

Comparative Study of Passivity and RST Regulator Applied to Doubly Fed Induction Machine

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Abstract – In this paper we are interested in the control of Doubly Fed Induction Machine (DFIM) using the Passivity Based Control (PBC). This work presents a solution to the problem of DFIM that requires a state observer. The proposed method shows very important advantages for nonlinear systems, especially in the trajectory tracking to achieve the needed DFIM performance. In the obtained results, the passivity provides high efficiency in DFIM based system, namely in its stability and robustness. An improvement behavior has been observed in comparison to the results given by the RST controller.

Keywords: DFIM, Output Desired values, Lagrangian Model, Passivity, and RST Regulator

1. Introduction

The choice made on Doubly Fed Induction Machine application, in comparison to some other applications, is due to its high-performance, mainly in storage systems, wind turbine generators or hybrid engines [1-4].

The interest of the DFIM comes primarily from its ability to handle large-speed variations around the synchronous speed. Furthermore, this machine doesn't require high cost power electronic equipment for control purposes [1-4].

In this work we present a nonlinear controller for the DFIM in motor mode and the main goal is to regulate the mechanical speed. Many authors have presented DFIM under field oriented control approaches presenting good response performances with decoupling flux regulation and electromagnetic torque [1, 2 and 5]. In this case, the flux value requires a direct measurement. To overcome this drawback, the passivity principle method is applied to control the DFIM without a flux observer for which a reduced computational time is required [6].

The main idea of PBC is to supply the closed-loop by an additional energy function with feeding back the output dynamics. The total energy is then brought towards the desired values [6-11].

The main application of the passivity principle to the DFIM is the tracking of both torque amplitude as well as rotor flux by using an inner closed loop that allows the desired values to take place.

The PBC procedure starts with a representation of the system to be controlled in Lagrangian form. Next, comes the construction of the desired dynamics structure for the controller design of a PBC [6-8]. In this work, the synthe-

sis of the controller is based on formulating the energy of the electrical part [7], and considering the mechanical effects as passive perturbation. As a result, the control problems are solved by using only the measured variables, so the state observer is not necessary.

In this paper, the obtained results of the PBC are compared to those of the RST controller presented in [5].

2. Lagrangian DFIM Model

As discussed in [8, 9] a large class of physical systems in control applications can be modeled by the general form of Lagrangian model.

In this work the Lagrangian model presented in [7] for induction machine is extended to the DFIM. Under the assumption of linear magnetic circuits and balanced operating conditions, the Lagrangian model of the DFIM in fixed stator reference frame (α, β) is presented by: electrical subsystem described by equation (1) and mechanical subsystem described by equation (2).

$$D_e(Pq_m)\ddot{q}_e + W_1(Pq_m)\dot{q}_m\dot{q}_e + R_e q_e = u^{\alpha\beta} \quad (1)$$

$$J\ddot{q}_m = C_{em}(\dot{q}_e, Pq_m) - C_r - f\dot{q}_m \quad (2)$$

where $D_e \in \mathcal{R}^{4 \times 4}$ is a positive defined inductance matrix given by:

$$D_e(Pq_m) = \begin{bmatrix} L_s I_2 & L_{sr} e^{jPq_m} \\ L_{sr} e^{-jPq_m} & L_r I_2 \end{bmatrix} \quad (3)$$

and $q_m, P, C_{em}, C_r, J, f$, denote respectively the mechanical position, the number of the pole pairs of DFIM, the electromagnetic torque, the load torque, the rotor inertia and the friction parameter; while $R_s, R_r, \dot{q}_e, L_s, L_r, L_{sr}$ and $u^{\alpha\beta}$ are the stator resistance, the rotor resistance, the

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current vector, the stator self-inductance, the rotor self-inductance, the mutual-inductance between both circuits and the voltage inputs respectively.

$W_1(Pq_m)$ can be expressed as [7]:

$$W_1(Pq_m) = \frac{\partial D_e(Pq_m)}{\partial \dot{q}_m} = \begin{bmatrix} 0 & L_{sr} j P e^{jPq_m} \\ -L_{sr} j P e^{-jPq_m} & 0 \end{bmatrix} \quad (4)$$

where

$$e^{jPq_m} = \begin{bmatrix} \cos(Pq_m) & -\sin(Pq_m) \\ \sin(Pq_m) & \cos(Pq_m) \end{bmatrix} \text{ is the rotation matrix,}$$

$$j = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \text{ is an anti-symmetric matrix,}$$

$$\dot{q}_e = [\dot{q}_s^T, \dot{q}_r^T]^T = [I_{s\alpha}, I_{s\beta}, I_{r\alpha}, I_{r\beta}]^T \text{ is the current vector,}$$

$$R_e = \text{diag}\{R_s I_2, R_r I_2\} \text{ is a diagonal matrix,}$$

$$[u^{\alpha\beta}] = [u_{s\alpha}, u_{s\beta}, u_{r\alpha}, u_{r\beta}]^T \text{ is the voltage inputs.}$$

The electromagnetic torque generated by the electrical subsystem is defined as [7]:

$$C_{em}(\dot{q}_e, Pq_m) = \frac{1}{2} \dot{q}_e^T W_1(Pq_m) \dot{q}_e \quad (5)$$

3. Desired States

Equation (1) can be modified into:

$$u^{\alpha\beta} = D_e(Pq_m) \ddot{q}_e + (W_1(Pq_m) \dot{q}_m + L(Pq_m, \dot{q}_m)) \dot{q}_e + (R_e - L(Pq_m, \dot{q}_m)) \dot{q}_e \quad (6)$$

where

$$L(Pq_m, \dot{q}_m) = \begin{bmatrix} 0 & 0 \\ L_{sr} j P e^{-jPq_m} & 0 \end{bmatrix} \dot{q}_m \quad (7)$$

$$R_e - L(Pq_m, \dot{q}_m) = \begin{bmatrix} R_s I_2 & 0 \\ -L_{sr} j P e^{-jPq_m} & R_r I_2 \end{bmatrix} \quad (8)$$

We can rewrite the electric dynamic of the DFIM in the desired model as:

$$u^{\alpha\beta*} = D_e(Pq_m) \ddot{q}_e^* + (W_1(Pq_m) \dot{q}_m + L(Pq_m, \dot{q}_m)) \dot{q}_e^* + (R_e - L(Pq_m, \dot{q}_m)) \dot{q}_e^* \quad (9)$$

Equation (9) can be developed into the following two equations:

$$u_s^{\alpha\beta*} = L_s \ddot{q}_s^* + L_{sr} e^{jPq_m} \ddot{q}_r^* + L_{sr} j P e^{jPq_m} \dot{q}_m \dot{q}_r^* + R_s \dot{q}_s^* \quad (10)$$

$$u_r^{\alpha\beta*} = L_{sr} e^{-jPq_m} \ddot{q}_s^* + L_r \ddot{q}_r^* - L_{sr} j P e^{-jPq_m} \dot{q}_m \dot{q}_s^* + R_r \dot{q}_r^* \quad (11)$$

After manipulating the previous equations, the desired total flux and the currents of the DFIM are obtained as follows [6-9]:

$$\dot{\phi}_r^{\alpha\beta*} = \frac{R_r C_{em}^*}{PB^2} j \phi_r^{\alpha\beta*} \quad (12)$$

$$\phi_r^{\alpha\beta*}(0) = \begin{bmatrix} B \\ 0 \end{bmatrix}$$

$$\dot{q}_r^* = \frac{u_r^{\alpha\beta*}}{R_r} - \frac{C_{em}^*}{PB^2} j \phi_r^{\alpha\beta*} \quad (13)$$

$$\dot{q}_s^* = \left(\frac{L_r C_{em}^*}{L_{sr} PB^2} j + \frac{1}{L_{sr}} I_2 \right) e^{jPq_m} \phi_r^{\alpha\beta*} \quad (14)$$

where * denotes the desired value and B the norm of the flux vector.

4. Convergence Proof of the Closed System

The dynamic equation of the state error for the electrical subsystem given by equation (15) is obtained by subtracting equation (9) from (6).

$$D_e(Pq_m) \dot{e}_e + (W_1(Pq_m) \dot{q}_m + L(Pq_m, \dot{q}_m)) e_e + (R_e - L(Pq_m, \dot{q}_m)) e_e = 0 \quad (15)$$

$$\text{where } e_e = \dot{q}_e - \dot{q}_e^* = [\dot{q}_s^T, \dot{q}_r^T] - [\dot{q}_s^{*T}, \dot{q}_r^{*T}]$$

In order to be sure that $R_e - L(Pq_m, \dot{q}_m) > 0$, the inputs $u^{\alpha\beta}$ should be as follows:

$$u^{\alpha\beta} = u^{\alpha\beta*} - k_1 e_e \quad (16)$$

with $u^{\alpha\beta*}$ representing the desired control signals. Thus the state error equation is given by:

$$D_e(Pq_m) \dot{e}_e + (W_1(Pq_m) \dot{q}_m + L(Pq_m, \dot{q}_m)) e_e + (R_e - L(Pq_m, \dot{q}_m) + k_1) e_e = 0 \quad (17)$$

and

$$k_1 = \text{diag}\{k_2, k_3\} \quad (18)$$

The state error convergence is calculated using the quadratic equation:

$$V_1 = \frac{1}{2} e_e^T D_e (Pq_m) e_e$$

As explained in [3], the derivative of previous equation with respect to time is given by:

$$\dot{V}_1 = -e_e^T (R_e - L(Pq_m, \dot{q}_m) + k_1)_{sym} e_e \quad (19)$$

where

$$(R_e - L(Pq_m, \dot{q}_m) + k_1)_{sym} = \begin{bmatrix} (R_s + k_2)I_2 & -\frac{1}{2}L_{sr}jPe^{jPq_m}\dot{q}_m \\ -\frac{1}{2}L_{sr}jPe^{-jPq_m}\dot{q}_m & (R_r + k_3)I_2 \end{bmatrix}$$

k_1 ensures that the matrix $(R_e - L(Pq_m, \dot{q}_m) + k_1)_{sym}$ is positive only if the following condition is satisfied:

$$(R_s + k_2)I_2 - \frac{1}{4(R_r + k_3)}(L_{sr}jPe^{jPq_m}\dot{q}_m)(-L_{sr}jPe^{-jPq_m}\dot{q}_m) > 0 \quad (20)$$

In this work the authors propose the dynamic coefficient such that $(k_3 \ll R_r) > 0$, where the DFIM machine is powered from the rotor side by using a weak gain $u_r^{\alpha\beta}$.

Using $e^{jPq_m}e^{-jPq_m} = I_2$ and $j^2 = -I_2$, equation (20) can be reduced as:

$$k_2 > \frac{L_{sr}^2}{4R_r}(P\dot{q}_m)^2 \quad (21)$$

In this case the input signals $u^{\alpha\beta}$ are expressed by:

$$u^{\alpha\beta} = u^{\alpha\beta*} - k_4 e_e \quad (22)$$

with $k_4 = \text{diag}\left\{k_2, \frac{k_2}{C}\right\}$, $k_2/C \ll R_r$ and $C > 0$.

Condition (21) allows the system described by equation (15) to be globally stable, and makes the system defined by equations (1) and (2) operating at its desired values with zero dynamic error (17)

5. Control Strategy

In this paper the control of DFIM illustrated in figure 1 is based on the rotor voltage control given as an image of the stator voltages, weighted with a weak gain. As a result, the DFIM will be only governed by the stator side. The stator voltages, given by equation (22), allow the torque trajectory and speed tracking of the DFIM to follow the desired behavior. The nonlinear feedback of the output k_2 , can be rewritten as follow:

$$k_2 > \frac{L_{sr}^2}{4\epsilon}(p\dot{q}_m)^2 \quad (23)$$

with $0 < \epsilon < R_r$,

To achieve the desired rotor speed and to generate the desired electromagnetic torque signal, a proportional-integral (PI) controller is inserted in the control structure. The accurate gains adjustment of the PI controller is necessary to obtain the best behavior of the DFIM.

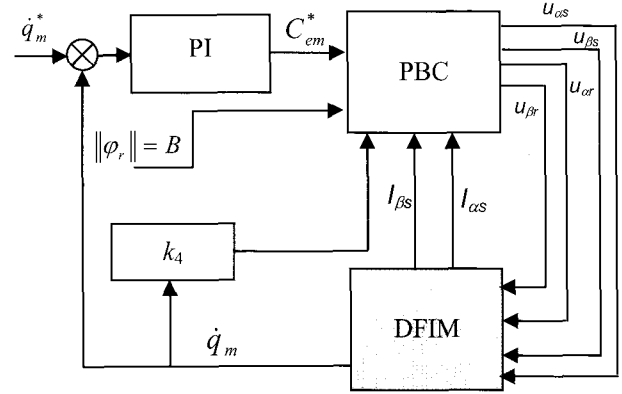


Fig. 1. The proposed PBC controller block applied to the DFIM

6. Simulation Results

The PBC controller was tested on the DFIM using the Matlab/Simulink platform in order to show up the efficiency of the proposed solution.

Figures 2.a, 2.b, and 2.c represent the results of the PBC controller concerning the speed, the electromagnetic torque and the current of the DFIM respectively. The parameters used in simulation are: the constant $\epsilon=1$, the desired flux amplitude $B=1.0253$ Wb, the desired rotation speed $\dot{q}_m^* = 150$ rad/s. The load torque of 10 Nm is applied at $t=1.5$ s.

The reference inputs are always tracked by the DFIM as shown in figures 2.a, 2.b, and 2.c with a complete rejection of the applied load torque.

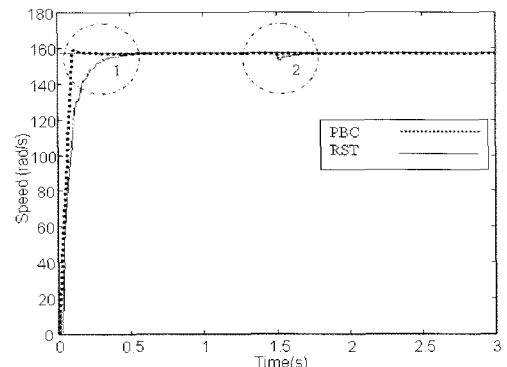


Fig. 2.a: Speed response of the DFIM

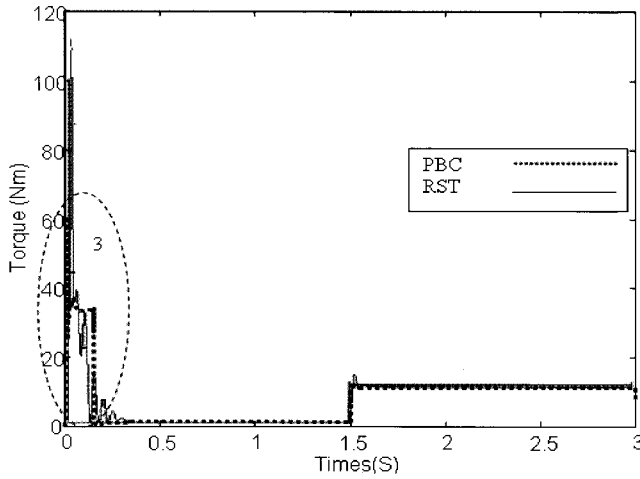


Fig. 2.b: Torque response of the DFIM

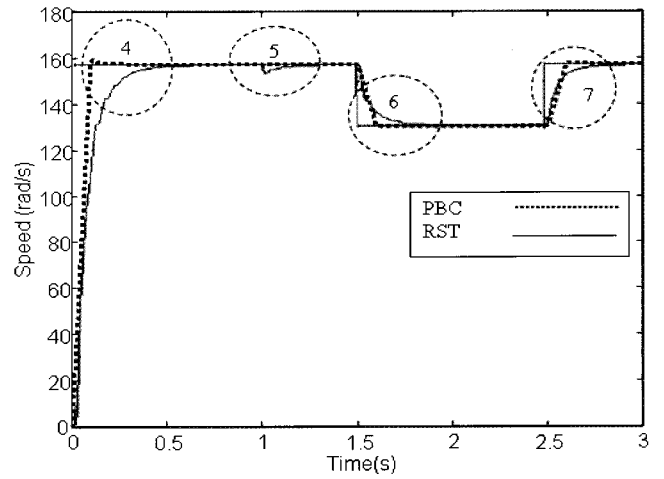


Fig. 3.a: Speed response to speed variation

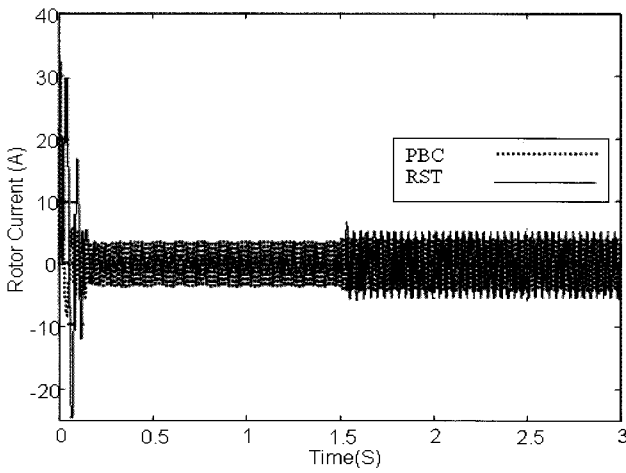


Fig. 2.c: Rotor current response of the DFIM

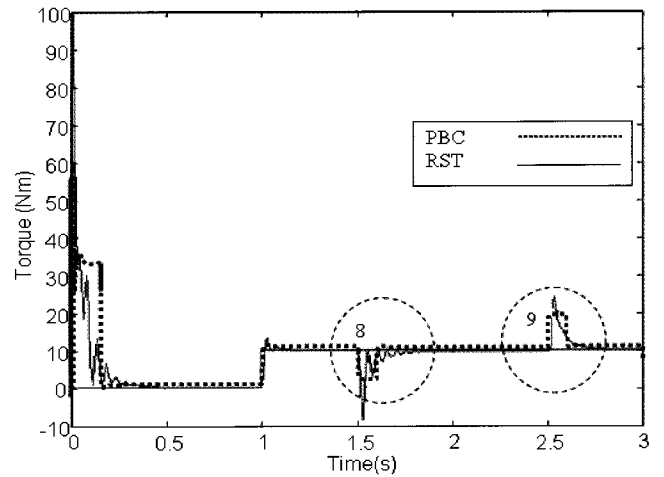


Fig. 3.b: Torque response to speed variation

7. Robust Control of the PBC Controller

7.1 Speed Variation

Figures 3.a, 3.b, and 3.c show the simulation results obtained by varying the speed according to the following values: $\dot{q}_m^* = 157$ rad/s applied within interval [0s-1.5s], 130 rad/s applied within interval [1.5s-2.5], and back to 157rad/s at 2.5s and up. A load of 10 Nm is applied at t=1s.

It can be noticed that the system is faithfully responding to the reference inputs. The response in terms of speed, electromagnetic torque, and the rotor current showed in figures 3.a, 3.b, and 3.c respectively follow accurately the input references. The shape of the rotor current is considered acceptable.

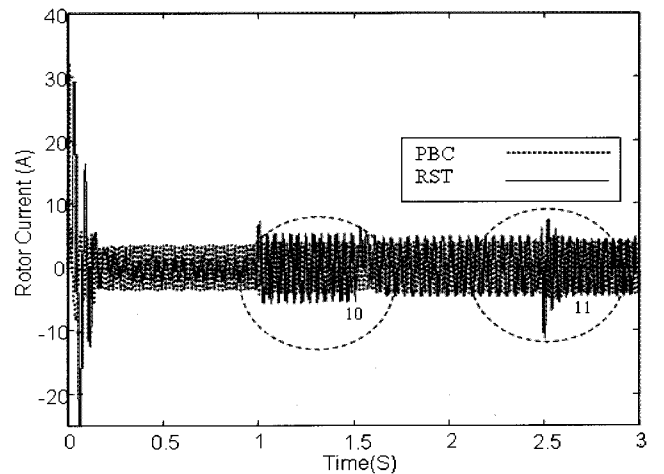


Fig. 3.c: Rotor current response to speed variation

7.2 Robust Control for Load Variation

Figures 4.a, 4.b, and 4.c show the simulation results ob-

tained by varying the load ($C_r=10\text{Nm}$ within interval [1s-2s] and 15Nm at $t=2\text{s}$ and up). The speed and the torque are not influenced by this variation.

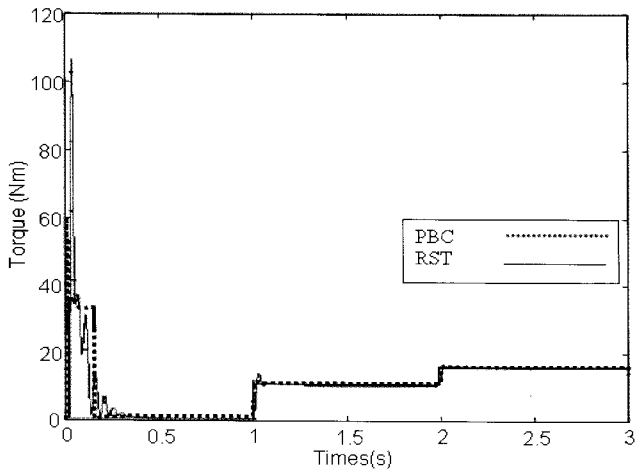


Fig. 4.a: Torque response to speed variation

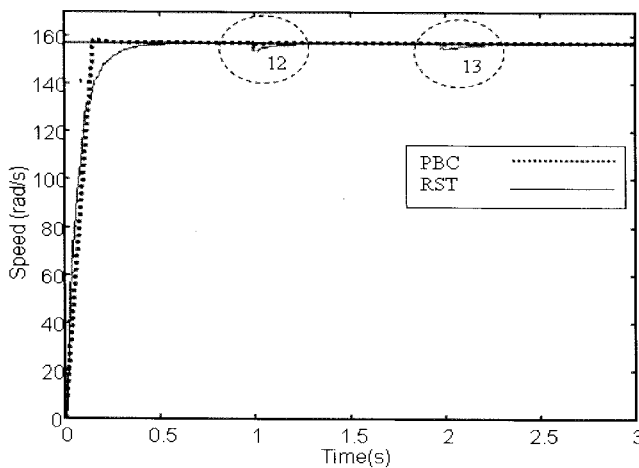


Fig. 4.b: Speed response to load variation

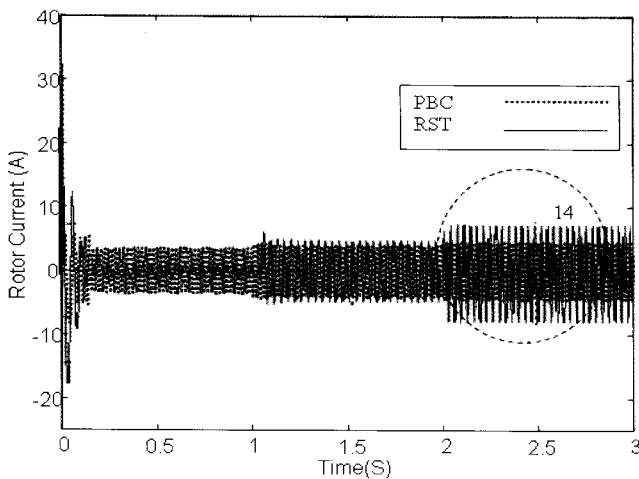


Fig. 4.c: Rotor current response to load variation

8. Comparative study of Results

In comparison with the results presented in [5], the simulation results of the PBC controller show a clear improvement in the torque, speed and current behaviors, where the fluctuations are highly reduced.

This advantage allows a safety realization since the power electronic components that constitute the control circuit are not overloaded. Hence, a low cost control system is obtained compared to [5] where the presence of fluctuations requires additional components in order to preserve the power components against overloads.

In this work the time response is reduced to 0.3s (that is 50% less than the results of the RST regulator [5]) as shown in rounded areas (1, 2, 4, 6, and 7) of figures 2 and 3. Moreover the PBC controller shows a total rejection of the 10 Nm load torque (applied at $t=1\text{s}$, $t=1.5\text{s}$ and $t=2\text{s}$ respectively). The rounded areas (2, 5, 12 and 13) of figures (2, 3 and 4) show an improved time rejection of perturbation compared with the time of RST controller presented in [5] and the impact of perturbation is clearly reduced.

The rounded area 3 shows a reduction of the torque peak at the first time response by approximately 40% (from 100Nm for the RST to 60Nm for the PBC). In comparison with the tests made in [5], ours are clearly better.

9. Conclusion

The speed-torque tracking controller for Doubly Fed Induction Machine has been presented. The main contribution of this work was to solve the problem of trajectories tracking without needing a state observer. Compared to the Field Oriented Control (FOC) using an RST regulator, the proposed passivity based control showed an improved simulation results. Furthermore, the disturbance impact has been rejected in a reduced time less than the RST controller one.

In order to validate the efficiency of the presented DFIM controller via a comparison with experimental results, a practical implementation is of the actual interest.

Parameters of the DFIM

$P_n=1.5\text{kW}$, $V_{sn}=220\text{V}$, $V_{nr}=12\text{V}$, $W_n=1500\text{tr/mn}$,
 $R_s=4.85\Omega$, $R_r=3.805\Omega$, $L_s=0.274\text{H}$, $L_r=0.274\text{H}$, $M=0.258\text{H}$,
 $P=2$, $J=0.031\text{kg/m}^2$, $f=0.008\text{ Nms/rd}$.

References

- [1] A. Dendouga, R. Abdessemed, M. L. Bendaas and A. Chaiba, "Decoupled Active and Reactive Power Control of a Doubly-Fed Induction Generator (DFIG)", in *Proceedings of Mediterranean Conference on Control and Automation Conference*, Greece, (2007).

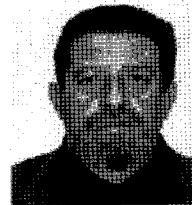
- [2] A. L. Nemours and R. Abdessemed, "Control of Doubly Fed Induction Motor Drive (DFAM) Using Adaptive Takagi-Sugeno Fuzzy Model Based Controller", *JEE*, Vol. 4, N°2 (2004).
- [3] A. Monroy, and L. Alvarez-Icaza, "Passivity Based Control of a DFIG Wind Turbine", in *Proceedings of American Control Conference*, Minnesota, USA, (2006).
- [4] B. Carles, A. Doria-cerezo and R. Ortega, "Power Flow Control of Doubly-Fed Induction Machine Coupled to a Flywheel", in *Proceedings of Control Application Conference*, Taiwan, (2004).
- [5] N. Akkari, A. Chaghi and R. Abdessemed, "Study and Simulation of RST Regulator Applied to a Double Fed Induction Machine (DFIM)" *Journal of Electrical Engineering & Technology*, Vol. no. 3, pp. 308-313, (2008).
- [6] G. Espinosa and R. Ortega, "State observers unnecessary for induction motor control", *System Control Letters*, Vol. 23, no5, pp. 315-323 (1994).
- [7] R. Ortega, P. J. Nicklasson and G. Espinosa "On speed control of induction motors," *Automatica*, Vol. 32, pp. 455-460 (1996).
- [8] R. Ortega, A. Loria, P. J. Nicklasson and H. Sira-Ramirez, "Passivity-based Control of Euler-Lagrange Systems", *Communications and Control Engineering*, Springer-Verlag, Berlin, (1998).
- [9] L. Gökdere, W. Brice and P. Nicklasson, "Correction to Passivity-based control of a class of Blondel-Park transformable machines" *IEEE Trans. Aut. Control*, Vol.AC-46, no.1, pp.172-178, (2000).
- [10] Acosta, J., R. Ortega, A. Astolfi and A. Mahindrakar, "Interconnection and damping assignment passivity-based control of mechanical systems with underactuation degree one", *IEEE Trans Aut. Control*, Vol.50, no.12, pp. 1936-1955 (2005).
- [11] G. Viola, R. Ortega, R. Banavar and J. Acosta, "Total energy shaping control of mechanical systems: simplifying the matching equations via coordinate changes", *IEEE Trans Aut. Control*, Vol.52, no.6, pp. 1093-1099 (2007).



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