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Nonlinear Feedback Linearization and Observation Algorithm for Control of a Permanent Magnet Synchronous Machine

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ABSTRACT

The aim of this study is to present a high dynamic current control and speed estimation strategy for Permanent Magnet Synchronous Motor (PMSM) drives without a speed transducer. The strategy is based on the exact linearization methodology and Extended Sliding Mode Observer (ESMO) algorithm. The performances of the proposed control strategy are analysed by simulations for a 1.6 kW PMSM. The obtained results show the effectiveness of the proposed robust current control approach and speed observation algorithm under load torque and stator resistance variation.

Key words: PMSM, extended sliding mode observer, nonlinear control

INTRODUCTION

AC Motors are divided into two types, Synchronous Motor (SM) and Induction Motor (IM). The nonlinear dynamic behaviour of these AC Motors induces the use of the robust feedback linearization control in order to assure a good performance and stability of the global system with respect to parameters variations (specifically resistance variation). However, as this feedback control requires the knowledge of certain variables (speed, torque) that are difficult to measure, an observer for estimation of these variables is necessary. Many results using a feedback linearization and observation approach for the control of an Induction Motor have been published (Asseu *et al.*, 2008; Asseu *et al.*, 2010). In this study, we revisit and use the feedback linearization algorithm and Observation technique to control a synchronous motor (Li and Li, 2006; Poulain *et al.*, 2008).

The class of synchronous machines is comprised of PMSM and wound SM. In recent years, PMSM are widely used in low and mid power applications such as computer peripheral equipments, robotics and adjustable speed drives. The high efficiency and simple controller of the PMSM drives (Dehkordi *et al.*, 2005; Xu and Gao, 2004) compared with the IM make them a good alternative in certain applications namely automobiles and aerospace technology.

Because of these advantages (high power density and reliability), PMSM are indeed excellent for use in high-performance servo drives where a fast and accurate torque response is required.

The central idea of this study consists in, on the one hand, to design a robust nonlinear control strategy in order to decouple and independently control the stator currents of the PMSM in a synchronous reference (d, q) frame and on the other hand, to determine an extended observer allowing an on-line estimation of rotor speed under the stator resistance variation. Note that a variation of the stator resistance (which varies with the temperature or the magnetic state and in the presence of disturbances) can induce an instability and degradation of the system.

For the parameter observation, the Extended Kalman Filter (Murat *et al.*, 2007; Blanchard *et al.*, 2007; Xi *et al.*, 2006), can be used for real-time estimation of rotor speed and stator resistance. Unfortunately, the initialization and the optimal choice of covariance and gain matrix are delicate, complex and require large computational demand in terms of CPU time and memory. Thus for the parameters estimation, this work uses a sliding mode observer (Ilioudis and Margaris, 2008; Asseu *et al.*, 2009) which, compared with the Kalman Filter, presents some gains easily adjusting and a simple algorithm.

Simulations results are presented to confirm the superior performances of our proposed theoretical findings.

Physical model of the PMSM: This research project, conducted in the Laboratory of Applied Electrical and Electronic (INPHB Yamoussoukro, Côte d'Ivoire) from February 2010 to August 2010 by a theoretical work, has been confirmed by simulations results for a 1.6 kW PMSM.

By assuming that the saturation of the magnetic parts and the hysteresis phenomenon are neglected, the electrical and mechanical equations of the PMSM in the rotor reference (d, q) frame are as follows (Pillay and Krishnan, 1988):

$$\begin{cases} V_d = R_s.I_d + L_d \dfrac{dI_d}{dt} - S_q \\ V_q = R_s.I_q + L_q \dfrac{dI_q}{dt} + S_d \end{cases} \quad \text{with} \quad \begin{cases} S_q = \omega_r.L_q.I_q \\ S_d = \omega_r.L_d.I_d + ?_r.F_f \end{cases} \tag{1}$$

The equation for the motor dynamics is:

$$J\frac{d\Omega}{dt} = T_{em} - T_L - f.\Omega \quad \text{where} \quad T_{em} = p.\left[\Phi_f.I_q + (L_d - L_q).I_d.I_q\right] \quad \text{and} \quad \omega_r = p.\Omega \tag{2}$$

Equivalent circuits of the motors are used for study and simulation of motors. From the (d, q) modeling of the motor using the stator voltage equations (Eq. 1), the equivalent circuit of the PMSM (Merzoug and Benalla, 2010) can be modeled by Fig. 1.

From Eq. 1, it is obvious that the dynamic model of PMSM is nonlinear because of the coupling between the speed and the electrical currents. By considering the case of a smooth-air-gap PMSM (Loria, 2009) (where the stator inductances are equal: $L_d = L_q$) and according to the field oriented principle where the direct axis current I_d is always forced to be zero which simplifies the dynamics and achieve maximum electromagnetic torque per ampere (in this condition $T_{em} = p.\Phi_f.I_q$), the PMSM model can be rewritten as follows:

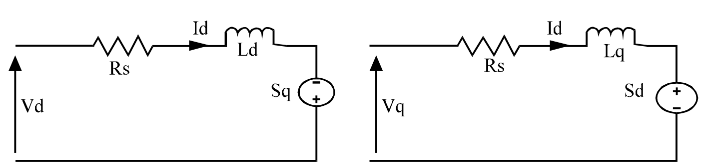

Fig. 1: PMSM equivalent circuit from dynamic equations

$$\begin{cases} \dot{X} = F(X) + G.U \\ Y = H(X) = [h_1(X) \;\; h_2(X)]^T = [I_d \;\; I_q]^T \end{cases} \tag{3}$$

with $X = [\ I_d\ I_q\ \Omega]^T$, $U = [\ V_d\ V_q\ ]^T$

$$F(X) = \begin{bmatrix} f_1(X) \\ f_2(X) \\ f_3(X) \end{bmatrix} = \begin{bmatrix} -\frac{R_s}{L_d} I_d + \frac{L_q}{L_d} p.I_q.\Omega \\ -\frac{R_s}{L_q} I_q - \frac{L_d}{L_q} p.I_d.\Omega - \frac{p.\Phi_f}{L_q}\Omega \\ -\frac{f}{J}.\Omega + \frac{p.F_f}{J} I_q - \frac{T_L}{J} \end{bmatrix}; \quad G = \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \\ 0 & 0 \end{bmatrix} = \begin{bmatrix} g_1 & 0 \\ 0 & g_2 \\ 0 & 0 \end{bmatrix}$$

Robust input-output linearization via feedback for a nonlinear system: The central idea of this section is to analyze the synthesis of feedback control for the nonlinear dynamic model of the PMSM given by the system Eq. 3. Thus, in order to control independently the currents (I_d, I_q) and then preserve the robustness performance and stability of the system under parameters variation (in particular the stator resistance variations) a robust input-output linearization approach, proposed by Marino *et al*. (2006), can be used for the system Eq. 3.

Therefore, we can see that the system Eq. 3 has relative degree $r_1 = r_2 = 1$ and can be transformed into a linear and controllable system by chosen:

An appropriate change of coordinates given by:

$$z_1 = h_1(x);\ z_2 = h_2\ (x) \text{ with } \dot{z}_1 = v_1\ ,\ \ \dot{z}_2 = v_2$$

where, $[v_1,\ \ v_2]^T$ are the new input vector of the obtained decoupled systems the feedback linearization control having the following form:

$$u = \begin{bmatrix} L_g h_1(x) & 0 \\ 0 & L_g h_2(x) \end{bmatrix}^{-1} \cdot \begin{bmatrix} v_1 - L_f h_1(x) \\ v_2 - L_f h_2(x) \end{bmatrix} = \begin{bmatrix} \frac{1}{L_q} & 0 \\ 0 & \frac{1}{L_d} \end{bmatrix}^{-1} \begin{bmatrix} v_1 - f_1 \\ v_2 - f_2 \end{bmatrix} \tag{4}$$

and two robust controllers C(s) defined by:

$$C(s) = \frac{R(s).H(s)^{-1}}{1 - R(s)} \quad \text{with} \quad R(s) = \frac{1}{(1 + t_0 s)^2} \quad \text{and} \quad H(s) = \frac{1}{1 + T\,s} \tag{5}$$

where, the real t_0 is an adjusting positive parameter. The block diagram structure for the control of (I_d, I_q) is shown in Fig. 2.

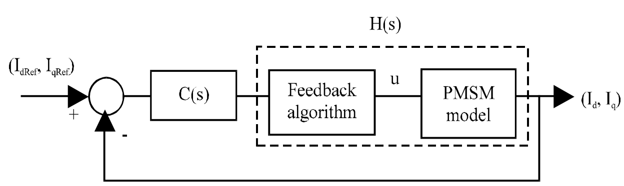

Fig. 2: Proposed currents control scheme

However, the control of a PMSM generally required the knowledge of the instantaneous speed of the rotor that is not measurable. Also, a variation of the stator resistance can induce a lack of field orientation. In order to achieve better dynamic performance, an on-line estimation of rotor speed and stator resistance is necessary. Here an ESMO is designed for on-line estimation of currents (I_d, I_q), torque (T_{em}), speed (ω_r) and stator resistance (R_s).

Extended Sliding Mode Observer (ESMO): Assume that among the state variable given by the system Eq.3, only the stator currents (I_d, I_q) noted (z_1, z_2) are measurable. Denote ($\hat{x}_1$,$\hat{x}_2$) the estimates of the rotor speed and stator resistance (ω_r, R_s). Consider that $\hat{z}_1$ and $\hat{z}_2$ are the estimates of the stator currents I_d and I_q. Thus, the proposed ESMO is a copy of the model Eq. 3 extended to the stator resistance equation and by adding corrector gains with switching terms (Asseu *et al.*, 2008):

$$\dot{\hat{X}}_e = Q\left(\hat{X}_e, U\right) + K.J_s \text{ with } \hat{X}_e = \left[\hat{I}_d\ \hat{I}_q\ \hat{?}_r\ \hat{R}_s\right]^T = \left[\hat{z}_1\ \hat{z}_2\ \hat{x}_1\ \hat{x}_2\right]^T$$

$$Q(\hat{X}_e,U) = \begin{pmatrix} -\dfrac{\hat{x}_2}{L_d}.z_1 + p.\hat{x}_1.z_2 + \dfrac{V_d}{L_d} \\ -p.\hat{x}_1.z_1 - \dfrac{\hat{x}_2}{L_q}.z_2 - \dfrac{p.\Phi_f}{L_q}.\hat{x}_1 + \dfrac{V_q}{L_q} \\ \dfrac{p.\Phi_f}{J}z_2 - \dfrac{f}{J}.\hat{x}_1 - \dfrac{T_L}{J} \\ \varepsilon \end{pmatrix} \tag{6}$$

where, ϵ is the slow variation of R_s and The switching Js is defined as:

$$J_s = \begin{bmatrix} \text{sign}(M_1) \\ \text{sign}(M_2) \end{bmatrix} \quad \text{with} \quad \begin{bmatrix} M_1 \\ M_2 \end{bmatrix} = \begin{bmatrix} p.z_2 & 0 \\ 0 & -(p.z_1 + \dfrac{p.\Phi_f}{L_q}) \end{bmatrix}^{-1} \begin{bmatrix} z_1 - \hat{z}_1 \\ z_2 - \hat{z}_2 \end{bmatrix} \tag{7}$$

In order to satisfy and verify the convergence condition for the system Eq. 6, the observer gain matrices K_1, K_2, K_3 and K_4 can be chosen by:

$$K = \begin{bmatrix} K_1 \\ K_2 \\ K_3 \\ K_4 \end{bmatrix} = \begin{bmatrix} p.z_2 & 0 \\ 0 & -(p.z_1 + \dfrac{p.\Phi_f}{L_q}) \\ q - \dfrac{f}{J} & 0 \\ 0 & q \end{bmatrix} \Delta;\ \Delta = \begin{bmatrix} n & 0 \\ 0 & n \end{bmatrix} \tag{8}$$

In order to implement the control algorithm in a DSP for real-time applications, the proposed ESMO must be discretized using Euler approximation (1st order). Thus the Discrete-time Extended Sliding Mode Observer (DESMO) is given by:

$$\hat{X}_e(k+1) = \hat{X}_e(k) + T_e.Q\left(\hat{X}_e(k), U(k)\right) + K(k).J_s(k) \tag{9}$$

where t = k.Te with T_e the sampling period and

$$\hat{X}_e(k) = \left[\hat{I}_d(k)\ \hat{I}_q(k)\ ?_r(k)\ \hat{R}_s(k)\right]^T$$

From the expressions defined in Eq.8, it can be seen that there are two positive adjusting gains: q and n which play a critical role in the potential stability of the scheme with respect to stator resistance estimation. These two adjusting gains must be chosen so that the estimator (Eq. 9) satisfies robustness properties, global or local stability, good accuracy and considerable rapidity.

RESULTS

We have used SIMULINK software of MATLAB to test in simulations the performance of the proposed DESMO algorithm, controlled by a robust feedback linearization technique (Fig. 3). The simulation tests are applied for a 1.6 kW PMSM which its parameters (Table 1) were determined using a least-squares identification procedure (Bodson *et al.*, 1993).

In order to illustrate the robustness of the nonlinear control and speed observer algorithm, the comparisons between the estimated state variables and the simulated ones have been performed for investigating the effectiveness of the proposed control scheme in the presence of stator resistance variation and a load torque (T_l = 1.5 N m).

Thus, the simulations are obtained at first in the nominal case with the parameters of the PMSM (Table 1) and then in the second case, with 50% variation of the nominal stator resistance ($R_s = 1.5R_{sn}$) in order to verify the behavior of the proposed DESMO algorithms with respect to stator resistance variation.

The two positive gains (q and n) must be adequately tuned in order to have a good performance, convergence and considerable rapidity of our proposed Feedback control and DESMO strategy.

The DESMO algorithm is initialized as follows: Te = 1 ms, q = 5.10^3 and n = 10^{-6}.

Simulation results: Figure 4 and 5 show the simulation results for a step input of the currents (I_{dRef} and I_{qRef}). One can see that in both nominal (Fig. 4) and non-nominal cases (Fig. 5), the

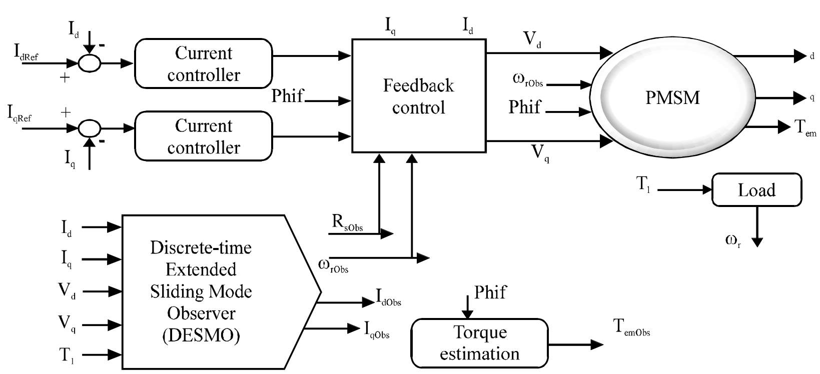

Fig. 3: Simulation scheme

Table 1: Nominal parameters of the PMSM

P_{mn} = 1.6 kW	U_n = 220/380 V	f_n = 0.0162 N m sec rad^{-1}
p = 3	Ω_n = 1000 rpm	J_n = 0.0049 kg m^2
R_{sn} = 2.06 Ω	$Phif_n$ = 0.29 Wb	$L_{qn} = L_{dn}$ = 9.15 mH

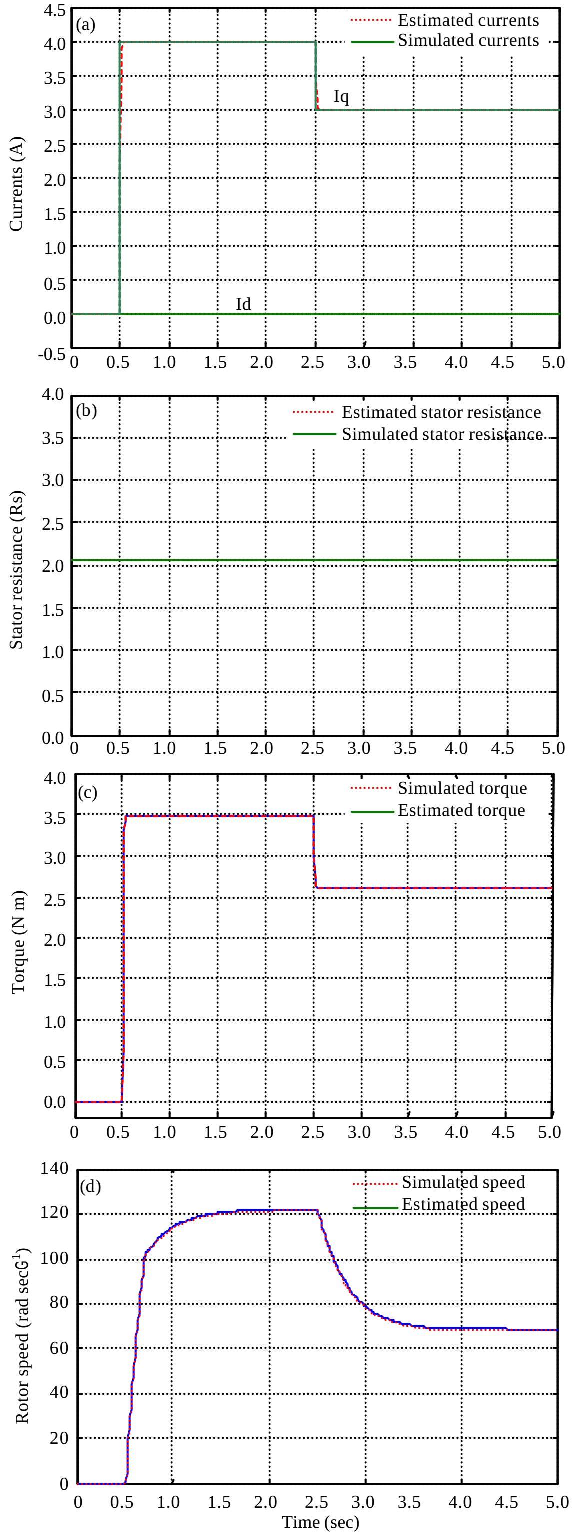

Fig. 4: (a-d) Nominal case ($R_s = R_{sn}$): Comparison between estimated and simulated values

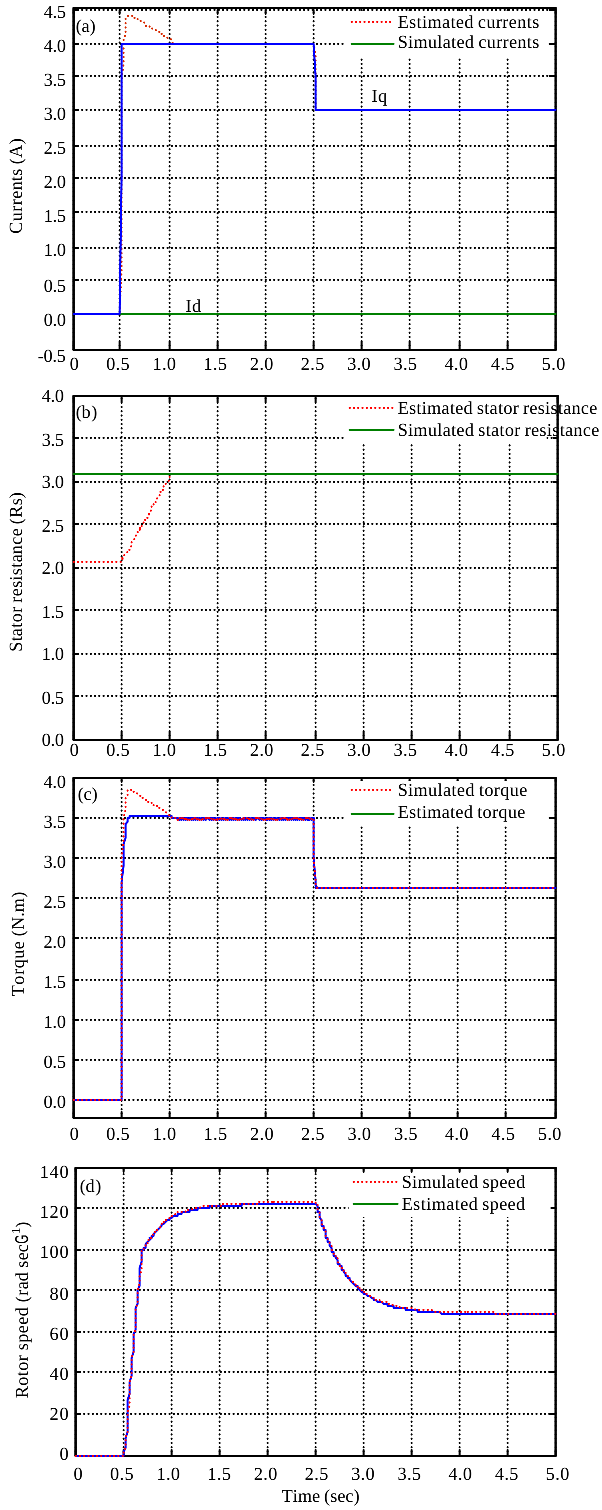

Fig. 5: (a-d) Non Nominal case ($R_s = 1.5R_{sn}$): Comparison between estimated and simulated values

estimated values of currents, rotor speed and torque converge very well to their simulated values due to the good stator resistance estimation.

Figure 4 and 5 indicate a good regulation, uncoupling and fast convergence between the stator currents (I_d and I_q) due to an excellent choice of the robust controllers C(s) given by the equation Eq. 5 and placed in the currents loop.

The waveforms show the good rotor speed estimation with a robustness to parametric variations because a stator resistance variation can not influence on the speed response that remains acceptable.

All those results confirm the validity, strong performance and high accuracy of the nonlinear feedback control and DESMO algorithm against stator resistance variations and load torque.

CONCLUSION

A nonlinear strategy and observation method have been proposed and used for the control of a PMSM. In this approach the components I_d and I_q, are regulated using a robust feedback linearization control, so that I_d is equal to zero which simplifies the dynamics, the controller and observer are designed and well integrated in the total PMSM system including load torque and parametric variations.

Best simulations results show fast response, good estimation and performances obtained with proposed control algorithms, with a perfect choice of the adjusting parameters. Thus, the currents control operates with enough stability and good speed estimation. Note also that the high accuracy and strong robustness to stator resistance variation and load in all the system confirm the advantages of the proposed decoupling control strategy and DESMO algorithm applied to the PMSM.

NOMENCLATURE

T_{em}, T_l : Electromagnetic and load torques (N.m)
I_d, I_q : (d, q)-axis stator currents (A)
p, J, f : p: pole number; J: inertia (kg.m^2); f: Damping coefficient (Nm.s/rad)
L_d, L_q : (d, q)-axis inductances (H)
R_s, T : Stator resistance (Ω) and Sampling period (s).
V_d, V_q : D-axis and q-axis stator voltage (V).
Φ_f : Rotor magnet flux linkage (Wb).
ω_r, Ω : ω_r: Rotor electrical radian speed and Ω: Mechanical rotor speed rad/s).

REFERENCES

Asseu, O., M. Koffi, Z. Yeo, X. Lin-Shi, M.A. Kouacou and T.J. Zoueu, 2008. Robust feedback linearization and observation approach for control of an induction motor. Asian J. Applied Sci., 1: 59-69.

Asseu, O., Z. Yeo, M. Koffi, T.R. Ori, G.L. Loum, T.J. Zoueu and A. Tanoh, 2009. Reduced-order sliding mode flux observer and nonlinear control of an induction motor. Trends Applied Sci. Res., 4: 14-24.

Asseu, O., S. Ouattara, K.E. Ali, Z. Yeo and M. Koffi, 2010. An extended kalman filter approach for flux-sensorless control of a linearized and decoupled induction motor drive. Trends Applied Sci. Res., 5: 91-106.

Blanchard, E., S. Adrian and C. Sandu, 2007. Parameter estimation method using an extended kalman filter. Proceedings of the Joint North America, Asia-Pacific ISTVS Conference and Annual Meeting of Japanese Society for Terramechanics, June 23-26, Fairbanks, Alaska, USA., pp: 1-14.

Bodson, M., J.N. Chiasson, R. Novotnak and R.B. Rekowski, 1993. High-performance nonlinear feedback control of a permanent magnet stepper motor. IEEE Trans. Control Syst. Technol., 1: 5-14.

Dehkordi, A., A.M. Gole and T.L. Maguire, 2005. PM synchronous machine model for real-time simulation. Proceedings of the International Conference on Power System Transients, June 19-23, Canada, pp: 1-6.

Ilioudis, V.C. and N.I. Margaris, 2008. PMSM sensorless speed estimation based on sliding mode observers. Proceedings of the IEEE Power Electronics Specialists Conference, June 15-19, Rhodes, pp: 2838-2843.

Li, J. and Y. Li, 2006. Speed sensorless nonlinear control for PM synchronous motor fed by three-level inverter. Proceedings of the IEEE International Conference Industrial Technology, Dec. 15-17, Mumbai, pp: 446-451.

Loria, A., 2009. Robust linear control of (chaotic) permanent-magnet synchronous motors with uncertainties. IEEE Trans. Circuits Syst., 56: 2109-2122.

Marino, R., P. Tomei and C.M. Verrelli, 2006. Nonlinear adaptive output feedback control of synchronous motors with damping windings. Proceedings of the 32nd Annual Conference on IEEE Industrial Electronics, Nov. 6-10, Paris, pp: 1131-1136.

Merzoug, M.S. and H. Benalla, 2010. Nonlinear backstepping control of Permanent Magnet Synchronous Motor (PMSM). Int. J. Syst. Control, 1: 30-34.

Murat, B., S. Bogosyan and M. Gokasan, 2007. Speed-sensorless estimation for induction motors using extended kalman filters. Ind. Electronics IEEE Trans., 54: 272-280.

Pillay, P. and R. Krishnan, 1988. Modeling of permanent magnet motor drives. IEEE Trans. Indus. Electr., 35: 537-541.

Poulain, F., L. Praly and R. Ortega, 2008. An observer for permanent magnet synchronous motors with currents and voltages as only measurements. Proceedings of the 47th IEEE Conference on Decision and Control, Dec. 9-11, Cancun, pp: 5390-5395.

Xi, X., Z. Meng, L. Yongdong and L. Min, 2006. On-line estimation of permanent magnet flux linkage ripple for PMSM based on a Kalman filter. Proceedings of the 32nd Annual Conference on IEEE Industrial Electronics, Nov. 6-10, Paris, pp: 1171-1175.

Xu, D. and Y. Gao, 2004. A simple and robust speed control scheme of permanent magnet synchronous motor. J. Control Theory Appl., 2: 165-168.