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A simple and robust Speed Tracking Control of PMSM

***Abstract**. This paper presents a simple and robust speed control scheme of Permanent Magnet Synchronous Motor (PMSM). It is to achieve accurate control performance in the presence of load torque and plant parameter variation. A Kalman filter is used to estimate the rotor speed. A nonlinear backstepping control which is based on both feedback laws and Lyapunov theory is easily implemented on a PMSM driver using a TMS1103 DSP. The effectiveness of the proposed robust speed control approach is demonstrated by simulation and experimental results instructions*

***Streszczenie.** Artykuł przedstawia prosty i solidny system kontroli prędkości silnika synchronicznego z magnesem stałym (PMSM). Filtr Kalmana jest użyty aby oszacować prędkość wirnika. Nieliniowe sterowanieopiera się na wykorzystaniu sprzężenia zwrotnego. Układ opracowano przy użyciu procesora sygnałowego TMS1103 DSP. Eksperymentyy i symulacje potwierdziły skuteczność metody. (**Skuteczne sterowanie prędkością silnika synchronicznego z magnesem stałym**)*

Keywords: Permanent magnet synchronous motor, backstepping design, sensorless drive, Kalman filter, robustness.
Słowa kluczowe: silnik synchroniczny, filtr Kalmana, sterowanie napędem.

Introduction

Permanent magnet synchronous motors (PMSM) are frequently used in industrial applications. Especially their compact design, high efficiency, high power/weight and torque/inertia ratios can be shown as the most important advantages of PMSMs. On the other hand, the high cost and their time-varying magnetic characteristics are the disadvantages of PMSMs [1–3]. However, the performance is sensitive to the variation of motor parameters, especially the rotor time-constant, and the saturation of the magnetizing inductance. Recently, much attention has been given to the possibility of identifying the changes in motor parameters of PMSM while the drive is in normal operation. This stimulated a significant research activity to develop PMSM vector control algorithms using nonlinear control theory in order to improve performances, achieving speed and torque tracking [1, 2, 5]. All this, usually require shaft mounted sensors for variable speed applications [1-21. However, these mechanical sensors will increase the complexity and lower the reliability of the drive system. In recent years, mechanical sensorless drives have received a wide attention [2]. The basic idea for sensorless drive is to estimate motor speed and position through measured stator terminal quantities. Traditional methods of detecting induced electromotive forces or calculating the stator flux linkage may work well under some operating conditions [3-4]. In general the performance of drives using such methods will deteriorate at low speeds as the back FEM is embedded in the noises generated by PWM inverters. Extended Kalman filter which can take advantage of the system noises has been used for motor state estimation [6].

This paper has been divided into two main research areas; the first the extended Kalman filter is used to estimate the motor speed, off line and the second part describes the design and the implementation of a nonlinear backstepping control for the speed tracking control of PMSM that has exact model knowledge. The asymptotic stability of the resulting closed-loop system is guaranteed according to Lyapunov stability theorem. The proposed controller is adopted to derive the control scheme. The combination of the extended Kalman filter and the proposed nonlinear backstepping control makes it possible to enhance the performance of the sensorless drive.

In the following sections the dynamic model of the PMSM is introduced with some important system properties are presented. The development of the nonlinear backstepping controller design for PMSM speed control is described. The structure of the extended Kalman filter for this particular application is discussed. The performance of the sensorless drive is studied through computer simulation and experimented results. Finally, some conclusions are drawn.

Mathematical Model of the PMSM

The model of a typical PMSM can be described in the well known (d–q) frame through the Park transformation as follows: the stator d, q equations in the rotor frame are expressed as follows [1, 2, 5, 11, 12]:

$$u_d = R_s i_d + P\phi_d - \omega\phi_q \qquad (1)$$
$$u_q = R_s i_q + P\phi_q + \omega\phi_d$$

where

$$\phi_d = L_d i_d \qquad (2)$$

$$\phi_q = L_q i_q + \phi_f \qquad (3)$$

Thus the dynamic model of a surface-mounted PMSM can be described as follows:

$$\begin{aligned} L_d \frac{di_d}{dt} &= -R_s i_d + P\omega L_q i_q + u_d \\ L_q \frac{di_q}{dt} &= -R_s i_q + P\omega L_d i_d - P\phi_f \omega + u_q \\ J\frac{d\omega}{dt} &= T_e - f\omega - T_L \\ T_e &= \frac{3}{2}P\left(\left(L_d - L_q\right)i_d i_q + \phi_f i_q\right) \end{aligned} \qquad (4)$$

Where id and i_q are the d–q axis currents, u_d and u_q are the d–q axis voltages, R_s is the stator resistance, L_d, L_d are d- and q- axes inductances, is the stator inductor, P is the pole pairs, J is the rotor moment of inertia, f is the viscous friction coefficient, T_L is the load torque, ω is the rotor angle speed in angle frequency, ϕ_f is the rotor magnetic flux linking the stator.

According to the electromagnetic torque T_e of motor given in (4), it can be seen that the torque control can by achieved by regulation of currents i_d and i_q in closed loops. The proposed control system is designed to achieve speed tracking objective. Voltages inputs are designed in order to guarantees the convergence of $(i_d,\ i_q)$ to their desired trajectory (i_d^*, i_q^*) by choose $i_d^* = 0$.

Nonlinear Backstepping Design

The Backstepping is a systematic and recursive design methodology for nonlinear feedback control. This approach is based upon a systematic procedure for the design of feedback control strategies suitable for the design of a large class of feedback linearisable nonlinear systems exhibiting constant uncertainty, and it guarantees global regulation and tracking for the class of nonlinear systems transformable into the parametric-strict feedback form. The backstepping design alleviates some limitations of other approaches [5, 6, 7,10]. It offers a choice of design tools to accommodate uncertainties and nonlinearities and can avoid wasteful cancellations. The idea of backstepping design is to select recursively some appropriate functions of state variables as pseudo-control inputs for lower dimension subsystems of the overall system. Each backstepping stage results into a new pseudo-control design, expressed in terms of the pseudo-control designs from the preceding design stages. When the procedure terminates, a feedback design for the true control input results and achieves the original design objective by virtue of a Lyapunov function, which is formed by summing up the Lyapunov functions associated with each individual design stage [9, 10, 11, 12].

a) *Backstepping technique*

Consider the system :

(5) $$\dot{x} = f(x) + g(x)u \quad , \quad f(u) = 0$$

where $x \in R_n$ is the state and $u \in R_n$ is the control input. Let $u_{des} = \alpha(x)$, $\alpha(0) = 0$ be a desired feedback control law, which, if applied to the system in (11), guarantees global boundedness and regulation of $x(t)$ to the equilibrium point $x = 0$ as $t \to \infty$, for all $x(0)$ and $V(x)$ is a control Lyapunov function, where:

(6) $$\frac{\partial V(x)}{\partial x}\left[f(x) + g(x)\alpha(x)\right] < 0\, ,\ V(x) < 0$$

Consider the following cascade system :

(7) $$\dot{x} = f(x) + g(x)y \quad , \quad f(0) = 0$$

(8) $$\dot{\zeta} = m(x,\zeta) + \beta(x,\zeta)u \quad , \quad h(0) = 0$$

(9) $$y = h(x)$$

where for the system in (7), a desired feedback $\alpha(x)$ and a control Lyapunov function $V(x)$ are known. Then, using the nonlinear block backstepping theory in [13,], the error between the actual and the desired input for the system in (7) can be defined as $e = y - \alpha$, and an overall control Lyapunov function $V(x,\zeta)$ for the systems in (7) and (8) can be defined by augmenting a quadratic term in the error variable e with $V(x)$:

(10) $$V(x,\zeta) = V(x) + \frac{1}{2}e^2$$

Taking the derivative of both sides gives:

(11) $$\dot{V}(x,\zeta) = \dot{V}(x) + \dot{e}\,e$$

From which solving for $u(x,\zeta)$, which renders $\dot{V}(x,\zeta)$ negative definite, yields a feedback control law for the full system in (7-9). One particular choice is :

(12) $$u = \left(\frac{\partial h(\zeta)}{\partial \zeta}\beta(x,\zeta)\right)^{-1}\left\{-c(y-\alpha) - \frac{\partial h(\zeta)}{\partial \zeta}m(x,\zeta) + \right.$$
$$\left. + \frac{\partial \alpha(x)}{\partial x}\dot{x} - \frac{\partial V(x)}{\partial x}g(x)\right\}, c > 0$$

b) *Application to PMSM*

In order to track the speed of PMSM, we employ the nonlinear backstepping design controller with the choice of appropriate regulated variables. The backstepping design procedure consists of the following steps:

Step 1: Direct current controller:

Let us define the direct current error as:

$e_d = i_d^* - i_d$ and the derivative according to the time as $\dot{e}_d = \dot{i}_d^* - \dot{i}_d$

Than accounting equation (4) implies:

(13) $$\dot{e}_d = -\dot{i}_d = \frac{1}{L_d}\left(R_s i_d - P\omega L_q i_q - u_d\right)$$

The Lyapunov candidate function given as:

(14) $$V_1 = \frac{1}{2}e_d^2$$

If this function is always positive (this is the case now) and its derivative is always negative, then the error will be stable and tend towards zero. The derivative of the function is written as $\dot{V}_1 = \dot{e}_d\, e_d$. In order that the derivative of the test is still negative, it must take the derivative of the form $V_1 = -K_1 e_d^2$ where K_1 is a positive design parameter introduced by the backstepping method, which must always be positive and nonzero to meet the stability criteria of Lyapunov function. In addition, this parameter can influence the dynamics of regulation. It is connected to the energy loss of the system. Thus the virtual control is asymptotically stable.

(15) $$\dot{V}_1 = -K_1 e_d^2 + e_d\left(K_1 e_d - \frac{1}{L_d}\left(R_s i_d - P\omega L_q i_q - u_d\right)\right)$$

In order to have:

$\dot{V}_1 = -K_1 e_d^2 \le 0$ (Semi-defined negative) it must be:

(16) $$K_1 e_d - \frac{1}{L_d}\left(R_s i_d - P\omega L_q i_q - u_d\right) = 0$$

with: $K_1 > 0$ We obtain:

(17) $$u_d = L_d\left(K_1 e_d + \frac{R_s}{L_d}i_d - \frac{P\omega L_q}{L_d}i_q\right)$$

Step 2: Speed tracking error:

For the PMSM system, the control objectives is mainly the location tracking. The definition of tracking error is as follows:

(18) $$e_\omega = \omega^* - \omega$$

Assuming that ω is the second-order differential function and by choosing ω^* the equilibrium point. Deriving e_ω according to the time as:

(19) $$\dot{e}_\omega = \dot{\omega}^* - \dot{\omega}$$

In order to make the speed tracking error tends to zero, Lyapunov function is constructed for the subsystem (19)

(20) $$V_2 = \frac{1}{2}e_\omega^2$$

The derivative of type (13) is as follows:

(21) $$\dot{V}_2 = e_\omega\,\dot{e}_\omega = e_\omega(-\dot{\omega})$$

In order to make $\dot{V}_2 < 0$ the simple solution is by choosing:

(22) $$\dot{e}_\omega = -K_2 e_\omega$$

Assumed control function from the equation (22) is as follow:

(23) $$\dot{e}_\omega = \frac{f}{J}\omega + \frac{1}{J}T_L - \frac{3}{2J}P\left(\left(L_d - L_q\right)i_d i_q + \phi_f i_q\right)$$

So that $\dot{V}_2 = -K_2 e_\omega^2 \le 0$ is realized, which can achieve global asymptotic speed tracking.

Consequently:

(24) $$\dot{V}_2 = e_\omega\left(\frac{f}{J}\omega_r + \frac{1}{J}T_L - \frac{3}{2J}P\left(\left(L_d - L_q\right)i_d i_q + \phi_f i_q\right)\right)$$

Step 3: Quadratic current error

In practice, the quadratic current i_q is not equal to the desired value. Let us define the quadratic current error as:

$$e_q = i_q^* - i_q$$

the derivative according to the time as

$$\dot{e}_q = \dot{i}_q^* - \dot{i}_q .$$

The equations (24) indicate what the virtual controls should be that in order to satisfy our control objectives. So they provide references for the next step of the Backstepping design, which is essentially to make the signal i_q^* behave as desired. So we define again error signal involving the desired variable, restructure a new Lyapunov function:

$$V_3 = \frac{1}{2} e_q^2 .$$

Considering equ. 1 and equ.26 :

$$\dot{e}_q = \frac{2}{3p\varphi_f}\left(K_1 J \dot{e}_1 + f\ \dot{\omega}\right) + \frac{R}{L_q} i_q + P\ \omega \frac{\phi_f}{L_q} + P\ \omega \frac{L_d}{L_q} i_q - \frac{1}{L_q} u_q \tag{25}$$

Therefore the desired quadratic current i_q^*

$$i_q^* = \frac{2J}{3p\phi_f}\left(K_2 e_\omega + \frac{f}{J}\omega_r + \frac{1}{J} T_L\right) \tag{26}$$

At last we extend the Lyapunov function to include all the errors: $V_T = V_2 + V_3$ and its time derivative as:

$\dot{V}_T = \dot{V}_2 + \dot{V}_3$.

$$\dot{V}_T = -K_1 e_d^2 - K_2 e_\omega^2 - K_3 e_q^2 + e_q\left(K_3 e_q + \frac{2}{3p\phi_f}\left(K_2 J + f\right)\dot{\omega} + \frac{R}{L_q} i_q + p\omega \frac{L_d}{L_q} i_q + \frac{1}{L_q} u_q + p\,\omega \frac{\phi_f}{L_q}\right) \tag{27}$$

At last, in order to make the derivative of the Lyapunov function $\dot{V}_T \le 0$ the q-axis voltage control input can be found by choosing, with : $K3 > 0$.

$$\left(K_3 e_q + \frac{2}{3p\phi_f}\left(-K_2 J + f\right)\left(-\frac{f}{J}\omega - \frac{1}{J}T_L + \frac{3}{2}p\frac{\phi_f}{J} i_q\right) + \frac{R}{L_q} i_q + p\,\omega \frac{L_d}{L_q} i_q + p\,\omega \frac{\phi_f}{L_q} + \frac{1}{L_q} u_q\right) = 0 \tag{28}$$

From the above we can obtain the control laws as:

$$u_q = L_q\left(K_3 e_q + \frac{2}{3p\phi_f}\left(-K_2 J + f\right)\left(-\frac{f}{J}\omega - \frac{1}{J}T_L + \frac{3}{2}p\frac{\phi_f}{J} i_q\right) + \frac{R}{L_q} i_q + p\,\omega \frac{L_d}{L_q} i_q + p\,\omega \frac{\phi_f}{L_q}\right) \tag{29}$$

So it implies that the resulting closed loop system is asymptotically stable and, hence, all the variable errors e_d, e_q and e_ω will converge to zero asymptotically. There for the id current will converge to its reference ($i_d = 0$) and the speed will converge also at its reference. As result, the desired control objective of speed tracking for the PMSM is indeed achieved by the proposed nonlinear backstepping control scheme.

Extended Kalman Filter Observer for PMSM

Now the extended Kalman filter observer will be applied to estimate the rotor speed which is feedback controlled by the previous exposed strategy of backstepping control. The EKF observer is based on the error of the stator currents generated from their measured and estimated values which must be converged toward zero via defined design.

The EKF has been described in many papers and is summarized in this section [16,17]. State equations for PMSM can be written as (31).

$$\begin{aligned} \dot{x} &= g(x,u) + w \\ y &= c.x + v \end{aligned} \tag{30}$$

Here

$$x = \begin{bmatrix} I_d & I_q & \omega & \theta \end{bmatrix},\ u = \begin{bmatrix} u_d & u_q \end{bmatrix} \qquad C = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix},\ y = \begin{bmatrix} I_d \\ I_q \end{bmatrix} \tag{31}$$

w and v are random disturbances. In fact w is the process noise which stands for the errors of the parameters; v is the measurement noise which stands for the errors in the measurement and sample. The noise covariance matrixes are defined as follows:

$$\begin{aligned} Q &= \mathrm{cov}(w) = E\left\{ww^T\right\} \\ R &= \mathrm{cov}(v) = E\left\{vv^T\right\} \end{aligned} \tag{32}$$

Kalman filter can be built by this follow derivation:

$$x(k+1) = f = \begin{cases} I_d(k) + \left(\dfrac{U_d}{L_d} - \dfrac{R.I_d}{L_d} + \omega \dfrac{L_q}{L_d} I_q\right) T_e \\ I_q(k) + \left(\dfrac{U_q}{L_q} - \dfrac{R.I_q}{L_q} - \omega \dfrac{L_d}{L_q} I_d - \omega \dfrac{\phi_f}{L_q}\right) T_e \\ \omega(k) \\ \theta(k) + \omega.T_e \end{cases} \tag{33}$$

Define matrix F *and* H *as*:

$$F = \frac{\partial f}{\partial x} = \begin{bmatrix} 1 - \dfrac{T_e}{\tau_d} & T_e \omega \dfrac{L_q}{L_d} & T_e \dfrac{L_q}{L_d} I_q & T_e \dfrac{u_d}{L_d} \\ -T_e \omega \dfrac{L_d}{L_q} & 1 - \dfrac{T_e}{\tau_q} & T_e\left(-\dfrac{L_d}{L_q} I_d - \dfrac{\phi_f}{L_q}\right) & T_e \dfrac{u_q}{L_q} \\ 0 & 0 & 1 & 0 \\ 0 & 0 & T_e & 1 \end{bmatrix} \tag{34}$$

$$h = \begin{bmatrix} i_d \\ i_q \end{bmatrix} \quad ; \quad H = \frac{\partial h}{\partial x} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \end{bmatrix} \tag{35}$$

$\tau_d = \dfrac{L_d}{R}, \tau_q = \dfrac{L_q}{R}$ are stator constants.

Extended Kalman filter can be realized by iteration as follows:

After deciding how to initialize the covariance matrices, the next step is prediction of the state vector at sampling time ($k+1$) from the input $u(k)$, state vector at previous sampling time, $x_{k|k}$:

$$\hat{x}_{k+1|k} = \hat{x}_{k|k} + \dot{x}.T_e \tag{36}$$

The notation $xk|k$ means that it is a predicted value at the $(k+1)th$ instant, and it is based on measurements up to k-th instant. In the following step of the recursive EKF computation, covariance matrix of prediction is computed.

$$P_{k+1|k} = F_{k|k}.P_{k|k}.F_{k|k}^T + Q_k \tag{37}$$

In the second stage which is the filtering stage, the next estimated states $\hat{x}_{k+1}$, are obtained from the predicted estimates x_{k+1} by adding a correction term $K(y-\hat{y})$ to the predicted value. This correction term is a weighted difference between the actual output vector *(y)* and the predicted output vector $(\hat{y})$, where K is the Kalman gain.

Next step is the computation of the Kalman filter gain matrix as:

(38) $$K_k = P_{k+1|k} C^T . \left(C.P_{k+1|k} C^T + R_k\right)^{-1}$$

The predicted state-vector is added to the innovation term multiplied by Kalman gain to compute state-estimation vector. The state-vector estimation (filtering) at time (k) is determined as:

(39) $$\hat{x}_{k+1|k+1} = \hat{x}_{k+1|k} + K_{k+1}\left(y_{k+1} . C.\hat{x}_{k+1|k}\right)$$

where

$$y_{k+1} = C.x_{k+1|k}$$

Here we define the estimation covariance computation as:

(40) $$P_{k+1|k+1} = \left[I - K_{k+1}.C\right].P_{k+1|k}$$

This observer can be constituted from the PMSM model.

The choice of the initial values for the matrices P, Q and R is very important for the EKF. Generally, $P_{0|0}$ determines the initial transient characteristics of the filter, but has little influence on the initial tuning procedure of the EKF. Since the algorithm does not require initial rotor position information and the motor is assumed to start from the standstill, the initial state vector $x_{0|0}$ is considered to be a null vector. Based on the discussion given by [Bolognani] after the trial-and-error procedure, initial values for the states and matrices P, Q and R were selected as follow:

$$\hat{x}_{0/0} = \begin{bmatrix} i_d \\ i_q \\ \omega \\ \theta \end{bmatrix} = \begin{bmatrix} 0 \\ 0 \\ 0 \\ 0 \end{bmatrix} ; P_{0/0} = \begin{bmatrix} 0.1 & 0 & 0 & 0 \\ 0 & 0.1 & 0 & 0 \\ 0 & 0 & 100 & 0 \\ 0 & 0 & 0 & 10 \end{bmatrix}$$

$$Q = \begin{bmatrix} 100 & 0 & 0 & 0 \\ 0 & 100 & 0 & 0 \\ 0 & 0 & 1000 & 0 \\ 0 & 0 & 0 & 0.01 \end{bmatrix} ; R = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix}$$

Based on the EKF and the Nonlinear Backstepping control, the proposed sensorless speed control of a PMSM is shown in Fig1. As depicted the proposed backstepping regulator compares the reference ω^* with speed ω_{est}, calculated with

the estimated speed given by Kalman filter and it is delivers as output the voltage reference v_q^* The direct current i_d is controlled to be zero (i_d^*) which can get the largest torque with the smallest phase current.

Experimental result

The performance of a PMS motor drive system under the proposed sensorless backstepping control, has been evaluated by computer simulation using Matlab/Simulink software.

The validity of the proposed control is confirmed by experimental data. The test PMS motor and inverter used for our experiment based DSPACE is a hardware test platform to validate control algorithm, it contains board, when the system is running, the control algorithm is download through the real-time RTI I/O interface with Matlab/Simulink link to the dSPACE which communicated with exterior hardware, because the controller has many parameters, we need make several experiments off line to optimize the parameters.

The speed tracking controller operated in a critical situation of benchmark commands rapidly changes as 200 – 1000 – 0 (tr/mn) areshowed in figure 2. The actual speed converges with reference speed in very short time with a negligible overshoot and no steady state error (h) and converges to the reference speed. It can be observed with the Zoomed response of case (e) that the speed response of the backstepping controller present better tracking characteristics. We can see that when the d axis current is set to zero (d), that is the PMSM is not running under weaken flux condition, with the proposed speed controller, the system can track the reference speed rapidly such as the both 200 rpm and 0 rpm, but still exists larger ripple when the speed large step occurs 1000 rpm.

Through these experimental results, we conclude that the proposed controller and estimation scheme of the speed yields adequately good results.

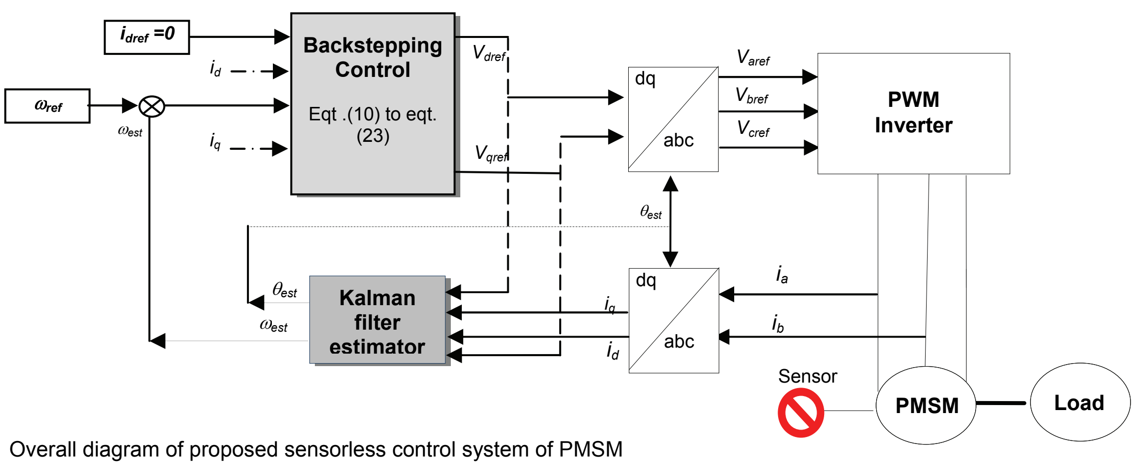

Fig. 1: Overall diagram of proposed sensorless control system of PMSM

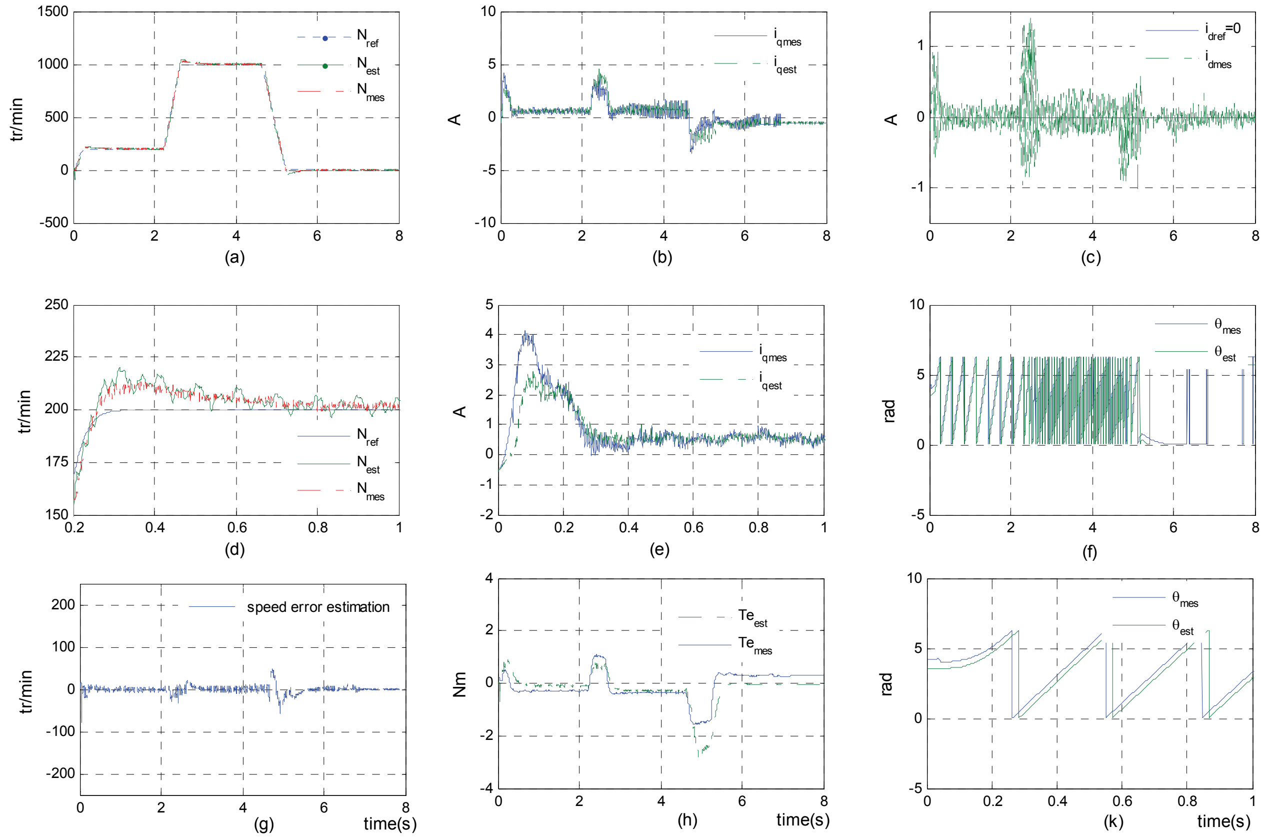

Fig. 2. Experimental results showing as follow:

(a) The speed reference (N_{ref})the actual rotor speed (N_{mes}), and its estimate (N_{est}) and the figure zoom shows at (d).

(b) The q components of the estimated stator current (i_{qest}) and actual inverter current (i_{qmes}) and the figure zoom shows at (e).

(c) The d components of the reference stator current (i_{dref}) and actual inverter current (i_{dmes}).

(f) The estimation rotor position (θ_{est}) and the actual rotor position (θ_{mes}) and the figure zoom shows at (k).

(g) The error speed estimation ($e_N = N_{mes} - N_{est}$)

(h) The estimated electromagnetic torque (Te_{est}) and actual electromagnetic torque (Te_{mes})

Conclusion

In this paper, a backstepping control scheme combined with kalman filter to control and estimate speed tracking PMSM in order to offer a choice of design tools to accommodate uncertainties and nonlinearities. This study has successfully demonstrated the design of the backstepping control for the speed control of a permanent magnet synchronous motor . The control laws were derived based on the motor model. By recursive manner, virtual control states of the PMSM drive have been identified and stabilizing laws are developed subsequently using Lyapunov stability theory. The performance of the proposed controller has been investigated in experimental plate using dSpace environments. The different results show its effectiveness and robustness at tracking a reference speed under critical situation of benchmark commands rapidly changes.

Annex 1

Table 1. PMSM system parameters

$L_d = L_q$ =1.45 mH	P_{rated} = 1.1KW
R = 1.67 Ω	V = 260V
J = 0.013 kgm^2	I_{rated} = 5.9A
B = 0.013Nm/rad/s	f = 50Hz
Φ_f = 0.17 Wb	P = 3

Annex 2

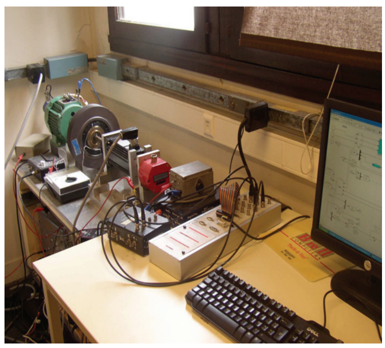

Fig.3 Test photo

Acknowledgements

This work was done on a research in collaboration with Mr . Damba Diallo, Mr. Mickael Hilairet and Mr. Ahmad Akrad Members at LGEP /SPEE Labs; Supelec, University Paris-Sud .

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