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Power Control of Wind Turbine based on Fuzzy Controllers

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Abstract

In this paper, we develop the overall model of the wind energy conversion system (WECS) structure based on induction generator (IG), and propose a study of the electrical parts (induction machine and static converter). Our study is developed on a wind conversion system in order to produce optimum power and to extract the maximal wind power. The goal of this paper is to control the power generated by the WECS and transmitted to the grid. We propose a new control strategy based on fuzzy logic in order to control the power generated by the WECS. The main drawback is that the WECS is highly nonlinear, and thus a nonlinear control strategy is required. An adaptive fuzzy power controller is proposed to overcome this problem. A simulation study is done to prove the validation of the strategy used in power control.

Keywords: Wind energ; Induction generato; Fuzzy logic control; Power control.

1. Introduction

In the last century, the human activities have increased in the field of production (industry, etc) and in development of human life quality. These new activities require more electrical energy [1]. The consequences of the increasing consumption affect significantly the environment and the world reserves of fossil fuel. Such situations move us to think using new sources of energy, sources that are renewables and clean. Renewable energies (solar, wind, etc.) constitute excellent solutions to both the increase of energy consumption and environment problems. These energies neglected in the past, find their proper place, obtained through research and studies that are increasingly diverse and multidisciplinary.

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In this paper, we focus on the conversion of wind energy into electrical energy that becomes competitive to other energy sources [2]. This source is object of advanced researches, which aim to

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develop techniques for extracting power with high reliability, lower cost and increased energy efficiency [2-4]. In this context, the present study focuses on wind energy using induction generator (IG). The aim of this paper is to present a comprehensive model of an induction generator based on a proposed structure and control strategies to optimize and control the output power transmitted to the network [1], [8]. Our aim is to develop new controller based on fuzzy logic control (FLC) in order to design a new generation of robust controllers.

The organization of this paper is as follow: in the second section, we establish the model of the wind conversion system. The third and fourth sections are devoted to vector control of IG and the control strategy of the WECS. In section 5, we develop power controllers based on fuzzy logic techniques. The sixth section is devoted to the simulation results and finally conclusions are summarized in the last section.

Nomenclature

ρ	Air density
R	Blade length
v	Wind speed
C_p	Power coefficient
Ω	Turbine angular speed.
R_s	Stator resistance
L_s, L_r	respectively stator and rotor inductances
M_{sr}	Mutual inductance
ϕ_{ds} and ϕ_{qs}	respectively direct and quadrature stator flux
ϕ_{dr} and ϕ_{qr}	respectively direct and quadrature rotor flux
T_W	Wind torque
T_e	Electromagnetic torque
p	Pair number of poles
B	Damping coefficient
J	Moment of inertia
ω_s	Electrical angular speed of stator
ω_r	Electrical angular speed of rotor
ω and Ω	Electrical and mechanical angular speed of motor
θ and θ_e	respectively mechanical and electrical rotor position.

2. Wind Conversion System

The WECS described in this article includes the wind turbine, IG, a diode rectifier, a filter and a PWM controlled inverter. In this system, the wind energy is transmitted through the turbine to the three-phase induction machine and generated in electrical form. This energy is transmitted directly to the grid. The control of the power extracted and transmitted to the grid is done by the control of the rotor voltages (Figure 1).

2.1. Turbine Model

The turbine power and torque developed are given by the following relations [2, 5, 6]:

$$P_m = \frac{1}{2}\rho\pi R^2 v^3 C_p(\lambda) \quad (1)$$

$$T_m = \frac{P_m}{\Omega} = \frac{1}{2\lambda}\rho\pi R^3 v^2 C_p \quad (2)$$

Where λ corresponds to the ratio between the turbine angular speed and the wind speed:

$$\lambda = \frac{\Omega R}{v} \quad (3)$$

The power coefficient (C_p) is the aerodynamic efficiency of the turbine and depends on the specific speed λ and the angle of the blades. It is different from a turbine to another, and it is usually provided by the manufacturer and can be defined by a mathematical approximation.

2.2. Generator Model

The generator chosen for the conversion of wind energy is the IG. The dynamic model of IG is presented in d-q frame (Park model) and is defined by the electrical equations, the flux linkage equations and the mechanical equation [7-9]. The electrical equations are:

$$\begin{aligned} v_{ds} &= \mathrm{R_s}\, i_{ds} + \frac{\mathrm{d}}{\mathrm{d}t}\phi_{ds} - \omega_s\, \phi_{qs} \\ v_{qs} &= \mathrm{R_s} i_{qs} + \frac{\mathrm{d}}{\mathrm{d}t}\phi_{qs} + \omega_s\, \phi_{ds} \\ v_{dr} &= \mathrm{R_r}\, i_{dr} + \frac{\mathrm{d}}{\mathrm{d}t}\phi_{dr} - \omega_r\, \phi_{qr} \\ v_{qr} &= \mathrm{R_s} i_{qr} + \frac{\mathrm{d}}{\mathrm{d}t}\phi_{qr} + \omega_r\, \phi_{dr} \end{aligned} \quad (4)$$

The flux linkage equations are:

$$\begin{aligned} \phi_{ds} &= \mathrm{L_s} i_{ds} + \mathrm{M_{sr}} i_{dr} \\ \phi_{qs} &= \mathrm{L_s} i_{qs} + \mathrm{M_{sr}} i_{qr} \\ \phi_{dr} &= \mathrm{L}_r i_{dr} + \mathrm{M_{sr}} i_{ds} \\ \phi_{qr} &= \mathrm{L_r} i_{qr} + \mathrm{M_{sr}} i_{qs} \end{aligned} \quad (5)$$

The mechanical equation of IG and the electromagnetic torque can be represented by:

$$\mathrm{J}\frac{\mathrm{d}}{\mathrm{d}t}\Omega = T_W - T_e - B\Omega \quad (6)$$

$$T_e = p(\phi_{ds} i_{qs} - \phi_{qs} i_{ds}) \tag{7}$$

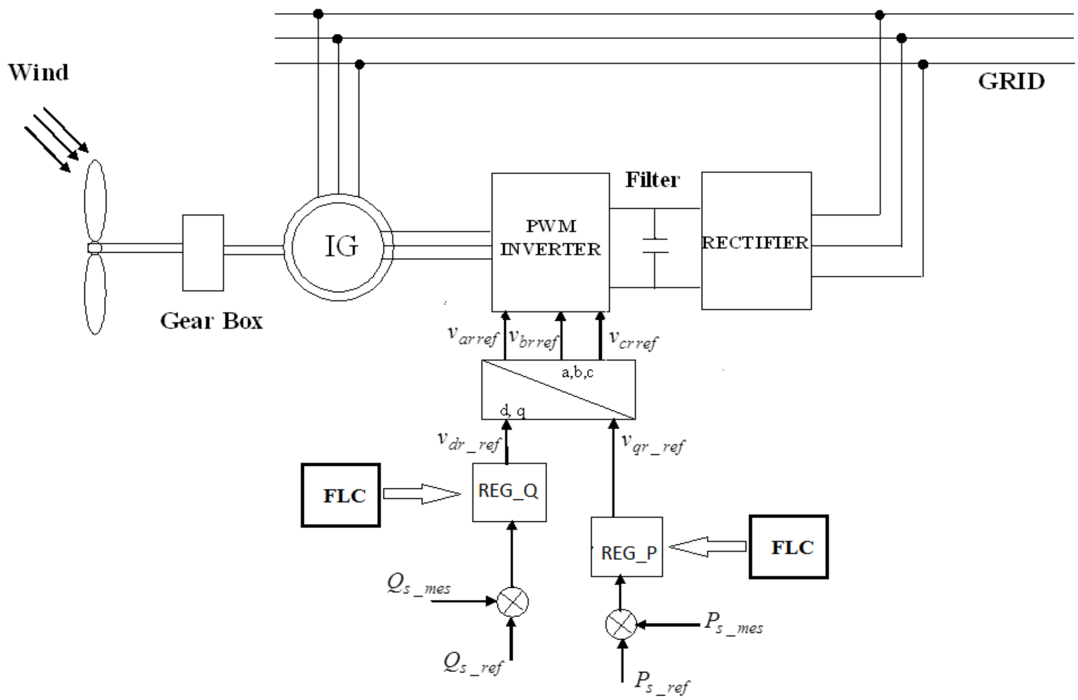

Fig. 1. Wind system based on induction generator.

3. Vector Control

The control of the active and reactive power of the induction generator can be obtained by using the rotor field oriented control. The principle is to maintain the armature flux and the field flux in an orthogonal or decoupled axis. To control the active and reactive power independently, we have to control the direct and quadrature rotor currents independently and then to make the direct and quadrature rotor voltages in decoupled axis by introducing the compensation terms. Substituting Eq. (5) in Eq. (4), the rotor voltages can be rewritten:

$$\begin{aligned} v_{dr} &= \mathrm{R}_r i_{dr} + \sigma L_r \frac{di_{dr}}{dt} - g\omega_s \sigma L_r i_{qr} \\ v_{qr} &= \mathrm{R}_r i_{qr} + \sigma L_r \frac{di_{qr}}{dt} + g\omega_s \sigma L_r i_{dr} + g\frac{MV_s}{L_s} \end{aligned} \tag{8}$$

Where: $\sigma = 1 - \frac{M^2}{L_r L_s}$, $g = 1 - \frac{\omega_r}{\omega_s}$.

In the same conditions, it appears that the v_{dr} and v_{qr} equations are coupled. A decoupling system is established, by introducing the compensation terms defined by:

$$\begin{aligned} Fem_d &= g\omega_s \sigma L_r i_{qr} \\ Fem_q &= -g\omega_s \sigma L_r i_{dr} - g\frac{MV_s}{L_s} \end{aligned} \tag{9}$$

4. Control Strategy

The active and reactive powers generated by IG are defined in the Park model are:

$$\begin{aligned} P_s &= V_{ds} i_{ds} + V_{qs} i_{qs} \\ Q_s &= V_{qs} i_{ds} - V_{ds} i_{qs} \end{aligned} \quad (10)$$

The stator flux vector is oriented on *d* axis: $\phi_{qs} = 0$, $\phi_{ds} = \phi_s$ $V_{qs} = V_s$, $V_{ds} = 0$. Then we can have:

$$\begin{aligned} P_s &= V_{qs} i_{qs} \\ Q_s &= V_{qs} i_{ds} \end{aligned} \quad (11)$$

The principle is to maintain the active and reactive power in a decoupled axis. The active power in the machine is controlled independently by the quadrature rotor current i_{qr} and the reactive power by the direct rotor current i_{dr}. From equations (4, 5, 11) we can obtain:

$$\begin{aligned} P_s &= -V_s \frac{M}{L_s} i_{qr} \\ Q_s &= -V_s \frac{M}{L_s} i_{dr} + \frac{V_s \phi_s}{L_s} \end{aligned} \quad (12)$$

Then, the simplified model of IG can be presented by figure (2).

5. Fuzzy Logic Control

The structure of a complete fuzzy control system is composed from the following blocs:

- Fuzzification,
- Knowledge base,
- Inference engine,
- Defuzzification.

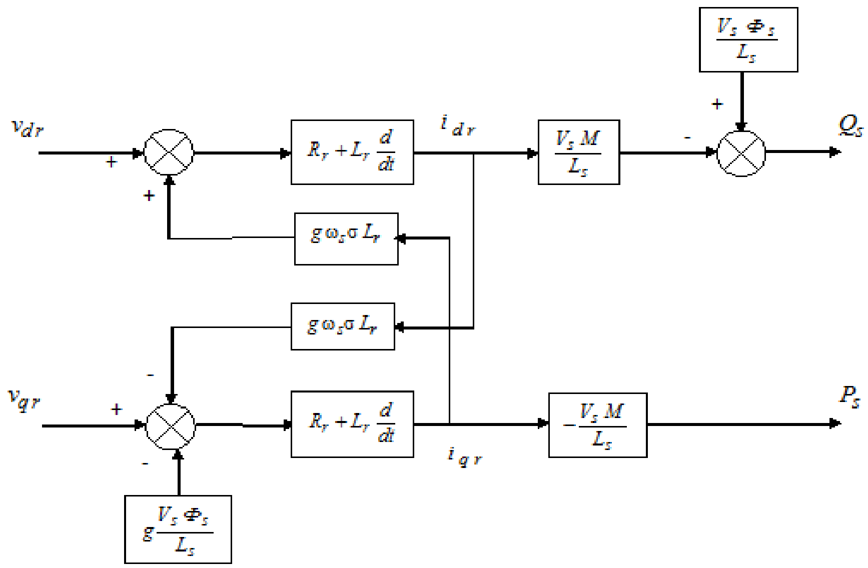

Fig. 2. Simplified model of induction generator

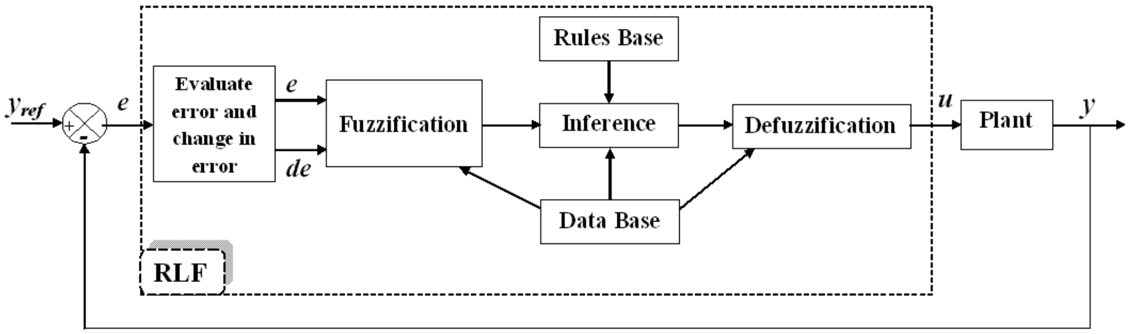

Fig. 3. Basic structure of fuzzy control system

Figure (3) shows the structure of a fuzzy logic controller.

5.1. Fuzzy logic principle

The fuzzification module converts the crisp values of the control inputs into fuzzy values. A fuzzy variable has values which are defined by linguistic variables (fuzzy sets or subsets) such as low, medium, high, big, slow, etc. Each fuzzy set is defined by a gradually varying membership function. In fuzzy set terminology, all the possible values that a variable can assume are named universe of discourse, and the fuzzy sets cover the whole universe of discourse. The shape of fuzzy sets can be triangular, trapezoidal, etc [9, 10].

A fuzzy control essentially embeds the intuition and experience of a human operator, and sometimes those of a designer and researcher. The data base and the rules form the knowledge base which is used to obtain the inference relation R. The data base contains a description of input and output variables using fuzzy sets. The rules base is essentially the control strategy of the system. It is usually obtained from expert knowledge or heuristics containing a collection of fuzzy conditional statements expressed as a set of IF-THEN rules, such as:

$$R^{(i)} : \textbf{If } x_1 \text{ is } F_1 \text{ and } x_2 \text{ is } F_2 \ldots\text{and } x_n \text{ is } F_n \quad \textbf{THEN } \; Y \text{ is } G^{(i)}, \; i=1, \ldots, m$$

where : $(x_1, x_2, \ldots, x_n)$ is the input variables vector, Y is the control variable, m is the number of rules, n is the number of fuzzy variables, $(F_1, F_2, \ldots F_n)$ are the fuzzy sets.

For the given rules base of a control system, the fuzzy controller determines the rule base to be fired for the specific input signal condition and then computes the effective control action (the output fuzzy variable) [8, 9].

The composition operation is the method by which such a control output can be generated using the rules base. Several composition methods, such as max-min, sup-min and max-dot have been proposed in the literature.

The mathematical procedure of converting fuzzy values into crisp values is known as ‘defuzzification’. A number of defuzzification methods have been suggested. The choice of defuzzification methods usually depends on the application and the available processing power. This operation can be performed by several methods of which the centre of gravity (or centroïd) and the height methods are common [11, 12].

5.2. Fuzzy logic controller

The general structure of a complete fuzzy control system is given in figure (5). The plant control $\boldsymbol{u}$ is inferred from the two state variables, error (e) and change in error (de) [9]. The elaboration of this controller is based on the phase plane. The control rules are designed to assign a fuzzy set of the control input u for each combination of fuzzy sets of e and de [13, 14].

Table 1. Rules Base.

		e				
	U	**NB**	**NM**	**ZR**	**PM**	**PB**
	NB	**NB**	**NB**	**NM**	**PM**	**ZR**
	NM	**NB**	**NM**	**NS**	**ZR**	**PS**
de	**ZE**	**NM**	**NS**	**ZR**	**PS**	**PM**
	PM	**NS**	**ZR**	**PB**	**PM**	**PB**
	PB	**ZR**	**PS**	**PM**	**PB**	**PB**

Table (1) shows the rules base. The rows represent the rate of the error change $\dot{e}$ and the columns represent the error e. Each pair $(e, \dot{e})$ determines the output level NB to PB corresponding to $\boldsymbol{u}$. Where: NB is negative big, NM is negative medium, NS is negative small, ZR is zero, PS is positive small, PM is positive medium and PB is positive big; they are labels of fuzzy sets and their corresponding membership functions are depicted in figure (4).

The continuity of input membership functions, reasoning method, and defuzzification method for the continuity of the mapping $u_{fuzzy}(e, \dot{e})$ is necessary. In this paper, the triangular membership functions, the max-min reasoning method, and the center of gravity defuzzification method are used, as those methods are the most frequently used in the literature [9, 12].

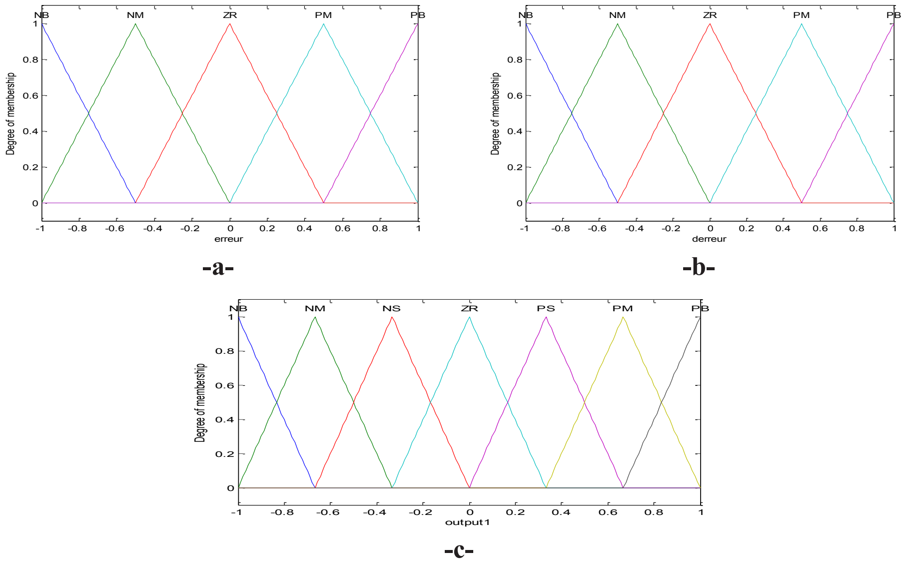

Fig. 4. Membership functions: -a- error (e) , -b- Δe , -c- output u.

The inferred value of the control action in correspondence to the values $X_{10}, X_{20},..X_{n0}$ of the states can be obtained by the Centre of Gravity method [13, 14]:

$$u = \frac{\sum_{j=1}^{n} \alpha_j u_j}{\sum_{j=1}^{n} \alpha_j} \quad (13)$$

where α_j is the degree of fulfilment of the j-th control rule. It can be computed by

$$\alpha_j = \mu_j(X_{j0}) \quad (14)$$

where $\mu_j(X_{j0})$ is the grade of membership of X_{j0}.

6. Simulation Results

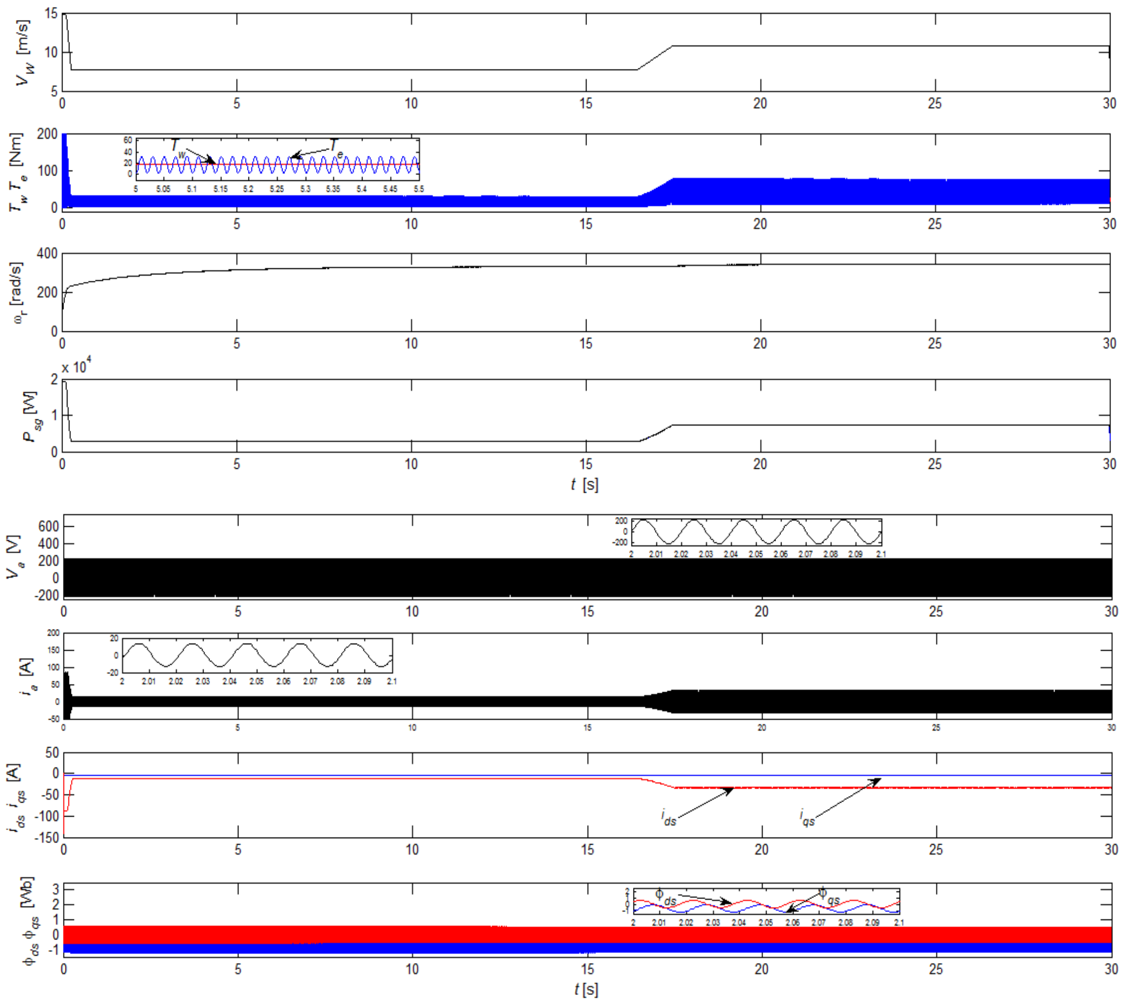

Fig. 5. Response of the system with PI controllers.

In this section, we have simulated, in Matlab-Simulink, the system described in Figure (1). IG Parameters: Rated output power 7,5 kW, Rated phase voltage 400V, f=50Hz, p=2, R_r=0.62Ω, R_s=0.455Ω, L_r=0.081H, L_s=0.084H, M_{sr}=0.078H, J=0.3125 kg.m^2 , f=0.00673 N.m/s. For simplicity, we have supposed that the inverter is perfect. First, we have simulated the system as it is described in figure (1). To extract the maximum power from the wind, the desired active power is the one delivered by the wind turbine.

In figure (6), we apply the fuzzy logic technique to control active and reactive powers. The results are with big satisfaction, the controller gives best performances in tracking the desired trajectory with no overshoot and with a negligible steady state error compared with the PI regulators. Figure (6) shows that the use of Fuzzy logic technique allowed us to have high performances to follow the desired trajectory. Figure (7), shows a comparison of the response of the WECS when using PI and Fuzzy logic controllers: the fuzzy control gives higher performance than the classical controller.

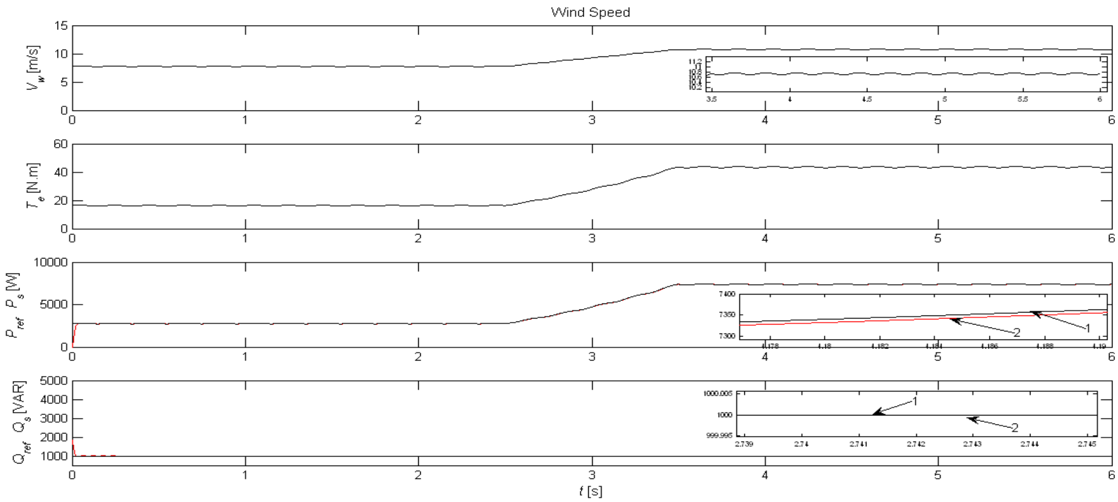

Fig. 6. Response of the system when using power Fuzzy logic controller: 1- Reference power, 2- Measured Power.

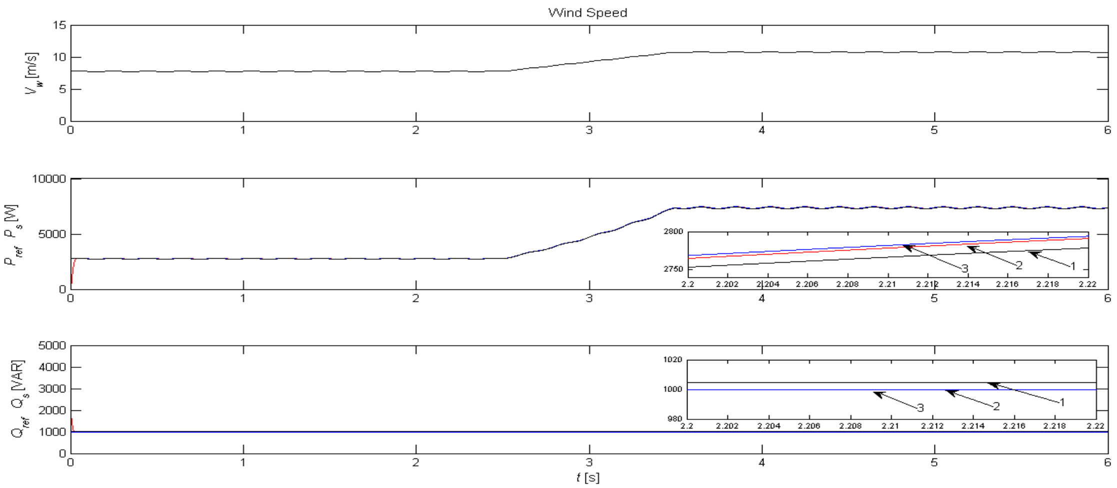

Fig. 7. Comparison of the closed-loop responses when using power fuzzy logic controller and PI controller:1- PI control, 2- Fuzzy control, 3-Reference power.

7. Conclusion

In this paper, a new method of control was designed and applied to control the power generated By the WECS. We have described the different structures of wind turbines based on the IG, we have established a model of the wind conversion chain, and designed a control strategy using the concept of vector control. The whole system was validated for variable speed using a PI controller. We have subsequently built a device for controlling the chain of the proposed conversion by using fuzzy logic technique. The overall system was tested for a variable wind speed. The simulation results show the possibility of extracting the maximal power from the wind, the control of the power generated to the grid by controlling the rotor voltages and the high performances of the controller based on fuzzy logic techniques.

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