Fuzzy Logic Based MPPT Controller for a Small Wind Turbine System

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***Abstract*-This paper describes the design of a maximum power point tracking (MPPT) strategy for a variable speed, small scale, wind turbine systems based on a fuzzy logic controller (FLC). The FLC has as input variables the change in mechanical power (ΔP_m), the change in rotor speed ($\Delta\omega$), and the sign of $\Delta P_m/\Delta\omega$. The change of reference generator current (ΔI^*) is the output variable. For small power applications, when the turbine inertia is relatively small, and the wind speed changes continuously, it is important to consider the transients in order to develop an accurate theoretical model and to attain optimal operation. Therefore, the mechanical power (P_m) is composed of the generator mechanical (input) power (P_g) plus the dynamic power, resulting in the dynamic power versus rotating speed curve. The controller is able to track the maximum power point for changing wind conditions, and is robust with respect to turbine parameter changes. The FLC is described, analyzed and validated by digital simulations.**

I. INTRODUCTION

Variable speed wind generator systems offer the possibility to extract the maximum available power from the wind and so to increase the amount of captured energy. Also, because the captured energy is larger, the life-cycle cost is lower for these types of wind turbines, in spite of the additional cost of power electronics and controllers required [1] - [2].

The configuration / architecture of a wind turbine system and the control strategies for tracking the maximum power points are the most important elements in achieving the goal of higher energy efficiency. To capture the maximum energy from the available wind, a maximum power point tracking (MPPT) control is necessary in order to adjust the turbine rotating speed according to the change of the wind speed, so that the tip speed ratio can be maintained at its optimal value [3].

Several studies and comparisons have been focused on finding the better maximization power control strategy. For example, in [4] two types of MPPT strategies have been identified, whether the turbine characteristics are supposed to be known or not. For the first type, the knowledge of the optimal characteristics allows to maximize the energy transfer by optimally controlling the torque, speed, or power. For the second type, an MPPT algorithm has to be implemented, which could be a perturb-and-observe (P&O) algorithm, which controls the speed reference of the generator in accordance to the magnitude and direction of active power change [5]. Another MPPT algorithm could be implemented as a fuzzy logic controller based on a set of rules which is derived from the system behavior or from the designed control strategy [6] - [8].

This paper proposes a fuzzy logic based MPPT control strategy designed in a simple and robust structure. The controller design is presented first. Digital simulations results with the proposed controller, compared with the knowledge (theoretical) of the wind turbine characteristics control are presented next, and finally the conclusions will be drawn.

II. CONTROL SYSTEM DESCRIPTION

The structure of a low power variable speed wind turbine system (VSWT), presented in Fig. 1, consists of a permanent magnet synchronous generator (PMSG) driven by a five-blades fixed pitch wind turbine, a diode bridge rectifier (DB), a hybrid DC-DC converter (HDC) - the element that regulates the turbine speed through the controlled PMSG current, and the load [9].

The wind turbine output torque T_{wt} and power P_{wt} varies with the wind speed [10]:

$$T_{wt} = 1/2 \cdot C_T(\lambda) \cdot \rho \cdot v^2 \cdot A \cdot R \tag{1}$$

where the tip-speed ratio $\boldsymbol{\lambda}$ is defined as:

$$\lambda = \omega \cdot R/v \tag{2}$$

and

A : blade swept area [m^2];
ρ : specific density of air [kg/m^3];
v : wind speed [m/s];
R : radius of the turbine blade [m];
ω : rotating speed [rad/s];
C_T : wind turbine torque coefficient; expression (3) was

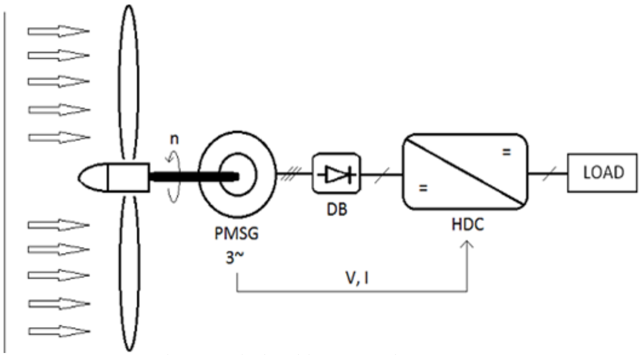

Fig. 1. Wind turbine control system.

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obtained from the wind turbine test.

$$C_T = C_{T0} + a \cdot \lambda - b \cdot \lambda^{2.5} \qquad (3)$$

where a, b, C_{T0} are the constants for the nominal tip-speed ratio λ_0.

The maximum power is obtained if [4]:

$$C_P(\lambda) = C_P(\lambda_{opt}) \qquad (4)$$

from:

$$P_{wt}^{\max} = 1/2 \cdot C_p(\lambda_{opt}) \cdot \rho \cdot A \cdot R^3 \cdot 1/\lambda^3 \cdot \omega^3 = k_{opt} \cdot \omega^3 \quad (5)$$

where C_P is the wind turbine power coefficient.

The dynamic equation of motion is:

$$T_{wt} - T_g = J \cdot (d\omega/dt) \qquad (6)$$

where

T_{wt} : wind turbine torque [N·m];
T_g : PMSG torque [N·m];
J : inertia of the wind turbine system [kg·m^2].

The inertia of the wind turbine system is composed of two inertias [11]:

$$J = J_{wt} + J_g \qquad (7)$$

where

J_{wt} : inertia of the wind turbine [kg·m^2];
J_g : inertia of the PMSG [kg·m^2].

The PMSG model (8) includes also the rectifier model:

$$\begin{aligned} & p_p \cdot \omega \cdot \sqrt{\Psi_{PM}^2 - (L_s \cdot I_{fp})^2} - [R \cdot I_{fp} + \\ & + k_v \cdot (V_{dc} + 2 \cdot V_{don})] = 0 \end{aligned} \qquad (8)$$

The rectified current is:

$$I_{dc} = k_i \cdot I_{fp} \qquad (9)$$

The rectified voltage is:

$$V_{dc} = 1/C_f \cdot \int (I_{dc} - I_{load}) \cdot dt \qquad (10)$$

$$T_g = 1.5 \cdot p_p \cdot I_{fp} \cdot \sqrt{\Psi_{PM}^2 - (L_s \cdot I_{fp})^2} \qquad (11)$$

where

p_p : number of pole pairs;
Ψ_{PM} : permanent magnet flux [Wb];
R_s : stator resistance [Ω];
L_s : stator inductance [H];
I_{fp} : peak phase current [A];
V_{don} : diode voltage drop [V];
C_f : filter capacitance [F];

A hybrid dc-dc converter is used to control the power delivered to the load [9]. The HDC input-to-output voltage ratio is:

$$V_{out} = \frac{D}{2-D} \cdot V_{rect} \qquad (12)$$

where:

V_{out} : output voltage;
V_{rect} : input (rectified *PMSG*) voltage;
D : duty cycle.

To obtain the desired rotating speed of the wind turbine, the generator torque must be changed. HDC works as a current controller, i.e. the converter controls the PMSG output current through the DB, in order to change the PMSG torque Tg.

The converter is implemented as an ideal, fast current source (the measured current will always be equal with the reference current). The PMSG is implemented with (8).

Fig. 2 illustrates the Matlab Simulink block diagram of the VSWT, including the MPPT control.

Because the wind speed changes with environmental conditions, the system should seek a maximum power operation point. P_1, P_2 and P_3 in Fig. 3 are the maximum power operating points at the corresponding ω_1, ω_2 and ω_3 rotating speeds for three different wind speeds v_1, v_2 and v_3 in the steady state regime [10].

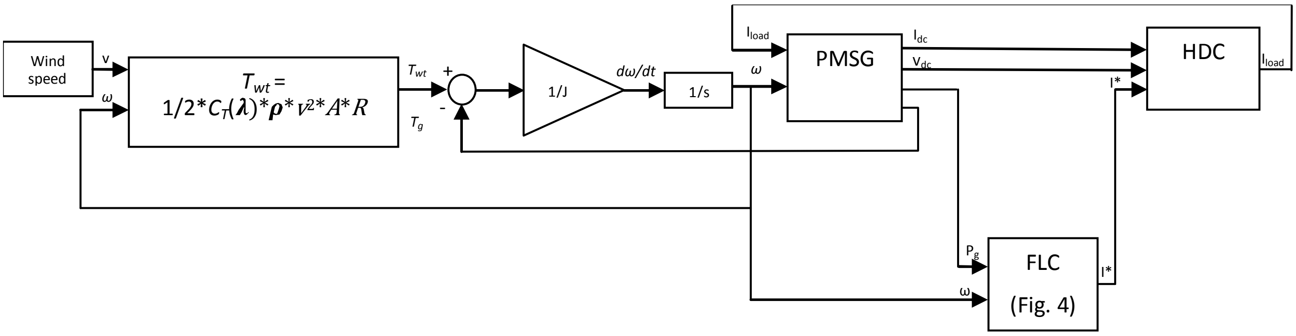

Fig. 2. Block diagram of the wind turbine control system.

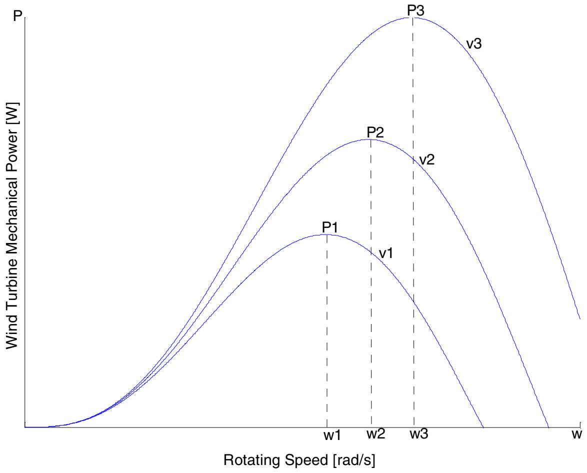

Fig. 3. Wind turbine characteristics illustrated for three wind speeds.

III. FUZZY LOGIC CONTROLLER

The MPPT - FLC has to extract the maximum available power from the wind by increasing or decreasing the reference rectified PMSG current. Changing the PMSG current changes the PMSG torque, which will modify the rotating speed according to (6). In the steady state, if the operating point is on the left side of the maximum power point on the curve (Fig. 3), to attain the optimum power operating point, the controller has to decrease the reference current and, as a result, the rotating speed increases. In this way the operating point will move to the right to a higher power point. In the other case, when the operating point is on the right side of the maximum power point, the reference current needs to be increased. In this way the speed will decrease and the operating point will move to the left, to a higher power point.

In some papers only the steady state operation is described and analyzed. This approximation works if the inertia of the turbine is relatively large, and the wind speed changes slowly.

For low power VSWT, working almost continuously in transient regimes, the energy stored by the rotor inertia is considerable and the controller must be able to account for it and correctly manage the dynamic operation.

The proposed FL controller is shown in Fig. 4. Its input variables are: change in mechanical power (ΔP_m), change in rotating speed ($\Delta\omega$) and the sign of $\Delta P_m/\Delta\omega$. The output variable is the change in dc reference current (ΔI^*). The considered mechanical power (P_m) it is composed by:

$$P_m = P_g + J \cdot \omega \cdot \frac{d\omega}{dt} \tag{13}$$

where

P_g : PMSG mechanical (input) power [W],

resulting the dynamic power versus rotating speed curve. These input and output variables are normalized in the range of [-1 1], according to the system behavior in order that the FLC block to be universal for other wind turbine systems. The used scale coefficients are k_w, k_P and the integrator gain k. The FLC algorithm is characterized by “if then” rules as shown in Table I. The fuzzy basic rules, which associates the fuzzy output to the fuzzy input, is derived from the desired system behavior and the designed control strategy. The rules are designed so that the controller always seeks a maximum power point, without stopping. The fuzzy values are: *N*

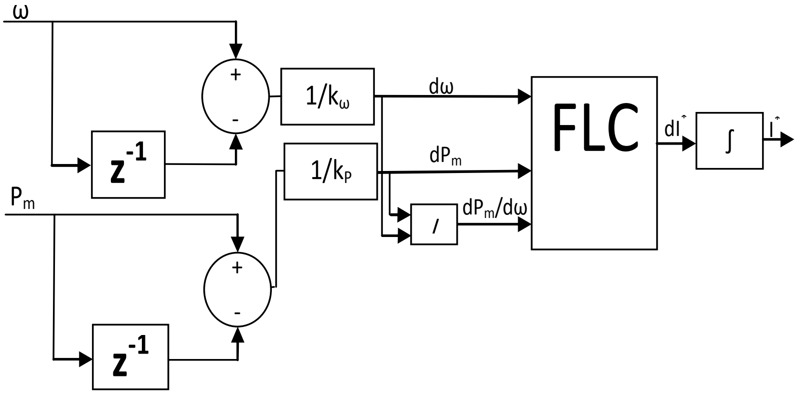

Fig. 4. MPPT FLC used for the wind turbine control system.

(negative), *NS* (negative small), *Z* (zero), *PS* (positive small) and *P* (positive). The output fuzzy sets are then identified using a fuzzy implication method, which is a *MIN-MAX* method. The triangular and trapezoidal membership functions of the FLC are used. The center of gravity (or centroid) defuzzification method was also implemented.

TABLE I
BASIC RULES OF THE FUZZY LOGIC CONTROLLER

dI*		dP_m									
		N		NS		Z		PS		P	
dω	N	N		N		N	N		N		N
	NS	N		NS		N	N		N		N
	Z	N	N	NS	NS	NS	PS	P	N	P	N
	PS		P		PS	P	PS	P		P	
	P		P		P	P	PS	P		P	
Fuzzy values in red are for $dP_m/ d\omega > 0$ (P) and in blue are for $dP_m/ d\omega < 0$ (N)											

IV. SIMULATION RESULTS

The wind turbine control system parameters are:

- Rated wind turbine power, $P_n = 5.5$ [kW];
- Rated wind speed, $v_0 = 11$ [m/s];
- Maximum speed, $n = 126$ [rpm];
- Pole pairs, $p_p = 16$;
- Turbine inertia, $J_{wt} = 140$ [kg·m^2];
- PMSG inertia, $J_g = 1.05$ [kg·m^2];
- Blade swept area, $A = 19.6$ [m^2];
- Radius of the turbine blade $R = 2.5$ [m];
- Maximum coefficient of power conversion $C_P = 0.42$;
- Nominal tip-speed ratio $\lambda_0 = \omega \cdot R / v_0$;
- Constants for the nominal tip speed ratio ($\lambda_0 = 3$): $a = 0.0986$, $b = 0.0113$, $C_{T0} = 0.0222$;
- Specific density of air $\rho = 1.225$ [kg/m^3];
- $k_{opt} = 2.98$;
- *PM* flux $\Psi_{PM} = 1.32$ [Wb];
- Stator resistance $R_s = 1.1$ [Ω];
- Stator inductance $L_s = 0.045$ [mH];
- Diode voltage drop $V_{don} = 0.8$ [V];
- Filter capacitance $C_f = 1\text{e-}3$ [F];
- $k_v = 3/\pi$; $k_i = 2/\pi$;
- $k_w = 4$; $k_P = 2000$; $k = 6$.

The sample time of the wind turbine system simulation is set to 1 ms and the sample time of the fuzzy logic controller is set to 100 ms.

Fig. 5 shows the step response of the fuzzy logic controller for a wind speed step variation from 7 to 10 [m/s].

The controller power response (in red) was compared with optimum points (in green) obtained with (5), knowing the steady state wind turbine characteristics, as in [4]. The MPPT - FLC response shows that the controller can seek and also can track the maximum power value for every wind speed.

Fig. 6 shows the power versus rotating speed characteristics for a wind speed step of 7 – 10 – 7 [m/s]. This figure also illustrates the proposed algorithm. The trajectories on the power curves are: in red is represented the mechanical power curve (P_m) and in blue the PMSG input mechanical power curve (P_g). Initially for a wind speed step of 7 [m/s] the operation climbs the power curve until it reaches to the maximum operating power point (MPP), where the operation almost reaches the steady state regime. When the wind velocity suddenly changes to 10 [m/s] the wind turbine power will jump on the higher power curve while the rotating speed cannot change instantaneously (because of the system inertia and because the command for the rotating speed is not yet established). Subsequently, the operation reaches the MPP on the 10 [m/s] curve. When the wind speed decreases back to 7 [m/s] the P_g also decreases with the decrease of the rotating speed until it reaches again the MPP on the 7 [m/s] curve. It can be noticed that for some instants the P_g is bigger or smaller than the P_m and that happens during transients because of the accelerating or decelerating torque and the corresponding mechanical energy, until the optimal stabilized rotating speed is reached.

Fig. 7 shows the power versus rotating speed curves obtained with MPPT-FLC for the inertia (J_1) decreased with 50% (Fig. 7. a.) and for the inertia (J_2) increased with 50% (Fig. 7. b.) of the wind turbine inertia, for a wind speed step of 7 – 10 - 7 [m/s]. These curves prove that the fuzzy logic based control strategy is robust with respect to changes in wind turbine system parameters.

Fig. 8 shows the power versus rotating speed curves obtained with MPPT-FLC for different values of the C_T for a wind speed of 10 [m/s]. The value of C_T was increased (C_{T1}) and decreased (C_{T2}) with 20% of the wind turbine specific C_T. These curves prove that the fuzzy logic based control strategy is robust with respect to changes in wind turbine characteristics.

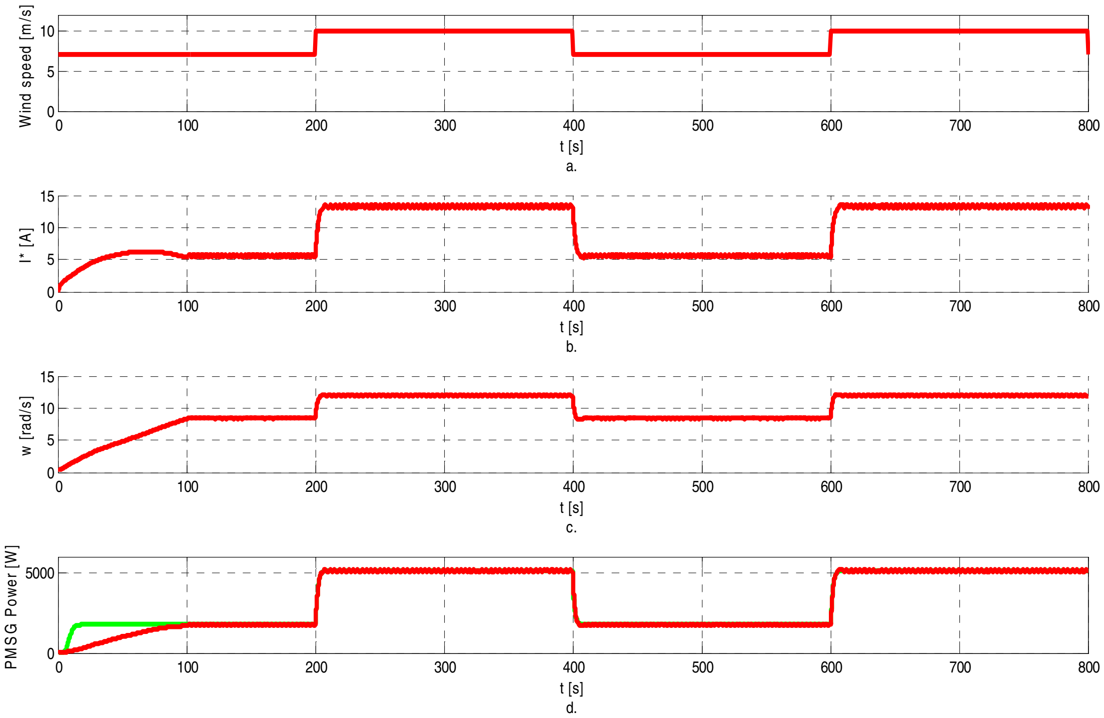

Fig. 5. Simulation results for a wind speed step between 7 - 10 [m/s]: a) Wind speed; b) Reference current; c) Rotating speed; d) PMSG mechanical power.

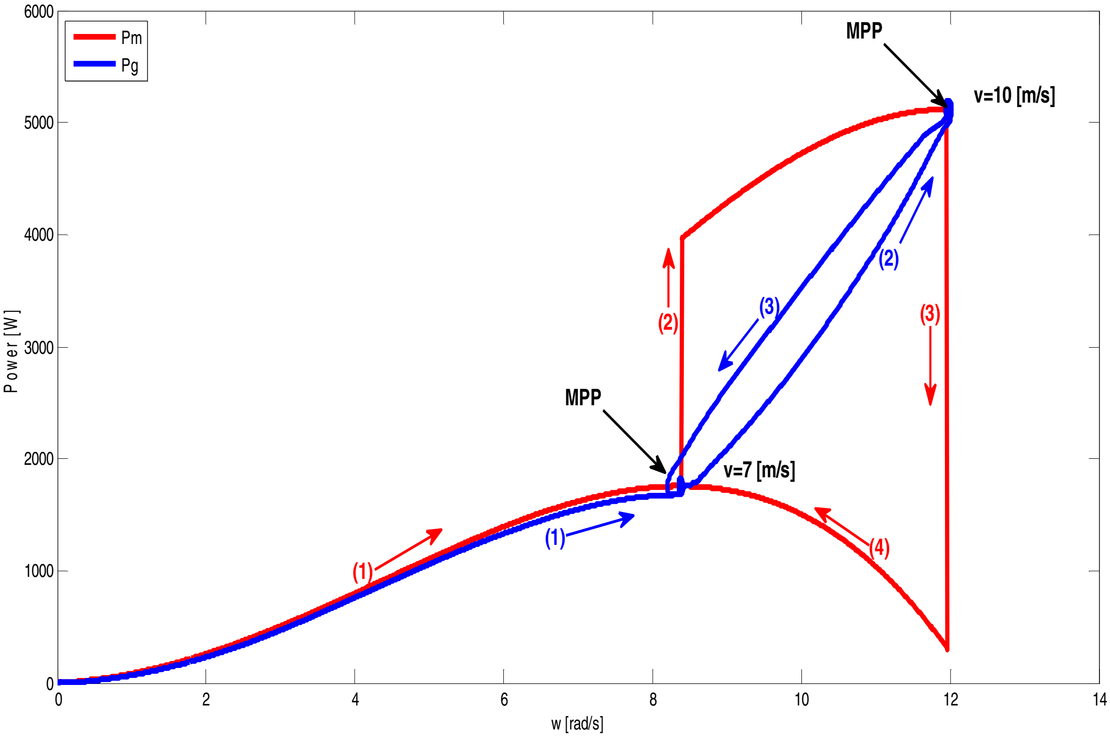

Fig. 6. Mechanical power (P_m) and PMSG input mechanical power (P_g) versus rotating speed (w) curves obtained for a wind speed step of 7-10-7 [m/s].

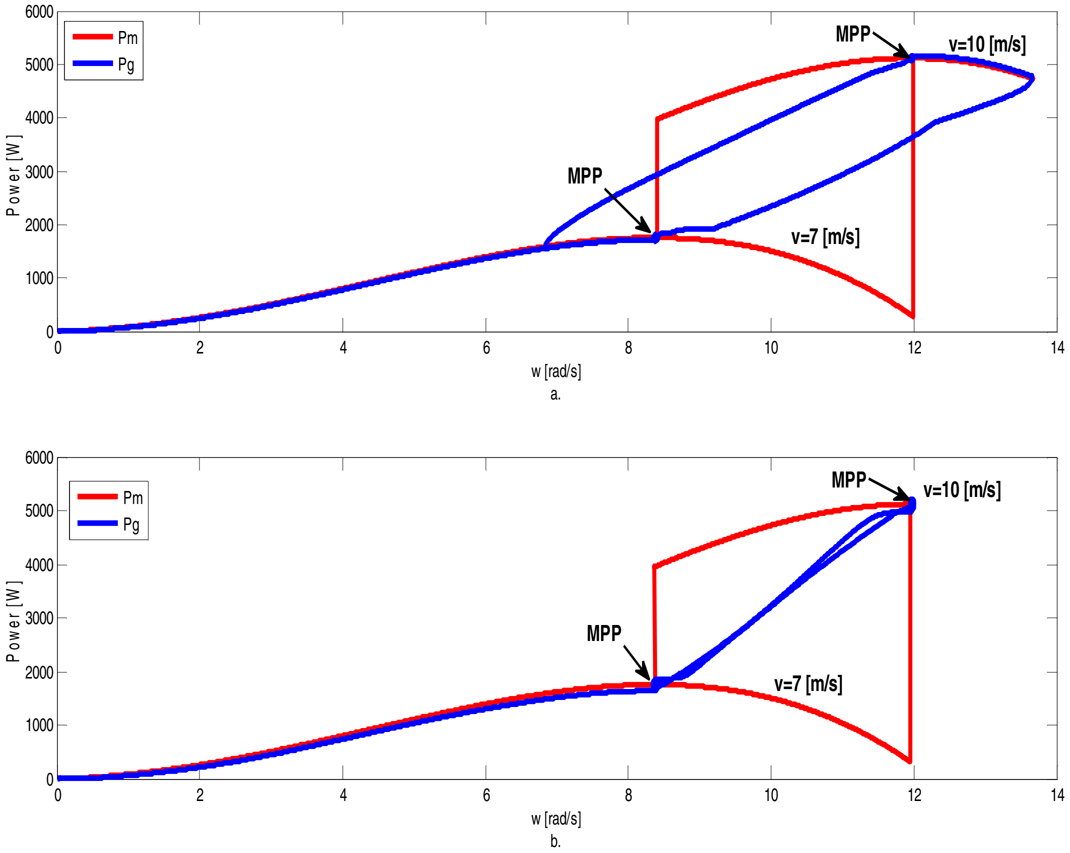

Fig. 7. Mechanical power (P_m) and PMSG input mechanical power (P_g) versus rotating speed (w) curves obtained for a wind speed step of 7-10-7 [m/s]: a). the value of J was decreased with 50% of the wind turbine system J; b). the value of J was increased with 50% of the wind turbine system J.

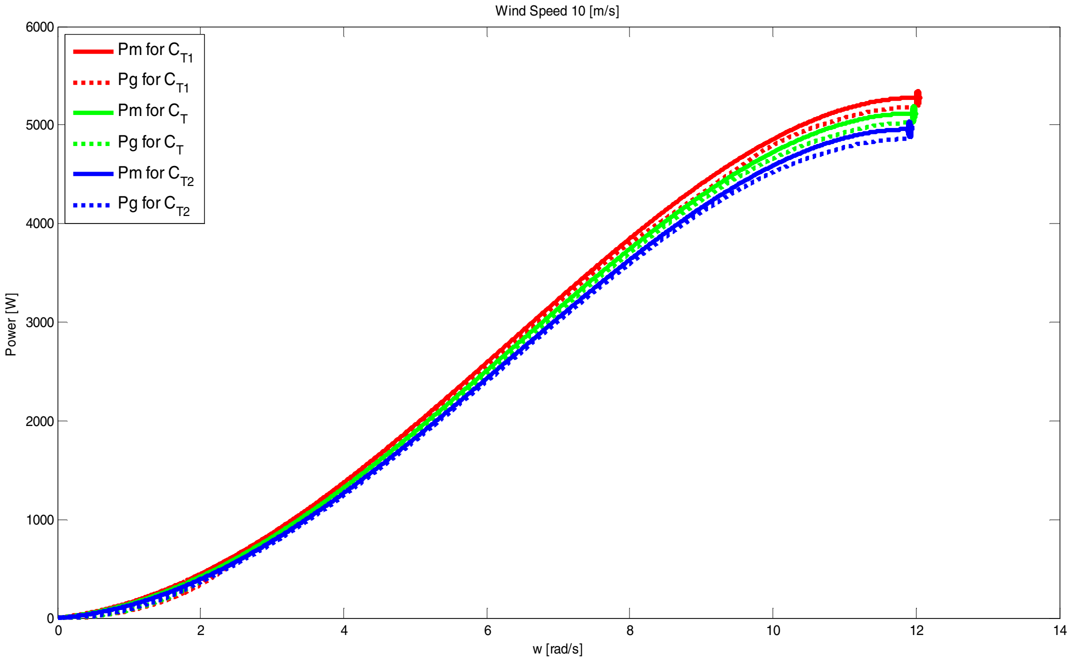

Fig. 8. Mechanical power (P_m) and PMSG input mechanical power (P_g) versus rotating speed (w) curves obtained for different values of C_T for a wind speed of 10 [m/s].

V. CONCLUSION

For low power wind systems, an MPPT control algorithm is a key component necessary to extract the maximum available power from the wind turbine system.

Simulation results presented in this paper prove that a good MPPT strategy can be implemented with a fuzzy logic controller. The advantages of the implemented controller are the fast response and its robustness. This FLC can be used even if the wind turbine systems parameters, wind turbine characteristics or the wind speed are changing or unknown. Another advantage is the simplicity and low computational cost of the FLC, designed just by the needed rules and the associated fuzzy operations.

It is also notable that the FLC does not require the knowledge of the wind speed.

It is concluded that the fuzzy logic is a valid tool for MPPT in small power wind systems.

Future work will be focused on testing the proposed control strategy on a wind turbine emulator setup in order to complete the validation of the simulation results.

ACKNOWLEDGMENT

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