Performances MPPT Enhancement in PMSG Wind Turbine System Using Fuzzy Logic Control

Mhamed Fannakh, Mohamed Larbi Elhafyani, Smail Zouggar, and Hassan Zahboune

Abstract In this paper, we use the Fuzzy Logic (FL) techniques to improve the power generated by a small Permanent Magnet Synchronous Generator (PMSG) wind turbine. The advantage of this non-linear technique is that it does not require the knowledge of the system mathematical model to obtain a maximum energetic efficiency. It can generate the optimal rotation speed reference without using the wind speed sensor; this reduces considerably the system cost. The proposed system delivers power to a resistive load through a PWM rectifier which offers the implementing control algorithms possibility. In first part, the wind turbine model and that of PMSG are presented to show the system nonlinearity. After that, the different steps of the proposed algorithms are developed namely the classical Hill Climb Searching method, the Single Input Fuzzy Logic Control (FLC), and the double inputs FLC. Finally, the performance of each algorithm is simulated, evaluated and compared in the MATLAB/Simulink platform. The obtained results indicate that the Fuzzy Logic Approach (FLA) is more effective than classical strategies. It is also particularly robust in stability and easy to implement in other systems.

Keywords Wind energy · PMSG · MPPT · Fuzzy logic control

1 Introduction

Population growth and industrialization, which have been accompanied by increased access to electricity, have all contributed to the Morocco's energy needs expansion. The renewable energy potential of Morocco is unquestionably considerable. The country has a significant potential for solar energy, with radiation levels which are around 5300 Wh/m^2. On the other hand, the Atlantic coast offers wind speeds that are higher than 6 m/s. A study carried out by Agency for the Promotion of Renewable Energy and Energy Conservation (ADEREE) with GTZ indicates that the wind

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potential of Morocco amounts to 7936 TWh/year [1]. Morocco has ambitious state plans aimed at systematically exploiting renewable energy sources whose objective is to reduce the country's dependence on fossil fuels imported from international markets. Another deployment area of renewable energies in Morocco lies in the use of photovoltaic panels or small wind generators in standalone system and to pumping water.

Small wind turbine systems are competitive in isolated windy regions. Indeed, energy conversion chains based on small wind turbines often use a PMSG associated with power converters [2]. In order to extract the maximum power from the wind turbine generator, various solutions were examined at different levels of the conversion chain. These studies can be classified according to the power nature to be maximized. Under the mechanical power maximization MPPT algorithms, we can find the Tip Speed Ratio (TSR), Optimal Torque Control (OTC) and Power Signal Feedback (PSF). The Hill Climbing Search (HCS), Incremental Conductance (INC) and Optimum Relation Based (ORB) MPPT are considered under electrical power maximization algorithms. Other advanced algorithms are discussed in the published literature such as neural network MPPT algorithm and fuzzy logic MPPT algorithm [3].

This study aims to examine the added value provided by FL in the search for the reference rotational speed which gives the Maximum Power Point (MPP).

2 System Modeling

The proposed system configuration is shown in Fig. 1. It includes a small wind turbine, Permanent Magnet Synchronous Generator (PMSG), IGBT rectifier, capacitor filter and resistive load. The wind turbine is coupled to the PMSG by the drive shaft. The three-phase IGBT rectifier with capacitor filter converts the AC generator voltages into DC voltage. A control system is used to track the Maximum Power Point (MPP) available regardless of the wind speed.

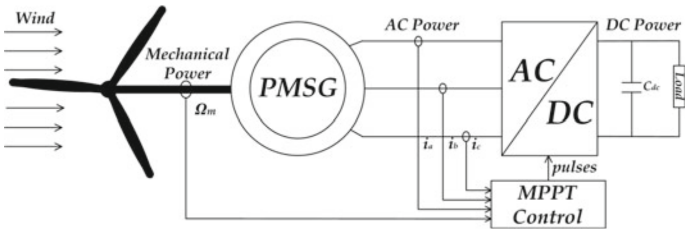

Fig. 1 Bloc diagram of the studied system

2.1 Wind Turbine Model

A wind turbine's role is to transform the kinetic energy of the wind into mechanical energy, the wind turbine blades capture only a part of the power contained as kinetic energy in the wind [4]:

$$P = \frac{1}{2}\rho\pi R^2 V_w^3 C_p(\lambda, \beta) \tag{1}$$

where ρ is the air density (1.225 kg/m^3), R is the blades radius (in m^2), V_w is the wind speed (in m/sec) and Cp is the power coefficient. It is a parameter that expresses the efficiency of the wind turbine in the transformation of wind kinetic energy into mechanical energy. It is a nonlinear function of the blades pitch angle β and the tip speed ratio λ between the rotor speed Ω_m and wind speed V_w, it is expressed as:

$$\lambda = \frac{R \cdot \Omega_m}{V_w} \tag{2}$$

Since the small wind turbines are equipped with fixed blades ($\beta = 0$), the coefficient Cp depends only on λ. In the literature, we find Cp in the form of λ and β coefficients analytic expression [5].

$$\begin{cases} C_p(\lambda, \beta) = C_1\left(\frac{C_2}{\gamma} - C_3\beta - C_4\right)e^{\frac{-C_5}{\gamma}} + C_6\lambda \\ \frac{1}{\gamma} = \frac{1}{\lambda+0.08\beta} - \frac{0.035}{\beta^3+1} \end{cases} \tag{3}$$

where $C_1 = 0.5176$, $C_2 = 116$, $C_3 = 0.4$, $C_4 = 5$, $C_5 = 21$, $C_6 = 0.0068$. Cp reaches its maximum of 0.48 when $\lambda = 8.12$ and $\beta = 0$.

2.2 PMSG Model on d-q Coordinate System and PWM Rectifier

The PMSG comprises three-phase windings system in its stator, 120° phaseshifted relative to each other. In the rotor, the permanent magnets are positioned to provide the excitation. In order to model the PMSG, we adopt the usual simplifying hypotheses listed in [6]. The PMSG mathematical model in park reference frame is given by Eq. 4:

$$\begin{cases} u_d = R_s \cdot i_d + L_d \cdot \frac{di_d}{dt} - \omega_e \cdot L_q \cdot i_q \\ u_q = R_s \cdot i_q + L_q \cdot \frac{di_q}{dt} + \omega_e \cdot L_d i_d + \omega_e \cdot \psi_f \end{cases} \tag{4}$$

where u_d and u_q are the d-axis and q-axis stator voltages (V), respectively; i_d and i_q are the d-axis and q-axis stator currents (A), respectively; L_d and L_q are the d-axis and q-axis inductances (H), respectively; R_s is the stator winding resistance (Ω); ψ_f is the permanent magnetic flux (Wb) and ω_e is the electrical rotating speed (rad/s) of the generator. In Laplace domain it can be expressed as:

$$\begin{cases} i_d = \frac{1}{R_s + s \cdot L_d} \cdot \left(u_d + \omega_e \cdot L_q \cdot i_q\right) \\ i_q = \frac{1}{R_s + s \cdot L_q} \cdot \left(u_q - \omega_e \cdot L_d i_d - \omega_e \cdot \psi_f\right) \end{cases} \tag{5}$$

The electromagnetic torque developed by the generator is written as:

$$T_{em} = \frac{3}{2} \cdot p\left(\left(L_d - L_q\right) \cdot i_d \cdot i_q + i_q \cdot \psi_f\right) \tag{6}$$

where p is the number of the pole pairs. The generator is with smooth rotor ($L_d = L_q$), this equation becomes:

$$T_{em} = \frac{3}{2} \cdot p \cdot i_q \cdot \psi_f \tag{7}$$

Contrary to classic rectifiers, PWM rectifiers are made using the IGBT transistors as switchable semiconductors. These devices offer the following advantages:

- Bidirectional power flow
- A controllable power factor
- Low Total Harmonic Distortion (THD)
- Adjustment and stability of DC link voltage

The PWM rectifier control can be considered as a dual problem with the PWM inverter control. Several control strategies have been proposed in recent works, the SVM technique is the most efficient technique [7].

3 Control Strategy for Power Maximization

A PMSG wind turbine is a generator whose characteristic (power/rotor speed) is strongly nonlinear, it's is influenced by the wind speed variation. In Fig. 2 the wind turbine is subject to wind speed variations where it appears clearly the power decrease and the change in the maximum power point MPP. Because of this nonlinear characteristic, a controllable rectifier is inserted between the PMSG and the load.

The improvement of the wind system efficiency requires maximizing the turbine power. That is possible if the operating rotor speed is well chosen. As indicated in Fig. 2, for each wind speed, the turbine can only provide its maximum power in a particular rotor speed. Therefore, the maximum power point search amounts to forcing the system to rotate at the optimal speed. The power control system called

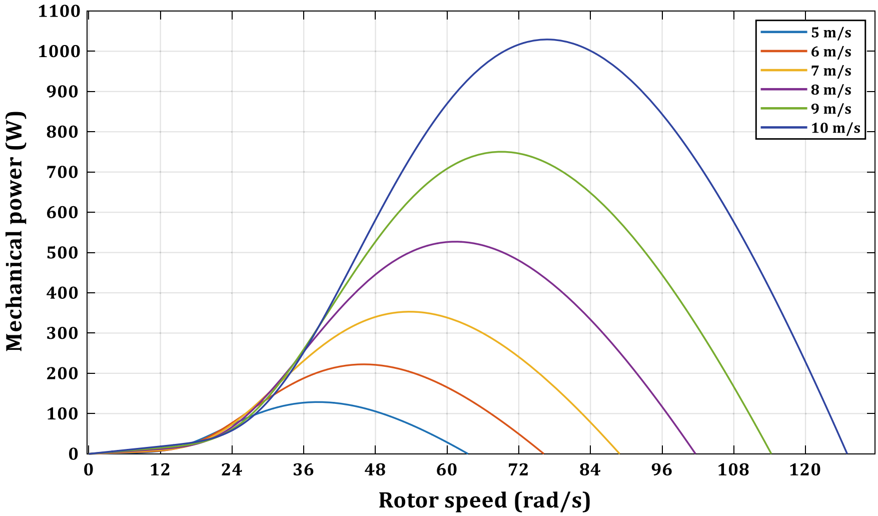

Fig. 2 Turbine power characteristic as a function of the rotor speed

MPPT (Maximum Power Point Tracking) aims firstly to find the optimal rotor speed and secondly drives the PMSG generator at this optimum speed by using regulation loops.

In the small WT, reducing the system cost, by eliminating the wind speed sensor, is widely recommended. In this interest, we propose a wind-sensorless MPPT strategy based on the HCS technique and FLC.

3.1 Hill Climbing Search MPPT

The HCS algorithm principle is to perturb the generator rotational speed reference. Consequently, the electrical produced power will be perturbed. If the power increases, the variation is maintained in the same direction until reaching the MPP. However, if the power decreases the variation direction is reversed to reach the maximum [8]. This method uses a fixed step size to increment or decrement the rotational speed reference. If the step size is too small, the tracking process would be slowed. If the step size is too large, then the system fluctuates around the MPP [9].

3.2 Single Input FLC MPPT

The FLA is one of the efficient algorithms that have the potential to vary the step size of rotational speed reference. The FL theory is described in [10]. The flowchart given in Fig. 3 describes the proposed Single Input FLC to search the rotational speed reference.

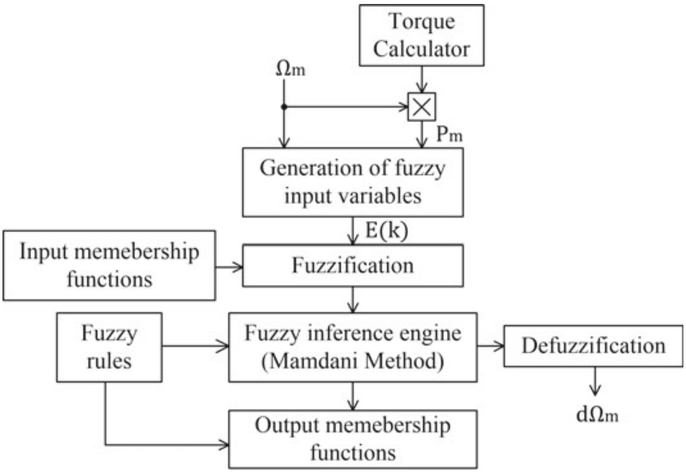

Fig. 3 Flow diagram of Single Input FLC

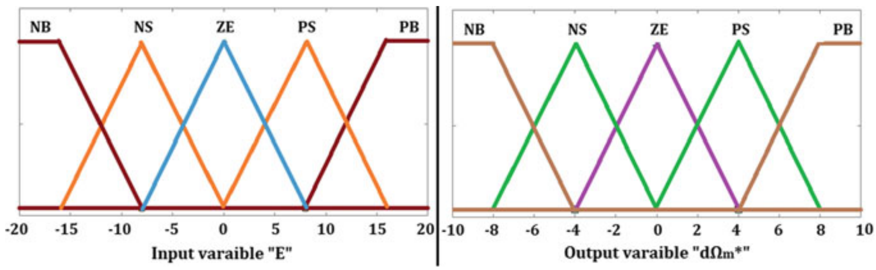

Fig. 4 Membership functions of input and output variable

The proposed FLC implementation can be formed in four steps:

- *Fuzzy inputs calculation*
  Error E(k) is the input variable of the Single Input FLC. It is calculated at k_{th} iteration by using Eq. 8:

$$E(k) = \frac{P_m(k) - P_m(k-1)}{\Omega_m(k) - \Omega_m(k-1)} \tag{8}$$

- *Fuzzification*
  It consists of converting digital input data into fuzzy quantities. The input/output variables which are the error E(k) and the change in reference rotational speed dΩm* are subjected to a fuzzification operation in five-term fuzzy set, positive big (PB), positive small (PS), zero (ZE), negative small (NS), and negative big (NB). For the membership functions, we have chosen for each variable the triangular and trapezoidal forms as shown in Fig. 4.

Table 1 Single Input FLC fuzzy rules

E	NB	NS	ZE	PS	PB
dΩm*	PB	PS	ZE	NS	NB

- *Rule base*
  The rule base presents the control strategy. It expresses the relationship that exists between the input variable and the output variable. From the behavior study of the system, we can establish the control rules. A set of five rules is represented in Table 1 where the input are fuzzy sets of error E(k) and the output of this rules table is the fuzzy sets of the change in rotational speed reference (dΩm*).
- *Defuzzification*
  When the fuzzy output is calculated, it must be transformed into a numerical value. There are several methods to achieve this transformation. The most used is the center of gravity method, which we adopted in this work.

3.3 Double Inputs FLC MPPT

The single input FLC presents some advantages listed in [11], but it also presents some challenges due to the fast changing in wind speed. This is can be improved by including a new input to FLC called "change in error". The error E(k) shows if the operation power point is located on the right or in the left of the maximum power point. While the change in error dE(k) expresses the moving direction of this operation point [9]. It is given by Eq. 9:

$$dE(k) = E(k) - E(k-1) \tag{9}$$

The structure of the proposed double inputs FLC is derived from that given in Fig. 3. The difference lies in adding the new input dE(k) before the fuzzification bloc. The E(k) and dE(k) membership functions are identical to that of input variable in Fig. 4. For the output variable (dΩm*) we keep the same membership function of Single Input FLC.

Once the fuzzification is done, it is possible to define the fuzzy rule-based system. Otherwise, the fuzzy MPPT algorithm must be provided with a rule base expressed in natural language to reason and draw conclusions [9]. Based on expertise a rule base consisting of 25 rules is designed as shown in Table 2:

Table 2 Double inputs FLC rule base

Fuzzy rules		dE				
		PB	PS	ZE	NS	NB
E	PB	PB	PB	PB	PS	ZE
	PS	PB	PB	PS	ZE	NS
	ZE	PB	PS	ZE	NS	NB
	NS	PS	ZE	NS	NB	NB
	NB	ZE	NS	NB	NB	NB

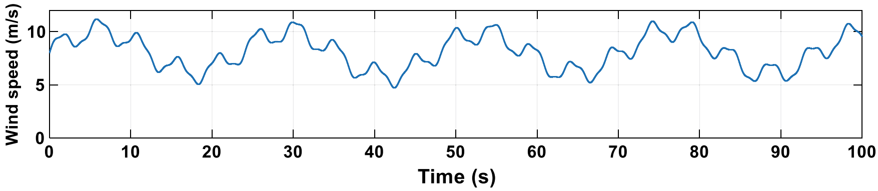

Fig. 5 Wind speed profile

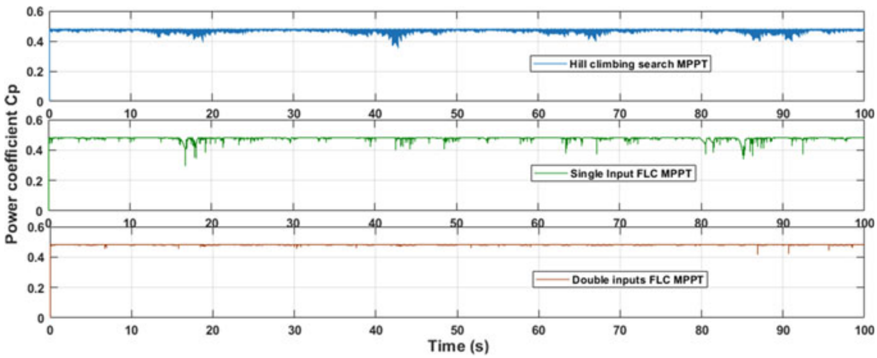

Fig. 6 Power coefficient curves

4 Simulation Results

To ensure the performance of the double inputs FLC, the proposed MPPT strategies are performed by numerical simulation through MATLAB/Simulink Software.

As indicated in Fig. 1, we apply the same random wind speed profile of all strategies as given in Fig. 5 in order to see the control efficiency.

From the obtained results, it can be clearly seen in the Fig. 6 of the power coefficient Cp that the time required to recover the maximum value after a wind speed variation is very short when the Double Inputs FLC is applied. The power coefficient value regains its maximum of 0.48 with minimum ripples.

The mechanical power curve in Fig. 7 is similar to the applied wind profile. This result ensures that the system is able to deliver stable and good quality energy.

It is noted in the Fig. 8 that the DC power delivered to the load varies with the wind speed variation.

The stator currents waveform in Fig. 9 obtained using the double inputs FLC has a sinusoidal form. The evaluation of harmonic spectrum in Fig. 10 allows seeing that the Total Harmonic Distortion (THD) to the current waveform is about, respectively, 54.2%, 13.95% and 5.21% for HCS, Single Input FLC and Double Inputs FLC. We note the Double Inputs FLC has the advantage of reducing harmonic pollution.

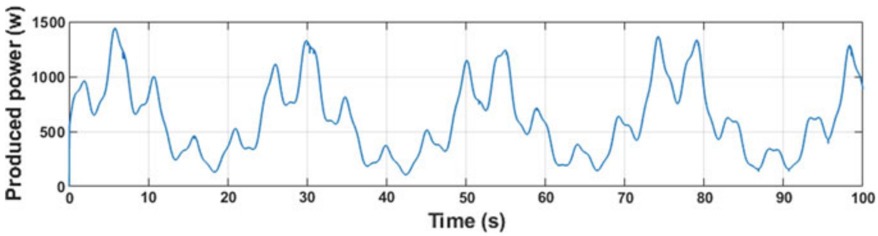

Fig. 7 Mechanical produced power

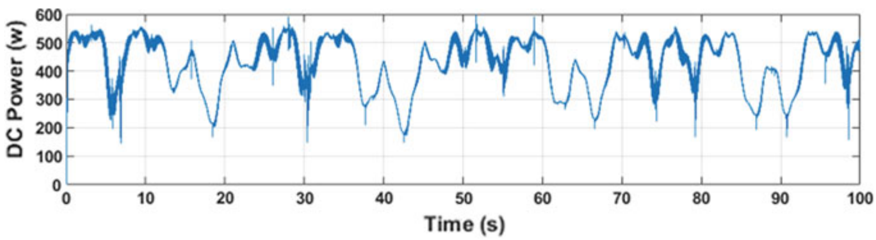

Fig. 8 DC side power

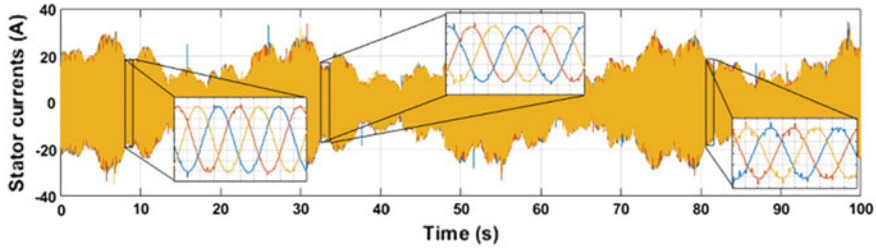

Fig. 9 Stator currents

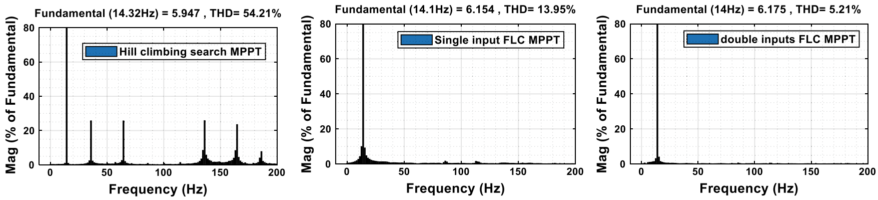

Fig. 10 FFT analysis

5 Conclusion

The main objective of this work was the maximization power from the PMSG wind turbine. The performance of the MPPT command was improved by FLC in two steps. In general, we note that the maximization by the FLC is satisfactory as shown by the results obtained using the MATLAB/Simulink tool. In perspective, this technique will be applied for a grid-connected PMSG wind turbine. Future works include also the implementation of these control techniques on the real system and validate their performance through the experimental results.

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