Modified Firefly Algorithm for Improved Maximum Power Extraction on Wind Energy Conversion System

Ratna Ika Putri*‡, Irwan Mahmudi**, Margo Pujiantara***, Ardyono P****, Taufik Taufik*****, Mauridhi Hery P******

* Department of Electrical Engineering, State Polytechnic of Malang, Malang, East Java, Indonesia

** Department of Electrical Engineering, Tadulako University, Tadulako, Indonesia

*** Department of Electrical Engineering, Faculty of Electrical Technology, Sepuluh Nopember Institute of Technology, Surabaya, Indonesia

**** Department of Electrical Engineering, Faculty of Electrical Technology, Sepuluh Nopember Institute of Technology, Surabaya, Indonesia

***** Department of Electrical Engineering, California Polytechnic State University, California, USA.

****** Department of Computer Engineering, Faculty of Electrical Technology, Sepuluh Nopember Institute of Technology, Surabaya, Indonesia

(ratna.ika@polinema.ac.id, irwan.mahmudi@untad.ac.id, margo@ee.its.ac.id, priyadi@ee.its.ac.id, taufik@calpoly.edu, hery@ee.its.ac.id)

‡ Corresponding Author; Ratna Ika Putri, State Polytechnic of Malang, Jl. Soekarno Hatta No.9, Malang, 65141, Indonesia, Tel: +62 341 404424,

Fax: +62 341 404420, ratna.ika@polinema.ac.id

Received: 11.10.2017 Accepted:10.12.2017

Abstract- This paper presents a maximum power extraction and control system using modified firefly algorithm (MFA) to achieve high efficiency maximum power extraction from a grid-tied wind turbine using permanent magnet synchronous generator (PMSG). To get maximum power extraction from the PMSG, the MFA adjusts duty cycle of boost converter based on rectifier's output voltage and current. Simulation results show that MFA successfully achieves tracking capability under varying wind speed to acquire the maximum power during constant power coefficient operation of the wind turbine. The MFA also yields higher efficiency, faster response and lower integral of time and absolute error (ITAE) compared to the particle swarm optimization (PSO) and the perturb and observe (P&O) counterparts. The proposed MFA was further tested empirically against P&O method to extract maximum power on a 500W lab-scale prototype of wind energy conversion system (WECS). The hardware test results demonstrate that MFA outperforms P&O method when used as an MPPT controller algorithm and yields greater efficiency. The efficiency of PMSG wind turbine with MFA is 93.63 %, while P&O produce 81.54 %.

Keywords Modified firefly algorithm, maximum power, wind turbine, PMSG.

1. Introduction

Increased electricity demand and reduction in fossil-based energy generation have caused the rapid growth in the global use of renewable energy. Among existing renewable energy sources, wind energy has experienced fast development as indicated by its largest market share [1-3]. The reason for such growth is mainly because wind energy has been considered a green source of energy that is free of CO2 emission, inexhaustible, and suitable for some applications with relatively low initial cost. However, utilization of wind energy is heavily dependent on intermittent wind speed which consequently has resulted in the prevalent use of variable speed wind turbines (VSWT) to convert wind energy to electricity [1,4-7]. Compared with the fixed speed wind turbine, VSWT is more effective because of its optimized wind energy conversion offering increased captured wind energy and less mechanical stress [8-10]. The type of generator employed by VSWT has mostly been PMSG due to its high reliability, higher efficiency and simple structure [5, 10,11].

As the wind fluctuates which in turn produces changing power, there is a critical need to optimize the capturing of the wind power. This is typically achieved by using the maximum power point that follows any wind speed. At the point of maximum power, PMSG must rotate at optimum speeds set via the generator speed setting using a power converter controller. Several methods to extract the maximum power has been studied which can be classified into two categories: direct power controller and indirect power controller. MPPT algorithms that employs the indirect power controller are the tip speed ratio (TSR), the power feedback signal (PSF), and the optimal torque (OT) [3]. TSR method is a simple algorithm, but requires an anemometer for wind speed measurement that is not always accurate on its implementation. The other two indirect power controller algorithms do not require measurement of wind speed; however, they require the use of mechanical sensor which will increase the cost of the overall wind generation system.

For the direct power controller method, a couple of algorithms that have been used are the perturb & observe (P&O) and the optimum relations based (ORB). ORB requires system parameters and different optimum curves for each application that makes it difficult to use [3]. P&O is simple and easy to implement because it does not require information of wind speed and wind turbine parameters. However, the determination of step size is critical to get the tracking speed and fast response. Large step size will accelerate the tracking speed but at the risk of oscillation in steady state conditions. Conversely small step size will increase the system's accuracy but at the cost of a slow response. Hence, improving the P&O will usually require adjustment of the step size, speed tracking, and tracking ability for the wind speed variation [3].

To overcome the disadvantages of the conventional P&O method, intelligent control techniques have been investigated. Previous studies have used genetic algorithm, fuzzy logic and particle swarm optimization (PSO) primarily on the P&O method to adjust step size [12-18]. Neural network, PSO and fuzzy logic have been explored to control wind turbine system to achieve maximum power [18-22]. In wind turbine control, the use of PSO produces accuracy and efficiency that are better than those resulted from the conventional P&O method [21].

Like PSO, firefly algorithm (FA) is also considered as a swarm intelligent method. For photovoltaic system, FA has resulted in faster response and higher accuracy than PSO [23]. The use of modified firefly algorithm (MFA) for MPPT on grid connected WTS with PMSG is presented in this paper. MFA controls generator speed through the adjustment of duty cycle on power converter to obtain the maximum power from wind turbine. The proposed maximum power extraction does not use mechanical sensor since the MFA algorithm provides the necessary voltage and current information. The proposed MFA adjusts duty cycle for boost converter based on output voltage and current of rectifier to get maximum power extraction so that optimal coefficient power can be maintained. Brightness of each firefly is given by the output power of the rectifier circuit as an objective function. The efficiency of MFA is compared with PSO and P&O methods. Simulation results demonstrate that the proposed MFA functions well even without any mechanical sensor and wind speed measurement. The proposed MFA was tested experimentally on a 500W WECS prototype whose results are being compared with those of P&O method.

2. Wind Turbine System

Figure 1 illustrates the proposed wind energy conversion system (WECS) with grid connection and maximum power extraction. An 8.5 kW PMSG is directly coupled to a three-blade horizontal-axis wind turbine. PMSG feeds a three-phase diode rectifier and a boost converter that increases conversion efficiency through maximum power extraction. The MPPT controller adjusts the duty cycle of the boost converter to reach the optimum generator speed using the proposed modified firefly algorithm that is based on rectifier's output voltage and current. The maximum output power will be achieved through duty cycle adjustment to control generator speed at any given wind speed. An inverter produces ac voltage to supply power to grid utilizing the grid side controller which consists of current controller and voltage controller

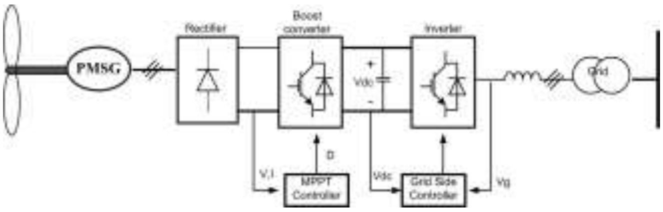


Fig 1. Block diagram system

A wind turbine generates the mechanical power as expressed by

$$P_m = \frac{1}{2} \times \pi \times \rho \times C_p(\lambda, B) \times A \times v^3 \qquad (1)$$

where P_m is the wind turbine output power, ρ is air density (1.225 Kg/m3), v is wind speed (m/s), A is the area swept (m2), and Cp(λ,B) is power conversion coefficient that follows a nonlinear function between tip speed ratio (λ) and pitch angle of rotor blade (B). The tip speed ratio (TSR) represents the comparison between turbine angular speed and wind speed. Cp plays the most important role to the power extraction efficiency [6, 24]. In fixed-pitch angle, where B is equal to 0, Cp follows:

$$C_p = U_1 \times \left(\frac{U_2}{\lambda i} - U_3\right) \times exp\left(\frac{-U_4}{\lambda i}\right) + (U_5 \times \lambda) \qquad (2)$$

$$\frac{1}{\lambda i} = \frac{1}{\lambda} - 0.035 \qquad (3)$$

$$\lambda = \frac{R \times \omega}{v} \qquad (4)$$

where R is the blade radius and ω is the angular speed, and U1 – U5 are coefficients. At a specific wind speed, Cp is optimal value at an optimal λ as shown in Fig 2. At optimal Cp, wind turbine will produce maximum power to yield an increased efficiency of the power extraction.

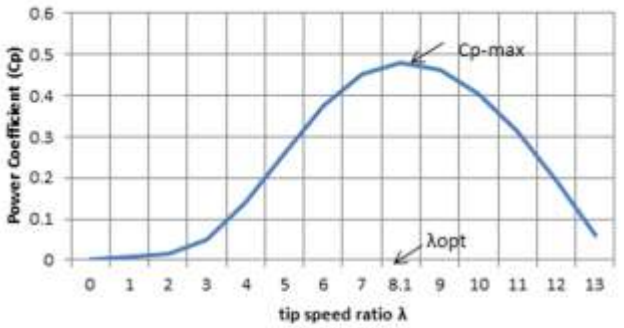


Fig 2. Power conversion coefficient curve

At another wind speed, wind turbine produces a different MPP. Therefore, MPPT is needed to maintain the optimal Cp through control of power converter. For varying wind speeds, the maximum output power is achieved when the rotor speed is optimal. From equations (1) to (4), the maximum output power is given by

$$P_{max} = k \times \omega_{opt}^{3} \qquad (5)$$

where k is a constant and ω_{opt} is the optimal rotor speed. The maximum output power of wind turbine is reached by controlling generator speed to obtain the optimal rotor speed.

3. Modified Firefly Algorithm (MFA) For Maximum Power Extraction

Firefly algorithm (FA) is inspired by the behavior of firefly swarms. There are three rules to develop FA: all fireflies have the same sex so that a firefly is attracted to other freely, attractiveness is proportional to their brightness and a firefly moved to follow the brighter firefly, and light intensity of a firefly is influenced by objective function to be optimized [24-25].

The brightness and light intensity variation are two important factors in FA. For maximization, the brightness may be simplified to be in proportion with the objective function. Two fireflies with position xi and xj have their distance (r) expressed by the Euclidean distance

$$r_{ij} = \sqrt{\sum_{k=1}^{m} \left(X_{ik} - X_{ij}\right)^{2}} \qquad (6)$$

The degree of attractiveness β is expressed by

$$\beta = \beta_o \times exp\,(\gamma \times r^{2}) \qquad (7)$$

where βo is initial attractiveness at r = 0 and is chosen as 1, and γ is the fixed light absorption coefficient that is an important parameter related to attractiveness variation. The larger the value of β, the faster fireflies move toward the lighter firefly.

The proposed MFA is developed based on the basic FA, where the parameters α and γ are important coefficients to update firefly position. In this paper, MFA is used for the MPPT of a wind turbine system (WTS). MPPT controller determines duty cycle of boost converter to get maximum power through the control of generator speed based on the voltage and current from the bridge rectifier. In this algorithm, firefly position is given as the duty cycle of the boost converter, and brightness of each firefly is given by the output power of the rectifier circuit. The number of fireflies used in the algorithm determines computing time. High firefly amount results in slower computing time while a few fireflies result in local maximum. Hence, to give reasonable computing time 10 fireflies are used.

Firefly speed to get the best position is affected by α and β. MFA will evaluate brightness based on the maximum output power. The other fireflies will follow those who have higher brightness. The major difference between the proposed MFA and the basic FA is the parameter α in MFA is updated continuously on every iteration as expressed by:

$$\alpha_t = \alpha_{t-1} \times 0.97^{k} \qquad (8)$$

Where α_(t-1) is a parameter randomization previous, and k is the iteration number. The larger the α, the wider the random motions of fireflies, making convergence of the algorithm slow. Also, the larger the iteration number will result in smaller α because the search almost reached an optimal solution. If βo equals 1 then firefly position is updated

$$X_i = X_i + exp\,(\gamma \times r^{2}) \times \left(x_i - x_j\right) + \alpha_t \times (randn - 0.4) \qquad (9)$$

Where randn is a random generated number normally distributed between 0 and 1. The position of fireflies will be between the upper limit (Ub), dmax, and the lower limit (Lb), dmin which establishes the duty cycle range for the boost converter. In this paper, dmax and dmin are set at 95 % and 5 % consecutively

A firefly will update its position based on Equation (9) while a firefly that has maximum brightness will maintain its position. If a firefly position has reached an optimum value, the program will be terminated and the corresponding duty cycle is conveyed to the boost converter. The flowchart of MFA is shown in Figure 3 with parameters listed in Table 1.

Table 1. Parameters of modified firefly algorithm

Population Size	10
β_0	1
γ	1.15
α_0	0.009

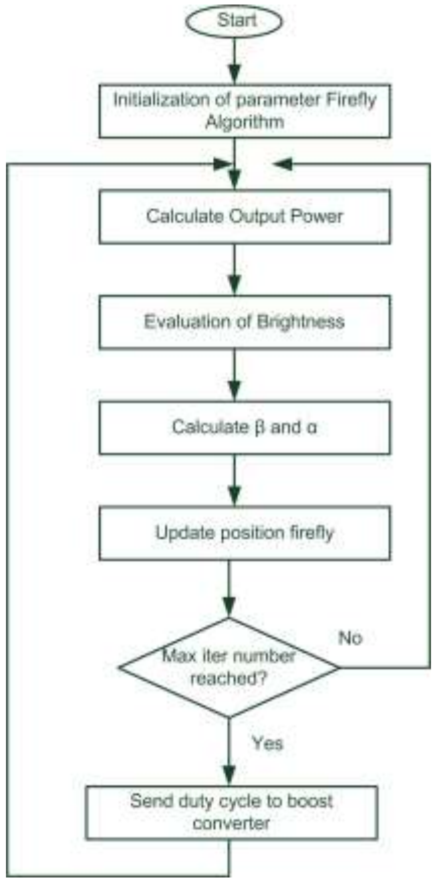


Fig 3. Flowchart of the modified firefly MPPT algorithm

Performance of MFA to extract maximum power will be compared to particle swarm optimization (PSO) method and perturb and observe (P&O) method. PSO will determine the duty cycle of boost converter to obtain maximum power point. PSO performance is determined by three variables; The particle position shows the duty cycle (d), the particle velocity is the step size of the duty cycle and the objective function is a function to maximize the converter power. The velocity (V) and particle position can be determined by

$$V_i^{k+1} = w V_i^k + C_1 r_1 (d_{Pbesti}^k - d_i^k) + C_2 r_2 (d_{Gbesti}^k - d_i^k) \quad (10)$$

$$d_i^{k+1} = d_i^k + V_i^k \quad (11)$$

In which w is a momentum factor, r_1 and r_2 are random values between 0 and 1, C_1 and C_2 are acceleration constants. The PSO parameters used are swarm size = 10, maximum iteration = 20, inertia weight factor (w) = 0.1, c_1 = 0.5 and c_2 = 0.7.

Like the MFA and PSO, the P&O method will also set the duty cycle of the boost converter to extract maximum power. Step size of duty cycle on the P&O method is 0.005

4. Grid Side Controller

Grid side controller controls a three phase voltage source inverter (VSI) that interfaces DC-link voltage and the grid. A simple passive L filter is connected between VSI and the grid to eliminate unwanted high frequency noise. The dynamic model of converter that is connected to grid in a rotating synchronous reference frame can be expressed by [26]

$$V_{dg} = V_{di} - L_f \times \frac{d_{id}}{dt} - (i_d \times R) + (\omega \times L_f \times i_q) \quad (12)$$

$$V_{qg} = V_{qi} - L_f \times \frac{d_{iq}}{dt} - (i_q \times R) - (\omega \times L_f \times i_d) \quad (13)$$

where ω is the grid frequency, V_{dg}, V_{qg}, V_{di}, V_{qi}, i_d, i_q are voltages and currents of the VSI and the grid in dq axes. R and L_f are resistance and inductance of the filter. The active and reactive powers are given by

$$P = 1.5 \times V_d \times I_d \quad (14)$$

$$Q = 1.5 \times V_d \times I_q \quad (15)$$

The grid side controller retains a constant DC-link voltage at 300V and reaches unity power factor through PWM control of the inverter. The grid side controller consists of two cascaded controllers as shown in Figure 4. The outer loop with a lower dynamic response adjusts the DC link voltage and generates a reference signal for the faster inner loop which controls the injected current into the grid. Voltage control for the outer loop utilizes DC link voltage as its reference input. Output control signal is a d-axis current reference (i_{d_ref}) to provide a reference to control the d-axis current. The current controller consists of two PI controllers for the d-axis and q-axis current, as well as a PI controller for the voltage control. A phase locked loop (PLL) will estimate the electrical angle θ of the grid currents.

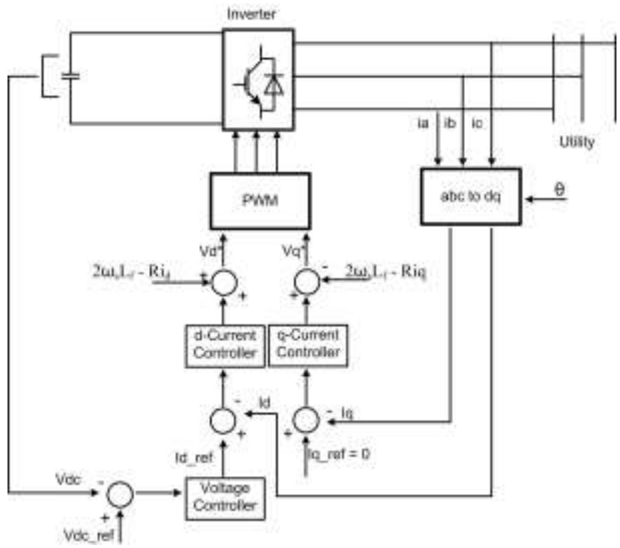


Fig 4. Grid side controller

Output of controller of d-axis current (U_{pid}) and q-axis current (U_{piq}) can be expressed by

$$v_d = U_{pid} - 2\omega L i_q + v_{dg} \quad (16)$$

$$v_q = U_{piq} + 2\omega L i_d + v_{qg} \quad (17)$$

Based on equation (16) and (17), the laplace transfer function for the PI controller output can be determined by

$$H(s) = \frac{I_d(s)}{U_{pid}(s)} = \frac{I_q(s)}{U_{piq}(s)} = \frac{1/R}{\left(\frac{L}{R}\right)s+1} \quad (18)$$

PI controller in Laplace transformation can be expressed by

$$U_{pi}(s) = K_p\left(1 + \frac{1}{Tis}\right)[I^*(s) - I(s)] \qquad (19)$$

In which Kp is a proportional constant, Ti is an integrator gain, and I* is the reference current in the Laplace transform. Substituting equation (19) at (18) and simplifying, the closed-loop transfer function of the d and q axis current control systems can be expressed by

$$H(s) = \frac{I(s)}{I^*(s)} = \frac{\left(\frac{1}{R}\right)Kp\left(s+\frac{1}{Ti}\right)}{s\left(\left(\frac{L}{R}\right)s+1\right)+\left(\frac{1}{R}\right)Kp\left(s+\frac{1}{Ti}\right)} \qquad (20)$$

By using the pole placement method, the proportional constants and integrator gain can be determined by

$$Kp = \frac{L}{T_{cl}} \qquad (21)$$

$$Ti = \frac{L}{R} \qquad (22)$$

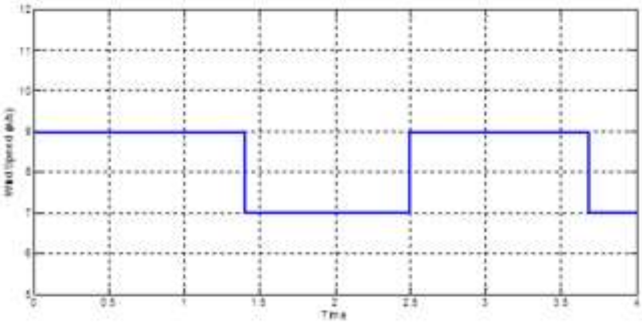
5. Simulation Results

Application of the MFA for maximum power extraction on the PMSG wind turbine system was simulated with MATLAB Simulink on the WECS shown in Fig 1. Wind Turbine System (WTS) and PMSG parameters used in the simulation are listed in Table 2. The system was simulated with two wind speed profiles applied to the proposed MPPT controller: a rectangular and random wind speeds. The simulation results of WTS with MFA were then compared with those obtained from PSO and conventional P&O methods.

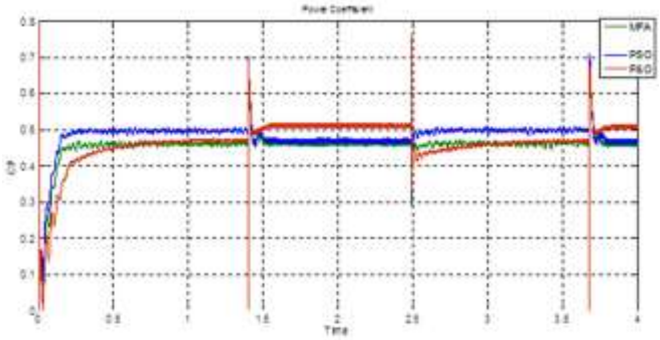
Table 2. PMSG and wind turbine simulation parameters

Items	Specification
Power rating	8.5 kW
Stator resistance	0.425 Ω
Stator inductance	0.0082 H
Pole pairs	10
PMSG flux	0.433 Wb
Turbine inertia	0.01197 kgm^2
Maximum Cp	0.48

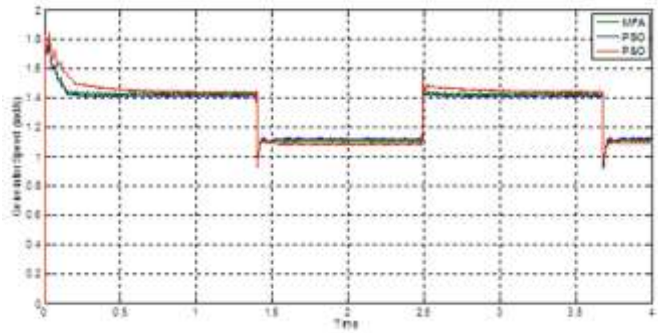
Figure 5 compares the performance for maximum power extraction of the proposed MFA with PSO and conventional P&O. The rectangular wind speed was simulated for 4 seconds with 7 m/s up to 9 m/s variation as shown in Fig 5(a). To get the maximum power under varying wind speeds, the WTS must work at maximum Cp. For time interval 0 < t < 1.4 s when wind speed is 9 m/s, MFA is able to operate the wind turbine to achieve an optimum *Cp* of 0.47 with faster response than that of P&O, while PSO produces *Cp* that exceeds 0.48. For time interval 1.4 s < t < 2.5 s when the wind speed changes to 7 m/s, MFA was able to maintain the wind turbine to operate at optimum *Cp* that is consistently better than those of PSO and P&O as depicted in Fig 5 (b). WTS can operate at maximum power while the generator speed follows the wind changes. Simulation results further indicate that MFA, PSO and P&O are able to adjust the generator speed to work at optimum speed and follow the changes in wind speed as pictured in Fig 5(c). However, based on generator speed response, MFA yields faster response than the other methods with P&O producing the worst response in following wind speed variation.



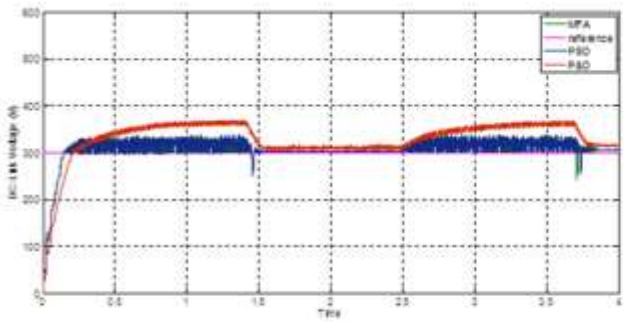
(a) Rectangular wind speed profile



(b) Power coefficient (*Cp*)



(c) Generator speed

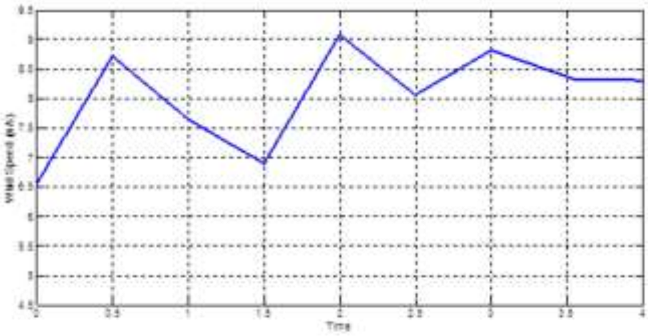


(d) DC link voltage

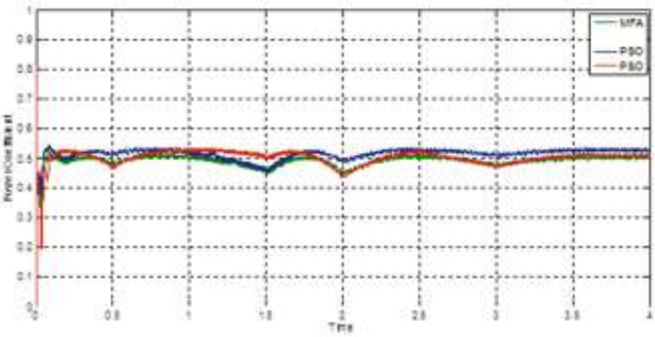
Fig 5. Simulation results of the proposed MFA with pulse wind speed

Simulation results as shown in Fig 5(d) prove that the grid side controller can maintain the DC link voltage under varying wind speed condition. The grid side controller uses a PI controller whose optimum parameters in the outer and inner loops are determined by the pole placement method. For the current control of grid side controller, the optimal parameters of the PI controllers are *Ti* of 0.001 and *Kp* of 1 while the control voltage has *Kp* = 100 and *Ti* = 10. The wind turbine with MFA for maximum power extraction can retain the DC link voltage at the set point of 300 V which is better than those obtained from PSO and conventional P&O.

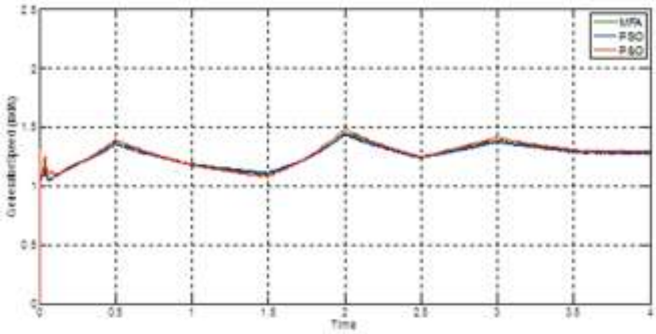
For the random wind speed profile test, wind speed variation from 6.5 m/s to 9 m/s was applied to the WECS system with the proposed MFA. Results from this test are presented in Fig 6 for the wind speed, power coefficient, generator speed, and DC link voltage. The proposed MPPT controller using MFA results in better performance than those of PSO and P&O. MFA is also able to maintain power coefficient that is better than the other two methods as shown in Fig 6(b). Figure 6 (c) shows the generator speed to change in wind speed, the greater the wind speed the greater the generator speed. At wind speed 9m/s yields generator speeds of 1.5rad/s. The DC link voltage can be maintained according to set point at 300 V under various wind speeds as illustrated in Fig 6(d). Figure 6 (e) shows the generator output power in which the output power is generated equals to the wind speed. The use of the P&O method results greater oscillation than the MFA and PSO methods. Compared to the other two methods, MFA produces better performance for the control of the DC link voltage which generates an Integral of Time and Absolute Error (ITAE) that is lower than those from the other two methods. For the random wind speed scenario, the ITAE value of the DC link voltage response is 15.15, compared with PSO and P&O which yield 39.22 and 276.2 respectively.



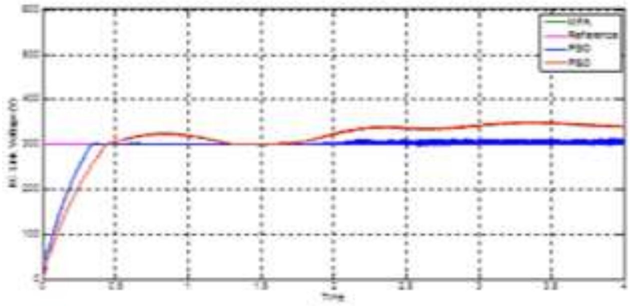
(a) Wind speed



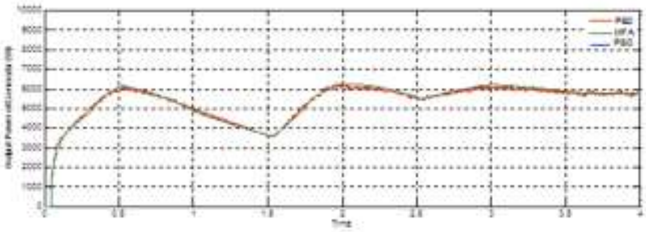
(b) Power coefficient



(c) Generator speed



(d) DC link voltage



(e) Generator Output Power

Fig 6. Simulation result of the proposed MFA with random wind speed

6. Experimental Results

The controller to extract maximum power using the proposed MFA algorithm was tested experimentally on a 500W WECS prototype as depicted in Fig 7 and Fig 8. The hardware model consists of a wind turbine emulator, a three phase diode rectifier, a boost converter, an MPPT controller and a resistive load. The wind turbine emulator consists of A-Y3-905 induction motors, a Schneider ATV61HU40N4 three phase variable speed drive and a 500W PMSG. The induction motors are controlled by the variable speed drive to drive the PMSG at a certain speed which is proportional to the wind speed. At a wind speed of 8 m/s, the generator will rotate at a speed of 600 rpm. The PMSG connects to the three phase diode rectifier and the boost converter. The MPPT controller with MFA algorithm sets the duty cycle of the boost converter to extract the maximum power. The performance of the proposed MFA algorithm was then compared with the conventional P&O method. Parameters and Specifications of the components used in the experiment are shown on Table 3.

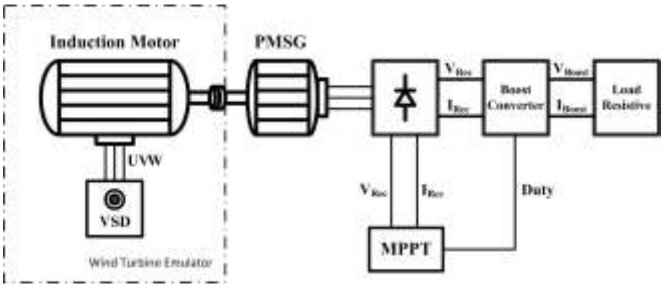


Fig 7. Block Diagram of WECS Hardware

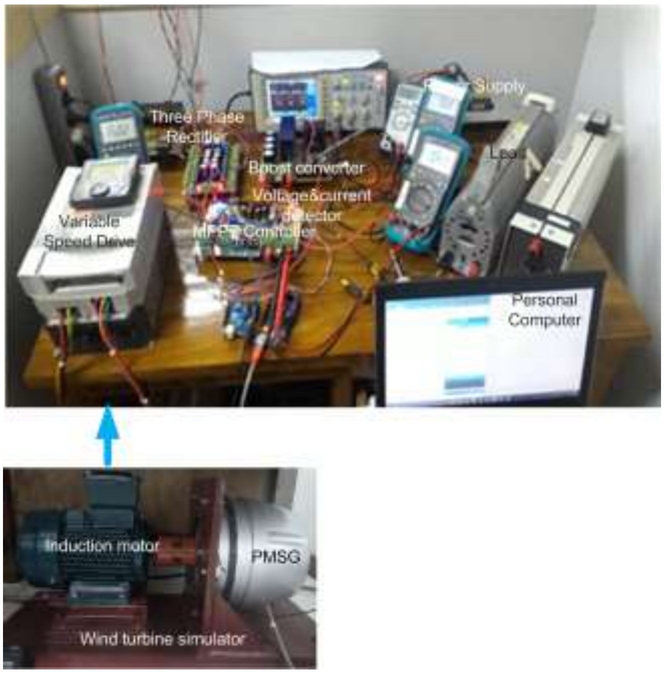


Fig 8. Experimental Setup

Table 3. Parameters and Specifications of the components used in the experiment

Permanent Magnet Synchronous Generator	
Rated power (w)	500
Rated rotation (rpm)	1000
Rated phase voltage (V)	160
Number of pole pairs	18
Stator phase resistance (Ω)	5.02
Induction Motor	
Output Power (kW)	1.5
Frequency (Hz)	50
D1-D6	SQL50A-100A
Optocoupler	FOD3182
Switch	IKW50N60T
Diode	VS-30EPH06PbF
Current Sensor	ACS754
Variable speed drive	Schneider ATV61HU40N4
D1-D6	SQL50A-100A
Optocoupler	FOD3182

To validate the performance of MFA, measurements were taken on the rectifier voltage and current without using the MPPT controller at several wind speeds and the speed of PMSG with load changes. For each wind speed, the load was subsequently increased and the generator speed was measured by a tachometer, and the rectifier output power which is equal to the boost converter input power was measured by a wattmeter. The results are the characteristic curves as shown in Fig 9.

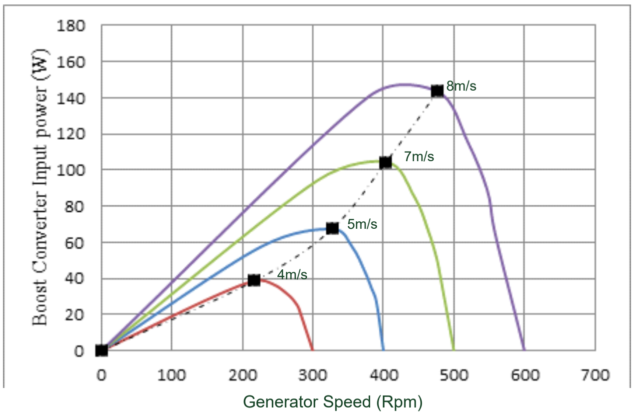


Fig 9. Real experimental characteristic curve of implemented WECS

The proposed MFA algorithm was tested by providing wind speed changes introduced by the wind turbine emulator as shown in Fig 10. The generated output power from the rectifier was measured and recorded on a personal computer as shown in Fig 11. The results show that the MPPT controller with the proposed MFA algorithm as well as the P&O method can track maximum power well. However, the MFA algorithm can extract maximum power greater than that of the P&O method. At a wind speed of 6 m/s and 7 m/s, the MPPT controller with MFA resulted in an average power 110.12W and 138.44W respectively. The conventional P&O method, on the other hand, generates an average power of 80.09W and 130.47W. Table 4 summarizes the characteristic curves resulted from the hardware test to compare the performance of MPPT power that can be extracted by the proposed MFA with the conventional P&O.

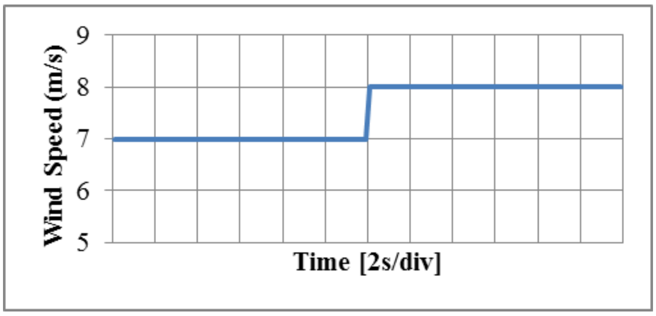


Fig 10. Wind Speed profile

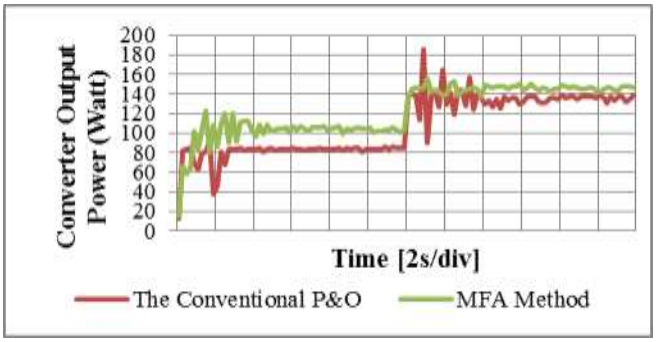


Fig 11. Experimental waveform of the converter input power extracted by the proposed controller

At a wind speed of 8m / s, the use of MFA as an MPPT algorithm produce an average power of 110.12W and maximum power of WECS based on the characteristic curve real measurement of 106.40W so that the efficiency of MPPT controller can be determined by the equation [27]

MPPT efficiency (%) =

$$\frac{MPPT\ extracted\ by\ MPPT\ Controller}{Real\ MPP\ Based\ on\ Characteristic} x\ 100 \qquad (23)$$

$$= \frac{100.12}{106.40} x\ 100 \ = 94.10\%$$

MFA algorithm has an average efficiency of 93.63% while the conventional P & O method only amounted to 81.54%.

Table 4. Parameter MPP based on real characteristic curve and MPP extracted by MPPT Controller

Wind speed (m/s)	Real MPP Based on characteristic (W)	MPP extracted by (W)		MPPT efficiency (%)	
		MFA	P&O	MFA	P&O
7	106.40	100.1	80.1	94.10	75.28
8	148.60	138.4	130.5	93.16	87.80
Average				93.63	81.54

7. Conclusion

A maximum power extraction for PMSG wind turbine system using the modified firefly algorithm has been presented. The proposed method offers the main benefit of not requiring wind speed measurement and wind turbine parameters. The proposed MFA described in this paper updates α while setting β at a constant value to obtain convergence quickly. Voltage and current from the generator side converter are taken by the MFA to get the maximum power through control the boost converter. Compared to PSO and P&O methods, the simulation results show successful tracking capability of the MFA to extract the maximum power from the PMSG wind turbine and to further maintain the DC link voltage at a constant set point value under wind speed change condition. The efficiency of PMSG wind turbine with MFA is 97.94 %, while with PSO and P&O produce 97.3 % and 93.75 % consecutively. MFA has been implemented in hardware as maximum power extraction on embedded system for control of a 500W lab-scale prototype of wind energy conversion system (WECS). Testing experiment demonstrates the use of MFA as MPPT controller algorithm generates greater efficiency compared with P&O method. In the future, MFA will be compared with PSO using one of statistical comparison methods and performance will be analyzed based on mean and variance results from multiple runs for each simulation. Additional, stability of the overall wind turbine system connected to grid will be discussed deeper to solve and to analyze in the near future.

Acknowledgments

The first author gratefully acknowledge the full financial support received from the Indonesian Ministry Research, Technology and Higher Education for the support this work.

References

[1] Huang C, Li F, Jin Z. “Maximum power point tracking strategy for large-scale wind generation systems considering wind turbine dynamics”. IEEE Trans. Ind. Electron. 62 (2015): 2530–2539.

[2] Soufi Y, Kahla S, Sedraoui M, Bechouat M. “Optimal control based RST controller for maximum power point tracking of wind energy conversion system”. Renewable Energy Research and Application (ICRERA), 2016 IEEE International Conference on IEEE, 20-23 Nov 2016.

[3] Kumar D, Chatterjee K. “A review of conventional and advanced MPPT algorithms for wind energy system”. Renew. Sustain. Energy Rev. 55 (2016): 957–970.

[4] Hong CM, Chen CH, Tungm CS. “Maximum power point tracking-based control algorithm for PMSG wind generation system without mechanical sensors”. Energy Conversion and Management. 69 (2013): 58-67.

[5] Harrouz A, Colak Ilhami, Kayisli K. “Control of A Small Wind Turbine System Application”. Renewable Energy Research and Application (ICRERA), 2016 IEEE International Conference on IEEE, 20-23 Nov 2016.

[6] Putri RI, Jasa L, Pujiantara M, Priyadi A, Purnomo MH. “Tuning PI controller based on multiobjective optimization approaches for speed control of PMSG wind turbine”. International Review of Automatic Control. 8 (2015): 315-321.

[7] Patel V, Kumar A, Chatterje K. “A review: maximum power extraction method in wind turbine system using different algorithm”. In: 2015 International Conference on Electrical, Electronics, Signals, Communication and Optimization (EESCO); 2015: pp. 1–6.

[8] Eltamaly AM, Farh HM. “Maximum power extraction from wind energy system based on fuzzy logic control”. Electr. Power Syst. Res. 97 (2013): 144–150.

[9] Ramos-Paja CA, A. Saavedra-Montes J, Arango E. “Maximum power point tracking in wind farms by means of a multivariable algorithm”. In: 2012

Workshop on Engineering Applications (WEA); 2012: pp. 1–6.

[10] Camara S.M, Camara B.M, Dakyo B, Gualous H. “Permanent magnet synchronous generator for offshore wind energy system connected to grid and battery modeling and control strategies”. International Journal of Renewable Energy Research 5. 2 (2015): 386 - 393.

[11] Cetinceviz Y, Uygun D, Demirel H. “Optimal Design and Verification of a PM Synchronous Generator For Wind Turbines”. International Journal of Renewable Energy Research 7. 3 (2017): 1324 -1332.

[12] Saad L, Hicham H, Khalid F. “Optimal tracking, modeling and control of aerogenerator based on PMSG driven by wind turbine”. Renewable Energy Research and Application (ICRERA), 2016 IEEE International Conference on IEEE, 20-23 Nov 2016..

[13] Ounnas D, Ramdani M, Cheniker S, Bouktir T. “A fuzzy tracking control design strategy for wind energy conversion system”. Renewable Energy Research and Application (ICRERA), 2016 IEEE International Conference on IEEE, 22-25 Nov 2015.

[14] Harrag A, Messalti S. “Variable step size modified P&O MPPT algorithm using GA-based hybrid offline/online PID controller”. Renew. Sustain. Energy Rev. 49 (2015): 1247–1260.

[15] Kortabarria I, Andreu J, Martínez de Alegría I, Jiménez J, Gárate JI, Robles E. “A novel adaptative maximum power point tracking algorithm for small wind turbines”. Renew. Energy. 63 (2014): 785–796

[16] Daili Y, Gaubert JP, Rahmani L. “Implementation of a new maximum power point tracking control strategy for small wind energy conversion systems without mechanical sensors”. Energy Convers. Manag. 97 (2015): 298–306.

[17] Kahla S, Soufi Y, Sedraoui M, Bechouat M. “On-Off control based particle swarm optimization for maximum power point tracking of wind turbine equipped by DFIG connected to the grid with energy storage”. Int. J. Hydrog. Energy. 40 (2015): 13749–13758.

[18] Amine HM, AbdelazizH, Najib E. “Wind turbine maximum power point tracking using FLC tuned with GA”. Energy Procedia. 62 (2014): 364–373.

[19] Venkataraman A, Maswood AI, Rahman SN, Gabriel O. “A Novel maximum power point tracking algorithm for a stand-alone unity power factor wind energy conversion system:. Renewable Energy Research and Application (ICRERA), 2013 IEEE International Conference on IEEE, 20-23 Oct 2013.

[20] Abdullah MA, Yatim AHM, Tan CW, Samosir AS. “Particle swarm optimization-based maximum power point tracking algorithm for wind energy conversion system”. In: 2012 IEEE International Conference on Power and Energy (PECon) 2012: pp. 65–70.

[21] Chakrabarti T, Sharma U, Manna S, Sarkar SK. “Design of intelligent maximum power point tracking (MPPT) technique based on swarm intelligence based algorithms”. In: 2015 International Conference on Power and Advanced Control Engineering (ICPACE) 2015: pp. 173–177.

[22] Sundareswaran K, Peddapati S, Palani S. “MPPT of PV systems under partial shaded conditions through a colony of flashing fireflies”. IEEE Trans. Energy Convers. 29 (2014): 463–472.

[23] Aissaoui AG, Tahour A, Essounbouli N, Nollet F, Abid M, Chergui M I. “A Fuzzy-PI control to extract an optimal power from wind turbine”. Energy Convers. Manag . 65 (2013): 688–696.

[24] Fister I, Fister Jr I, Yang XS, Brest J. “A comprehensive review of firefly algorithms”. Swarm Evol. Comput. 13 (2013): 34–46.

[25] Massan SR, Wagan AI, Shaikh MM, Abro R. “Wind turbine micrositing by using the firefly algorithm”. Appl. Soft Comput. 26 (2015): 450–456.

[26] Setiawan I, Facta M, Priyadi A, Purnomo MH. “Investigation of symmetrical optimum PI controller based on plant and feedback liniearization in grid tie inverter systems”. International Journal of Renewable Energy Research 7. 3 (2017): 1228 - 1234.

[27] H. Fathabadi, “Novel high efficient speed sensorless controller for maximum power extraction from wind energy conversion systems,” Energy Convers. Manag., vol. 123(2016): 392-401.