

Maximum Power Point Tracking Algorithm for Variable Speed Wind Turbine System

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Abstract — This paper aims to apply a maximum power point tracking (MPPT) algorithm into a wind turbine with variable speed generator model, jointly the wind energy conversion system (WECS). There are several types of wind turbine in different configurations and their efficiencies in energy extraction are different depending on their aerodynamic designs. In general, their power efficiencies are bounded by the natural aerodynamic limits. Hence, the MPPT algorithm is expected to improve and increase the power efficiency to the maximum level within the limited boundary. In this paper, the wind turbine is modelled after a horizontal-axis wind turbine (HAWT) because it has the higher power coefficient, while the generator will be a variable speed synchronous generator due to the speed variation feature and higher optimal rotor speed. The performance of system is simulated in MATLAB-SIMULINK.

Keywords – wind turbine; renewable energy; MPPT; control

I. INTRODUCTION

Wind energy is one of the important renewable energy sources. As opposed to the currently existing carbon-based energy sources such as coal, petroleum, and natural gas, wind energy has the advantages that it is clean, unpolluted, inexhaustible, and free in term of its natural existence [1]. Current trend shows that wind energy is getting popular to replace the traditional energy sources due to the expectable depletion of traditional energy resource and the humankind's effort in reduction of carbon dioxide emission but not affecting the usable energy production for the continuous developments. Wind energy, although with the advantages mentioned, is still developed at preliminary stage of power generation. Generally, wind energy is converted into kinetic energy before the conversion to the usable electrical energy. Wind energy is converted to low speed rotational energy via blades and through the gear box, the rotational energy is used to drive the generator for electric power generation [2].

Wind energy is an abundant resource with free cost but it is important to study the way to maximize the power generation by wind energy [3,4]. Several control methods of wind energy conversion system has been proposed by researchers to

maximize the wind energy harvest. However, most of the proposed methods have rather low efficiency to extract power [5,6,7]. Besides, the extracted energy is the very unstable since the nature of wind flow is spontaneous which this situation will lower the power extraction and subsequently reduce the efficiency of power generation.

Although wind turbine presents non-linear characteristics, there is a particular operating point which the wind system is able to produce the maximum output power for a given wind speed. Thus, various control approaches have been investigated to control the power condition on the wind turbine and therefore wind energy is aimed to be extracted optimally at any given time. In this paper, maximum power point tracking (MPPT) algorithm based on perturb and observe has been studied to control the wind turbine for maximum output power. The generator mechanical rotor speed and the immediate wind speed are sensed for the computational of tip speed ratio and the power coefficient of the wind turbine. By controlling the blade angle, wind turbine rotor speed is changed and both parameters the tip speed ratio and the wind turbine's power coefficient is varied. Based on these parameters, MPPT perform perturbation on the blade angle and track the maximum power coefficient of the wind turbine. Wind turbine which is operated at the maximum power coefficient can have maximum the wind energy harvesting which this approach can improve the efficiency of the power generation.

The structure of this paper is described as follows. Section II describes the modelling of wind turbine. Section III explains the MPPT algorithm. Section IV shows the performance of MPPT in maximizing the wind energy harvesting. Finally, Section V concludes the finding of this paper.

II. WIND TURBINE MODELLING

Every wind turbine is characterized by its own physical appearance, mechanical transmission system and the electrical transmission system. These characteristics are subjected to the aerodynamics elements. In overall, all the characteristics are defining and identifying the wind turbine performance and efficiency.

A. WECS Power Characteristic

The tip speed ratio, λ , is the ratio of the blade tip speed to the actual wind speed. The concept of tip speed ratio is applicable to lift-type wind turbine only, such as the horizontal-axis wind turbine (HAWT), Darrieus and vertical-axis wind turbine (VAWT). λ reflects the energy efficiency of a wind turbine. Wind, as a flow of air particles, carries kinetic energy from one place to another. When it comes across a wind turbine, the wind turbine extracts the kinetic energy by its blade which moved by the air particles. Hence, the more air particle the blades touch in a revolution, the more energy is received by the wind turbine. Low value of λ means a lot of energetic air particles pass through the gaps of wind blades and least energy captured by the wind turbine. Hence theoretically there is an optimal λ point where the wind turbine has the most energy efficiency. Eq. (1) describes the relation of λ and the wind speed, V_w .

$$\lambda = \frac{R\Omega}{V_w} \tag{1}$$

where,

- λ represents the tip speed ratio;
- R represents the blade's radius;
- Ω represents rotor rotational speed;
- V_w represents the wind speed;

There is a λ point where the wind turbine can perform the maximum energy extraction. When the wind blades are rotating at very high speed, the rotation area has become as obstructive as a wall to the wind flow, thus blocking the energy extraction. At this situation, wind turbine will have low λ where the blade's tip speed either very low or very high. Optimum λ is very depending on type of wind turbine. In literature, the optimum λ for HAWT is around six to ten. In graphical methods, λ is often plotted with respect to power coefficient, C_p to relate the two variables in wind turbine power characteristic.

C_p is a variable representing the efficiency of wind energy extraction, which is in the range of 0 to 1. According to Betz's Law, there is no turbine can capture more than 59 % of kinetic energy in wind. Therefore in practice, there is no wind turbine can have C_p exceed 59 %. Fig. 1 shows the graph of C_p versus λ for three different wind speeds.

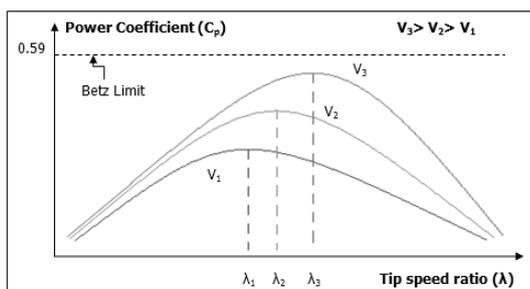


Figure 1. Power coefficient, C_p , versus tip speed ratio, λ , graph for different wind speeds.

The wind turbine block of SIMULINK which used in this paper is the variable pitch wind turbine block. The wind turbine model has been prior designed with several equations and conditions. Firstly, the relationship of wind turbine block power coefficient, C_p and tip speed ratio, λ , is described by (2).

$$C_p = C_1 \left(\frac{C_2}{\lambda_i} - C_3 - C_4 \right) e^{-\frac{C_5}{\lambda_i}} + C_6 \lambda \tag{2}$$

where,

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

The output power and blade swept area are shown in (4) and (5) respectively.

$$P_0 = C_p(\lambda, \beta) \frac{\rho A}{2} V_w^3 \tag{4}$$

$$A = \pi R^2 \tag{5}$$

where,

- P_0 represents mechanical output power of the turbine (W);
- $C_p(\lambda, \beta)$ represents power coefficient, in terms of λ and β ;
- ρ represents air density (kg/m^3);
- A represents blade swept area (m^2);
- V_w represents wind speed (m/s);
- λ represents tip speed ratio;
- β represents blade pitch angle ($^\circ$);

To have maximum efficiency, it is essential to determine the optimum λ . However, Fig. 2 shows the power coefficient curve for varying λ for maximum C_p investigation. From the result, it can be noted that the maximum of C_p is about 48 %.

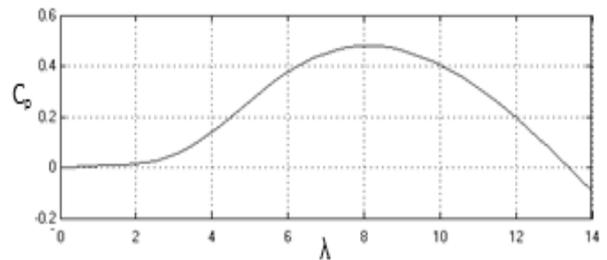


Figure 2. The power coefficient curve for varying tip-speed ratio.

B. Wind Turbine with Variable Speed Generator

The wind turbine model is used to generate mechanical torque. The negative value of output torque means the wind

turbine is providing torque. Result in Fig. 3 shows the output torque is positive for wind speed smaller than 7 m/s, which represent that the wind turbine is not providing power, but consuming power from the load. Hence, the value of wind speed at 7 m/s could be possibly as the cut-in speed of the wind turbine model and the result of output mechanical torque.

For a range of wind speed is shown in Fig. 3, the effect of both varying generator speed and wind speed on the output torque is investigated in simulation and the results are shown in Fig. 4. It can be noticed that higher wind speed can provide larger torque and hence larger power to the load. For instance, at Ω 1.5 m/s, the turbine output torque by wind speed 12 m/s is about -0.38 W, but the turbine output torque by wind speed 18 m/s is about -1.35 W. wind turbine at higher output torque can provide larger output power, hence improving the power efficiency of the power generation.

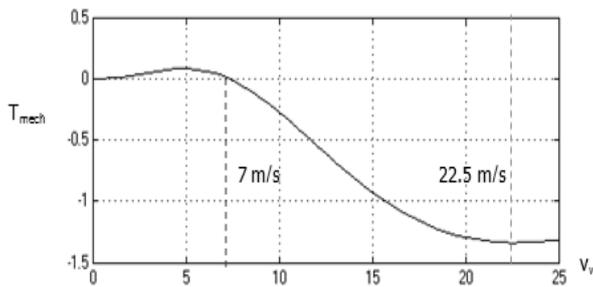


Figure 3. The output mechanical torque (y-axis, p. u.) versus wind speed (x-axis, m/s) for generator speed of 1.2 p. u.

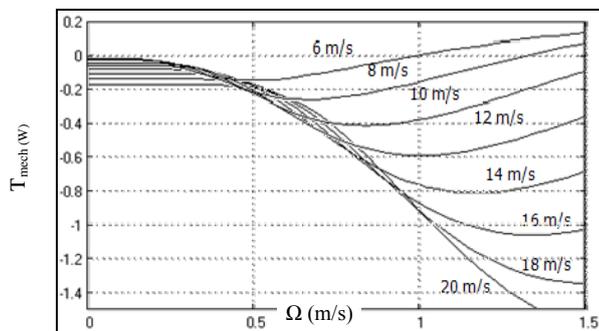


Figure 4. Output torque for varying generator speed and different wind speeds.

III. MAXIMUM POINT POINT TRACKING

Currently, there are a few MPPT algorithms developed for the existing wind turbine [8,9,10]. The speed control method is the most common method used in wind turbine system. Speed control method acquires wind speed and generator speed data for analysis and control.

The speed control method requires feedback from the generator speed or rotor speed. Fig. 5 depicts the output power curves for a range of rotor speeds for two different cases at wind speed.. The arrows show the tracking steps of a speed control MPPT. By sensing wind speed and rotor speed of generator, the tip speed ratio at an instance is computed and compared to the optimum value.

Consider Fig. 5 at wind speed V_{w1} , the trading process is started at rotor speed Ω_0 and finally speed control MPPT will control the blade angle to reach rotor speed Ω , for the optimum value. When the wind speed is changed to V_{w2} , the MPPT will perform continuous track until Ω_2 which is the maximum power point in the case of wind speed V_{w2} .

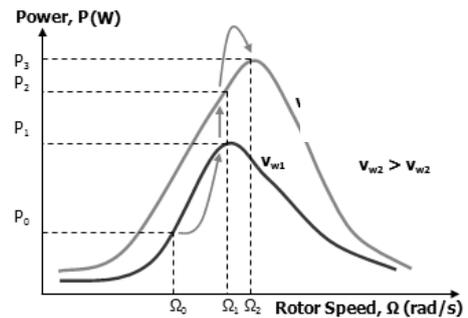


Figure 5. Speed control MPPT algorithms.

The perturb and observe (P&O) MPPT method compares the change in magnitude of the wind speed, $V_w(t)$, and power coefficient, C_p , for two consecutive time instances, and the MPPT will make decision based on these information. The two time instants are the delayed time instant, $t(k-d)$, and the current time instant, $t(k)$. The chronological change in $V_w(t)$ and their corresponding $C_p(t)$ might be different. There are three categories of total nine cases possible to be considered in the MPPT algorithm. The three categories to be discussed are wind speed decreases over time interval, wind speed increases over time interval, and wind speed remains unchanged over time interval; whilst the nine cases in there will be three categories of $V_w(t)$ corresponding to the changes of C_p will be described as below.

A. Category I:

This category describes the wind speed decreases over the time interval, represented by $V_w(k-d) > V_w(k)$. Since the wind speed is decreasing, the tip-speed ratio will increase correspondingly if the rotational speed remains constant. It will sweep across three C_p cases, which are the increasing slope, peak, and decreasing slope, as shown in Fig. 6.

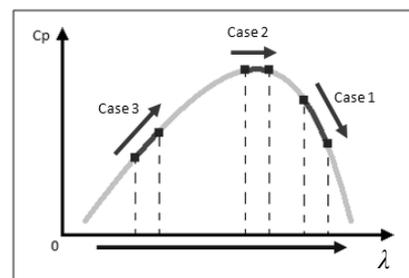


Figure 6. The characteristic graph for MPPT cases 1, 2, and 3.

In Case 1, the Ω should be increased in order to have smaller λ to approach maximum point of C_p . However in Case 3, the Ω should be decreased so that the maximum C_p can be tracked. In Case 2, since the C_p is in the maximum position, the Ω should be remained unchanged.

B. Category II:

This category illustrates the wind speed increase over the time interval, represented by $V_w(k-d) > V_w(k)$. Since the wind speed is increasing, the tip-speed ratio will decrease correspondingly if the rotational speed remains constant. It will sweep across three C_p cases, which are the increasing slope, peak, and decreasing slope, as shown in Fig. 7.

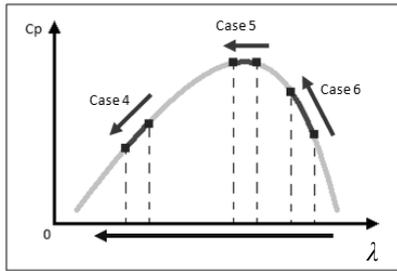


Figure 7. The characteristic graph for MPPT cases 4, 5, and 6.

Consider Case 4, the Ω should be increased in order to increase the value of λ in order to approach optimum C_p , but the Ω should be decreased in Case 6 to increase the λ , so that the maximum C_p can be obtained. In Case 5, since the C_p is in the maximum position, the Ω should be remained unchanged.

C. Category III:

This category expresses the wind speed unchanged over time interval, represented by $V_w(k-d) = V_w(k)$. If the wind speed remains unchanged, the tip-speed ratio should be a constant if rotational speed remains constant too. However, it cannot be assumed the C_p is at the optimal value. Hence, it needs to sweep across three C_p cases: the increasing slope, peak, and decreasing slope to test for the best condition, as shown in Fig. 8.

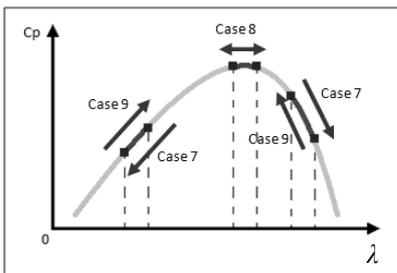


Figure 8. The characteristic graph for MPPT cases 7, 8, and 9.

In Case 7, the Ω can be either increased or decreased depends on the decrement of the C_p in next cycle. Case 9 is similar to Case 7, where the Ω can be either increased or decreased, but it depends on the increment of C_p in next cycle. Again, the Ω should be remained unchanged in Case 8 since the C_p has reached its maximum point. Table I summarizes the rotational speed responses for all MPPT cases.

IV. PERFORMANCE OF MPPT

The MPPT block has been tested and verified using different types of inputs, which are the gradually increasing wind speed, the gradually decreasing wind speed and the step change of constant wind speed.

TABLE I. ROTATIONAL SPEED RESPONSES FOR MPPT CASES

Category-Case	Wind Speed, V_w	Power Coefficient, C_p	Rotational Speed, Ω
I-1	Increase	Decrease	Increase
I-2	Increase	Maintain	Maintain
I-3	Increase	Increase	Decrease
II-4	Decrease	Decrease	Increase
II-5	Decrease	Maintain	Maintain
II-6	Decrease	Increase	Decrease
III-7	Maintain	Decrease	Decrease
III-8	Maintain	Maintain	Maintain
III-9	Maintain	Increase	Increase

An increasing wind speed is used for the first simulation, as shown in Fig. 9, where $V_w(k) > V_w(k-d)$. It is assumed that the wind speed is increased from 10 m/s to 30 m/s. The output Ω responding to the increasing wind speed is shown in Fig. 10. The initial input of rotational speed was set to be 5 rps. The MPPT make decision on increasing the rotational speed gradually until the rotor speed has reached approximately 8 rps. The corresponding C_p for the increasing wind speed is as shown in Fig. 11. As the input wind increases over time, the responding output rotational speed is also increasing. Hence, the power coefficient is improved to 45 %, which is closed to the nominal maximum 48 %.

A constant-slope decreasing wind speed is used for the second test, where $V_w(k) < V_w(k-d)$. The input wind speed is assumed to be decreased from 30 m/s to 10 m/s, as shown in Fig. 12. MPPT has reduced the rotational speed from 8 rps to 4.5 rps, as shown in Fig. 13. MPPT is able to maintain the power coefficient within the range of 25 % to 42 % for the decreasing wind speed, as shown in Fig. 14.

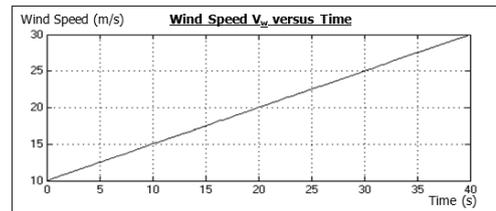


Figure 9. The test wind of increasing wind speed.

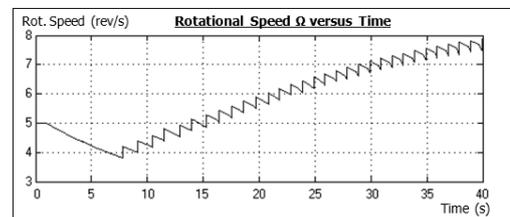


Figure 10. The rotational speed response for increasing wind speed.

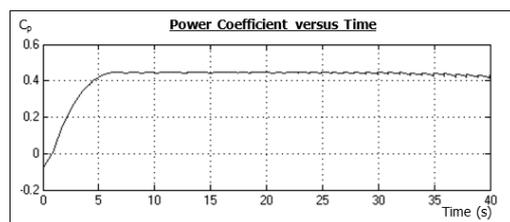


Figure 11. The power coefficient, C_p for increasing wind speed.

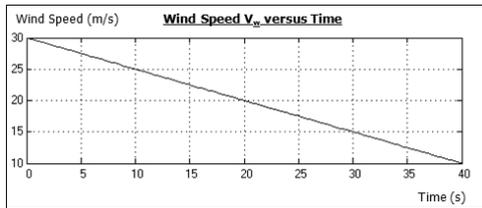


Figure 12. The test wind of decreasing wind speed.

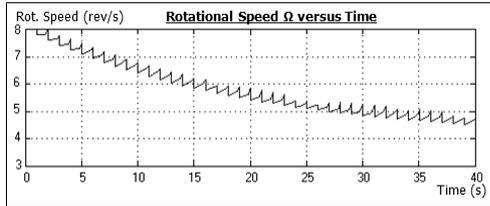


Figure 13. The rotational speed response for decreasing wind speed.

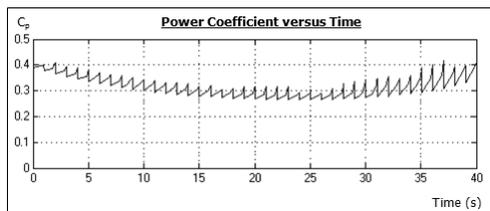


Figure 14. The power coefficient, C_p for decreasing wind speed.

In order to test the robustness of MPPT in a dynamic environment, a step change of wind speed is introduced to the wind turbine system, as shown in Fig. 15. It is assumed that the wind started with a speed of 18 m/s for the first 5 s and then the wind speed is drastically decremented to 14 m/s for another 5 s. Although a step change in wind speed is unlikely happened in natural condition, as wind speed is always increasing or decreasing in a continuous manner, the test wind of step change is used to examine the response of the MPPT algorithm in the sudden change of the environment conditions.

The rotational speed response by MPPT is shown in Fig. 16. The general trend of the rotational speed is increasing from 5 rps to 5.5 rps during the wind speed at 18 m/s, and the rotational speed is decreased to 4.5 rps during wind speed at 14 m/s. Fig. 17 shows the result of C_p for the step change in wind speed. At wind speed of 18 m/s, the rotational speed is corrected so that power coefficient is maintained at about 45 %. When the step change happens, the power coefficient has dropped drastically to about 35 % due to the unmatched rotational speed in the sudden changed in wind speed. However, the MPPT managed to respond very fast by boosting up and fluctuates the rotational speed such that the power coefficient is successfully compensated back to 45 %.

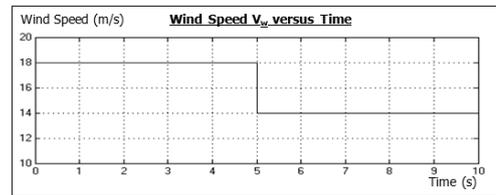


Figure 15. The test wind of step change wind speed.

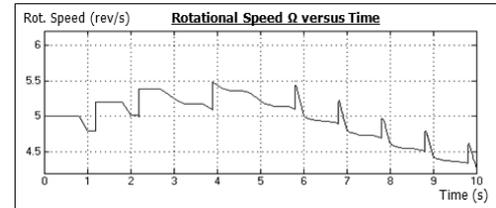


Figure 16. The rotational speed response for step change wind speed.

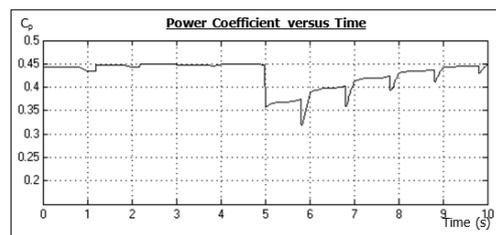


Figure 17. The power coefficient, C_p for step change wind speed.

V. CONCLUSION

A MPPT algorithm has been designed and implemented as a controller for the wind system. From the result analysis, the MPPT has been proven to be useful in tracking the maximum power point, and it is able to respond to the changes of wind speed and power coefficient. The system is expected to harvest and store up the wind energy collected instead of dissipate as unused energy. The overall result of the system has been justified to be positive.

APPENDIX

TABLE II. WIND TURBINE PARAMETERS

Parameters	Value	Description
C_1	0.5176	Constant
C_2	116	Constant
C_3	0.4	Constant
C_4	5	Constant
C_5	21	Constant
C_6	0.0068	Constant
β	0°	Blade pitch angle
ρ	1.1839 kg/m ³	Air density
R	26.64 m	Blade radius

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