

Improvement of perturb and observe method for maximum power point tracking in wind energy conversion system using fuzzy controller

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ABSTRACT

One of the main problems in wind energy conversion system (WECS) is how to achieve maximum output power in different wind speeds. Maximum methods for maximum power point tracking in wind energy conversion systems require the knowledge of system characteristics and mechanic sensors. So, using these methods practically will follow with high price and an abundant difficulties. In this paper, new method for maximum power point tracking based on fuzzy controller has been presented that is maximum power point tracking with high power coefficient without requiring mechanical sensors and knowing system characteristics. Wind energy conversion system is simulated by using tracking system based on fuzzy controller in MATLAB/SIMULINK and simulation results prove the advantages of suggested tracking method such as increase of power coefficient in wind turbine and decrease of fluctuations about maximum power point.

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1. Introduction

A lot more attention should be paid to the use of renewable energy resources because of a growing energy demand, limitations of fossil fuel resources, and pollution caused by the burning of fossil fuel [1, 2]. Among renewable energy, wind energy is the most economic means for producing electricity [3, 4]. Owing to turbine specifications and quick changes in wind, it is possible to harness the optimum wind energy in WECS through wind turbine action in the case of variable speed [5, 6]. In recent decades, several methods have

been presented for controlling the maximum power point tracking [7, 8]. Many of these methods require knowledge of system specifications and mechanical sensors such as anemometers. This raises WECS cost and decreases accuracy as a result of approximation regarding wind generator characteristics. So, extensive research has been done to improve tracking-control methods of the maximum power point without the need for wind speed measurement, knowledge of system specifications, and the mechanical parameters of turbines to reduce cost and increase efficiency [9,10].

An algorithm of tracking the maximum

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power available in the WECS for DC micro-grid application is proposed in [10], which is independent of the machine and wind-turbine parameters. An analysis of the performance of MPPT in a grid connected to the PMSG-based WECS using a linear relationship between optimum speed and wind velocity to increase the speed of the controller response is presented in [11], which the generator side converter is used to track the maximum wind power through field oriented control. An MPPT technique, based on DC current as the perturbing variable for small-scale WECSs, is proposed in [12], with the algorithm using two modes of operation: a perturb and observe mode, and a prediction mode.

As a whole, there are three tracking methods of the maximum power point in the WECS. These methods are wind speed measurement (WSM) [13], power signal feedback (PSF) [14, 15], perturbation and observation (P&O) or hill climbing search (HCS) [16]. Figure 1 shows a WECS by control method, based on wind speed measurement.

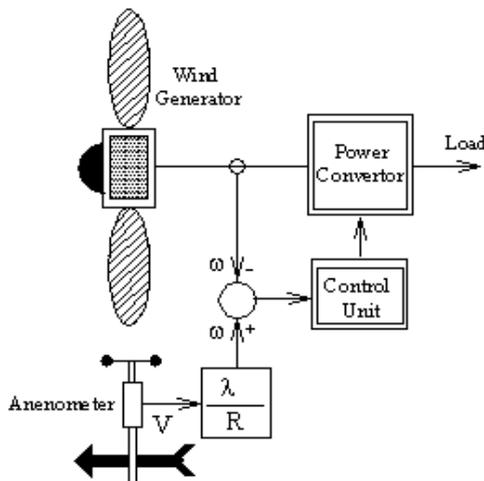


Fig. 1. Control system based on wind speed measurement method

In the wind speed measurement method, the measured wind speed and required rotor speed for achieving the maximum power generation will be calculated. In addition, measured actual rotor speed is compared with the calculated optimum rotor speed and the resulting error is used for controlling a power converter. The wind speed measurement method has good efficiency with quick response capabilities. But it requires an accurate anemometer, thus increasing the cost of the system, while decreasing the accuracy of the system [17].

In [20], the power signal feedback method used for the maximum power point tracking in WECSs is dealt with. In the power signal feedback method, the optimum power characteristics of a wind generator versus rotor speed are preserved in a micro-controller memory. The optimum power output of a wind generator is calculated on the basis of turbine output power characteristic and is compared with measured actual power output. The resulting error is used for controlling a power converter. In [21] the wind speed measurement method has been used for maximum power point tracking in WECS.

Figure 2 shows a control system based on the power signal feedback method. The main problem with this method is that the power curve versus angular speed of turbine should be determined through simulation or practical test. So, this is a difficult and expensive method to use.

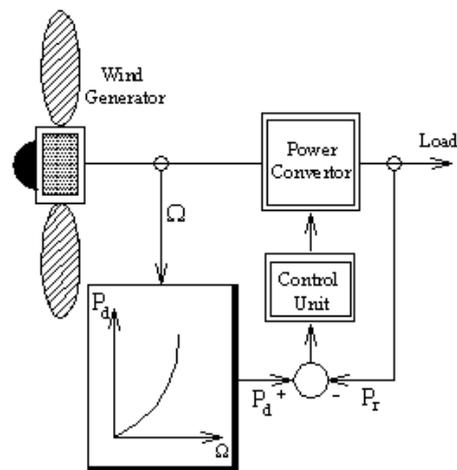


Fig. 2. Control system based on power signal feedback method

Figure 3 shows a control system based on the perturbation and observation method. In [18] and [19] the perturbation and observation method has been used for the maximum power point tracking in WECSs. In the perturbation and observation method, rotor speed changes, and output power is observed in order to regulate the next change in rotor speed. Perturbation and observation method regulates turbine speed according to a comparison result between calculated output powers consecutively in wind generator.

The perturbation and observation tracking method has high certainty, low complexity, and low cost because it does not require an accurate anemometer to measure wind speed, and there is also no need to have knowledge

of the system specifications [20]. So, among the mentioned tracking methods, the perturbation and observation tracking method is the best choice for the maximum power point tracking in WECS.

In this paper, by presenting proper suggestions, the problem of the perturbation and observation method has been removed and a complete system has been achieved for the maximum power point tracking in WECSs. To remove the present problem in perturbation and observation tracking method, the suggestion of using a variable changes step for constant changes has been made to change the angular speed of the turbine and a tracking method has been presented, based on fuzzy controller to get the maximum output power energy conversion system. Specifications of the suggested maximum power point tracking method is an increase of the power coefficient in wind turbine and a decrease in fluctuations about the maximum power point in addition to an absence of need for knowledge of optimum power characteristics in wind generator and wind speed measurements.

2. Wind System Model

Parts of a WECS are a wind generator, diode rectifier DC-DC, generator and tracking

control system [21, 22]. Figure 4 shows the general structure of a WECS. A wind generator consists of a wind turbine connected to a permanent magnet synchronous generator [23].

2.1. Wind Turbine

Output power of wind turbine changes proportionally to wind speed. Owing to non-linear turbine specifications, maintaining the maximum power output is difficult under all circumstances of wind speed. Figure 5 shows the output power specification of a wind turbine versus angular speed of wind turbine [23,29].

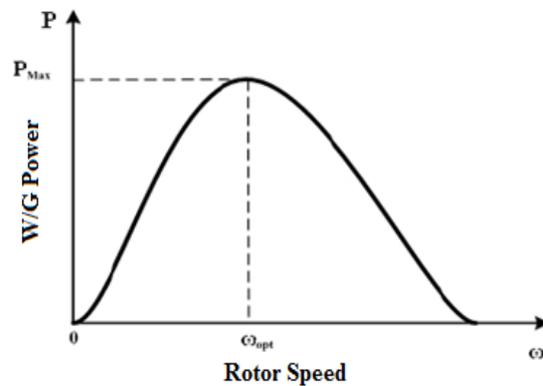


Fig. 5. Typical turbine power as function of the shaft rotating speed

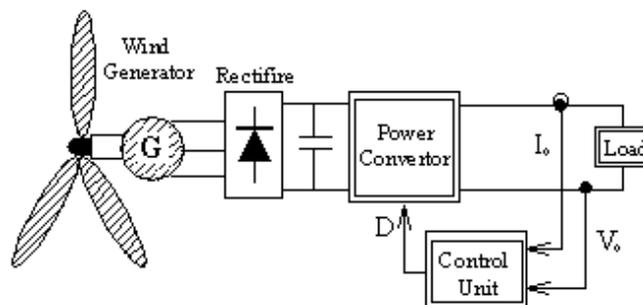


Fig. 3. Control system based on the perturb and observe method

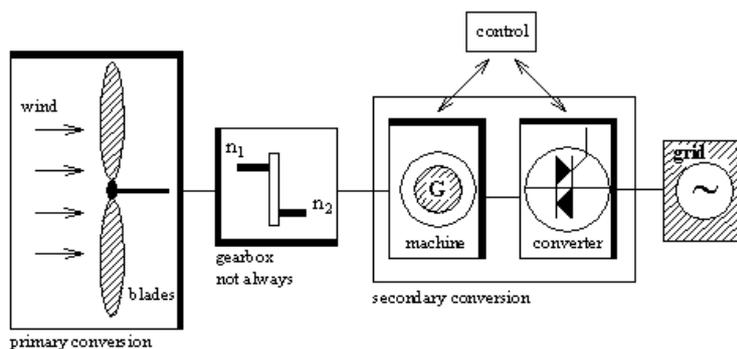


Fig. 4. Structure of wind energy conversion system

According to output power specification versus rotor speed of wind turbine, a wind turbine will have different output of power for different rotor speeds in each specific wind speed. So, based on this specification, there is an optimum wind turbine rotor speed in each specific wind speed producing the maximum power in each specific wind speed. The kinetic energy produced by wind is expressed as follows [30]:

$$E_k = \frac{1}{2}mv^2 \tag{1}$$

where E_k is kinetic energy, m is air mass and v is wind speed. Mass m is expressed as follows:

$$m = \rho(Ad) \tag{2}$$

where ρ is air density (kg/m^3), A is the swept area of the rotor blade (m^2) and d is the distance travelled by the wind (m). Wind turbine output power (P_w) is defined as follow [31,32]:

$$P_w = \frac{E_k}{t} = \frac{\frac{1}{2}\rho(Ad)v^2}{t} = \frac{1}{2}\rho AV^3 \tag{3}$$

The expressed power in (3) is the ideal power received by a wind turbine. Actual power of the wind turbine depends on turbine power coefficient shown by $C_p(\lambda,\beta)$. The power coefficient function is dependent on two factors: the tip-speed ratio (λ), and the pitch angle (β) [33]. A non-linear function of the tip-speed ratio and angle of blade pitch is expressed as follows [24, 25]:

$$C_p(\lambda, \beta) = c_1 \left(\frac{c_2}{\lambda_i} - c_3\beta - c_4 \right) e^{-\frac{c_5}{\lambda_i} + c_6\lambda} \tag{4}$$

$$\lambda_i = \left[\frac{1}{\lambda + c_7\beta} - \frac{c_8}{\beta^3 + 1} \right]^{-1} \tag{5}$$

The power coefficient curve has been described by different fitted equations in the papers. The coefficients C_1 - C_8 are shown in Table.

Tip-speed ratio (λ) expresses the ratio between angular speed of turbine blade tip

and the wind speed, and is defined as follows [26, 27]:

$$\lambda = \frac{\omega R}{v} \tag{6}$$

ω is the angular speed of the turbine (rad/s) and R is the turbine radius (m). So, actual power received by wind turbine is expressed as follow:

$$P_w = \frac{1}{2} C_p(\lambda, \beta) \rho AV^3 \tag{7}$$

Figure 6 shows the power coefficient curve of a wind turbine (C_p) versus tip-speed ratio (λ) for different blade pitch. According to Fig. 6, it is observed that, for a constant pitch angle, the maximum power coefficient is achieved when the tip-speed ratio attains an optimum value. The power coefficient of wind turbine for a value of optimum tip-speed ratio is the maximum and equals 0.48 when the angle of blade pitch is zero.

If air density (ρ), swept area (A) and wind speed are constant, the output power will be a function of power coefficient in wind turbine. So, to achieve the maximum output power, the power coefficient should be the maximum, requiring λ_{opt} .

2.2. Permanent Magnet Synchronous Generator

PMSG in wind energy applications, because of motivation specification, is able to work with high power coefficient and high efficiency and gets greater consideration. The main advantage of using a permanent magnet synchronous generator is the ability of functioning wind speeds with great trouble. Using permanent magnet synchronous generator presents an optimum solution for wind turbines with variable speeds. Equations of torque and voltage in a steady state of a permanent magnet synchronous generator are expressed as follow [28]:

$$E = K_e \omega_m \tag{8}$$

$$T_e = K_t I_a \tag{9}$$

Table 1. Coefficients C_1 - C_8

C_1	C_2	C_3	C_4	C_5	C_6	C_7	C_8
0.5176	116	0.4	5	21	0.0068	0.08	0.035

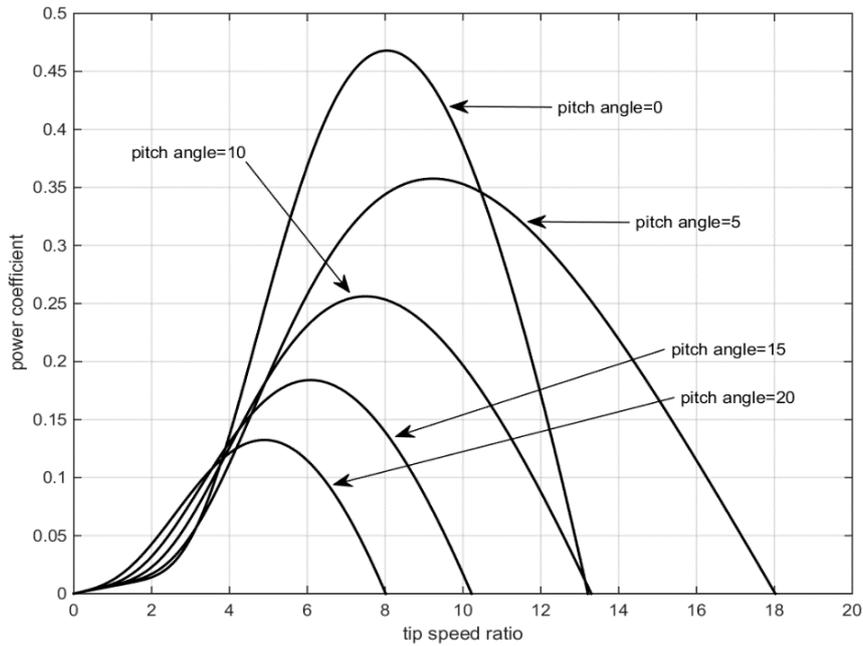


Fig. 6. Power coefficient as function of the tip-speed ratio

T_e is electromagnetic torque of the generator, E is induced voltage, I_a is armature current and ω_m is angular speed of rotor. According to (8) and (9), it is found that induced voltage in generator is proportional to angular speed of rotor. So, it is possible to control the angular speed of a rotor by controlling the voltage of a permanent magnet synchronous generator. This subject is the basis of maximum tracking methods in maximum power point.

2.3. Boost Converter

In WECSs, it is possible to control the angular speed of a rotor by controlling the voltage of a permanent magnet synchronous generator. It requires the use of a DC-DC converter in WECS to control output voltage of generator by regulating duty cycle of the converter. The used converter is a boost converter. The basic circuit of a boost converter has been shown in Fig. 7.

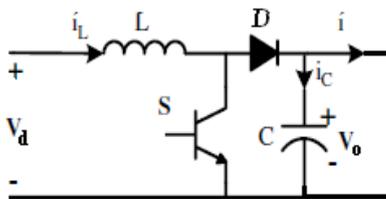


Fig. 7. Basic circuit of boost converter

The relation between input voltage and output voltage of a boost converter is expressed as follow [29]:

$$V_o = \frac{1}{1-D} V_d \tag{10}$$

where V_d is input voltage, V_o is output voltage, D is duty cycle of the converter.

2.4. Control System Based on Perturbation and Observation Method

Received power of WECSs from wind energy is not only dependent wind specifications but also on the control method used in the WECS [9, 23]. Extensive researches have been done on tracking methods of the maximum power output in WECS. Among the tracking methods, the perturbation and observation method is the best choice for maximum power point tracking in WECSs because of some specifications such as high confidentiality and low complexity and cost. This method is based on creating changes in rotor speed of turbine with constant pitches and observing changes in power. In permanent magnet synchronous generator, the output voltage is proportional to rotor speed. So, a change in the output voltage of the generator causes change in the rotor's angular speed. Voltage change is accomplished by regulating the duty cycle of a DC-DC converter. Figure 8 shows the maximum power point tracking algorithm in perturbation and observation method. In this algorithm, in addition to power change, the way of changing the speed in the previous status is considered for determination of changing the speed in next status.

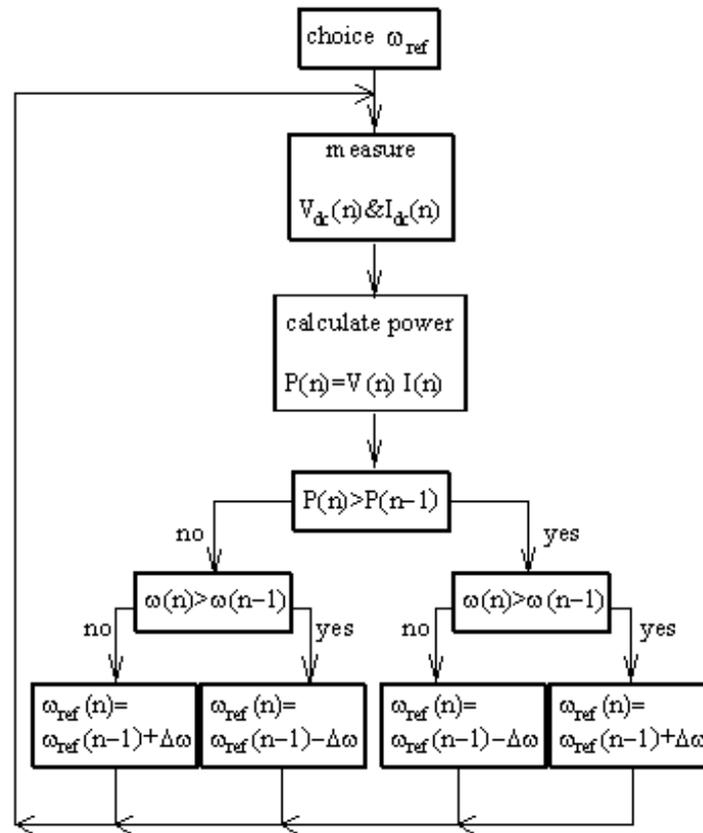


Fig. 8. Maximum power point tracking algorithm based on the perturb and observe method

According to the expressed algorithm, tracking method of perturbation and observation in each wind speed is that of controlling the output voltage surface of the generator and, consequently, controlling angular speed of turbine in tracking the maximum output power point. So, a change in the duty cycle of the converter changes the output voltage of the wind generator. The output power is then observed and increases or decreases of output voltage in wind generator will be noted in the next status. If increase of output voltage in wind generator causes increase of power, the output voltage of the wind generator will increase in the next status and vice versa [9, 27].

There is a major problem in the perturbation and observation method that influences its efficiency. This problem is the presence of an inverse relation between efficiency and the convergence speed of the control method [21]. In the tracking method of the conventional perturbation and observation method, changes in the pitch is constant. So, if the rate of changes in the pitch is high, the convergence speed increases but efficiency decreases because of fluctuations in the maximum power point, and if the role of

pitch changes is small, fluctuation in the maximum power point decreases, leading to a decrease in the convergence speed, without hampering the disturbance control method and observation in the maximum power point and fluctuations, as disturbance and observation control method is an inevitable specification.

3. Control System Design on Fuzzy Controller

The suggested solution in this paper uses a variable changing pitch instead of a constant changing pitch in the perturbation and observation method. By using a variable changing pitch in the perturbation and observation tracking method, it is possible to solve this problem and, in this respect, a higher convergence speed is achieved, increasing the method efficiency. In this regard, we use a fuzzy controller to determine the variable pitch. A tracking control method, based on a fuzzy controller, has the same reason as that of the perturbation and observation method that uses changes of duty cycle in the converter for the maximum power point tracking. The block diagram of the suggested tracking method has been shown in Fig. 9.

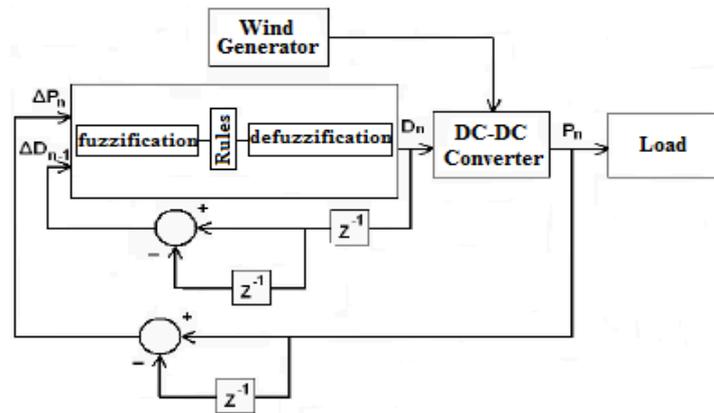


Fig. 9. Block diagram of maximum power point tracking system based on fuzzy controller

In this method, the inputs are output power changes of turbine and changes of duty cycle in the converter, and the output is the duty cycle of the converter. The fuzzy rules used in the fuzzy controller are shown in Table 1. In this Table:

- nl: high negative, nm: medium negative, ns: small negative, z: zero, ps: small positive, pm: medium positive, pl: large positive
- vs: very small, ms: medium small, bav: below average, av: average, aav: above average, ml: medium large, vl: very large.

In the fuzzy controller method, changes in output power and changes in converter duty cycle are observed in each moment and identified by using the rule Table and membership functions, and, by applying a fuzzy extractive method of duty cycle for the converter in the next status.

4.Simulation Results

In order to scrutinize the proficiency of the suggested maximum power point tracking method, WECS, like in Fig. 4, is first simulated by a conventional perturbation and observation tracking method in MATLAB/SIMULINK and output specifications are studied [40]. Then, the system is simulated by

a tracking method, based on fuzzy controller and the simulation results are compared with the conventional method. WECS includes a wind turbine, permanent magnet synchronous generator, diode rectifier and DC-DC converter. Power capacity and parameters of wind turbine is shown in Table 2 and specifications of permanent magnet synchronous generator is shown in Table 3 [21]. By coding in Matlab software, the maximum power point tracking system has been operated by two conventional perturbation and observation methods and a method based on fuzzy controller. Angular speed curves of wind turbine for different wind speeds and by conventional perturbation and observation tracking method is shown in Fig. 10, which shows that the use of a conventional perturbation and observation tracking method in WECSs decreases convergence speed.

Table 2. The Parameters of the Wind Turbine

Parameter	Value
Rated Power	1 Kw
Rated Wind Speed	9 m/s
Pitch Angle	0 deg
Optimum Power Coefficient	0.48

Table 1. Fuzzy Rule

$\Delta D_n / \Delta P_n$	Nl	nm	Ns	z	Ps	pm	pl
nl	Vl	vl	ml	bav	Ms	vs	vs
nm	Vl	ml	aav	bav	Bav	ms	vs
ns	Ml	aav	aav	av	Bav	bav	vs
z	Vs	ms	bav	av	Aav	ml	vl
ps	Ms	bav	bav	av	Aav	aav	ml
pm	Vs	ms	bav	aav	Aav	ml	vl
pl	Vs	vs	ms	aav	Ml	vl	Vl

Table 3. The Parameters of Permanent Magnet Synchronous Generator

Parameter	Value
Rated power	1 kW
Stator resistor	0.318 Ω
D-axis inductance	4.04 mH
Q-axis inductance	5.28 mH
Rotor flux	0.26 Wb
Inertia	0.0078 Kg.m ²
Number of pole	4

Angular speed curves of wind turbine for different wind speeds and tracking method based on fuzzy controller is shown in Fig. 11. As has been seen in Fig. 11, the use of a tracking system based on fuzzy controller increases the convergence speed. To compare the proficiency of the two methods, power coefficient curves of wind turbine and the output power of wind turbine has been shown for the two tracking methods in Fig. 12. As has been seen in Fig. 12, by using tracking system based on perturbation and observation method, power coefficient of wind turbine with optimum rate that is 0.48 is so far. Fluctuations in the maximum power point increased and convergence speed decreased. So, the received power of the wind turbine will not be the maximum from wind energy. The reason is the use of a constant changing pitch to change the duty cycle of the converter in order to regulate turbine rotor speed. By using a tracking system based on a fuzzy controller, power co-efficiency of wind turbine increases and approaches its maximum rate. So, received power of wind turbine for each wind speed increases by using a fuzzy controller method, and fluctuations in turbine's output power decreases the maximum power point by using the suggested method. So the suggested method efficiency is more than in the conventional perturbation and observation method. Moreover, by changing the wind speed, the system's output power will approach the maximum rate by using a tracking method, based on a fuzzy controller with high speed.

5. Conclusion

In this paper, a new method of maximum power point tracking with a modified perturbation and observation method with

variable pitch has been presented for WECS with variable speed. This method is independent of turbine and generator specifications. The suggested maximum power point tracker to decrease cost and increase system confidentiality does not have any mechanical sensor. Results of simulation showed that the suggested maximum power point tracking method could automatically search for optimum points and, by reducing fluctuations in maximum power point, and increase of convergence speed, tracks the maximum output power for changes in climatic circumstances such as variations in wind speeds.

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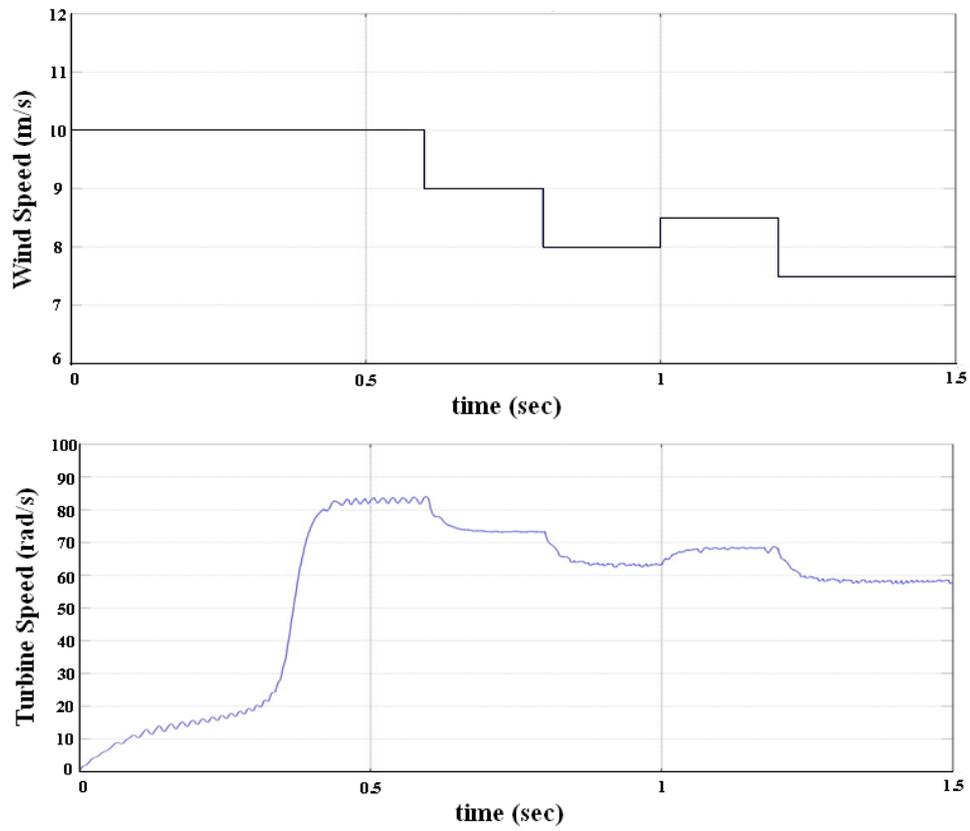


Fig. 10. The curve of rotor speed versus time

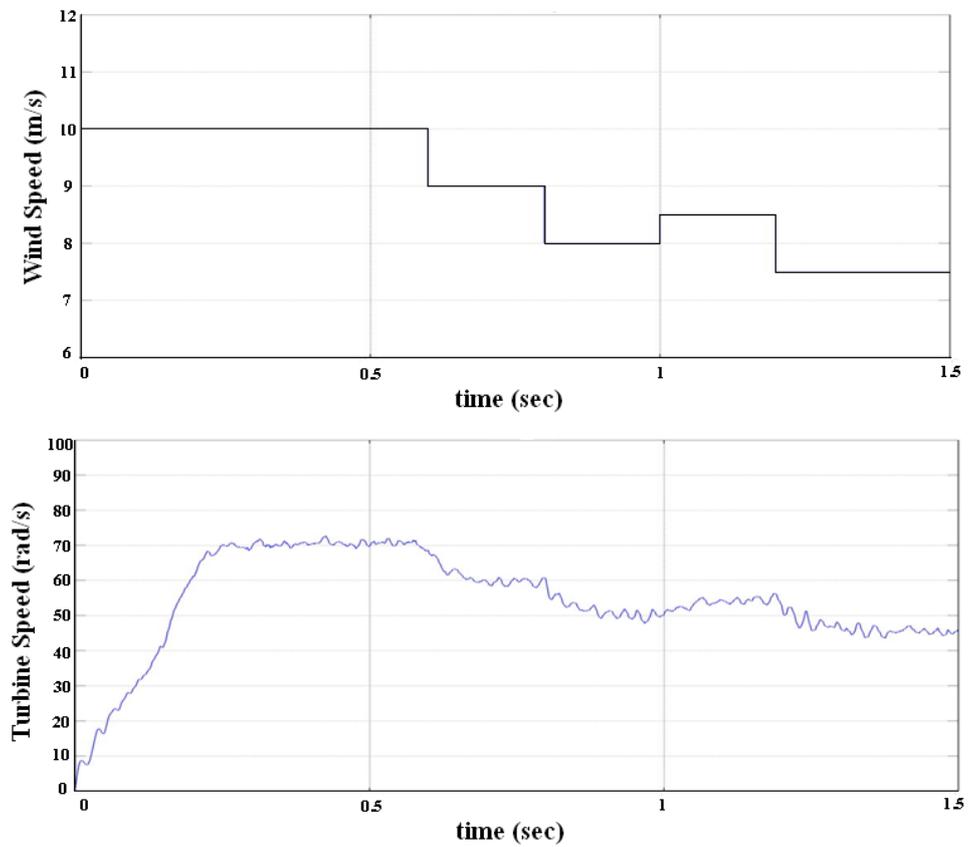


Fig. 11. The curve of rotor speed versus time

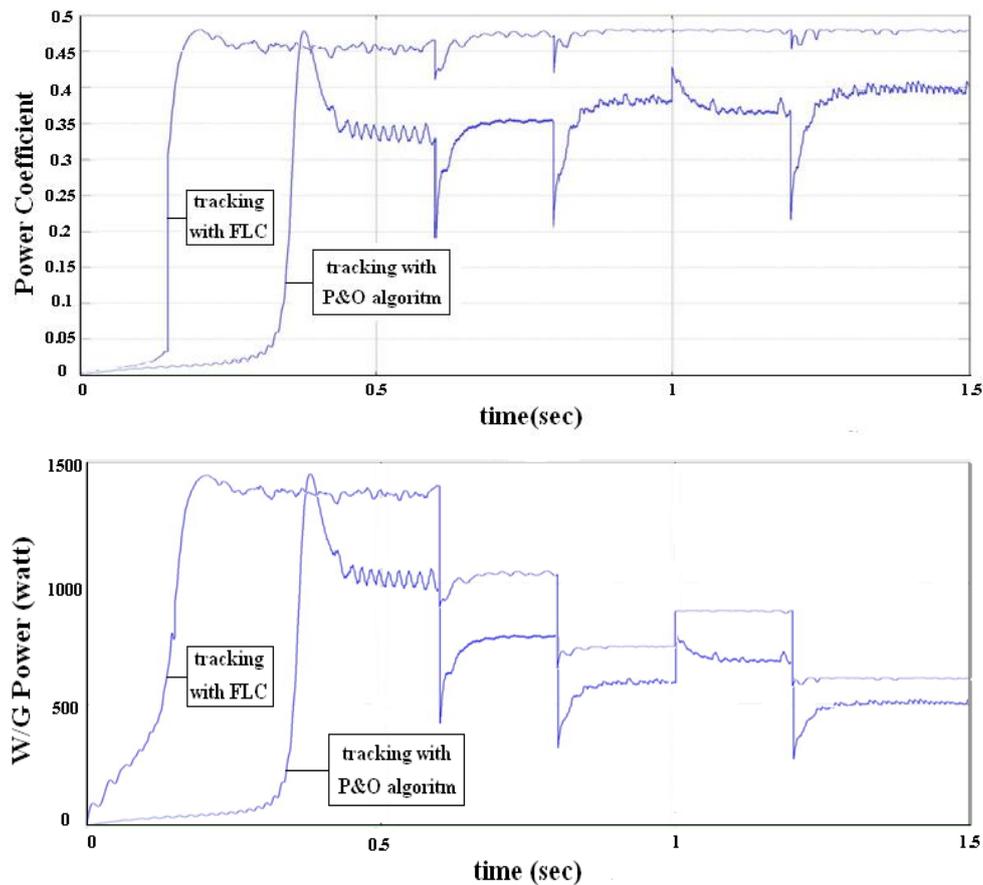


Fig. 12. The curves of power coefficient and output power of wind turbine versus time

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