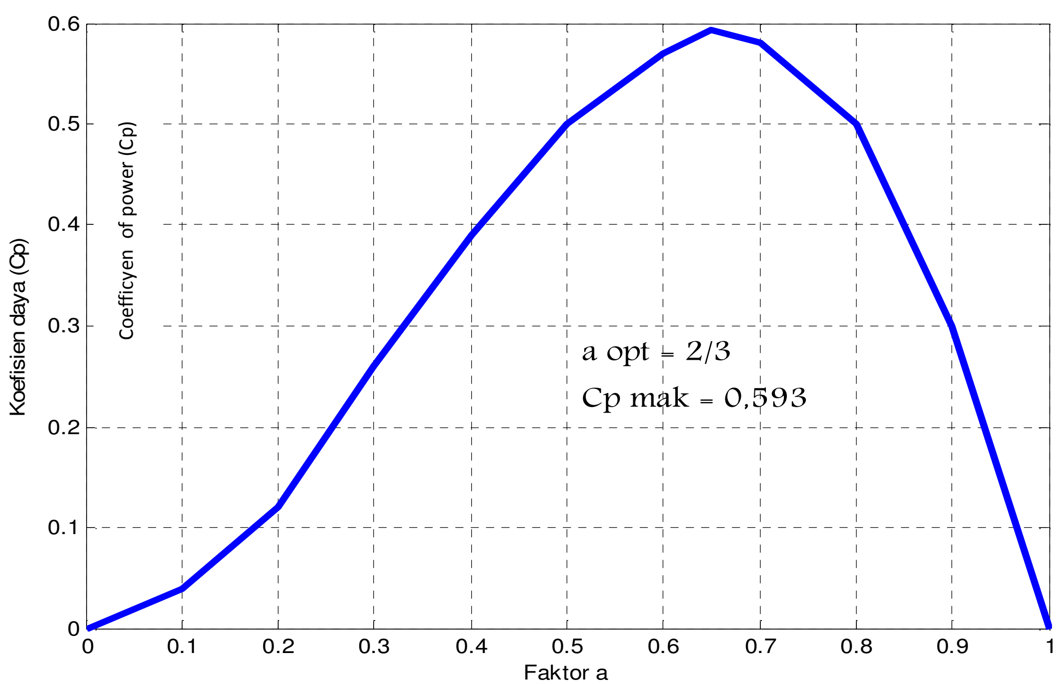

Figure 2: Coefficient of power versus flow induction factor [9]

From references are known values of the constants , C_1 = 0,5175, C_2 = 116, C_3 = 0,4 , C_4 = 5 , C_5 = 21 , C_6 = 21. [9-10].

$$Cp\ (\lambda,\theta) = C1.\ (C2\ \lambda_i - C_3\ \theta - C_4)\ e.^{-C5\ \lambda i} + C_6 .\lambda \qquad (13)$$

$$\lambda_i = 1/(\lambda + 0.08\ \theta)\ -\ 0.0035/\theta(^3 + 1) \qquad (14)$$

To position the blade pitch angle, θ varies from $(0\text{-}20)^0$, then Cp has evolution as the result simulation. The variation value is obtained through numerical calculation equation (13-14). Design optimization of the position of a wind turbine blade pitch angle, done to find the relationship power output and rotational speed wind turbine with wind speed variations.

Method of Development to Build a Wind Turbine Prototype

Wind turbine prototype was tested by the wind blowing in the wind speed and the position of blade pitch angle varied, the data recording test results that include wind speed at a certain distance before and after the blade, the rotational speed and blade pitch angle position.

Table 2: Experimental with a variation of Blade Position Angle and Wind Speed

Pitch Angle (o)	Wind Speed						
	7.5 m/s	7.0 m/s	6.5 m/s	4.8 m/s	4.1 m/s	3.1 m/s	2.8 m/s
	ω(RPM)	ω(RPM)	ω(RPM)	ω(RPM)	ω(RPM)	ω(RPM)	ω(RPM)
0	0	0	0	0	0	0	0
5	130	0	0	64	0	55	41
10	168	65	115	64	68	45	34
15	163	111	97	60	56	47	32
20	94	81	70	42	43	37	29
25	103	76	54	40	37	30	22
30	66	54	41	33	32	26	16
35	48	39	30	27	28	18	0
40	40	31	26	21	22	16	0
45	31	25	20	17	19	11	0
50	25	22	17	14	14	0	0
55	23	20	0	11	0	0	0
60	18	12	0	0	0	0	0
65	15	0	0	0	0	0	0
70	12	0	0	0	0	0	0
75	0	0	0	0	0	0	0
80	0	0	0	0	0	0	0
85	0	0	0	0	0	0	0
90	0	0	0	0	0	0	0

The relationship of TSR to wind speed variations and the position of the blade pitch angle, the coefficient of variation of wind speed at the blade pitch angle, and coefficient of variation of the power of the TSR on the blade pitch angle is calculated. Wind turbine rotational speed is read via the view that display in monitor with Pulls per Second unit. PPS readings are converted to the rotations per minute (RPM). Furthermore the data obtained by experiments as shown in Table 2.

RESULT AND DISCUSSION

The simulation of wind turbine generating, wind turbine parameter relationships and specific locations for wind speed wind turbine are installation. Relations obtained by the simulation of wind turbine power coefficient (Cp) of the tip speed ratio (TSR) for the pitch angle position (0-20)^o which is capable of producing the greatest power is shown in Figure 3

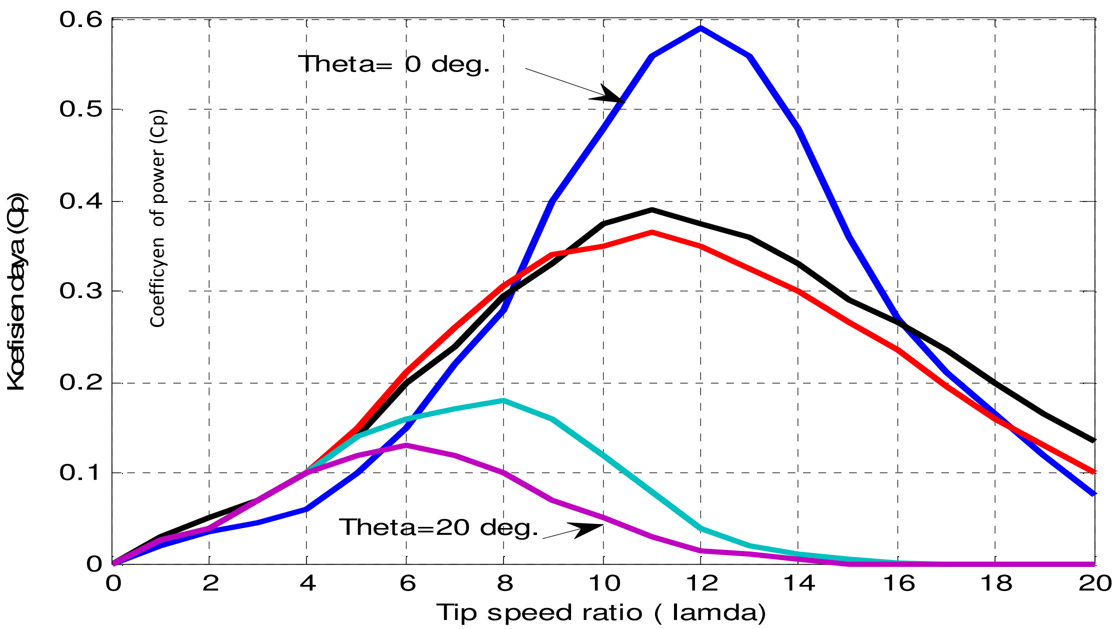

Figure 3: Simulation of power variation coefficient Cp on TSR for optimum pitch angle

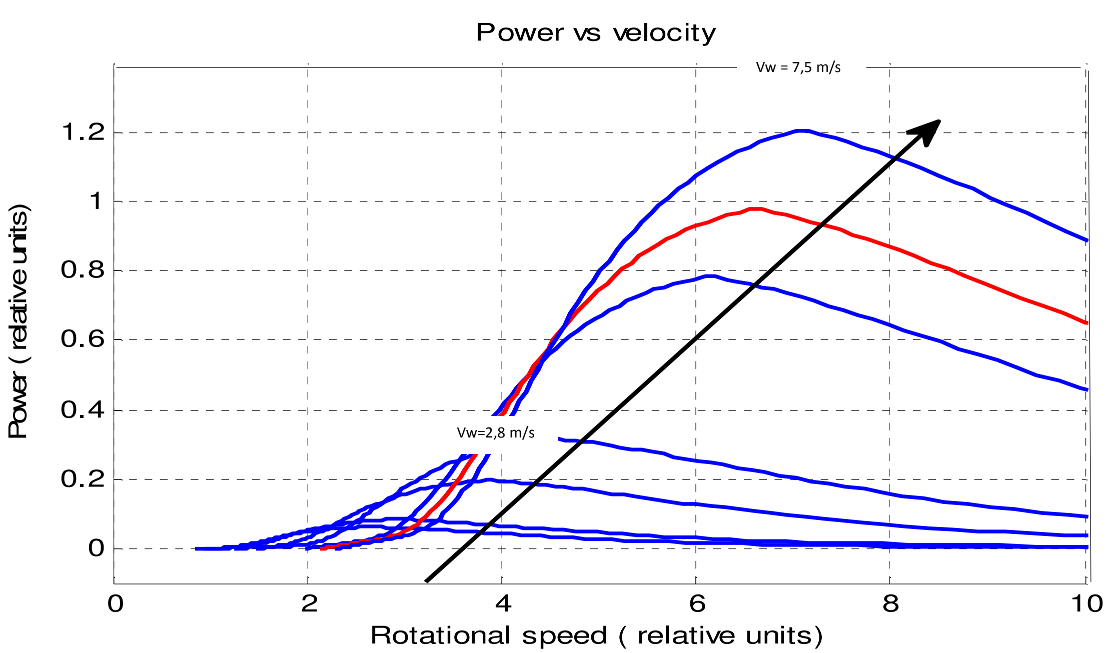

Figure 4: Wind power versus the rotational speed and the wind speed variation

The relationship of wind turbine power output of wind turbine rotational speed is illustrated by Figure 4. When the data has been processed it can be used to find the relationship: the speed of rotation of the blade pitch angle to the wind speed variation in Figure 5., The power coefficient of wind turbine blade pitch angle of the wind speed variation Figure 6. And the turbine power coefficient (Cp) of the tip speed ratio (TSR) is illustrated by Figure 7.

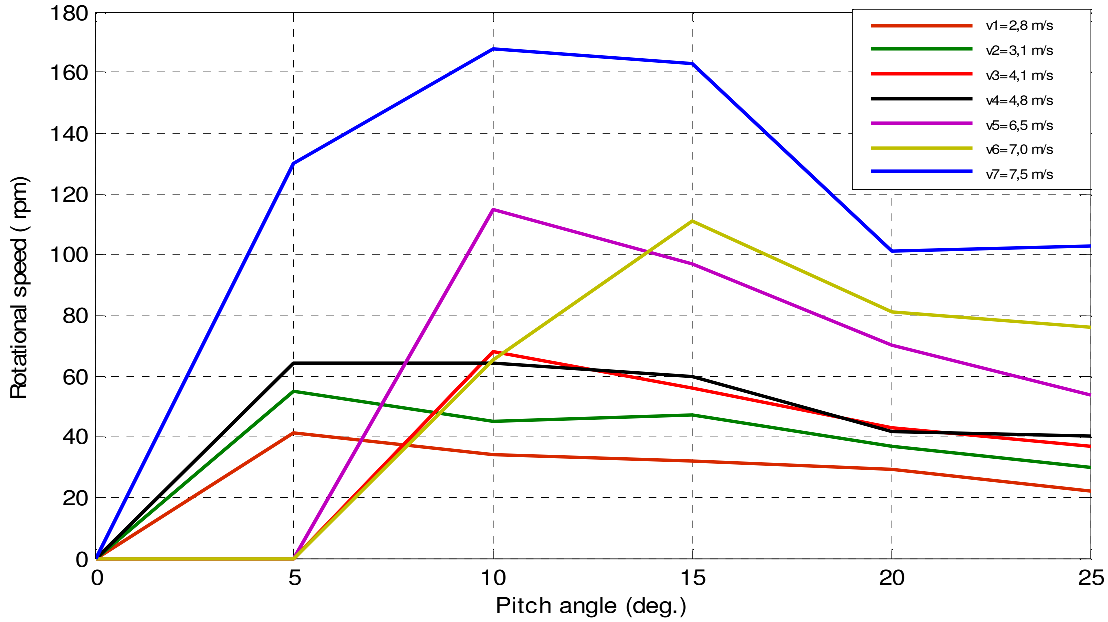

Figure 5: Rotation speed versus blade angle position and wind speed variation

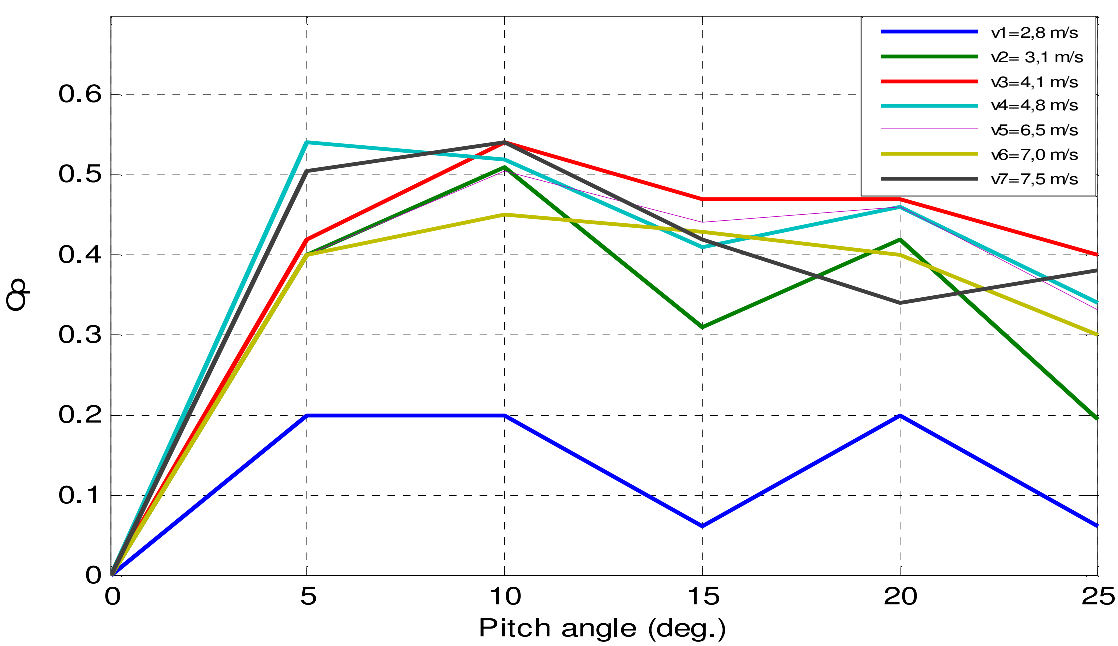

Figure 6: Power coefficient versus position on blade pitch angle variation and wind speed

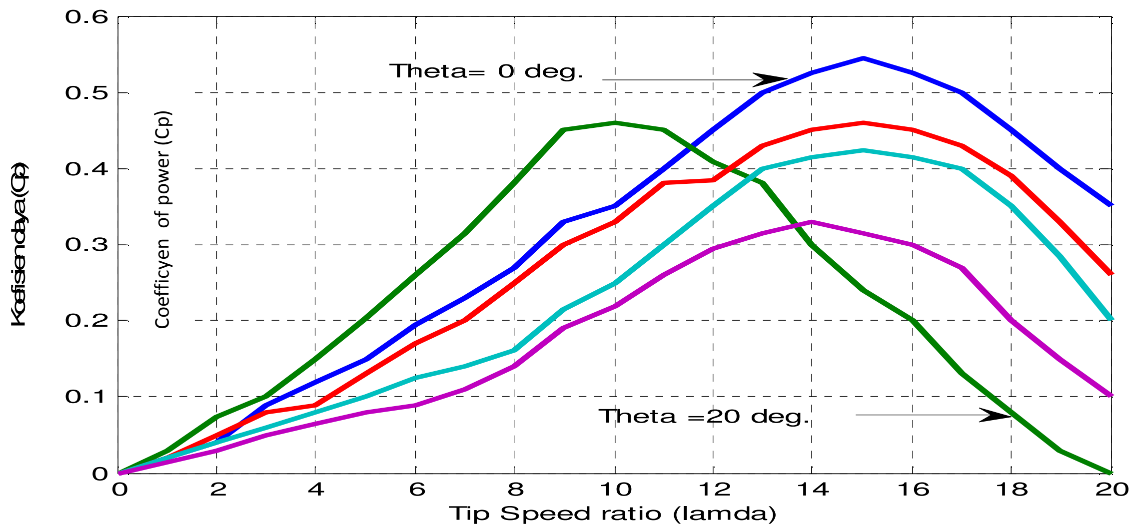

Figure 7: The variation of power coefficient (Cp) versus TSR on the pitch angle variation

Testing of Wind Turbine Prototype

Optimum pitch angle wind turbine is relationship with the angular velocity that can produce maximum power. Optimum blade pitch angle position was evaluated by two approaches. First through the relationship of power coefficient of wind speed with blade pitch angle varied. Second through the relationship of wind speed in RPM blade pitch angle varied.

The first approach is known that the position of the optimum blade pitch angle that produces maximum power coefficient is at the entire range of wind speeds (2.8 to 7.5) m / s, have a pitch angle position: 10, 15, and 20 deg. For wind speed 2.8 m /s, pitch angle position 10, 15, and 20 de. Have a relatively low power coefficient Cp values above 0.3. At the wind speed 7.5 m /s pitch angle to position the working area of the turbine 5^o-20^o. At wind speeds of 7.5 m /s maximum TSR achieved. On the pitch angle positions 5^o-70^o. The pitch angle position in 75^o-90^o, the TSR = 0. Power coefficient of wind turbines at each wind speed and pitch angle coefficient calculated through the relationship, the relationship of wind speed and blade pitch angle illustrated by Figure (8-10).

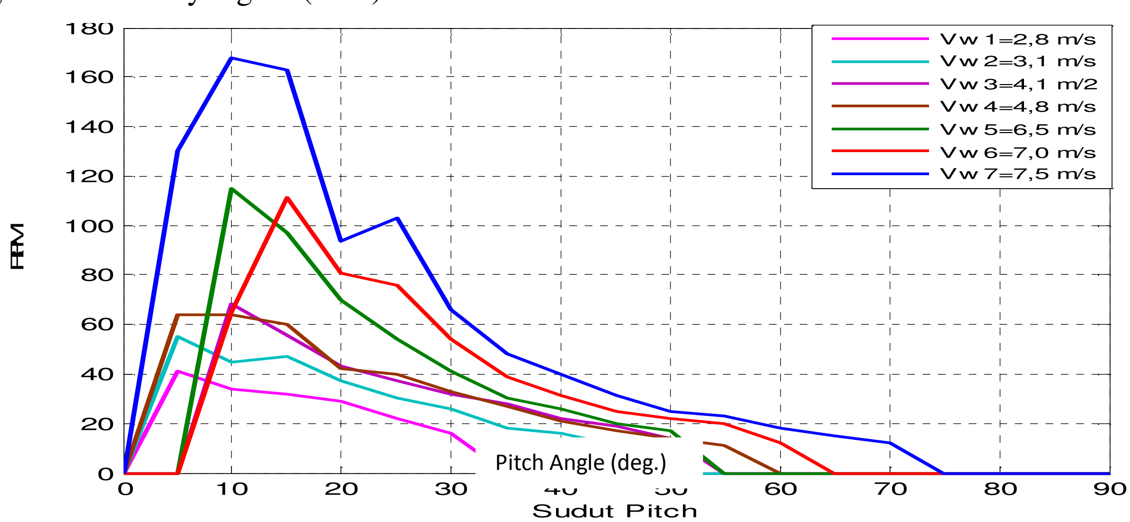

Figure 8: Pitch angle position versus RPM on wind speed variation

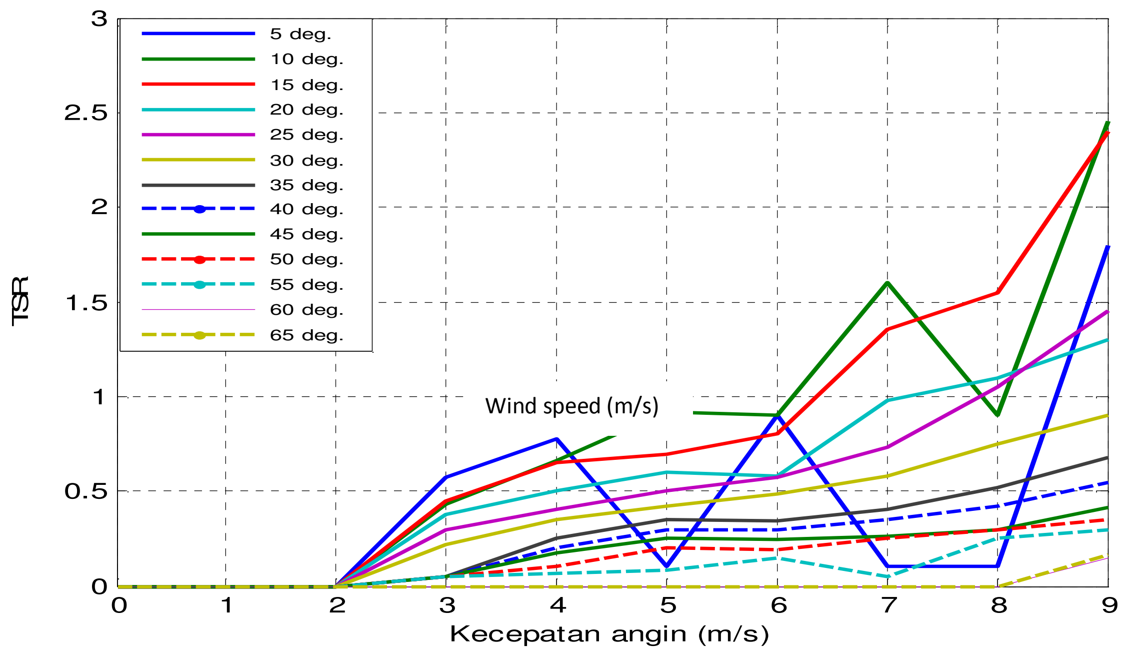

Figure 9: Wind speed versus TSR on the pitch angle variation

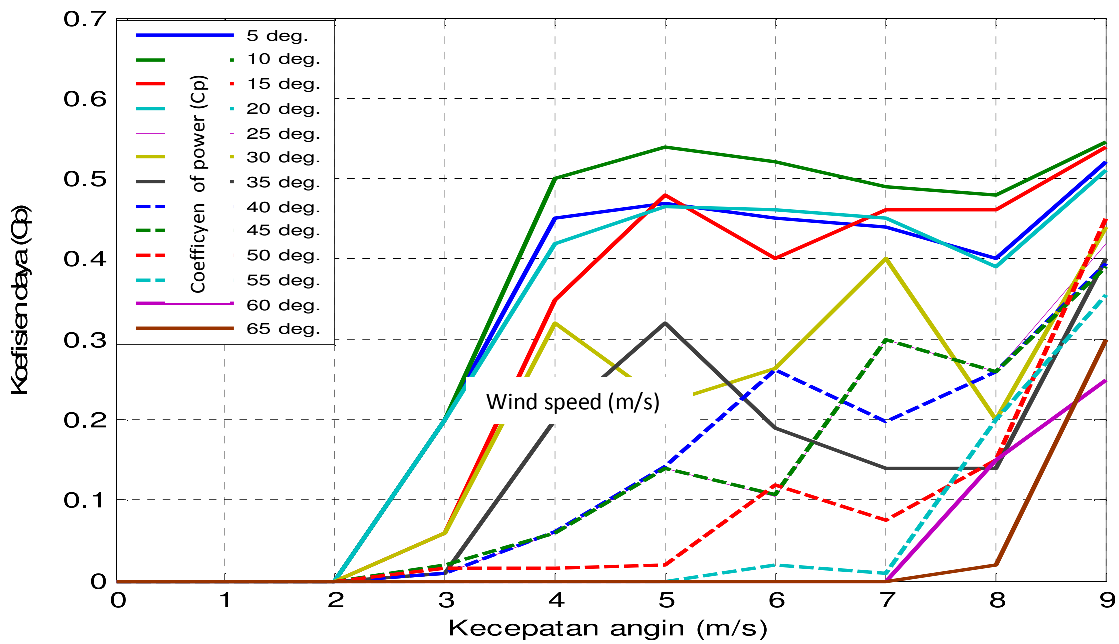

Figure 10: Wind speed versus Cp on the pitch angle variation

DISCUSSION

Figure 11 Illustrates the comparative wind turbine power coefficient (Cp) simulation results of a prototype wind turbine blade pitch angle to position ($\theta = 0^o$) and position angle ($\theta = 15^o$). The compilation of wind turbine power production from the simulation model compared with the production of wind power wind turbine prototype is illustrated by Figure 12.

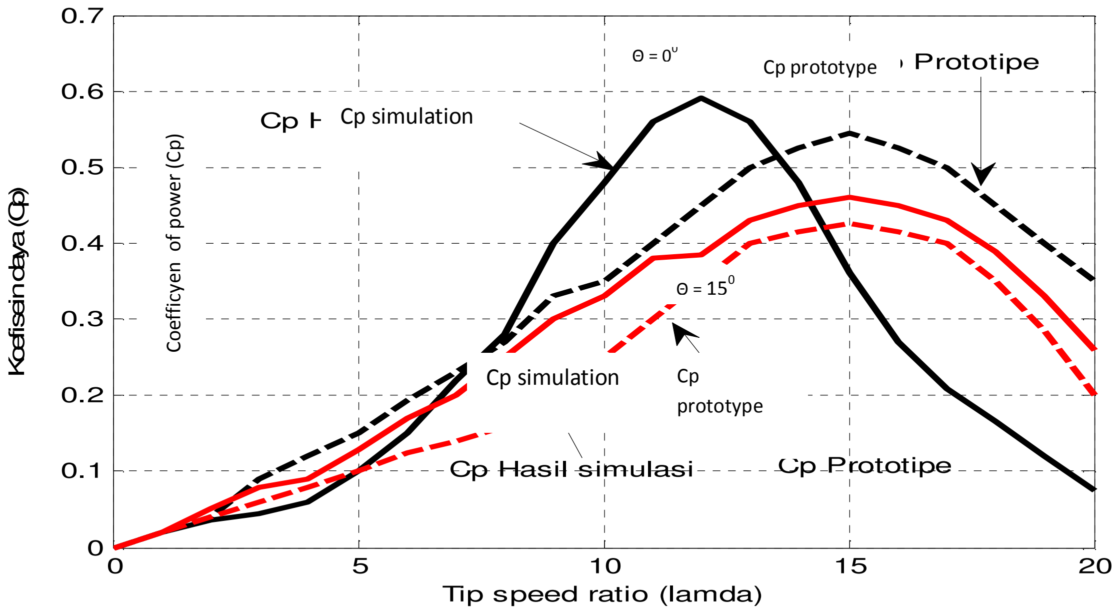

Figure 11: Relationship TSR versus Cp at (0° and 15°) for simulation and prototype

Wind turbines are designed through simulation when given wind speed 7.5 m / s, capable of producing the maximum power coefficient of 0.59 for the position of the pitch angle is zero, and when the blade angle positions 10 and 15 degrees produces the value of Cp = 0.54 and when the position of the pitch angle of 20 degrees produces the value of Cp = 0.51. Wind turbines are built through prototype, capable of producing maximum power coefficient values in the range between the angular position of the blade angle range of 00-150 with a maximum value of Cp = 0.545, and when the position of blade pitch angle is at position 200 wind turbines generating a maximum value of Cp 0, 51

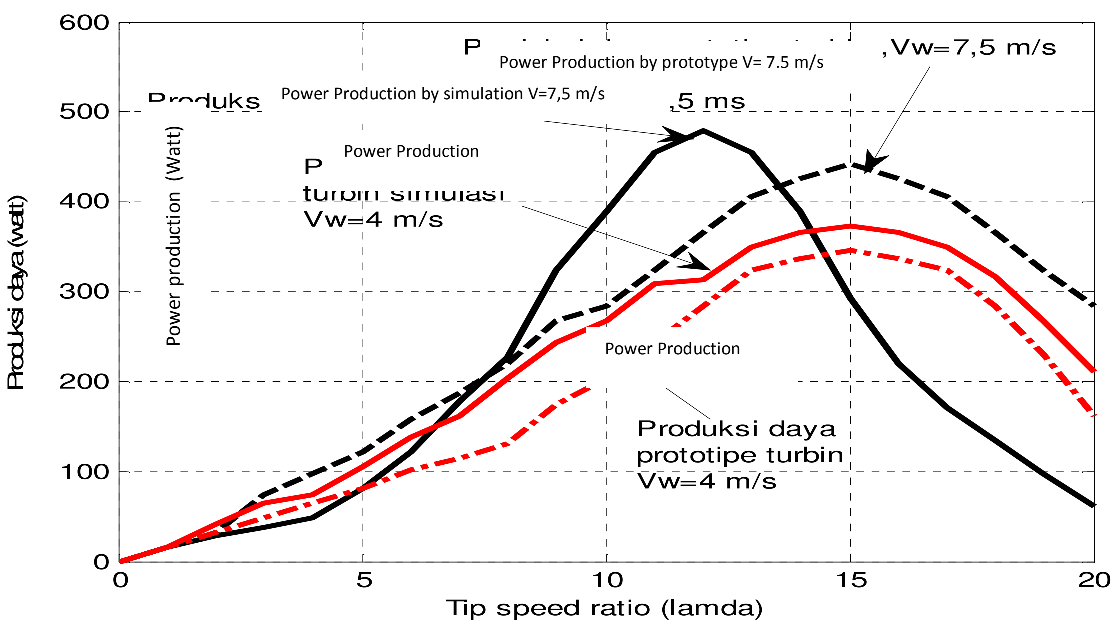

Figure 12: Wind power Versus TSR on wind speed variation 4 m/s and 7.5 m/s. In simulation and prototype wind turbine

The position of the pitch angle wind turbine that produces the maximum RPM for wind speeds 2.8-7.5m/s. The position of the blade pitch angle10, 35 with wind speed 2.8 m/s will generate 40 RPM, The position of the blade pitch angle 10.15 with wind speed 4.8 / s generate 69 RPM, and the position of blade angle 10.87 with wind speed 7.5 m / s generate 168 RPM; The results of the design pitch angle regulator capable of regulating blade angle range 0 to 90 degrees with intervals of 5 ± 0.39 degrees.

CONCLUSION

Based on the analysis as above, it was concluded that:

1. The results of the design of wind turbines with simulation for wind speed 7.5 m / s, and a pitch angle position 0^o produced the maximum Cp=0.59 and of the wind turbine prototype generated maximum Cp=0.545. Difference of the two Cp values of 4.5%. When the blade pitch angle position is 15o, the wind turbine simulation results have a value of Cp=0.47 and the wind turbine prototype has Cp=0.42, so that differences in Cp values of simulation results and wind turbine prototype has value = 5%.
2. At wind speeds 7.5 m / s., the wind turbines simulation is capable of generating power production at = 479 Watt, and the wind turbine prototype turbine generates power = 426 Watt. For wind speed blows 4 m / s. the wind turbines simulation power produce for = 373 Watt and wind turbine prototype = 345 Watt. Thus, if the difference in power production are expressed in percent, then for wind speed 7.5 m / s. = 11.06% and for wind speeds of 4 m / s = 6.97%

Nomenclature

A	rotor swept area [m^2]
Cp	power coefficient [pu]
R	maximum rotor radius (m)
P_{aero}	aerodynamic power [W]
T_{rot}	torsional rotation at the turbine's rotor [N.m]
T_a	aerodynamic torque[N.m]
T_g	torque generator [N.m]
T_{aux}	torque auxiliary [N.m]
J_g	generator inertia [kg/m^2]
J_t	rotor inertia [kg/m^2]
γ	arodynamic damping coefficient [N.m.s/rad]
c_T	torsion coefficien (-)
v	wind speed (m/s)
ω_t	rational speed (rad/s)
T_o	optimum torsion (N.m)
v_o	optimum wind speed (m/s)
C_{op}	optimum power coefficient(-)
B_t	friction coefficien of turbine

Greek symbols

ω_{rot}	angular speed of rotor
η	efficiency (-)
λ	tip speed ratio [pu.]

λ_o	optimal tip speed ratio [pu.]
ρ	air density (kg/m^3)
θ	pitch angle blade (^{o})
u	Hellman coefficient (-)

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