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Backstepping Control for a Five-Phase Permanent Magnet Synchronous Motor Drive

Anissa Hosseyni[1,3], Ramzi Trabelsi[1,2], Atif Iqbal[4], Med Faouzi Mimouni[1,3]
[1]Monastir National Engineering School, Ibn Eljazzar City, 5019 Monastir, Tunisia
[2]High Institute of Applied Sciences and Technology, Ibn Khaldoun City, 4003 Sousse, Tunisia
[3]Research Unit: Etude des Systèmes Industriels et des Energies renouvelables ESIER, Rue Ibn Eljazzar, 5019 Monastir, Tunisia
[4]Department of Electrical Engineering, Aligarh Muslim University, Aligarh, India

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ABSTRACT

This paper deals with the synthesis of a speed control strategy for a five-phase permanent magnet synchronous motor (PMSM) drive based on backstepping controller. The proposed control strategy considers the nonlinearities of the system in the control law. The stability of the backstepping control strategy is proved by the Lyapunov theory. Simulated results are provided to verify the feasibility of the backstepping control strategy.

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Corresponding Author:

Anissa Hosseyni,
Monastir National Engineering School,
Ibn Eljazzar City, 5019 Monastir, Tunisia.
Email: hosseyni.anissa@yahoo.com

1. INTRODUCTION

Three-phase machines are widely used in the industrial world. Certainly they are the most studied and used for long in terms of control and implementation. However, once the applications require very high power, problems appear as well on the inverter as on the machine. For this reason, multilevel converter technology is employed. Another solution is to segment the power by using multiphase machines (machines which the number of phases is greater than three) supplied by a multi-legs inverter [1]-[2]. Multiphase machines have an increasing interest due to the attractive features compared with the three-phase machines.

The multiphase machines offered numerous advantages. Indeed, multiphase motors reduce the current per phase without increasing the stator voltage then the semiconductor current rating can be reduced [3], which reduce the equipment costs and the constraints applied to semiconductors devices due to series/parallel connections.Increasing the number of phases enables the reduction of torque ripples in multiphase machines [4], thus the interest of multiphase machine has grown in the applications requiring lower vibration and acoustics. Multiphase motors are able to continue the operating under the loss of one or more phases which mean higher fault tolerance thus multiphase motors are suitable candidate in applications which require higher reliability [5]-[6]. Due to those advantages, multiphase motors are used in many sensitive applications such as marine systems and aerospace applications [7].

PMSM has become more attractive and competitive to induction motors due to many reasons such as the development of the technology components of the power electronics, the advent of digital processors with high computing power. PMSM have gained an increasing attention due to the development of permanent magnet material [8]. Their main features are: low inertia and high torque [9].

Multiphase motors are invariably supplied by multiphase inverters. There are few techniques to control the five-phase inverter. However, SVM has become the most popular due to its easiness of digital implementation and higher dc bus utilization [10]. In [11], the five-phase SVM is a simple extension of the three phase one without considering the particularity of multiphase motors. However, this technique introduces low order harmonics which cannot be controlled, when only large vectors are used for reference synthesis. To eliminate the low order harmonic currents, it is essential to eliminate the voltage components in the second plane as shown in [10].The synthesis of this technique consists on combining medium and large vectors in appropriate manner.

There are many strategies to control the multiphase PMSM; one of the most popular ones is the field oriented control. This technique has been widely studied and developed since the advances in power semi-conductors technology. Indeed, it requires the calculation of Park transformation, the evolution of trigonometric functions and the regulation. The synthesis of the field oriented control strategy consists on transforming the five-phase PMSM into a system of decoupled equations in order to make the electromagnetic torque similar to the DC machine [12].

However, this strategy doesn't take into account the effects of non-linearity. To compensate this limitation, many nonlinear control techniques have been proposed, the sliding mode control [13], the input–output linearization control [14], the direct torque control [3] and the backstepping control [15]-[18].

A backstepping controller is a robust and powerful methodology that has been studied in the last two decades. The most appealing point of it is the use of the so-called "virtual control" to decompose systematically a complex nonlinear control design problem into simpler and smaller ones. Backstepping control design is divided into various design steps. Each step deals with a single input–single-output design problem, and each step provides a reference for the next design step. The overall stability is achieved by Lyapunov theory for the whole system [18]. Several methods of applying the backstepping control to PMSM drives have been presented. In [15], a robust adaptive integral backstepping control of three-phase PMSM with uncertainties is designed. In [16], a new adaptive backstepping control that achieves global asymptotic rotor speed tracking for the full-order, nonlinear model of a PMSM, the system parameters is adjusted online by fuzzy logic control. In [17], the authors proposed an improved Direct Torque Control (DTC) of PMSM based on backstepping control.

In this paper, a backstepping control design is applied in the speed tracking and currents controllers. The stability of the whole system is proved by the Lyapunov stability theory.This paper deals with the synthesis of the backstepping control for a five-phase PMSM drive. This paper is organized in five sections including the introduction. In section 2, the mathematical model of the machine is presented. Then, the backstepping controller is presented in section 3. Section 4 is devoded to the simulations results and the last section deals with results.

2. MODEL OF FIVE PHASE PMSM

The equivalent model of a five phase PMSM is presented in a decoupled rotating frame $\left(d_p - q_p - d_s - q_s\right)$ as [2]-[3]:

$$\begin{cases} \dfrac{dI_{dp}}{dt} = -a_1 I_{dp} + \omega_e I_{qp} + \dfrac{1}{L_p} v_{dp} \\ \dfrac{dI_{qp}}{dt} = -a_1 I_{qp} - \omega_e I_{dp} - a_2 \omega_e + \dfrac{1}{L_p} v_{qp} \\ \dfrac{dI_{ds}}{dt} = -a_3 I_{ds} + 3\omega_e I_{qs} + \dfrac{1}{L_s} v_{ds} \\ \dfrac{dI_{qs}}{dt} = -a_3 I_{qs} - 3\omega_e I_{ds} + \dfrac{1}{L_s} v_{qs} \\ \dfrac{d\Omega}{dt} = \dfrac{1}{J}\left(T_{em} - T_r\right) - \dfrac{f}{J}\Omega \end{cases} \tag{1}$$

Where the stator currents $\left(I_{dp}, I_{qp}, I_{ds}, I_{qs}\right)$ and the speed ω_e are the state variables. The stator voltages $\left(v_{dp}, v_{qp}, v_{ds}, v_{qs}\right)$ are the control variables.

Where $a_1 = \frac{R_s}{L_p}; a_2 = \frac{\sqrt{\frac{5}{2}}\Phi_{max}}{L_p}; a_3 = \frac{R_s}{L_s}$

The expression of electromagnetic torque is given by:

$$T_{em} = \sqrt{\frac{5}{2}}\Phi_{max} P I_{qp} \tag{2}$$

Eq.(1) can be written as:

$$\begin{cases} \frac{dI_{dp}}{dt} = f_1 + \frac{1}{L_p} v_{dp} \\ \frac{dI_{qp}}{dt} = f_2 + \frac{1}{L_p} v_{qp} \\ \frac{dI_{ds}}{dt} = f_3 + \frac{1}{L_s} v_{ds} \\ \frac{dI_{qs}}{dt} = f_4 + \frac{1}{L_s} v_{qs} \\ \frac{d\Omega}{dt} = f_5 \end{cases} \tag{3}$$

Where f_1 to f_5 are given by:

$$\begin{cases} f_1 = -a_1 I_{dp} + \omega_e I_{qp} \\ f_2 = -a_1 I_{qp} - \omega_e I_{dp} - a_2 \omega_e \\ f_3 = -a_3 I_{ds} + 3\omega_e I_{qs} \\ f_4 = -a_3 I_{qs} - 3\omega_e I_{ds} \\ f_5 = a_4 I_{qp} - \frac{1}{J} T_r - a_5 \Omega \end{cases} \tag{4}$$

Where $a_4 = \frac{\sqrt{\frac{5}{2}}\Phi_{max} P}{J}; a_5 = \frac{f}{J}$

The control objective is to make the mechanical speed Ω track desired reference Ω_c: a backstepping controller is used to achieve the tracking. The stator voltages $\left(v_{dp}, v_{qp}, v_{ds}, v_{qs}\right)$ are considered as inputs.

3. SPEED BACKSTEPPING CONTROLLER

The basic idea of the Backstepping controller is to make closed loop systems equivalent in cascade subsystems of order one stable under Lyapunov approach which gives them the qualities of robustness and global asymptotic stability. In other words, it is a multi-step method, at each step of the process a virtual command is generated to ensure the convergence of the system to its equilibrium state. This can be reached from Lyapunov functions which ensure step by step the stabilizing of each synthesis step [18]. In what follows, we introduce a control based on the backstepping technique for five- phase PMSM to achieve control with sensor. The purpose of this command is to allow, the speed control according to the reference trajectory and also to force the current I_{dp} equal to zero. The synthesis of this control can be achieved in two steps.

Step 1: calculation of the reference currents

In this step, the purpose is to make the rotor speed tacks its desired reference. To achieve this, you define a function $f = (\Omega_c)$ where Ω_c is the reference speed. The speed error is defined by:

$$e_\Omega = \Omega_c - \Omega \quad (5)$$

The derivative of Eq.(5) gives:

$$\dot{e}_\Omega = \dot{\Omega}_c - \dot{\Omega} \quad (6)$$

Taking into account Eq.(3), Eq.(6) can rewritten as follows:

$$\dot{e}_\Omega = \dot{\Omega}_c - f_5 \quad (7)$$

To check the tracking performances, let's choose the first Lyapunov function v_1, such as:

$$v_1 = \frac{1}{2} e_\Omega{}^2 \quad (8)$$

Using Eq. (7), the derivative of Eq. (8) is given by:

$$\dot{v}_1 = e_\Omega (\dot{\Omega}_c - f_5) \quad (9)$$

This can be rewritten as follows:

$$\dot{v}_1 = -k_1 e_\Omega^2 \quad (10)$$

Where k_1 should be positive parameter, in order to guarantee a stable tracking, which gives:

$$\dot{e}_\Omega = \dot{\Omega}_c - \dot{\Omega} = -k_1 e_\Omega \quad (11)$$

The currents references are given by:

$$\begin{cases} \left(I_{qp}\right)_c = (\dot{\Omega}_c + \frac{1}{J}T_r + a_5\Omega + k_1 e_\Omega)/a_4 \\ \left(I_{dp}\right)_c = 0 \\ \left(I_{qs}\right)_c = 0 \\ \left(I_{ds}\right)_c = 0 \end{cases} \tag{12}$$

Step 2: Calculation of the reference stator voltages

In this step, the purpose is to achieve the current references calculated previously. Let us define the current errors:

$$\begin{cases} e_{iqp} = \left(I_{qp}\right)_c - I_{qp} \\ e_{idp} = \left(I_{dp}\right)_c - I_{dp} \\ e_{ids} = \left(I_{ds}\right)_c - I_{ds} \\ e_{iqs} = \left(I_{qs}\right)_c - I_{qs} \end{cases} \tag{13}$$

Setting Eq. (12) in Eq. (13), one obtains:

$$\begin{cases} e_{iqp} = (\dot{\Omega}_c + \frac{1}{J}T_r + a_5\Omega + k_1 e_\Omega)/a_4 - I_{qp} \\ e_{idp} = -I_{dp} \\ e_{ids} = -I_{ds} \\ e_{iqs} = -I_{qs} \end{cases} \tag{14}$$

Then, Eq.(7) is given by:

$$\dot{e}_\Omega = a_4 e_{iqp} - k_1 e_\Omega \tag{15}$$

The time derivative of Eq. (13) yields:

$$\begin{cases} \dot{e}_{iqp} = (\dot{I}_{qp})_c - \dot{I}_{qp} \\ \dot{e}_{idp} = (\dot{I}_{dp})_c - \dot{I}_{dp} \\ \dot{e}_{ids} = (\dot{I}_{ds})_c - \dot{I}_{ds} \\ \dot{e}_{iqs} = (\dot{I}_{qs})_c - \dot{I}_{qs} \end{cases} \tag{16}$$

Setting Eq. (3) in Eq. (16), one obtains:

$$\begin{cases} \dot{e}_{iqp} = (\dot{I}_{qp})_c - \dot{I}_{qp} = (\dot{I}_{qp})_c - f_2 - \frac{1}{L_p} v_{qp} \\ \dot{e}_{idp} = (\dot{I}_{dp})_c - \dot{I}_{dp} = (\dot{I}_{dp})_c - f_1 - \frac{1}{L_p} v_{dp} \\ \dot{e}_{ids} = (\dot{I}_{ds})_c - \dot{I}_{ds} = (\dot{I}_{ds})_c - f_3 - \frac{1}{L_s} v_{ds} \\ \dot{e}_{iqs} = (\dot{I}_{qs})_c - \dot{I}_{qs} = (\dot{I}_{qs})_c - f_4 - \frac{1}{L_s} v_{qs} \end{cases} \tag{17}$$

It is to be noted that Eq. (17) includes the stator voltage. This yields to define a new Lyapunov function based on the stator currents errors and speed error:

$$v_2 = \frac{e_\Omega{}^2 + e^2_{iqp} + e^2_{idp} + e^2_{ids} + e^2_{iq2}}{2} \tag{18}$$

The derivative of Eq. (18) is given by:

$$\dot{v}_2 = e_\Omega \dot{e}_\Omega + e_{iqp} \dot{e}_{iqp} + e_{idp} \dot{e}_{idp} + e_{ids} \dot{e}_{ids} + e_{iqs} \dot{e}_{iqs} \tag{19}$$

By setting Eq. (15) and Eq. (17) in Eq. (19), one can obtain:

$$\begin{aligned} \dot{v}_2 = & -k_1 e^2_\Omega - k_2 e^2_{iqp} - k_3 e^2_{idp} - k_4 e^2_{ids} - k_5 e^2_{iqs} + e_{iqp}(k_2 e_{iqp} + a_4 e_\Omega + \dot{I}_{qpc} - f_2 - \frac{1}{L_p} v_{qp}) \\ & + e_{idp}(k_3 e_{idp} + \dot{I}_{dpc} - f_1 - \frac{1}{L_p} v_{dp}) + e_{ids}(k_4 e_{ids} + \dot{I}_{dsc} - f_3 - \frac{1}{L_s} v_{ds}) + e_{iqs}(k_5 e_{iqs} + \dot{I}_{qsc} - f_4 - \frac{1}{L_s} v_{qs}) \end{aligned} \tag{20}$$

The derivative of the complete Lyapunov function Eq. (20) could be negative definite, if the quantities between parentheses in Eq. (20), would be chosen equal to zero.

$$\begin{cases} k_2 e_{iqp} + a_4 e_\Omega + (\dot{I}_{qp})_c - f_2 - \frac{1}{L_p} v_{qp} = 0 \\ k_3 e_{idp} + (\dot{I}_{dp})_c - f_1 - \frac{1}{L_p} v_{dp} = 0 \\ k_4 e_{ids} + (\dot{I}_{ds})_c - f_3 - \frac{1}{L_s} v_{ds} = 0 \\ k_5 e_{iqs} + (\dot{I}_{qs})_c - f_4 - \frac{1}{L_s} v_{qs} = 0 \end{cases} \tag{21}$$

The stator voltages then deduced as follows:

$$\begin{cases} v_{qp} = L_p\left(k_2 e_{iqp} + a_4 e_\Omega + (\dot{I}_{qp})_c - f_2\right) \\ v_{dp} = L_p\left(k_3 e_{idp} + (\dot{I}_{dp})_c - f_1\right) \\ v_{ds} = L_s\left(k_4 e_{ids} + (\dot{I}_{ds})_c - f_3\right) \\ v_{qs} = L_s\left(k_5 e_{iqs} + (\dot{I}_{qs})_c - f_4\right) \end{cases} \tag{22}$$

Where k_2, k_3, k_4 and k_5 are positive parameters selected to guarantee a faster dynamic of the stator current and rotor speed. Then, Eq. (16) is given by:

$$\begin{cases} \dot{e}_{iqp} = -k_2 e_{iqp} - a_4 e_\Omega \\ \dot{e}_{idp} = -k_3 e_{idp} \\ \dot{e}_{ids} = -k_4 e_{ids} \\ \dot{e}_{iqs} = -k_5 e_{iqs} \end{cases} \tag{23}$$

We can rearrange the dynamical equations from (14) and (23) as:

$$\begin{bmatrix} \dot{e}_\Omega \\ \dot{e}_{idp} \\ \dot{e}_{iqp} \\ \dot{e}_{ids} \\ \dot{e}_{iqs} \end{bmatrix} = \Re \begin{bmatrix} e_\Omega \\ e_{idp} \\ e_{iqp} \\ e_{ids} \\ e_{iqs} \end{bmatrix}$$

$$\begin{bmatrix} \dot{e}_\Omega \\ \dot{e}_{idp} \\ \dot{e}_{iqp} \\ \dot{e}_{ids} \\ \dot{e}_{iqs} \end{bmatrix} = \begin{bmatrix} -k_1 & 0 & a_4 & 0 & 0 \\ 0 & -k_3 & 0 & 0 & 0 \\ -a_4 & 0 & -k_2 & 0 & 0 \\ 0 & 0 & 0 & -k_4 & 0 \\ 0 & 0 & 0 & 0 & -k_5 \end{bmatrix} \begin{bmatrix} e_\Omega \\ e_{idp} \\ e_{iqp} \\ e_{ids} \\ e_{iqs} \end{bmatrix}$$

Where $\Re$ can be shown to be Hurwitz as a result of the matrix operation, this proves the boundedness of all the states.

The backstepping control block of a five-phase PMSM is shown in Fig.1.According to the vector control principle, the direct axis current I_{dp} in the (d_p, q_p) subspace and the direct and quadrature currents components I_{ds}, I_{qs} in the (d_s, q_s) subspace are forced to be zero to achieve maximum torque.The input of the backstepping control design is the speed error e_Ω which generates the q_p axis current reference $(I_{qp})_c$. Then, the stator voltages components $(v_{dp}, v_{qp}, v_{ds}, v_{qs})$ are generated according speed error and current errors as described as Eq.22.

4. RESULTS AND ANALYSIS

Figure 1 shows the backstepping control of the five-phase PMSM described in section 3. Simulations results are perfomated using Matlab/Simulink. Simulated results were obtained for a five-phase PMSM fed by a SVM voltage source inverter technique based on combining large and medium vectors. In order to confirm the effectiveness of the backstepping control, we propose to simulate the response of five-phase PMSM under the backstepping controller. The reference speed is chosen as a time ramp profile which is increased from standstill to rated value 157rad/s then it is reversed to reach -157rad/s and finally it is nullified. Figure 2(a) shows the actual and reference speed under the load torque disturbance to verify the speed tracking performance of the backstepping controller. It is clear that the rotor speed converges perfectly to its reference with high accuracy. The load torque suddenly applied to five-phase PMSM is 5N.m at 0.5s. The speed tracking response of the backstepping control strategy is zoomed in Figure 2(b).

It is clear that the rotor speed takes nearly 1ms to track the reference speed again. The speed error e_{Ω} and tracking errors $e_{iqp}, e_{idp}, e_{ids}$ and e_{iqs} are shown respectively in Figure 2(c), Figure 2(j), Figure 2(g) and Figure 2(j). It can be seen that the tracking errors remain at zero despite the load torque disturbance. Figure 2(e) shows the (d_p, q_p, d_s, q_s) stator current components. It is to be noted that the (d_p, d_s, q_s) stator current components are almost nulls even under the application of load torque. Figure 2(d) shows the electromagnetic torque whose profile is the same one of the q_p stator current component shown in Figure 2(e). Thus, it is clearly concluded that the backstepping control gives a high performances and good quality response.

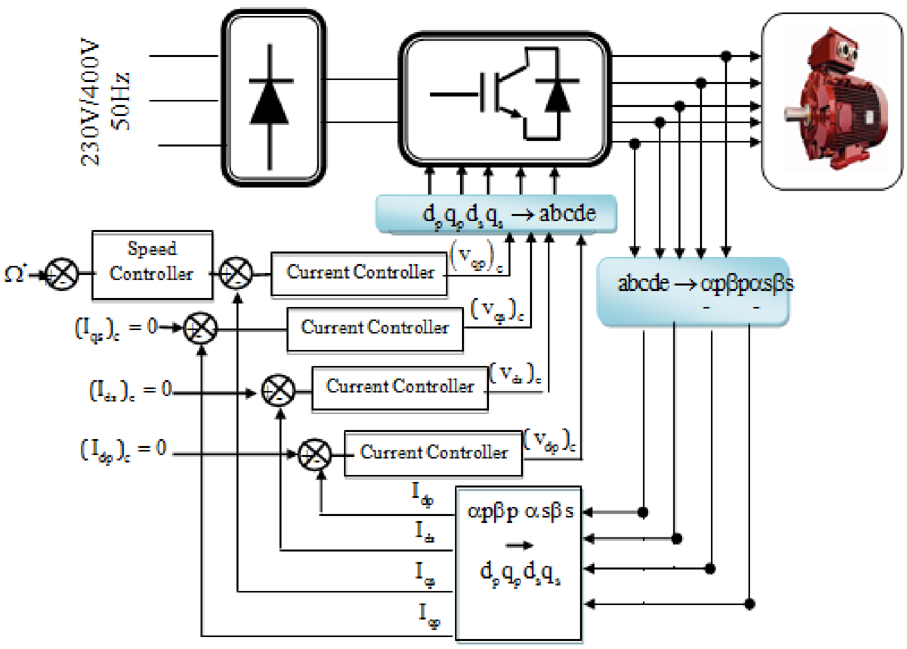
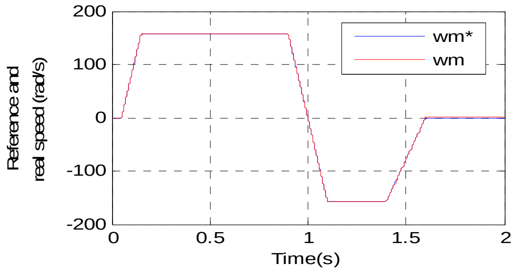
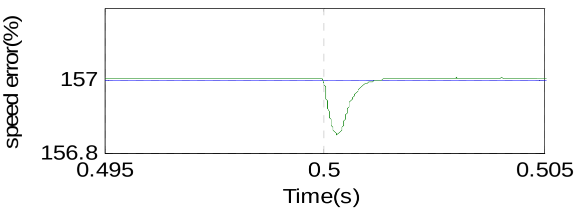


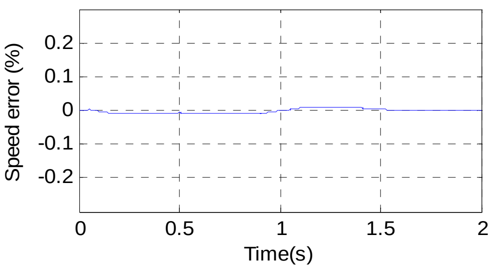
Figure 1. Block diagram of the Backstepping control structure of five-phase PMSM drive



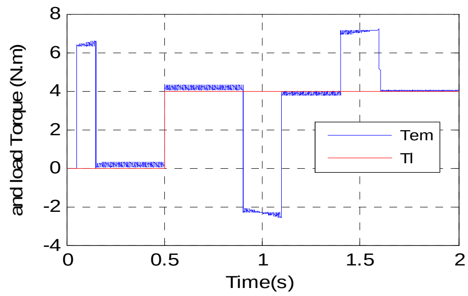
(a) Actual and reference speed



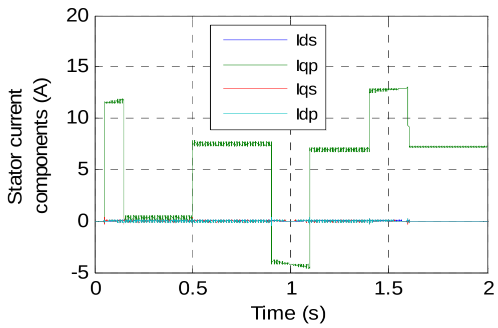
(b) Zoom around 0.5s



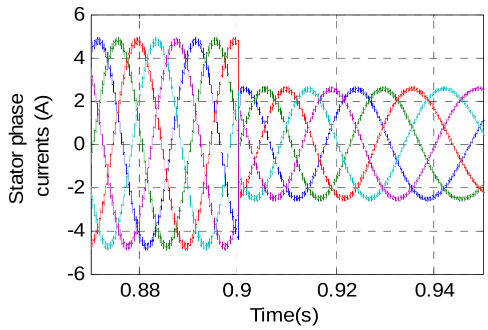
(c) Speed error (%)



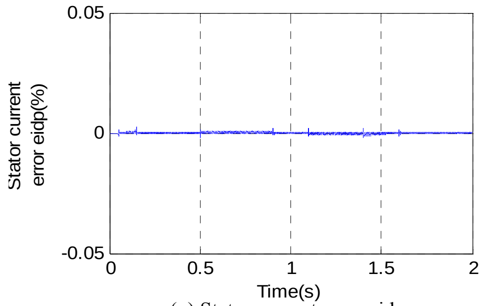
(d) Electromagnetic and load Torque



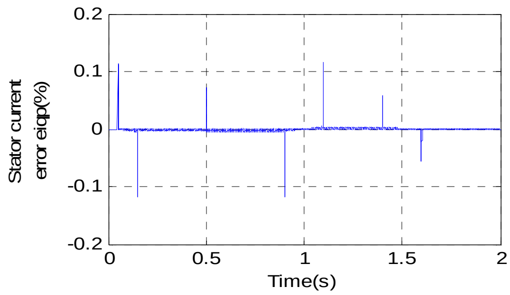
(e) Stator current components



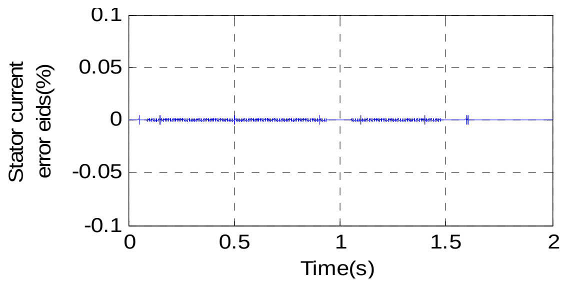
(f) Stator phase currents



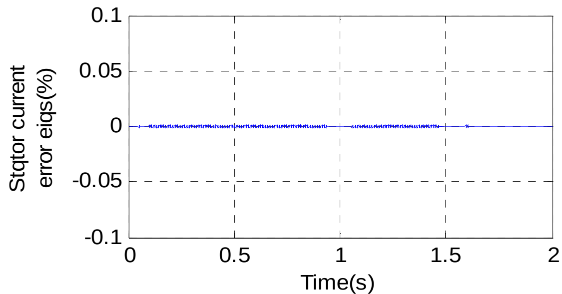
(g) Stator current error eidp



(h) Stator current error eiqp



(i) Stator current error eids



(j) Stator current error eiqs

Figure 2. Response of a five phase PMSM under the Backstepping control strategy

5. CONCLUSION

In this paper, we have developed a backstepping controller for a five phase PMSM. The stability of the proposed control strategy is proved by Lyapunov theory. Simulated results prove the effectiveness and the feasibility of the backstepping control strategy.

Table 1. Parameters of five-phase PMSM

R_S	1Ω
L_p	8e - 3H
J	$0.002Kg / m^2$
P	2
Φ_{max}	0.175T

NOMENCLATURE

R_s	Stator resistance
L_p	Inductance of the main fictitious machine
L_s	Inductance of the secondaryfictitious machine.
P	Number of pole pairs
ω_e	Electrical speed
Ω	Mechanical speed
Φ_{max}	Amplitude of magnet flux
p	Laplace operator
$I_{dp}, I_{qp}, I_{ds}, I_{qs}$	stator currents d_p, q_p, d_s, q_s axis compounds
$v_{dp}, v_{qp}, v_{ds}, v_{qs}$	stator voltages d_p, q_p, d_s, q_s axis compounds.
J	Inertia moment

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