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A new robust SIDA-PBC approach to control a DFIG

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ABSTRACT

Credible control and overall stabilization of closed-loop nonlinear systems presented in a port-controlled hamiltonian structure (PCH-D) were forever the development of the simultaneous interconnection and damping assignment passivity-based control (SIDA-PBC) method. The robustness and reliability of the method called into question against noise and certainly modelling errors. Indeed, a new scheme has been presented to control a doubly fed induction generator (DFIG) based on the energy form and exploiting the electrical parameters of the closed loop system. The results obtained provide a new technique and implement more freedom when designing the diagram of the advanced controller during the production of active power. The contribution of this paper is researching on the advanced nonlinear methodes used, many simulations were carried out in simulation using the MATLAB/Simulink environment under important operating conditions, allowing to demonstrate the feasibility of the proposed method and verify the performance considering the robustness.

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1. INTRODUCTION

Passive-based control (PBC) has become a research tool for nonlinear control, mainly because of its ease of application to physical systems (mechanical, electrical, and electromechanical) [1], [2]. In recent years, assignment-passivity-based interconnection and control (SIDA-PBC) has been developed as a flexible and general nonlinear system controller design method, and introduced tools that affect interconnection and internal energy loss considerations [2]. This approach enables a robust controller with a clear physical interpretation of the system's connection to its environment [3]–[6]. In particular, the total energy of the closed loop is the difference between the system energy and the energy provided by the controller [7]–[10]. Furthermore, power generation is an interesting research area for nonlinear control. They are especially used by doubly fed induction generator (DFIG).

This research analyzes the use of SIDA-PBC as a method to control the power provided by this entrainement. The result is a new approach to designing controllers for these workouts, focusing on energy characteristics such as balance and fitness to achieve desired goals. Therefore, a power controller was obtained from the new scheme and simulated using the DFIG model in the MATLAB Simulink environment. To apply the SIDA-PBC method to generator induction, a connection control Hamiltonian (PCH) model is derived for the entire electromechanical system [2], [11]. The SIDA-PBC controller decouples the input of the induction generator, exploiting the internal characteristics of the system to achieve the desired goal without intermediate steps [12]–[15].

2. DFIG: PCH MODELISATION WITH SIDA-PBC

2.1. Machine modelisation

Willingly, the PARK coordinate system linked to the rotating field of the DFIG is written as (1) [16].

$$\begin{cases} V_{ds} = R_s I_{ds} + \frac{d\Phi_{ds}}{dt} - \omega_s \Phi_{qs} \\ V_{qs} = R_s I_{qs} + \frac{d\Phi_{qs}}{dt} + \omega_s \Phi_{ds} \\ V_{dr} = R_r I_{dr} + \frac{d\Phi_{dr}}{dt} - (\omega_s - \omega)\Phi_{qr} \\ V_{qr} = R_r I_{qr} + \frac{d\Phi_{qr}}{dt} + (\omega_s - \omega)\Phi_{dr} \\ J\frac{d\omega}{dt} = M\left(I_{dr} I_{qs} - I_{ds} I_{qr}\right) - C_r - C_f \omega \end{cases} \tag{1}$$

and flux equations can be written as (2).

$$\begin{aligned} \dot{\Phi}_{ds} &= V_{ds} - R_s I_{ds} + \omega_s L_s I_{qs} + \omega_s M I_{qr} \\ \dot{\Phi}_{qs} &= V_{qs} - R_s I_{qs} - \omega_s L_s I_{ds} - \omega_s M I_{dr} \\ \dot{\Phi}_{dr} &= V_{dr} - R_r I_{dr} + (\omega_s - \omega) L_r I_{qr} + (\omega_s - \omega) M I_{qs} \\ \dot{\Phi}_{qr} &= V_{qr} - R_r I_{qr} - (\omega_s - \omega) L_r I_{dr} - (\omega_s - \omega) M I_{ds} \end{aligned} \tag{2}$$

where:

$$\dot{\Phi}_s = V_s - R_s I_2 I_s - \omega_s L_s J_2 I_s - \omega_s M J_2 I_r \tag{3}$$

$$\dot{\Phi}_r = V_r - R_r I_2 I_r - (\omega_s - \omega) M J_2 I_s - (\omega_s - \omega) L_r J_2 I_r \tag{4}$$

and,

$$J_{DFIG} \frac{d\omega}{dt} = L_{sr} I_s^T J_2 I_r - C_r - C_f \omega \tag{5}$$

with: $\Phi_s = \begin{bmatrix} \Phi_{ds} \\ \Phi_{qs} \end{bmatrix}$, $\Phi_r = \begin{bmatrix} \Phi_{dr} \\ \Phi_{qr} \end{bmatrix}$, $I_s = \begin{bmatrix} I_{ds} \\ I_{qs} \end{bmatrix}$, $I_r = \begin{bmatrix} I_{dr} \\ I_{qr} \end{bmatrix}$, $I_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$, $J_2 = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$

The state variables are:

$$x = \left[\Phi_s{}^T, \Phi_r{}^T, J_{DFIG}\omega\right]^T = [x_e^T, x_m]^T$$

with: $x_e^T = \left[\Phi_s{}^T, \Phi_r{}^T\right]$, $x_m = J_{DFIG}\omega$: are the electrical and Mechanical state variables respectively. The passive energy equation as in (6).

$$H(x) = \frac{1}{2} x_e^T L^{-1} x_e + \frac{1}{2J_{DFIG}} x_m^2 \tag{6}$$

With: $L = \begin{bmatrix} L_s I_2 & M I_2 \\ M I_2 & L_r I_2 \end{bmatrix}$

For the previous equation, the derivatives of electrical and mechanical state variables as in (7).

$$\begin{cases} \frac{\partial H}{\partial x_e} = L^{-1} x_e \\ \frac{\partial H}{\partial x_m} = J_{DFIG}^{-1} x_m \end{cases} \Rightarrow \begin{cases} \frac{\partial H}{\partial x_e} = L^{-1} x_e = I = [I_s^T, I_r^T]^T \\ \frac{\partial H}{\partial x_m} = J_{DFIG}^{-1} x_m = \omega \end{cases} \tag{7}$$

Lastly, the matrices control written as:

$$J(x) = \begin{bmatrix} -\omega_s L_s J_2 & -\omega_s M J_2 & 0_{2\times1} \\ -\omega_s L_s J_2 & -(\omega_s - \omega) L_s J_2 & M J_2 I_s \\ 0_{1\times2} & M I_s^T J_2 & 0 \end{bmatrix}, R(x) = \begin{bmatrix} R_s I_2 & 0_{2\times2} & 0_{2\times1} \\ 0_{2\times2} & R_r I_2 & 0_{2\times1} \\ 0_{1\times2} & 0_{1\times2} & C_f \end{bmatrix}$$

$$\mathrm{g}(x) = \begin{bmatrix} I_2 & 0_{2\times2} & 0_{2\times1} \\ 0_{2\times2} & I_2 & 0_{2\times1} \\ 0_{1\times2} & 0_{1\times2} & 1 \end{bmatrix}, u = [V_s^T \quad V_r^T \quad T_r]^T$$

With: $0_{2\times2} = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$, $0_{2\times1} = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$, $0_{1\times2} = [0 \quad 0]$, $J(x) = J(x)^{-1}$, $R(x) = R(x)^T \geq 0$

Conclusively, the mathematical control is:

$$\dot{x} = \left[\begin{bmatrix} -\omega_s L_s J_2 & -\omega_s M J_2 & 0_{2\times1} \\ -\omega_s M J_2 & -(\omega_s - \omega) L_s J_2 & M J_2 I_s \\ 0_{1\times2} & M I_s^T J_2 & 0 \end{bmatrix} - \begin{bmatrix} R_s I_2 & 0_{2\times2} & 0_{2\times1} \\ 0_{2\times2} & R_r I_2 & 0_{2\times1} \\ 0_{1\times2} & 0_{1\times2} & T_f \end{bmatrix}\right] \nabla H + \begin{bmatrix} I_2 & 0_{2\times2} & 0_{2\times1} \\ 0_{2\times2} & I_2 & 0_{2\times1} \\ 0_{1\times2} & 0_{1\times2} & 1 \end{bmatrix} \begin{bmatrix} V_s^T \\ V_r^T \\ T_r \end{bmatrix}$$

$$\dot{y} = \begin{bmatrix} I_2 & 0_{2\times2} & 0_{2\times1} \\ 0_{2\times2} & I_2 & 0_{2\times1} \\ 0_{1\times2} & 0_{1\times2} & 1 \end{bmatrix} \nabla H$$

2.2. SIDA-PBC methode

The energy equation as in (8) [3], [12], [17]-[22].

$$H_d(x) = \frac{1}{2} \tilde{x}^T P_d \tilde{x}, P_d = P_d^T > 0 \tag{8}$$

SIDA-PBC methode is solving $F_d(x)$ and countering $F_d(x) + F_d^T \leq 0$.

$$[J(I_s, \omega) - R] \partial H + \begin{bmatrix} V_s \\ 0_{2\times1} \\ C_{em} \end{bmatrix} + \begin{bmatrix} 0_{2\times2} \\ I_2 \\ 0_{1\times2} \end{bmatrix} V_r = F_d(x) P_d \tilde{x} \tag{9}$$

To simplify the solution, we offer P_d diagonal.

$$P_d = \begin{bmatrix} P_s & 0_{2\times2} & 0_{2\times1} \\ 0_{2\times2} & P_r & 0_{2\times1} \\ 0_{1\times2} & 0_{1\times2} & P_\omega \end{bmatrix} > 0 \text{ , } F_d(x) = \begin{bmatrix} F_{11}(x) & F_{12}(x) & 0_{2\times1} \\ F_{21}(x) & F_{22}(x) & F_{23}(x) \\ F_{31}^T(x) & F_{32}^T(x) & F_{33}(x) \end{bmatrix}$$

Where: $F_d(x)$ is suit P_d.

By the (9) and the equilibria (7), we have:

$$-(\omega_s L_s J_2 + R_s I_2) \tilde{I}_s - \omega_s L_s J_2 \tilde{I}_r = (L_s F_{11} P_s + M F_{12} P_r) \tilde{I}_s + (M F_{11} P_s + L_r F_{12} P_r) \tilde{I}_r \tag{10}$$

For everything $\tilde{I}_s, \tilde{I}_r$, there is a unique solution given by:

$$F_{11} = -\frac{1}{P_s}\left(\omega_s J_2 + \frac{L_r}{\mu} R_s I_2\right) \tag{11}$$

$$F_{12} = \frac{M}{P_r \mu} R_s I_2 \tag{12}$$

With: $\mu = L_s L_r - M^2 > 0$

The calcul of F_{12} of $J_d(x)$ is possible set to zero.

The choice of $F_{31}(x)$ be easy by having this precedent term equal to zero. Of course, it appears in $F_d(x) + F_d^T(x)$, and $F_{32}(x)$ is not critical because his contribution to the $F_d(x) + F_d^T(x)$ perhaps centered by an appropriate choice of $F_{23}(x)$ that given the presence of the command [22]–[24].

$$[F_{31}^T(x) P_s \quad F_{32}^T(x) P_r] L \tilde{\imath} + F_{33}(x) P_\omega J_{DFIG} \widetilde{\omega} = M I_s^T J_2 I_r - C_f \omega = M[-I_r^{*T} J_2 \quad I_s^T J_2] \tilde{\imath} - C_f \widetilde{\omega} \tag{13}$$

From the term $\tilde{\omega}$ we obtain:

$$F_{33} = -\frac{C_f}{P_\omega J_{DFIG}} \quad (14)$$

While the remaining equations can be arranged in ways:

$$\left(L\begin{bmatrix} P_s F_{31}(x) \\ P_r F_{32}(x) \end{bmatrix} - M\begin{bmatrix} J_2 I_r^* \\ -J_2 I_s \end{bmatrix}\right) = 0 \quad (15)$$

With: $L = \begin{bmatrix} L_s J_2 & M I_2 \\ M I_2 & L_r I_2 \end{bmatrix}$

By adding to (10) a vector $G(x) \in \Re^4$

$$\tilde{\imath}^T\left(L\begin{bmatrix} P_s F_{31}(x) \\ P_r F_{32}(x) \end{bmatrix} - M\begin{bmatrix} J_2 I_r^* \\ -J_2 I_s \end{bmatrix} - G(x)\right) = 0 \quad (16)$$

Or: $\tilde{\imath}^T . G(x) = 0$

and fixing the front of (16)=0 we have:

$$\begin{bmatrix} P_s F_{31}(x) \\ P_r F_{32}(x) \end{bmatrix} = \frac{M}{\mu}\begin{bmatrix} L_r J_2 I_r^* + M J_2 I_s \\ -L_r J_2 I_s - M J_2 I_r \end{bmatrix} + \begin{bmatrix} G_c(x) \\ G_D(x) \end{bmatrix} \quad (17)$$

and by introducing the therm:

$$\begin{bmatrix} G_c(x) \\ G_D(x) \end{bmatrix} = L^{-1} G(x) \quad (18)$$

With:

$G_c(x), G_D(x) \in \Re^2$

As mentioned above, in order to satisfy the antisymmetry condition, it is necessary to find a solution with $F_{31}(x) = cst$, which can be easily achieved by choosing [16], [23]–[25].

$$G_c(x) = -\frac{M^2}{\mu} J_2 \tilde{I}_s \quad (19)$$

With this equation, we result:

$$G(x) = \begin{bmatrix} -\frac{M^2 L_r}{\mu} J_2 \tilde{I}_s + M G_D \\ -\frac{M}{\mu} J_2 \tilde{I}_s + L_r G_D \end{bmatrix} \quad (20)$$

and, in order to ensure $\tilde{\imath}^T G(x) = 0$, we fix:

$$G_D(x) = -\frac{M^2}{\mu} J_2 \tilde{I}_r \quad (21)$$

Lastely, by replacing (19) and (21) in (17) we have:

$$F_{31} = \frac{M}{P_s \mu} J_2 (M I_s^* + L_r I_r^*) = \frac{M}{P_s \mu} J_2 \Phi_r^* \quad (22)$$

$$F_{32} = -\frac{M}{P_r \mu} J_2 (L_s I_s + M I_r) = -\frac{M}{P_r \mu} J_2 \Phi_s \quad (23)$$

In the next step, the item $F_d(x)$, is selected, which is directly affected by the control measure [16], [24]–[26]. To satisfy the symmetry constraints of J_d, and simplify the state, we choose:

$F_{21} = -F_{12}$, $F_{23}(x) = -F_{32}(x)$, $F_{22} = -\frac{k_r}{2P_r} I_2 < 0.$

With:

$$F_d(x) + F_d^T(x) = \begin{bmatrix} -\frac{2L_rR_s}{P_s}I_2 & 0_{2\times2} & \frac{M}{P_s\mu}J_2\Phi_r^* \\ 0_{2\times2} & -\frac{k_r}{p_r}I_2 & 0_{2\times1} \\ -\frac{M}{P_s\mu}\Phi_r^* & 0_{1\times2} & -\frac{2C_f}{P_\omega J_{DFIG}} \end{bmatrix} \quad (24)$$

Analysis to determine this is easy to complete $F_d(x) + F_d^T(x) < 0$ if and only if the parameters P_s and P_ω satisfied:

$$P_s > \left(\frac{J_{DFIG}M^2}{4C_fL_rR_s\mu}|\Phi_r^*|^2\right)P_\omega$$

The equations of tensions of the DFIG in closed loop is written as:

$$V_r = R_rI_r + (\omega_s - \omega)J_2(MI_s + L_rI_r) - K_s(L_s\tilde{I}_s + M\tilde{I}_r) - K_r(L_r\tilde{I}_r + M\tilde{I}_s) + K_\omega J_2\Phi_s\tilde{\omega} \quad (25)$$

With:

$$K_r > 0\,, K_\omega = \frac{P_\omega J_{DFIG}M}{P_r\mu} > 0 \; et \; K_s > \frac{M^2}{4C_fL_rL_r\mu}|\Phi_r^*|^2\, K_\omega$$

The global system control diagram is shown in Figure 1:

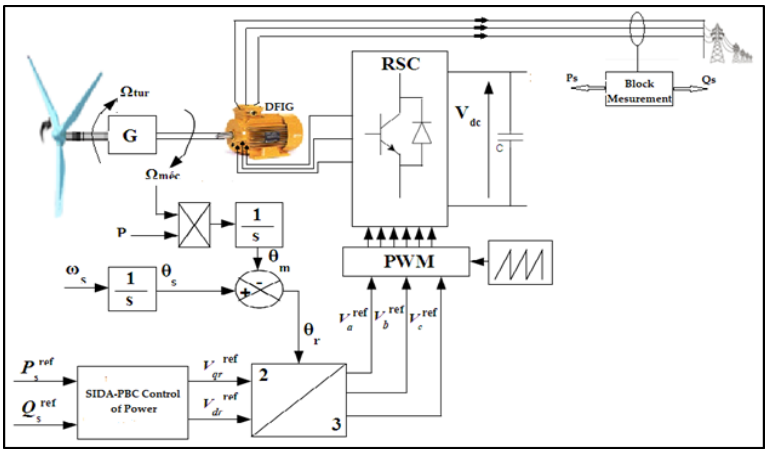


Figure 1. SIDA-PBC control scheme

3. DISCUSS THE RESULTS

Using the MATLAB environment simulation and with the parameters of the doubly fed induction generator (DFIG) mentioned in Table 1 in the appendix; we therefore obtained in Figure 2 the tests results of the track and regulation for the SIDA-PBC control. Figure 3 presents the results of the robustness tests, Figure 3(a) results of 30% variation of inductance and Figure 3(b) results of 30% variation of resistance.

Table 1. DFIG parameters [2]

Parameter	Value
nominal power	100 Kw
Stator resistance	0.4 Ω
Rotor resistance	0.1 Ω
Stator inductance	0.07 H
Rotor inductance	0.02 H
Mutual inductance	0.03 H
Moment of inercia	0.5 Kg.m²
coefficient of friction	0.002 N.m.s/rad
number of pole pairs	2

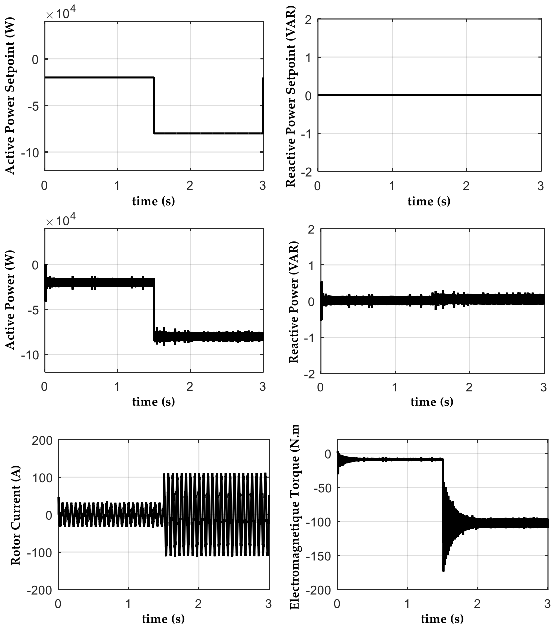
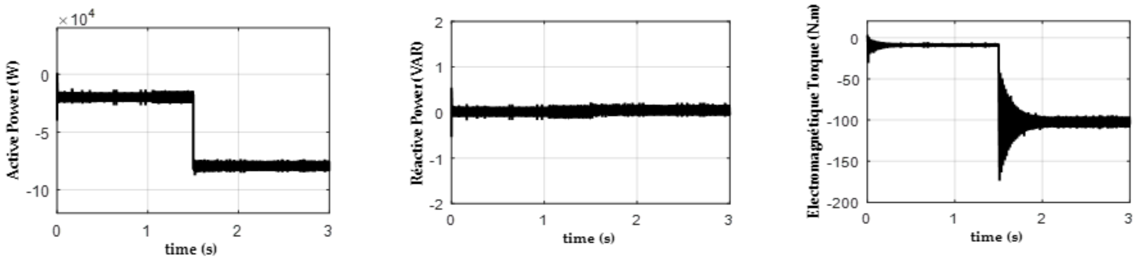
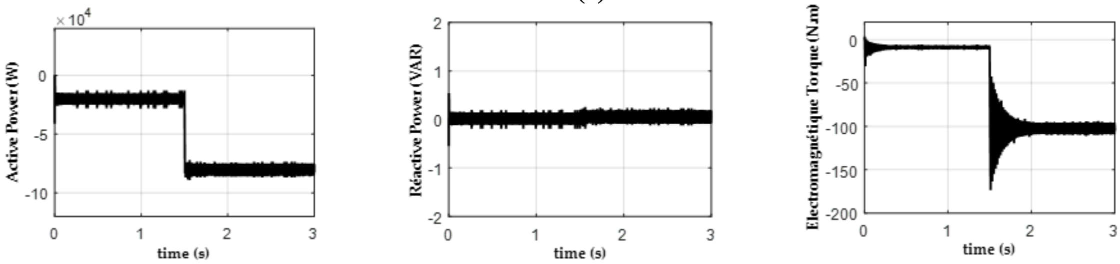


Figure 2. Tests results of the track and regulation



(a)



(b)

Figure 3. Robustness tests (a) results of 30% variation in inductance and (b) results of 30% change in resistance

4. CONSULTATION

Evaluation of power controller performance by nonlinear control of the generator performance by the controller based on switching and damping (SIDA-PBC) considerations. We ran a series of MATLAB/Simulink simulations. In a tracking test, the controlled variable successfully follows the target path without exceeding the active and reactive powers and without steady-state static errors. The 3-phase stator current draw is low at the start and sinusoidal at steady state. The rotor current frequency is 17.5 Hz thanks to a good choice of PWM control strategy in the inverter. Proportional electromagnetic torque and active power have the same appearance at constant speed.

In simulations tests, we notice very good sensitivity to disturbances caused by abrupt setpoint changes from -20 KW to -80 KW, active and reactive powers are unaffected. The three-phase rotor current is sinusoidal. Electromagnetic torque and active power output are not affected. Robustness tests show that a

+50% variation in resistance (Rs, Rr) and +30% in inductance (Ls, Lr) has very little effect on response time and osciations amplitudes.

5. CONCLUSION

The presented research focuses on active and reactive powers advanced control of a doubly fed induction generator by a new structure of passivity. Robustness results show a very good sensitivity. Active and reactive powers always stay within tolerance for disturbances this means that the variation of the parameters (resistances and inductances rotorique and statorique) little impact on response time. It has been shown that very good results can be obtained thanks to the UPS sine-triangle PWM control strategy.

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