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A Doubly Fed Induction Motor Control Using Passivity

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Abstract: In this study the Double Fed Induction Machine (DFIM) is controlled by passivity. The idea of passivity is based on the use of Euler-Lagrange principle of machine total energy exploitation. This structure presents very important advantages for nonlinear systems, specially in the trajectory tracking to insure the desired operation. Presented results show the passivity efficiency when applied to DFIM in separated frames, not only from stability point view but also robustness of model parameters variations is concerned. These advantages encourage an easy practical implementation for optimal loaded DFIM performance with variable references.

Key words: Passivity, desired functioning, performances, Lagrange model, double fed induction machine

INTRODUCTION

The use of the Double Fed Induction Machine (DFIM) to variable speeds for the waters treatments and the cooling industrial circuits is justified by the best mastering of big powers transfer and distinctly improved efficiencies (Morel *et al*., 1998). Many authors have presented DFIM as vectoriel control approaches (Wang and Ding, 1993; Vas, 1990; Drid *et al*., 2005) having a good response performances with flux decoupled regulation with respect to electromagnetic torque. In control, the flux value necessitates a direct measurement, or implanting an observer in the feedback loop.

In practice, an observer needs a very rapid calculators to replace physical sensors. In this study, the passivity principle is applied to control the DFIM without an observer (Ortega *et al*., 1996). In The Control Based on the Passivity PBC, the DFIM dynamics is brought towards the desired dynamics. Moreover, the convergence speed of the desired behavior is improved via feeding back the output dynamics.

The PBC consists of modifying the energy towards the desired value, which represents a minimum for desired coordinates. As a result, the system converges to a minimum one (Ortega and Espinosa, 1991). Furthermore, the controller PBC injects an additive damping term in the system in order to improve the convergence speed towards the wished state with respect to theat reacheed by a natural dissipation supplied by the system.

PASSIVITY CONCEPTS

In this research, we present the law of globally stable control by a nonlinear dynamic output feedback, without observer as proposed in (Espinosa and Ortega, 1994). In order to solve the torque and rotor flux amplitude tracking problem of double fed asynchronous machine in separate referential, the closed loop has to satisfy:

$$\lim_{t\to\infty}\left(C_{em}-C^{*}_{em}\right)=0\ ,\quad \lim_{t\to\infty}\left\|\phi_r^{\alpha\beta}\right\|=\beta \tag{1}$$

where C_{em}^{*} is the desired torque.

We can summarize the conception step of the control based on the passivity in the following essential steps (Ortega and Espinosa, 1991):

- Represent system to be controlled in the form of Lagrangian control.
- Establish the structure of the desired dynamics.
- Resolve the problem of choice of the desired coordinates.

To formulate the control problem in the ideal case, it has been supposed that all states are measurable, all the parameters are known and the load torque C_r is a known smooth and bounded function, with the known bounded first derivative. In addition, the absolute value of the desired rotoric is taken as being a constant value $\beta>0$ (Ortega and Espinosa, 1993).

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LAGRANGIENNE DOUBLE FED INDUCTION MACHINE MODEL

The Lagrangian model of the Double Fed Induction Machine is presented by the use of Euler-Lagrange equation as:

$$D_e(Pq_m)\ddot{q}_e + W_1(Pq_m)\dot{q}_m\dot{q}_e + R_e q_e = Mu^{\alpha\beta} \quad (2)$$

$$J\,\ddot{q}_m = C_{em}(\dot{q}_e, Pq_m) - C_r \quad (3)$$

$$W_1(Pq_m) = \frac{\partial D_e(Pq_m)}{\partial q_m} = \begin{bmatrix} 0 & L_{sr}jPe^{jPq_m} \\ -L_{sr}jPe^{-jPq_m} & 0 \end{bmatrix}, \quad (4)$$

$$C_{em}(\dot{q}_e, Pq_m) = \frac{1}{2}\dot{q}_e^T W_1(Pq_m)q_e, M = [I_4] \quad (5)$$

where $\dot{q}_e = [\dot{q}_s^T, \dot{q}_r^T]^T = [I_{s\alpha}, I_{s\beta}, I_{r\alpha}, I_{r\beta}]^T$ is the currents vector and q_m is the mechanical position of the rotor.

$$D_e(Pq_m) = \begin{bmatrix} L_s I_2 & L_{sr}e^{jPq_m} \\ L_{sr}e^{-jPq_m} & L_r I_2 \end{bmatrix}; R_e = \mathrm{diag}\{R_s I_2, R_r I_2\}$$

D (Pq_m) = D^T_e (Pq_m)>0 is a positive defined inductance matrix with:

$$e^{jn_p q_m} = \begin{bmatrix} \cos(Pq_m) - \sin(Pq_m \\ \sin(Pq_m \cos(Pq_m) \end{bmatrix} \quad (6)$$

being the rotation matrix and $j = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$ being an antisymmetric matrix J is the rotor inertia. Using the law of Gauss-Ampere the flux vector is calculated as:

$$\phi\alpha\beta = D_e(Pq_m)\dot{q}_e \quad (7)$$

The control signals $[u^{\alpha\beta}] = [u_{s\alpha}, u_{s\beta}, u_{r\alpha}, u_{r\beta}]^T$ are the stator and the rotor voltages, respectively.

The obtained model is exactly the same as the one obtained by Park's transformation in (Nemmour and Abdessemed, 2004).

The flux in Eq. 7 can be written in $\alpha\beta$ referential as:

$$\phi_r^{\alpha\beta} = \begin{bmatrix} \phi_{r\alpha} \\ \phi_{r\beta} \end{bmatrix} = \left\|\phi_r^{\alpha\beta}\right\| \begin{bmatrix} \cos\rho \\ \sin\rho \end{bmatrix} \quad (8)$$

where $\left\|\phi_r^{\alpha\beta}\right\|$ is the rotoric flux vector amplitude. The rotation speed of this vector is given as (Ortega and Espinoja, 1993):

$$\dot{\rho} = \frac{R_r}{P\left\|\phi_r^{\alpha\beta}\right\|^2} C_{em} \quad (9)$$

with C_{em} given in (5).

$$\phi_r^{\alpha\beta^*} = \begin{bmatrix} \phi^*_{r\alpha} \\ \phi^*_{r\beta} \end{bmatrix} = \beta \begin{bmatrix} \cos\rho^* \\ \sin\rho^* \end{bmatrix} \quad (10)$$

$$\rho^* = \arctan\left(\frac{\phi^*_{r\alpha}}{\phi^*_{r\beta}}\right)$$

$$\dot{\rho}^* = \frac{R_r}{P\beta^2} C^*_{em}$$

It can be easly noticed that:

$$\lim_{t\to\infty} \phi_r^{\alpha\beta} = \phi_r^{\alpha\beta^*} \quad \Rightarrow$$

$$\lim_{t\to\infty}\left\|\phi_r^{\alpha\beta}\right\| = \beta \text{ et} \lim_{t\to\infty} \frac{R_r}{P\left\|\phi_r^{\alpha\beta}\right\|^2} C_{em} = \frac{R_r}{P\beta^2} C_{em}^*$$

Hence, $\lim_{t\to 0} C_{em} = C_{em}^*$

As a result of previous study, it can be stated that if the control law insures the rotoric flux regulation with an internal stability, the problem of the torque control is solved.

DETERMINATION OF DESIRED COORDINATES

In designing the controller, Eq. (2-3) can be modified to:

$$D_e(Pq_m)\ddot{q}_e + \left(W_1(Pq_m)\dot{q}_m + L(Pq_m)\right)\dot{q}_e + \left(R_e - L(Pq_m, \dot{q}_m)\right)\dot{q}_e = Mu^{\alpha\beta} \quad (11)$$

$$L(Pq_m, \dot{q}_m) = \begin{bmatrix} 0 & 0 \\ L_{sr}jPe^{-jPq_m} & 0 \end{bmatrix}\dot{q}_m \quad (12)$$

$$R_e - L(Pq_m, \dot{q}_m) = \begin{bmatrix} R_s I_2 & 0 \\ -L_{sr}jPe^{-JPq_m}\dot{q}_m & R_r I_2 \end{bmatrix} \quad (13)$$

The desired electric dynamic of the motor is given by (Ortega and Espinosa, 1993):

$$D_e(Pq_m)\ddot{q}_m + \left(W_1(Pq_m)\dot{q}_m + L(Pq_m,\dot{q}_m)\right)\dot{q}_e^* + \left(R_e - L(Pq_m,\dot{q}_m)\right)\dot{q}_e^* = M\ u^{\alpha\beta^*} \quad (14)$$

The statoric voltages, given in Eq. 14, can be written as:

$$L_s\ddot{q}_s^* + L_{sr}e^{jPq_m}\ddot{q}_r^* + L_{sr}jPe^{jPq_m}\dot{q}_m\dot{q}_r^* + R_s\dot{q}_s^* = u_s^{\alpha\beta^*} \quad (15)$$

In this study, the rotoric voltage is taken as an image of the statoric voltages, weighted with a weak gain. In this way the DFIM will be only governed by the statoric side. The rotoric flux of the system is given by (Ortega and Espinosa, 1993):

$$\dot{\phi}_r^{\alpha\beta^*} = \frac{R\,C_{em}^*}{P\beta^2} j\phi_r^{\alpha\beta^*};\ \phi_r^{\alpha\beta^*}(0) = \begin{bmatrix}\beta\\0\end{bmatrix} \quad (16)$$

After transformations, the desired currents q_r^* and q_s^* are:

$$\dot{q}_r^* = -\frac{C_{em}^*}{P\beta^2} j\phi_r^{\alpha\beta^*} \quad (17)$$

$$\dot{q}_s^* = \left(\frac{L_r C_{em}^*}{L_{sr}P\beta^2} j + \frac{1}{L_{sr}} I_2\right) e^{jPq_m}\phi_r^{\alpha\beta^*} \quad (18)$$

GLOBAL DYNAMIQUE DISCUSSION

The calculation of the controller depends only on measured variables. With $u^{\alpha\beta} = u^{\alpha\beta}$, the state error Equation is given by (Ortega and Espinosa, 1993):

$$D_e(Pq_m)\dot{e}_e + \left(W_1(Pq_m)\dot{q}_m + L(Pq_m,\dot{q}_m)\right)e_e + \left(R_e - L(Pq_m,\dot{q}_m)\right)e_e = 0 \quad (19)$$

where

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

In order to insure that R_e-$L(P_{qm}, q_m)>0$, the input $u^{\alpha\beta}$ is to be defined as:

$$u^{\alpha\beta} = u^{\alpha\beta^*} - K_3 e_e \quad (20)$$

Thus the state error equation becomes:

$$D_e(Pq_m)\dot{e}_e + \left(W_1(Pq_m)\dot{q}_m + L(\ddot{}Pq_m,\dot{q}_m)\right)e_e + \left(R_e - L(Pq_m,\dot{q}_m) + K_1\right)e_e = 0 \quad (21)$$

and

$$K_1 = \mathrm{diag}\{K_3, 0\} \quad (22)$$

The error convergence is given by the quadratic equation

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

for which the derivative with respect to time around a trajectory is given by:

$$\dot{V}_1 = -e_e^T\left(R_e - L(Pq_m,\dot{q}_m) + K_1\right)_{sym} e_e \quad (23)$$

$$\left(R_e - L(Pq_m,\dot{q}_m) + K_1\right)_{sym} = \begin{bmatrix}(R_s + K_3)I_2 & \frac{1}{2}L_{sr}jPe^{jPq_m}\dot{q}_m \\ -\frac{1}{2}L_{sr}jPe^{-jPq_m}\dot{q}_m & R_r I_2\end{bmatrix}$$

K3 insures that the matrix $(R_e\text{-}L(P_{qm}, q_m) + K_1)_{sym}$ is positive only if the following condition is satisfied:

$$(R_s + K_3)I_2 - \frac{1}{4R_r}\left(L_{sr}jPe^{jPq_m}\dot{q}_m\right)\left(-L_{sr}jPe^{-jPq_m}\dot{q}_m\right) > 0 \quad (24)$$

Equation 24 can be written in a reduced form as:

$$e^{jPq_m}e^{-jPq_m} = I_2 \ \text{ et }\ j^2 = -I_2$$

$$K_3 > \frac{L_{sr}^2}{4R_r}\left(P\dot{q}_m\right)^2 \quad (25)$$

and using: $e^{jpqm}\,e^{-jpqm} = I_2$ et $j^2 = -I_2$

Since this expression varies as a function of time, we K_3 can be defined as a feedback of the output and it varies as a function of time as:

$$K_3 > \frac{L_{sr}^2}{4\varepsilon}\left(P\dot{q}_m\right)^2 \ \text{ Ou: } 0<\epsilon<R_r$$

Under these conditions, the system in feedback loop (21) is globally asymptotically stable, when the torque tracking is insured as well as the regulation of the flux amplitude while respecting internal stability. For the speed control, the strategy proposed in (Kim *et al*., 1996) has been used:

$$C_{em}^* = J\ddot{q}_m^* - Z + C_r \quad (26)$$

$$\dot{Z} = -aZ + b\left(\dot{q}_m - \dot{q}_m^*\right),\ \ a, b > 0 \quad (27)$$

The schematic of the proposed controller is given in Fig. 1.

The obtained control by this strategy uses equations (10-15) and (20-22) to end with the control law given by

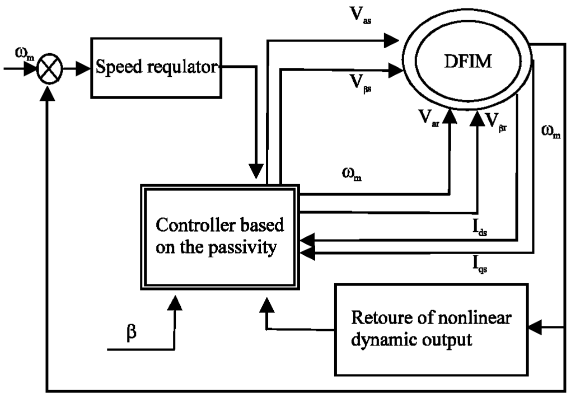

Fig. 1: Control of the DFIM based on the passivity

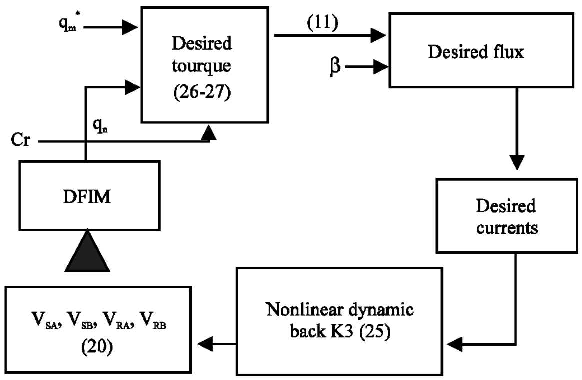

Fig. 2: Conception of the controller

the Eq. 15, based on feeding back the nonlinear output dynamic k_3 introduced in the equation 20. In Fig. 2, the controller design steps are presented.

SIMULATION RESULT

The passivity principle was tested on the DFIM with the following physical parameters: P = 1.5 kW, 220 V, 12V.r_s = 4.85Ω, r_r = 3.805 Ω, l_s = 0.274 H, l_r = 0.274 H, m = 0.258H, J = 0.031 kg m^2, f = 0.008 N.m.s/rd. The used simulation parameters are: ε =1, a = 200, b = 50 and the desired references are: Flux amplitude β = 1.0253, the desired angular speed q_m = 150 rad sec^{-1} and a load torque of 10 N.m.

In a first test of the passivity, the DFIM was driven by a reference speed of 150 rad sec^{-1} and a load torque of 10 N.m. where the direction of rotation and the load torque are inversed at t = 3.5 sec.

Obtained response is shown in the Fig. 3, where the desired reference is clearly followed with a complete rejection of the applied load torque.

Figure 4 (a-c) present, respectively the developed electromagnetic torque and the current flowing in the

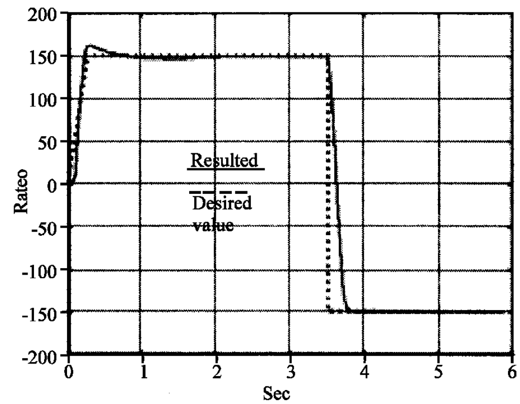

Fig. 3: Response of the angular speed

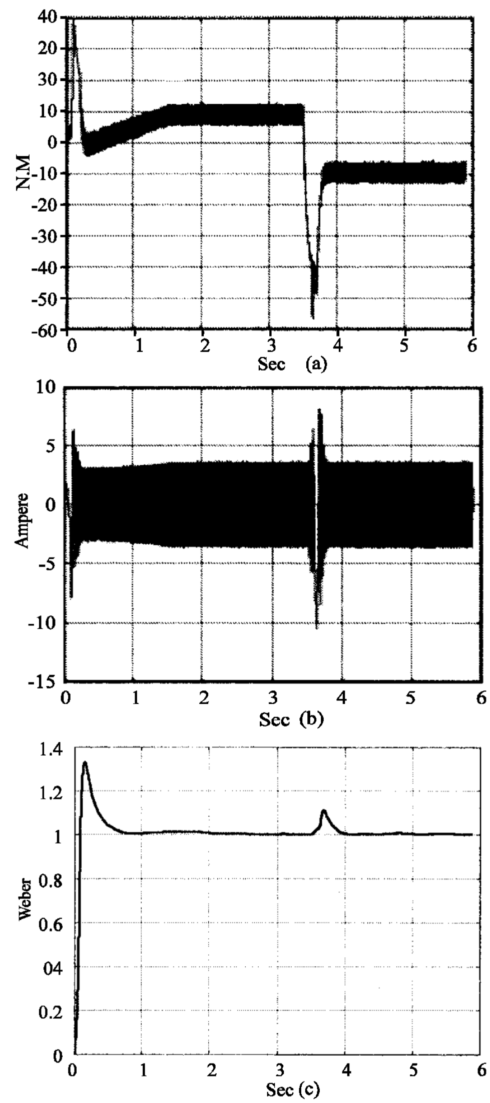

Fig. 4: a/Electromagnetic torque, b/statoric current, c/flux

statoric solenoids A for referential (αβ). The peaks values of the current due to the starting up or references change imply a practical implementation of this controller.

The Fig. 5 (a-c) present, respectively the obtained results concerning the speed, the electromagnetic torque and the current of the DFIM without changing the other parameters. For the two speed references of 100 and 150 rad sec^{-1}; with a load torque varying from 0 N.m to 10 N.M, the references are always followed by the DFIM as shown in the presented responses.

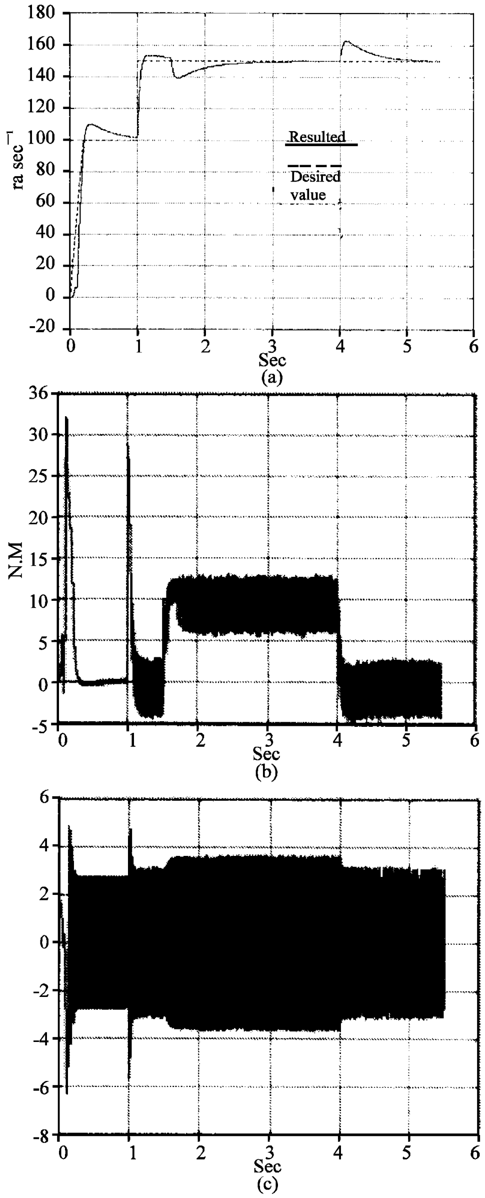

Fig. 5: a/Angular speed, b/electromagnetic torque, c/statoric current

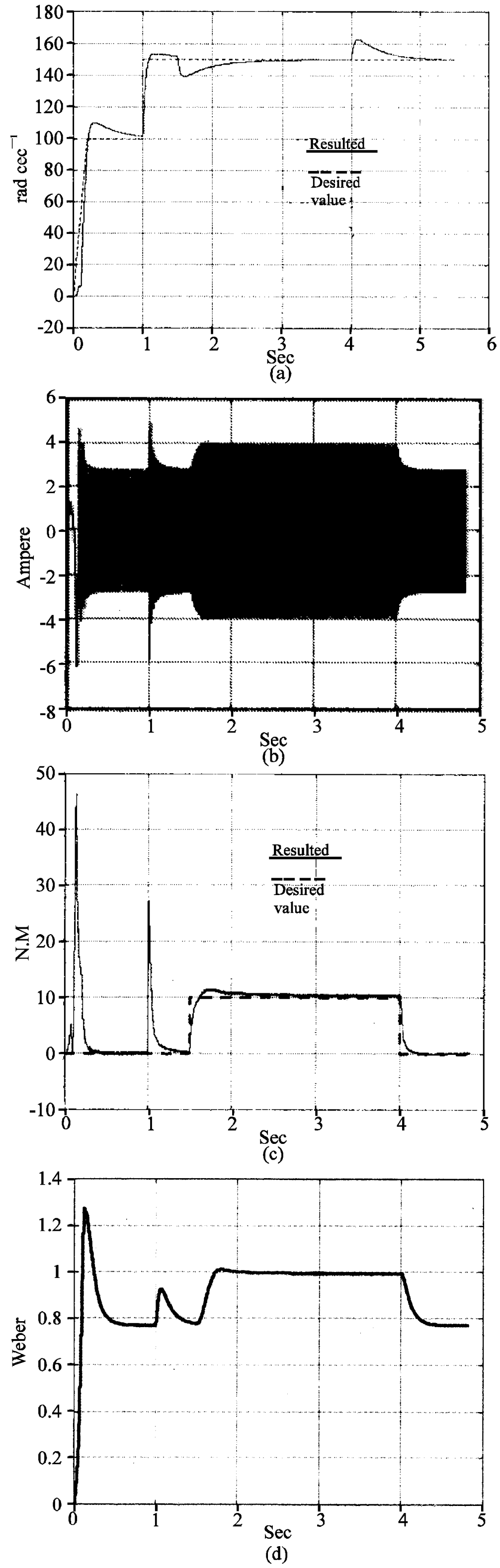

Fig. 6: a/Angular speed, b/electromagnetic torque, c/statoric current, d/flux

The robustness of the PBC against the DFIM parameters change is verified, by changing the values of the resistances to 75% and reducing the inductances values L_s and L_r to 25%. The obtained results are shown in Fig. 6 (a-d). The speed and electromagnetic torque responses (Fig (6-a) and (6-b), respectively) maintain following the inputs references. An increase in the consumed current is associated with peaks of average importance when compared to the normal case as shown in Fig (6-b). The Fig. 6-d shows an acceptable behavior of magnetic flux with respect to the normal state conditions.

CONCLUSION

The nonlinear control based on the DFIM passivity modeled in separated frame is presented. The application of the passivity allows an elaborated control, flux regulation, torque control, speed and current regulation. The advantages of this method are the non need of an observer for measured variables. Moreover, the presence of modeling errors and/or external perturbators do not affect the DFIM.

Thus, the passive control allows an important robustness to the global structure with feedback and trajectory planifications of flux, speed and torque.

In a future research, the passivity in conjunction with intelligent control can be adopted to improve time response and to obtain optimal simulation gains.

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