Speed Tracking for a PMSM via IDA-PBC

D.S. Martinez-Padron * R. Alvarez-Salas * F. Pazos-Flores *
G. Espinosa-Perez ** V.M. Cardenas-Galindo *

* *Facultad de Ingenieria, Universidad Autonoma de San Luis Potosi Av. Manuel Nava 8, 78290 San Luis Potosi, S.L.P., Mexico (e-mail: daniel.stingmtz@gmail.com, ralvarez@uaslp.mx)*
** *Facultad de Ingenieria, Universidad Nacional Autonoma de Mexico Edificio de Posgrado, Ciudad Universitaria 04510, Cd. de Mexico, Mexico*

Abstract: This paper presents a controller design to solve speed tracking problem for a permanent magnet synchronous motor (PMSM). This scheme is based on interconnection and damping assignment passivity-based control (IDA-PBC) technique recently proposed to solve the tracking control problem for mechanical underactuated system. The proposed approach consists in regulating the dynamics of the tracking error, with a port-controlled Hamiltonian (PCH) structure, to zero. The stability proof and numerical results that illustrate the performance of the controller are presented.

Keywords: PMSM; PCH system; IDA-PBC; Speed tracking.

1. INTRODUCTION

Passivity-based control (PBC) is an important tool in nonlinear control design, mainly because of its straightforward application to physical systems. Interconnection and damping assignment passivity-based control (IDA-PBC) has been introduced in Ortega et al. (2002b) as a technique that regulates the behaviour of a nonlinear systems assigning a desired port-controlled Hamiltonian (PCH) structure to the closed-loop.
Since the introduction of IDA-PBC many controllers have been reported in the literature, applied to mechanical systems (Ortega et al. (2002a)), power systems ((Maya-Ortiz and Espinosa-Perez, 2004), Galaz et al. (2003)), electrical machines (Petrovic et al. (2001), Akrad et al. (2007)) among others. However, the basic IDA-PBC is restricted to stabilization of fixed points and the tracking is considered an open issue (Ortega and Garcia-Canseco, 2004). In this sense, the stabilization problem of Hamiltonian systems has been much investigated because it can be performed by modifying the energy function and injecting damping. However, for trajectory tracking control is necessary to modify the energy function into a time-varying one and the time-varying property spoils the passivity in general (Fujimoto et al., 2003). There are few works that address the trajectory tracking control problem and the methodology to do this is not clear. The framework proposed in the literature to solve this problem is to convert it into one of stabilization (Fujimoto et al., 2003) (Borja and Espinosa, 2013) but it is not always possible, the Hamiltonian structure could be not preserved. Hence, in Fujimoto et al. (2003) is presented a way to satisfy this condition via generalized canonical transformations only for PCH systems. Nevertheless, in Borja and Espinosa (2013), a methodology to solve this problem for mechanical underactuated systems is proposed. The procedure consists in obtaining an error system taking advantage of the interconnection between the realizable trajectories and the system that preserves the PCH structure.The tracking is achieved when the error system is stabilized to zero.
The goal of this paper is present the controller design using this approach to achieve the speed tracking trajectories in a permanent magnet synchronous motor (PMSM). The remainder of this paper is organized as follows. In section 1, the IDA-PBC method is introduced. The strategy to solve the trajectory tracking control is recalled in section 2. In section 3, the controller design and the dynamic of trajectories are described. Simulation results are presented in section 4.

2. IDA-PBC METHODOLOGY

IDA-PBC was introduced as a method to control physical system described by port-Hamiltonian models of the form

$$\Sigma : \begin{cases} \dot{x} = [J(x) - R(x)] \dfrac{\partial H}{\partial x}(x) + g(x)u \\ y = g^T(x) \dfrac{\partial H}{\partial x}(x) \end{cases} \tag{1}$$

where $x \in \Re^n$ is the state vector, $u \in \Re^m$ is the control action with $m < n$, $H : \Re^n \to \Re$ is the total stored energy, $J(x) = -J^T(x)$, $R(x) = R^T(x) \geq 0$ are the natural interconnection and damping matrices, respectively. The choice of PCH models was motivated by the fact that they are natural candidates to describe many physical models. However, the IDA-PBC methodology is extended to a more general class of systems as described in the following proposition.

Proposition 1. (Ortega and Garcia-Canseco (2004)) Consider the system

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

Assume there are matrices $g^{\perp}(x)$, $J_d(x) = -{J_d}^T(x)$, $R_d(x) = {R_d}^T(x) \geq 0$ and a function $H_d : \Re^n \to \Re$ that verifies the partial differential equation (PDE) :

$$g^{\perp}(x)f(x) = g^{\perp}(x)\left[J_d(x) - R(x)\right]\nabla H_d, \tag{3}$$

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

$$x_* = \arg\min H_d(x) \tag{4}$$

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

$$\begin{aligned} \beta(x) &= \left[g^{\perp}(x)g(x)\right]^{-1} g^{\perp}(x) \\ &\times \left\{\left[J_d(x) - R(x)\right]\nabla H_d - f(x)\right\} \end{aligned} \tag{5}$$

takes the PCH form

$$\dot{x} = \left[J_d(x) - R_d(x)\right]\nabla H_d \tag{6}$$

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

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

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

Proof. Setting up the right-hand side of (2), with $u = \beta(x)$, equal to the right-hand side of (6) we get the matching equation

$$f(x) + g(x)u = \left[J_d(x) - R_d(x)\right]\nabla H_d. \tag{8}$$

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 the pseudo-inverse of $g(x)$. Stability of x_* is established noting that, along the trajectories of (6), we have

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

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

3. TRACKING VIA IDA-PBC

The objective of IDA-PBC methodology is to design a control law such as the interconnection between the system and the controller results in a desired structure and energy function with a minimum in the desired equilibrium point. In this way, in Borja and Espinosa (2013), a methodology to solve the tracking control problem for mechanical underactuated system is presented. The objective of this technique is to get a controller such that the interconnection between it, the trajectories and the system results in a desired structure and energy function. Notice that the interconnection between the trajectories and the system represents the tracking error dynamics, therefore if the controller stabilize it to zero then it is possible ensure that the tracking trajectories is achieved. This approach is described in the following.

3.1 Trajectory tracking strategy

Suppose the system in generalized coordinates given by

$$\begin{bmatrix} \dot{q} \\ \dot{p} \end{bmatrix} = \begin{bmatrix} 0 & I \\ -I & 0 \end{bmatrix} \begin{bmatrix} \nabla_q H \\ \nabla_p H \end{bmatrix} + \begin{bmatrix} 0 \\ G(q) \end{bmatrix} u \tag{10}$$

where $(q, p) \in \Re^n$ are the generalized position and momenta, respectively. The matrix $G(q) \in \Re^{n \times m}$ represents the way that the control acts to the system. In other hand, the energy function of the system is given by

$$H = \frac{1}{2} p^T M^{-1}(q) p + V(q) \tag{11}$$

where $M \in \Re^{n \times m}$ is the inertia matrix and $V(q)$ is the potential energy. Consider the tracking error definition $\bar{x}(t) = x(t) - x_d(t)$. Applying this definition to the system (10), it is possible to define the error system of the form

$$\begin{bmatrix} \dot{\bar{q}} \\ \dot{\bar{p}} \end{bmatrix} = \begin{bmatrix} 0 & I \\ -I & 0 \end{bmatrix} \begin{bmatrix} \nabla_q H \\ \nabla_p H \end{bmatrix} + \begin{bmatrix} 0 \\ G(q) \end{bmatrix} u - \begin{bmatrix} \dot{q}_d \\ \dot{p}_d \end{bmatrix} \tag{12}$$

where q_d and p_d are the desired trajectories. The physical systems presents limitations in the behaviour that can be imposed. For this reason the desired trajectories necessarily must be restricted to behaviours that the system is able to realize. Thus, consider the following definition.

Definition 1. A trajectory is realizable if and only if there exist at least one u^* such that the states of the closed-loop system satisfy $x(t) = x_d(t)$. In case there is no exist any u^* then the trajectory $x_d(t)$ is not realizable.

Consider that $p_d = M(q)\dot{q}_d$, consequently the dynamic of trajectories can be described as follows

$$\begin{bmatrix} \dot{q}_d \\ \dot{p}_d \end{bmatrix} = \begin{bmatrix} 0 & I \\ -I & 0 \end{bmatrix} \begin{bmatrix} \nabla_{qd} H_a \\ \nabla_{pd} H_a \end{bmatrix} + \begin{bmatrix} 0 \\ G(q) \end{bmatrix} u^* \tag{13}$$

$$H_a = \frac{1}{2} {p_d}^T M^{-1}(q) p_d + V(q_d) \tag{14}$$

Therefore, the open-loop system error is defined as

$$\begin{bmatrix} \dot{\bar{q}} \\ \dot{\bar{p}} \end{bmatrix} = \begin{bmatrix} 0 & I \\ -I & 0 \end{bmatrix} \begin{bmatrix} \nabla_q H \\ \nabla_p H \end{bmatrix} - \begin{bmatrix} 0 & I \\ -I & 0 \end{bmatrix} \begin{bmatrix} \nabla_{qd} H_a \\ \nabla_{pd} H_a \end{bmatrix} + \begin{bmatrix} 0 \\ G(q) \end{bmatrix} \bar{u} \tag{15}$$

Once obtained the error system, the next step is to stabilize it via IDA-PBC. If the error is stabilized $\bar{x}^* = 0$ then tracking is achieved. For any system it is important that the trajectories are realizable, this fact allows to be able to solve the PDE associated to this approach and find the controller that solve the problem (Borja and Espinosa (2013)). Notice that it is necessary to know the realizable trajectories in order to compute the controller from their dynamics. For some systems it is a simple task, however, for others this is difficult and it becomes a disadvantage of this approach.

For the system (2), the desired closed-loop error system has the following structure

$$\dot{\bar{x}} = F_d(\bar{x}) \nabla H_d(\bar{x}) \tag{16}$$

where the desired energy function, say $H_d(x)$ satisfies $x_* = \arg\min H_d(x)$ with the condition $\left[F_d(\bar{x}) + {F_d}^T(\bar{x})\right] \leq 0$.

Assume the next conditions

- The equilibrium $x_* = 0$ is assignable to the error system of (2).
- There exist a structure (16) that satisfies the PDE (Borja and Espinosa, 2013).

If the condition described above are satisfied, then the controller that stabilizes the error system to zero is given for the next equation

$$u = \left(g^T g)\right)^{-1} g^T \left[F_d(x) \nabla H_d \bar{x} - F(x) \nabla H x + \dot{x}_d\right] \tag{17}$$

4. MAIN RESULT

4.1 PMSM model

The PMSM is described in (dq) coordinates as follows (Chiasson (2005))

$$\begin{aligned} L_s \frac{di_d}{dt} &= -R_s i_d + n_p \omega L_s i_q + u_d \\ L_s \frac{di_q}{dt} &= -R_s i_q - n_p \omega L_s i_d - K_m \omega + u_q \\ J \frac{d\omega}{dt} &= K_m i_q - \tau_L \end{aligned} \tag{18}$$

where R_s is the stator resistance, L_s is the stator inductance, K_m is the back-efm constant, J is the rotor moment of inertia, n_p is the number of pole pairs, ω is the angular speed of the rotor, i_d, i_q are the direct and quadrature currents, u_d, u_q are the direct and quadrature voltages and τ_L is the load torque.

Assume the following condition

- The variables i_d, i_q and ω are available for measurement.
- The parameters R, L, n_p, K_m and J are known.
- The load torque τ_L is constant but unknown.

Considering

$$x = \begin{bmatrix} x_1 \\ x_2 \\ x_3 \end{bmatrix} = \begin{bmatrix} L_s i_d \\ L_s i_q \\ J\omega \end{bmatrix} \tag{19}$$

and the energy function $H(x) = \frac{1}{2} x^T Q x$ with

$$Q = \begin{bmatrix} \frac{1}{L_s} & 0 & 0 \\ 0 & \frac{1}{L_s} & 0 \\ 0 & 0 & \frac{1}{J} \end{bmatrix} \tag{20}$$

where the gradient of $H(x)$ is

$$\nabla H(x) = \begin{bmatrix} \frac{1}{L_s} x_1 & \frac{1}{L_s} x_2 & \frac{1}{J} x_3 \end{bmatrix}^T \tag{21}$$

Then, the system (18) with $F(x) = J(x) - R(x)$ can be written in form

$$\dot{x} = F(x) \nabla H(x) + g(x) u \tag{22}$$

where the damping matrix is given by

$$R(x) = \begin{bmatrix} -R_s & 0 & 0 \\ 0 & -R_s & 0 \\ 0 & 0 & 0 \end{bmatrix} \tag{23}$$

and the interconnection matrix

$$J(x) = \begin{bmatrix} 0 & 0 & -n_p x_2 \\ 0 & 0 & -K_m + n_p x_1 \\ n_p x_2 & K_m - n_p x_1 & 0 \end{bmatrix} \tag{24}$$

4.2 The error system

Consider that the desired trajectories have the form

$$\begin{bmatrix} \dot{x}_{1d} \\ \dot{x}_{2d} \\ \dot{x}_{3d} \end{bmatrix} = \begin{bmatrix} \frac{-R_s}{L_s} & 0 & \frac{n_p x_{2d}}{J} \\ 0 & \frac{-R_s}{L_s} & \frac{-K_m + n_p x_{1d}}{J} \\ 0 & \frac{K_m}{L_s} & 0 \end{bmatrix} \begin{bmatrix} x_{1d} \\ x_{2d} \\ x_{3d} \end{bmatrix} + u_a \tag{25}$$

According to the last section and considering the physical constraints, it is possible to obtain the the open-loop error dynamics

$$\begin{bmatrix} \dot{\bar{x}}_1 \\ \dot{\bar{x}}_2 \\ \dot{\bar{x}}_3 \end{bmatrix} = \begin{bmatrix} \frac{-R_s}{L_s} & 0 & \frac{n_p \bar{x}_2}{J} \\ 0 & \frac{-R_s}{L_s} & \frac{-K_m + n_p \bar{x}_1}{J} \\ 0 & \frac{K_m}{L_s} & 0 \end{bmatrix} \begin{bmatrix} \bar{x}_1 \\ \bar{x}_2 \\ \bar{x}_3 \end{bmatrix} + \bar{u} \tag{26}$$

4.3 Controller and stability analysis

Proposition 2. Consider the open-loop error dynamics (26) with a desired equilibrium point

$$\bar{x}_* = [\,0,\ 0,\ 0\,]^T \tag{27}$$

The control law

$$\bar{u} = \begin{bmatrix} -\dfrac{R_s\,(K_d-1)}{L_s}\bar{x}_1 + \dfrac{n_p}{J}\lambda_1 + \dfrac{n_p K_c}{J}\bar{x}_2\bar{x}_3 \\ \dfrac{R_s\,(K_d-1)}{L_s}\bar{x}_2 - \dfrac{n_p K_c}{J}\bar{x}_1\bar{x}_3 + \dfrac{n_p}{J}\lambda_2 + K_m\bar{x}_3 \end{bmatrix} \tag{28}$$

where $\lambda_1 = x_2x_3 - x_{2d}x_{3d}$ and $\lambda_2 = x_2x_3 - x_{1d}x_{3d}$ renders x_* asymptotically stable with all internal signals bounded.

Proof. Assume that the trajectories dynamics can be described in port-Hamiltonian form

$$\dot{x}_d = F(x_d)\nabla_{x_d} H(x_d). \tag{29}$$

Define the desired closed-loop energy function

$$H_d(x) = \frac{1}{2}\bar{x}^T Q_d \bar{x} \tag{30}$$

with

$$Q_d = \begin{bmatrix} q_1 & 0 & 0 \\ 0 & q_2 & 0 \\ 0 & 0 & q_3 \end{bmatrix} \tag{31}$$

and the desired structure as follows

$$F_d = \begin{bmatrix} F_{11} & F_{12} & F_{13} \\ F_{21} & F_{22} & F_{23} \\ F_{31} & F_{32} & F_{33} \end{bmatrix} \tag{32}$$

Equating the right-hand sides of (26) and (29) and pre-multiplying by $g^{\perp}(x)$ is obtained the so-called matching equation. In order to look for a solution, it can be written in an equivalent way as

$$F_{21}q_1\bar{x}_1 + F_{22}q_2\bar{x}_2 + F_{23}q_3\bar{x}_3 = -\frac{R}{L}\bar{x}_2 - \left(\frac{n_p\bar{x}_1 - K_m}{J}\right)\bar{x}_3 \tag{33}$$

$$F_{31}q_1\bar{x}_1 + F_{32}q_2\bar{x}_2 + F_{33}q_3\bar{x}_3 = -\frac{K_m}{L}\bar{x}_2. \tag{34}$$

Choosing

$$Q_d = \begin{bmatrix} \dfrac{1}{L_sK_d} & 0 & 0 \\ 0 & \dfrac{1}{L_sK_d} & 0 \\ 0 & 0 & \dfrac{1}{JK_c} \end{bmatrix} \tag{35}$$

and $F_{21} = F_{33} = F_{31} = 0$, $F_{32} = -K_mK_d$, $F_{22} = -RK_d$ and $F_{23} = -(n_p\bar{x}_1 - K_m)K_c$ are proposed, where K_d and K_c are design parameters. In order to preserve the structure it is proposed $F_{12} = 0$, $F_{11} = -RK_d$ and $F_{13} = n_p\bar{x}_2K_c$. Hence, the closed-loop system takes the desired port-Hamiltonian form

$$F_d = \begin{bmatrix} -R_sK_d & 0 & n_p\bar{x}_2K_c \\ 0 & -R_sK_d & -\left(n_p\bar{x}_1 - K_m\right)K_c \\ 0 & -K_mK_d & 0 \end{bmatrix} \tag{36}$$

Finally, to proof stability $H_d(\bar{x})$ is taken as Lyapunov candidate function and

$$\dot{H}_d(\bar{x}) \leq -\alpha\left(\bar{x}_1^2 + \bar{x}_2^2\right) \leq 0 \tag{37}$$

where

$$\alpha = \frac{2K_dR_s}{L_s^2} + \frac{2K_dR_s}{L_s^2} \tag{38}$$

which directly shows that current errors decay to zero. To proof asymptotic stability, the LaSalle's invariance principle is used

$$\dot{H}_d(\bar{x}) = 0 \Rightarrow \bar{x}_1 = \bar{x}_2 = 0 \tag{39}$$

According to the system (36)

$$\begin{bmatrix} \dot{\bar{x}}_1 \\ \dot{\bar{x}}_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{matrix} F_{11}q_1\bar{x}_1 + F_{12}q_2\bar{x}_2 + F_{13}q_3\bar{x}_3 \\ F_{21}q_1\bar{x}_1 + F_{22}q_2\bar{x}_2 + F_{23}q_3\bar{x}_3 \end{matrix} \tag{40}$$

then

$$\begin{bmatrix} \dot{\bar{x}}_1 \\ \dot{\bar{x}}_2 \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \end{bmatrix} = \begin{bmatrix} 0 \\ K_mK_c \end{bmatrix} q_3\bar{x}_3 \Rightarrow \bar{x}_3 = 0 \tag{41}$$

Therefore, the equilibrium point is asymptotically stable.

4.4 Trajectories system

Once the controller is obtained, it is necessary to know the desired trajectories from dynamics (25). For the PMSM it is easy to obtain the references for speed tracking. First, consider a reference $\omega_d(t)$ as a free parameter chosen by the user. Then, the remaining trajectories can be determined from (21) and they are given by

$$i_q{}^* = \frac{J}{K_m}\frac{d\omega^*}{dt} \tag{42}$$

$$i_d{}^* = -\frac{R_sJ}{K_mn_pL_s\omega^*}\frac{d\omega^*}{dt} - \frac{K_m}{n_pL_s} - \frac{J}{K_mn_p\omega^*}\frac{d^2\omega^*}{dt^2} \tag{43}$$

In addition, the trajectories are restricted by the following equation.

$$J\frac{d\omega^*}{dt} = K_mi_q{}^* - \tau_L. \tag{44}$$

Hence, it is necessary to know the load torque.

5. SIMULATION RESULTS

The simulation was performed in Matlab/Simulink with the PMSM parameters given in the table 1 with $K_d = 150$ and $K_c = 120$ and without load torque. For the speed trajectory two cases are presented, the first reference is $\omega^* = 30\sin(t)[rad/s]$ with an offset of $30[rad/s]$ and the other one is a speed profile shown in Fig. 5.

The speed tracking for the first case is shown in Fig. 1, the reference is depicted with dotted line and the measured speed solid line. Fig. 2 shows the relative speed tracking error whose maximum value does not exceed 0.5 $[rad/s]$. The tracking of the current references of $i_d(t)$ and i_q (dotted line) and the actual currents (solid line) are shown in Fig. 3 and Fig. 4, respectively. Moreover, in Fig. 5 the second reference speed and the actual speed are shown. The relative speed error is presented in Fig. 6.

Table 1. PMSM parameters

Parameter	Value
Stator resistance (R_s)	0.7 [Ω]
Stator inductance (L_s)	0.6 [mH]
Back-efm constant (K_m)	0.0355 [$V/(rad/s)$]
Rotor inertia (J)	0.0000048035 [$N-m-s^2$]
Pole pairs (n_p)	4

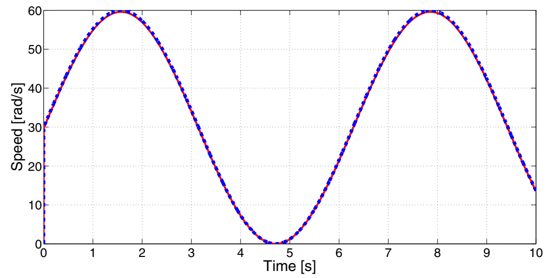

Fig. 1. Actual speed and reference trajectory.

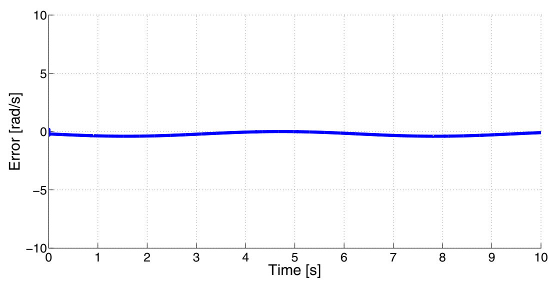

Fig. 2. Speed tracking error.

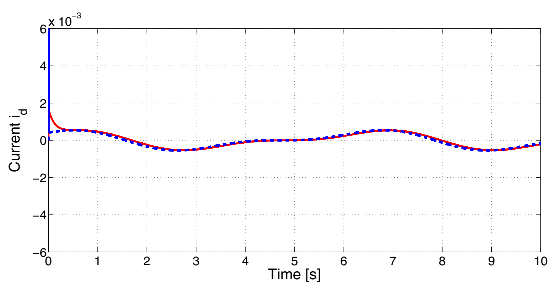

Fig. 3. Actual current i_d and the reference trajectory.

6. CONCLUSION

In this paper is presented a speed tracking control law for a PM synchronous motor via IDA-PBC. One of the disadvantage of these controller is the fact that it is necessary to compute the first and second derivatives of the user defined reference to generate the remaining trajectories. However, it is possible to obtain them efficiently from numerical estimation. Additionally, the load torque has to be known to satisfy the matching condition since it is part of the trajectories system. In future work, a load torque estimator will be included.

Notice that the control law performs both the control of position and torque. This is achieved for the first

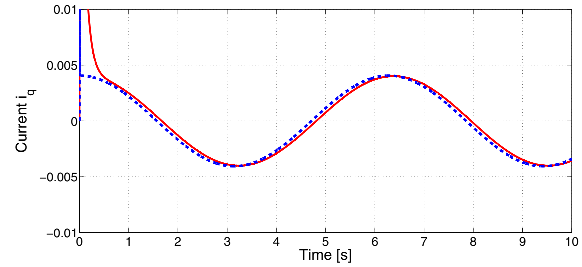

Fig. 4. Actual current i_q and reference trajectory.

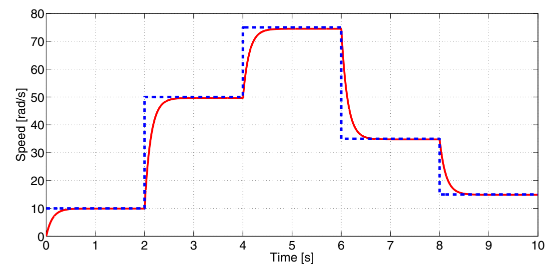

Fig. 5. Actual speed and speed profile.

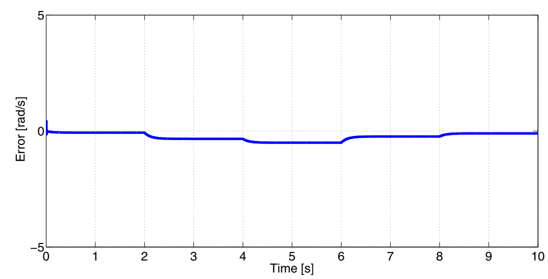

Fig. 6. Speed tracking error with a speed profile.

one simply by calculating the derivative of the reference. The tracking torque trajectories is achieved through the i_q component taking it as the free parameter an then obtaining the remaining trajectories.

Ongoing work addresses the controller implementation on an FPGA-based experimental set-up to validate the numerical results.

REFERENCES

Akrad, A., Hilairet, M., Ortega, R., and Diallo, D. (2007). Interconnection and damping assignment approach for reliable pm synchronous motor control. In *2007 IET Colloquium on Reliability in Electromagnetic Systems*, 1–6. doi:10.1049/ic:20070036.

Borja, P. and Espinosa, G. (2013). Seguimiento de trayectorias para sistemas mecanicos subactuados via ida-pbc. In *Congreso Nacional de Control Automatico*.

Chiasson, J. (2005). *Modeling and High Performance Control of Electric Machines*. IEEE Press Series on Power Engineering. Wiley.

Fujimoto, K., Sakurama, K., and Sugie, T. (2003). Trajectory tracking control of port-controlled hamiltonian systems via generalized canonical transformations. *Automatica*, 39(12), 2059 – 2069.

Galaz, M., Ortega, R., Bazanella, A.S., and Stankovic, A.M. (2003). An energy-shaping approach to the design of excitation control of synchronous generators. *Automatica*, 39(1), 111 – 119.

Maya-Ortiz, P. and Espinosa-Perez, G. (2004). Output feedback excitation control of synchronous generators. *International Journal of Robust and Nonlinear Control*, 14(9-10), 879–890.

Ortega, R., Spong, M.W., Gomez-Estern, F., and Blankenstein, G. (2002a). Stabilization of a class of underactuated mechanical systems via interconnection and damping assignment. *IEEE Transactions on Automatic Control*, 47(8), 1218–1233.

Ortega, R. and Garcia-Canseco, E. (2004). Interconnection and damping assignment passivity-based control: A survey. *European Journal of Control*, 10(5), 432 – 450.

Ortega, R., van der Schaft, A., Maschke, B., and Escobar, G. (2002b). Interconnection and damping assignment passivity-based control of port-controlled hamiltonian systems. *Automatica*, 38(4), 585 – 596.

Petrovic, V., Ortega, R., and Stankovic, A.M. (2001). Interconnection and damping assignment approach to control of pm synchronous motors. *IEEE Transactions on Control Systems Technology*, 9(6), 811–820.