Revue des Energies Renouvelables Vol. 22 N°2 (2019) 269 - 278
DOI: https://doi.org/10.54966/jreen.v22i2.744

Backstepping speed controller design for a multi-phase permanent magnet synchronous motor drive

Fayçal Mehedi [1*], Lazhari Nezli [2], Mohamed Oul Hadj Mahmoudi [2], Rachid Taleb [1] and Djamel Boudjana [2]

[1] Department of Electrical Engineering, Hassiba Benbouali, University of Chlef
Hay Salem, National Roods N°19, Chlef, 02000, Algeria
[2] Process Control Laboratory, PCL
Ecole Nationale Polytechnique, ENP
10 Avenue Hassen Badi, B.P. 182, El Harrach, 16200, Algiers, Algeria

(reçu le 25 Juin 2019 - accepté le 28 Juin 2019)

Abstract - *This paper deals with the synthesis of a speed control strategy for a six-phase permanent magnet synchronous motor (PMSM) drive based on backstepping controller (BC). The Backstepping control is a systematic and recursive design methodology for nonlinear feedback control. The results demonstrate that backstepping controller has the advantage of rapid response, no overshoot and stability compared with PI controller.*

Résumé - *Cet article traite de la synthèse d'une stratégie de contrôle de la vitesse pour un moteur synchrone à aimants permanents à six phases (PMSM) basé sur un contrôleur Backstepping (BC). Le contrôle backstepping est une méthodologie de conception systématique et récursive pour le contrôle à rétroaction non linéaire. Les résultats démontrent que le contrôleur backstepping offre l'avantage de la réponse rapide, de l'absence de dépassement et de la stabilité par rapport au contrôleur PI.*

Keywords: Six-phase permanent-magnet synchronous motor (PMSM) - Vector control - Backstepping controller (BC) - PI controller - Robustness.

1. INTRODUCTION

Multi-phase machines have many advantages over a conventional 3-phase system as mentioned in [1]. One of them is a fact that for the same power rating a phase currents are much smaller in the multiphase system. The other beneficial properties are a reduction of electromagnetic torque ripples and higher power density coefficient [2]. Due to a larger number of phases, multiphase machines are characterized by an inherent fault tolerance that can be improved. Theapplication of the appropriate fault-tolerant algorithm reduces torque ripples [3, 4].

In high-power applications often machines with multiple three-phase windings are used. The most common case is a six-phase machine. There are two kinds of these machines [1].The first is symmetrical machine in which stator windings are shifted by 60°. The most common is asymmetrical machine.In this kind of machine, the stator winding is composed of two 3-phase windings, which are spatially shifted by 30°.

Many different multiphase machine control schemes such as multiphase direct torque control (DTC) and field orientation control (FOC) have been introduced [5-7]. Control system design is a multi-stage process including more than designing the controller itself. Before a controller is designed, a control engineer must have sufficient knowledge of the system to be controlled. The classical proportional integral (PI) control technique isuniversally employed in the current six-phase PMSM systemdue to its high reliability and simple implementation [8].

However, linear PI controller for application to an multiphase machine driven have some disadvantages such as parameter tuning complications, mediocre dynamic performances and reduced robustness [9]. It is dif cult to meet the requirement of high-

[*] Faycalmehedi@yahoo.fr

performance speed control needed for the nonlinear drive system. Therefore, advanced nonlinear control methods such as robust theory, predictive control [10], sliding mode control [11], backstepping technique [12] and artificial intelligence [9] have been introduced into the motors control system.

To overcome the poor robustness and static and dynamic performances of PI controller, the backstepping speed controller design for six-phase PMSM has been presented.

Among the various intelligent controllers, backstepping controller is the simplest, robust and better than others in terms of quick response time, also insensitivity to parameter and load variations etc [12].

The idea of backstepping control is to select some state variables as control inputs for lower order subsystems for the overall system. Each backstepping stage results into a new control design expressed in terms of control designs from the previous stage. When the procedure terminates, a feedback design of true control input results and achieves the original design objective by virtue of a Lyapunov function [13, 14]. This technique has been successfully applied to electrical motor drives [15-17].

This paper is organized as follows. Section 2 introduces the mathematical model of a six-phase PMSM. In section 3 the field oriented strategy by employing the PI controller of the six-phase PMSM is presented. Section 4 provides the application of the backstepping control based on six-phase PMSM speed control system. The effectiveness of the control scheme is verified through simulations results in section 5. Related conclusions are given in section 6.

2. MODEL OF SIX-PHASE PMSM DRIVE

The basic equations that describe electric part of a six-phase PMSM in natural phase reference frame are shown below [14, 15].

$$\nu_{si} = R_s i_i + \frac{d\varphi_{si}}{dt} \tag{1}$$

For each phase i = 1 ... 6.

It can be used a generalized six-dimensional Clark transformation matrix T_{6s} to change the coordinate from natural coordinates to vector space. With the principle of amplitude unchanged, the transformation matrix is shown in (2).

$$T_{6_s} = \frac{1}{\sqrt{3}} \begin{bmatrix} 1 & \cos(\gamma) & \cos(2\gamma) & \cos(3\gamma) & \cos(4\gamma) & \cos(5\gamma) \\ 0 & \sin(\gamma) & \sin(2\gamma) & \sin(3\gamma) & \sin(3\gamma) & \sin(5\gamma) \\ 1 & \cos(2\gamma) & \cos(4\gamma) & \cos 6\gamma) & \cos(8\gamma) & \cos(10\gamma) \\ 0 & \sin(2\gamma) & \sin(4\gamma) & \sin(6\gamma) & \sin(8\gamma) & \sin(10\gamma) \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \\ 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} & 1/\sqrt{2} \end{bmatrix} \tag{2}$$

Where $\gamma = \pi/3$.

For realizing the complete decoupling of voltage equation, it is necessary to transform the vector space to rotational coordinates. The generalized six-dimensional Park transformation matrix T_{6s} has been given out as (3). And the complete transformation matrix from natural coordinates to rotational coordinates T_{1s} is equal to $T_{6s} * T_{6s}$.

$$T_{6_r} = \begin{bmatrix} \cos(\theta) & \sin(\theta) & 0 & 0 & 0 & 0 \\ -\sin(\theta) & \cos(\theta) & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix} \tag{3}$$

The model of the six-phase PMSM is presented in a rotating d-q-x-y frame as [15],

$$\begin{cases} \nu_{ds} = R_s i_{ds} + L_d \dfrac{d i_{ds}}{d t} - w_r L_q i_{qs} \\ \nu_{qs} = R_s i_{qs} + L_q \dfrac{d i_{qs}}{d t} + w_r L_d i_{ds} + w_r \phi_m \\ \nu_{xs} = R_s i_{xs} + L_{ls} \dfrac{d i_{xs}}{d t} \\ \nu_{ys} = R_s i_{ys} + L_{ls} \dfrac{d i_{ys}}{d t} \\ \nu_{0ps} = R_s i_{0ps} + L_{ls} \dfrac{d i_{0ps}}{d t} \\ \nu_{0ms} = R_s i_{0ms} + L_{ls} \dfrac{d i_{0ms}}{d t} \end{cases} \tag{4}$$

The stator flux vector components are equal,

$$\begin{cases} \varphi_{ds} = L_d i_{ds} + \phi_m \\ \varphi_{qs} = L_q i_{qs} \\ \varphi_{xs} = L_{ls} i_{xs} \\ \varphi_{vs} = L_{ls} i_{vs} \\ \varphi_{ys} = L_{ls} i_{ys} \\ \varphi_{0ps} = L_{ls} i_{ops} \end{cases} \tag{5}$$

The electromagnetic torque expression is given by,

$$T_e = 3p\left(\phi_m i_{qs} + (L_d - L_q) i_{ds}\, i_{qs}\right) \tag{6}$$

On the other hand, the mechanical equation of the machine is,

$$J_m \frac{d w_r}{d t} = p\, T_e - p\, T_r - f_m w_r \tag{7}$$

3. VECTOR CONTROL MODEL OF THE SIX-PHASE PMSM

Vector control technique aims to make equivalence between the six-phase PMSM and DC motor. This objective can be achieved by controlling the d-axis current component to zero, so the torque depends only on the amplitude of q-axis current. Therefore, the reference currents can be calculated using the following equation [3].

The reference value of current controller in the q axis was setting to the output value of the speed controller.

$$\begin{cases} i_{ds}^* = 0 \\ i_{qs}^* = \dfrac{1}{3p\varphi_f} T_e^* \end{cases} \tag{8}$$

For the speed control as the input was set the desired speed of the system. In order to regulate the flux was used current regulator in the d axis, which value was setting to zero. Additionally, decoupling in current controllers with SEM signals is applied. The block scheme of FOC system for multiphase PMSM is presented in figure 1.

In order to keep the current control performance, a decoupling control is needed. Indeed, d-q components of the reference voltage vectors are calculated by,

$$\begin{cases} v_{ds}{}^* = v_d' + w_r L_q i_{qs} \\ v_{qs}{}^* = v_q' + w_r (L_d i_{ds} + \phi_f) \end{cases} \tag{9}$$

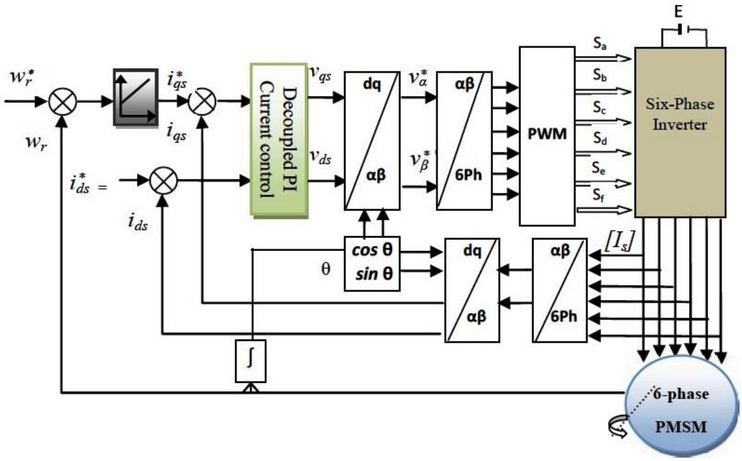

Fig. 1: Vector control for the six-phase PMSM

4. DESIGN OF BACKSTEPPING CONTROLLER

Step 1

Assuming that system parameters are known, first the speed tracking error is defined as (9)

$$e_w = w_r^* - w_r \tag{10}$$

Where w_r* is the desired mechanical rotor speed.

Dynamic equation of motor is

$$\frac{de_w}{dt} = -\frac{dw_r}{dt} = \frac{1}{J_m}\left(f_m w_r + T_r - 3p(\phi_m i_{qs} + (L_d - L_q))\, i_{ds}\, i_{qs}\right) \tag{11}$$

Assuming that the current i_{ds}, i_{qs} are the virtual control volume in dq coordinate system, the backstepping design method is used to make the speed tracking error converge to zero. For type (11), the first "Lyapuov" function is constructed [18].

$$V = \frac{1}{2} e_w^2 \tag{12}$$

After derivation, we have

$$\frac{dV}{dt} = e_w \frac{de_w}{dt} = \frac{e_w}{J_m}\left(f_m w_r + T_r\right) - \frac{3p}{J_m} e_w \left(\phi_m i_{qs} + (L_d - L_q)\, i_{ds}\, i_{qs}\right) \quad (13)$$

In order to guarantee the global stability, assumptions,

$$\frac{dV}{dt} = -K_w e_w^2 \leq 0 \quad (14)$$

Where K_w is the normal number.

Stability function can be gotten as follows.

$$i_{ds}^* = 0 \quad (15)$$

$$i_{qs}^* = \frac{1}{3p\phi_m}\left(f_m w_r + T_r + K_w J_m e_w\right) \quad (16)$$

Because the current part is not control quantity, so the current error is defined as the virtual error variables.

$$e_d = i_{ds}^* - i_{ds} \quad (17)$$

$$e_q = i_{qs}^* - i_{qs} \quad (18)$$

Among them, i_{ds}*, i_{qs}* are the expected value, i_{ds}, i_{qs} are the tracking value.

After derivation, we have

$$\frac{de_w}{dt} = \frac{1}{J_m}\left(3p\phi_m e_q + 3p(L_d - L_q) e_d\, i_{qs} - K_w J_m e_w\right) \quad (19)$$

<u>Step 2</u>

The differential equations of steady state error e_d, e_q is defined as,

$$\frac{de_d}{dt} = -\frac{\nu_{ds}}{L_d} + \frac{R_s}{L_d} i_{ds} - w_r \frac{L_q}{L_d} i_{qs} \quad (20)$$

$$\frac{de_q}{dt} = \frac{K_w J_m - f_m}{3p\phi_m}\left(-K_w e_w + \frac{3p\phi_m}{J_m} e_q + \frac{3p}{J_m}(L_d - L_q) e_d\, i_{qs}\right) - \frac{\nu_{qs}}{L_q} + \frac{R_s}{L_q} i_{qs} + w_r \frac{L_d}{L_q} i_{ds} + w_r \frac{\phi_m}{L_q} \quad (21)$$

The new 'Lyapuov' function is defined as,

$$V_1 = \frac{1}{2} e_w^2 + \frac{1}{2} e_d^2 + \frac{1}{2} e_q^2 \quad (22)$$

After derivation, we have,

$$\dot{V}_1 = e_w \frac{de_w}{dt} + e_w \frac{de_d}{dt} + e_q \frac{de_q}{dt} \quad (23)$$

For the global stability of current loop, need to meet $\dot{V}_1 \leq 0$ and the control voltage can be gotten combining (23).

$$\nu_{ds} = K_d L_d e_d + \frac{3p}{r}(L_d - L_q) L_d e_w i_{qr} + R_s i_{ds} - w_r L_q i_{qs} \quad (24)$$

$$v_{qs} = \frac{(K_w J_m - f_m) L_q}{3p\phi_m}\left(-K_w e_w + \frac{3p\phi_m}{J_m} e_q + \frac{3p}{J_m}(L_d - L_q) e_d i_{qs} \right) + R_s i_{qs} + \frac{3p\phi_m L_q}{J_m} e_w + K_q I_q e_q + w_r L_q i_{ds} + w_r \phi_m \tag{25}$$

Thus the derivative type (23) of Lyapunov function is,

$$\dot{V}_1 = -K_w e_w^2 + K_d e_d^2 + K_q e_q^2 \leq 0 \tag{26}$$

Among them, K_m, K_d, K_q are the feedback gain of normal number. So the system is stable.

5. SIMULATION AND ANALYSIS

In order to verify the effectiveness of backstepping method control, simulations were carried out usingMatlab/Simulink software. The machine parameters are given in **Table 1**.

The first test consists of the tracking test and sensitivity to the load torque variation on six-phase PMSM for the two controllers. For this objective and in the time t = [0.5s - 1s], the load torque is kept equal to its value T_r =10 N.m and a step change of the reference speed from 150 rad/s to -150 rad/s at t = 1.5s.

The simulation results are presented in figure 2. This figure express that the effect produced by the load torque variation is very clear on the speed curve of the system with PI controller, while the effects are almost negligible for the system with the backstepping controller (figure 2**a**).

It can be noticed that these last have a nearly perfect speed disturbance rejection (less than 1%). The electromagnetic torques (figure 2**b**, figure 2**c**) do not have much difference between the two control strategies whose responding time are all very quick.

The current I_q current has the same torque's form, I_d is kept zero (figure 2**d**, figure 2**e**).

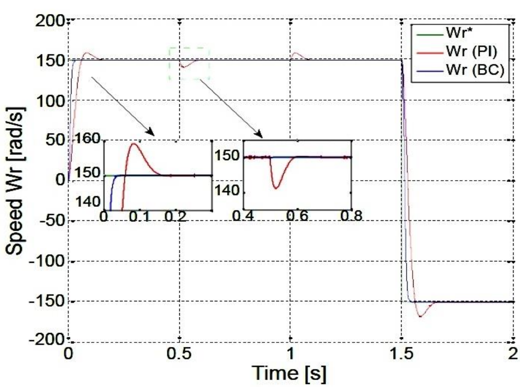

Fig. 2: **(a)** Speed response

The second test consists of the robustness test of the system. An example of the robustness of the backstepping controller compared with the conventional PI controllers.

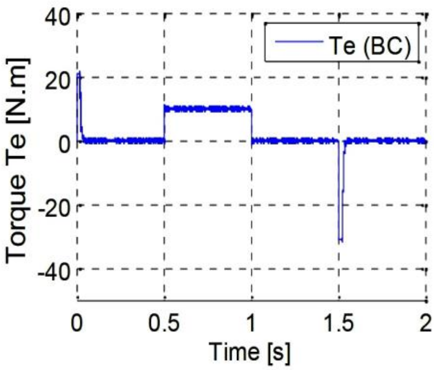

Fig. 2: **(b)** Torque response of BC

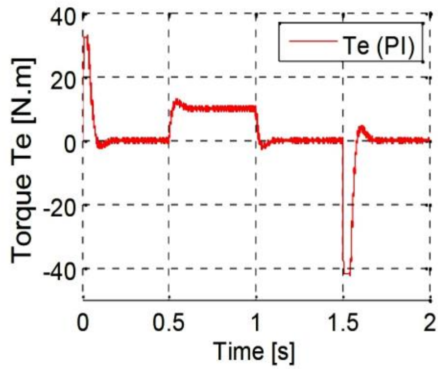

Fig. 2: **(c)** Torque response of PI

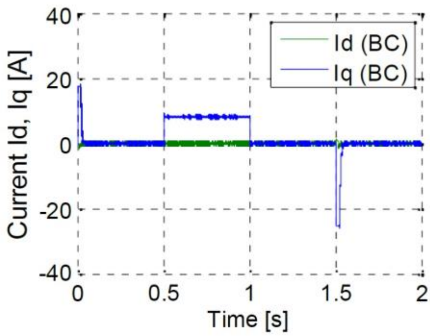

Fig. 2: **(d)** Stator current components I_d, I_q of BC

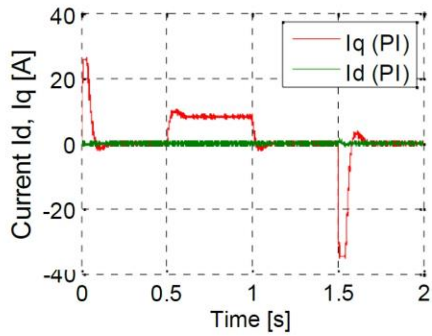

Fig. 2: **(e)** Stator current components I_d, I_q of PI

Fig. 2: Simulation results of six-phase PMSM in BC et PI controllers

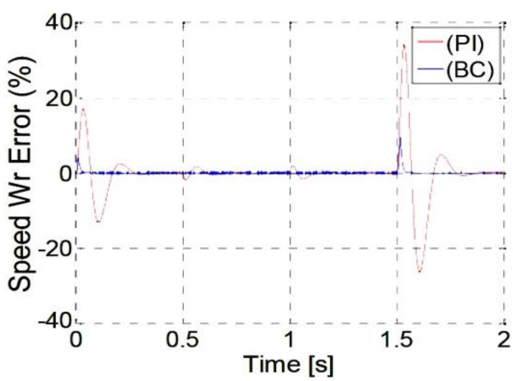

Fig. 3: Robustness test of the six-phase PMSM (J_m =2*J_m)

In order to test the robustness of the used controllers, the machine inertia has been doubled. Figure 3 shows the percent error on the speed responses against parameter variation (inertia variation) of PI and BC for six-phase PMSM.

As illustrated by the figure, the effect appears more significant for PI controller compared with the backstepping controller where the percent of error on the speed responses is clear during the application of load torque and when the change of the reference speed. Thus it can be concluded that these last are robust against this parameter variation.

6. CONCLUSION

A new robust nolinear speed control approach of a six-PMSM has been presented. This design is governed by a backstepping strategy which guarantees the robust performances and gives satisfactory results. Besides, the proposed controller has a simple architecture.

The proposed controller has been analysed using Matlab/Simulink software. The simulation results show its effectiveness at tracking a reference speed under parameter uncertainties and nonlinearities. Finally, as a further improvement of the proposed strategy, it will be interesting to combine the proposed backstepping controller with a nonlinear observer in order to estimate the sixphase PMSM speed and parameters.

APPENDIX

Table 1. List of symbols

Symbol	Significance
v_{ds}, v_{qs}, i_{ds}, i_{qs}	d and q axis stator voltages and currents
v_{xs}, v_{ys}, i_{xs}, i_{ys}	x and y axis stator voltages and currents
R_s	Stator resistance
L_s	Stator inductance
L_{ls}	Leakage inductance of stator
ϕ_f	Main magnetic flux of the permanent magnet
P	Number of pole pairs
J_m	Inertia moment
f_m	Viscous damping
w_r	Rotational speed
T_r	Load torque
T_e	Electromagnetic torque

Table 2. Parameters of six-phase PMSM

Parameters	Rated value
R_s	3 Ω
L_s	40 mH
I_{ls}	4 mH
p	2
J_m	0.02 kg/m^2
ϕ_f	0.620 Web

REFERENCES

[1] E. Levi, '*Power Electronics and Motor Drives*', The Industrial Electronics Handbook, Second Edition, Chapter 3, pages: (3) 1 - (3)31, 2011.

[2] J. Staszak, K. Ludwnek, Z. Gawecki, J. Kurkiewicz and T. Bekier, '*Utilization of Permanent Magnet Synchronous Motors in Industrial Robots*', Proc. IEEE

Conference on Information and Digital Technologies, Zilina, Slovakia, pp. 342 - 347, 2015.

[3] A. Hosseyni, R. Trabelsi, M.F.i Mimouni and A. Iqbal, '*Fault Tolerant Vector Controlled Five-Phase Permanent Magnet Synchronous Motor Drive with an Open Phase'*, IEEE International Multi-Conference on Systems, Signals & Devices (SSD), Hammamet, Tunisia, 2018.

[4] H. Shi, P. Li and Ch. Su, '*Robust Predictive Fault-Tolerant Control for Multi-Phase Batch Processes With Interval Time-Varying Delay* ', IEEE Access, Vol. 7, pp. 148 - 162, 2019.

[5] M. Janaszek, '*Structures of Vector Control of n-Phase Motor Drives based on Generalized Clarke transformation*', Bulletin of the Polish Academy of Sciences Technical Sciences, Vol. 64, N°4, pp. 865 - 878, 2016.

[6] A. Hosseyni, R. Trabelsi, M.F. Mimouni and A. Iqbal, '*Vector Controlled Five-Phase Permanent Magnet Synchronous Motor Drive*', IEEE 23rd International Symposium on Industrial Electronics, Istanbul, Turkey, pp. 2122 - 2127, 2014.

[7] X. Wang, Z. Wang, M. Cheng and Y. Hu X, *'Remedial Strategies of T-NPC Three-Level Asymmetric Six-Phase PMSM Drives Based on SVM-DTC*', IEEE Transactions on Industrial Electronics, Vol. 64, N°9, pp. 6841 - 6853, 2017.

[8] X. Zhang, L. Sun, K. Zhao, and L. Sun, '*Nonlinear speed control for PMSM system using slidingmode control and disturbance compensation techniques'*, IEEE Transactions on Power Electronics, Vol. 28, N°3, pp. 1358 - 1365, Mar. 2013.

[9] F. Mehedi, L. Nezli, M.O. Mahmoudi and R. Taleb, '*Fuzzy logic based vector control of multiphase permanent magnet synchronous motors*', Revue des Energies Renouvelables, Vol. 22, N°1, pp. 161 - 170, 2019.

[10] B. Bossoufi, H.A. Aroussi, M. El Ghamrasni and Y. Ihedrane, '*Speed control for PMSM drive system using predictive control*', IEEE 8th International Conference on Electronics, Computers and Artificial Intelligence, ECAI, Ploiesti, Romania, 2016.

[11] F. Mehedi, L. Nezli, M.O. Mahmoudi and R. Taleb, *'Robust speed control of five-phase permanent magnet synchronous motor using super-twisting sliding mode control*', Revue des Energies Renouvelables, Vol. 20, N°4, pp. 649 - 657, 2017.

[12] B. Sari, M.F. Benkhoris, M.A. Hamida and S.E. Chouaba, '*A Backstepping Torque Control of a Five Phase Permanent Magnet Synchronous Machine*', 7th International Conference on Systems and Control, ICSC, Valencia, Spain, 2018.

[13] G. Prior and M. Krstic, '*Quantized – Input Control Lyapunov Approach Permanent Magnet Synchronous Motor Drives*', IEEE Transactions on Control Systems Technology, Vol. 21, N°5, pp 1784 - 1794, 2013.

[14] M. Ouassaid, M. Cherkaoui, and Y. Zidani, '*A nonlinear speed control for a PM synchronous motor using an adaptive backstepping control approach*', IEEE International Conference on Industrial Technology, Vol. 3, pp. 1287 - 1292, 2004.

[15] F.F.M. El-Sousy, M.F. El-Naggar, A. Mahmoud, A. Abu-Siada and K.A. Abuhasel, '*Robust Adaptive Neural-Network Backstepping Control Design for High-Speed Permanent-Magnet Synchronous Motor Drives: Theory and Experiments',* IEEE Access, Vol. 7, pp. 99327- 99348, 2019.

[16] H. Mekki, O. Benzineb, L. Chrifi-Alaoui, D. Boukhetala, and M. Tadjine, '*Robust Fault Reconstruction with Integral Backstepping Control Design for IM Drives*', 6th International Conference on Control Engineering & Information Technology, CEIT, Istanbul, Turkey, 2018.

[17] T. Ameid, A.i Menacer, H. Talhaoui, I. Harzelli and A. Ammar, '*Backstepping control for induction motor drive using reduced model in healthy state: Simulation and experimental study*', 6th International Conference on Systems and Control, ICSC, pp. 162 - 167, Batna, Algeria, 2017.

[18] L.Y. Zhou and Z. Ke-gang, '*Adaptive Back-stepping Control of Permanent Magnetic Synchronous Motor Based on Slide Mode Observer*', Third International Conference on Measuring Technology and Mechatronics Automation, Shangshai, China, 2011.