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A comparative study between a simplified fuzzy PI and classic PI input-output linearizing controller for the wind-turbine doubly fed induction generator

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Abstract. The paper presents a comparative study of a linearizing control with classic PI and fuzzy PI controllers of the active and reactive stator power of a doubly fed induction generator (DFIG) applied to a wind-energy conversion systems (WECS).
The paper discusses the operating principles of the power-generation scheme. Simulation results show that the preented input-output linearizing control provides a decoupled control, perfect tracking of the generated active and reactive power and robustness the active- and reactive-power variations.

Keywords: Doubly-Fed Induction Generator (DFIG), Input-Output linearization, Fuzzy Logic Controller (FLC).

Primerjalna študija poenostavljenega mehkega PI in klasičnega regulatorja pri dvojno napajanem asinhronskem generatorju v vetrnih elektrarnah

V prispevku smo predstavili primerjalno študijo uporabe klasičnega in mehkega regulatorja PI za linearizirano krmiljenje delovne in jalove moči pri dvojno napajanem asinhronskem generatorju v vetrnih elektrarnah. Predstavili smo principe delovanja obeh regulatorjev. Rezultati simulacije potrjujejo, da predlagano krmiljenje ponuja nadzor odklopa, beleženje proizvedene delovne in jalove moči in stabilnost pri odstopanju proizvedene moči.

1 INTRODUCTION

Wind energy is one of the most important and promising sources of the renewable energy all over the world, mainly because it is considered to be non-polluting and economically viable. At the same time, there has been a rapid development of the related wind-energy conversion technology [1].

In terms of the wind-power generation technology, because of the numerous technical benefits (higher energy yield, reduced power loses and improved supply), the modern MW-size wind turbines always use a variable-speed operation which is achieved by the converter system [2].

The used converters are typically associated with individual generators and they contribute significantly sto the costs of wind turbines. Among the variable-speed wind-turbine generators, doubly-fed induction generators (DFIGs) and permanent-magnet synchronous generators (PMSGs) with primary converters are emerging as the preferred technologies [2].

DFIG is widely used for the variable-speed generation, and it is one of the most important generators for the wind-energy conversion systems.

Both the grid-connected and stand-alone operation are feasible through an AC/DC/AC frequency converter [1, 3]. The major DFIG advantage is that the power electronic equipment has to handle a fraction (20-30%) of the total system power in order to guarantee the stability in acceptable conditions [1, 4].

In order to improve control of the active and reactive power generated by DFIG [1], the paper proposes a robust simplified input-output linearizing Fuzzy-PI controller. The controller exhibits excellent dynamics and steady-state performances.

The paper presents a comparative analysis of a simplified input-output linearizing control with a proportional integral (PI) controller and a fuzzy-PI controller for the doubly-fed induction wind-energy conversion system (WECS). Theoretical analysis, modeling and simulation results are provided. A control strategy is developed to control the active and reactive power in order to maximize the wind energy production.

Fig.1 shows the DFIG wind-energy conversion system structure

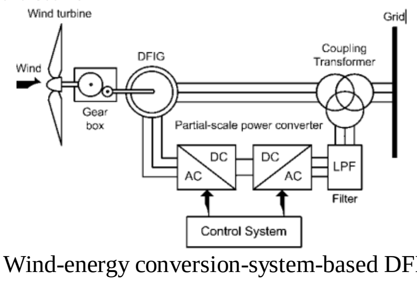

Figure 1. Wind-energy conversion-system-based DFIG.

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2 TURBINE MODEL

Wind turbines convert the wind kinetic energy into mechanical energy by producing a torque. Since the wind-energy is in the form of the kinetic energy, its magnitude depends on the air density and the wind speed.The wind power developed by the turbine is given by equation (1) [15, 16]:

$$P_t = \frac{1}{2} C_p(\lambda) \rho \pi R^2 V^3 \tag{1}$$

where ρ is the air density, R is the radius of the wind turbine, V is the speed of the wind, Cp (λ,β) is the power coefficient, β is the blade pitch angle, and λ is the tip speed ratio of the rotor blade tip speed to the wind speed and is defined by [1]:

$$\lambda = \frac{\Omega_t R}{V} \tag{2}$$

The expression of the turbine torque:

$$C_t = \frac{1}{2} C_m(\lambda, \beta) \rho \pi R^3 V_1^2 \tag{3}$$

In the model, the Cp (λ ,β) value of the turbine rotor is approximated using a non-linear function according to [1].

$$C_p = f(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right) exp\left(\frac{-C_5}{\lambda_i}\right) + C_6\lambda \tag{4}$$

With

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \tag{5}$$

and

$C_1 = 0.5176$; $C_2 = 116$; $C_3 = 0.4$; $C_4 = 5$

$C_5 = 21$; $C_6 = 0.0068$.

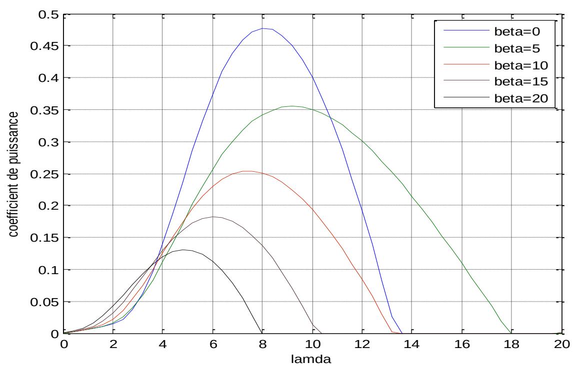


Figure 2. Power coefficient as a function of the speed ratio (λ) and the angle (β).

3 MATHEMATICAL MODEL OF THE TURBINE DFIG MODEL

The most significant feature of the wound-rotor machine, which is widely used for the wind-power generation, is that it has to be fed from both the stator and the rotor side. Normally, the stator is directly connected to the grid and the rotor is interfaced through a variable-frequency back-to-back AC- DC- AC power converter to provide a bidirectional rotor power flow [5].

The DFIG operating principle can be analyzed using the classical theory of rotating fields and the well known d-q model, as well as both the three-to-two and the two-to-three axes transformation. In order to deal with the machine dynamic behavior in the most realistic possible way, both the stator and rotor variables are referred to their corresponding natural reference frames in the developed model. In other words, the stator-side current and voltage components are referred to a stationary reference frame, while the rotor-side current and voltage components are referred to a reference frame rotating at the rotor electrical speed [5,6].

The stator and rotor voltage components are:

$$\begin{cases} V_{sd} = R_s I_{sd} + \dfrac{d\phi_{sd}}{dt} - \omega_s \phi_{sq} \\ V_{sq} = R_s I_{sq} + \dfrac{d\phi_{sq}}{dt} - \omega_s \phi_{sd} \\ V_{rd} = R_r I_{rd} + \dfrac{d\phi_{rd}}{dt} - (\omega_s - \omega_r)\phi_{rq} \\ V_{rq} = R_r I_{rq} + \dfrac{d\phi_{rq}}{dt} - (\omega_s - \omega_r)\phi_{rd} \end{cases} \tag{6}$$

where:

$V_{sd}, V_{sq}, V_{rd}, V_{rq}, I_{sd}, V_{sq}, V_{rd}, V_{rq}$ represent the direct and quadrature voltage and current for the stator and rotor respectively.

The magnetic equations are:

$$\begin{cases} \phi_{sd} = L_s I_{sd} + L_m I_{rd} \\ \phi_{sq} = L_s I_{sq} + L_m I_{rq} \\ \phi_{rd} = L_r I_{rd} + L_m I_{sd} \\ \phi_{rq} = L_r I_{rd} + L_m I_{sq} \end{cases} \tag{7}$$

The expression of the electromagnetic torque based on the dq stator fluxes and dq rotor currents is:

$$C_e = -p \frac{L_m}{L_s} (\phi_{rd} I_{sq} - \phi_{rq} I_{sd}) \tag{8}$$

The DFIG active and reactive power of the stator and rotor of the are:

$$\begin{cases} P_s = \left(V_{sd}\, I_{sd} + V_{sq}\, I_{sq}\right) \\ Q_s = \left(V_{sq}\, I_{sd} - V_{sd}\, I_{sq}\right) \end{cases} \tag{9}$$

4 GENERAL CONCEPT OF THE INPUT-OUTPUT LINEARIZING CONTOL

In order to linearize the system, the MIMO system is considered [8]:

$$\begin{cases} \dot{x} = f(x) + g.u \\ y = h(x) \end{cases} \tag{10}$$

where x is the state vector; u is the output; f and g are smooth vector fields; h is a smooth scalar function.
In order to obtain the input-output linearization of the multi-input multi-output system, output y of the system is differentiated until the inputs appear:

$$\dot{y} = L_f h(x) + L_g h(x) u \tag{11}$$

where L_f and L_g represent the Lie derivative of h(x) with respect to f(x) and g(x) respectively. If $L_{g_i} h_j(x)=0$ for all i, then the inputs do not appear and we have to differentiate again [8]:

$$y = L^{r-1}{}_f\, h(x) + L_g h(x) u \tag{12}$$

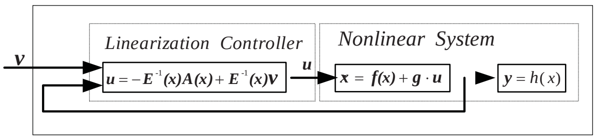


Figure 3. Schematic diagram of the input-output linearizing control.

where *r* is the relative rank of ***y***. Performing the above procedure for each input *yi*, we get a total of *m* equations in the above form written as [8].

$$\begin{bmatrix} y^{(r)}{}_1 \\ \cdots \\ \cdots \\ y^{(r_m)}{}_m \end{bmatrix} = A(x) + E(x) \begin{bmatrix} u_1 \\ \cdots \\ \cdots \\ u_m \end{bmatrix} \tag{13}$$

where the $m{*}m$ matrix ***E(x)*** is defined as [8-9]:

$$E(x) = \begin{bmatrix} L_{g1} L_f^{\,r-1} h_1 & \cdots & \cdots & L_{gm} L_f^{\,r-1} h_1 \\ \cdots & \cdots & \cdots & \cdots \\ \cdots & \cdots & \cdots & \cdots \\ L_{g1} L_f^{\,r_m-1} h_m & \cdots & \cdots & L_{gm} L_f^{\,m-1} h_m \end{bmatrix} \tag{14}$$

$$A(x) = \left[L^{r}{}_f h_1 \quad \cdots \quad \cdots \quad L^{r_m}{}_f h_m\right]^T \tag{15}$$

Matrix ***E(x)*** is the decoupling matrix for the system. If ***E(x)*** is nonsingular, then original input ***u*** is controlled by the coordinate transformation [7]:

$$u = E^{-1}(x)A(x) + E^{-1}(x)v \tag{16}$$

where

$$v = \left[v_1 \quad \cdots \quad \cdots \quad v_m\right]^T \tag{17}$$

Substituting (15) into (13) provides a linear differential relation between the output ***y*** and new input v:

$$\begin{bmatrix} y^{(r)}{}_1 \\ \cdots \\ \cdots \\ y^{(r_m)}{}_m \end{bmatrix} = \begin{bmatrix} v_1 \\ \cdots \\ \cdots \\ v_m \end{bmatrix} \tag{18}$$

The procedure of the input-output linearizing control is shown in Fig. 1.

5 A SIMPLIFIED INPUT-OUTPUT LINEARIZING CONTROL WITH A PI CLASSIC CONTROLLER

In the stator flux-field-oriented frame

$$\phi_{sd} = \phi_s \text{ and } \phi_{sq} = 0 \tag{19}$$

$$\begin{cases} V_{sd} = V_s \\ V_{sq} = 0 \end{cases} \tag{20}$$

Substituting (19) into (7) yields:

$$\begin{cases} I_{sd} = \dfrac{\phi_s}{L_s} - \dfrac{L_m}{L_s} I_{rd} \\ I_{sq} = -\dfrac{L_m}{L_s} I_{rq} \end{cases} \tag{21}$$

According to (21) the direct and quadrature components of the stator and rotor currents are linear and so the state vectors are [7]:

$$x = \left[x_1 \quad x_2\right]^T = \left[i_{rd} \quad i_{rq}\right]^T \tag{22}$$

By substituting (7), (19), and (21) into (6), we get the following aquations hold:

$$\begin{cases} V_{rd} = R_r I_{rd} + \left(L_r - \dfrac{L_m^{\,2}}{L_s}\right)\dfrac{d}{dt} I_{rd} - g\omega_s \left(L_r - \dfrac{L_m^{\,2}}{L_s}\right) I_{rq} \\ V_{rq} = R_r I_{rq} + \left(L_r - \dfrac{L_m^{\,2}}{L_s}\right)\dfrac{d}{dt} I_{rq} + g\omega_s \left(L_r - \dfrac{L_m^{\,2}}{L_s}\right) I_{rd} + g_s \dfrac{L_m V_s}{L_s} \end{cases} \tag{23}$$

Arranging (23) as in (10):

$$\begin{cases} \dfrac{di_{rd}}{dt} = -\dfrac{R}{\sigma L_r} I_{rd} + \left(\dfrac{\omega_s}{L_r}\right)\dfrac{d}{dt} I_{rq} - \dfrac{\omega_r}{L_r} I_{rq} + \dfrac{u_{rd}}{\sigma L_r} \\ \dfrac{di_{rq}}{dt} = -\dfrac{R}{\sigma} i_{rq} - \omega_s L_r i_{rd} + \omega_r L_r I_{rd} + \dfrac{u_{rq}}{\sigma} \end{cases} \tag{24}$$

Defining the input of the DFIG system:

$$u = \begin{bmatrix} u_1 & u_2 \end{bmatrix}^T = \begin{bmatrix} u_{rd} & u_{rq} \end{bmatrix}^T \tag{25}$$

Since the rotor-side controller decouples the active and reactive power, the stator active and reactive powers are selected as the output [7-9]:

$$y = \begin{bmatrix} y_1 \\ y_2 \end{bmatrix} = \begin{bmatrix} p_s \\ Q_s \end{bmatrix} = \begin{bmatrix} u_{sd} i_{sd} + u_{sq} i_{sq} \\ u_{sq} i_{sq} + u_{sd} i_{sq} \end{bmatrix} \tag{26}$$

From (21) and (26) it follows:

$$\begin{cases} y_1 = \dfrac{\phi_s}{L_s} u_{sd} - \dfrac{L_m}{L_s}(u_{sd} i_{rd} + u_{sq} i_{rq}) \\ y_2 = \dfrac{\phi_s}{L_s} u_{sq} - \dfrac{L_m}{L_s}(u_{sq} i_{rd} + u_{sd} i_{rq}) \end{cases} \tag{27}$$

Differentiating (27) until the input appears:

$$\begin{cases} \dot{y}_1 = \dfrac{\dot{u}_{sd}}{L_s}(\phi_s - L_m i_{rd}) - \dfrac{L_m}{L_s}\dot{u}_{sq} i_{rq} - \dfrac{L_m}{L_s}(u_{sd} f_1 + u_{sq} f_2) \\ -\dfrac{L_m u_{sd}}{\sigma L_s L_r} u_{rd} - \dfrac{L_m u_{sq}}{\sigma L_s} u_{rq} \\ \dot{y}_1 = \dfrac{\dot{u}_{sq}}{L_s}(\phi_s - L_m i_{rd}) - \dfrac{L_m}{L_s}\dot{u}_{sd} i_{rq} - \dfrac{L_m}{L_s}(u_{sq} f_1 - u_{sd} f_2) \\ -\dfrac{L_m u_{sq}}{\sigma L_s L_r} u_{rd} - \dfrac{L_m u_{sd}}{\sigma L_s} u_{rq} \end{cases} \tag{28}$$

Rewriting (28) in the form of (13):

$$\begin{bmatrix} \dot{y}_1 \\ \dot{y}_2 \end{bmatrix} = A(x) + E(x)\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \tag{29}$$

where:

$$A(x) = \begin{bmatrix} \dfrac{\dot{u}_{sd}}{L_s}(\phi_s - L_m x_1) - \dfrac{L_m}{L_s}\dot{u}_{sq} x_2 - \dfrac{L_m}{L_s}(u_{sd} f_1 + u_{sq} f_2) \\ \dfrac{\dot{u}_{sq}}{L_s}(\phi_s - L_m x_1) - \dfrac{L_m}{L_s}\dot{u}_{sd} x_2 - \dfrac{L_m}{L_s}(u_{sq} f_1 + u_{sd} f_2) \end{bmatrix} \tag{30}$$

$$E(x) = \begin{bmatrix} \dfrac{L_m u_{sd}}{\sigma L_s L_r} & -\dfrac{L_m u_{sq}}{\sigma L_s} \\ -\dfrac{L_m u_{sq}}{\sigma L_s L_r} & \dfrac{L_m u_{sd}}{\sigma L_s} \end{bmatrix} \tag{31}$$

Since *E(x)* is nonsingular, the control scheme is given from (16) as:

$$\begin{bmatrix} u_{rd} \\ u_{rq} \end{bmatrix} = E^{-1}(x)\left[-A(x) + \begin{bmatrix} v_1 \\ v_2 \end{bmatrix}\right] \tag{32}$$

To track the control and to obtain a robust control of the parameter variations, the input system is[8]:

$$\begin{bmatrix} v_1 \\ v_2 \end{bmatrix} = \begin{bmatrix} \dot{y}_1^* - k_{p1} e_1 - k_{i1}\int e_1 dt \\ \dot{y}_2^* - k_{p2} e_2 - k_{i1}\int e_2 dt \end{bmatrix} \tag{33}$$

where $e1$ is the error between the demanded and the achieved active power, and $e2$ is related to the reactive power [6-7].

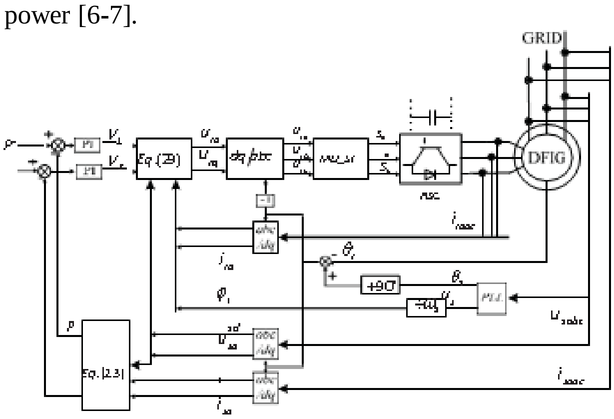


Figure 4. DFIG control diagram using a simplified input-output linearizing control

6 SIMPLIFIED INPUT-OUTPUT LINEARIZING CONTROL WITH A FUZZY-PI CONTROLLER

This type of control system is based on the fuzzy logic that makes use of the tolerance, uncertainty, imprecision and fuzziness in the human decision-making process, offers a very satisfactory performance with no need of a detailed mathematical model of the system.

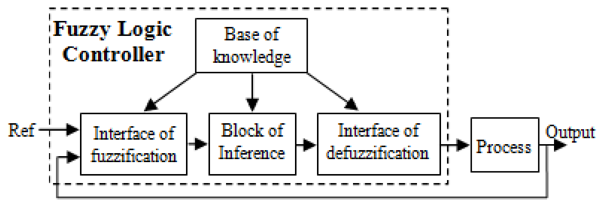


Figure 5. Structure of the proposed fuzzy logic controller.

As shown in Fig. 5, our focus is on the fuzzy logic control based on mamdani system. This system has three main parts. First, by using the input membership functions, the inputs are fuzzified, then based on the rule base and inference system, outputs are produced and finally the fuzzy outputs are defuzzified and applied to the main control system. At any time interval,the error and the error change rate are chosen as inputs. Fig. 4 shows a block diagram where the fuzzy controllers are integrated into the rotor side converter to control the DFIG. The main objective of this part is to control the active and the reactive power.

7 FLC DESIGN

The inputs of the fuzzy controller are the error (e) and the error change rate (Δe) and its output is (Δu). The universe of (e), (Δe), and (Δu) are partitioned into three fuzzy sets, i.e. N (negative), Z (zero) and P (positive). Each fuzzy set is represented by either a triangular or a trapezoidal membership function.
The FLC rule base contains nine rules based on IF-THEN [4].

8 SIMULATION RESULTS AND DISCUSSION

Some illustrations will be introduced now in order to show the dynamic performances of the proposed control system. The controllers are tested at reference tracking and robustness to parameter variations. Our simulations are made on a 1.5 MW generator connected to a 398 V/50 Hz grid.

The DFIG parameters are:
Rs = 0.012 Ω, *Ls* = 0.0137 H, *Rr* =0.021 Ω, *Lr* = 0.0136 H, *Lm* = 0.0135 H, *F* = 0.0024 Nm/s, *J* = 0.0031 kg. m^2 and *R* = 35.25 m.

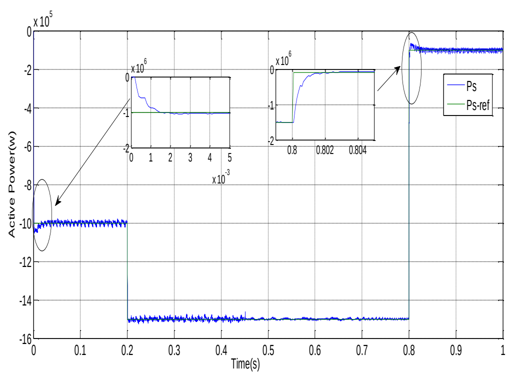
8.1 Pursuit test

The aim of test is to the study the behaviour of the two controllers at reference tracking with the machine speed constant at its nominal value. As seen from the simulation results shown in Fig.6, the active and reactive powers of the two controllers track almost perfectly their references, contrary to the FLC controller where the coupling effect between the two axes is very clear.

8.2 Sensitivity to the speed variations

The aim of this test is to analyze the impact of speed variations on the DFIG active and reactive powers.

Power curves at variation show important oscillations of the PI controller system with, while they are almost negligible for the fuzzy PI system. Here, there are any variations and the power variations are very small. This result is attractive for the wind-energy applications for ensuring stability and quality of the generated power at speed variations.



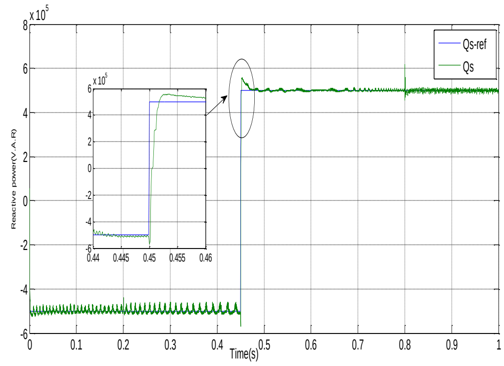


Figure 6. Active and reactive powers for PI classic controller

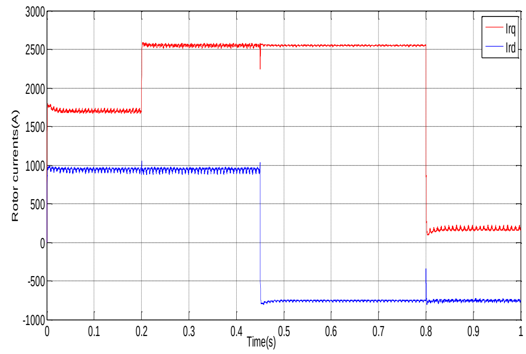


Figure 7. Rotor currents at reference tracking for the PI classic controller

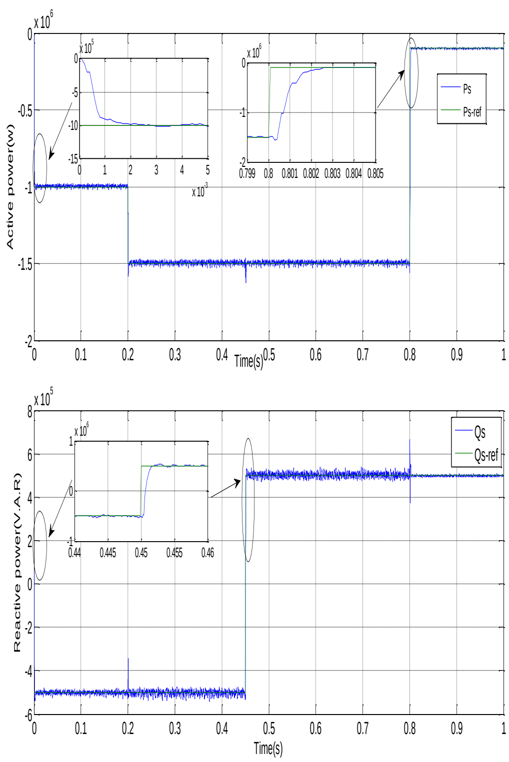


Figure 8. Active and reactive power for the PI fuzzy controller

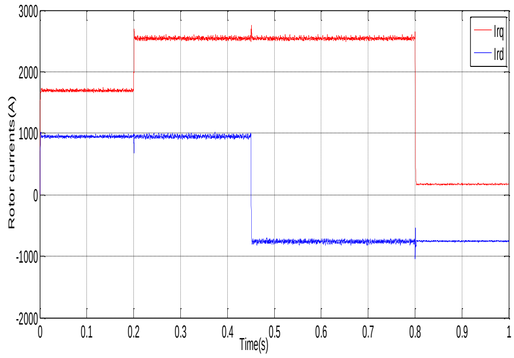


Figure 9. Rotor currents at reference tracking for the PI-fuzzy controller

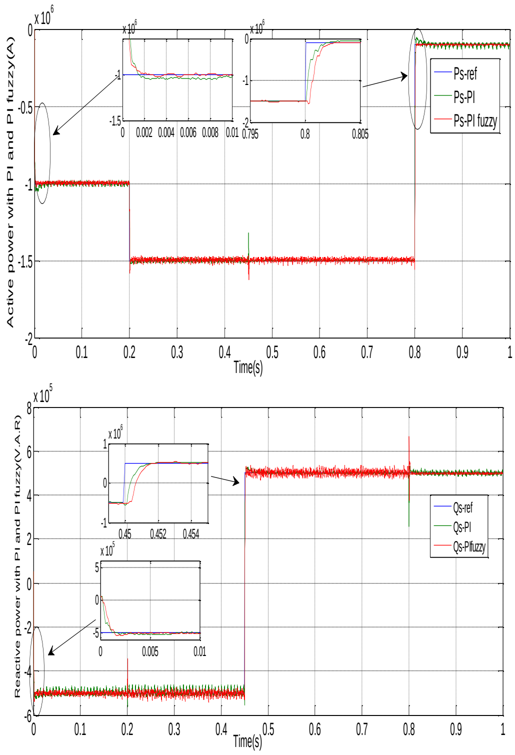


Figure 10. Active and reactive power at speed variations for PI classic and PI-fuzzy controller

9 CONCLUSION

A simplified input-output linearizing fuzzy control applied to a turbine DFIG is propose. A simulation study is made to use it on DFIG of a wind-energy conversion system. The performance of classic PI controller and fuzzy controller used in a wind-power generation are compared. While the design parameters of the PI classic controller have to be tested and adjusted, the fuzzy controller shows strong robustness to parameter of the control system. Comparing the simulation results shows that the fuzzy controller outperforms the PI classic controller. The results are highly consistent with the theoretical calculations and validate correctness of the presented simulation system.

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