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ORIGINAL ARTICLE

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Control of a permanent magnet synchronous motor with a fuzzy sliding-mode controller

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Abstract This paper is concerned with the topics in the speed control of a permanent magnet synchronous motor (PMSM). First, the vector control scheme in the synchronously rotating reference frame is used to formulate the PMSM model as the system plant. Then, the modern control theory using a sliding mode with fuzzy controller is presented to design the corresponding closed-loop system and Matlab/Simulink software is used for computer simulation. The original PMSM is stable, sluggish with large overshoot deficiency. It can be shown that the proposed fuzzy sliding-mode controller not only can delete the overshoot problem and achieve very good tracking performance without zero steady-state errors, but can also obtain good robustness to system parameter uncertainty. This proposed fuzzy-sliding mode controller for PMSM can be applied to the positioning control of the robot arms to suppress unnecessary vibrations. For assembly lines, this proposed controller can be used to obtain fast tracking ability, less steady-state errors, and robustness for different velocity movements.

Keywords Permanent magnet synchronous motor · Fuzzy controller · Fuzzy sliding-mode controller

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1 Introduction

Permanent magnet synchronous motors are being increasingly used in a wide range of applications because of their high power density and efficiency. A comprehensive comparison of performance was made for the various motors under different operating conditions from previous research. The PMSM was observed to possess the inherent advantages of high efficiency, power factor, and it also does not have copper losses of rotor winding. As a result, the PMSM has been the study object by many currently researchers, such as [1] who have successfully applied the field-oriented regulating in the speed control for PMSM.

The torque of PMSMs is proportional to the q-axis current in the synchronous reference frame which is preferred to that in the stationary reference frame. In the conventional proportional-integral (PI) plus decoupling current control, the current control is slow and has overshoots on the speed when the fixed gains are used [2–4]. In this kind of classical control, most of the automatic control problems are usually solved by mathematical tools based on the system models. But in the real world, there are many complex industrial processes whose real models cannot be easily developed. Hence, a fuzzy logic controller [5] using linguistic information is applied to model the qualitative aspects of human knowledge, providing an alternative to conventional control techniques. It also possesses robustness, model-free, universal approximation theorem and rule-based algorithm [6]. A performance comparison of the conventional PI and fuzzy controllers is provided for the speed control as shown in [7–9]; the experiments and simulation results both confirm that the proposed fuzzy control approach provides better tracking and disturbance rejection performance than the conventional one.

But the fuzzy controller has a disadvantage. The amount of rule base of the fuzzy controller is bigger when the sensitivity of the output is high, and how to reduce memory capacity is crucial. In this paper, a new method for controlling a synchronous permanent magnet motor using a sliding-mode with fuzzy controller design is presented.

Regardless of small or big angular velocity during the movements of the PMSM, it proves that the proposed fuzzy-sliding mode control is robust for uncertain items of the system modes by effectively suppressing vibrations.

2 The plant model of PMSM

By using a synchronously rotating reference frame as shown in Fig. 1, the voltage, current, and flux linkages of the three phases of the stator can be transferred to direct-axis, quadrature-axis, and zero-sequence components, respectively. Because the three phases are in equilibrium states, based on the q-d axis synchronously rotating reference frame, the voltage equation of the PMSM can be obtained as follows [10]:

$$V_{qs}^{e} = r_s i_{qs}^{e} + \frac{d}{dt}\lambda_{qs}^{e} + \omega_e \lambda_{ds}^{e} \tag{1}$$

$$V_{ds}^{e} = r_s i_{ds}^{e} + \frac{d}{dt}\lambda_{ds}^{e} - \omega_e \lambda_{qs}^{e} \tag{2}$$

where

$$\lambda_{ds}^{e} = L_d i_{ds}^{e} + L_{md} I_{fd} = L_d i_{ds}^{e} + \lambda_{fd} \tag{3}$$

$$\lambda_{qs}^{e} = L_q i_{qs}^{e} \tag{4}$$

v_{qs}^{e}, v_{ds}^{e} : the q-axis and d-axis equivalent stator voltage,
i_{qs}^{e}, i_{ds}^{e} : the q-axis and d-axis equivalent stator current,
L_q, L_d: the q-axis and d-axis equivalent self-inductances,
λ_{qs}^{e}, λ_{ds}^{e} : the q-axis and d-axis equivalent flux linkages,
λ_{fd} : the rotor equivalent flux linkages,
I_{fd}: the d-axis equivalent excitation current,
L_{md}: the d-axis equivalent stator mutual inductance,

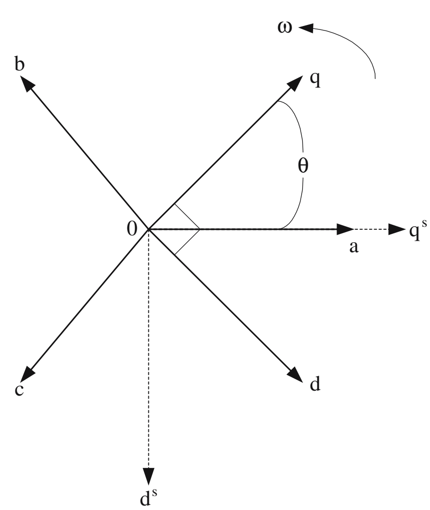


Fig. 1 Relationship between three-phase abc and synchronously rotating reference frame qdo

r_s: the equivalent stator winding resistance,
ω_e: the angular speed of rotor in electrical radians per second,

The transient output power p_s, and output torque T_e of the three-phase stator can be defined as:

$$p_s = v_a i_a + v_b i_b + v_c i_c = \frac{3}{2}\left(v_q i_q + v_d i_d\right) \tag{5}$$

$$T_e = \frac{3}{2}\frac{P}{2}\left[\left(L_d - L_q\right) i_{ds}^{e} i_{qs}^{e} + \lambda_{fd} i_{ds}^{e}\right] \tag{6}$$

$$T_e = \frac{3}{2}\frac{P}{2}\left(\lambda_{ds}^{e} i_{qs}^{e} - \lambda_{qs}^{e} i_{ds}^{e}\right) \tag{7}$$

and the dynamic equation of the motor is:

$$T_e = T_L + B_m \omega_m + J_m \dot{\omega}_m \tag{8}$$

where

P: the number of poles of the motor,
T_L: the load torque of the motor,
B_m: the motor viscous friction coefficient,
J_m: the rotor inertia of the motor,
ω_m: the angular speed of rotor in mechanical radians per second,
θ_m: the mechanical angle,

The state space equation can be found as:

$$\dot{i}_{qs}^{e} = \frac{1}{L_q}\left(v_{qs}^{e} - r_s i_{qs}^{e} - \omega_e L_d i_{ds}^{e} - \omega_e \lambda_{fd}\right) \tag{9}$$

$$\dot{i}_{ds}^{e} = \frac{1}{L_d}\left(v_{ds}^{e} - r_s i_{ds}^{e} + \omega_e L_q i_{qs}^{e}\right) \tag{10}$$

$$\dot{\omega}_m = \frac{1}{J_m}\left(T_e - T_L - B_m \omega_m\right) \tag{11}$$

$$\dot{\theta}_m = \omega_m \tag{12}$$

3 The speed field-oriented control of the PMSM

The speed closed-loop control of the PMSM is shown in Fig. 2. The rotor of the PMSM is the permanent magnet and the flux linkage is constant. The d-axis stator current command is set to zero, and the motor torque can be controlled by the q-axis stator current. This block diagram includes speed controller, q-axis stator current controller, d-axis stator current controller, voltage decouping unit, the transformation unit between synchronously rotating reference frame and three phase static axis, and the inverter driver unit. The inverter driver unit adopts the sinusoidal pulse

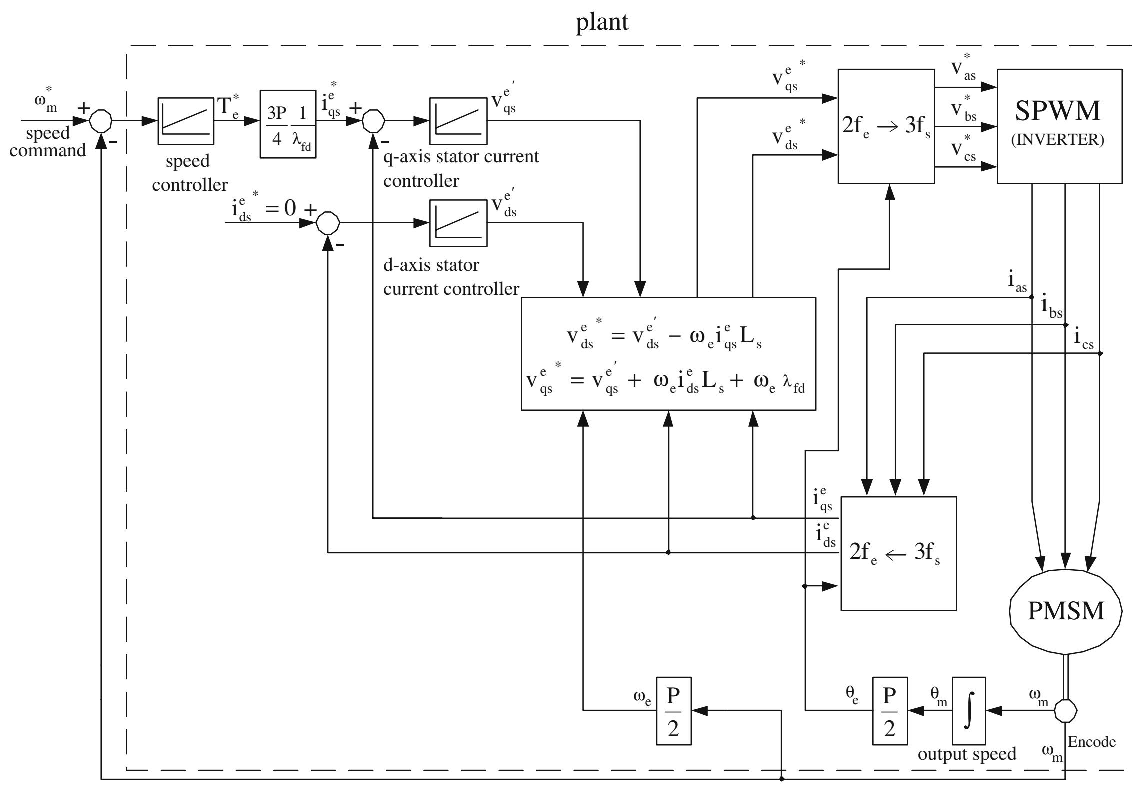


Fig. 2 Speed field-oriented control in the closed loop of PMSM

width modulation (SPWM). The simulation plant is also shown in Fig. 2.

The parameters of the PMSM [11] and the corresponding speed step transient responses of the PMSM are presented as Table 1 and Fig. 3, respectively. It can be seen that the system is stable but there exists large overshoot deficiency.

4 Fuzzy sliding-mode control theory and design

4.1 Fuzzy control

The speed fuzzy control of the PMSM is shown in Fig. 4. The system input is$r$, output is y, and the error is $e = r - y$. The error and the error rate are adjusted so that their values will lie in the range of the membership function. The fuzzy output inferred is converted into clear values, and the center of gravity for the defuzzifier is adopted. A proportional coefficient is used to accommodate with the system output [6]. The triangles as shown in Fig. 5 are chosen for the membership functions for three linguistic variables. The definition of the input and output linguistic terms will define the

Table 1 The parameters of 1hp Y-connection three-phase revolving PMSM

Symbol	Title	Unit	Numerical
V_{rated}	Rated voltage	Vrms	220
r_s	Stator equivalent winging resistance	Ω	4.67
λ_{fd}	Rotor equivalent flux linkages	wb	0.06325
B_m	Motor viscous friction coefficient	N·m/rad/s	0.00013263
N_{rated}	Rated speed	rpm	1800
L_s	Stator self-inductance	H	0.04494
P	The number of poles	poles	4
J_m	Rotor inertia of motor	kg·m^2	0.0000457

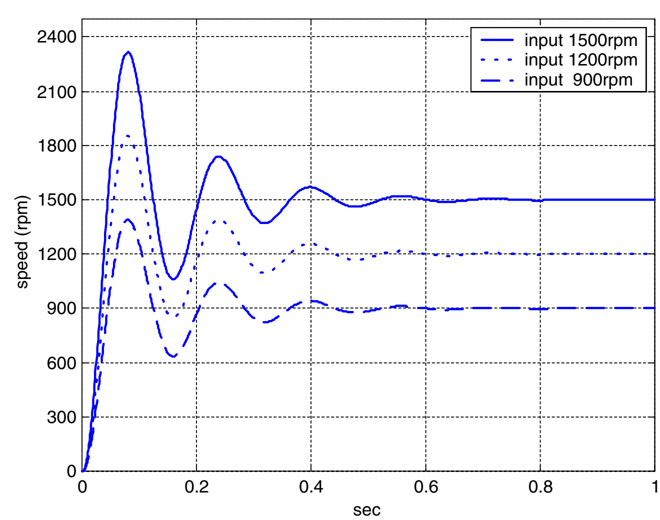
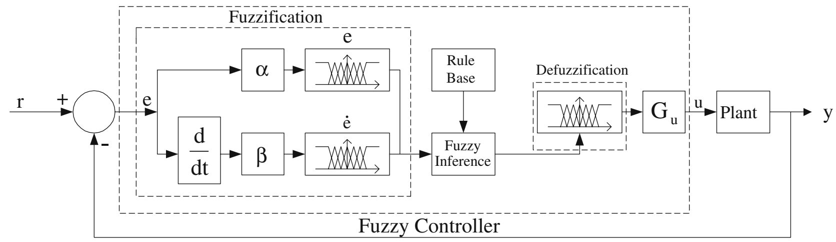


Fig. 3 The transient response of the original system

Fig. 4 The speed control with fuzzy controller for PMSM



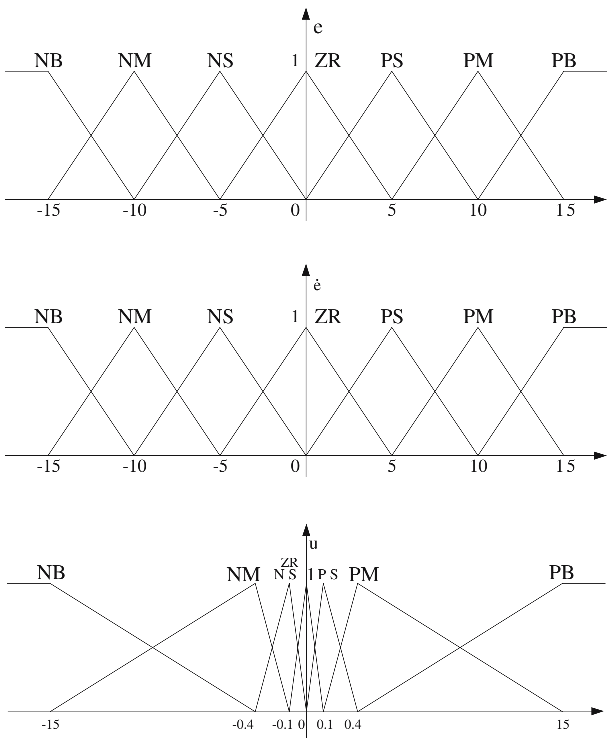


Fig. 5 The membership function of three linguistic variables (e, ė and u)

three linguistic variables onto seven linguistic terms. All linguistic variables are defined as follows:

$$T(e) = \{NB, NM, NS, ZR, PS, PM, PB\} \\ = \{-15, -10, -5, 0, 5, 10, 15\} \quad (13)$$

Table 2 7×7 fuzzy rule base

		e (error)						
		NB	NM	NS	ZR	PS	PM	PB
ė	PB	ZR	PS	PM	PB	PB	PB	PB
	PM	NS	ZR	PS	PM	PB	PB	PB
	PS	NM	NS	ZR	PS	PM	PB	PB
	ZR	NB	NM	NS	ZR	PS	PM	PB
	NS	NB	NB	NM	NS	ZR	PS	PM
	NM	NB	NB	NB	NM	NS	ZR	PS
	NB	NB	NB	NB	NB	NM	NS	ZR

$$T(\dot{e}) = \{NB, NM, NS, ZE, PS, PM, PB\} \\ = \{-15, -10, -5, 0, 5, 10, 15\} \quad (14)$$

$$T(u) = \{NB, NM, NS, ZE, PS, PM, PB\} \\ = \{-15, -0.4, -0.1, 0, 0.1, 0.4, 15\} \quad (15)$$

where *NB* Negative Big, *MM* Negative Medium, *NS* Negative Small, *ZR* Approximately Zero, *PS* Positive Small, *PM* Positive Medium, and *PB* Positive Big. The corresponding fuzzy rule base is shown in Table 2.

The system transient response for a step input is shown in Fig. 6. It can be seen there exists overshoot and the response is sluggish. The fuzzy sliding-mode controller will be employed to improve this insufficiency.

4.2 Fuzzy sliding-mode control

Fuzzy sliding-mode control is a variable structure system. It is combined with fuzzy and sliding surface. Three sufficient and necessary conditions of sliding-mode controller are shown in Fig. 7 and described as follows [12]:

– Approaching condition: No matter what the state trajectory of the system, x(0), begins, at finite time interval, the state will approach to the sliding surface, s (x)=0.

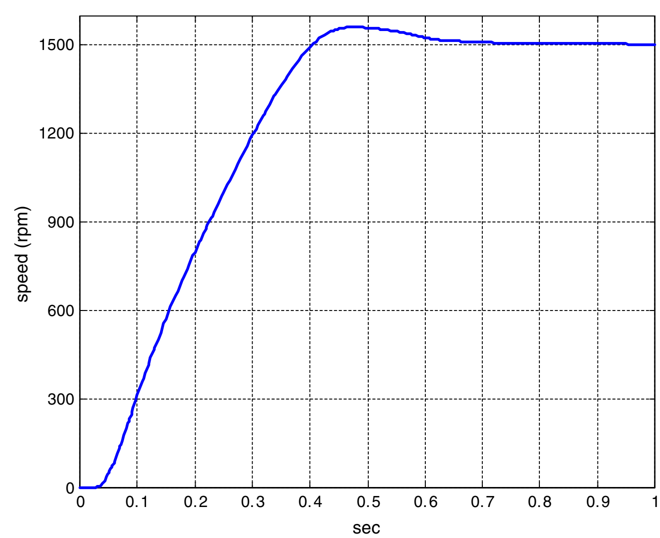


Fig. 6 The transient response of PMSM with fuzzy controller for a 1,500 rpm input

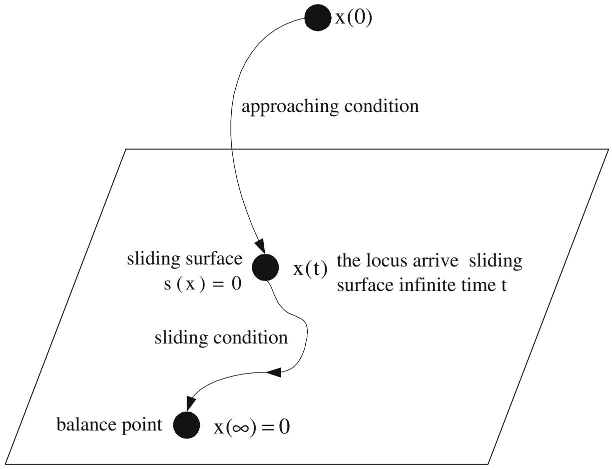


Fig. 7 Approaching and sliding conditions of sliding-mode system

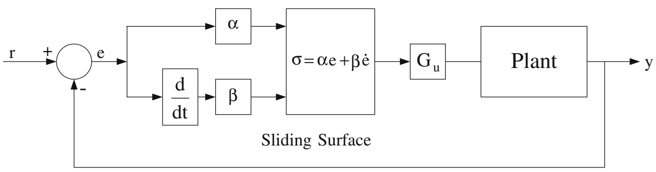


Fig. 8 The speed control with sliding-mode controller for PMSM

– Sliding condition: When the state trajectory reaches to sliding surface, the state will slide in the plan and approach to the equilibrium point.
– Stable: The final state will arrive at stable point, x(∞)=0. This is so called the equilibrium point.

4.3 Control scheme approval

Assuming that a sliding surface is as shown in Fig. 8,

$$\sigma = \alpha e + \beta \dot{e} = 0 \tag{16}$$

where α ≥ 0, β ≥ 0 and

$$e = r - y \tag{17}$$

$$\dot{e} = r - \dot{y} \tag{18}$$

where *r* is the objective value, *y* is the system actual output, *e* is the error.

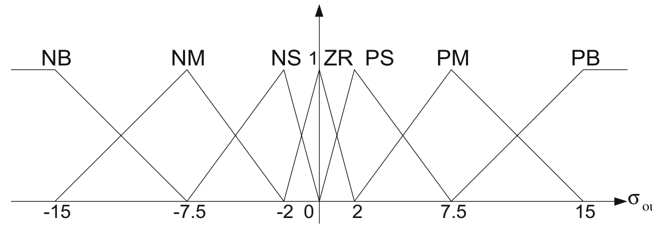


Fig. 10 The membership functions for the input of the fuzzification

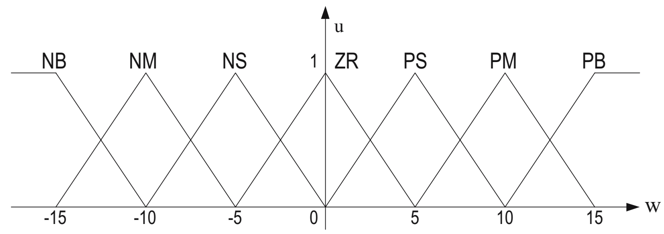


Fig. 11 The membership functions for the input of the defuzzification

If the state is in the sliding surface

$$\sigma(t) = \alpha(r - y) + \beta\left(-\dot{y}\right) = 0 \tag{19}$$

By using Laplace transform with step input,

$$\alpha\left[\frac{r}{s} - Y(s)\right] - \beta s Y(s) = 0 \tag{20}$$

$$\alpha\frac{r}{s} = (\alpha + \beta s)Y(s) \tag{21}$$

From inverse Laplace transform

$$\frac{Y(s)}{r} = \frac{1}{s} + \frac{-1}{s + \frac{\alpha}{\beta}} \tag{22}$$

and get

$$y(t) = r - re^{-\frac{\alpha}{\beta}t} \tag{23}$$

$$\lim_{t\to\infty} y(t) \approx r. \tag{24}$$

By choosing suitable values of α and β, it can be shown that at finite time, the final state of the system output will

Fig. 9 The speed control with fuzzy sliding-mode controller for PMSM

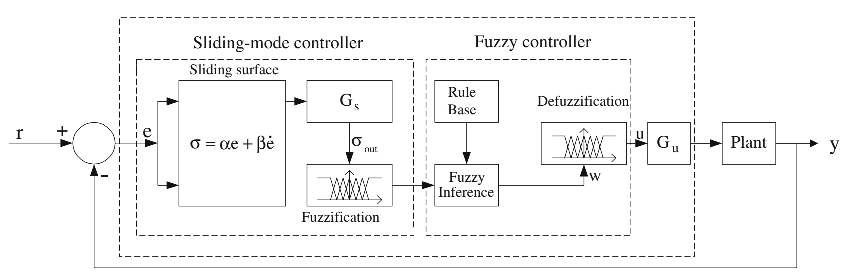


Table 3 The rule base of fuzzy sliding-mode controller

Input variable σ_{out}	NB	NM	NS	ZR	PS	PM	PB
Output variable u	NB	NM	NS	ZR	PS	PM	PB

approach to the objective value. For example, if we want the system to get 99% of that value at finite time 0.8 s, then

$$\frac{y}{r} = 1 - e^{-\frac{\alpha}{\beta}t} = 1 - e^{-\frac{\alpha}{\beta}(0.8)} \geq 0.99 \tag{25}$$

By choosing $\frac{\alpha}{\beta} = 6$, then

$$\frac{y}{r} = 1 - e^{-6(0.8)} = 0.99177 \geq 0.99 \tag{26}$$

where $\frac{\alpha}{\beta}$ is the slope of the sliding surface.

This result of the simulation will be shown in the next section.

The sliding-mode controller combines with the fuzzy controller as shown in Fig. 9. The error e and error rate ė are combined to be one variable for the sliding surface. Instead of using two variables for setting up fuzzy rule base on the fuzzy controller, this corresponding value will be the input for constituting the fuzzy sliding-mode rule base. This means that in the fuzzy controller, the 7×7 rule base will be reduced to only a 7×1 rule base.

The triangles as shown in Figs. 10 and 11 are chosen for the membership functions [13] of the two linguistic variables, the input of the fuzzification and the defuzzification are as follows:

$$T(\sigma_{out}) = \{NB, NM, NS, ZR, PS, PM, PB\} = \{-15, -7.5, -2, 0, 2, 7.5, 15\} \tag{27}$$

$$T(w) = \{NB, NM, NS, ZE, PS, PM, PB\} = \{-15, -10, -5, 0, 5, 10, 15\} \tag{28}$$

The rule base of fuzzy sliding-mode controller is as shown in Table 3.

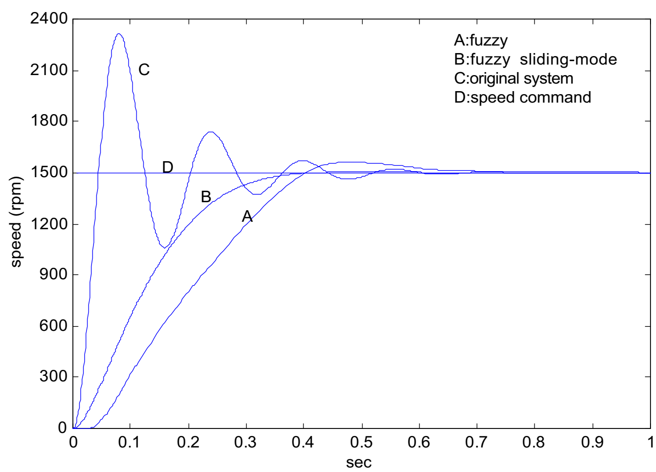


Fig. 12 Transient response comparison for a step input 1,500 rpm

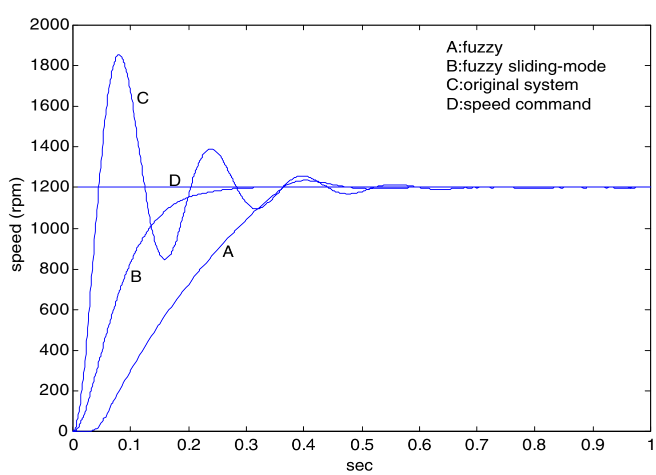


Fig. 13 Transient response comparison for a step input 1,200 rpm

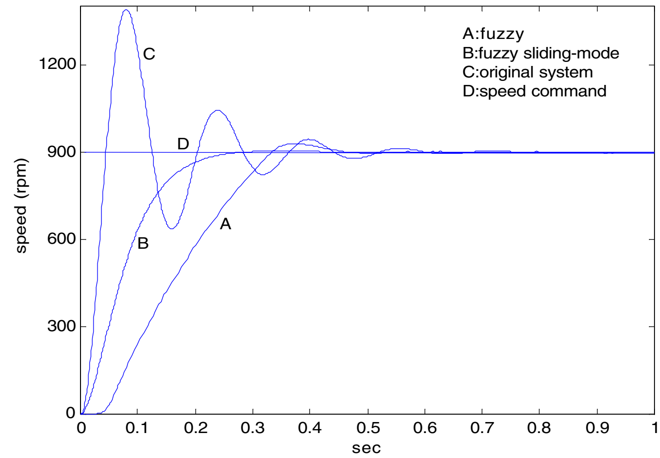


Fig. 14 Transient response comparison for a step input 900 rpm

5 Simulation results

The system transient responses of fuzzy and fuzzy sliding-mode controllers for a step input 1,500, 1,200, and 900 rpm are as shown in Figs. 12, 13, 14, respectively. The objective of the system is to get 99% of the objective value at finite time 0.8 s. The fuzzy control uses 7×7 fuzzy rule base, and the proposed fuzzy sliding-mode controller only uses 7×1 rule base. In fuzzy control, the average settling time is 0.7 s, but in the proposed fuzzy-sliding control, the average settling time is 0.35 s. These transient responses of the proposed fuzzy-sliding mode control systems do not exhibit any overshoots; that is, the outputs never exceed their final values during the transients. The proposed fuzzy-sliding mode control system can minimize the settling time, make precise tracking property, and eliminate steady-state errors with better time optimal control. This advanced precisely manufactured technology of the proposed PMSM controller is very suitable in robotics or assembly when one wants to push the state-of-the-art with faster and more accurate velocity profile of the control systems.

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