Rotor Speed Control Maximum Power Point Tracking for Small Wind Turbine

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***Abstract*— Due to the change of energy source to renewable energy, the trend of wind turbine is increased in last 5 years. Small Wind Turbine that convert kinetic energy to electric energy needs a rectifier to convert AC to DC. Rectifier used in this paper is active rectifier. Because of its power characteristics, wind turbine needs maximum power point tracking (MPPT) to track its maximum power. This paper shows that by using active rectifier, the algorithm of tracking a maximum power able to be tracked by controlling its rotor angular speed. The simulation result proves that the speed control and MPPT algorithm, perturb and observe, is able to be implemented in various wind speed.**

Keywords- Wind turbine, Active rectifier, Permanent Magnet Synshronous G, speed control, MPPT

I. INTRODUCTION

The transition of energy source from fossil fuel to renewable energy is continuously executed by the decrease of fossil fuels. The most common renewable energy system is solar cell and wind turbine. Nowadays, wind turbine system is one of solution to produce renewable energy for both low power and high power. In last five years, the trend of the wind turbine system market has shown an agresive 20% annual increase in worldwide and the industry predict approximately 750 MW of installed capacity in 2020 [1] .

Essentially, wind turbine is a machine system for converting kinetic energy to electric energy. Wind turbine system consist of blade, rotor, generator and AC-DC converter. The type of wind turbine used is variable speed horizontal wind turbine. For generator, this paper uses permanent magnet synchronous generator (PMSG) because PMSG is becoming very common among small scale wind turbines as it provides good efficiency at low speed.

AC-DC converter is needed to control the generator's output. The most common AC-DC converter is diode rectifier but it give the high harmonic. Thus, active rectifier is proposed because the rectifier is fully controlled by space pulse widht modulation (SPWM) thus the harmonic can be controlled. Active rectifier consist of 6 switch controlled by PWM. This SPWM is controlled by voltage oriented control, where the input for S PWM is the reference voltage. The reference voltage is controlled by current control which the reference is the output of the speed control. Then, a maximum power point tracking (MPPT) algorithm allows the turbine to find and operate at its maximum power point by giving speed reference to speed control. The ilustration about this overal system is shown in Figure 1. This study will discuss the model and simulation of MPPT and speed controller on a small-scale wind turbine that has been tested through simulation on Simulink MATLAB software.

II. WIND TURBINE, PMSG, ACTIVE RECTIVIER MODEL

A. Previous Work

There was many methologies to control active rectifier, Voltage Oriented Control (VOC) and Direct Power Control

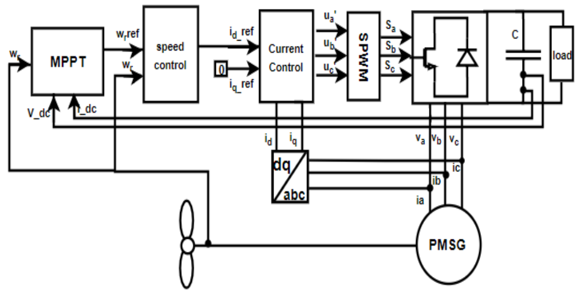


Figure 1. Small Wind Turbine System

(DPC). VOC guarantees high dynamic and static performance via an internal current control loop [2]. But the quality depends mainly on the current control strategy. However, the problem was founded when combined it to the MPPT. It's hard to find the right maximum power by using VOC. This methology using speed as the control variable where the speed reference will update continously by the MPPT.

B. Wind Turbine Model

Turbine mechanical power generated by wind turbine expressed as [3]

$$P = \frac{1}{2}\rho C_p A V_w^3 \qquad (1)$$

Where ρ is air density(kg/m^3), A is rotor blade swept area (*m^2*), V_w represent wind velocity (*m/s*). Power coefficient, C_p, can be represented as [3]:

$$C_p = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e_5^{-c/\lambda_i} + C_6\lambda \qquad (2)$$

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

$$\lambda = \omega_m * \frac{R}{V_w} \qquad (4)$$

The value of C_1 to C_6 depend on the type of rotor. In this paper, the value of C_1 to C_6 determined as follow,
$C_1 = 20$; $C_2 = 140$; $C_3 = 0.4$; $C_4 = 28$; $C_5 = 21$; $C_6 = 0.068$

C. PMSG Model

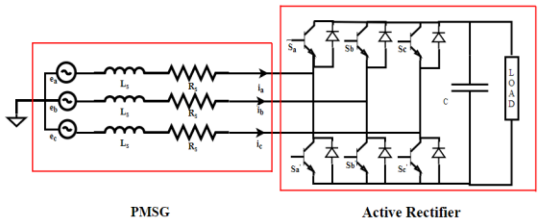


Figure 2. PMSG and Active Rectifier Circuit diagram

The PMSG and active rectifier are represented into single electrical circuit diagram as shown in Fig.

Phase voltage of PMSG represented as:

The electromagnetic force of each phase [4] can be obtained as follows:

$$e_a = p\,\Psi_f = -N\omega_r\Psi_F' sin\theta_e \quad (5)$$

$$e_b = p\,\Psi_f = -N\omega_r\Psi_f' sin(\theta_e - \frac{2}{3}\pi) \quad (6)$$

$$e_c = p\,\Psi_f = -N\omega_r\Psi_f' sin(\theta_e + \frac{2}{3}\pi) \quad (7)$$

Ψ_f is the flux linkage, and N is number of pole pairs of generator, θ_e .is rotor angular angle

$$Va = e_a - (i_a * R_s) - \left(L_{sd} * \frac{di_a}{dt}\right) + \left(\frac{1}{2} * M * \frac{di_b}{dt}\right) + \left(\frac{1}{2} * M * \frac{di_c}{dt}\right) \quad (8)$$

$$Vb = e_b - (i_b * R_s) - \left(L_{sd} * \frac{di_b}{dt}\right) + \left(\frac{1}{2} * M * \frac{di_a}{dt}\right) + \left(\frac{1}{2} * M * \frac{di_c}{dt}\right) \quad (9)$$

$$Vc = e_c - (i_c * R_s) - \left(L_{sd} * \frac{di_c}{dt}\right) + \left(\frac{1}{2} * M * \frac{di_b}{dt}\right) + \left(\frac{1}{2} * M * \frac{di_a}{dt}\right) \quad (10)$$

Through Park transformation, generator voltage can be expressed in *dq* rotating reference frame [4] .

$$\begin{bmatrix} v_{ds} \\ v_{qs} \end{bmatrix} = \begin{bmatrix} cos\theta_e & -sin\theta_e \\ sin\theta_e & cos\theta_e \end{bmatrix} \sqrt{\frac{2}{3}} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix} \begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} \quad (11)$$

The current in *dq* reference frame represented as

$$\frac{d}{dt}\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} = -\begin{bmatrix} \frac{R_s}{L_{sd}} & -\frac{L_{sd}}{L_{sq}}\omega_e \\ \frac{L_{sd}}{L_{sq}}\omega_e & \frac{R_s}{L_{sq}} \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \begin{bmatrix} \frac{1}{L_{sd}} & 0 \\ 0 & \frac{1}{L_{sq}} \end{bmatrix} \begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} \quad (12)$$

Therefore, the electromagnetic torque and machine equivalent mechanical torque can be expressed as

$$Te = N\{\Psi_f + (L_{sd} - Lsq)i_{sd}\}i_{sq} \quad (13)$$

$$Tm = \frac{P}{\omega_r} = \frac{1}{2}\rho\,\pi R^2 C_p \frac{V_w^3}{\omega_r} \quad (14)$$

Hence the rotor speed can be calculated

$$\frac{d\omega r}{dt} = \frac{Te - Tm - B\omega_r}{j_t + j_p} \quad (15)$$

D. Active Rectifier Condition

Active rectifier is represented as 6 pulse rectifier with 6 switching conditions. According to figure 1, the switching conditions are based on the respond of controller's signal, u_a, u_b, and u_c. As shown in figure 3, The controller's response is compared to carrier signal(green line) in PWM. If the response is higher than the carrier, PWM's value is 1, otherwise, if the response lower than the carrier signal, the PWM's value is 0. The switch is on or off by the value of PWM. If the PWMA = 1 PWMB = 1 and PWMC = 0, means $S_a = 1$, $S_b = 1$, $S_c = 0$, $S_a' = 0$, $S_b' = 0$, $S_c' = 1$. Then the circuit diagram for this condition is shown in figure 4(a).

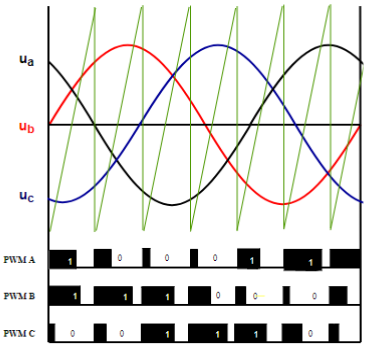


Figure 3 Switching Condition for Active Rectifier

E. Combine Circuit Model

According to figure 2, the 6 condition in table 1 can be representated by using the circuit diagram that is showed in figure 4.

From electric circuit analysis, conditions in figure 4(a) and 4(b) represented into matrices as follows

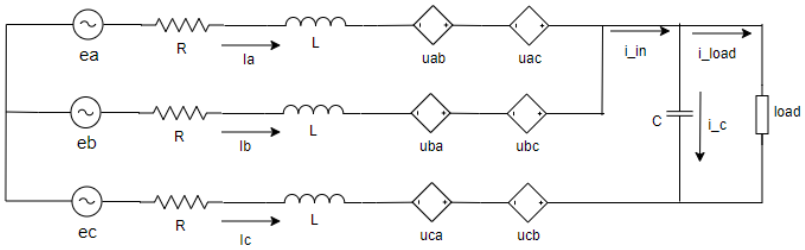
Condition 4(a):

$$\begin{bmatrix} \frac{di_a}{dt} \\ \frac{di_b}{dt} \\ \frac{di_c}{dt} \\ \frac{dv_{dc}}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-R_s}{2*L_s} & \frac{R_s}{4*L_s} & \frac{R_s}{4*L_s} & \frac{-1}{4*L_s} \\ \frac{R_s}{4*L_s} & \frac{-R_s}{2*L_s} & \frac{R_s}{4*L_s} & \frac{-1}{4*L_s} \\ \frac{R_s}{4*L_s} & \frac{R_s}{4*L_s} & \frac{-R_s}{2*L_s} & \frac{1}{2*L_s} \\ \frac{1}{C} & \frac{1}{C} & 0 & \frac{-1}{C*R_{load}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \\ v_{dc} \end{bmatrix} + \begin{bmatrix} \frac{1}{2*L_s} & \frac{-1}{4*L_s} & \frac{-1}{4*L_s} \\ \frac{-1}{4*L_s} & \frac{1}{2*L_s} & \frac{-1}{4*L_s} \\ \frac{-1}{4*L_s} & \frac{-1}{4*L_s} & \frac{1}{2*L_s} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (16)$$

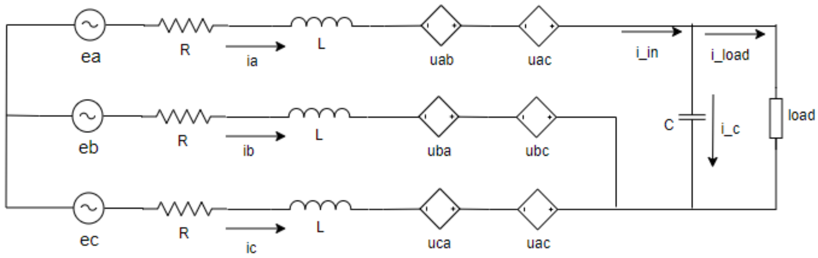
Condition 4(b):

$$\begin{bmatrix} \frac{di_a}{dt} \\ \frac{di_b}{dt} \\ \frac{di_c}{dt} \\ \frac{dv_{dc}}{dt} \end{bmatrix} = \begin{bmatrix} \frac{-R_s}{2*L_s} & \frac{R_s}{4*L_s} & \frac{R_s}{4*L_s} & \frac{-1}{2*L_s} \\ \frac{R_s}{4*L_s} & \frac{-R_s}{2*L_s} & \frac{R_s}{4*L_s} & \frac{1}{4*L_s} \\ \frac{R_s}{4*L_s} & \frac{R_s}{4*L_s} & \frac{-R_s}{2*L_s} & \frac{1}{4*L_s} \\ \frac{1}{C} & 0 & 0 & \frac{-1}{C*R_{load}} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \\ v_{dc} \end{bmatrix} + \begin{bmatrix} \frac{1}{2*L_s} & \frac{-1}{4*L_s} & \frac{-1}{4*L_s} \\ \frac{-1}{4*L_s} & \frac{1}{2*L_s} & \frac{-1}{4*L_s} \\ \frac{-1}{4*L_s} & \frac{-1}{4*L_s} & \frac{1}{2*L_s} \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} e_a \\ e_b \\ e_c \end{bmatrix} \quad (17)$$

Where, R_s is Stator resistance, Ls is stator inductance, V_{dc} is DC link voltage, r_{load} is load resistance.



(a)



(b)

Figure 4. Electric Circuit Diagram (a) $S_a = 1$ $S_b = 1$ $S_c = 0$ (b) $S_a = 1$ $S_b = 0$ $S_c = 0$

III. Controller Strategy

As shown in figure 5, The controller is devided by 2 part: double close loop control consist of current control and speed control, and the last part is MPPT.

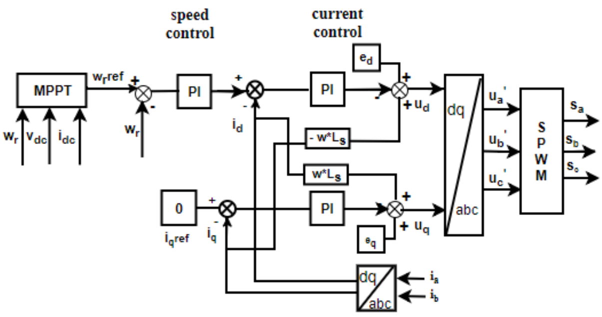


Figure 5. Controller block diagram

A. Current Control

For controlling the three-phase current, the transformation into i_d, i_q is needed. The controller control id and iq than use PI control to regulate of each error. The reference of id is based on the output of speed control. Due to control the unit power factor, the reference of i_q is set to 0.

After calculating the approtiate u_d and u_q, space vector PWM control method coud be directly used to calculate the control signal of switches in the main circuit [5]. The calculation is shown in equation (18) and (19).

$$u_d = e_d + \omega_r * L_s * i_q - K_p * (i_d^* - i_d) - \int K_i * (i_d^* - i_d) dt \quad (18)$$

$$u_q = e_q - \omega_r * L_s * i_d - K_p * (i_q^* - i_q) - \int K_i * (i_q^* - i_q) dt \quad (19)$$

B. Speed Control

The controller of the speed also use PI control. The input of the control is the error of speed reference from the output of MPPT and the actual rotor angular speed whereas the output is the reference for i_d. The calculation is shown in equation (20).

$$I_d ref = K_p * (\omega_r^* - \omega_r) + \int K_i * (\omega_r^* - \omega_r) dt \quad (20)$$

C. MPPT

To track the maximum power from the double close-loop controller, a *Perturb and Observe* (P&O) MPPT algorithm is used. MPPT also ensure the turbine to work at its maximum power. P&O algorithm work by changing the control parameter and observe the output change [6]. This algorithm have low complexity, high efficiency, and does not require sensors or system requirements.

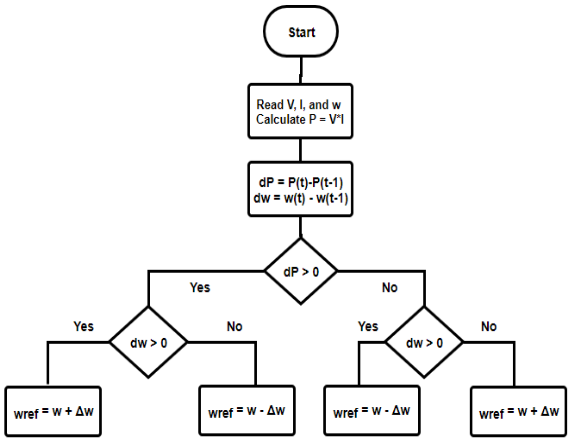


Figure 6. MPPT flowchart

Electric power compared with previous power. If ΔP is positive and the speed change is positive, the reference speed will increase. The detail algorithm is shown in figure 6.

IV. RESULT

The proposed model in this paper simulated using Simulink MATLAB S-Function block. First, we need doing a test to track maximum power for various wind speed (V_w). The test is done by adding continously the $\omega_r$ref as ω_r can't follow $\omega_r$ref. The ilustration is shown in Figure 7.From this test, we know where the maximum power is, thus after the MPPT is implemented, we can conclude that the controller and MPPT is work in its maximum power. The test shows the maxium power of 6 m/s, 7 m/s, 8 m/s in Figure 8. The simulation shown the responses of system for various the wind speed are shown in Figure 9. .

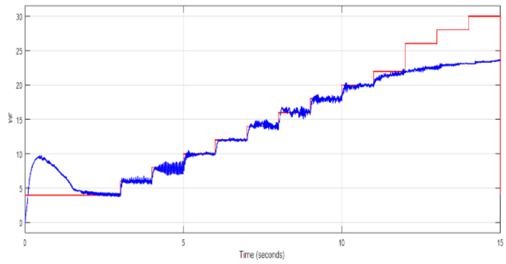
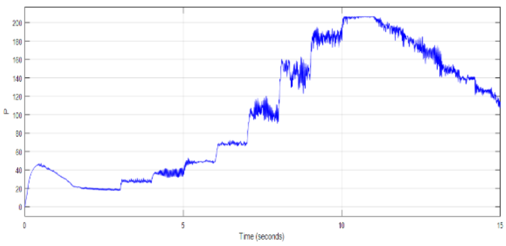
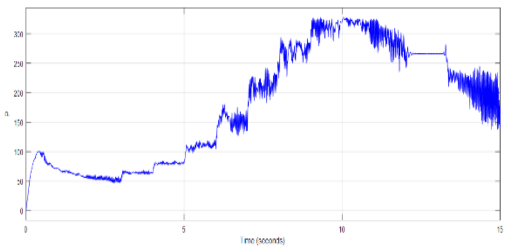


Figure 7. wr for MPP testing in Vw = 6 m/s



(a)



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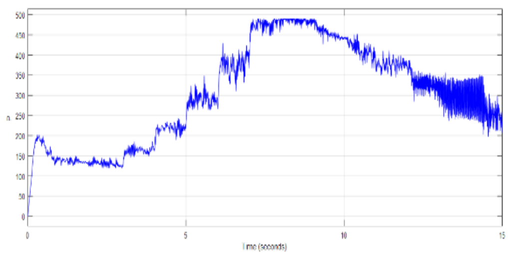
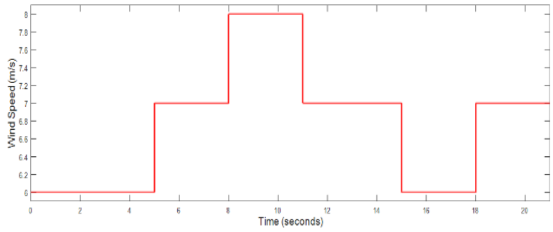


(c)

Figure 8. Turbine Power MPP testing (a)6 m/s, (b)7 m/s, (c)8 m/s.



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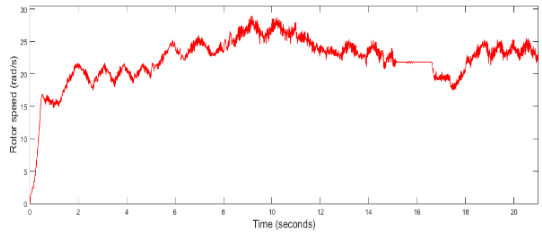

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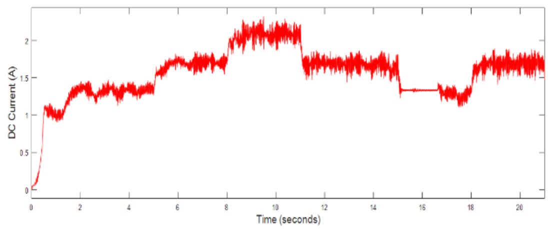

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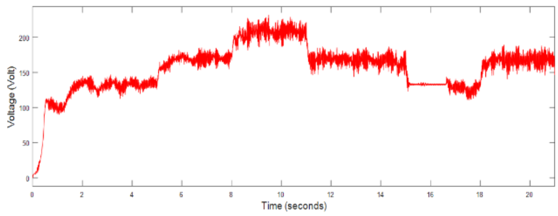

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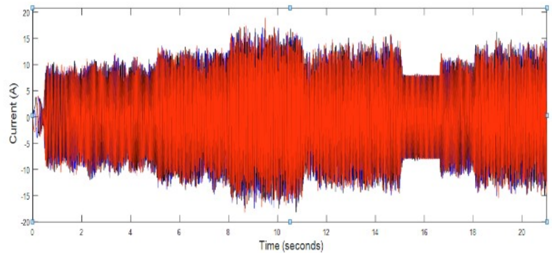

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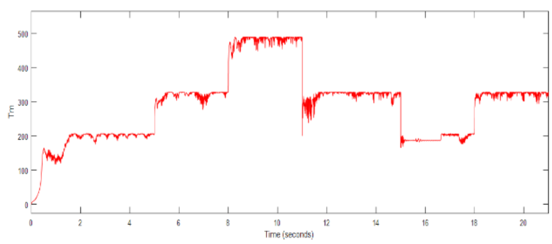

(f)

Figure 9. Wind turbine system with MPPT for various wind speed (a) wind speed (b) ω_r (c) i_{dc} (d) v_{dc} (e)i_{abc} (f) P

According to figure 9, The model of active rectifier is successfully simulated. The rectifier has produced DC current and voltage. The rotor speed is also successfully controlled by looking at ω_r following the reference that come from the MPPT. When Figure 9(e) is compare to figure 8, the Power's values is equal to the maximum power from the testing simulation. Thus, MPPT algorithm could track its maximum power and perform the turbine rotor speed to work in its maximum power.

V. Conclusion

This paper proposed a model of active rectifier for small wind turbine which is controlled by speed control and MPPT. The model and controller successsfully simulated using Simulink MATLAB S-Function block. The simulation tested system by giving a various wind speed. The system performed great result either in speed control or in MPPT. The MPPT algorithm forces rotor angular speed to produce a maximum power and the simulation strongly show system work in its maximum. Furthermore, acording to simulation, the system is able to be implemented by further improvement.

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