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Comparative study of different MPPT methods for wind energy conversion system

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Abstract. In this paper we present a comparative study of different MPPT methods for a wind energy system based on permanent magnet synchronous generator (PMSG). These techniques are: Hill Climbing Search (HCS), Optimal Torque Control (OTC), Power Signal Feedback (PSF) and Fuzzy Logic control (FLC). These methods are developed with the aim of comparing their performance on the wind system energy efficiency, according to the response time, the maximum power to be achieved and the system behaviour during the optimal power point tracking MPP. And for a better analysis study, we simulated the system under variable wind speed conditions. The results show that intelligent control based on fuzzy logic is more efficient and presents better performance compared to other MPPT algorithms.

1. Introduction

A wind energy system is one of the most widely used renewable energy sources in isolated sites, thanks to its economic and environmental advantages compared to other systems based on fossil energy sources. Several research papers present modeling and optimization studies of wind energy systems for small installations [1]-[3], using permanent magnet synchronous generators (PMSG) because of its high reliability, requires less maintenance, no need for gearboxes and more efficiency. Also to get maximum power at all times and whatever the weather conditions, the use of an MPPT controller is required to operate the system in its maximum power point MPP. In the literature, there are two types of MPPT methods: direct and indirect methods. The direct techniques are independent of the knowledge of generator characteristics and the climatic conditions, namely, Hill Climbing Search (HCS) [5] [6] and Fuzzy Logic controller (FLC) [4]-[8]. The indirect methods are based on knowledge of the generator characteristics such as Optimal Torque Control (OTC) and Power Signal Feedback (PSF) [3] [11].

In this work, we present a modeling and simulation study of a wind energy system consists of wind turbine, PMSG generator, ac/dc converter, dc/dc booster converter and a DC load. Thus, an MPPT controller was developed to optimize the system energy efficiency by tracking the optimum operating point, using different MPPT algorithms that are analyzed and compared in order to optimize their performance on our system.

2. Modelling of Wind Energy System

In this work, we propose a wind energy conversion system consists of wind turbine, PMSG generator which converts the mechanical energy of the turbine into electrical energy, a ac/dc diode rectifier to convert AC voltage to DC Voltage, dc/dc boost converter that allows to be achieved the desired output voltage and power by controlling the MPPT controller, and the complete system supplies a DC electrical load using a DC bus line. Fig. 1 shows the proposed system architecture.

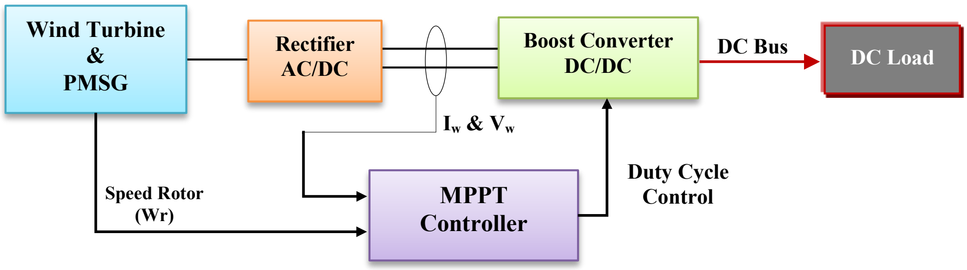

Figure 1. Wind energy system architecture.

2.1. Wind Turbine Modelling

The mechanical power P_m generated by the turbine is given by (1):

$$P_m = \frac{1}{2}\rho S C_p(\lambda,\beta) V_w{}^3 \quad (1)$$

Where: C_p is the turbine power coefficient which depends on the tip speed ratio of the rotor blades λ and the blade pitch angle β. V_w is the wind speed (m/s), ρ is the air density (Kg/m^3), S is the area of swept of turbine.

The power coefficient C_p is as follows:

$$C_p(\lambda,\beta) = C_1\left(C_2\frac{1}{\lambda_i} - C_3\beta - C_4\right)e^{\frac{-C_5}{\lambda_i}} + C_6\lambda \quad (2)$$

Where: C_1=0.5176, C_2=116, C_3=0.4, C_4=5, C_5=21, C_6=0.0068 and the parameter λ_i is defined by:

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

The input mechanical torque T_m for the PMSG generator is obtained by:

$$T_m = \frac{P_m}{\omega_r} \quad (4)$$

Where, ω_r is the rotor speed of a wind turbine.

The tip speed ratio TSR of the wind turbine is defined as following:

$$\lambda = \frac{\omega_r R}{V_w} \quad (5)$$

Where, R is the radius of wind turbine rotor in meters (m).

Tables 1 and 2 summarize the parameters of the wind turbine and the PMSG generator used in this study:

Table 1. Parameters of the wind turbine.

Parameter	Value
Nominal Mechanical Output Power	8.5 kW
Base Wind Speed	12 m/s
Air Density **ρ**	1.225kg/m^3
Pitch Angle **β**	0°

Table 2. Parameters of PMSG.

Parameter	Value
Number of Pole Pairs	5
Stator Phase Resistance	0.425 Ω
Armature Inductance	0.000835 H
Friction Factor	0.001189 Nms
Inertia constant	0.01197 kg.m^2

Fig. 2 shows the wind turbine mechanical power as a function of the rotor speed P_m (ω_r) for various wind speed values:

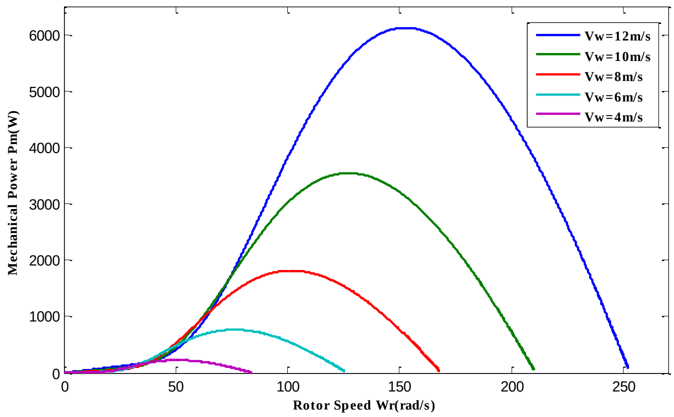

Figure 2. Pm(ω_r) Wind turbine mechanical power for various wind speed values.

Fig. 3 shows the wind turbine mechanical torque as a function of the rotor speed T_m (ω_r) for different wind speed values.

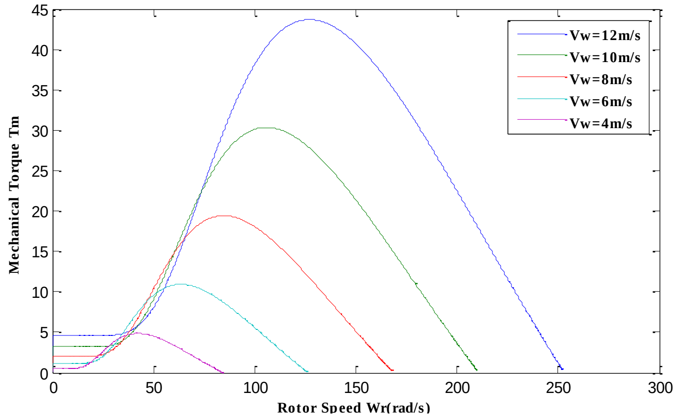

Figure 3. Tm(ω_r) Wind turbine mechanical torque for various wind speed values.

Fig. 4 shows the power coefficient $C_p(\lambda)$ for various pitch angle values β. the optimal value of C_p is corresponding to β=0 and to the tip speed ratio optimal value (λ_{opt}=8.144) which equal to 0.48.

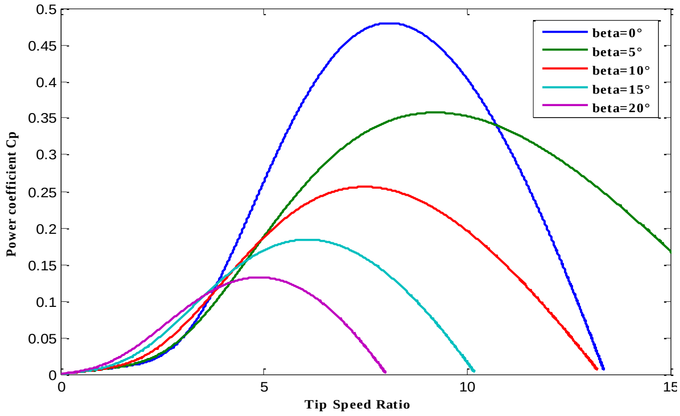

Figure 4. Power coefficient for various values of the pitch angle β.

According to these characteristics of the wind turbine, it can be seen that for the different wind speed values, there is an operating point where these characteristics P_m, T_m and C_p are optimal. This shows the need for the use an MPPT controller to reach and track this maximum power point whatever the variation in wind speed.

2.2. Modelling of DC/DC Boost Converter

A DC/DC boost converter is one of the most widely used converters in a wind energy conversion chain, which converts a low input voltage into a high output voltage. It has an adaptation interface between the PMSG generator and the electrical load in order to operate the system in its maximum power point by controlling its MOSFET transistor using a PWM signal and the duty cycle of the MPPT controller. Fig. 5 shows the equivalent circuit of boost converter:

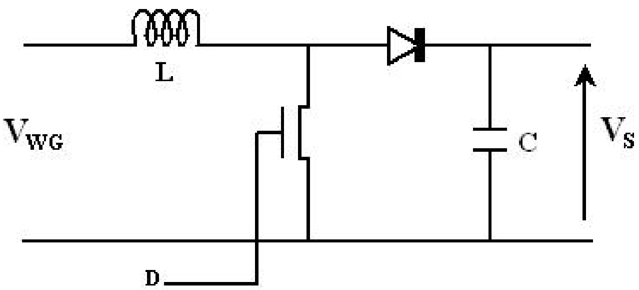

Figure 5. Boost converter.

The output voltage of the boost converter is expressed as a function of the input voltage by:

$$V_s = \frac{V_{WG}}{1-D} \tag{6}$$

Where: D is the duty cycle.

3. MPPT Algorithms

In wind energy conversion system, the use of an MPPT controller is essential, seen its important role to extract the maximum energy produced by the PMSG generator whatever wind speed, its principle based on the execution of MPPT algorithm which allows to reach and track the maximum power point MPP. There are several MPPT techniques used in wind systems, that they can be distinguished according to two types: Direct methods and other indirect. Indirect methods such as Optimal Torque Control (OTC) and Power Signal Feedback (PSF) are based on knowledge of the wind turbine characteristics $C_{p\text{-}opt}$ and λ_{opt} [1] [3]. However, direct methods do not require prior knowledge of these characteristics, namely: Hill Climbing Search (HCS) [8] [9] and Fuzzy Logic control (FLC) [9] [10].

In this work, we propose the development of its algorithms and compare their performance on our system efficiency.

3.1. Optimal Torque Control (OTC) Method

The principle of the OTC control is to adjust the torque of PMSG generator to its reference torque for the different wind speeds, it requires knowledge of the optimal turbine characteristics $C_{p\text{-}opt}$ and λ_{opt}.

In the optimal case ($C_{p\text{-}opt}$ and λ_{opt}), and according to the equations (1), (4) and (5), wind speed, mechanical power and optimum torque can be written as follows:

$$V_w = \frac{\omega_{r.opt} R}{\lambda_{opt}} \tag{7}$$

$$P_{m.opt} = \frac{1}{2}\rho \pi R^2 C_{p.opt} V_w^3 = K_{opt}.\omega_{r.opt}^3 \tag{8}$$

$$T_{m.opt} = \frac{P_{m.opt}}{\omega_{r.opt}} = K_{opt}.\omega_{r.opt}^2 \tag{9}$$

Where K_{opt} is a constant determined by the wind turbine characteristics and is defined by:

$$K_{opt} = \frac{1}{2} \cdot \frac{\rho \cdot \pi \cdot R^5 \cdot C_{p.opt}}{\lambda_{opt}^3} \tag{10}$$

Fig. 6 shows the block diagram of the OTC method:

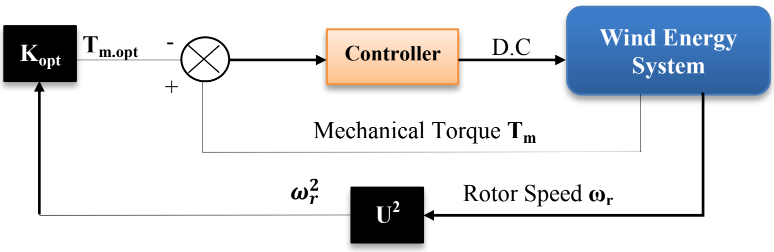

Figure 6. OTC method.

3.2. Power Signal Feedback (PSF) Method

The PSF technique allows to maximize the output power of a PMSG generator by calculating the reference power for a particular wind speed, using the equation (8) of the power optimal. Then a comparison is made between this calculated power and the current power to generate a control signal which is applied to the boost converter, in order to ensure that the power coefficient C_p and the tip speed ratio λ are always at its optimum values. Fig. 7 shows the principle of the PSF method:

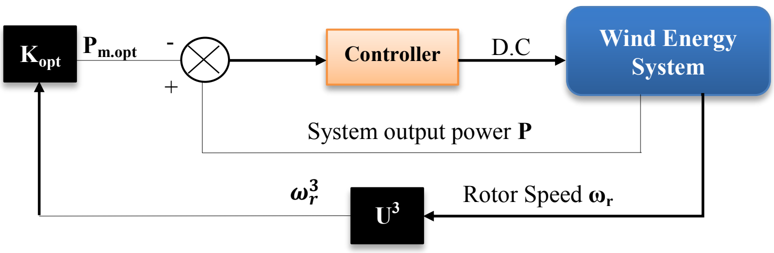

Figure 7. PSF method.

3.3. Hill Climbing Search (HCS) Method

The HCS method is the most technique MPPT used in a wind system because of its simplicity and independence to wind turbine characteristics, the power coefficient maximal $C_{p\text{-}opt}$ and the tip speed ration optimal λ_{opt}. Its principle is based essentially on a periodic perturbation (incrementing or decrementing) of the wind turbine rotor speed in small step, then observing the effect of this perturbation on the output power P of the PMSG generator, by comparing the current value of the power with its previous value. And as explained by the flow chart of this algorithm in Fig. 8, If a small increase of the rotor speed results in an increase of output power (case ΔP/Δω>0), the perturbation will continue in the same direction, Otherwise (case ΔP/Δω<0), the perturbation will be in the opposite direction, this strategy is repeated until reaching the maximum power point corresponds to the zero slope ΔP/Δω=0.

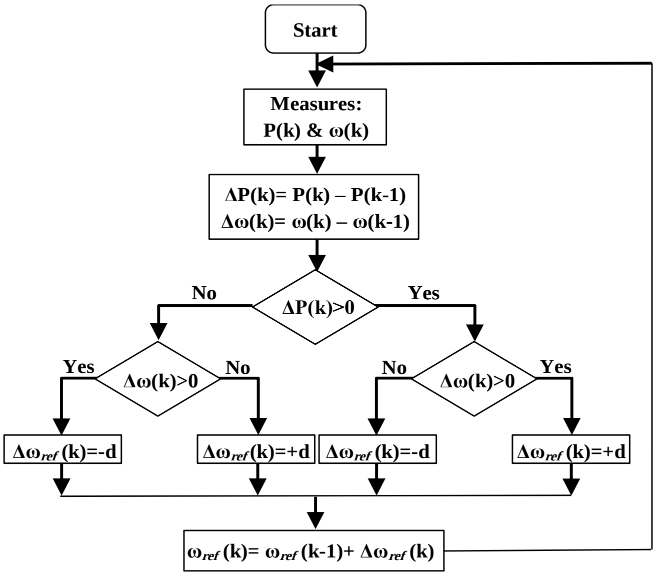

Figure 8. Hill Climbing Search method flowchart.

3.4. *Fuzzy logic (FLC) MPPT*

The MPPT technique based on fuzzy logic recently introduced one of the intelligent methods used in wind systems to determine and track the operating point corresponding to the maximum power whatever of the wind speed. Compared with conventional control techniques, this control is robust and does not need exact knowledge of the system mathematical model. A FLC controller includes three functional blocks: Fuzzification, Inference engine and Defuzzification. Thus, it is characterized by input variables, output variables, membership functions and fuzzy rules. The fig. 9 shows the block diagram of FLC MPPT controller for wind system:

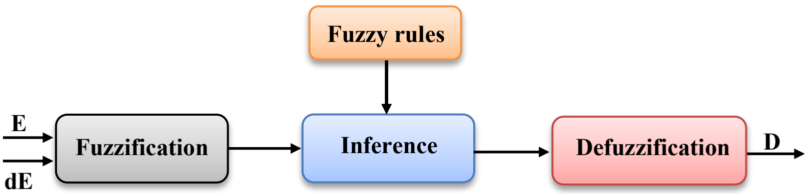

Figure 9. FLC MPPT controller.

The input variables of the fuzzy controller are the error E(k) and the change of error dE(k) which are defined by (11) and (12), while the output is the duty cycle D.

$$E(k) = \frac{P(k)-P(k-1)}{\omega(k)-\omega(k-1)} \tag{11}$$

$$dE(k) = E(k) - E(k-1) \tag{12}$$

Where P(k) and ω(k) are the output power and the rotor speed of the wind generator, respectively.

The principle followed by the fuzzy controller to reach the maximum power point is as follows: In the first step, the controller converts the input and output variables into linguistic variables in the form of membership functions (fuzzification step), which are defined in five fuzzy subsets: NB (negative big), NS (negative small), ZE (zero), PS (positive small) and PB (positive big). Fig. 10 shows the memberships functions of E(k), dE(k) and D(k). In the second step, the controller establishes logical relations between the input variables and the output variable while defining membership rules (inference step), using the MIN-MAX inference method, the defined inference rules are shown in table 3. And in the final step, the controller converts the fuzzy subsets of the output variable into a numerical value, which is the duty cycle applied to the dc/dc boost converter, using the defuzzification method of the center of gravity which is the simplest and fastest.

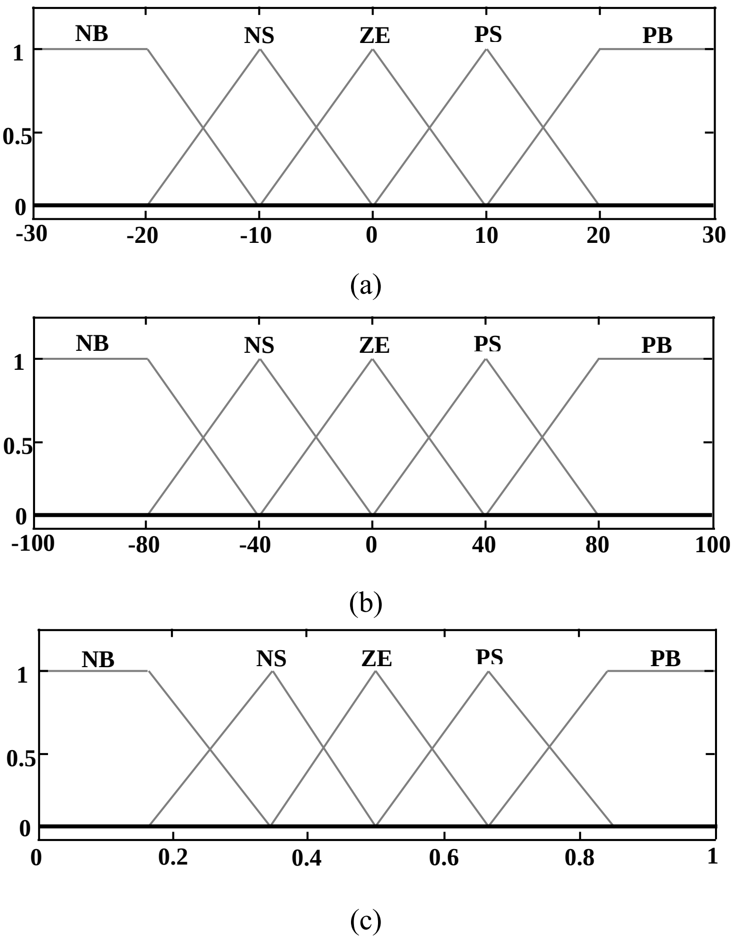

Figure 10. Membership functions for: (a) Input E, (b) Input dE, (c) Output D.

Table 3. Fuzzy logic rules.

E	dE				
	NB	NS	ZE	PS	PB
NB	NB	NB	NS	PS	PB
NS	NB	NB	NS	PB	PS
ZE	ZE	ZE	ZE	ZE	ZE
PS	NS	NS	NS	ZE	ZE
PB	NS	NB	NB	ZE	ZE

4. Simulation Results and Discussion

In this work, a detailed implementation and simulation of a wind system was carried out using the Matlab/Simulink software, based on the equations and technical parameters of wind turbine and PMSG generator described previously. Also an MPPT controller has been developed to optimize the performance of the proposed system under varying wind speed conditions, with different MPPT approaches that have been simulated, evaluated and compared.

Figs. 11 and 12 show the simulation results corresponding respectively to the power coefficient and output mechanical power for the wind turbine with different wind speed values (12m/s and 10m/s), using the Optimal Torque Control (OTC) method, the Power Signal Feedback (PSF) method, the Hill Climbing Search (HCS) Method and the Fuzzy Logic Control (FLC).

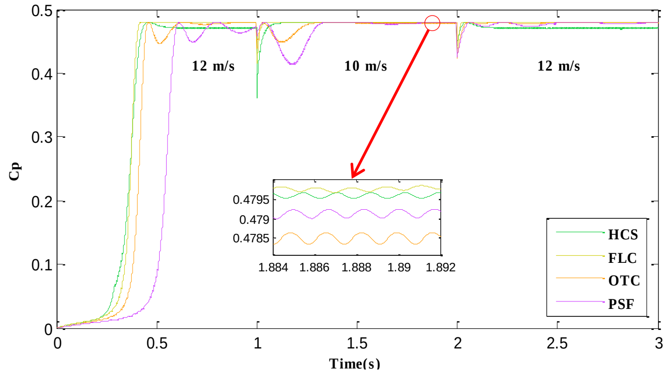

Figure 11. Power coefficient (Cp) for different MPPT methods.

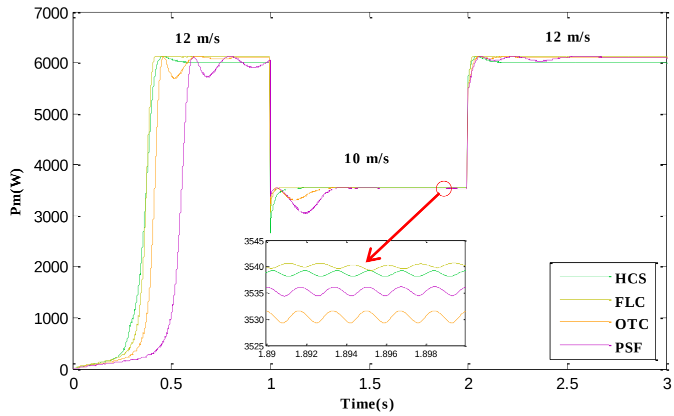

Figure 12. Wind turbine mechanical power for different MPPT methods.

From these results, we noticed that the control based on fuzzy logic is most efficient technique compared to other methods. It achieves maximum power with more stability, precision and better response time. However, the PSO and OTC methods require slow response time to determine the MPP, which remains less than that of the FLC, with more oscillations resulting in a loss of energy. For that, it can be stated that the FLC intelligent control is a robust and efficient approach, it has better performance and a good dynamic response under variable wind speed conditions.

5. Conclusions

In this paper, four MPPT techniques like OTC, PSF, HCS and FLC are developed and compared to optimize the power produced by a wind energy system under varying conditions. According to the performance analysis of each method, we noted that the MPPT controller based on the fuzzy logic allows determining and tracking the maximum power point with more efficiency, fast response and high reliability compared to other controllers based on OTC, PSF and HCS. Therefore, it is concluded that the FLC based approach offers better advantages and good performance for a wind energy conversion system.

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