# Interconnection and Damping Assignment Approach for Reliable PM Synchronous Motor Control

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***Index Terms*— Permanent magnet synchronous motor (PMSM), energy-shaping, port-controlled Hamiltonian systems, IDA-PBC methodology, non linear observer.**

***Abstract*— The goal of this paper is to design a high performance speed controller for a PMSM drive. The controller is passivity based using the energy shaping technique namely Interconnection and Damping Assignment. Under some assumptions, a linear controller is derived associated to a non linear observer to estimate the load torque which is unknown. The important point developed in this paper is the proof of the global stability, which is mandatory in a drive especially in embedded or transportation applications where reliability is a key issue. Simulation and experimental results prove the feasibility of the approach.**

## I. Introduction

After the introduction of rare-earth magnetic materials, permanent magnet synchronous motors (PMSMs) rapidly gained popularity in high-performance variable frequency drive. This popularity is justified by several advantages over commonly used motors. The absence of the external rotor excitation eliminates losses on the rotor and makes PMSMs highly efficient. In addition, the absence of the rotor winding renders slip rings on the rotor and brushes obsolete, and thus reduces the maintenance costs. In addition, new magnetic materials are capable of creating high magnetic fields which yield high power density. This in turn implies rapid dynamic response due to high torque-to-inertia ratio.

Several stable position and velocity controllers for PMSMs have been reported in the control literature. These controllers can be designed using, for instance, backstepping principles [1], feedback linearization [2], cascade control or passivity methods [3],[4]. The availability of a complete theoretical analysis gives the user additional confidence in the design, and may provide some guidelines in the difficult task of commissioning the controller. Experimental evidence, illustrating the practical viability of cascade control may be found in many references, but global stability could not be proved.

In this paper, we apply the recently developed energy-shaping controller design technique to design a new globally stable controller for PMSMs. Analogously to "standard" passivity-based control (PBC), the new methodology is based on energy shaping and passivation principles, and focused on the interconnection and damping structures of the system. This is the so called Interconnection and Damping Assignment (IDA) approach. The resulting scheme consists of a static state feedback with a nonlinear load torque observer for estimate the unknown load torque.

Interconnection and damping assignment passivity-based control is a technique that regulates the behavior of nonlinear systems assigning a desired (port-controlled Hamiltonian) structure to the closed-loop. Since the introduction of this controller design methodology seven years ago, many theoretical extensions and practical applications have been reported in the literature. The theoretical developments include some variations and shortcuts that are useful when dealing with particular classes of systems, and the incorporation of additional features to handle control scenarios other than just stabilization. On the application side the method has provided solutions to a wide variety of physical problems.

This paper is organized as follows. In Section II, we briefly describe the IDA-PBC design methodology of [4],[6],[11] which extends the ideas of PBC of Euler-Lagrange systems to the broader class of port-controlled Hamiltonian (PCH) systems. In section III, we present an asymptotically stabilizing controller for PMSM by modifying the interconnection of the PMSM. Under some assumptions, a linear controller is derived associated to a non linear observer to estimate the load torque which is unknown. Section V shows closed-loop performance of the proposed controller in simulations. We conclude the paper with some final remarks and the comparison with cascade IP controller.

## II. The IDA-PBC Methodology

Interconnection and Damping Assignment passivity-based control (IDA-PBC) was introduced in [5], [6] as a procedure to control physical systems described by port-controlled Hamiltonian (PCH) models of the form

$$\begin{array}{rcl} \dot{x} & = & [\mathcal{J}(x) - \mathcal{R}(x)]\nabla H(x) + g(x)u + \zeta \\ y & = & g^T \nabla H(x) \end{array} \tag{1}$$

where $x \in \Re^n$ is the state vector, $u \in \Re^m$, $m < n$ is the control action, $H : \Re^n \longrightarrow \Re$ is the total stored energy, $\mathcal{J}(x) = -\mathcal{J}^T(x)$, $\mathcal{R}(x) = \mathcal{R}^T(x) \geq 0$ are the natural interconnection and damping matrices, respectively. The vectors $u$ and $y \in \Re^m$ are conjugated variables whose product has units of power. The choice of PCH models was motivated by the fact that they are natural candidates to describe many physical systems (see [7] for a list of references).

Unfortunately, in some engineering applications physical PCH models are too complex for control design and a reduction stage is usually needed. These reductions are usually *adhoc* and destroy the PCH structure. On the other hand, they yield well established models that are widely accepted in practice - hence the interest of extending IDA-PBC to a more general class of systems as described in the following proposition.

**Proposition 1 :** Consider the system

$$\dot{x} = f(x) + g(x)u \tag{2}$$

assume there are matrices $g^{\perp}(x)$, $\mathcal{J}_d(x) = -\mathcal{J}_d^T(x)$, $\mathcal{R}_d(x) = \mathcal{R}_d^T(x) \geq 0$ and a function $H_d(x) : \Re^n \longrightarrow \Re$ that verify the partial differential equation (PDE)

$$g^{\perp}(x)f(x) = g^{\perp}(x)[\mathcal{J}_d(x) - \mathcal{R}_d(x)]\nabla H_d \tag{3}$$

where $g^{\perp}(x)$ is a full-rank left annihilator of $g(x)$, that is, $g^{\perp}(x)g(x) = 0$, and $H_d(x)$ is such that

$$x^* = argmin(H_d(x)) \tag{4}$$

with $x^* \in \Re^n$ the (locally) equilibrium to be stabilized. Then, the closed-loop system (2) with the control $u$, where

$$\begin{array}{rcl} u & = & \left[g^T(x)g(x)\right]^{-1} g^T(x) \\ & \times & \left\{\left[\mathcal{J}_d(x) - \mathcal{R}_d(x)\right]\nabla H_d - f(x)\right\} \end{array} \tag{5}$$

takes the PCH form

$$\dot{x} = [\mathcal{J}_d(x) - \mathcal{R}_d(x)]\nabla H_d \tag{6}$$

with $x^*$ a (locally) stable equilibrium. It will be asymptotically stable if, in addition, $x^*$ is an isolated minimum of $H_d(x)$ and the largest invariant set under the closed-loop dynamics (6) contained in

$$\left\{x \in \Re^n | \left[\nabla H_d\right]^T \mathcal{R}_d(x)\nabla H_d = 0\right\} \tag{7}$$

equals $x^*$. An estimate of its domain of attraction is given by the largest bounded level set $\{x \in \Re^n | H_d(x) \leq c\}$.

Proof : Setting up the right hand side of (2) equal to the right hand side of (6), we get the matching equation

$$f(x) + g(x)u = [\mathcal{J}_d(x) - \mathcal{R}_d(x)]\nabla H_d \tag{8}$$

Multiplying on the left by $g^{\perp}(x)$, we obtain the PDE (3). The expression of the control is obtained by multiplying on the left by the pseudo-inverse of $g(x)$. Stability of $x^*$ is established noting that, along the trajectories of (6), we have

$$\dot{H}_d = -\left[\nabla H_d\right]^T \mathcal{R}_d(x)\nabla H_d \leq 0 \tag{9}$$

Hence, $H_d(x)$ qualifies as a Lyapunov function. Asymptotic stability follows immediately invoking the La Salle's invariance principle and the condition (7). Finally, to ensure the solutions remain bounded, we give the estimate of the domain of attraction as the largest bounded level set of $H_d(x)$.

## III. Permanent Magnet Synchronous Motor Control via IDA-PBC

### A. Motor Model

The PMSM is modeled in the standard dq reference frame model given as follows :

$$\begin{array}{rcl} L_d \frac{di_d}{dt} & = & -R_s i_d + \omega L_q i_q + v_d \\ L_q \frac{di_q}{dt} & = & -R_s i_q - \omega L_d i_d - \omega\phi + v_q \\ J\frac{d\omega}{dt} & = & P\left(\left(L_d - L_q\right) i_d i_q + \phi i_q\right) - \tau_l \end{array} \tag{10}$$

In these equations $P$ is the number of pole pairs, $v_d, v_q, i_d, i_q$ are voltages and currents in the dq frame, $L_d$ and $L_q$ are stator inductances (which are equal in the case of cylindrical rotor), $R_s$ is the stator winding resistance, $\tau_l$ is an unknown load torque, and $\phi$ and $J$ are the flux produced by the magnets and the moment of inertia normalized with $P$ . The angular velocity $\omega$ is measured in electrical radians per second (the connection between electrical and mechanical variables is simply $\omega = P\omega_m$ ).

The energy function of the system is given by

$$H(x) \quad = \quad \frac{1}{2}\left[\frac{1}{L_d}x_1^2 + \frac{1}{L_q}x_2^2 + \frac{P}{J}x_3^2\right]$$

where we have defined the state vector as $x = [x_1, x_2, x_3]^T = [L_d i_d, L_q i_q, (J/P)\,\omega]^T$. The system (10) can then be rewritten in the PCH form

$$\begin{array}{rcl} g & = & \begin{bmatrix} 1 & 0 \\ 0 & 1 \\ 0 & 0 \end{bmatrix} \quad u = \begin{bmatrix} v_d \\ v_q \end{bmatrix} \quad \zeta = \begin{bmatrix} 0 \\ 0 \\ -\frac{\tau_l}{P} \end{bmatrix} \\ \mathcal{J}(x) & = & \begin{bmatrix} 0 & 0 & x_2 \\ 0 & 0 & -(x_1+\phi) \\ -x_2 & (x_1+\phi) & 0 \end{bmatrix} \\ \mathcal{R}(x) & = & \begin{bmatrix} R_s & 0 & 0 \\ 0 & R_s & 0 \\ 0 & 0 & 0 \end{bmatrix}. \end{array}$$

A key step for the success of the IDA-PBC methodology is the adequate choice of the desired interconnection and damping matrices.

### B. The desired equilibrium state

The desired equilibrium state for synchronous machines is usually selected based on the so called "maximum torque per ampere" principle as $x^* = [x_1^*, x_2^*, x_3^*]^T = [0, (L_q\tau_l/P\phi), (J/P)\,\omega^*]^T$, with $\omega^*$ the speed reference.

### C. Controller and Stability Analysis

*1) Known Load Torque Controller:* Application of IDA-PBC to speed control of PMSMs has been reported in [4]. In this section we propose to fix the structure of the desired energy function

$$H_d(x) = \frac{1}{2}\left[\frac{1}{L_d}x_1^2 + \frac{1}{L_q}\left(x_2 - x_2^*\right)^2 + \frac{P}{J}\left(x_3 - x_3^*\right)^2\right] \tag{11}$$

where $x_1^* = 0$ and select

$$\mathcal{J}(x) - \mathcal{R} = \begin{bmatrix} -r_1 & J_{12} & J_{13} \\ -J_{12} & -r_2 & J_{23} \\ -J_{13} & -J_{23} & 0 \end{bmatrix}$$

with $r_i > 0$, and the functions $J_{ij}$ are defined. After some simple calculations the equation (3) becomes an algebraic equation :

$$-J_{13}\frac{x_1}{L_d} - J_{23}\frac{\tilde{x}_2}{L_q} = \gamma x_1 x_2 + \phi\frac{x_2}{L_q} - \frac{\tau_l}{P} \qquad (12)$$

with $\gamma = 1/L_q - 1/L_d$ and $\tilde{x}_2 = x_2 - x_2^*$. To find the solution of equation (12), we make a simplification taking $J_{23} = -\phi$ to be constant, so that $-J_{23}\frac{\tilde{x}_2}{L_q}$ is equal to $\phi\frac{x_2}{L_q} - \frac{\tau_l}{P}$. Now, we plug back the proposed $J_{23}$ into the algebraic equation (12) and compute the function $J_{13}$ as

$$J_{13} = \left(1 - \frac{L_d}{L_q}\right) x_2$$

Thus the controller expression is given by :

$$\begin{aligned} v_d &= (R_s - r_1)\frac{x_1}{L_d} + J_{12}\frac{x_2 - x_2^*}{L_q} \\ &+ \frac{PL_d}{JL_q}x_2x_3^* - \frac{P}{J}x_2x_3^* - \frac{PL_d}{JL_q}x_2x_3 \\ v_q &= (R_s - r_2)\frac{x_2}{L_q} + r_2\frac{x_2^*}{L_q} - J_{12}\frac{x_1}{L_d} \\ &+ \frac{P}{J}\phi x_3^* + \frac{P}{J}x_1x_3 \end{aligned} \qquad (13)$$

where $x^*$ is the desired equilibrium point, and $J_{12}$, $r_1$, $r_2$ are design parameters, with $r_1, r_2 > 0$, and $J_{12} \in \Re$.

Selecting $J_{12} = \frac{PL_d}{J}x_3$, which, upon substitution in (13), yields the linear control law

$$\begin{aligned} v_d &= (R_s - r_1)\frac{x_1}{L_d} - \frac{PL_d}{J}\frac{x_2^*}{L_q}x_3 \\ &+ \frac{PL_d}{JL_q}x_2x_3^* - \frac{P}{J}x_2x_3^* \\ v_q &= (R_s - r_2)\frac{x_2}{L_q} + r_2\frac{x_2^*}{L_q} \\ &+ \frac{P}{J}\phi x_3^* \end{aligned} \qquad (14)$$

The gradient of $H_d(x)$ at $x^*$, $\left.\frac{\partial H_d(x)}{\partial x}\right|_{x=x^*} = 0$ and the Hessian $\frac{\partial^2 H_d(x)}{\partial x^2} > 0$ is positive definite. This ensures global asymptotic stability of $x^*$ with Lyapunov function $H_d(x)$.

*2) Unknown Load Torque Controller:* In practical applications the load torque is, of course, unknown, and we propose to estimate it using a nonlinear observer proposed in [4]

$$\begin{aligned} \frac{d\hat{\omega}}{dt} &= \frac{P}{J}\left(\gamma x_1 + \frac{\phi}{L_q}\right)x_2 - l_1(\hat{\omega} - \omega) - \frac{1}{J}\hat{\tau}_l \\ \frac{d\hat{\tau}_l}{dt} &= l_2(\hat{\omega} - \omega) \end{aligned} \qquad (15)$$

where $l_1$ and $l_2$ are some positive design parameters.

## D. The proof of the global stability of the system

The proof of the global stability of the system composed of the controller, the observer and electrical machine is established invoking a theorem on stability of cascaded systems stated in [9]

**Proposition 2 :** Consider the PMSM (10) in closed-loop with the control law (14) where $x_2^*$ is replaced by $L_q\hat{\tau}_l/P\phi$ generated by (15). We have that $lim_{t\longrightarrow\infty}x(t) = x^*$ for all initial conditions.

Proof : Let us define the estimation error $\tilde{\tau}_l = \hat{\tau}_l - \tau_l$, and write the closed-loop system in the following form :

$$\dot{x} = [\mathcal{J}_d(x) - \mathcal{R}_d(x)]\nabla H_d(x) + \varphi(x)\tilde{\tau}_l \qquad (16)$$

with $\varphi(x) = \frac{1}{\phi}\begin{bmatrix} \frac{-L_d x_3}{J} \\ \frac{r_2}{P} \\ 0 \end{bmatrix}$

The estimator (15) combined with the motor dynamics, produces the following linear tracking error dynamics :

$$\begin{bmatrix} \dot{\tilde{\omega}} \\ \dot{\tilde{\tau}}_l \end{bmatrix} = \begin{bmatrix} -l_1 & -\frac{1}{J} \\ l_2 & 0 \end{bmatrix}\begin{bmatrix} \tilde{\omega} \\ \tilde{\tau}_l \end{bmatrix} \qquad (17)$$

where $\tilde{\omega} = \hat{\omega} - \omega$, and its eigenvalues $\lambda_{1,2}$ are :

$$|\lambda I - A| = \begin{vmatrix} \lambda + l_1 & \frac{1}{J} \\ -l_2 & \lambda \end{vmatrix} = \lambda(\lambda + l_1) + \frac{l_2}{J} = \lambda^2 + l_1\lambda + \frac{l_2}{J}$$

$$\lambda_{1,2} = \frac{-l_1 \pm \sqrt{l_1^2 - 4\frac{l_2}{J}}}{2}$$

This is an autonomous linear system, which is asymptotically stable for all positive gains $l_1$ and $l_2$. Thus, the estimation errors decay exponentially to zero.

The overall error dynamics is a cascade composition like the ones studied in [[9],Th.2], whose conditions we will now verify. First, the nominal part of the first subsystem (16), namely $\dot{x} = [\mathcal{J}_d(x) - \mathcal{R}_d(x)]\nabla H_d(x)$, is globally asymptotically stable. Further, the Lyapunov function $H_d$ is a quadratic function, thus it satisfies the bounds

$$\begin{aligned} \left\|\frac{\partial H_d}{\partial x}(x)\right\|\|x\| \leq c_1 H_d(x), &\qquad \forall\|x\| \geq \eta \\ \left\|\frac{\partial H_d}{\partial x}(x)\right\| \leq c_2, &\qquad \forall\|x\| \leq \eta \end{aligned}$$

where $c_1, c_2, \eta > 0$.This is condition (A.1) of [[9],Th.1]. Second, from inspection of the definitions of $\varphi(x)$ above, and the fact that $\tilde{\tau}_l$ is bounded, we have that the interconnection term satisfies the bound

$$\|\varphi(x)\| \leq c_3 + c_4|x_3|$$

for some $c_3, c_4 > 0$, as required by condition (A.2). Finally, the last condition of the theorem, requiring that the second subsystem in (16) be globally uniformly asymptotically stable and that its response to initial condition be absolutely integrable, is satisfied since the subsystem (17) is linear and exponentially stable. This completes the proof of our proposition.

## IV. Simulation Results

Computer simulations were performed with Matlab/Simulink to evalute the performance of the derived linear controller. Throughout, the PM synchronous motor was modeled using (10) with parameters of a three-phase : $P = 3$, $R_s = 0.255\Omega$, $\phi = 0.17$ Wb, and $J = 2.8.10^{-4}$ Kg.m$^2$. Although this PMSM has the salient rotor case $L_d = 4$ mH and $L_q = 3.6$ mH. The simulation results for the linear controller from proposition 2 are given in Figs. 1-3.

Fig. 1 shows the load torque $\tau_l$ applied to the motor, along with its dynamic estimate $\hat{\tau}_l$ which is used in the controller. The rate of convergence of the load torque estimate is determined by the pole placement of the system (17). Select the suited locations of eigenvalues of the observer $p_1$ and $p_2$, then

$$f(p) = (p - p_1)(p - p_2) = p^2 - (p_1 + p_2)p + p_1 p_2 \quad (18)$$

For these simulations, both system poles were set (arbitrarily) to $p_1 = p_2 = -200 \Rightarrow$ the amortissement $\xi \geq 1$ and we can get the values of the estimator parameter $l_i$ from (18) $l_1 = 2p_d = 400$ , and $l_2 = (J/4)l_1^2 = 11.2$ .

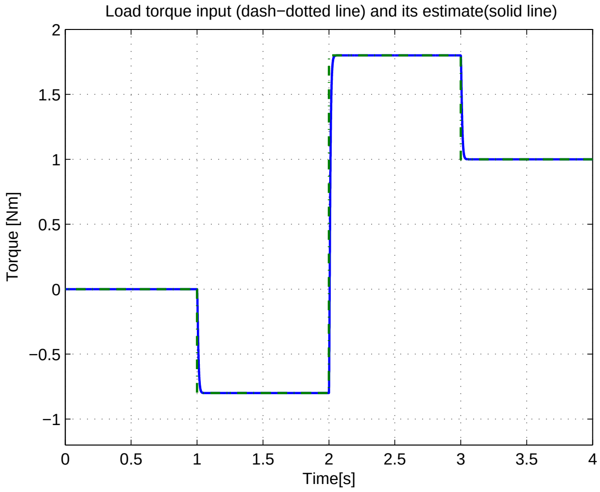


Fig. 1. Representation of the load torque and its estimate.

For instance, setting the tuning parameters $r_1 = 10\,Rs$, $r_2 = 5$. Fig. 2 show a simulation result for some speed variations with constant load torque that is set to $\tau_l = 0.7$ Nm, where the motor rated torque is equal to 3.2 Nm. As the figure show, steady-state speed reference tracking is established at all speeds without bias and without integrator in the controller equations. The current peaks shown in Fig. 3 are limited during the transients mode, although the stator current are not directly limited. Fig. 4 - 6 shows the transient reponse of rotor speed and stator currents for different values of the the controller parameter $r_2$. As expected, increased action proportional to the speed error (decrease in $r_2$) leads to the increase in the speed of the response, but also increases the response overshoot. In addition, this increase also leads to more aggressive stator currents, with large peaks during the transients. A rapid transient response and low stator currents

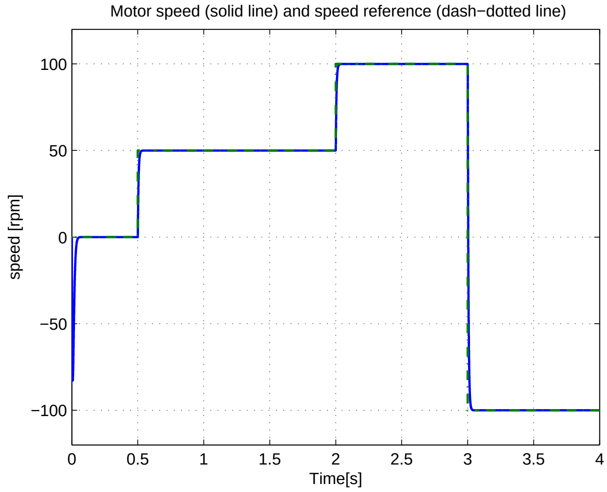


Fig. 2. Representation of the rotor speed.

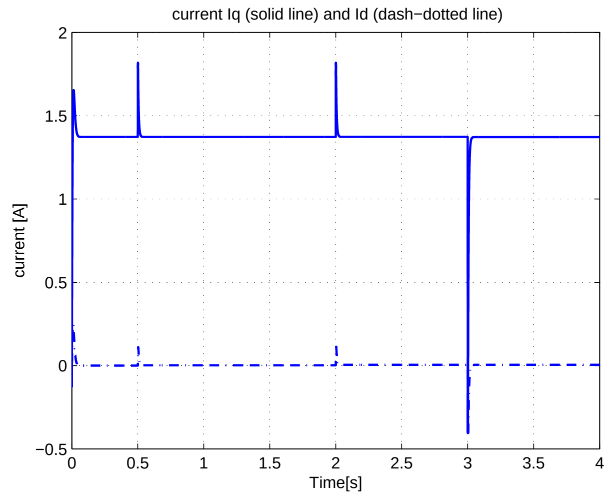


Fig. 3. Representation of the stator currents.

peaks and small response overshoots is reached with the selection of $r_2 = 5$.

### A. Robustness tests

In order to test the performance of the implemented controller in the presence of parameter variations, changes in the PMSM stator winding resistance, stator inductances and the moment of inertia are emulated. Fig. 7 presents the obtained results for the resistances increasing by $50\%$ showing that it is quite insensitive to large change in machines resistance. Fig. 8 and Fig. 9 presents the obtained results for the inductances $L_q$ decreasing by $50\%$ and the inductances $L_d$ increasing by $50\%$ showing that it is quite insensitive to large change in machines inductances. Fig. 10 presents the obtained results for increasing five times of the moment of inertia showing increase in the speed of the response, and also increases the response overshoot.

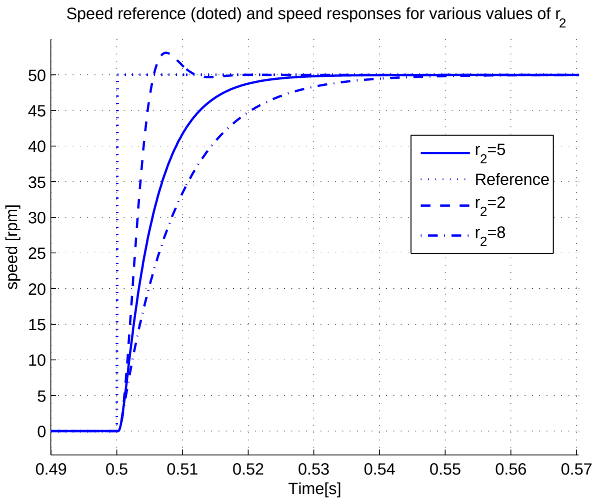


Fig. 4. Representation of the rotor speed for various values of parameter $r_2$.

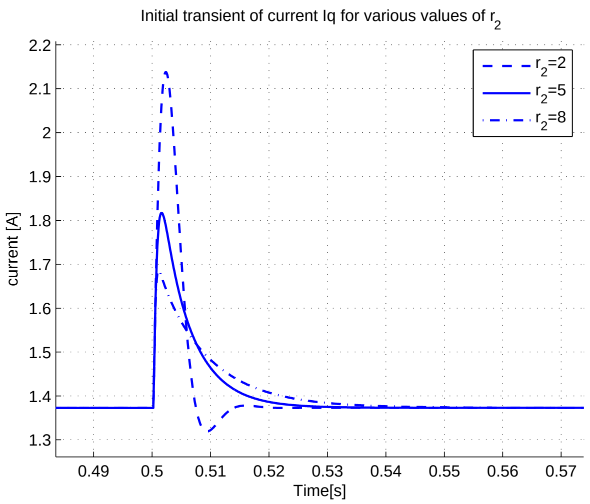


Fig. 5. Representation of the current Iq for various values of parameter $r_2$.

## *B. Comparison of IDA-PBC and cascade IP Controller*

Cascade IP control systems are usually constructed by two control loops. Inner loop with fast dynamic to regulate the currents, while the outer loop to regulate the speed. Fig. 11-12 show a simulation result for some speed variations with constant load torque that is set to $\tau_l = 0.7$ Nm, and the stator currents. This figures show that the behavior of cascade IP controller is the same as that of the proposed IDA-PBC but global stability is proved for IDA-PBC.

## V. Conclusions

In this paper an globally convergent controller for permanent magnet synchronous motors that consists of a nonlinear static state feedback and a nonlinear observer has been established. The importance of this result lies in the fact that the IDA-PBC methodology give a reliable controller that achieves the closed-loop stability for PMSMs. The nonlinear controller has been simplified to obtain a linear one, which is compatible with the industry standard control.

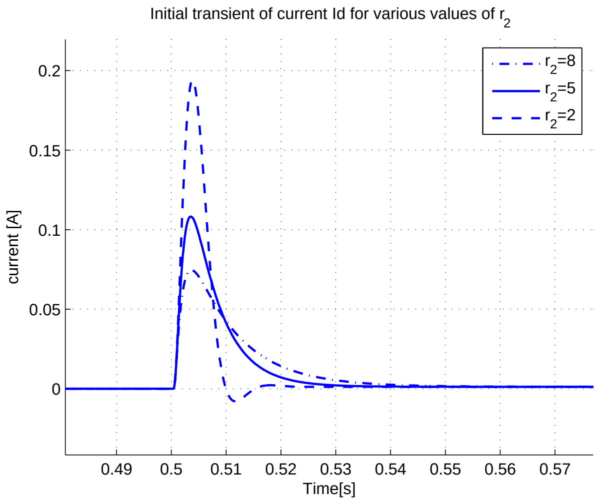


Fig. 6. Representation of the current Id for various values of parameter $r_2$.

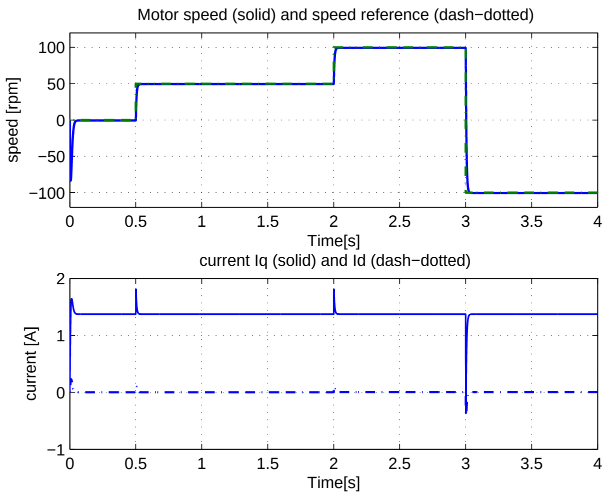


Fig. 7. Representation of the rotor speed and the stator currents for the resistances increasing.

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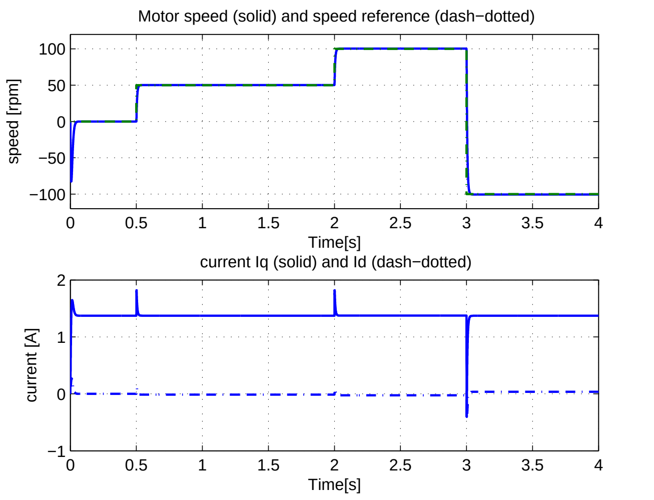


Fig. 8. Representation of the rotor speed and the stator currents for the inductance $L_q$ decreasing.

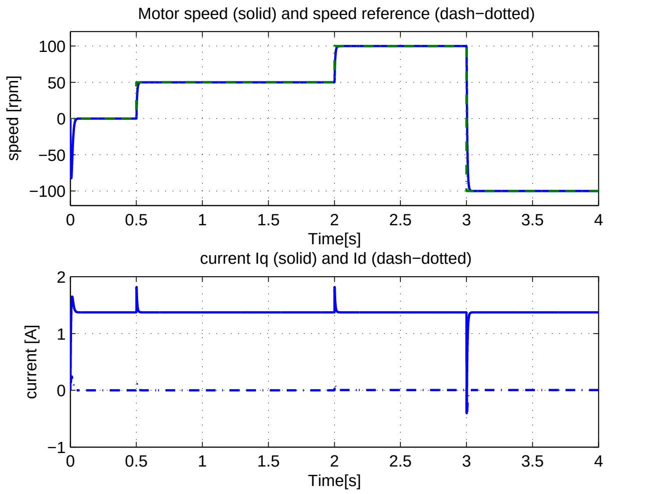


Fig. 9. Representation of the rotor speed and the stator currents for the inductance $L_d$ increasing.


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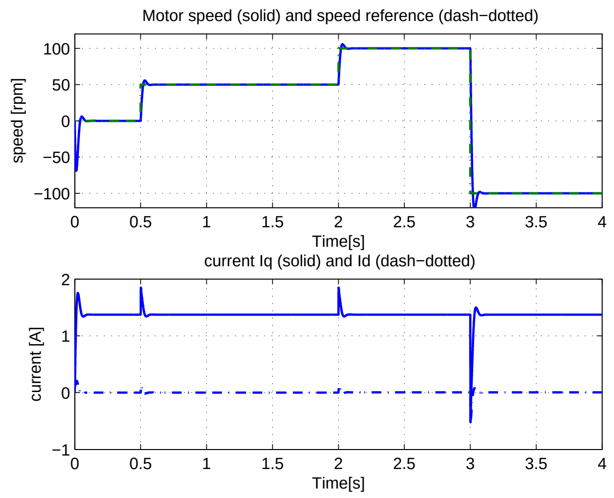


Fig. 10. Representation of the rotor speed and the stator currents for the increasing five times of the moment of inertia.

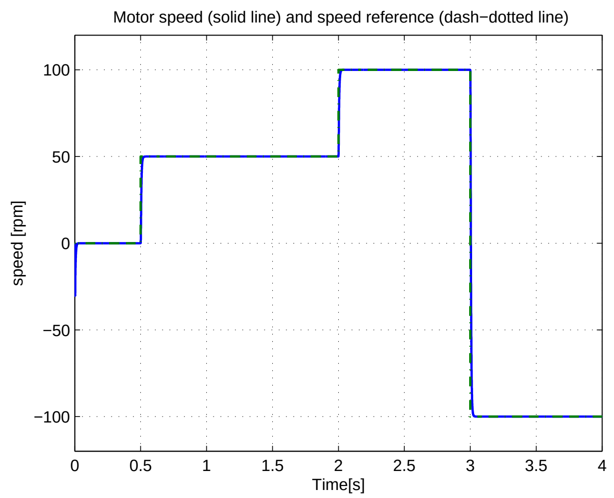


Fig. 11. Representation of the rotor speed for cascade IP controller.

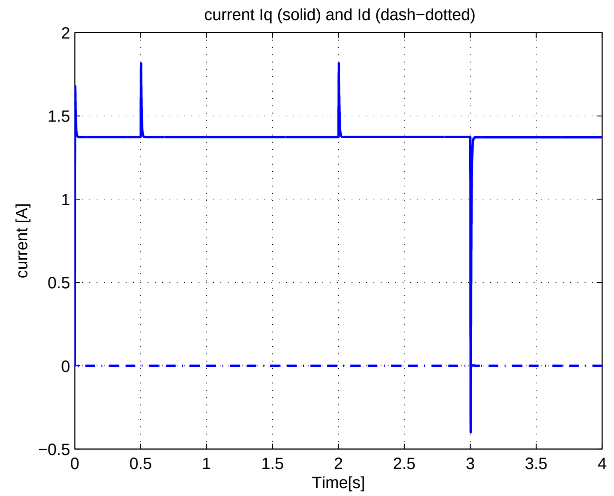


Fig. 12. Representation of the stator currents for cascade IP controller.