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SIMULATION AND MODELLING OF PASSIVITY BASED CONTROL OF PMSM UNDER CONTROLLED VOLTAGE

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The aim of the present paper is the study of the behaviour of passivity based control and difficulties due to synthesis for various operating conditions of a synchronous motor with a permanent magnets. The study takes into account the guarantee of satisfactory static and dynamic performance. It also allows the system to be insensitive to disturbances and uncertainties on the parameters. A number of estimation techniques have been developed to achieve speed and position sensorless permanent magnet synchronous motor (PMSM) drives. Most of them suffer from variation of motor parameters such as the stator resistance, stator inductance and torque constant. Also it is known that conventional linear estimators are not adaptive variations of the operating point in a nonlinear system.

K e y w o r d s: passivity based control (PBC), Permanent magnet synchronous motor (PMSM), synthesis, voltage, modelling, simulation

1 INTRODUCTION

The use of electrical machines is expanding rapidly owing to their good performance. The control of machines is the primary concern of control theory research. In fact, an electrical machine is characterised by a non linear behaviour. Adding to that the major difficult tasks to be executed which require a higher precision under rapid trajectories. In order to meet performance criteria always in increase, algorithms of control more and more complex are developed. The progress is not sufficient thus a theory for non linear system is necessary. However, the non linear theory for general systems is complicated and seldom worthy in technological applications. But, from the accomplished works in these last three decades, aiming to improve performance advanced research had allowed emergence of new non linear control techniques for electrical machine application. In this context a method has been proposed in [1] allowing a new control PBC (Passivity Based Control). [2] et al. made similar development on robust passivity based control. Using a shaping of the total energy of the closed-loop system plus an injection of depreciation using the properties of energy dissipation system. The development of this method had allowed many improvements.

It uses essentially Lagrangian structure of mechanical systems in order to make a decreasing Lyapunov function.

It is necessary to know the position of the rotor. The stator currents of the PMSM are controlled to generate constant torque using the rotor position signal.

It is possible to distinguish two fundamental steps while using passive control for a given system. The system modelling is put under the EL formalism and its (possible) passivity is used to create relations describing the stabilizing control. From these relations and by using a variety of techniques (control with variable structure a control based on average representation); the dynamic of the corrector is computed (if it exists) and the control value.

2 GENERAL FORMULATION OF THE PASSIVITY CONTROL

In classical control theory, linear models are considered. If the equations describing a system are nonlinear, the system is linearized, which means that the nonlinear equations are approximated with a linear system. This linear system is then used to determine the control laws. The control laws derived from such an approach are sufficient in many practical applications, but in some cases the linear approach is not sufficient. Therefore, a theory for nonlinear control systems is needed. Unfortunately, nonlinear theory for general systems is complicated and rarely useful in engineering applications.

To make nonlinear theory more useful, it is necessary to consider theory for classes of systems with certain properties. The class of passive Euler-Lagrange (EL) systems consists of systems that can be described by the EL equations and do not contain an internal energy source. Examples of passive EL systems are passive electrical circuits, mechanical systems, and robots. With these special properties in mind, a more useful nonlinear control theory can be presented and nonlinear controllers can be constructed from this theory.

Achieve the stabilized control, the EL properties are used which exist in all the machine circuits. The first property states that any control circuit can be represented under EL formalism [3].

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2.1 Definition of passivity

It is difficult to develop a general nonlinear control theory, because each type of nonlinear system has its own characteristics. Therefore, theories for specialised types of systems are potentially more useful in the analysis of nonlinear systems [4, 5]. In this article we study a class of systems called Euler- Lagrange systems (EL systems). An EL system is a system whose dynamics are described by the EL equations. These equations are described in this article. We also define and investigate a special class of EL systems called passive EL systems. Most of the theory in this study is connected to that class of systems.

This article presents the fundamental mathematical theory for analysis of passive EL systems. The presentation is based upon reference [3].

The basic idea of the passivity consists in shaping the total energy of the system then in adding a damping term. EL equation allows obtaining easily the formulation after having formulated the total energy of the system; it is modified to desired (minimum) value. The system converge of computers allow to implement these new strategies in industry. In classical control theory, the linear models are considered. The non-linear equations are linearized.

3 EULER–LAGRANGE MODELS FOR PMSM

The purpose of this paper is to survey recent developments on passivity-based control of nonlinear dynamical systems. In the first part of the paper we treat general systems and develop a unified framework for passivity-based nonlinear control design. Exploiting the particular inherent structure of physical systems, we can reasonably expect to design a stabilizing controller with better performance.

In the second part, we turn our attention to the practically important class of nonlinear systems described by Euler-Lagrange (EL) equations.

3.1 Relation between the flux and current vectors

We consider the reference system of $\alpha\beta$ axes of the PMSM By applying Gauss' and Ampere's law the flux is given by

$$\Psi_{\alpha\beta} = D_e(pq_m)\dot{q}_e + \Psi_f(pq_m) \tag{1}$$

where $\Psi_{\alpha\beta} = \big(\Psi_\alpha\,,\,\Psi_\beta\big)^\top$ is the flux vector, $\dot{q}_e = \big(i_\alpha,\,i_\beta\big)^\top$ currents vector, p is the number of poles, $q_m = \theta_m$ is the mechanical position of the rotor, Ψ_f flux vector of magnets and $D_e\big(pq_m\big)= D_e\big(pq_m\big)^\top\big(pq_m\big) > 0$ is the inductance matrix.

The flux vector of the magnets is

$$\Psi_f(pq_m) = \varphi_f \begin{pmatrix} \cos(pq_m) \\ \sin(pq_m) \end{pmatrix} \tag{2}$$

with: $D_e\big(p\,q_m\big)=$

$$\begin{pmatrix} L_d\cos^2(pq_m)+L_q\sin^2(pq_m) & (L_d-L_q)\cos(pq_m)\sin(p_m) \\ (L_d-L_q)\cos(pq_m)\sin(p_m) & L_d\cos^2(pq_m)+L_q\sin^2(pq_m) \end{pmatrix}. \tag{3}$$

Knowing that the machine under study is smooth pole given by

$$D_e(pq_m) = \begin{pmatrix} L_d & 0 \\ 0 & L_q \end{pmatrix}. \tag{4}$$

- Kinetic energy.
  If we consider the electric charge $q_e \in \Re^2$ and the rotoric position $q_m \in \Re$ as generalized coordinates of the system we can calculate the electrical energy and mechanical as follows:

a) Kinetic electrical energy is

$$T_e(q_m\,,\,\dot{q}_e) = \sum_{k=1}^{2}\int_0^\sigma \Psi_{\alpha\beta}\mathrm{d}\sigma = \frac{1}{2}\dot{q}_e^\top D_e(pq_m)\dot{q}_e + \Psi_f^\top(pq_m)\dot{q}_e \tag{5}$$

b) Mechanical kinetic energy is

$$T_m(\dot{q}_m) = \frac{1}{2}J\dot{q}_m^2 \tag{6}$$

where J is the moment of inertia, $\dot{q}_m = \omega_m$ is the speed. If we assume: (i) there is no captive effect, and (ii) the shaft of the motor is rigid (with no torsion effect) then the potential energy can be considered null,

$$V(q_m, \dot{q}_m) = 0\,. \tag{7}$$

We can define a new function between the kinetic and potential energy

$$L(q,\dot{q}) = T(q,\dot{q}) - V(q)\,. \tag{8}$$

The utilization of this function L called Lagrangian function in (9) gives EL equations for a conservative system [6, 11].

If we consider the system $\sum_{EL}$ in equilibrium with behavior in term of $(q,\dot{q})$, we obtain by using Alember's principle for the forces that appear in the system the following equality [3, 6, 7].

$$\frac{\mathrm{d}}{\mathrm{d}t}\Big[\frac{\partial T(q,\dot{q})}{\partial \dot{q}_i}\Big] - \frac{\partial T(q,\dot{q})}{\partial q_i} + \frac{\partial V(q)}{\partial q_i} = Q_i^e,\ i = 1,\ldots,n \tag{9}$$

where the first terms derive from kinetic energy, the third term corresponds to the conservative forces from potential energy and the second term of the equality represents the generalized forces. Lagrangian function [8, 12, 13] is given by

$$L(q_m,\dot{q}_m,\dot{q}_e) = \frac{1}{2}\dot{q}_e^\top D_e(pq_m)\dot{q}_e + \Psi_f^\top(pq_m)\dot{q}_e + \frac{1}{2}J\dot{q}_m^2 \tag{10}$$

We assume that the electrical and mechanical dissipation effects are due simultaneously to winds resistance considered constant and to friction coefficient. The Rayleigh function of the PMSM is given by (11).

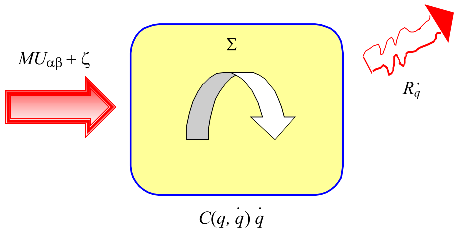

Fig. 1. Exchanges of energy components corresponding to EL

- Quadratic dissipation function

In most cases we assume that the Rayleigh dissipation function is a quadratic function of the form

$$F(\dot{q}_m,\dot{q}_e)=F_e(\dot{q}_e)+F_m(\dot{q}_m)=\frac{1}{2}\dot{q}_e^\top R_e\dot{q}_e+\frac{1}{2}B\dot{q}_m^2 \quad (11)$$

with resistance matrix $R_e=\mathrm{diag}\{R_a\,,\,R_a\}$ and friction coefficient B.

- Generalized external forces

There are three different types of external forces that we consider in this report: control input forces, dissipation forces, and forces from the interaction between the system and its environment (disturbance forces).

The control forces are assumed to enter the system linearly and can thus be described as Mu, where M is a constant control matrix and u is the control vector, that is, a vector containing all the control signals.

$$Q_i^e=\begin{pmatrix}Q_e\\Q_m\end{pmatrix}\ \text{where } i=1,2\,. \quad (12)$$

a) Electrical forces: the voltages applied to the stator windings are considered the only the external electrical forces to the system as

$$Q_e=U_{\alpha\beta}=[U_\alpha\quad U_\beta]^\top \quad (13)$$

b) Mechanical forces: the torque is the only external force of mechanical system. It is in general a non linear function of the speed given by $Q_m=-\tau_L$. (14)

3.2 EL Model of the PMSM

By using EL equation below to the function (10) in order to obtain EL model of PMSM.

$$\frac{\mathrm{d}}{\mathrm{d}t}\Big[\frac{\partial L(q,\dot{q})}{\partial\dot{q}_i}\Big]-\frac{\partial L(q,\dot{q})}{\partial q_i}+\frac{\partial F(q)}{\partial q_i}=Q_i\,,\quad i=1,\dots,n\,. \quad (15)$$

Using equations (11) and (14) the following system is obtained.

$$D_e(pq_m)\ddot{q}_e+W_1(pq_m)p\dot{q}_m\dot{q}_e+W_2(pq_m)p\dot{q}_m+R_e\dot{q}_e = I_2U_{\alpha\beta}\,, \quad (16)$$

$$J\ddot{q}_m+B\dot{q}_m=\tau(\dot{q}_e,pq_m)-\tau_L\,. \quad (17)$$

Remark 1. The model of the PMSM obtained by EL equation can also be obtained from Concordia model as

$$U_{\alpha\beta}=R_{\alpha\beta}I_{\alpha\beta}+L_{\alpha\beta}\frac{\mathrm{d}I_{\alpha\beta}}{\mathrm{d}t}+\omega\,\varepsilon_{\alpha\beta}\,. \quad (18)$$

The electromagnetic torque developed by the motor is

$$\tau(\dot{q}_e,pq_m)=\frac{1}{2}\dot{q}_e^\top W_1(pq_m)\dot{q}_e+W_2^\top(pq_m)\dot{q}_e \quad (19)$$

with W_1 the derivative of inductance matrix given by

$$W_1(pq_m)=\frac{\partial D_e(pq_m)}{\partial(pq_m)}=(L_d-L_q)\times \times\begin{pmatrix}-2\cos(pq_m)\sin(pq_m) & \cos^2(pq_m)-\sin^2(pq_m)\\ \cos^2(pq_m)-\sin^2(pq_m) & -2\cos(pq_m)\sin(pq_m)\end{pmatrix}. \quad (20)$$

The derivative of the flux vector by the PM is

$$W_2(pq_m)=\frac{\partial\Psi_f(pq_m)}{\partial(pq_m)}=\varphi_f\begin{pmatrix}-\sin(pq_m)\\ \cos(pq_m)\end{pmatrix}. \quad (21)$$

Remark 2. The PMSM has smooth pole that means $L_d=L_q$, then matrix D_e is diagonal and has constant elements and $W_1=0$. Considering remark 2 the model of the PMSM becomes

$$\begin{aligned}&L_d\ddot{q}_\alpha-\varphi_f\sin(pq_m)p\dot{q}_m+R_\alpha\dot{q}_\alpha=U_\alpha\,,\\ &L_q\ddot{q}_\beta+\varphi_f\cos(pq_m)p\dot{q}_m+R_a\dot{q}_\beta=U_\beta\,, \quad (22)\\ &J\ddot{q}_m+B\dot{q}_m+\varphi_f\sin(pq_m)\dot{q}_\alpha-\varphi_f\cos(pq_m)\dot{q}_\beta=-\tau_L\,.\end{aligned}$$

Note that the model (16) to (19) can be put in the form

$$D(q)\ddot{q}+W(q,\dot{q})+R\dot{q}=MU_{\alpha\beta}+\xi \quad (23)$$

$$D(q)=\mathrm{diag}'\{D_e,J\}\,,\ R=\mathrm{diag}\{R_e,B\}\,,$$
$$M=\big[I_2,\,0_{1\times2}\big]^\top,\ \ \xi=\big[0,0,-\tau_L\big]^\top,\ \ \dot{q}=\frac{\mathrm{d}q}{\mathrm{d}t}\,.$$

3.3 Feedback based on passivity

We assume an ideal case the states (current, speed, position) are measurable and without noise.

Consider the model of PMSM (16), (17); we define a vector v and the output vector given by

$$v=[U_\alpha\ \ U_\beta\ \ -\tau_L]^\top \quad (24)$$

$$Y=[\dot{q}_e\ \ \dot{q}_m]^\top\,. \quad (25)$$

and we can formulate:

Lemma 1. *The above choice of vectors of input and output v and Y the PMSM defined by the relation M given by $M\colon v\mapsto Y$ is passive.*

Proof. Let H_m be the Hamiltonian of the motor it is the total energy E_{tot} [9, 12, 13]. It is given by

$$H_m(q_m,\dot{q}_e,q_m)=E_{tot}=T(\dot{q}_e,\dot{q}_m)+V(q_m,q_e)\,. \quad (26)$$

We obtain

$$H_m(q_m,\dot{q}_e,\dot{q}_m)=\frac{1}{2}\dot{q}_e^\top D_e(pq_m)\dot{q}_e+\psi_f^\top(pq_m)\dot{q}_e+J\dot{q}_m^2\,.$$

The derivative of H_m with respect to time along the trajectory (16)–(19) can be expressed by

$$\dot{H}_m(q_m, \dot{q}_e, q_m) = -\dot{q}^\top R\dot{q} + Y^\top v + \frac{\mathrm{d}}{\mathrm{d}t}(\psi_f^\top(pq_m)\dot{q}_e) \quad (27)$$

with positive symmetric matrix $R = \mathrm{diag}\{\mathrm{Re}, B\}$.

By integration of $\dot{H}_m$ on $[0\ T_m]$ we obtain

$$\underbrace{H_m(T_m) - H_m(0)}_{\text{stored energy}} = \underbrace{-\int_0^{T_m} \dot{q}^T R\dot{q} d\sigma}_{\text{dissipated energy}} + \underbrace{\int_0^{T_m} Y^T v d\sigma + \left[\psi_f^T(pq_m)\dot{q}_e\right]_0^{T_m}}_{\text{supplied energy}}. \quad (28)$$

Knowing that the stored energy $H_m(T_m) \geq 0$ and $H_m(0)$, the round off (28) permits to derive the inequality of dissipation

$$\int_0^{T_m} Y^\top v \mathrm{d}\sigma \geq \lambda_{\min}\{R\}\int_0^{T_m} \|\dot{q}\|^2 \mathrm{d}\sigma - \left(H_m(0) + \left[\psi_f^\top(pq_m)\dot{q}_e\right]_0^{T_m}\right). \quad (29)$$

By taking

$$\begin{aligned} \alpha_m &= \lambda_{\min}\{R\}, \\ \beta_m &= -\left(H_m(0) + \left[\psi_f^\top(pq_m)\dot{q}_e\right]_0^{T_m}\right) \end{aligned} \quad (30)$$

We can deduce [10, 12] that the relation M linking the vector of output Y with the input vector v is passive as for the PMSM.

R e m a r k 3. Based on the proof of lemma 1 and on the model (16), (17), it is clear that the vector given by

$$W(q_e, q_m, pq_m) = \begin{pmatrix} W_1(pq_m)\dot{q}_e + W_2(pq_m)p\dot{q}_m \\ -\frac{1}{2}q_e^\top W_1(pq_m) + W_2^\top(pq_m))\dot{q}_e \end{pmatrix} \quad (31)$$

contains forces with no work (non-dissipative forces).

4 DESIGN OF THE CONTROL

Under the preceding conditions the control proposed assures internal stability, torque control, speed and position control in closed loop

$$\lim_{t\to\infty}(\tau - \tau_L = 0\,,\ \lim_{t\to\infty} \dot{q}_m = \dot{q}_m^\bullet \text{ or } \lim_{t\to\infty} q_m = q_m^\bullet \quad (32)$$

where $\tau^\bullet$, $\dot{q}_m^\bullet$, $q_m^\bullet$ are respectively the electromagnetic torque, the desired speed and the desired position. The first step of the synthesis determines the desired dynamics which will be compatible with the constraints of PMSM. Considering equation (16) we can propose the following.

$$D_e(pq_m)\ddot{q}_e^\bullet + \frac{1}{2}(W_1(pq_m)p\dot{q}_m)\dot{q}_e^\bullet + \frac{1}{2}(W_1(pq_m)p\dot{q}_m + R_e)\dot{q}_e^\bullet + W_2(pq_m)p\dot{q}_m = U_{\alpha\beta}^\bullet\,. \quad (33)$$

$\dot{q}_e^\bullet$ is the desired currents vectors. The equation of the error is calculated by subtracting (33) from the two first relations of relation (23), thus we obtain

$$D_e(pq_m)\dot{e}_e + \frac{1}{2}(W_1(pq_m)p\dot{q}_m)e_e + \frac{1}{2}(W_1(pq_m)p\dot{q}_m + R_e)e_e = U_{\alpha\beta} - U_{\alpha\beta}^\bullet \quad (34)$$

$$\text{where} \qquad e_e = \dot{q}_e - \dot{q}_e^\bullet \quad (35)$$

is the currents error vector. To show the convergence of pursuit of the current error we consider the quadratic function

$$V_e(e_e) = \frac{1}{2}e_e^\top D_e(pq_m)e_e\,. \quad (36)$$

The derivative to time of Ve along the trajectory (24) is given by

$$\dot{V}_e(e_e) = -e_e^\top\left(R_e + \frac{1}{2}W_1(pqm)p\dot{q}_m\right)e_e + e_e^\top\left(U_{\alpha\beta} - U_{\alpha\beta}^\bullet\right). \quad (37)$$

By choosing

$$U_{\alpha\beta} = U_{\alpha\beta}^\bullet \quad (38)$$

the expression of $\dot{V}_e$ becomes

$$\dot{V}_e(e_e) = -e_e^\top\left(R_e + \frac{1}{2}W_1(pq_m)p\dot{q}_m\right)e_e\,. \quad (39)$$

We remark the positivity of the dissipative term

$$\left(R_e + \frac{1}{2}W_1(pq_m)p\dot{q}_m\right) \quad (40)$$

4.1 Damping matrix

To accelerate the convergence to equilibrium the derivative of $\dot{V}_e(e_e)$ must be more negative. To this we inject an additive term K_e of supplementary expression in the initial control expression (34). The role of this term is to increase certain values of $\left(R_e + \frac{1}{2}W_1(pq_m)p\dot{q}_m\right)$. Then the control is

$$U_{\alpha\beta} = U_{\alpha\beta}^\bullet - K_e e_e \quad (41)$$

where K_e is a 2×2 matrix and equation (34) becomes

$$De(pq_m)\dot{e}_e + \frac{1}{2}\left(W_1(pq_m)p\dot{q}_m\right)e_e + \left(\frac{1}{2}W_1(pq_m)p\dot{q}_m + R_e + K_e\right)e_e = 0_{2\times 1} \quad (42)$$

By choosing the same quadratic function V_e, its derivative along (42) is given by

$$\dot{V}_e(e_e) = -e_e^\top\left(R_e + \frac{1}{2}W_1(pqm)p\dot{q}_m + K_e\right)e_e\,. \quad (43)$$

The function $\dot{V}_e$ is defined and negative if

$$K_e = K_e^\top > -R_e - \frac{1}{2}W_1(pq_m)p\dot{q}_m\,. \quad (44)$$

This condition is verified by choosing

$$K_e(pq_m, \dot{q}_m) = -\frac{1}{2}W_1(pq_m)p\dot{q}_m + k_e I_2 \tag{45}$$

and $k_e > R_a \dots$ — the operating point $e_e = 0$ is stable.

4.2 Proof of exponential convergence of error by CBP

We consider the quadratic function V_e given by (36), which by passivity of $D_e(pqm)$ and Rayleigh coefficient satisfies the following inequality

$$0 \le \lambda_{\min}\{D_e\}\|e(t)\|^2 \le V_e \le \lambda_{\max}\{D_e\}\|e(t)\|^2 \tag{46}$$

where $\lambda_{\min}\{D_e\}$, $\lambda_{\max}\{D_e\}$ are minimum values of $\{D_e\}$. And the derivative $\dot{V}_e$ given by (43) which, by passivity of dissipation term $\frac{1}{2}W_1(pq_m)p\dot{q}_m+R_e+K_e(pq_m,\dot{q}_m)$ and Rayleigh coefficient satisfies the following inequality

$$\dot{V}_e \le -\lambda_{\min}\Big\{\frac{1}{2}W_1(pq_m)p\dot{q}_m + R_e + K_e(pq_m, \dot{q}_m)\Big\}\|e(t)\|^2 \tag{47}$$

From (46) and (47) we can deduce the following inequality

$$\dot{V}_e \le -\alpha_{ep}V_e \tag{48}$$

$$\alpha_{ep} = \frac{-\lambda_{\min}\{\frac{1}{2}W_1(pq_m)p\dot{q}_m + R_e + K_e(pq_m, \dot{q}_m)\}}{\lambda_{\max}\{D_e(pq_m)\}}\,. \tag{49}$$

By integrating (48) we obtain

$$V_e(t) \le V_e(0)e^{-\alpha_{ep}t}\,. \tag{50}$$

From relations (46) and (50) we obtain

$$e_e(t) \le \sqrt{m_{ep}}\|e_e(0)\|e^{-(\alpha_{ep}t/2)}\,. \tag{51}$$

We deduce that the error $e_e(t)$ converges exponentially.

Remark 5. The ratio of convergence can be ameliorated by acting on damping K_e.

4.3 Calculation of desired currents $\dot{q}_e^\bullet$

The PMSM works with maximum torque if the desired current $i_d^\bullet$ in the reference dq is null. Knowing that the torque in reference dq and at i_d null is given by

$$\tau^\bullet = \frac{3}{2}p\varphi_f i_q^\bullet\,. \tag{52}$$

The currents in reference dq are

$$i_d^\bullet = 0\,, \qquad i_q^\bullet = \frac{2}{3}\frac{\tau^\bullet}{pQ_f}\,. \tag{53}$$

Using the transformation matrix, the desired currents in reference $\alpha\beta$ are

$$\dot{q}_e^\bullet = \frac{2}{3}\frac{\tau^\bullet}{pQ_f}\begin{bmatrix} -\sin(pq_m) \\ \cos(pq_m) \end{bmatrix} \tag{54}$$

with: $$v = D_e(pq_m)\ddot{q}_e^\bullet + \frac{1}{2}W_1(pq_m)p\dot{q}_m\dot{q}_e^\bullet + \Big(\frac{1}{2}W_1(pq_m)p\dot{q}_m + K_e(pq_m, \dot{q}_e) + R_e\Big)\dot{q}_e^\bullet\,. \tag{55}$$

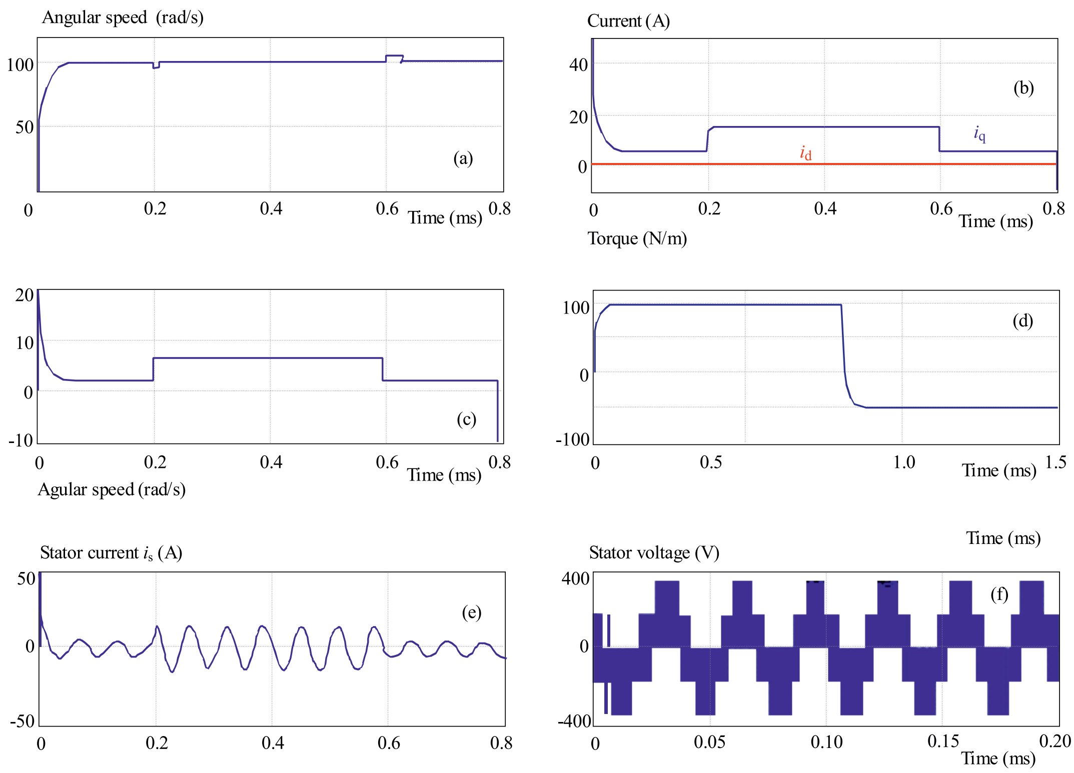

Fig. 2. PBC simulation results

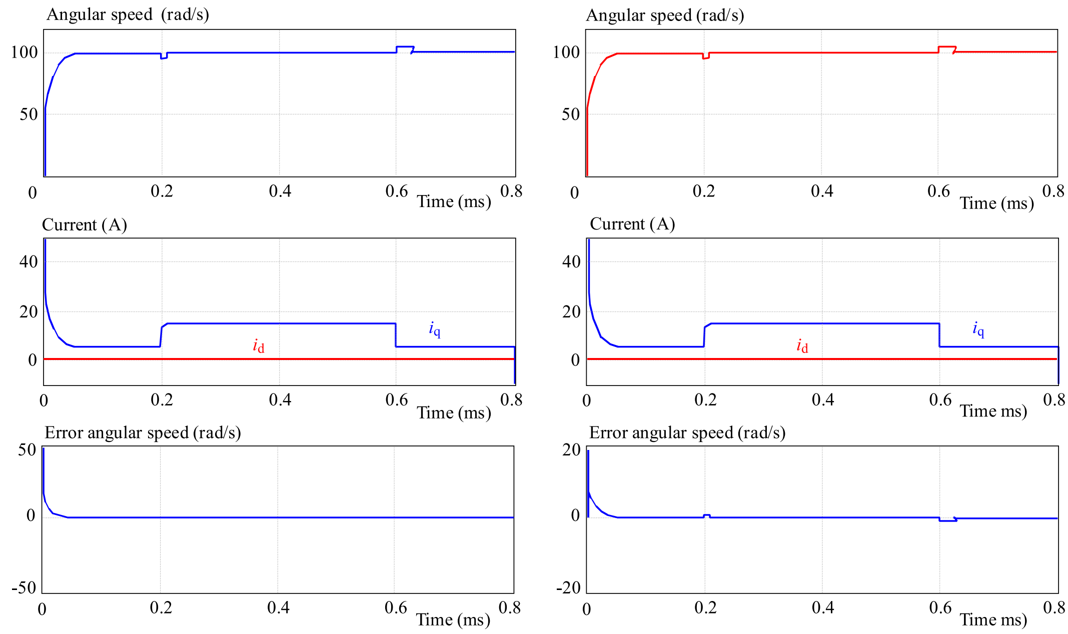

Fig. 3. Simulation results with variation of parameters

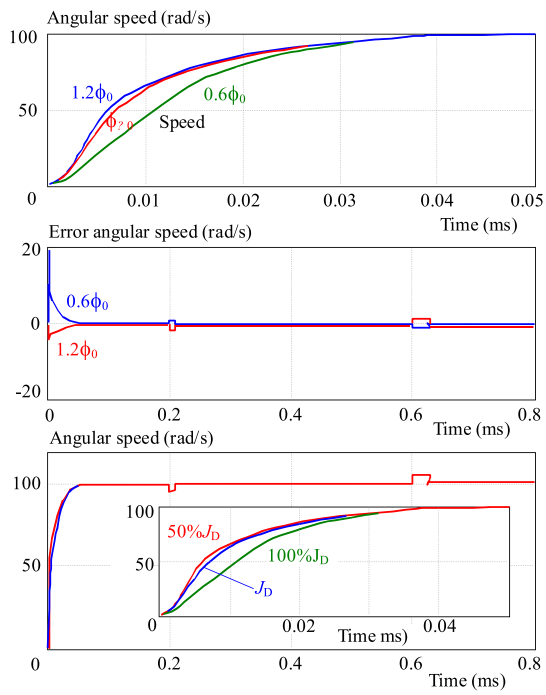

Fig. 4. Simulation results with variation of parameters

and considering Remark 6,

$$D_e(pq_m)\ddot{q}_e + \frac{1}{2}W_1(pq_m)p\dot{q}_m\dot{q}_e + \Big(\frac{1}{2}W_1(pq_m)p\dot{q}_m + R_e + K_e(pq_m,\dot{q}_e)\Big)\dot{q}_e = v\,. \tag{56}$$

Equation (56) can be represented as follows

$$\sum\nolimits_{BF} \quad v \mapsto \dot{q}_e\,. \tag{57}$$

The last relation permits to formulate the following lemma.

Lemma 3. *The relation input-output ES $\sum_{BF}$ of input vector v and output vector $\dot{q}_e$ is passive.*

Proof. Passivity of the PMSM in closed loop: Considering the quadratic function

$$H_{BF}(pq_m,\dot{q}_e) = \frac{1}{2}\dot{q}_e^\top D_e(pq_m)\dot{q}_e \tag{58}$$

we calculate the derivative of H_{BF} along (56), and using (24) we obtain

$$H_{BF}(pq_m,\dot{q}_e) = \dot{q}_e^\top v - \dot{q}_e^\top (R_e + k_e I_2)\dot{q}_e\,. \tag{59}$$

Using the same steps as for the proof of Lemma 1 we obtain the following inequality of dissipation

$$\int_0^{T_{bf}} \dot{q}_e^\top v\mathrm{d}s \geq \lambda\min\{R_e + k_e I_2\}\int_0^{t_{bf}} \|\dot{q}_e\|^2\mathrm{d}s - H_{BF}(0)\,. \tag{60}$$

By taking

$$\alpha_{BF} = \lambda_{\min}\{R_e + k_e I_2\}\,, \qquad \beta_{BF} = -H_{BF}(0) \tag{61}$$

one can conclude that the system is passive.

5 SIMULATION TESTS

To illustrate the set up performance of the PBC an idle run has been simulated with a set up value of 100 rd/s with nominal load ($T_L = 4$ Nm) from $t = 0.2$ s until $t = 0.6$ s. We note that the load has no influence on speed response which follows its reference without overrun, Fig. 2(a). In Fig. 2(d) we tested the control when changing the sense of rotation of the engine with the same load torque as previously. The set up value is 100 rd/s; made to −100 rd/s after 0.8 s from start. The results of the simulation show that the performances required by this control technique are satisfactory, Fig. 2(a) to (f). We note that the decoupling is not sensitive to instantaneous variations of current i_q and that the rejection of the perturbation is rapid, Fig. 2(b). The current i_d oscillates around zero, Fig. 2(b), and the electromagnetic torque is the image of current i_q, Fig. 2(c). To evaluate the performance of speed set up of the machine PMSM, we have tested the robustness of this set up with respect to the electrical and mechanical parameter variation of the machine, Fig. 3(a) to (d). The simulations were made for a period of 0.8 s with increasing stator resistance to 100 % and increase of inductances L_d and L_q to 100 %, Fig 3(a). On the other hand in Fig. 3(b) there is a decrease in stator resistance and inductance of 50 %. Figure 3(d) represents the variation of the moment of inertia J ($2J_0$ and $0.5J_0$). The results obtained show that the variations influence only but lightly the response time. Thus for the PBC the decoupling is maintained constant even with the variation of parameters, Fig. 3(a),(b).

- Variation of electrical parameters:

$$\text{a} : R = 100\% R_0\,;\ L_d = L_q = 100\% L_0\,, \varphi = \varphi_0\,,$$

$$\text{b} : R = 50\% R_0\,;\ L_d = L_q = 50\% L_0\,, \varphi = 0.6\varphi_0\,,$$

$$\text{c} : \varphi = 0.6\varphi_0\,, \varphi = 1.2\varphi_0\,.$$

- Variation of mechanical parameters:

$$\text{d} : J = 100\,\% J_0\,, J = 50\,\% J_0$$

(R_0, L_0, φ_0, J_0 represent the nominal values of the motor). vskip-4mm

6 CONCLUSION

The work presented in this article is a modest contribution to the study of performance of non linear control based on passivity applied to PMSM associated to a three phased three level inverter.

According to the results we observe that the PBC has good performance for the start and the rejection of perturbation of the machine.

The objectives of this control are a control of speed and tracking with maximum torque and the obtained good performance. It shows a better robustness with the variation of parameters.

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