

Maximum Output Power Tracking of Wind Turbine Using Intelligent Control

Muldi Yuhendri^{1,2}, Mochamad Ashari², Mauridhi Hery Purnomo²

¹ Department of Electrical Engineering, Universitas Negeri Padang (UNP)
Jln. Dr. Hamka, Air Tawar, Padang 25132, Indonesia, Ph/Fax: +62751-445998/7055644

² Department of Electrical Engineering, Institut Teknologi Sepuluh Nopember (ITS)
Campus ITS Keputih, Surabaya 60111, Indonesia, Ph/Fax: +6231-5947302/5931237
e-mail: muldi10@mhs.ee.its.ac.id*, ashari@ee.its.ac.id, hery@ee.its.ac.id

Abstrak

Daya output turbin angin ditentukan oleh kecepatan angin. Daya output turbin angin dapat diatur dengan mengendalikan kecepatan generator dan sudut pitch turbin angin. Ketika kecepatan angin di bawah rating turbin, daya output generator dapat maksimum dengan mengendalikan kecepatan generator pada titik koefisien daya maksimum. Ketika kecepatan angin di atas rating turbin, daya output turbin akan melebihi rating daya generator. Dalam kondisi ini, daya output turbin perlu diregulasi agar sesuai dengan rating daya generator. Daya output turbin dapat diregulasi dengan mengatur sudut pitch turbin. Dalam paper ini dikembangkan strategi kontrol berbasis kendali cerdas untuk mengendalikan kecepatan generator dan sudut pitch turbin, sehingga daya output maksimum (MOPT) turbin angin dapat diperoleh pada setiap variasi kecepatan angin. Kecepatan generator dikendalikan dengan PI-fuzzy logic controller (PI-FLC) berbasis direct field oriented control (DFOC). Sudut pitch turbin dikendalikan dengan recurrent Elman neural network (RENN). Hasil simulasi dengan simulink Matlab menunjukkan bahwa aplikasi kedua pengendali ini sukses meregulasi daya output ketika kecepatan angin di atas rating turbin dan daya output generator dapat maksimum ketika kecepatan angin di bawah rating turbin.

Kata kunci: MOPT, turbin angin, PI-FLC, RENN, DFOC

Abstract

The Output power of wind turbine is determined by wind speed. The Output power can be adjusted by controlling the generator speed and pitch angle of wind turbine. When the wind speed below the wind turbine rated, the output power of generator can be maximized by controlling the generator speed at point of maximum power coefficient. When the wind speed above the wind turbine rated, output power of wind turbine will exceed the power generators rated. In this condition, the output power of wind turbine needs to be regulated to conform to the generator power rate. Output power of wind turbine can be regulated by adjusting the pitch angle of wind turbine. In this paper is developed the control strategies based intelligent control for controlling the generator speed and pitch angle of wind turbine, so the maximum output power tracking (MOPT) of wind turbine can be obtained at any wind speed variations. Generator speed is controlled using PI Fuzzy Logic Controller (PI-FLC) based Direct Field Oriented Control (DFOC). Pitch angle of wind turbine is controlled using Elman Recurrent Neural Network (RENN). The simulation results with Matlab Simulink shows that the both controller was successfully regulates the output power when the wind speed above the wind turbine rated and the output power can be maximum when the wind speed below the wind turbine rated.

Keywords: MOPT, wind turbine, PI-FLC, RENN, DFOC

1. Introduction

Wind turbine operation can be divided in two different operation regions. The first region describes wind turbine operation during below the wind speed rated. In this region, the wind power is lower than the rated power output of wind turbine generator. The second operation region describes wind turbine operation during above the wind speed rated winds. In this region wind power is greater than the rated power output of wind turbine generator. In the first region, the main task of control system is to maximize the power output of wind turbine by maximizing wind power capture. Variable speed wind turbine has been developed to maximizing wind power capture. There have been many control strategies are applied to variable speed wind

turbine. Variable speed wind generation system based on vector control has been developed in [1-9]. Vector control based on intelligent control has been developed in [10-14]. In [1-14], the wind turbine is operated with pitch angle fixed. It causes the wind turbine can not be operated on a second region. For wind turbine operation in the second region, has developed a variable speed wind turbine with pitch angle-regulated [15-17]. Several control strategies have been applied, among others, robust digital control [15], intelligent control based on RBFNN [16], and improved Elma Neural Network based Modified Particle Swarm Optimization [17].

In this paper, a MOPT strategy of WECS is developed to both operation regions, so the wind turbine can be operated for above the wind speed rated. The Maximum output power is obtained by adjusting the generator speed and pitch angle of wind turbines. Generator speed is controlled using PI-FLC based on DFOC method. Pitch angle of wind turbine is controlled using RENN. Control strategy is shown in Figure 1. In zone 1, the wind speed is lower than the wind speed rated ($v_1 \leq v \leq v_2$), while in zone 2 the wind speed above the wind speed rated of wind turbine ($v_2 \leq v \leq v_3$). For zone 1, the generator speed ω_m is controlled at maximum power coefficient C_{p_max} with pitch angle β constant, such that the maximum output power can be obtained at each wind speed variations. For zone 2, the generator speed ω_m was maintained constant and pitch angle β is controlled to lower the power coefficient, so that the output power of wind turbine in accordance with the rating of maximum power the generator.

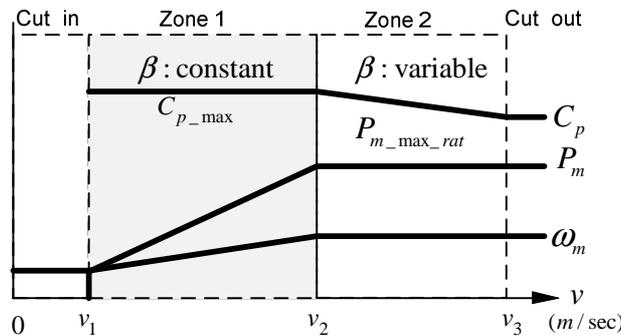


Figure 1. Control strategy of wind turbine

2. Research Method

Model of WECS is shown in Figure 2. The model consists of horizontal wind turbine, squirrel cage induction generator (SCIG), voltage source converter, DC supply, resistor load and controllers. Converter is modulated by space vector pulse width modulation (SVPWM).

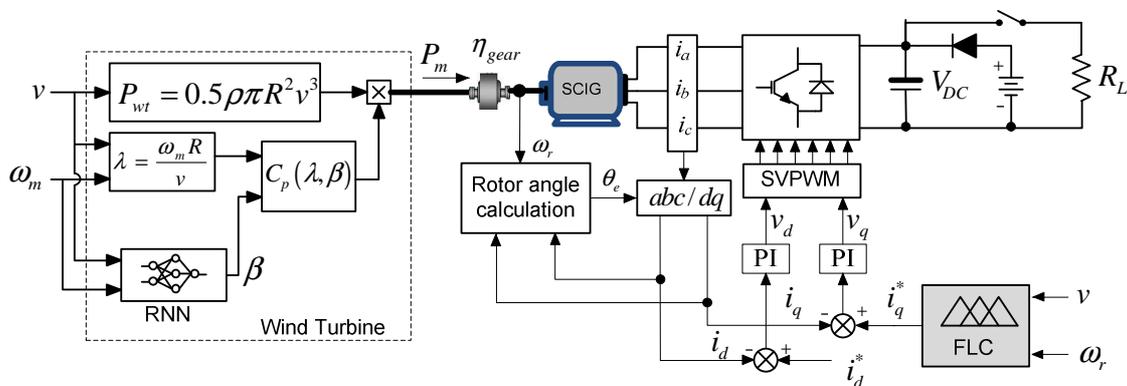


Figure 2. WECS models for MOPT

DC supply is used for initial operation and supplying the generator when the WECS in the cut-in condition. For generator excitation, the capacitor mounted on the DC side of the converter. Model details are described in the following sections.

2.1. Squirrel Cage Induction Generator (SCIG)

In DFOC method, SCIG is modeled in dq axis. General equation of SCIG voltages in dq axis are described as [19-20]:

$$\begin{bmatrix} v_{qs} \\ v_{ds} \\ v_{qr} \\ v_{dr} \end{bmatrix} = \begin{bmatrix} R_s + pL_s & 0 & pL_m & 0 \\ 0 & R_s + pL_s & 0 & pL_m \\ pL_m & -\omega_r L_m & R_r + pL_r & -\omega_r L_r \\ \omega_r L_m & pL_m & \omega_r L_r & R_r + pL_r \end{bmatrix} \begin{bmatrix} i_{qs} \\ i_{ds} \\ i_{qr} \\ i_{dr} \end{bmatrix} \quad (1)$$

where v_{dqs} and v_{dqr} are stator and rotor voltages in dq axis, respectively. i_{dqs} and i_{dqr} are stator and rotor currents in dq axis, respectively. R_s and R_r are stator and rotor resistance, L_s and L_r are stator and rotor leakage inductance, respectively. Torque and power of SCIG are given by [19] :

$$P_e = 1.5 (v_{ds} i_{ds} + v_{qs} i_{qs}) \quad (2)$$

$$P_m = T_m \omega_m \quad (3)$$

$$T_e = T_m - J \dot{\omega}_m - D \omega_m \quad (4)$$

where P_e , P_m and T_m are output power of SCIG, Mechanical power of wind turbine and mechanical torque of wind turbine, respectively. J , D and T_e are moment inertia, damping of wind turbine and electromagnetic torque of SCIG, respectively.

2.2. Wind Turbine

Wind turbine model is developed based on mechanical power equation of wind turbine. Mechanical power of wind turbine P_m can be written as [18]:

$$P_m = 0.5 \pi \rho C_p (\lambda, \beta) R^2 v^3 \quad (5)$$

where ρ , λ and R are air density, Tip speed ratio (TSR) and blade radius of wind turbine, respectively. Power coefficient is determined by TSR and the pitch angle of wind turbine. The relationship of power coefficient, TSR and pitch angle of wind turbine $C_p(\lambda, \beta)$ can be expressed as [18] :

$$C_p(\lambda, \beta) = c_1 \left(\frac{c_2}{\lambda_i} - c_3 \beta - c_4 \right) e^{\frac{-c_5}{\lambda_i}} + c_6 \lambda \quad (6)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (7)$$

where c_1 - c_6 are constants value of wind turbine. TSR is ratio of the angular velocity of wind turbine with wind speed, which is formulated by [10]:

$$\lambda = \frac{\omega_m R}{v} \quad (8)$$

From equations (5)-(8) can be concluded that the mechanical power can be regulated by controlling the generator speed and the pitch angle of wind turbine. Mechanical power of

wind turbine varies on each change of wind speed and has a maximum point at the particular generator speed [18]. Maximum mechanical power P_{m_max} is obtained at the point of maximum power coefficient C_{p_max} , as shown in Figure 3.

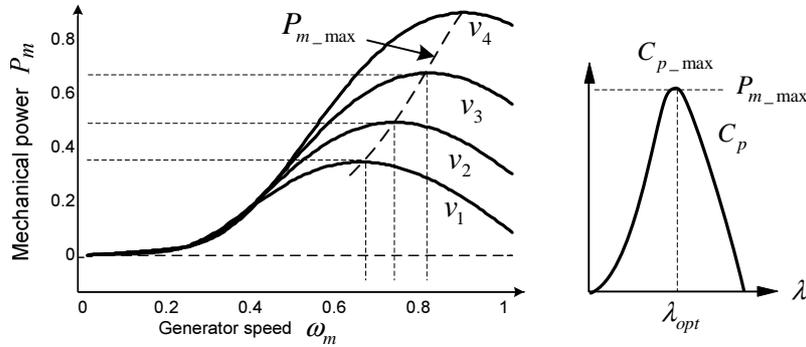


Figure 3. Power characteristics of wind turbines

2.3. Generator Speed Control

The generator speed is controlled by DFOC method. In this method, the generator speed is controlled by adjusting the torque component and field component. In DFOC method, rotor angle θ_e is calculated from the stator current feedback that has been converted into the dq axis, that defined as [20]:

$$\theta_e = \int (\omega_m + \omega_{s1}) dt \tag{9}$$

$$\omega_{s1} = \frac{L_m R_r}{|\psi_r| L_r} i_{qs} \tag{10}$$

$$|\psi_r| = \frac{L_m i_{ds}}{1 + (L_r/R_r) s} \tag{11}$$

where ω_{s1} and ψ_r are slip frequency and rotor flux, respectively. Output controller DFOC are stator current references in dq axis (i_{ds}^* and i_{qs}^*), which can be written as:

$$i_{qs}^* = \frac{2}{3} \frac{2}{p} \frac{L_r}{L_m} \frac{T_e^*}{|\psi_r|} \tag{12}$$

$$i_{ds}^* = \psi_r^* L_m^{-1} \tag{13}$$

where L_m , p and are magnetizing inductance and number of pole, respectively. In this paper, i_{qs}^* is controlled using PI-FLC, whereas the i_{ds}^* is made constant, as illustrated in Figure 2. The generator speed control scheme is shown in Figure 4. This controller consists of two FLC, namely FLC1 and FLC2. FLC1 is used to tracking the generator speed reference for maximum output power. For zone 1, the speed reference of generator gives a chance varies according to wind speed variations. For zone 2, speed reference of generator is made constant at each wind speed variations, as illustrated in Figure 1. FLC2 is used to control the generator speed to fit the reference speed obtained from FLC1, so that the generator working at maximum output power point. FLC2 made in the PI-FLC scheme. In PI-FLC, the gain factor K_i is used for gain the error input and K_p for gain the change of error [20-21].

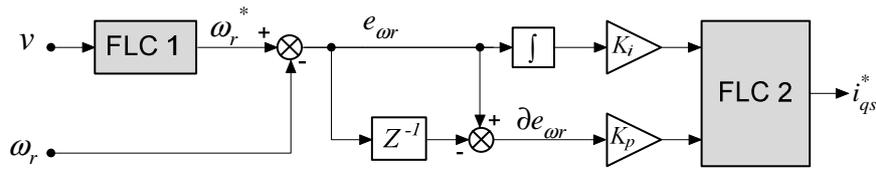


Figure 4. Scheme of the generator speed control

The Input of FLC1 is wind speed v and the output is generator speed references ω_r^* . The output FLC1 ω_r^* compared with actual generator speed ω_r . The speed error e_{ω_r} and change of error ∂e_{ω_r} are used as input of PI controller. Output gain K_i and K_p of the PI controller are used as input FLC2. FLC2 output is the reference of stator currents in q axis i_{qs}^* . Figure 5 shows the input and output membership function of FLC1 and FLC2.

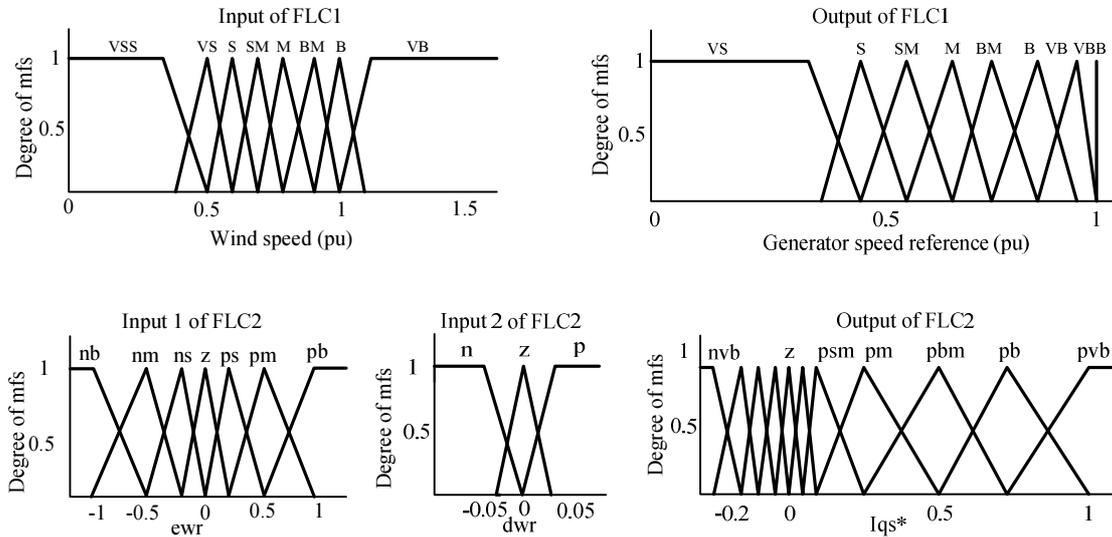


Figure 5. Membership function of FLC1 and FLC2

The references of stator current i_{ds}^* and i_{qs}^* are compared with feedback of stator current i_{ds} and i_{qs} . Stator current errors are compensated by a PI compensator to obtain the voltage references in the dq axis v_{dq}^* . For obtain the references of magnitude and phase angle of voltage reference for SVPWM, v_{dq}^* are converted to $v_{\alpha\beta}$. The magnitude and phase angle of SVPWM can be written as follow [20]:

$$m = \sqrt{(V_{\alpha}^2 + V_{\beta}^2)} \text{ and } \theta = \tan^{-1}(V_{\beta}/V_{\alpha}) \tag{14}$$

where m and θ are magnitude and phase angle of the voltage. SVPWM will modulate the gate of converter switch based on m and θ .

2.4. Pitch Angle Control Using Recurrent Elman Neural Network (RENN)

Pitch angle of wind turbine is controlled to remain constant at the maximum power coefficient for zone 1 and varies for zone 2. The variation of pitch angle in zone 2 serves to reduce the power coefficient, so the mechanical power of wind turbine remain under power rating of generator at high wind speed. The pitch angle of wind turbine is controlled using

RENN. Figure 6 shows the RENN scheme. RENN inputs are wind speed v and generator speed ω_m , respectively. Output of RENN is pitch angle of wind turbine β .

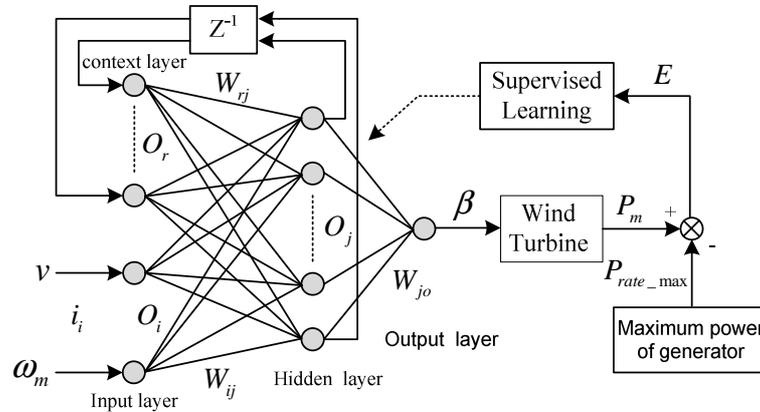


Figure 6. RENN scheme to control the pitch angle of wind turbine

RENN consists of Input layer, context layer, hidden layer and output layer [23]. The output of input layer RENN O_i is defined as:

$$O_i(k) = \text{net}_i = i_i(k), \quad i = 1, 2 \tag{15}$$

where (k) represents the k_{th} iteration, i_i is input values of the input layer for k_{th} iteration. Output the context layer O_r can be written as [23]:

$$O_r(k) = \alpha O_r(k-1) + O_j(k-1), \quad 0 \leq \alpha \leq 1 \tag{16}$$

with α is gain feedback in the context layer. The output of hidden layer O_j is activated by tansig transfer function, which is formulated by :

$$O_j(k) = \text{Tansig}(\text{net}_j) = \text{Tansig} \left(\sum_i W_{ij} \times O_i(k) + \sum_r W_{rj} \times O_r(k) \right) \tag{17}$$

$$\text{Tansig}(n) = 2 / \left(\left(1 + e^{-2n} \right) - 1 \right) \quad r = 1, 2, \dots, 5 \quad \text{and} \quad j = 1, 2, \dots, 5$$

where W_{ij} and W_{rj} are the weight of input neuron to hidden neuron and weight of context neuron to hidden neuron, respectively. The output layer RENN is activated by linear transfer function, so that the β can be written as:

$$\beta(k) = \text{net}_o(k) = \sum_j W_{jo} \times O_j(k) \tag{18}$$

with W_{jo} is the weight of hidden neuron to output neuron. RENN trained with supervised learning method. In learning process, the W_{ij} , W_{rj} and W_{jo} is updated steepest descent algorithm [22], can be written as:

$$W_x(k+1) = W_x(k) + \eta_x \Delta W_x, \quad x = ij, rj, jo \tag{19}$$

where ΔW_x is change of the weight, can be formulated by:

$$\Delta W_{ij} = \delta_o W_{jo} O_j (1 - O_j) O_i \quad (20)$$

$$\Delta W_{rj} = \delta_o W_{jo} O_j (1 - O_j) O_r \quad (21)$$

$$\Delta W_{jo} = \delta_o O_j \quad (22)$$

where δ_o is error term to be propagated, which is given by:

$$\delta_o = -\frac{\partial(E)}{\partial\beta} \frac{\partial\beta}{\sum_j W_{jo} \times O_j} \quad (23)$$

$$E = 0.5(P_m - P_{rate_max})^2 = 0.5e^2 \quad (24)$$

where E , P_m and P_{rate_max} are error in learning process, mechanical power of wind turbine and maximum power rate of generator, respectively. The pitch angle of wind turbine β is trained with wind speed 5 m/s - 20 m/s. Figure 7 shows the performance of training. RENN training reach the error goal in epochs 337 with training error $2.967e-6$.

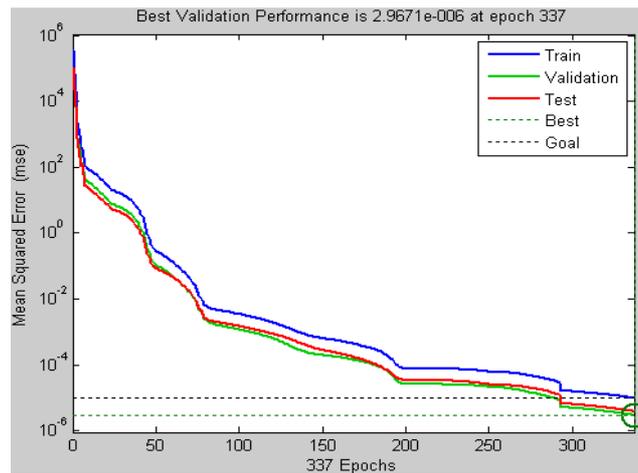


Figure 7. Performance of RNN training

3. Results and Analysis

The WECS model has been designed as shown in Figure 2 is simulated using Matlab. Design parameter of WECS is shown in Table 1.

Table 1. Design Parameter of WECS

Variable	Parameter	Variable	Parameter
SCIG	200 HP 460 Volt 60 Hz J : 0,02 Nms ²	Wind turbine	R blade : 12 m
DC Link	DC Supply : 460 Volt C : 8.5 mF		cut in : 5 m/s
			cut out : 20 m/s
Load	R _L : 20 ohm		zone 1 : 5 m/s – 10 m/s
		zone 2 : 11 m/s – 20 m/s	

The first simulation is training the pitch angle β using RENN. The Figure 8 shows the pitch angle β from RENN training result.

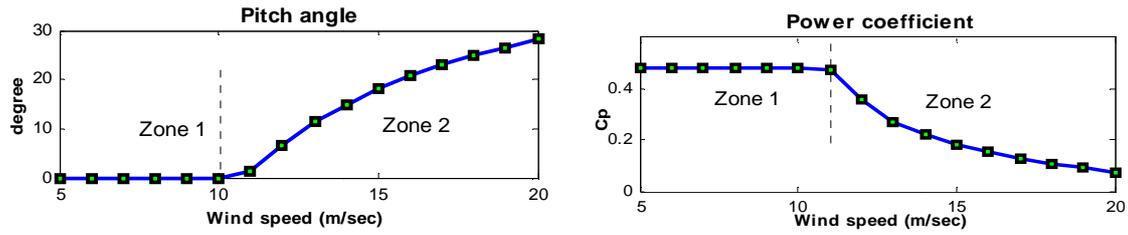


Figure 8. Pitch angle and power coefficient of wind turbine

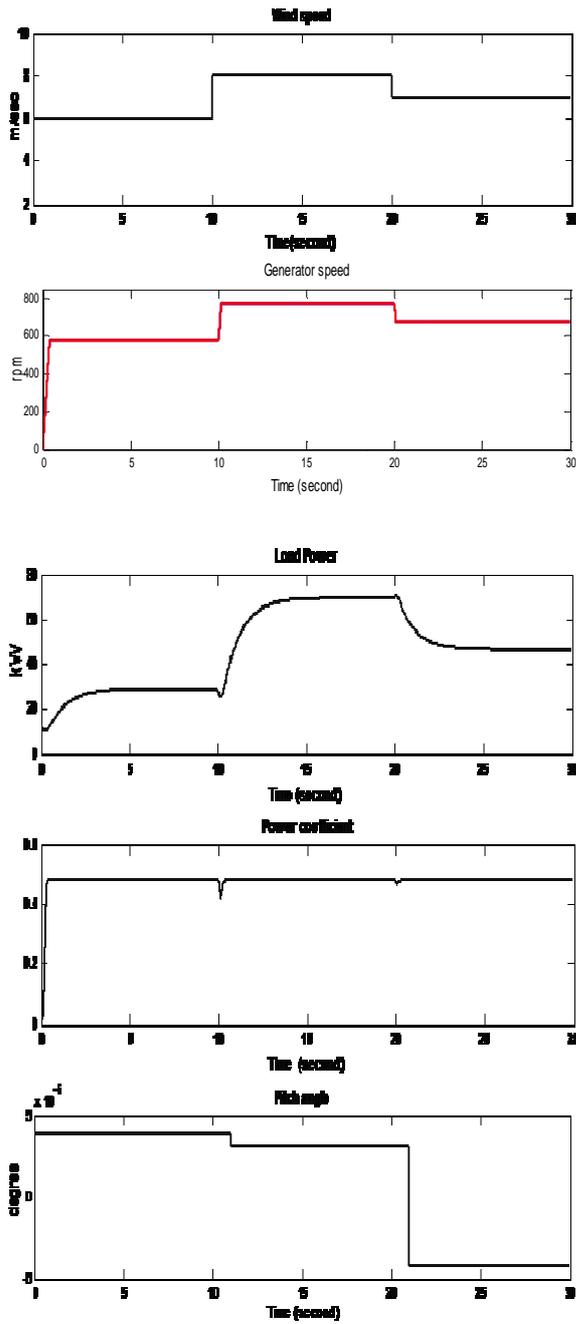


Figure 9. Simulation results of zone 1

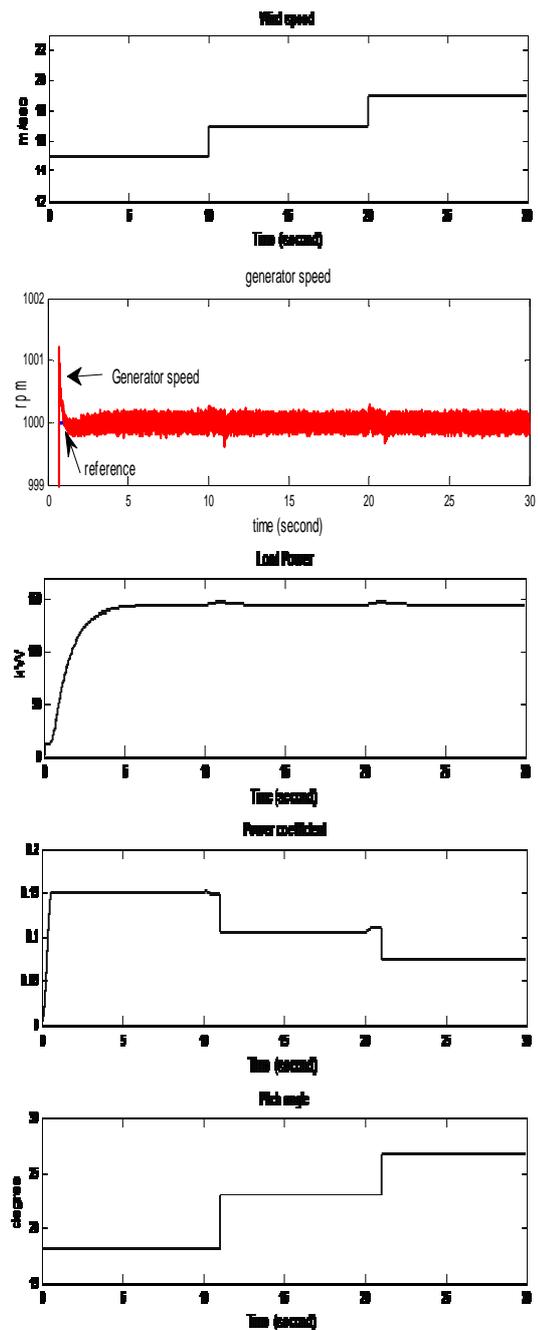


Figure 10. Simulation results of zone 2

The power coefficient graph in Figure 8 is obtained from the calculation using the equation (6)-(8). The highest power coefficient found on the pitch angle 0 with $C_{p,max}$ 0.48. For Figure 8, the wind turbine is operated with a reference speed at the $C_{p,max}$ point for zone 1 and a constant 1000 rpm for zone 2. For zone 2, the pitch angle grows large when the wind speed increases. From the Figure 8 can be concluded that the increase in pitch angle of wind turbine will reduce the power coefficient.

The second simulation, the generator is operated in zone 1 with varying wind speed 6 m/s, 8 m/s and 7 m/s, respectively. Figure 9 shows the results of simulation. The generator speed graph shows validity of the PI-FLC. It can be seen from the actual speed can follow the reference speed. For wind speed 6 m/s, PI-FLC just gives error 1.8 rpm at transient condition and ± 0.2 rpm at steady condition, as shown in Figure 11. The power coefficient graph shows that the values can be constant at maximum point 0.48 in each wind speed variations. Change the power coefficient value occurs only during transient changes in wind speed. The RENN controller gives the pitch angle remains constant 0 with error $\pm 0.00004^\circ$ at every variation of wind speed.

Figure 10 shows the simulation results of zone 2 with winds speed 15 m/s, 17 m/s and 19 m/s, respectively. The generator speed graph shows the speed remains constant 1000 rpm on every variation of wind speed. Error of generator speed is shown in Figure 11. The output power graph shows the output power constant at rated generator on every variation of wind speed. It shows the validity of RENN to control the pitch angle of wind turbine. When the wind speed increases, the pitch angle also increases and the power coefficient decrease. It is gives the output power remain constant at maximum power of generator.

Figure 11 shows the error of generator speed for zone 1 and zone 2. For wind speed 6 m/s, the error is 1.8 rpm at transient condition and ± 0.2 rpm at steady state condition. For wind speed 15 m/s, the error is 1.3 rpm at transient condition and ± 0.1 rpm at steady state condition. It is shows that PI-FLC is valid for both operation regions.

This result is better compared with the results in [15]. In [15], the ripple of generator speed ± 0.7 rpm with the ripple of pitch angle ± 0.4 at wind speed 15 m/s.

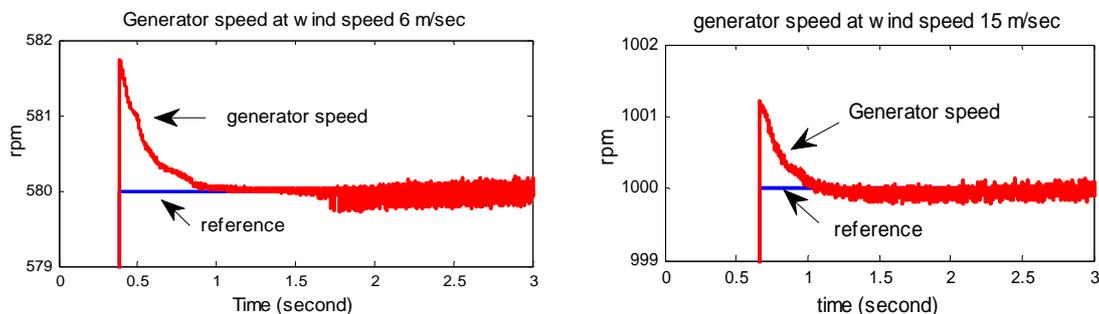


Figure 11. Error of generator speed

4. Conclusion

Control strategy of MOPT for WECS is developed in this paper. The maximum output power is obtained by controlling the generator speed and pitch angle of wind turbine. The generator speed is controlled using PI-FLC and pitch angle is controlled using RENN. The both controller is valid for two operation regions of wind turbine. It was shown by the simulation results. For zone 1, the output power of generator can be maximized at maximum power coefficient point in each wind speed variations. Speed control using PI-FLC based DFOC method gives the actual speed of generator can follow the reference speed with error 1.8 rpm at transient condition and 0.2 rpm at steady state condition. Pitch angle control of wind turbine using RENN just gives error 0.00004° in each wind speed variations. The same result was also shown by the simulation result for zone 2.

References

- [1] Chen WL, Hsu YY. Controller Design an Induction Generator Driven by a Variable Speed Wind Turbine. *IEEE Transaction on Energy Conversion*. 2006; 21(3): 625 – 635.
- [2] Cardenas R, Pena R. Sensorless Vector Control of induction machines for variable vpeed wind energy applications. *IEEE Transaction on Energy Conversion*. 2006; 19(1): 196–205.
- [3] AJ Mahdi, WH Tang, L Jiang, QH Wu. *A Comparative Study on Variable Speed Operations of a Wind Generation System Using Vector Control*. International conference on Renewable Energy and Power Quality (ICREPQ). 2010.
- [4] Senjyu, S Tamaki, N Urasaki, K Uezato, H Higa, T Funabashi, H Fujita. Sensor-less MPPT Control for Wind Generation System with SCIG”, *ELSEIVER Renewable Energy*. 2008; 30: 1-6.
- [5] Aouzellag D, Ghedamsi K, Berkouk EM. Network Power Fluc Control of a Wind Generator. *ELSEIVER Renewable Energy*. 2008; 30: 1-8.
- [6] Ahmed T, Nishida K, Nakaoka M. Advanced Control of PWM Converter with Variable Speed Induction Generator. *IEEE Industry Application*. 2006; 42(4): 934–945.
- [7] W Qiao, Wei Z, JM Aller. Wind Speed Estimation Based Sensorless Output Maximization Control for a Wind Turbine Driving a DFIG. *IEEE Transactions On Power Electronics*. 2008; 23(3): 1156-1169.
- [8] Agarwal V, RK Aggarwal, PK Patidar, CK Patki. A Novel Scheme for Rapid Tracking of Maximum Power Point in Wind Energy Generation Systems Energy Conversion. *IEEE Transactions on*, 2010; 25(1): 228-236.
- [9] R Mittal, KS Sandu, DK Jain. Isolated Operation of Variable Speed Driven PMSG for Wind Energy Conversion System. *IACSIT International Journal of Engineering and Technology*. 2009; 1(3): 269-273.
- [10] Khalil AGA, Lee DC, Seok JK. *Variable speed wind generation based on FLC for Maximum Output Power Tracking*, 35th Annual IEEE Power Electronic Specialists Conference. Jerman. 2004.
- [11] E Adzic, Z Ivanovic, M Adzic. Maximum Power Search in Wind Turbine Based on Fuzzy Logic Control. *Journal Acta Polytechnica Hungarica*. 2009; 6(1): 131-149.
- [12] A Meharrar, M Tioursi, M atti, AB Stambouli. A Variable Speed Wind Generator Maximum Power Tracking Based On ANFIS. *Elseiver : Expert Systems with Applications*. 2011; 38: 7659–7664.
- [13] WM Lin, CM Hong. Intelligent Approach To MPPT Control Strategy For Variable-Speed Wind Turbine Generation System. *Elseiver: Energy*. 2010; 35: 2440-2447.
- [14] CY Lee, YX Shen, Jung CC. Neural Networks and PSO Based MPPT for Small Wind Power Generator. *World Academy of Science, Engineering and Technology*. 2009; 60: 17-23.
- [15] H. Camblong. Digital robust control of a Variable Speed Pitch Regulated Wind Turbine for Above Rated Wind Speeds. *Elseiver: Control engineering practice*. 2008; 16: 946-958.
- [16] AS Yilmaz, Z Ozer. Pitch Angle Control in Wind Turbine Above the Rated Wind Speed by Multi-layer Perceptron and RBFNN. *Elseiver: Expert System with Applications*. 2009; 36: 9767-9775.
- [17] WM Lin, CM Hong. A New Elman Neural Network-Based Control Algorithm for Adjustable-Pitch Variable Speed Wind-Energy Conversion Systems. *IEEE Transactions On Power Electronics*. 2011; 66(2): 1847-1853.
- [18] Burton T, Sharpe D, Jenkin N, Borsanyi E. *Wind Energy Handbook*. West Sussex: John Wiley & Sons. 2001
- [19] Boldea I, Nasar SA. *The Induction Machine Handbook*. Florida: CRC Press. 2002.
- [20] Bose KB. *Modern Power Electronic and AC Drives*. Upper Saddle River: Prentice Hall. 2001.
- [21] Reznik L. *Fuzzy Controller*. Oxford: Newnes. 1997.
- [22] Widi A. Stabilisator system tenaga berbasis jaringan saraf tiruan berulang untuk sistem mesin tunggal. *Journal Telkomnika*. 2010; 8(1): 65-72.
- [23] LR Medsker, LC Jain. *Recurrent Neural Network Design and Application*. London: CRC Press. 2001.