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SPEED CONTROL OF PERMANENT MAGNET SYNCHRONOUS MOTOR USING DIFFERENT STRATEGY OF SLIDING MODE APPROACH

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Abstract

In order to optimize the speed-control performance of the PMSM system with different disturbances and uncertainties, hybrid nonlinear speed-controls for the PMSM, based sliding-mode control, is developed. A sliding-mode controller (SMC) is designed, based on conventional reaching law but the amount of chattering and reaching time are high. To raise this problem, two different control strategies will be studied; the first that combines sliding mode control with fuzzy logic (FSMC) and the second one combines the sliding mode control with robust integral backstepping (I-Back-SMC) strategy. A comparative study of these three types of controls was given to improve the performance significantly. Simulation results illustrate the validity and the effectiveness of the suggested methods.

Keywords: Fuzzy logic control, Sliding ode control, Integral backstepping, Permanent magnet synchronous motor.

1. Introduction

In our fast-paced world, permanent magnet synchronous motors commonly used in industrial automation for traction, robotics or aerospace require greater power and heightened intelligence. The efficiency of electrical machine drives is greatly reduced at light loads, where the flux magnitude reference is held on its initial value. Moreover, expert control algorithms are employed in order to improve machine performance [1-2]. In this paper we are interested by hybrid control based

Nomenclatures

C_{em}	Electro magnetique torque, (N.m)
(d, q)	Axes for direct and quadrate park subscripts.
f	Viscous friction and iron-loss coefficient
I_s	Stator Currents, (A)
J	Inertia moment of the moving element, (kgm^2)
L_s, L_r	Self-inductance of stator and rotor, (H)
M	Mutual magnetizing inductance
p	Is number of pole pairs
R_s, R_r	Stator and rotor resistances, (Ω)
s, r	Stator and rotor subscripts
T_l	Load torque, (N.m)
$V_d V_q$	Stator voltage in direct and quadrate park subscripts, (V)

Greek Symbols

(α, β)	Axes for stationary reference frame subscripts
ϕ_f	Permanent magnet rotor flux linkage, (Wb)
ϕ_{ref}	Rotor flux reference, (Wb)
ϕ_s , ϕ_r	Stator and rotor flux, (Wb)
Ω	Rotor angular frequency, (rad/s)
Ω_{ref}	Rotor speed reference (rad/s)

Abbreviations

FLC	Fuzzy Logic Control
FSMC	Fuzzy Sliding Mode Control
HC	Hybrid Controllers
I-Back	Integral Backstepping
I-Back-SMC	Integral Backstepping-Sliding Mode Control
Max	Maximum
PMSM	Permanent Magnet Synchronous Motor
VSS	Variable Structure Systems

on sliding mode control (SMC), Integral Backstepping and Fuzzy logic.

One of the most traditional controls applied to PMSM is the variable structure systems (VSS) also known as sliding mode. This approach is mainly a discontinuous control technique [3-5]. If a sliding surface is properly designed, the representative point will be forced by the control vector to hit the sliding surface. The discontinuous control forces the representative point to slide on the chosen sliding surface and reaches the origin. Around the surface **s** is often irritated by high frequency oscillations known as chattering. Sliding mode control (SMC) can exponentially drive the system state to a chattering sliding mode but tends to produce conservative designs [6-8]. To exploit the advantages of sliding modes, the objective of this paper is to use this structure control by combining it with other approaches to make the control robust with minimal chattering.

Among the existing control design techniques, we propose in this paper fuzzy logic control (FLC). It is suitable for nonlinear or complex systems characterized by parametric fluctuation or uncertainties [9-12]. By combining the fuzzy logic structure and sliding modes, we can get better performance and a reduced number of fuzzy rules [13-14]. In reference [15], the author demonstrates that fuzzy logic controllers may have slight performance advantages over other control methods, but they must be, carefully tuned to achieve maximum performance.

In the literature, another control structure named Backstepping approach is an attractive control technique due to the robustness, which is based on a recursive algorithm for designing a control for a class of nonlinear system. So, a Backstepping controller for PMSM combined with sliding mode control for speed control is proposed. By adding an integral action at each step of the Backstepping algorithm, asymptotic rejection of some classes of non-matched disturbances is obtained. The controller exhibits excellent dynamics and steady-state performances. It is robust to load disturbances and parameter uncertainties. The practical stability of the controller scheme is studied via Lyapunov analysis where sufficient conditions are given. [16-20].

This paper introduces hybrid controllers (HC) which consists of a connected sliding mode controller (SMC) and a fuzzy controller (FSMC) and integral Backstepping (I-Back-SMC) for the speed control of a permanent magnet synchronous motor (PMSM) drive. Therefore, we can organize this paper as follows; mathematical model of the PMSM are presented in section 2. The Sliding Mode Control is presented in section 3, Fuzzy-sliding mode Controller is discussed in section 4, and the robust integral Backstepping controller of PMSM is the subject of section 5. The simulation results are presented in section 6. Finally, some concluding remarks end the paper.

2. Mathematical Model of the PMSM

The model of PMSM can be described in the well-known (d–q) frame through the Park transformation as follows:

$$\dot{X} = F + g.U \tag{1}$$

with:

$X = [\ I_d \quad I_q \quad \Omega]$

$U = [\ V_d \quad V_q]$

$$F = \begin{bmatrix} -\frac{R_s}{L_d} I_d + \frac{L_q}{L_d} p\Omega I_q \\ -\frac{R_s}{L_q} I_q - \frac{L_d}{L_q} p\Omega I_d - \frac{\phi_f}{L_q} p\Omega \\ \frac{3p}{2J}\left[(L_d - L_q) I_d I_q + \phi_f I_q\right] - \frac{f}{J}\Omega - \frac{T_l}{J} \end{bmatrix} \text{ and: } g = \begin{bmatrix} \frac{1}{L_d} & 0 \\ 0 & \frac{1}{L_q} \\ 0 & 0 \end{bmatrix}$$

3. Sliding Mode Controllers Design

Speed control of motors mainly consists of two loops, the inner loop for current and the outer loop for speed. Speed controller calculates the difference between the reference speed and the actual speed producing an error, which is fed to the inner loop current controller [2]. Since the speed control loop of the PMSM is essentially a first order system, the SMC design is conventional in its derivation, and is based on the Lyapunov stability concept [18-19].

The control algorithm includes two terms, the first for the exact linearization, and the second discontinuous one for the system stability.

$$U = U_{eq} - U_n \tag{2}$$

U_{eq} is calculated starting from the expression

$$\dot{s}(x) = 0 \tag{3}$$

U_n: is given to guarantee the attractively of the variable controlled towards the commutation surface. Its simplest equation is given by:

$$U_n = k sign\ s(x) \qquad k > 0 \tag{4}$$

The sliding surfaces are chosen by:

$$\begin{cases} s(\Omega) = \Omega_{eq} - \Omega_n \\ s(\mathrm{i_q}) = \mathrm{I_q}_{eq} - \mathrm{I_q}_n \\ s(\mathrm{i_d}) = \mathrm{I_d}_{eq} - \mathrm{I_d}_n \end{cases} \tag{5}$$

The outer loop for speed controller and the intern loops of stator currents regulation are given by:

$$I_q^* = I_{qn} + I_{qeq} \tag{6}$$

$$I_{qn} = \frac{k_\Omega}{e} s(\Omega) \qquad \text{if} \qquad s(\Omega) < e_\Omega \tag{7}$$

$$I_{qn} = k_\Omega sign(\omega_r) \qquad \text{if} \qquad s(\Omega) \geq e_\Omega \tag{8}$$

where: e_Ω: represents the error between Ω_{eq} and Ω_n. And:

$$V_q^* = V_{qn} + V_{qeq} \tag{9}$$

$$V_{qn} = \frac{k_q}{e} s(\mathrm{i}_q) \qquad \text{if} \qquad s(I_q) < e_q \tag{10}$$

$$V_{qn} = k_q sign\ s(\mathrm{i}_q) \qquad \text{if} \qquad s(\mathrm{I_q}) \geq e_\mathrm{q} \tag{11}$$

where:

e_q: represent the error between I_{qeq} and I_{qn}

$$V_d^* = V_{dn} + V_{deq} \tag{12}$$

$$V_{dn} = \frac{k_d}{e} s(\mathrm{I}_d) \qquad \text{if} \qquad s(I_d) < e_\mathrm{d} \tag{13}$$

$$V_{dn} = k_d sign\ s(\mathrm{I}_d) \qquad \text{if} \qquad s(I_d) \geq e_\mathrm{d} \tag{14}$$

where: e_d: represent the error between I_{deq} and I_{dn}

To satisfy the stability condition of the system, the gains k_Ω,k_q and k_d should be taken positive by selecting the appropriate values. Reduced chattering may be achieved without sacrificing robust performance by combining the attractive features of fuzzy logic with SMC presented in the next section.

4. Fuzzy-Sliding Mode Controller

In fact, for any control device, which presents non-linearity such as delay or hysteresis, limited frequency commutation is often imposed. In other side, the state oscillation will be preserved even in vicinity of the sliding surface. This behaviour is known by chattering phenomenon.

This highly undesirable behaviour may excite the high frequency unmodeled dynamics. The electrical subsystem has a sub-controller with sliding surfaces S, and the dynamic of switched surface give it as follow:

$$s(\Omega) = \dot{e}(\Omega) + m_1 e(\Omega) \tag{15}$$

With: $e(\Omega) = \Omega_{ref} - \Omega$and $m_1 > 0$

The control U is inferred from the two state variables, error (e) and error variation Δe [21-22]. The actual inputs are approximate of the closer values of the respective universes of discourse. Hence, the fuzzy field inputs are described by singleton fuzzy sets. The design of this controller is based on the phase plan. The control rules are designed to assign a fuzzy set of the control input U for each combination of fuzzy sets of (e) and Δe.

Table 1. Rules base for speed control.

$\mathbf{D_u}$		$\mathbf{DE_n}$				
		NB	**NM**	**ZR**	**PM**	**PB**
$\mathbf{E_n}$	**NB**	NB	NB	NM	NM	ZR
	NM	NB	NM	NM	ZR	PM
	ZR	NM	NM	RZ	PM	PM
	PM	NM	ZR	PM	PM	GP
	PB	ZR	PM	PM	GP	GP

Table (1) shows one of possible control rule base. The rows represent the rate of the error change (e) and the columns represent the error (e). Each pair (e, e) determines the output level NB to PB corresponding to U. Here NB is negative big, NM is negative medium, ZR is zero, PM is positive medium and PB is positive big, are labels of fuzzy sets and their corresponding membership functions are depicted in Figs. 1 to 3, respectively. The continuity of input membership functions, reasoning method, and defuzzification method for the continuity of the mapping fuzzy U (e, e) is necessary. In this paper, the triangular membership function, the max-min reasoning method, and the center of gravity defuzzification method are used, as those methods are most frequently used frequently in the literature [21-22].

The used diagram block for the simulation is given in Fig. 4.

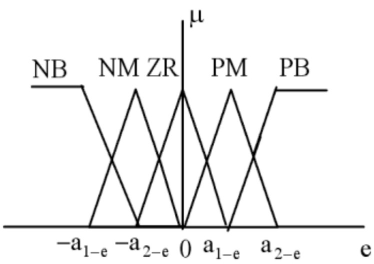

Fig. 1. Membership functions for input e.

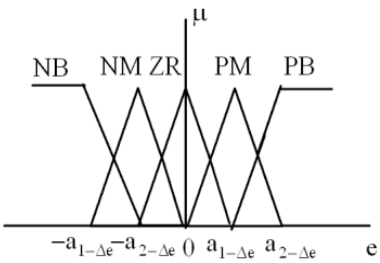

Fig. 2. Membership functions for input Δ*e*.

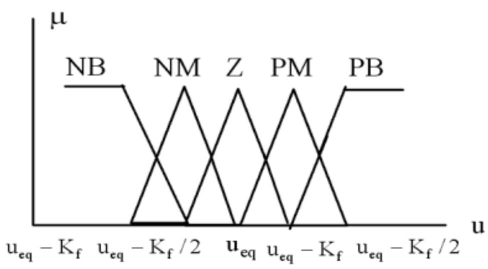

Fig. 3. Membership functions for output.

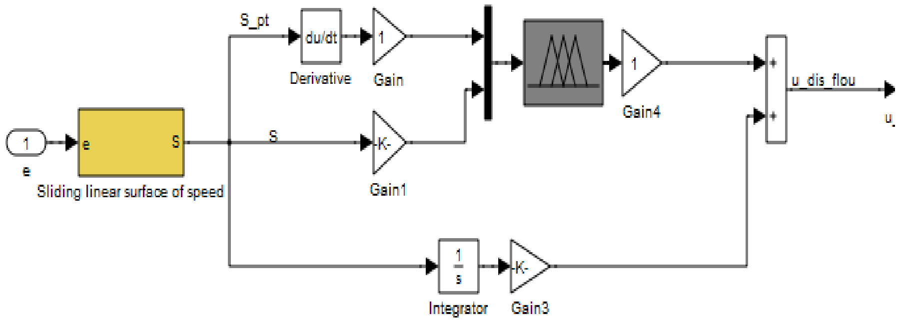

Fig. 4. Structure of Fuzzy logic controller with sliding speed surfaces.

5. New Robust Integral Backstepping Controller Based Sliding Mode

We present in this section a robust integral Backstepping controller combined with sliding mode. The controller is design based on a modified Backstepping technique, in order to ensure a high precision control and guarantee high performance speed tracking. However due to parameter uncertainties and/or disturbances the Backstepping-based controller fails to eliminate steady-state speed error. Then, in order to ensure a high precision control of the steady-state velocity, an integral action is introduced in the Backstepping controller [19-20].

5.1. Control objective

By using the measurement of the currents, the control objective is to design a controller such that the rotor speed tracks a desired reference Ω^* despite the parametric uncertainties. Furthermore, to avoid the reluctance effect $(L_d \neq L_q)$, the current I_d is forced to zero, i.e. $(I_d^* = 0)$. This synthesis is carried out in two steps. Speed loop: to solve speed-tracking problem, define the following tracking error variable as follow:

$$z_\Omega = \Omega^* - \Omega + k_\Omega' \int_0^t (\Omega^* - \Omega)dt \tag{16}$$

With$k_\Omega' \int_0^t (\Omega^* - \mathrm{i})dt$: Is the integral term added to the rotor speed tracking error. Next, in order to design the speed control which is designed to force I_q to track I_{qn}, we take the time derivative of equation (16) and by replacing I_q by I_{qn} , which can be considered as a new input.

$$\dot{z}_\Omega = \dot{\Omega}^* + \frac{p}{J}\left(L_d - L_q\right)I_d I_q^* + \frac{f}{J}\Omega - \frac{p}{J}\phi_f I_q^* + \frac{1}{J}T_l + k_\Omega^{'}\left(\Omega^* - \Omega\right) \quad (17)$$

Choosing the following candidate Lyapunov function $V_\Omega = \frac{1}{2}z_\Omega^2$ and taking the time derivative along the trajectories of equation (17), we get

$$\dot{V}_\Omega = z_\Omega[\dot{\Omega}^* + \frac{p}{J}\left(L_d - L_q\right)I_d I_q^* + \frac{f}{J}\Omega - \frac{p}{J}\phi_f I_q^* + \frac{1}{J}T_l + k_\Omega^{'}\left(\Omega^* - \Omega\right)] \quad (18)$$

Following the Backstepping method, by choosing then the virtual control input i_q^* as:

$$I_q^* = \frac{J}{p(L_d - L_q)I_d + p\phi_f}[k_\Omega z_\Omega + \dot{\Omega}^* + \frac{f}{J}\Omega + \frac{1}{J}T_l + k_\Omega^{'}\left(\Omega^* - \Omega\right)] \quad (19)$$

$$z_\Omega = \Omega^* - \Omega + k_\Omega^{'} \quad (20)$$

Then:

$$\dot{V}_\Omega = -k_\Omega z_\Omega^2 \quad (21)$$

With $k_\Omega > 0$

The different controllers used in this paper can be presented as shown in Fig. 5.

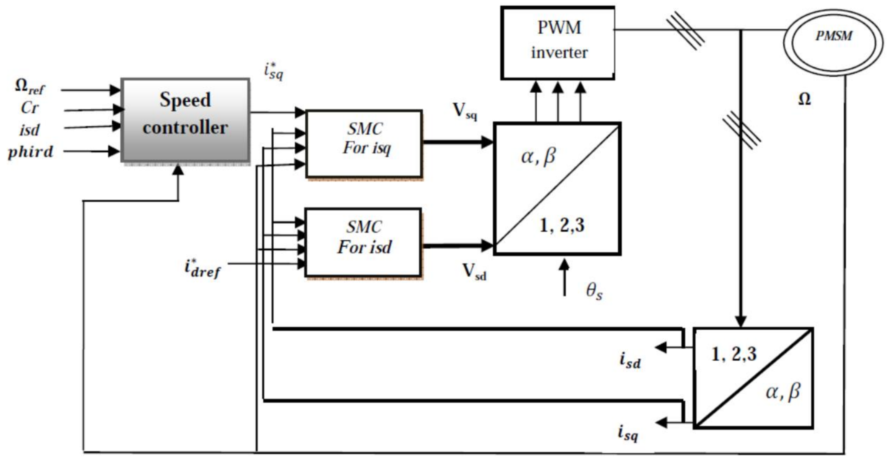

Fig. 5. PMSM speed control.

6. Simulation Results

The used diagram block for the simulation is given in Fig. 4. It is composed of two identical currents controllers for the three control strategies SMC, FSMC and I-back SMC; their difference is located at the speed controller. These approaches have been tested to compare the response characteristics and the speed control performances. The specifications of the motor and the parameters of controllers in this paper are shown in Table 2.

Table 2. Motor parameters.

R_s	0.12Ω	L_d	**0.0014 H**
ϕ_f	0.12 Wb	**Ω**	157 rad/s
P	4	L_q	0.0028 H
f	0.0014	J	0.0011 kgm^2

The performance of the motor when a load torque applied to the machine's shaft is originally set to its nominal value (0N.m) and steps up to 10 N.m at t = 1s. The desired speed 157 rad/sec. For backstepping controllers the gains used is given as follow: $k_{\Omega}^{\prime} = 1200$ and $k_{\Omega} = 0.2$

For Figs. 5 and 6 at t=1.5s we applied a variation of stator inductances with variation of 150% of their rate value and inertia J-s=6.J of their rate value. The main of this test is the sensibility of the different controllers to inductances and inertia.

Figure 6 shows the PMSM speed, torque and currents using SMC, FSMC and I-back SMC controllers. These results can be summarized in the table (3). We can mention a good robustness, fast and smooth dynamic response for PMSM speed control with different techniques proved by speed error turn around zero under high load torque and parameters variations. Stator current presents a good robustness with small oscillation, at time of load torque variation, in FSMC and SMC. Simulation results can show clearly the effectiveness of I-Back-SMC for decreasing chattering during uncertainties and high torque compared with FSMC who gives less performance and present oscillation as in zoom torque and current, can reduce chattering frequency but not enough to give better performance of speed control. Figure 7 presents a stator current results in three phases, it’s clearly see that FSMC present the max drop (-29 to 29) at time of load torque variation compared with SMC and I-Back-SMC (-21 to 21), this last confirm that in high load torque FSMC gives less results.

To illustrate the mathematical analysis and, hence to investigate the performance of the proposed PMSM controllers, Figure 8 present a robustness test, we applied a variation of 200% of stator resistance of their rate value at t=1.5s. We can observe that for FSMC and SMC present a diminution of speed at time of stator resistance variation justified by the Zoom speed compared with I-Back-SMC who gives better results and a fast convergence to the desired speed. These responses illustrate high performances of the proposed techniques combined with sliding mode during transient and steady states.

Table 3. Comparative results.

	SMC	***FSMC***	***I-back-SMC***
Time of reaching (s)	0.003	0.22	0.008
Torque range (N.m)	-1 to 10	0 to 10.5	0 to 14
Max Id Drop (A)	1.2	1.2	0.6
Max Is drop (A)	-21 to 21	-29 to 29	-21 to 21
Chattering reduction	maximum	medium	minimum

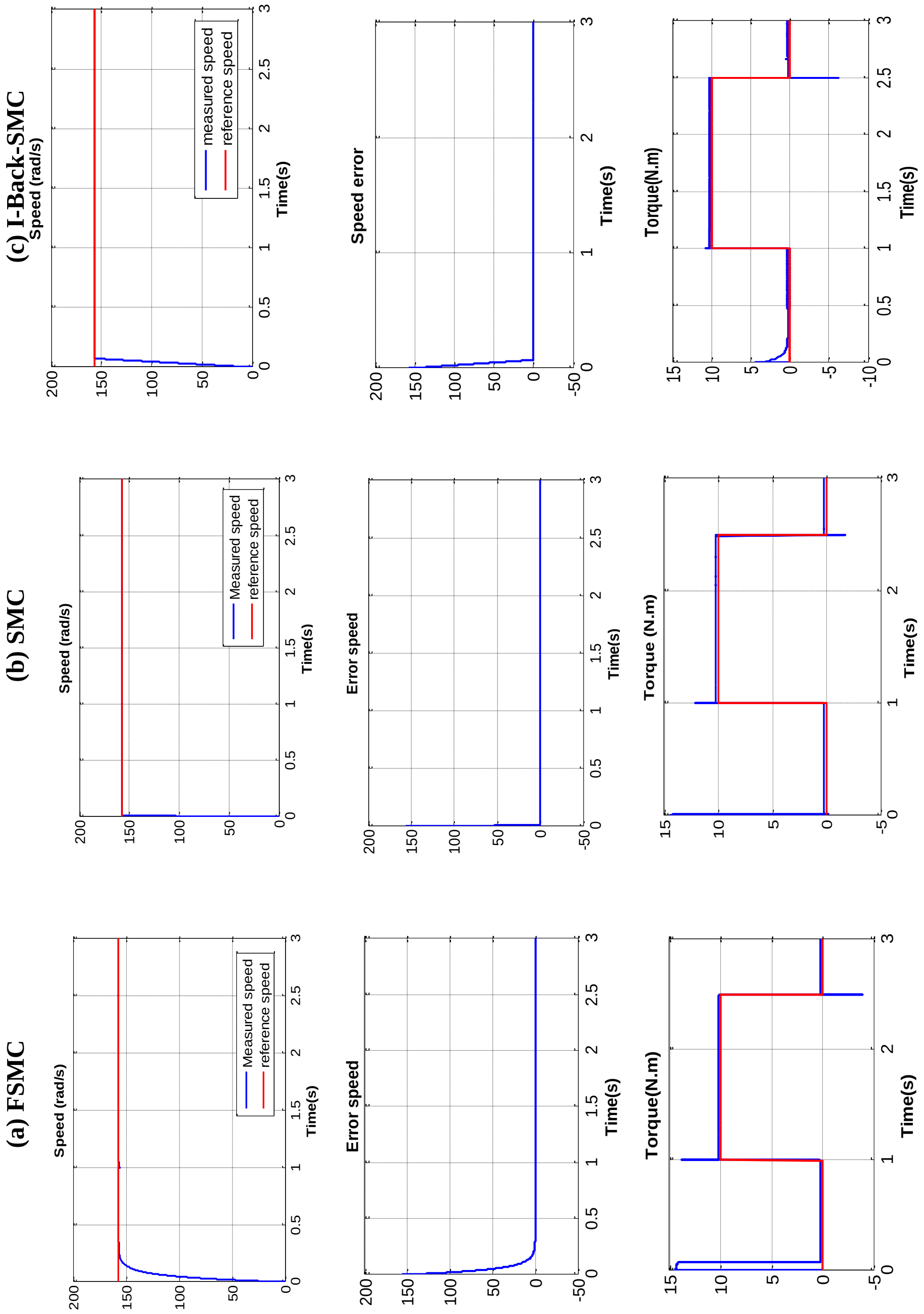

Fig. 6. PMSM speed control using SMC, FSMC and I-Back-SMC.

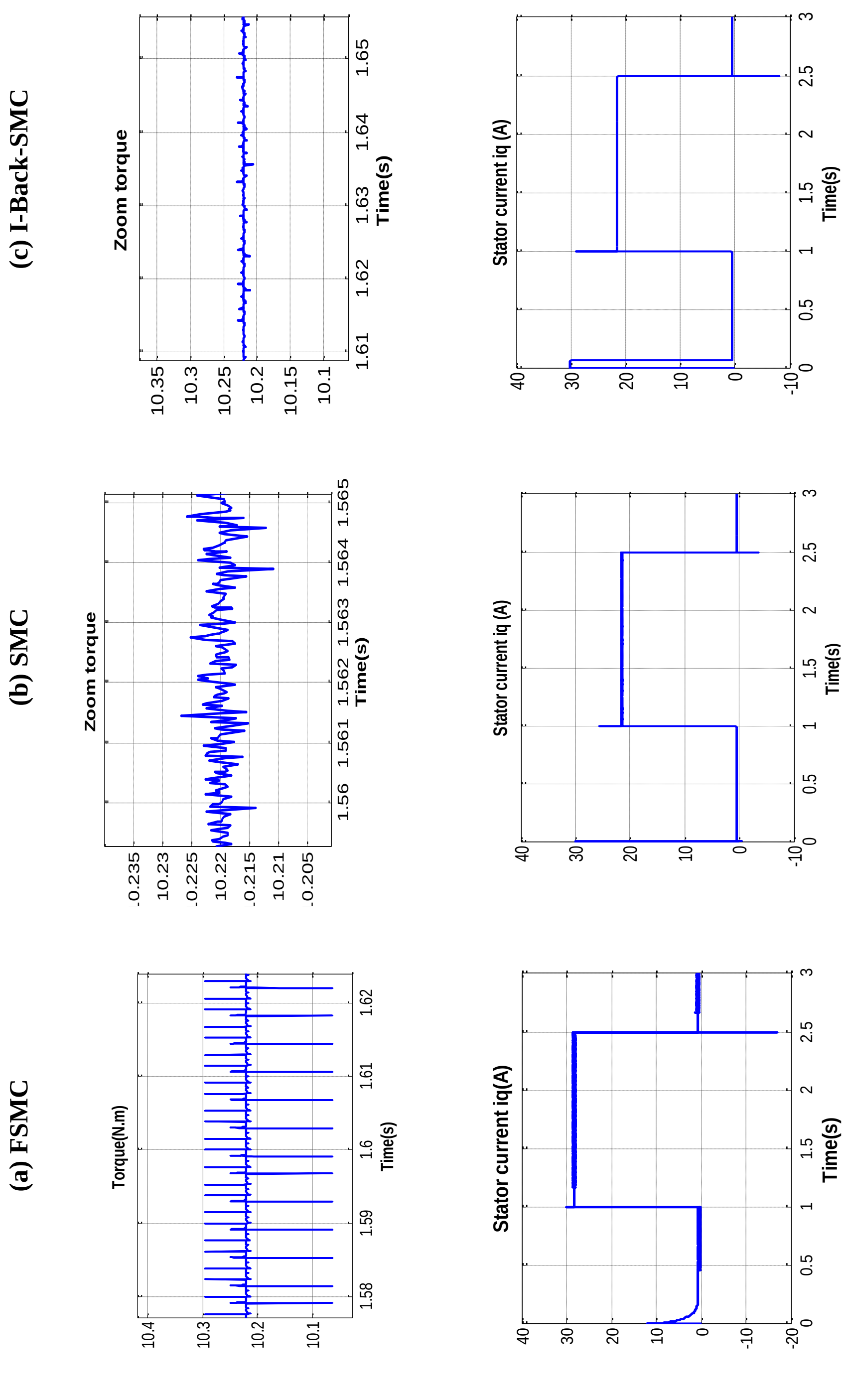

Fig. 6. PMSM speed control using SMC, FSMC and I-Back-SMC. (*continued*).

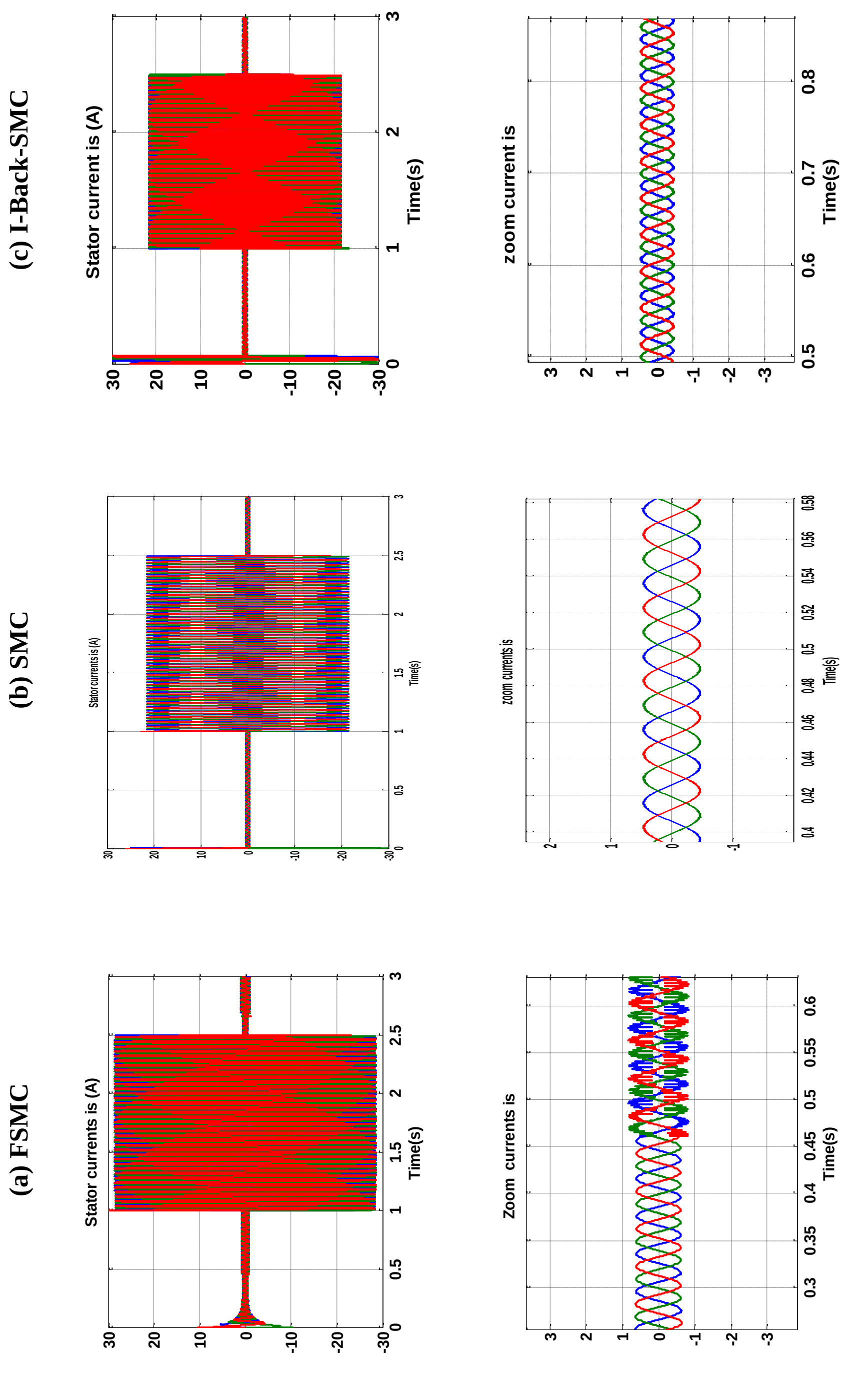

Fig. 7. PMSM speed control using SMC, FSMC and I-Back-SMC.

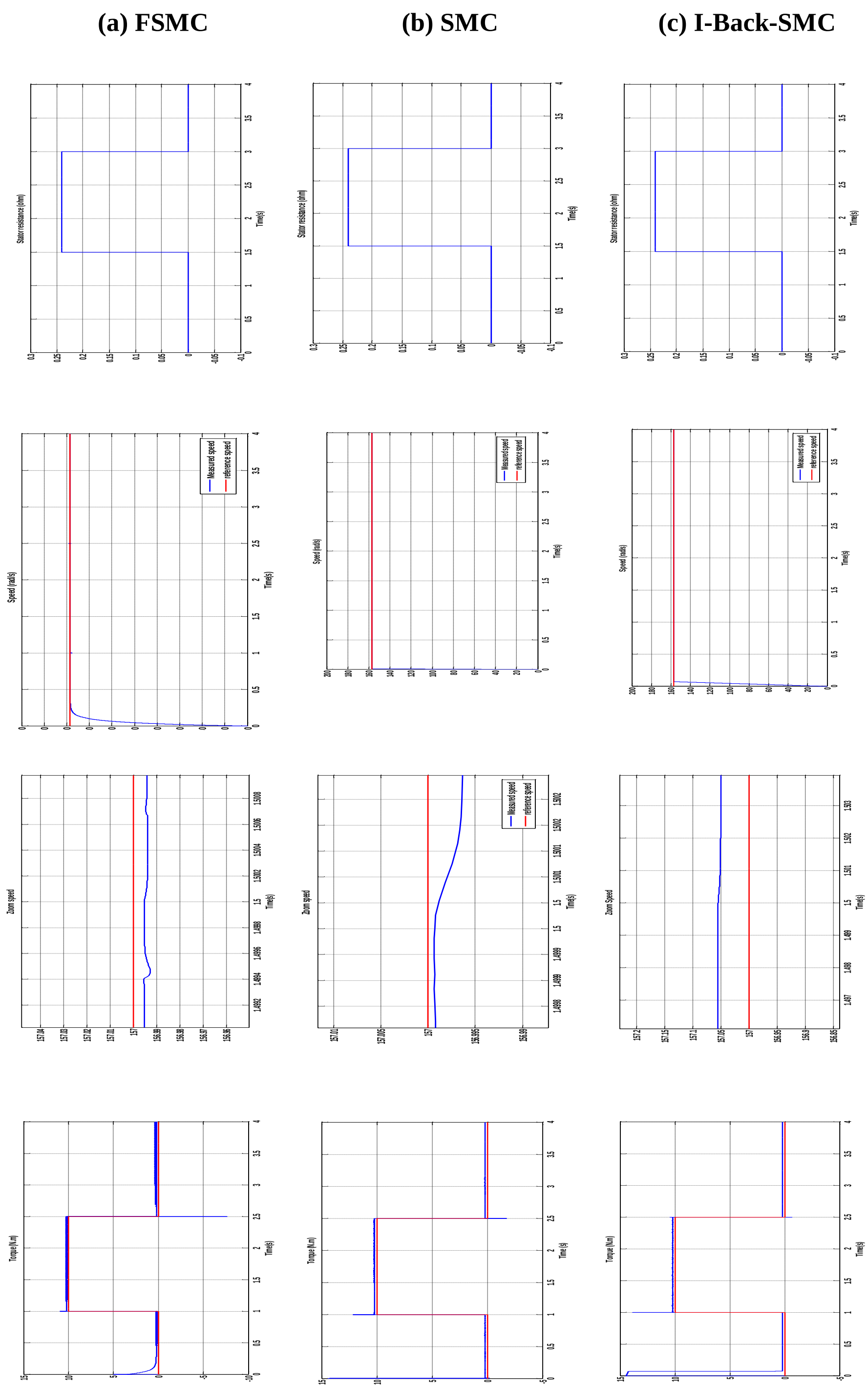

Fig. 8. PMSM speed control using SMC, FSMC and I-Back-SMC.

7. Conclusion

This paper based on Speed control with different methods as integral backstepping controller and Fuzzy logic based sliding mode control for PMSM, which is addressed in part, as a tool for a nonlinear control speed, and in another part as a tool for studying dynamic stability. However, the simulation results exhibited a significant improvement in performance. This improvement manifests itself at the speed of signal quality, and the level of almost total rejection of the perturbation. The main contribution here is to design hybrid control for PMSM, the switched controllers is used to ensure the stability and fastness of the control system. In this work FLC has advantages to decrease chattering in SMC and gives a good robustness with a high load torque but in our case in the same conditions with I-Back is simple, easy and gives better results in robustness test justified by zoom currents, stator resistance and load torque. Compared to the conventional FLC simulations results illustrate the superiority of the proposed I-Back and gives a perfect combination with SMC in the aspects of computation, stability and robustness performance.

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