PASSIVITY–BASED CONTROL WITH SIMULTANEOUS ENERGY–SHAPING AND DAMPING INJECTION: THE INDUCTION MOTOR CASE STUDY

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Abstract: We argue in this paper that the standard procedure used Passivity–Based Controller (PBC) designs of splitting the control action into energy–shaping and damping injection terms is not without loss of generality, and actually reduces the set of problems that can be solved with PBC. Instead, we suggest to carry out simultaneously both stages. As a case in point, we show that the practically important example of the induction motor *cannot be solved* with a PBC in two stages. It is, however, solvable carrying out *simultaneously* the energy–shaping and the damping injection. The resulting controller is a simple output feedback scheme that ensures *global exponential convergence* of the generated torque and the rotor flux norm to their desired (constant) values. To the best of our knowledge, this is the first output feedback scheme that ensures such strong stability properties for this system.

Keywords: Nonlinear control, Passivity-based control, Energy-shaping, Induction motors.

1. INTRODUCTION

Passivity–based control (PBC) is a generic name given to a family of controller design techniques that achieve the control objective via the route of passivation, that is, rendering the closed–loop system passive with a desired storage function (that usually qualifies as a Lyapunov function for the stability analysis.) If the passivity property turns out to be (output) strict, with an output signal with respect to which the system is detectable, then asymptotic stability is ensured. See the fundamental monograph (van der Schaft, 2000), and (Ortega and Garcia-Canseco, 2004) for a recent survey.

As is well–known, (van der Schaft, 2000), a passive system can be rendered strictly passive simply adding a negative feedback loop around the passive output—an action sometimes called L_gV control (Sepulchre *et al.*, 1997). For this reason, it has been found convenient in some applications, in particular for mechanical systems (Takegaki and Arimoto, 1981), (Ortega *et al.*, 2002*b*), to split the control action into two terms, an energy–shaping term which, as indicated by its name, is responsible of assigning the desired energy/storage function to the passive map, and a second L_gV term that injects damping for asymptotic stability.

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The purpose of this paper is to bring to the readers attention the fact that splitting the control action in this way is not without loss of generality, and actually reduces the set of problems that can be solved via PBC. This assertion is, of course, not surprising since it is clear that, to achieve strict passivity, the procedure described above is just one of many other possible ways. The main objective of the paper is to show that the practically important example of the induction motor *cannot be solved* with a PBC in two stages. It is, however, solvable carrying out *simultaneously* the energy–shaping and the damping injection.

2. PBC WITH SIMULTANEOUS ENERGY SHAPING AND DAMPING INJECTION

To be more specific let us consider the Interconnection and Damping Assignment (IDA) PBC proposed in (Ortega *et al.*, 2002*a*) applied to nonlinear systems of the form

$$\dot{x} = f(x) + g(x)u \tag{1}$$

where $x \in \mathbb{R}^n$ is the state vector and $u \in \mathbb{R}^m, m < n$ is the control action. In IDA–PBC stabilization of an equilibrium is achieved assigning to the closed–loop the form [2]

$$\dot{x} = [J_d(x) - \mathcal{R}_d(x)]\, \nabla_x H_d \tag{2}$$

where $H_d : \mathbb{R}^n \to \mathbb{R}$ is the desired total stored energy, that should satisfy

$$x_\star = \arg\, \min H_d(x) \tag{3}$$

with $x_\star \in \mathbb{R}^n$ the equilibrium to be stabilized, and $J_d(x) = -J_d^\top(x)$ and $\mathcal{R}_d(x) = \mathcal{R}_d^\top(x) \geq 0$, which represent the desired interconnection structure and dissipation, respectively, are chosen by the designer.

Fixing (for simplicity) a static state feedback control $u = \hat{u}(x)$, and setting the right hand sides of (1) and (2) equal we obtain

$$f(x) + g(x)\hat{u}(x) = [J_d(x) - \mathcal{R}_d(x)]\, \nabla_x H_d.$$

Under the assumption of full–rank $g(x)$, reduces to the well–known *matching equation* of IDA–PBC

$$g^\perp(x) f(x) = g^\perp(x)\, [J_d(x) - \mathcal{R}_d(x)]\, \nabla_x H_d \tag{4}$$

where $g^\perp(x)$ is a left annihilator of $g(x)$, that is, $g^\perp(x)g(x) = 0$, and the control law expression

$$\begin{aligned} \hat{u}(x) = {} & [g^\top(x)g(x)]^{-1} g^\top(x) \;\times \\ & \{-f(x) + [J_d(x) - \mathcal{R}_d(x)]\nabla_x H_d\}. \end{aligned} \tag{5}$$

When the design is carried out in two stages we first solve (4) with $R_d(x) = 0$. Then, we add to $\hat{u}(x)$ a damping injection term of the form $-K_{di} g^\top(x) \nabla_x H_d,\ K_{di} = K_{di}^\top > 0$, which yields the particular damping matrix

$$R_d(x) = g(x) K_{di} g^\top(x).$$

In the next section we will show that, for the problem of output feedback torque control of induction motors with quadratic in the increments desired energy function, it is not possible to solve (4) with $R_d(x) = 0$. But the problem is solvable if we allow for a general damping matrix.

[2] All vectors in the paper are *column* vectors, even the gradient of a scalar function denoted $\nabla_{(\cdot)} = \frac{\partial}{\partial(\cdot)}$.

3. INDUCTION MOTOR: MODEL AND EQUILIBRIA

In this section the basic motor model and the analysis of its equilibria are presented. The latter is needed because, in contrast with the large majority of controllers proposed for the induction motor, we are interested in this paper in the stabilization of a *given equilibrium* that generates a desired torque and rotor flux amplitude.

3.1 Model

The standard three-phase induction motor represented with a two-phase model defined in an arbitrary reference frame, which rotates at an arbitrary speed $\omega_s \in \mathbb{R}$, is given by (Krause *et al.*, 1995)

$$\begin{aligned} \dot{x}_{12} = {} & -[\gamma \mathcal{I} + (\omega + u_3)\mathcal{J}]\, x_{12} + \\ & + \alpha_1 (\mathcal{I} - T_r \omega \mathcal{J})\, x_{34} + \alpha_2 u_{12} \end{aligned} \tag{6}$$

$$\dot{x}_{34} = -(\frac{1}{T_r}\mathcal{I} + \mathcal{J}u_3)x_{34} + \frac{L_{sr}}{T_r} x_{12} \tag{7}$$

$$\dot{\omega} = \alpha_3 x_{12}^\top \mathcal{J} x_{34} - \tau_L \tag{8}$$

in which $\mathcal{I} \in \mathbb{R}^2$ is the identity matrix,

$$\mathcal{J} = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} = -\mathcal{J}^\top,$$

$x_{12} \in \mathbb{R}^2$ are the stator currents, $x_{34} \in \mathbb{R}^2$ the rotor fluxes, $\omega \in \mathbb{R}$ the rotor speed, $u_{12} \in \mathbb{R}^2$ are the stator voltages, $\tau_L \in \mathbb{R}$ is the load torque and $u_3 := \omega_s - \omega$. The parameters, all positive, are defined as

$$\gamma := \frac{R_s}{L_s \sigma} + \frac{L_{sr}}{\sigma L_s L_r T_r};\ \ \sigma := 1 - \frac{L_{sr}^2}{L_s L_r}$$
$$\alpha_1 := \frac{L_{sr}}{\sigma L_s L_r T_r};\ \ \alpha_2 := \frac{1}{\sigma L_s}$$
$$\alpha_3 := \frac{L_{sr}}{L_r};\ \ T_r := \frac{L_r}{R_r}$$

with L_s, L_r the windings inductances, R_s, R_r the windings resistances and L_{sr} the mutual inductance. Notice that, without loss of generality, the rotor moment of inertia and the number of pole pairs are assumed equal to one.

As first pointed out in the control literature in (Ortega and Espinosa, 1993), the signal u_3 (equivalently ω_s) effectively acts as an additional control input. Below, we will select u_3 to transform the periodic orbits of the system into constant equilibria.

3.2 Controlled Outputs and Equilibria

We are interested in this paper in the problem of regulation of the motor torque and the rotor flux amplitude, that we denote,

$$\begin{aligned} y_1 &= h_1(x) = \alpha_3 x_{12}^\top \mathcal{J} x_{34} \\ y_2 &= h_2(x) = |x_{34}| \end{aligned} \tag{9}$$

respectively, to some constant desired values $y_\star = [y_{1\star}, y_{2\star}]^\top$, where we defined $x^\top := \left[x_{12}^\top, x_{34}^\top\right]$. To solve this problem using IDA–PBC it is necessary to express the control objective in terms of a desired equilibrium. We make at this point the following important observation:

- From (8) we see that to operate the system in equilibrium, $y_{1\star} = \tau_L$—hence, the load torque is assumed known. See, however, Remark 1.

As is well–known (Marino *et al.*, 1999), the zero dynamics of the induction motor is periodic, a fact that is clearly shown computing the angular speed of the rotor flux. Towards this end, we define the rotor flux angle $\rho := \arctan \frac{x_4}{x_3}$, and evaluate [3]

$$\dot{\rho} = R_r \frac{y_1}{y_2^2} - u_3,$$

from which have the following simple lemma whose proof is obtained via direct substitution.

Lemma 1. Consider the induction motor model (6)–(8) with u_3 fixed to the constant

$$u_3 = u_{3\star} := R_r \frac{y_{1\star}}{y_{2\star}^2}. \tag{10}$$

Then, the set of assignable equilibrium points, denoted $[\bar{x}, \bar{\omega}]^\top \in \mathbb{R}^5$, which are compatible with $h(\bar{x}) = y_\star$ is defined by $\bar{\omega} \in \mathbb{R}$ and

$$\begin{aligned} \bar{x}_{12} &= \frac{1}{L_{sr}} \begin{bmatrix} 1 & -L_r \frac{y_{1\star}}{y_{2\star}^2} \\ L_r \frac{y_{1\star}}{y_{2\star}^2} & 1 \end{bmatrix} \bar{x}_{34} \\ |\bar{x}_{34}| &= y_{2\star} \end{aligned} \tag{11}$$

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Among the set of assignable equilibria defined above we select, for the electrical coordinates, the one that ensures field orientation (Krause *et al.*, 1995) and denote it

$$x_\star := [\frac{-L_r}{L_{sr}} \frac{y_{1\star}}{y_{2\star}}, \frac{y_{2\star}}{L_{sr}}, 0, y_{2\star}]^\top. \tag{12}$$

Remark 1. In practical applications an outer loop PI control around the velocity error is usually added. The output of the integrator, on one hand, provides an estimate of τ_L while, on the other hand, ensures that speed also converges to the desired value as shown via simulations in Section 6.

4. IDA–PBC OF INDUCTION MOTOR

The following important aspects of the induction motor control problem are needed for its precise formulation:

- The only signals available for measurement are x_{12} and ω.

- Since we are interested here in torque control, and this is only defined by the stator currents and the rotor fluxes, its regulation can be achieved applying IDA–PBC *to the electrical subsystem only.* Boundedness of ω will be established in a subsequent analysis.

Although with IDA–PBC it is possible, in principle, to assign an arbitrary energy function to the electrical subsystem, we will consider here only a quadratic in errors form

$$H_d(x) = \frac{1}{2} \tilde{x}^\top P \tilde{x}, \tag{13}$$

with $\tilde{x} := x - x_\star$ and $P = P^\top > 0$ a matrix to be determined. As first observed in (Fujimoto and Sugie, 2001), fixing $H_d(x)$ transforms the matching equation (4) into a set of algebraic equations—see also (Rodriguez and Ortega, 2003) for application of this, so–called "Algebraic IDA–PBC", to general electro–mechanical systems.

The electrical subsystem (6)–(7) with $u_3 = u_{3\star}$ can be written in the form

$$\dot{x} = f(x, \omega) + \begin{bmatrix} \mathcal{I} \\ 0_{2\times 2} \end{bmatrix} u_{12}.$$

Therefore, the matching equation (4) concerns only the third and fourth rows of $f(x, \omega)$ and it takes the form

$$(-\frac{1}{T_r}\mathcal{I} + \mathcal{J} u_{3\star}) x_{34} + \frac{L_{sr}}{T_r} x_{12} = [F_3(x) \quad F_4(x)] P \tilde{x}, \tag{14}$$

where, to simplify the notation, we define the matrix

$$F(x) := J_d(x) - \mathcal{R}_d(x),$$

that we partition into 2×2 sub-matrices as

$$F(x) = \begin{bmatrix} F_1(x) & F_2(x) \\ F_3(x) & F_4(x) \end{bmatrix}. \tag{15}$$

[3] From this relation it is clear that, if u_3 is fixed to a constant, say $\bar{u}_3$, and $y = y_\star$, x_{34} is a vector of constant amplitude rotating at speed $\rho(t) = (R_r \frac{y_{1\star}}{y_{2\star}^2} - \bar{u}_3)t + \rho(0)$.

The *output feedback condition* imposes an additional constraint that involves now the first and second rows of $f(x,\omega)$. Indeed, from (5) we see that the control can be written as

$$u_{12} = \hat{u}_{12}(x_{12},\omega) + S(x,\omega)x_{34}$$

where $\hat{u}_{12}(x_{12},\omega)$ is given in (24) and we have defined

$$S(x,\omega) := \frac{\alpha_1}{\alpha_2}\left(T_r\omega\mathcal{J} - \mathcal{I}\right) + \frac{1}{\alpha_2}\left[F_1(x)P_2 + F_2(x)P_3\right], \tag{16}$$

with P partitioned as

$$P := \begin{bmatrix} P_1 & P_2 \\ P_2^\top & P_3 \end{bmatrix}; \;\; P_i \in \mathbb{R}^{2\times 2},\; i = 1,2,3.$$

It is clear that $S(x,\omega)$ has to be set to zero to satisfy the output feedback condition.

We thus have the following:

IDA–PBC Problems. Find matrices $F(x)$ and $P = P^\top > 0$ satisfying (14) and $S(x,\omega) = 0$ with the additional constraint that

- *(Energy–shaping)*

$$F(x) + F^\top(x) = 0, \tag{17}$$

or the strictly weaker

- *(Simultaneous energy–shaping and damping injection)*

$$F(x) + F^\top(x) \leq 0. \tag{18}$$

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5. MAIN RESULTS

5.1 Solvability of the IDA–PBC Problems

Proposition 1. The energy–shaping problem is *not solvable*. However, the simultaneous energy–shaping and damping injection one is solvable.

Proof. First, we write the matching equation (14) in terms of the errors as

$$\frac{L_{sr}}{T_r}\tilde{x}_{12} - \left(\frac{1}{T_r}\mathcal{I} + u_{3\star}\mathcal{J}\right)\tilde{x}_{34} = [F_3(x) \quad F_4(x)]P\tilde{x},$$

which will be satisfied if and only if

$$[F_3(x) \quad F_4(x)]P = [\frac{L_{sr}}{T_r}\mathcal{I} \quad -\left(\frac{1}{T_r}\mathcal{I} + u_{3\star}\mathcal{J}\right)]. \tag{19}$$

Since P and the right hand side of the equation are constant, and P is full rank, we conclude that F_3 and F_4 should also be constant. (To underscore this fact we will omit in the sequel their argument.)

Let us consider first the energy–shaping problem. From (15) and (17) we have that $F_2 = -F_3^\top$. Then, setting (16) to zero and replacing the latter it is obtained that

$$F_1(x)P_2 - F_3^\top P_3 = \alpha_1\left(\mathcal{I} - T_r\omega\mathcal{J}\right) \tag{20}$$

On the other hand, from the first two columns of (19) it follows that

$$F_3 = \left(\frac{L_{sr}}{T_r}\mathcal{I} - F_4P_2^\top\right)P_1^{-1} \tag{21}$$

Substitution of (21) into (20) leads to

$$\begin{aligned} F_1(x)P_2 - P_1^{-1}\left(\frac{L_{sr}}{T_r}\mathcal{I} - P_2F_4^\top\right)P_3 = \\ = \alpha_1\mathcal{I} - \alpha_1T_r\omega\mathcal{J} \end{aligned} \tag{22}$$

Invoking again (17) we have that $F_1(x)$ must be skew-symmetric, that without loss of generality we can express in the form

$$F_1(x) = \beta_1(x)\mathcal{J} + \beta_2\mathcal{J},$$

where $\beta_2 \in \mathbb{R}$. Looking at the x–dependent terms we get

$$\beta_1(x)\mathcal{J}P_2 + \alpha_1T_r\omega\mathcal{J} = 0,$$

which can be achieved only if $P_2 = \lambda\mathcal{I}$, with $\lambda \in \mathbb{R}$, and $\beta_1(x) = -\lambda^{-1}\alpha_1T_r\omega$.

The constant part of (22), considering that $P_2 = \lambda\mathcal{I}$, reduces to

$$\lambda\beta_2\mathcal{J} - P_1^{-1}\left(\frac{L_{sr}}{T_r}\mathcal{I} - \lambda F_4^\top\right)P_3 = \alpha_1\mathcal{I}$$

which—using the fact that P_3 is full rank—can be expressed as $F_4^\top = GP_3^{-1}$, where we have defined the constant matrix

$$G := \frac{1}{\lambda}\left[\frac{L_{sr}}{T_r}P_3 + P_1\left(\alpha_1\mathcal{I} - \lambda\beta_2\mathcal{J}\right)\right]$$

Finally, since F_4 must also be skew–symmetric, we have that

$$G = P_3^{-1}(-G^\top)P_3,$$

i.e., G must be similar to $-G^\top$, and consequently both have the same eigenvalues. A necessary condition for the latter is that $\operatorname{trace}(G) = 0$, that is not satisfied because

$$\operatorname{trace}(G) = \frac{1}{\lambda}\left[\frac{L_{sr}}{T_r}\underbrace{\operatorname{trace}(P_3)}_{>0} + \alpha_1\underbrace{\operatorname{trace}(P_1)}_{>0}\right],$$

which is different from zero. This completes the proof of the first claim.

We will now prove that if we consider the largest class of matrices (18) the problem is indeed solvable, and actually give a very simple explicit expression for $F(x)$ and P. For, we set $P_2 = 0$, and it is easy to see that

$$\begin{aligned} F_2(x) &= \alpha_1\left(\mathcal{I} - T_r\omega\mathcal{J}\right)P_3^{-1} \\ F_3(x) &= \frac{L_{sr}}{T_r}\mathcal{I}P_1^{-1} \\ F_4(x) &= -\left(\frac{1}{T_r}\mathcal{I} + u_{3\star}\mathcal{J}\right)P_3^{-1} \end{aligned}$$

and $F_1(x)$ free provide a solution to (14) and make (16) equal to zero. It only remains to establish

(18). For, we fix $P_1 = \frac{L_{sr}}{T_r}\mathcal{I}$, $P_3 = \alpha_1 \mathcal{I}$ and $F_1(x) = -\mathcal{K}(\omega)$, with $\mathcal{K}(\omega) = \mathcal{K}^\top(\omega) > 0$, then

$$F(x) = \begin{bmatrix} -\mathcal{K}(\omega) & \mathcal{I} - T_r \omega \mathcal{J} \\ \mathcal{I} & -\alpha_1^{-1}\left(\frac{1}{T_r}\mathcal{I} + u_{3\star}\mathcal{J}\right) \end{bmatrix}.$$

A simple Schur complement analysis shows that $F(x) + F^\top(x) < 0$ if and only if

$$\mathcal{K}(\omega) > \frac{L_{sr}}{4\left(L_s L_r - L_{sr}^2\right)} \left[T_r^2 \omega^2 + 4\right] \mathcal{I}. \qquad (23)$$

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5.2 Proposed Controller

Once the solvability of the problem with simultaneous energy–shaping and damping injection has been established, the final part of the design is the explicit definition of the resulting IDA–PBC and the assessment of its stability properties. This is summarized in the proposition below whose proof follows immediately from analysis of the closed–loop dynamics $\dot{x} = F(x)\nabla H_d$, with $F(x) + F^\top(x) < 0$, and (8).

Proposition 2. Consider the induction motor model (6)–(8) with outputs to be regulated given by (9). Assume that

A.1 The measurable states are the stator currents x_{12} and the rotor speed ω.
A.2 All the motor parameters are known.
A.3 The load torque is constant and known.

Fix, the desired equilibrium to be stabilized as (12), with $y_\star = [\tau_L, y_{2\star}]^\top$, $y_{2\star} > 0$, and set $u_3 = R_r \frac{y_{1\star}}{|y_{2\star}^2|}$ and $u_{12} = \hat{u}_{12}(x_{12}, \omega)$ with

$$\hat{u}_{12}(x_{12}, \omega) = \frac{1}{\alpha_2}\left[\gamma \mathcal{I} + (\omega + u_{3\star})\mathcal{J}\right] x_{12} + \qquad (24)$$
$$+ \frac{\alpha_1}{\alpha_2}\left(\mathcal{I} - T_r \omega \mathcal{J}\right) x_{34\star} - \mathcal{J} x_{12} - \frac{L_{sr}}{\alpha_2 T_r}\mathcal{K}(\omega)\tilde{x}_{12}]$$

with $\mathcal{K}(\omega)$ satisfying (23). Then, the x–subsystem admits a Lyapunov function

$$H_d(x) = \frac{L_{sr}}{2T_r}|\tilde{x}_{12}|^2 + \frac{\alpha_1}{2}|\tilde{x}_{34}|^2.$$

that satisfies $\dot{H}_d \leq -\kappa H_d$, for some $\kappa > 0$. Consequently, for all initial conditions,

$$\lim_{t\to\infty} x(t) = x_\star, \quad \lim_{t\to\infty} y(t) = y_\star$$

exponentially fast. Furthermore $\lim_{t\to\infty} \omega(t) = \omega_\infty$.

6. SIMULATION RESULTS

The performance of the proposed controller was investigated by simulations considering two experiments described below. The considered motor parameters, taken from (Ortega and Espinosa, 1993), were $L_s = 84mH$, $L_r = 85.2mH$, $L_{sr} = 81.3mH$, $R_s = 0.687\Omega$ and $R_r = 0.842\Omega$, with an unitary rotor moment of inertia. Regarding the controller parameters, following field oriented ideas, the rotor flux equilibrium value was set to

$$x_{34\star} = \begin{bmatrix} \beta \\ 0 \end{bmatrix}$$

with $\beta = 2$, while $x_{12\star}$ where computed according to (11). In order to satisfy condition (23), it was defined $\mathcal{K} = k\mathcal{I}$ with

$$k = \frac{L_{sr}}{\left(L_s L_r - L_{sr}^2\right)}\left[T_r^2 \omega^2 + 4\right]$$

In a first experiment the motor was initially at standstill with a zero load torque. At startup, the load torque was set to $\tau_L = 20Nm$ and this value was maintained until $t = 40sec$ when a new step in this variable was introduced changing to $\tau_L = 40Nm$. Figure 1 shows the behavior of the stator currents where it can be noticed how, according to the field oriented approach, one of the stator currents remains (almost) constant while the second one is dedicated to produce the required generated torque. In this sense, in Figure 2 it can be observed how the rotor flux is aligned with the reference frame since one of the components equals β while the other is zero. The internal stability of the closed–loop system is illustrated in Figure 3 where the rotor speed is presented. As expected, besides its boundedness, it can be noticed that when the load torque is increased, this variable decreses. In Figure 4 the main objective of the proposed controller is depicted. Here it is shown how the generated torque regulation objective, both before and after the load torque change, is achieved. Figure 5 shows the boundedness of the control (stator voltages) inputs.

The second experiment was aimed to illustrate the claim stated in Remark 1. In this sense, the control input u_3 was set to

$$u_3 = \hat{u}_{3\star} = R_r \frac{\hat{y}_{1\star}}{y_{2\star}^2}$$

where the estimate of the load torque is obtained as the output of a PI controller, defined over the speed error between the actual and the desired velocities, of the form

$$\hat{y}_{1\star} = k_p\left(\omega - \omega_d\right) + k_i \int \left(\omega - \omega_d\right) dt$$

Figure 6 shows the rotor speed behavior when the desired velocity is (initially) $\omega_d = 100rpm$ and at $t = 50sec$ it is changed to $\omega_d = 150rpm$. In this simulation it was considered $\tau_L = 10Nm$, $k_i = -.1$ and $k_p = -1$. All the other parameters were the same than in the first experiment.

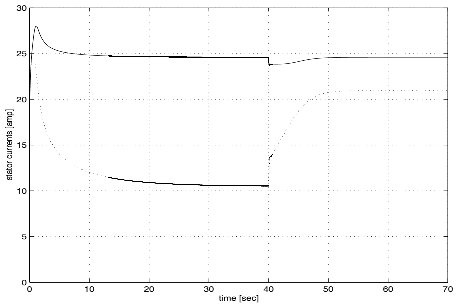

Fig. 1. Stator currents

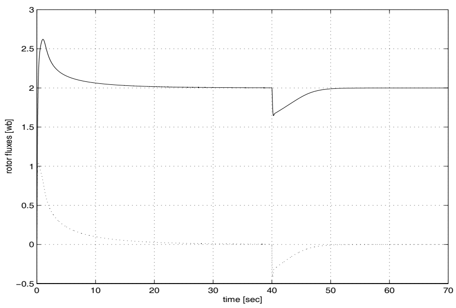

Fig. 2. Rotor fluxes

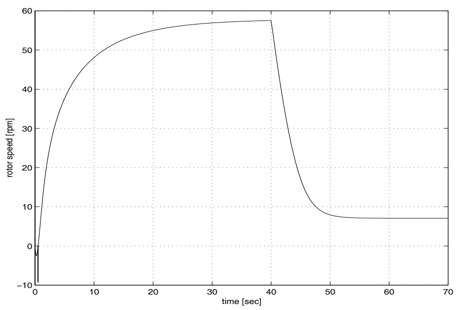

Fig. 3. Rotor speed

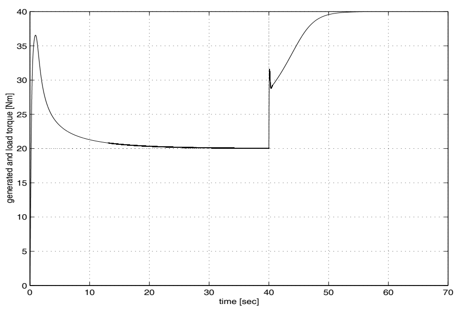

Fig. 4. Generated and load torque

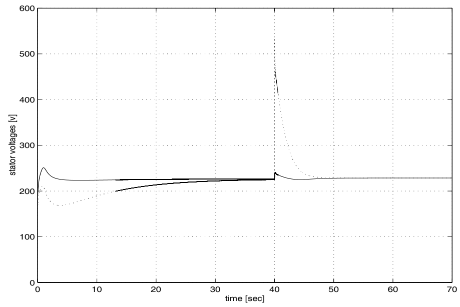

Fig. 5. Stator voltages

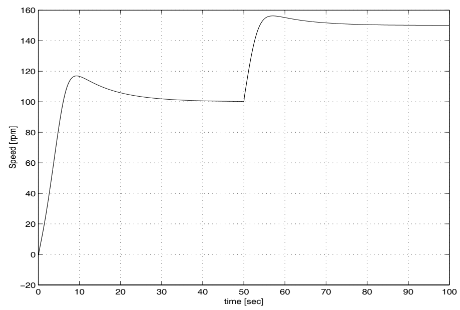

Fig. 6. Speed behavior

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