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Evaluation of the passivity-based power control of a doubly-fed induction generator with unknown constant torque

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Abstract: A performance evaluation study of a passivity-based power control scheme for a doubly-fed induction generator with unknown constant torque is presented in this paper. An algebraic identification approach is applied for the on-line estimation of the torque. Then the passivity-based controller is combined with the proposed torque estimation to regulate the electric machine towards the specified power generation conditions. Some computer simulation results are included to show the efficient performance of the control scheme and the fast and effective estimation of the torque.

Keywords: Passivity-based control, induction generator, torque identification.

1. INTRODUCTION

Nowadays, contrary to what was previously thought in (Fitzgerald et al., 2003) about the use of the induction machine as a generator, it is common to find electric energy generation systems with a induction generator, especially generation systems with a Doubly-Fed Induction Generator (DFIG). According to (Ackermann, 2006), (Bianchi et al., 2007), (Santos-Martin et al., 2008), this fact is due to the high performance that can be achieved with this kind of device under variable-speed operation and to the possibility for feeding directly the rotor winding using high efficient power converters, which makes feasible to carry out the energy conversion process using only a small fraction of the energy managed by whole power system.

For the remarkable features of the DFIG, it can be seen in the literature this generator is used in different kind generation systems, being the wind generation system the most important (Cárdenas et al., 2013). For example, in (Batlle et al., 2009) it is shown how DFIG is used in a different generation system to the wind generation system, where a flywheel is employed as storage system. In this work, the control objective was to change the direction of the power flow of the generation system with the network (toward or from the flywheel) depending on the load demand. In (Batlle et al., 2009) a passivity-based control was proposed to achieve the control objective and in the (López-García et al., 2013) is shown how this control can deal with this problem establishing a viable solution from both a dynamic performance perspective and a practical implementation. However, the main problem is that to use this control strategy is necessary to know the torque.

Certainly, there exist numerous identification methods reported in the literature that could be applied for estimation of the torque. Nevertheless, most of these identification methods are asymptotic, recursive and slow (Isermann and Munchhof, 2011). On the other hand, recently an algebraic parametrical identification method for linear systems has been proposed in (Fliess and Sira-Ramírez, 2003) showing a fast response for the estimation of the system parameters.

Thus, the main purpose of this study is to evaluate the performance of the passivity-based power control scheme reported in (Batlle et al., 2009) for a doubly-fed induction generator considering the unknown torque. The algebraic parametric identification approach is applied for the on-line estimation of the torque. Then the passivity-based controller is combined with the proposed torque estimation to regulate the electric machine towards the specified power generation conditions. Some computer simulation results are included to show the efficient performance of the control scheme and the fast and effective estimation of the torque.

The rest of the paper is organized as follows: In Section 2, the mathematical model considered for the DFIM is presented, together with the control problem formulation and the algebraic estimation of the torque delivered. The controller evaluation with the estimation of the torque delivered is carried out in Section 3. Section 4 is devoted to state some concluding remarks.

2. PROBLEM FORMULATION

In this section the mathematical model of the DFIG, the control problem and the conditions under which it is solvable, and the algebraic estimation approach of the torque delivered to the machine by the prime mover are presented.

2.1 DFIG model

Under the assumption of linear magnetic circuits and balanced operating conditions, according to (Krause et al., 2002), the equivalent two-phase model of the symmetrical

DFIM, represented in a rotating dq reference frame fixed to the stator voltage vector is given by

$$\frac{di_s}{dt} = -\omega_s \mathbf{J} i_s - \omega\beta\mathbf{J}\lambda_r - \gamma i_s + \alpha\beta\lambda_r + \frac{\beta L_r}{L_{sr}} u_s - \beta u_r \quad (1)$$
$$\dot{\lambda}_r = -(\omega_s - \omega)\mathbf{J}\lambda_r + \alpha L_{sr} i_s - \alpha\lambda_r + u_r \quad (2)$$
$$J\dot{\omega} = \frac{L_{sr}}{L_r} i_s^T \mathbf{J}\lambda_r - B\omega + T_m \quad (3)$$

where ω_s is the rotation speed for the reference frame, ω is the rotor speed, $i_s = [i_{s1}, i_{s2}]^T$ are the stator currents, $\lambda_r = [\lambda_{r1}, \lambda_{r2}]^T$ are the rotor fluxes, u_s and u_r are the stator and rotor voltages, respectively, while the all positive parameters are given by

$$\alpha = \frac{R_r}{L_r};\ \beta = \frac{L_{sr}}{\mu};\ \gamma = \frac{1}{\mu}\left(\frac{R_s L_r^2 + R_r L_{sr}^2}{L_r}\right)$$

with $\mu = L_s L_r - L_{sr}^2$ and

$$\mathbf{J} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} = -\mathbf{J}^T$$

Here L_s, L_r are stator and rotor proper inductances, L_{sr} is the mutual inductance, R_s, R_r are the winding resistances, J is the inertia coefficient, B is the damping coefficient and T_m is the applied mechanical torque.

As in (López-García et al., 2013), considering that the flux vector $\lambda = \mathcal{L}_e i$ with $\lambda = \left[\lambda_s^T, \lambda_r^T\right]^T$ and $i = \left[i_s^T, i_r^T\right]^T$, where λ_s are the stator fluxes and i_r the rotor currents, while

$$\mathcal{L}_e = \begin{bmatrix} L_s\mathbf{I}_2 & L_{sr}\mathbf{I}_2 \\ L_{sr}\mathbf{I}_2 & L_r\mathbf{I}_2 \end{bmatrix};\ \mathbf{I}_2 = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} \quad (4)$$

the model (1)–(3) can be equivalently written as

$$\dot{\lambda}_s = -\omega_s L_s \mathbf{J} i_s - \omega_s L_{sr}\mathbf{J} i_r - R_s i_s + u_s \quad (5)$$
$$\dot{\lambda}_r = -(\omega_s - \omega)L_{sr}\mathbf{J} i_s - (\omega_s - \omega)L_r \mathbf{J} i_r - R_r i_r + u_r \quad (6)$$
$$J\dot{\omega} = L_{sr} i_s^T \mathbf{J} i_r - B\omega + T_m \quad (7)$$

Remark. Under generator operation of the DFIM, T_m is the torque delivered to the machine by a controlled primary mover while $T_g = L_{sr} i_s^T \mathbf{J} i_r$ is torque produced by the machine itself. In this paper it is considered that T_m is constant, assumption that is not restrictive since usually the primary mover is equipped with a speed controller (Munteanu et al., 2008).

Remark. From a controller design perspective, one advantage exhibited by the DFIM is that the complete state vector is measurable, i.e. mechanical speed and both stator and rotor currents can be used to structure of the control scheme.

2.2 Power control problem

From the generated power viewpoint, model (5)–(7) exhibits the following structure if it is assumed that the stator terminals are connected to an infinite bus with voltage magnitude U and frequency determined by ω_s. Active ($\mathcal{P}$) and reactive ($\mathcal{Q}$) power at the stator side are given by

$$\mathcal{P}_{ab} = I_s^T V_s;\ \ \mathcal{Q}_{ab} = -I_s^T \mathbf{J} V_s$$

where I_s and V_s are the vectors of stator currents and voltages, respectively, in the natural ab reference frame for the induction machine [1]. In the dq reference frame considered for representing the machine model, these expressions take the form

$$\mathcal{P} = U i_{s1};\ \ \mathcal{Q} = -U i_{s2} \quad (8)$$

which clearly exhibit the advantage of the representation, since control of the active and reactive power can be carried out by controlling each of the components of the stator current vector i_s.

Taking into account the information presented above, the control problem solved in this paper can be stated as

Consider the DFIM model given by (5)–(7). Assume that

- **A.1** *The mechanical speed and both stator and rotor currents are available for measurement.*
- **A.2** *The torque delivered by the prime mover is constant and unknown.*
- **A.3** *The model parameters are known.*
- **A.4** *Stator voltages have fixed frequency and amplitude, i.e. stator windings are directly connected to the line grid.*

Under these conditions, design a control law for the rotor voltages $u_r = u_r(i_s, i_r, \omega)$ such that

$$\lim_{t\to\infty} \mathcal{P} = \mathcal{P}_\star;\ \ \lim_{t\to\infty} \mathcal{Q} = \mathcal{Q}_\star$$

with the desired power defined by $\mathcal{P}_\star$, $\mathcal{Q}_\star$, guaranteeing internal stability.

One passivity-based Power control of a DFIM was reported in (Batlle et al., 2009) and evaluated in (López-García et al., 2013), where this control power problem was solved, considering that the torque is known. The control strategy is given by

$$\begin{aligned} u_r = {} & (\omega_s - \omega)\mathbf{J}\left(L_{sr} i_s + L_r i_r\right) + R_r i_r + \\ & p_s F_{21}\left(L_s e_s + L_{sr} e_r\right) + p_r F_{22}\left(L_{sr} e_s + L_r e_r\right) + \\ & J p_m F_{23} e_m \end{aligned} \quad (9)$$

where

$$\begin{aligned} F_{21} &= -\frac{L_{sr} R_s}{\mu p_r}\mathbf{I}_2 \\ F_{22} &= -\frac{k_r}{2p_r}\mathbf{I}_2 \\ F_{23} &= \frac{L_{sr}}{\mu}\mathbf{J}^T\left(L_s i_s + L_{sr} i_r\right) \\ e_s &= i_s - i_{s\star} \\ e_r &= i_r - i_{r\star} \\ e_m &= \omega - \omega_\star \end{aligned}$$

while $k_r > 0$, $p_r > 0$, $p_m > 0$ and

$$p_s > \left(\frac{J L_{sr}^2}{4B\mu L_r}\|L_{sr} i_{s\star} + L_r i_{r\star}\|^2\right) p_m$$

[1] In the ab reference frame the stator variables are represented in a fixed reference frame while the rotor variables are expressed with respect to a reference frame that rotates at an angular speed given by ω (Krause et al., 2002).

The closed-loop equilibrium point is given by

$$i_{s\star} = \frac{1}{U}\begin{bmatrix}1 & 0\\ 0 & -1\end{bmatrix}\begin{bmatrix}\mathcal{P}_\star\\ \mathcal{Q}_\star\end{bmatrix}$$
$$i_{r\star} = \frac{1}{\omega_s L_{sr}}\left[-\left(\omega_s \mathbf{I}_2 + R_s\mathbf{J}^T\right) i_{s\star} + \mathbf{J}^T u_s\right]$$
$$\omega_\star = \frac{1}{B\omega_s}\left[\mathcal{P}_\star - R_s\|i_{s\star}\|^2\right] + \frac{T_m}{B}$$

As pointed out in (Batlle et al., 2009), the structure of the presented controller can be further simplified, from a tuning point of view, by defining

$$k_s = \frac{p_s L_{sr} R_s}{\mu p_r};\quad k_m = \frac{p_m J L_{sr}}{\mu p_r}$$

since, under these conditions, the controller takes the form

$$u_r = (\omega_s - \omega)\mathbf{J}\left(L_{sr} i_s + L_r i_r\right) + R_r i_r -$$
$$k_s\left(L_s e_s + L_{sr} e_r\right) - k_r\left(L_{sr} e_s + L_r e_r\right) +$$
$$k_m \mathbf{J}\left(L_s i_s + L_{sr} i_r\right) e_m$$

with $k_r > 0$, $k_m > 0$ and

$$k_s > \left(\frac{L_{sr}^2}{4B\mu L_r}\|L_{sr} i_{s\star} + L_r i_{r\star}\|^2\right) k_m$$

The main problem about this strategy control is that, from an implementation point of view, it is clear that it is necessary to know the torque to use this control strategy. However, it is known that to measure this variable it is difficult and expensive, then, one viable solution is to identify it. Thus, an algebraic approach for on-line torque estimation is proposed in this paper.

2.3 On-line algebraic torque estimation

Consider that measurements of the electric current signals and velocity are available to be used in the synthesis of an on-line torque identification scheme. Then, multiplying equation (7) by $(t - t_0)$ one gets

$$J(t-t_0)\dot{\omega} = L_{sr}(t-t_0) i_s^T \mathbf{J} i_r - B(t-t_0)\omega + (t-t_0)T_m \qquad (10)$$

where t_0 is the start time when the torque estimation is performed.

By integrating equation (10) with respect to time one gets

$$J(\Delta t)\omega - J\int_{t_0}^{t}\omega dt = L_{sr}\int_{t_0}^{t}(\Delta t) i_s^T \mathbf{J} i_r dt - B\int_{t_0}^{t}(\Delta t)\omega dt + \int_{t_0}^{t}(\Delta t)T_m dt \qquad (11)$$

with $(\Delta t) = t - t_0$.

Hence from equation (11) the following algebraic identifier (formula) is obtained for on-line torque estimation:

$$\widehat{T}_m = \frac{\int_{t_0}^{t}|n|\,dt}{\int_{t_0}^{t}|d|\,dt},\quad t > t_0 \qquad (12)$$

where n and d are output variables of the dynamic system

$$\dot{\eta}_1 = B(\Delta t)\omega - L_{sr}(\Delta t) i_s^T \mathbf{J} i_r - J\omega$$
$$\dot{\eta}_2 = (\Delta t)$$
$$n = \eta_1 + J(\Delta t)\omega$$
$$d = \eta_2 \qquad (13)$$

3. CONTROLLER EVALUATION

The usefulness of the passivity-based power control scheme with on-line torque identification is evaluated in this section. This evaluation was carried out using a numerical simulation under the MATLAB/Simulink environment to assess the performance of the control law for a specific operating condition. The reference for the stator active power was $\mathcal{P}_\star = -1750.7[W]$ with a desired stator power factor $PF_{s\star} = 1$, while the unknown mechanical torque was kept at $T_m = 5[N-m]$.

In the evaluation there were considered constant the machine parameters, which are included in Table 1, the controller gains $k_s = 1700$, $k_r = 1000$ and $k_m = 0.18$, and the stator terminal voltages was fixed at $U = 220[V]$.

Table 1. DFIG parameters

$R_s = 4.92[\Omega]$
$R_r = 4.42[\Omega]$
$L_s = 0.725[H]$
$L_r = 0.715[H]$
$L_{sr} = 0.71[H]$
$J = 0.00512[kg\cdot m^2]$
$B_r = 0.005[N\cdot m/rad/s]$

The Fig. 1 shows the effective on-line estimation of the torque using the algebraic identifier (12). One can observe a fast torque estimation before 0.1 s. The performance of the passivity-based power control scheme combined with the algebraic torque identification is described in Figs. 2-5. Here, the estimated torque is used in the control implementation at $t > 0.1$ s. The convergence of the active and reactive powers, electric currents and velocity towards the values specified for the machine is clearly verified.

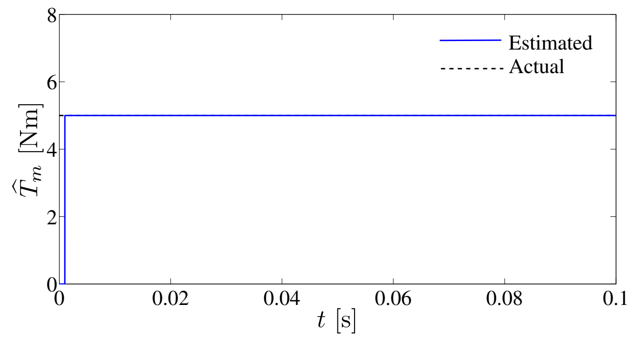

Fig. 1. On-line algebraic estimation of the torque for $PF_{s\star} = 1$.

The numerical evaluation of the control law was carried out under drastic conditions, since it was assumed that the generator was at standstill (all the initial conditions were set zero. In spite of this drastic operating condition, in all the figures it can be shown how the desired behavior is achieved in a very short time and it is clear that a transient response of considerable magnitude is exhibited, but this

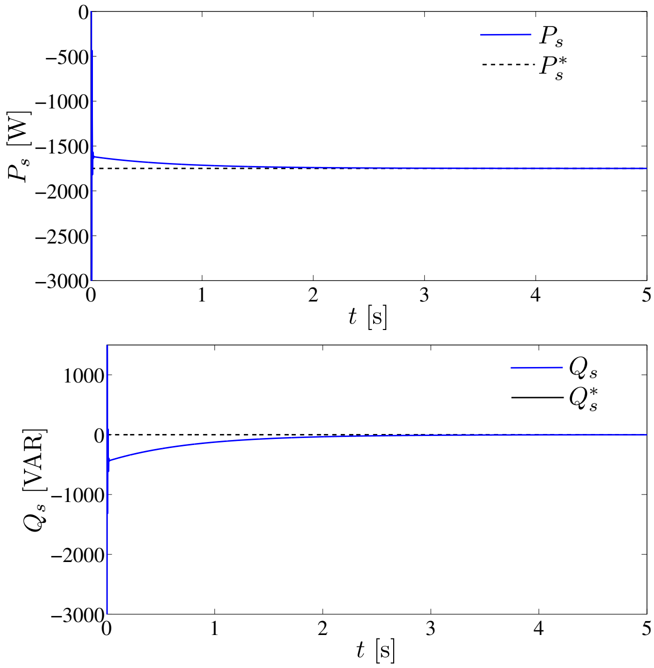

Fig. 2. Stator powers using passivity-based control and algebraic torque identification for $PF_{s\star} = 1$.

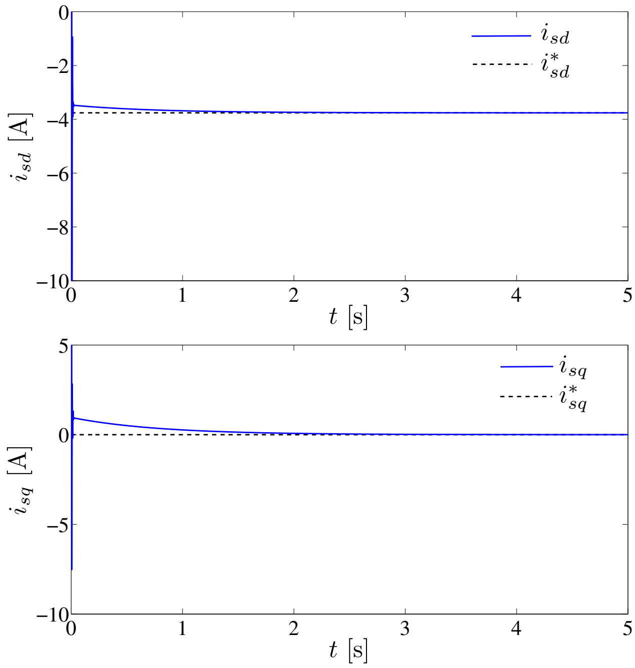

Fig. 3. Stator electric currents using passivity-based control and algebraic torque identification for $PF_{s\star} = 1$.

behavior is due to the stringent initial conditions imposed to the generator.

It is important to note that the power factor $PF_{s\star} = 1$ is not a restrictive operating condition for the passivity-based power control with the algebraic torque identifier, since this can be operated under conditions with reactive power different of the zero. To show this situation, a second experiment is presented in Figs. 6-10. In this case the reference for the stator active power was $\mathcal{P}_\star = -1400.6[W]$ while for the reactive power was $\mathcal{Q}_\star = -1050.4[VAR]$, with a Lagging desired reactive power $PF_{s\star} = (-)0.8$.

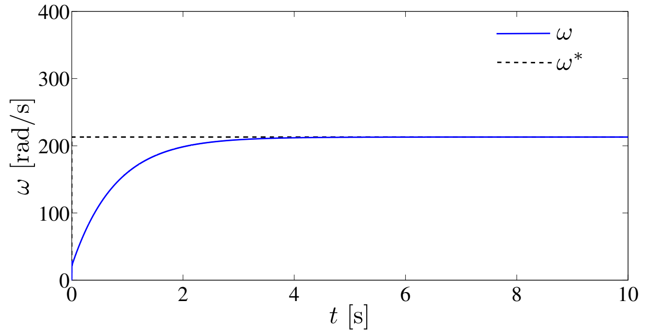

Fig. 4. Velocity response using passivity-based control and algebraic torque identification for $PF_{s\star} = 1$.

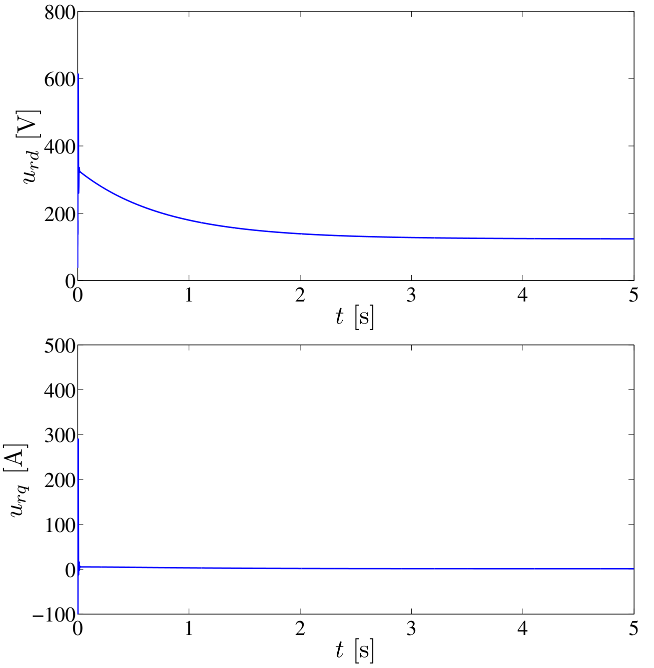

Fig. 5. Rotor voltages using passivity-based control and algebraic torque identification for $PF_{s\star} = 1$.

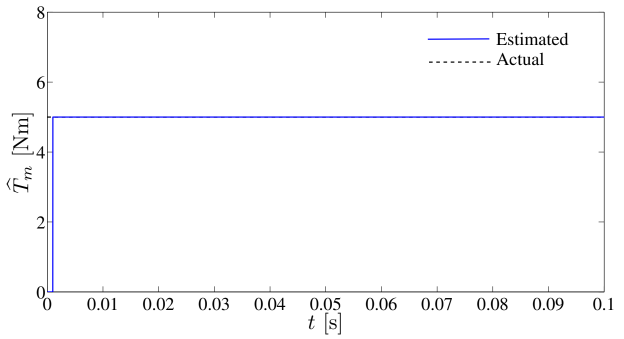

Fig. 6. On-line algebraic estimation of the torque for $PF_{s\star} = (-)0.8$.

In the same way that in the first experiment, the convergence properties of the controller are well illustrated. Again, the same remark that in the previous experiment concerning the considerable transient response applies.

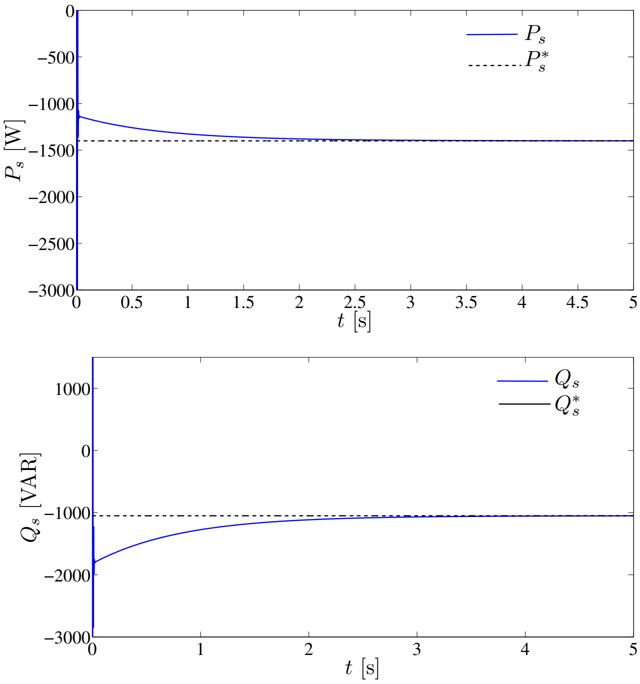

Fig. 7. Stator powers using passivity-based control and algebraic torque identification for $PF_{s\star} = (-)0.8$.

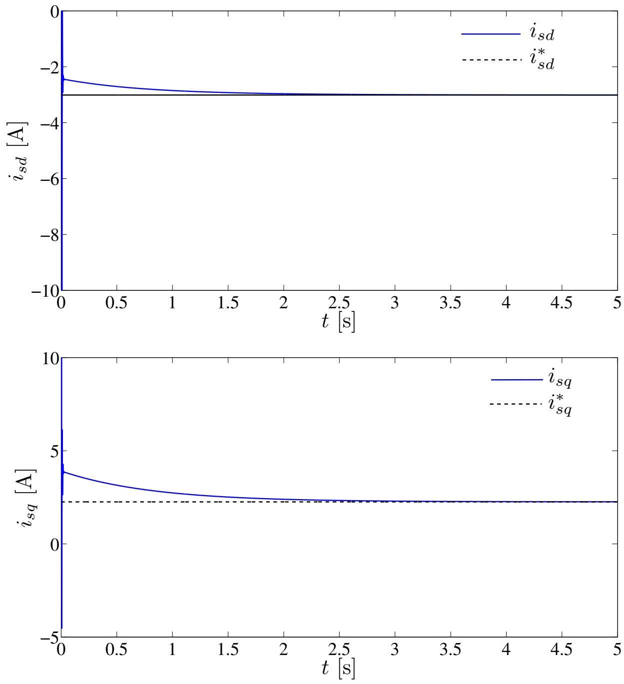

Fig. 8. Stator electric currents using passivity-based control and algebraic torque identification for $PF_{s\star} = (-)0.8$.

4. CONCLUSION

An algebraic identification approach was proposed for on-line torque estimation in a controlled doubly-fed induction generator. The proposed torque identifier was evaluated with a passivity-based power control scheme. The numerical results manifests the efficient performance of the controller and a fast and effective estimation of the torque. Therefore, we can conclude that the passivity-based power

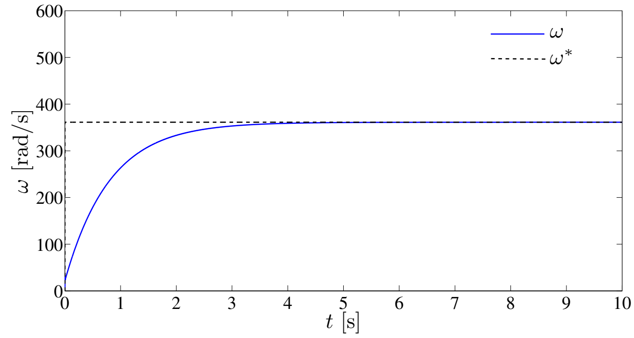

Fig. 9. Velocity response using passivity-based control and algebraic torque identification for $PF_{s\star} = (-)0.8$.

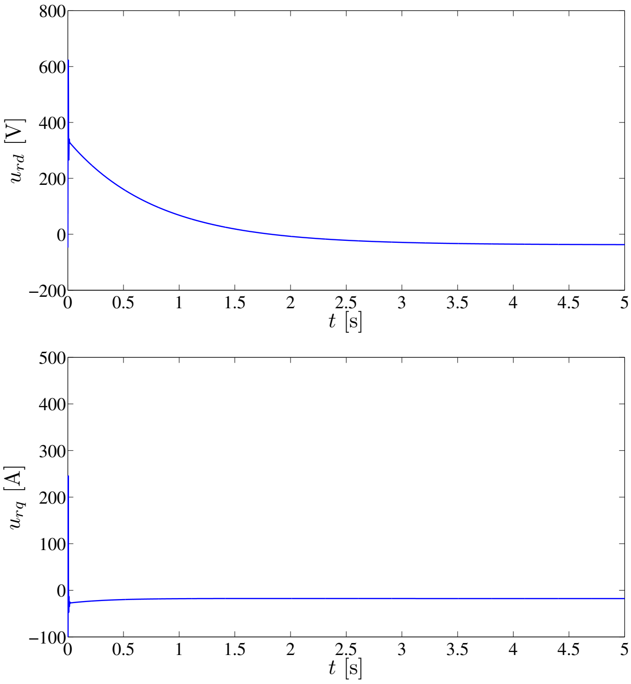

Fig. 10. Rotor voltages using passivity-based control and algebraic torque identification for $PF_{s\star} = (-)0.8$.

control approach combined with on-line algebraic torque identification represents a very good solution to the efficient power control problem of doubly-fed induction generators. Further studies consist on the synthesis of a on-line torque estimation scheme considering additive noise contaminating measurements and control inputs.

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