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Maximum Power Point Tracking of Wind Energy Conversion System using Fuzzy- Cuckoo Optimization Algorithm Strategy

Mohammad Sarvi[1], Mohammad Parpaei[2]

[1] Electrical Engineering Department, Imam Khomeini International University, Qazvin, Iran. Email: sarvi@eng.ikiu.ac.ir
[2] Electrical Engineering Department, Imam Khomeini International University, Qazvin, Iran. Email: parpaei@edu.ikiu.ac.ir

Abstract

Nowadays the position of the renewable energy is so important because of the environment pollution and the limitation of fossil fuels in the world. Energy can be generated more and more by the renewable sources, but the fossil fuels are non-renewable. One of the most important renewable sources is the wind energy. The wind energy is an appropriate alternative source of fossil fuel. The replacement rate of renewable energy to fossil fuels is rising, although the production cost is higher than fossil fuels. To further reduce cost of wind production, many methods have been proposed. One of the suitable approaches is the maximum power point tracking strategy. In this paper, a new intelligent maximum power point tracker called Fuzzy- Cuckoo strategy for small- scale wind energy conversion systems is proposed. The maximum power point tracker proposed uses measured wind speed to detect the maximum output power and its respective optimal rotational speed. The main contribution of the proposed approach is to exactly track the maximum power point, so the output power fluctuations captured by wind turbine are less than conventional approaches. The simulations are performed in MATAL/SIMULINK software. The superiority of the proposed approach is validated in two situations, low and rapid changes in wind speed. The maximum power point of wind energy conversion systems can be tracked by the proposed approach in any situation. The higher accuracy of the Fuzzy- cuckoo strategy than the conventional trackers is another advantage of the proposed approach.

Keywords: Intelligent controller, Metaheuristic optimization approach, Wind energy conversion systems.

1. Introduction

Fossil fuel reserves reduction causes that the whole countries, especially the countries that have not enough fossil fuel sources, pay special attention to the renewable energy as a second energy source. China and USA are two countries that concentrate on the wind energy conversion systems (WECS) than other countries. WECSs are used to change the wind energy to electrical energy by electrical machines such as the permanent magnet synchronies generators (PMSGs). The small- Scale WECSs are suitable alternative sources for urban regions or remote places that connection to power grid is impossible [1]. The main disadvantage of the renewable energy is that the electricity production costs from various renewable energy sources are higher than fossil fuel. To improve this problem, maximum power point tracking (MPPT) is a matter that is expressed. The maximum power point trackers control the WECSs at the optimal output power. There are many approaches to track the maximum power point, but all approaches are based on three main classifications. The first strategy is the methods based on iteratively search, the second strategy is the methods based on the static parameters of the wind turbine and wind speed, and the third strategy is the methods based on hill- climb searching (HCS) control. The many approaches have been proposed to implement the maximum power point trackers in the WECSs. Reference [2] presents a relationship between DC electrical variables and mechanical variables of turbine. Reference [3] proposes an alternative approach using mechanical model of the permanent magnet synchronous generator (PMSG) in order to estimate both position and speed of the wind turbine. Reference [4] develops a new approach using perturb and observe (P&O) and optimum relationship– based (ORB). Reference [5] presents a modified MPPT controller using Fuzzy logic controller (FLC). Reference [6] proposes a new MPPT approach using neural networks (NNs) for modeling of wind turbine systems and NNs describe relationship between input and output. Reference [7] introduces a novel approach of radial basis function neural network (RBFNN) and particle swarm optimization (PSO). Reference [8] presents a two stages MPPT approach. In the first stage, the large iterative steps and in the second stage, the conventional P&O have been used to exactly track the maximum power point. Reference [9] describes a direct control using output observation and directly adjusting duty cycle of boost converter. Reference [10] develops a control strategy for the generator side converter with output maximization of a PMSG. Reference [11] present a new maximum power point tracking based on adaptive neuro- fuzzy interface system (ANFIS). Reference [12] presents a new MPPT strategy based on Wilcoxon radial basis function network (WRBFN) with hill-climb searching (HCS). Reference [13] proposes a new sensorless control strategy based on a model reference adaptive system (MRAS) observer for estimating the rotational speed. Reference [14] proposes a new adaptive intelligent optimization algorithm that uses a new advance P&O to detect the maximum power point. Reference [15] uses a new approach to estimate position and speed of the wind turbine in order to track the maximum power point. In reference [16], the rotor position is estimated based on the flux linkage.

In this paper, a novel strategy based on an intelligent optimization algorithm, namely Cuckoo optimization algorithm (COA), and the fuzzy logic controller is proposed. The proposed approach is based on the optimum relationship- based (ORB). The main contribution of the proposed approach is to exactly track the maximum power point, so the output power fluctuations captured by wind turbine are less than the conventional approaches such as PSO and fuzzy logic trackers. The higher accuracy of the Fuzzy- Cuckoo strategy than the conventional trackers is another advantage of the proposed approach.

This paper has been organized as follows: section 2 describes the wind energy conversion system. Section 3 introduces the Cuckoo optimization algorithm. Section 4 presents the proposed maximum power point tracker. The simulation results in several case studies are given in Section 5, and finally section 6 states the conclusion.

2. Description of Wind Energy Conversion System

The proposed approach will be applied to the following WECS as Figure 1. As shown in Fig.1, PMSG is coupled to a wind turbine. The mechanical output power is transferred to the electrical power by PMSG. The AC electrical power produced by PMSG will be rectified by a three-phase diode bridge rectifier, and the rectified power is fed to the boost converter.

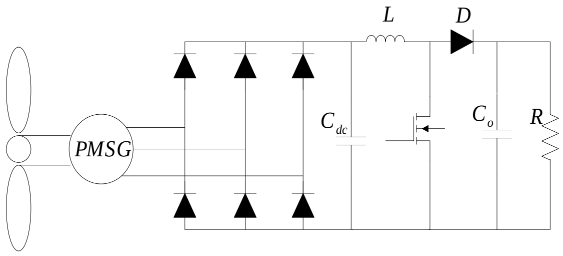

Fig.1. Wind energy conversion system

2.1. Wind Energy Conversion System Characteristics

The output power derived by the wind turbine blades is expressed as [16]:

$$P = \frac{1}{2} \times A \times \rho \times C_p \times V_\omega^3 \quad (18)$$

Where P is the output power (in watt), ρ is the air density (in kg/m^3), C_p is the power coefficient, and V_ω is the wind speed (in m/s). A is area swept by the blades (in m^2) determined as:

$$A = \pi \times R^2 \quad (19)$$

Where R is radius of blades (in m).

Power coefficient C_p is a nonlinear function of the pitch angle β and tip speed ratio λ as follows:

$$C_p = 0.5176\left(116\left(\frac{1}{\lambda_i}\right) - 0.4 \times \beta - 5\right) \times \exp\left(-21\left(\frac{1}{\lambda_i}\right)\right) + 0.0068\lambda \quad (20)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08 \times \beta} - \frac{0.035}{\beta^3 + 1} \quad (21)$$

$$\lambda = \frac{R\omega_t}{V_\omega} \quad (22)$$

Where λ is the tip speed ratio (TSR), β is the pitch angle (in degree), and ω_t is the rotational speed of turbine (in rps).

Fig.2 shows the output power captured by wind turbine versus rotational speed. According to this figure, the output power function has a one global optimum point, and it is a non-linear function of the rotational speed.

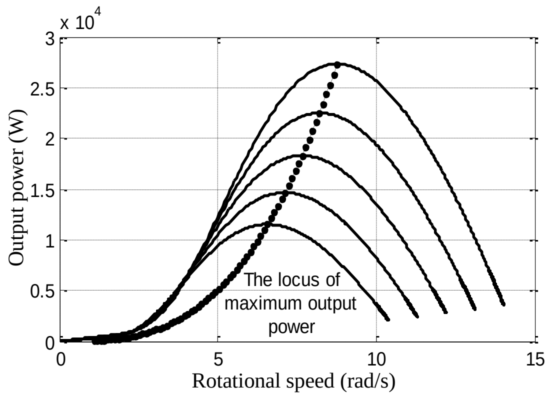

Fig.2. Output power versus rotational speed

3. Cuckoo Optimization Algorithm

Cuckoo optimization algorithm (COA) is a new intelligent evolutionary algorithm that is proper for continuous non- linear problems. It is inspired by the special kind of bird called Cuckoo. The superiority of COA has been proven than particle swarm optimization (PSO) and genetic algorithm (GA) by [17]. The main advantage of the COA is that this optimization algorithm is robust to dynamic changes. The special lifestyle of Cuckoo has been formulated as an optimization algorithm in order to fine the maximum/minimum value of objective functions. The following section meticulously describes the COA.

To start the optimization process, it is necessary to initialize the starting points as an array. Each of the evolutionary optimization algorithms specifies a special name for this array. For instant, in PSO, DE, GA this array is called "Particle Position", "Stochastic Population", and "Chromosome", respectively. In cuckoo optimization algorithm, this array is also called "Habitat".

In order to solve a N- dimensional optimization problem, we need to form an array of 1×N as follows:

$$x_i^t = (x_{1i}^t, x_{2i}^t, \dots, x_{di}^t) \quad (23)$$

Where d is dimension of the objective function, i is i^{th} habitat, and t is t^{th} generation. Therefore, a candidate habitat matrix of size $N_P \times N_d$ (N_P is the number of habitats) is randomly generated.

In nature, each cuckoo lays 5 to 20 eggs, so the number of eggs is randomly determined from 5 to 20 for each cuckoo at each generation of the optimization process. Each cuckoo lays in the special distance from its habitat called egg laying radius (ELR) as follows:

$$ELR = K \times \frac{Number\ of\ current\ cuckoo'segg}{Total\ number\ of\ egg} \times (x_u - x_l) \quad (24)$$

Where K is an integer number, x_u , x_l are upper and lower of variable limits, respectively.

Cuckoos lay their eggs in other host bird's nests according to their ELR. Some of the eggs in host bird's nests will be recognized and thrown out by host bird, so p% of all eggs will be killed. When the cuckoo's eggs hatch, they throw the host bird's eggs out from nests. Cuckoo's chicks grow in the host bird's nests. When they become mature, they immigrate to new area with more food and more similarity of eggs to host bird's eggs. To immigrate, the best value experienced will be determined as a new area that other cuckoos immigrate to there. When they want to immigrate to a new area, they do not fly all way to the destination habitat. They only fly a part of whole way with a deviation like Figure 3.

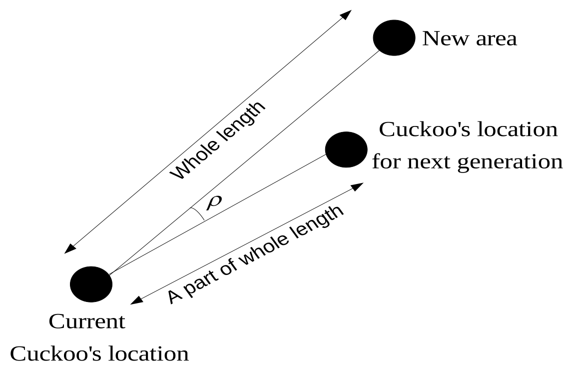

Fig.3. Immigration of a cuckoo to a new location for next generation

4. Fuzzy logic controller

The five main steps of fuzzy controller are input and output variables, fuzzy rule, fuzzification, inference, and defuzzification. The maximum power point $P_{m,optimal}$ and its respective rotational speed $\omega_{optimal}$ are calculated by COA. These values are compared with the actual values of the output power $P_{m,actual}$ and of the rotational speed ω_{actual}, respectively. As seen in Figure 4, we have two input variables for fuzzy logic controller; the first input is the difference between the maximum power point and the actual power point as Equation (8). The second input is the difference between the optimal rotational speed that belongs to the maximum power point and the actual rotational speed as Equation (9).

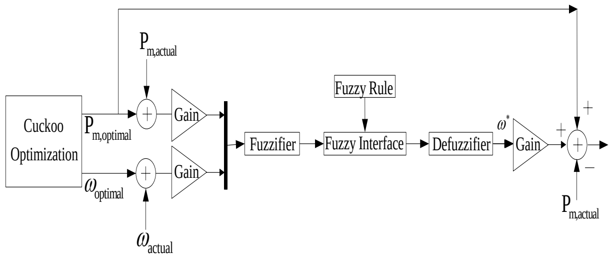

Fig.4. Configuration of the proposed MPP tracker

$$\Delta P_m = P_{m,optimal} - P_{m,actual} \tag{25}$$

$$\Delta\omega = \omega_{optimal} - \omega_{actual} \tag{26}$$

A mamdani inference is used as fuzzy inference system. Fuzzy controller based on these inputs and fuzzy rules change the duty cycle of boost converter. The input and output membership functions are shown in Figures 5 and 6. Fuzzy rules are shown in Table 1.

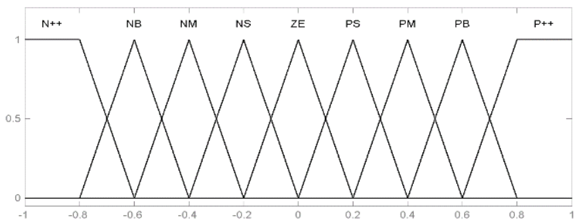

Fig.5. Input and output membership function of ΔP_m and ω^*, respectively

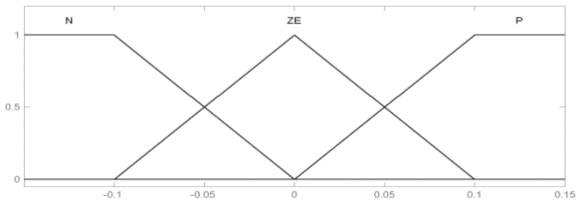

Fig.6. Input membership function of Δω

Table.1.
Rules table of fuzzy logic applied to the WECS

ΔP	N++	NB	NM	NS	ZE	PS	PM	PB	P++
N	P++	PB	PM	PS	ZE	NS	NM	NB	N++
ZE	NB	NM	NS	NS	ZE	PS	PM	PM	PB
P	N++	NB	NM	NS	ZE	PM	PM	PB	PB

5. Simulation results

In order to validate the performance of the proposed approach, the proposed Fuzzy- Cuckoo tracker is applied to the wind turbine with following parameter values:

Table.2.
Parameter values of the simulated system

Air density (ρ)	1.2929 (KG/m^3)
Radius of blade (R)	7.4 (m)
Pitch angle (β)	0
Parameter values of PMDG	
Stator phase resistance	0.98 (Ω)
Stator phase resistance	2.83 (mH)
Pole pairs	3
Inertia	30 (kg.m2)
Parameter values of BOSST converter	
Inductance	400e-6 (H)
Capacitance	800e-6 (F)
Load	
Load	30 (Ω)

The simulations are performed in MATLAB environment. The schematic diagram of the proposed MPP tracker is completely shown in Figure 7.

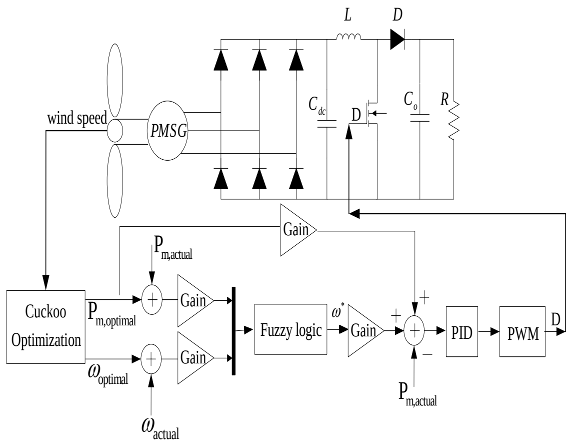

Fig.7. Completely schematic diagram of the proposed MPP tracker

A three- phase diode bridge rectifies the voltage generated by PMSG, and the dc- link capacitor C_{dc} is used to smooth the voltage ripple of the dc voltage generated by the three- phase diode bridge rectifier. Finally, the boost converter is used to control wind turbine in the maximum power point by adjusting the duty cycle.

To confirm the ability of the proposed MPP tracker, in the first case, wind speed pattern will be changed slowly as Fig.

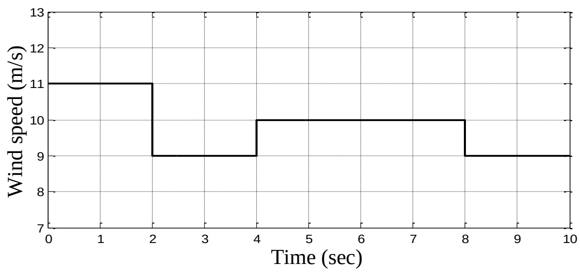

Fig.8. Assumed wind speed profile

Fig.9- a shows the output power of wind turbine tracked by the proposed Fuzzy- Cuckoo controller, and Figure 9- b shows the optimal rotational speed calculated by cuckoo optimization according to the wind speed pattern (as Fig.8).

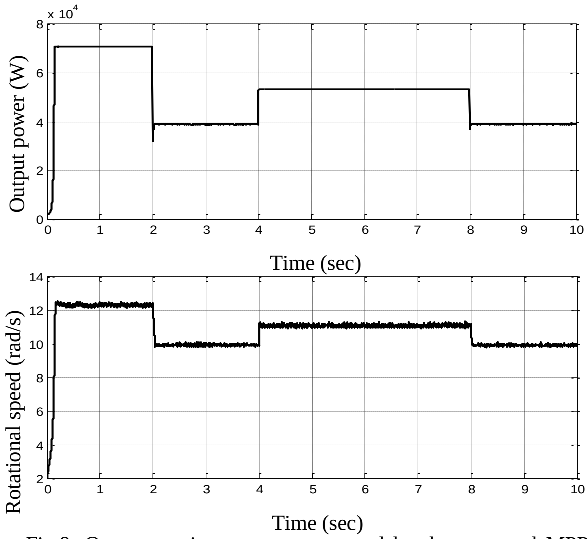

Fig.9. Output maximum power captured by the proposed MPP tracker and rotational speed calculated by cuckoo optimization algorithm while the wind speed is slowly changed

As seen in Fig.9, the proposed fuzzy- cuckoo tracker is capable of tracking the maximum power point in normal wind changes. To prove the superiority of the proposed fuzzy- cuckoo approach than conventional MPP trackers such as PSO and fuzzy trackers in normal wind changes, a comparison with these trackers is provided in following figures. Figure 10 shows the new assumed pattern of wind speed.

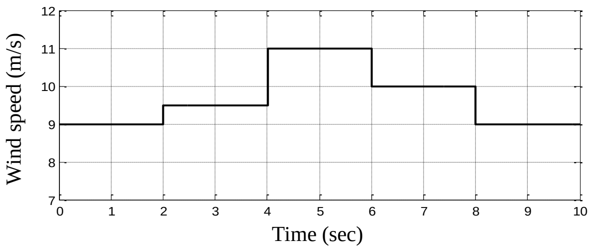

Fig.10. Assumed wind pattern for comparison purpose

Fig.11 shows the maximum output power tracked by fuzzy- cuckoo, PSO, and fuzzy trackers.

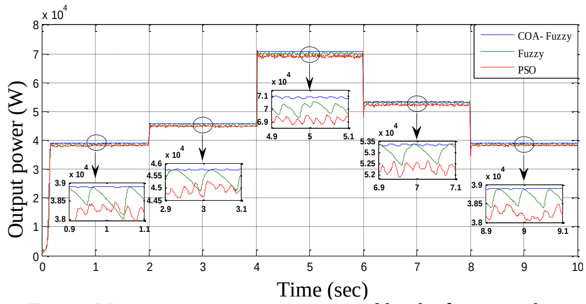

Fig.11. Maximum output power captured by the fuzzy- cuckoo, PSO, and fuzzy MPP trackers

As it is clearly observed, the proposed fuzzy-cuckoo outperforms PSO and fuzzy MPP trackers. Figure 11 shows that fluctuations of the proposed approach are also less than PSO and fuzzy, as well as higher mean value of the output power.

One of the difficulties in MPPT trackers is the fast variations of the wind speed. In this case, for further demonstration, the fast variations of the wind speed are applied to the MPP trackers. Figure 12 shows the fast wind variations, and Figure 13 shows the power tracked by fuzzy- cuckoo, PSO, and fuzzy trackers.

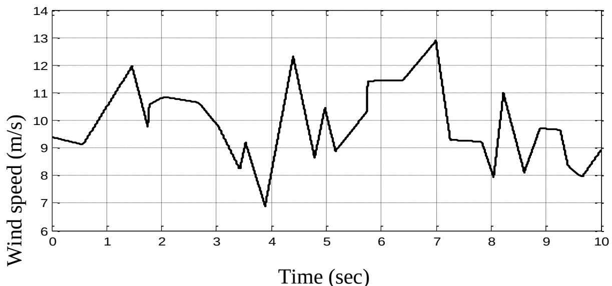

Fig.12. Fast wind variations profile.

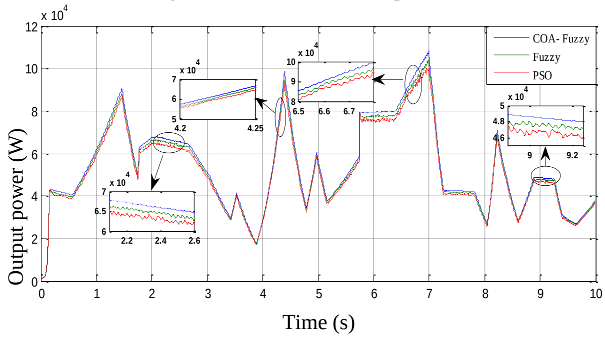

Fig.13. Simulation results in fast variations of the wind speed

As it is shown in Fig.13, the proposed fuzzy-cuckoo controller outperforms the conventional MPP trackers such as PSO and fuzzy trackers.

6. Conclusion

In this paper, an accurate MPP tracker called Fuzzy-cuckoo tracker has been applied to the small-scale WECS with a PMSG and a three-phase diode bridge rectifier. The proposed MPP tracker uses Cuckoo optimization algorithm to detect the maximum power point of the mechanical power curve and its respective rotational speed. The wind speed is measured by anemometer as an input of the Cuckoo optimization algorithm. The difference of the optimum output power that is calculated by the Cuckoo optimization algorithm and actual output power has been fed the Fuzzy as the first input, and the difference of the rotational speed that belongs to the optimum output power and actual rotational speed has also been fed the Fuzzy as the second input. Finally, the output of Fuzzy logic has been used as a set- point. The implementation of the proposed MPP tracker is very simple because only the measurement of the wind speed and the rotational speed are required. In comparison with other conventional MPP trackers such as PSO, and Fuzzy trackers, the proposed MPP trackers are more accurate and robustness (Figures 11 and 13).

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