Speed Control of Switched Reluctance Motor using Adaptive Fuzzy Backstepping Sliding Mode Control

Case Study

Nha Phi Hoang
Ha Noi University of Industry
Ha Noi capital, Viet Nam
nhaph@haui.edu.vn

Hung Pham Van
Ha Noi University of Industry
Ha Noi capital, Viet Nam
phamvanhung@haui.edu.vn

Abstract *– The Switched Reluctance Motors (SRMs), with many outstanding advantages, are gradually being widely applied in industries, households, and recommended in many works. However, most studies in the field of SRM control only concentrate on the mathematical model of the motor itself, neglecting the nonlinearity introduced by the inverter, which is responsible for switching between phases to drive the motor. This paper proposes an adaptive backstepping sliding mode control algorithm based on the SRM nonlinear model that combines both the motor and the inverter. Firstly, a backstepping sliding mode controller is used to track the desired value and ensure the stability of the system according to the Lyapunov criterion. Secondly, a fuzzy logic system is added to adjust the controller parameters to account for uncertainty and external disturbance, as well as to minimize the chattering phenomenon. Finally, a few simulation scenarios are performed to assess the effectiveness of the proposed controller. The simulation results clearly demonstrate that the proposed controller surpasses the previously published H infinity controller in terms of speed control quality for the combined nonlinear model of SRM. The proposed controller exhibits zero steady-state error, zero overshoot, and a short settling time of approximately 0.5 seconds. Moreover, the system's output quickly stabilizes when affected by disturbance noise.*

Keywords: *switched reluctance motors, adaptive control, backstepping sliding mode control, fuzzy logic system*

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1. INTRODUCTION

Switched reluctance motor have been proposed since 1946, and there are two types: rotary switched reluctance motors (SRMs) and linear switched reluctance motor (LSRM). Both types consist of a stator and rotor, with windings only on the stator poles, and they do not use permanent magnets. These motors operate through an inverter, which switches between phases.

SRMs offer several advantages due to their operational principles and structure [1]. These advantages include a high starting torque [2], a simple structure, low manufacturing costs, and high stability [3]. As a result of these benefits, SRMs are gradually finding wider applications, particularly in the field of electric vehicles for tourism [4]. However, SRMs also come with certain drawbacks, including significant pulsating torque [5], challenging control requirements, and high nonlinear characteristics [6]. The strong nonlinearity of SRMs can be attributed to their inherent structure, combined with the phase-switched converter, which introduces resonance nonlinearity [7]. The inherent structure of SRMs, in conjunction with the phase-switched converter, contributes to the pronounced nonlinearity of these motors. Consequently, when controlling an SRM, it is crucial to consider the impact of nonlinearities in the motor's kinetics, arising from the simultaneous excitation of stator phases [8]. Addressing this issue poses a key challenge that needs to be resolved [9]. Several studies have proposed mathematical models for SRMs and control strategies for switched reluctance motor drive systems based on these models [10-24]. While [10, 17, 24] address the basic learning model of the SRM, [11] presents the nonlinear model of the switched reluctance motor with consideration of the influence of mutual inductance between phases. The issue of flux is also mentioned in [12, 13], where the authors use third-order Fourier series analysis to approximate the flux curve and compare it with the flux characteristic in the Matlab library. Then, direct torque control is applied to improve the control quality of hybrid electric vehicle systems using SRM. However, due to the difficulty in determining the flux characteristics caused by unknown parameters, the process of determining the SRM model encounters difficulties. Therefore, the authors in [14, 18] linearized this characteristic, while [15] used a neural network to identify the model. Related to the modeling of the switched reluctance motor, the document [16] considers the friction coefficient in the model and proposes the ovel Direct Instantaneous Torque Control (DITC) to reduce torque ripple. In the field of SRM control, [19] proposes the use of a PID controller combined with a genetic algorithm applied to the linear SRM model to achieve good control performance. However, it should be noted that the SRM model used in this study is an ideal case taken from the Matlab library. Another approach investigated in the literature is the application of predictive control combined with torque control to optimize flux, as studied in [22]. This method aims to enhance the performance of SRM control by considering both torque and flux optimization.

Additionally, there are other research directions exploring sensorless SRM control using nonlinear state observers, as mentioned in [20] and [23]. These methods aim to achieve control without the need for external sensors, relying on observer-based techniques to estimate the motor's states. Furthermore, the use of sliding mode observers for SRM control is discussed in [21]. Sliding mode control is a robust control technique that can handle system uncertainties and disturbances effectively. However, the majority of these studies have primarily concentrated on the mathematical model of the motor itself, overlooking the nonlinearity introduced by the inverter. In this paper, we aim to develop a control algorithm for the nonlinear model of SRM that takes into account both the motor and the inverter.

The research group led by Rigatos was the first to publish a comprehensive mathematical model that incorporates both the motor and the switch (inverter) [25]. However, their approach treated the SRM as a combined linear model for control algorithm design. Specifically, they used the H infinity nonlinear feedback controller for the combined linear model of SRM and proved its stability using Lyapunov theory, but the consideration of nonlinearity was incomplete. However, there are still some limitations in the control quality of the SRM system, specifically regarding large overshoot (around 20%) and long settling time (around 7 seconds). In particular, when changing the setpoint value, the overshoot can reach up to 50%. Building on this research [25], we retained the combined model of SRMs and applied an adaptive Backstepping sliding mode control algorithm to enhance the performance of the SRM drive system.

Several published works, including references [26-29], have employed the Backstepping nonlinear algorithm for speed control of SRMs. The Backstepping algorithm for SRMs was first introduced in [27], where a Backstepping controller combined with a state observer was proposed to stabilize the speed control. Subsequently, [26] further proposed a Backstepping control scheme combined with a state observer to achieve speed stabilization. In [28], the Backstepping algorithm was presented for SRM control considering the saliency effect. Additionally, the Backstepping technique was used in [29] to reduce circuit current ripple and improve control performance. However, it has been observed that the Backstepping control algorithm has limited adaptability to slow load noise. In the most recent research [30], a Backstepping combined sliding mode controller is chosen to address this limitation. However, the sliding control coefficient of the controller is quite difficult to select and maintain fixed during the control process, leading to limitations in the ability to respond quickly and reduce vibration for the SRM when the sliding controller changes state at the working point. To overcome this difficulty, this paper proposes the use of a fuzzy controller to flexibly adjust the parameters of the sliding control signal. By incorporating fuzzy controller into Backstepping combined sliding mode controller, the sliding surfaces can be adjusted automatically to limit the chattering phenomenon that can be caused by using the function sgn(S) and a model that includes a switch. Consequently, this paper proposes the use of a backstepping adaptive control algorithm based on fuzzy logic to address the aforementioned issues and improve control quality, even in the presence of significant noise.

Following the introductory section, the paper proceeds to present the combined nonlinear model of the SRM in Section 2, and subsequently introduces the adaptive backstepping sliding mode control algorithm based on the fuzzy logic system in Section 3. Finally, in Section 4, the simulation results obtained with the proposed controller are presented. This section evaluates various performance metrics such as settling time, overshoot, and steady-state error under different load and speed setpoint.

2. THE COMBINED NONLINEAR MODEL OF SWITCHED RELUCTANCE MOTORS

In this specialized research paper on SRM control, the mathematical model of SRMs is derived from the fundamental equations of electrical machines. The dynamics of reluctance motors include equations of voltage, equation of torque and equation of mechanics, which are represented as in (1)

$$\begin{cases} u_j = R.i_j + \dfrac{d\psi_j}{dt} \\ T_j(\theta, i_j) = \dfrac{\partial W_j^{'}}{\partial \theta} \\ J\dfrac{d^2\theta}{dt^2} = T_e - T_l \end{cases} \tag{1}$$

where j = 1, 2, 3, 4. (consider with 4-phase switching reluctance motor). In (1), uj is the voltage of phase j, R is the resistance of phase j, i_j is the current of phase j, θ is the rotor angular, T_j is the torque of phase j, the load torque T_l, the moment of inertia J and ψ_j is flux of phase j in, determined by (2)

$$\psi_j = \int_0^{2\pi} (u_j - R.i_j)dt \quad (2)$$

The magnetic field counterpart, W'_j, is determined by (3)

$$\partial W'_j(\theta, i_j) = \int_0^{i_j} \psi_j(\theta, i_j)di_j \quad (3)$$

Which is a nonlinear function of current if the magnetic circuit is linear, the total torque T_e produced is equal to the sum of moments in the phases, as expressed in (4).

$$T_e(\theta, i_1, i_2, i_3, i_4) = \sum_{j=1}^{4} T_j(\theta, i_j) \quad (4)$$

To effectively control the switched reluctance motor, it is crucial to accurately determine the magnetic flux characteristic, denoted as $\psi_j(\theta, i_j)$. For ease of research and development of control algorithms, it is common to approximate the magnetic flux characteristic as a continuous function, as demonstrated in reference [31], which can be expressed as follows:

$$\psi_j(\theta, i_j) = \psi_s(1 - e^{-i_j f_j(\theta)}) \quad (5)$$

where j = 1, 2, 3, 4, ψ_s represents the saturation flux. The equation is also used in [32] and [33] for online parameter identification of the model and performance optimization in angle control. If we ignore the higher - order components in the Fourier series, we get the function $f_j(\theta)$ in (6)

$$f_j(\theta) = a + b\sin[N_r\theta - (j-1)\frac{2\pi}{n}] \quad (6)$$

where N_r is the number of rotor poles, n represents the number of phases, while a and b are coefficients obtained through the transformation of the Fourier series [34].

The moment of phase j is expressed as follows

$$T_j(\theta, i_j) = \frac{\psi_s}{f_j^2(\theta)} \frac{df_j(\theta)}{d\theta} \{1 - [1 + i_j f_j(\theta)]e^{-i_j f_j(\theta)}\} \quad (7)$$

To represent the SRM system in a mathematical model with state variables such as position, velocity, and current, we can derive the state space equations from equations (1) and (4). The state space equation of the switched reluctance motor includes the following equations, where ω represents the rotor velocity

$$\begin{cases} \dfrac{d\theta}{dt} = \omega \\ \dfrac{d\omega}{dt} = \dfrac{1}{J}\left\{\sum_{j=1}^{4} T_j(\theta, i_j) - T_l(\theta, \omega)\right\} \\ \dfrac{di_j}{dt} = -\left(\dfrac{\partial\psi_j}{\partial i_j}\right)^{-1}\left(Ri_j + \dfrac{\partial\psi_j}{\partial\theta}\omega\right) + \left(\dfrac{\partial\psi_j}{\partial i_j}\right)^{-1} u_j \end{cases} \quad (8)$$

The state model of the switched reluctance motor drive system is presented below based on [25]. Considering an 8/6 switched reluctance motor with 4 phases the state vector is defined as follows $x = [\theta, \omega, i_1, i_2, i_3, i_4]^T = [x_1, x_2, x_3, x_4, x_5, x_6]^T$. The equation of the motor's state as follows.

$$\dot{x}_1 = x_2 \quad (9)$$

$$\dot{x}_2 = \frac{1}{J}\left[T_1(\theta, x_3) + T_2(\theta, x_4) + T_3(\theta, x_5) + T_4(\theta, x_6) - T_l(x_1, x_2)\right]$$
$$= \frac{1}{J}\begin{bmatrix} \dfrac{\psi_s}{f_1^2(x_1)}\dfrac{\partial f_1(x_1)}{\partial x_1}\left\{1 - [1 + x_3 f_1(x_1)]e^{-x_3 f_1(x_1)}\right\} + \\ \dfrac{\psi_s}{f_2^2(x_1)}\dfrac{\partial f_2(x_1)}{\partial x_1}\left\{1 - [1 + x_4 f_2(x_1)]e^{-x_4 f_2(x_1)}\right\} + \\ \dfrac{\psi_s}{f_3^2(x_1)}\dfrac{\partial f_3(x_1)}{\partial x_1}\left\{1 - [1 + x_5 f_3(x_1)]e^{-x_5 f_3(x_1)}\right\} + \\ \dfrac{\psi_s}{f_4^2(x_1)}\dfrac{\partial f_4(x_1)}{\partial x_1}\left\{1 - [1 + x_6 f_4(x_1)]e^{-x_6 f_4(x_1)}\right\} \\ -Bx_2 - mgl\sin(x_1) \end{bmatrix} \quad (10)$$

and $\dot{x}_3$, $\dot{x}_4$, $\dot{x}_5$, $\dot{x}_6$ are

$$\dot{x}_{j+2} = \left[\psi_s e^{-x_{j+2}f_j(x_1)} f_j(x_1)\right]^{-1} u_j + \left[-\psi_s e^{-x_{j+2}f_j(x_1)} f_j(x_1)\right]^{-1} \left[\left(\psi_s e^{-x_{j+2}f_j(x_1)}\right)\left(x_{j+2}\frac{\partial f_j(x_1)}{\partial x_1}\right)x_2 + Rx_{j+2}\right] \quad (11)$$

$$\frac{\partial f_j}{\partial x_1} = bN_r\cos\left(N_r x_1 - (j-1)\frac{2\pi}{4}\right) \qquad j = 1,2,3,4 \quad (12)$$

It is mentioned that in the state-space description provided above, the term Bx_2 represents the damping effect that opposes the rotational motion of the machine, while $mglsin(x_1)$ corresponds to the mechanical load torque, for instance in the case that the SRM lifts a rod of length l with a mass m attached to its end [25].

From (10) we put

$$g_j(\boldsymbol{x}) = \frac{1}{J}\left[\frac{\psi_s}{f_j^2(x_1)}\frac{\partial f_j(x_1)}{\partial x_1}\left\{1 - e^{-x_{j+2}f_j(x_1)}\right\}\right]$$
$$h_j(\boldsymbol{x}) = \frac{1}{J}\left[\frac{\psi_s}{f_j^2(x_1)}\frac{\partial f_j(x_1)}{\partial x_1}\left\{-f_j(x_1)e^{-x_{j+2}f_j(x_1)}\right\}\right] \quad (13)$$

where j = 1, 2, 3, 4

Equation (10) can be rewritten as

$$\dot{x}_2 = \sum_{j=1}^{4}\left[g_j(\boldsymbol{x}) + h_j(\boldsymbol{x})x_{j+2}\right] - \frac{B}{J}x_2 - \frac{mgl}{J}\sin(x_1) \quad (14)$$

Differentiating equation (14) with respect to time, we get

$$\ddot{x}_2 = \sum_{j=1}^{4}\left[\dot{g}_j(\boldsymbol{x}) + \dot{h}_j(\boldsymbol{x})x_{j+2} + h_j(\boldsymbol{x})\dot{x}_{j+2}\right] - \frac{B}{J}\dot{x}_2 - \frac{mgl}{J}\cos(x_1)\dot{x}_1 \quad (15)$$

From equation (11), we set:

$$p_j(\boldsymbol{x}) = \left[-\psi_s e^{-x_{j+2}f_j(x_1)} f_j(x_1)\right]^{-1}\begin{bmatrix} Rx_{j+2} + \left(\psi_s e^{-x_{j+2}f_j(x_1)}\right) \\ \left(x_{j+2}\frac{\partial f_j(x_1)}{\partial x_1}\right)x_2 \end{bmatrix}$$
$$q_j(\boldsymbol{x}) = \left[\psi_s e^{-x_{j+2}f_j(x_1)} f_j(x_1)\right]^{-1} \quad (16)$$

We can rewrite equations (11) as follows

$$\dot{x}_{j+2} = p_j(\boldsymbol{x}) + q_j(\boldsymbol{x})u_j \qquad j = 1,2,3,4 \tag{17}$$

Replace (17) and (16) into (15), we have

$$\ddot{x}_2 = \sum_{j=1}^{4}\left[\dot{g}_j(\boldsymbol{x}) + \dot{h}_j(\boldsymbol{x})x_{j+2} + h_j(\boldsymbol{x})p_j(\boldsymbol{x}) + h_j(\boldsymbol{x})q_j(\boldsymbol{x})u_j\right] - \frac{B}{J}\dot{x}_2 - \frac{mgl}{J}\cos(x_1)\dot{x}_1 \tag{18}$$

The switched reluctance motor operates on the principle of supplying voltage to each phase. For an SRM with a pole configuration of 8/6 and a phase number of 4, we can derive the following expression for each phase *j*, where *j* can take values 1, 2, 3, or 4.

$$u_j = k_j.u \tag{19}$$

Where k_j represents the phase transition key, it is a variable that can only have the values of 0 or 1. Equation (18) can be reformulatedas follows

$$\begin{aligned}\ddot{x}_2 =& \sum_{j=1}^{4}\left[\dot{g}_j(\boldsymbol{x}) + \dot{h}_j(\boldsymbol{x})x_{j+2} + h_j(\boldsymbol{x})p_j(\boldsymbol{x})\right] \\ &+ \sum_{j=1}^{4}\left[h_j(\boldsymbol{x})q_j(\boldsymbol{x})k_j\right]u - \frac{B}{J}\dot{x}_2 - \frac{mgl}{J}\cos(x_1)\dot{x}_1\end{aligned} \tag{20}$$

Set

$$\begin{aligned}F(\boldsymbol{x}) &= \sum_{j=1}^{4}\left[\dot{g}_j(\boldsymbol{x}) + \dot{h}_j(\boldsymbol{x})x_{j+2} + h_j(\boldsymbol{x})p_j(\boldsymbol{x})\right] \\ G(\boldsymbol{x}) &= \sum_{j=1}^{4}\left[h_j(\boldsymbol{x})q_j(\boldsymbol{x})k_j\right]\end{aligned} \tag{21}$$

We can express equation (20) in a different form as follows

$$\ddot{x}_2 = F(\boldsymbol{x}) + G(\boldsymbol{x})u - \frac{B}{J}\dot{x}_2 - \frac{mgl}{J}\cos(x_1)\dot{x}_1 \tag{22}$$

Set

$$\begin{aligned}f(\boldsymbol{x}) &= \mathrm{F}(\boldsymbol{x}) - \frac{B}{J}\dot{x}_2 - \frac{mgl}{J}\cos(x_1)\dot{x}_1 \\ g(\boldsymbol{x}) &= G(\boldsymbol{x})\end{aligned} \tag{23}$$

We have

$$\ddot{x}_2 = f(\boldsymbol{x}) + g(\boldsymbol{x})u \tag{24}$$

For backstepping to be applied, one must rewrite (23) using a strict feedback form as follows

$$\begin{cases}\dot{z}_1 = z_2 \\ \dot{z}_2 = f(\boldsymbol{x}) + g(\boldsymbol{x})u\end{cases} \tag{25}$$

with *f*(*x*), *g*(*x*) are defined in (23).

Due to the challenges associated with synthesizing a stable speed controller for the switched reluctance motor (SRM), a design method that combines the backstepping technique with fuzzy adaptive sliding control is considered suitable. This is because the nonlinear state model of the SRM, represented by equation (25) in the form of 2nd order tight backpropagation, is highly susceptible to external noise. By combining these techniques, it is possible to effectively address these challenges and improve the overall performance of the SRM speed controller.

3. BACKSTEPPING SLIDING ADAPTIVE CONTROLLER BASED ON FUZZY LOGIC SYSTEM

3.1 SYNTHESIS OF BACKSTEPPING SLIDING MODE CONTROLLER FOR SRM

By utilizing the backstepping and sliding technique, the controller is designed for the nonlinear model (equation 25) as follows

Step 1: Put

$$e_1 = z_1 - z_{1d} \tag{26}$$

where Z_{1d} represents the setpoint of speed. Differentiating equation (26) with respect to time, we get

$$\dot{e}_1 = \dot{z}_1 - \dot{z}_{1d} = \dot{z}_1 - \dot{z}_{1d} \tag{27}$$

Put

$$e_2 = z_2 - \alpha \tag{28}$$

where *α* is the virtual control signal then we have

$$\dot{e}_1 = \dot{z}_1 - \dot{z}_{1d} = e_2 + \alpha - \dot{z}_{1d} \tag{29}$$

To obtain $e_1 \to 0$, we consider the Lyapunov function candidate of e_1 as follows

$$V_1 = \frac{1}{2}e_1^2 \tag{30}$$

Differentiating equation (30) with respect to time, we have

$$\dot{V}_1 = e_1\dot{e}_1 = e_1\left(e_2 + \alpha - \dot{z}_{1d}\right) \tag{31}$$

To have $\dot{V}_1 = -c_1 e_1^2 + e_1 e_2$ with $c_1 > 0$, the virtual control signal is

$$\alpha = -c_1 e_1 + \dot{z}_{1d} \tag{32}$$

Step 2: The sliding surface is defined as follows:

$$S = \mu e_1 + e_2 ; \mu > 0 \tag{33}$$

To ensure a stable closed system and tracking error of zero, we determine the sliding control signal *u*(*t*) by defining a Lyapunov function for the closed system, as shown in equation (34).

$$V = V_1 + \frac{1}{2}S^2 \tag{34}$$

Differentiating equation (34) with respect to time, we have

$$\begin{aligned}\dot{V} &= -c_1e_1^2 + e_1e_2 + S\dot{S} = -c_1e_1^2 + e_1e_2 + S\left(\mu\dot{e}_1 + \dot{e}_2\right) \\ &= -c_1e_1^2 + e_1e_2 + S\left(\mu\dot{e}_1 + f(\boldsymbol{x}) + g(\boldsymbol{x})u - \dot{\alpha}\right) \\ &= -c_1e_1^2 - c_2e_2^2 - KS\,\mathrm{sgn}(S);\ K \geq 0\end{aligned} \tag{35}$$

if

$$e_1e_2 + c_2e_2^2 + S\left(K\,\mathrm{sgn}(S) + \mu\dot{e}_1 + f(\boldsymbol{x}) + g(\boldsymbol{x})u - \dot{\alpha}\right) = 0 \tag{36}$$

Therefore, we select the control signal as depicted in equation (37)

$$u = -\frac{e_2\left(e_1 + c_2 e_2\right)}{S g(\boldsymbol{x})} - \frac{K\,\mathrm{sgn}(S) + \mu \dot{e}_1 + f(\boldsymbol{x}) - \dot{\alpha}}{g(\boldsymbol{x})} \tag{37}$$

Theorem: The proposed controller (37) guarantees asymptotical stability of SRM system with the nonlinear state model (25).

Proof: Choose a Lyapunov function for a closed system of the following form:

$$V = V_1 + \frac{1}{2} S^2 \tag{38}$$

Derivative V with respect to time, we have

$$\begin{aligned} \dot{V} &= \dot{V}_1 + S\dot{S} = -c_1 e_1^2 + e_1 e_2 + S\left(\mu \dot{e}_1 + \dot{e}_2\right) \\ &= -c_1 e_1^2 + e_1 e_2 + S\left(\mu \dot{e}_1 + f\left(\boldsymbol{x}\right) + g\left(\boldsymbol{x}\right) u - \dot{\alpha}\right) \end{aligned} \tag{39}$$

Replace u in (37) into (39), we have:

$$\dot{V} = -c_1 e_1^2 - c_2 e_2^2 - KS\,\mathrm{sgn}(S) \le 0 \tag{40}$$

Therefore, the SRM system is asymptotically stable.

3.2. SYNTHESIS OF BACKSTEPPING ADAPTIVE CONTROLLER FOR SRM BASED ON FUZZY LOGIC SYSTEM

One of the disadvantages of sliding control is the phenomenon known as "chattering," which refers to the shaking of the system when it is close to the working point due to high-frequency sign changes in the control signal function. To overcome this drawback, the paper proposes the addition of a fuzzy logic system to adjust the gain of the sliding control component. The fuzzy logic system used in this paper is based on the Sugeno model [35, 36].

The input to the fuzzy logic system consists of the speed state and angular acceleration of the reluctance motor, while the output is the gain factor.

Each input language variable contains three triangular fuzzy sets with names corresponding to the digitized fuzzy sets [-1 0 1] with values [-10 0 10] belongs to the real number line R, respectively (as shown in Fig. 1). The notation [-1 0 1] represents the linguistic terms [small - zero - big]. One the other hand, the output variables are represented by constants with a digitized name of [-2 -1 0 1 2], which are interpreted as [very small - small - zero - big - very big]. The corresponding real values on the R scale are [2 1 0.01 1 2], as shown in Fig. 2. Furthermore, Table 1 provides the fuzzy tuning rules for the parameter K.

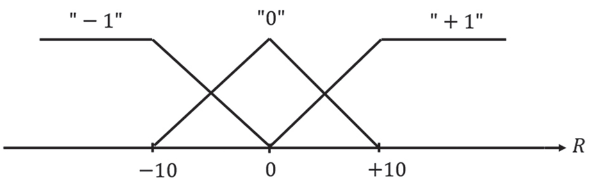


Fig. 1. Fuzzy set of input language variables e_1, $\dot{e}_1$

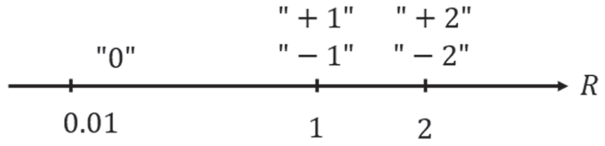


Fig. 2. Constant value for output variable

Table 1. Fuzzy tuning rules for the parameter K

K		e_1		
		-1	0	1
	0	-1	-2	
$\dot{e}_1$	0	1	0	-1
	-1	2	1	0

3.3. CONTROLLER STRUCTURE DIAGRAM

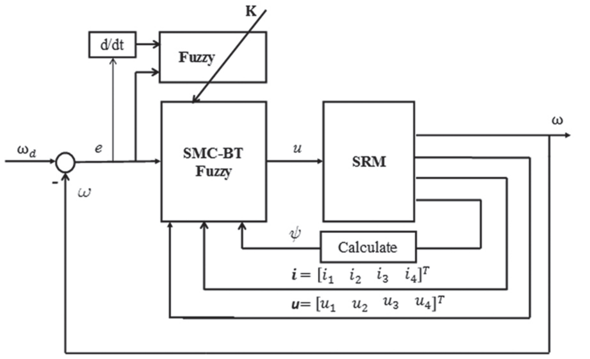
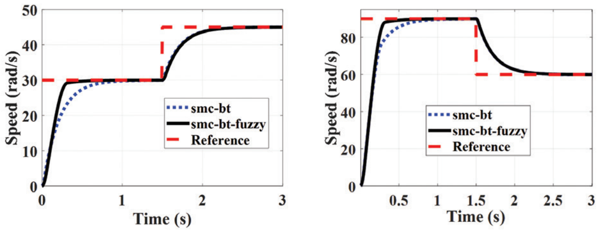


Fig. 3. The proposed control structure diagram for the SRM

Fig. 3 illustrates the structure of the adaptive backstepping sliding mode control algorithm based on a fuzzy logic system for the SRM, as described in sections 3.1 and 3.2. The backstepping sliding mode controller's gain K is adjusted by a fuzzy logic controller to address the phenomenon of "chattering" caused by high-frequency sign changes in the control signal function. It is assumed that the state variables of the SRM are directly observable for the implementation of the control.

4. THE SIMULATION RESULTS

This section compares the performance of the system using the backstepping adaptive controller based on fuzzy logic (smc-bt-fuzzy) with the system using the backstepping sliding mode controller (smc-bt) under different scenarios. Additionally, the results obtained in [25] are also compared. The parameters of the SRM are obtained from [23]. Figs. 4a and 4b illustrate the response of the system when the setpoint of speed changes from 30 rad/s to 45 rad/s and from 90 rad/s to 60 rad/s, respectively. The results indicate that both controllers, smc-bt-fuzzy and smc-bt, effectively track the setpoint of the SRM speed with zero overshoot and zero steady-state error. They also exhibit similar control quality in the case of a second setpoint where the speed reference value changes minimally. The specific control qualities are presented in Table 2, which show that the proposed controller can achieve a controlled variable that reaches 90% and 95% of the reference speed within approximately 0.1 s and 0.18 s, respectively. This performance is faster compared to the smc-bt controller.



(a) (b)

Fig. 4. System speed response to variable setpoint of speed

Table 2. Control quality of systems when changing the setpoint of speed

Setpoint changes	In case of the fist setpoint		In case of the second setpoint	
Controller	smc-bt-fuzzy	smc-bt	smc-bt-fuzzy	smc-bt
Over shoot	0%	0%	0%	0%
Settling time	0.18s	0.38s	0.57s	0.57s
Steady-state error	0	0	0	0
Rise time	0.1s	0.5s	0.3s	0.3s

The faster rise time achieved by the smc-bt-fuzzy controller suggests improved dynamic response and quicker attainment of the desired speed compared to the smc-bt controller. Notably, these results are superior to those obtained in [25], which utilized a nonlinear H-infinity controller that produced an overshoot of approximately 20% and a settling time of approximately 7 s.

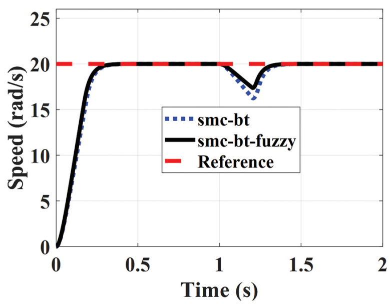
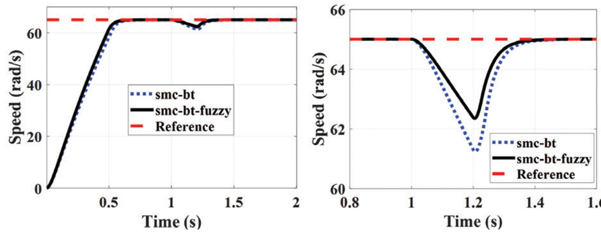


Fig. 5. Speed response at 20 rad/s with increasing load

Next, the system's response is analyzed in the presence of load disturbances. Specifically, Figs. 5 and 6 illustrate the scenario where the load increases while the system operates at speeds of 20 and 65 rad/s, respectively. Conversely, Figs. 7 and 8 represent the case where the system operates at speeds of 22 and 82 rad/s, respectively, while undergoing a sudden decrease in load.



(a) (b)

Fig. 6. Speed response at 65 rad/s with increasing load

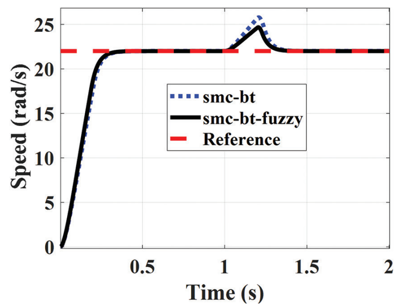
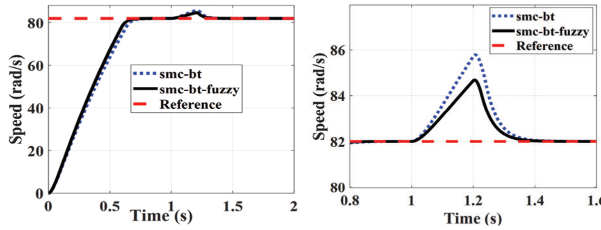


Fig. 7. Speed response at 22 rad/s under load reduction



(a) (b)

Fig. 8. Speed response at 82 rad/s under load reduction

Fig. 6b is an enlarged image of Fig. 6a, providing a clearer assessment of the control quality of the two systems during the load increase process. Similarly, Fig. 8b is an enlarged image of Fig. 8a, aiding in the evaluation of the control quality during the load reduction process.

Table 3. Control quality of two systems under load change

Load changes	In case of increased load		In case of reduced load	
Controller	smc-bt-fuzzy	smc-bt	smc-bt-fuzzy	smc-bt
Over shoot	4%	6%	2.7%	5%
Settling time	0.35s	0.37s	0.3s	0.35s
Steady-state error	0	0	0	0

The results in Fig. 6b, Fig. 8b and Table 3 indicate that the backstepping adaptive controller based on fuzzy logic helps the system return to the desired positions with zero steady-state error. Additionally, it exhibits comparable setting times but achieves a reduction in overshoot by 30% to 50% compared to the backstepping sliding mode controller.

5. CONCLUSION

In this paper, we present the application of the adaptive backstepping sliding mode control algorithm based on fuzzy logic for controlling the speed of an SRM drive system. This approach considers the inherent nonlinearity introduced by the inverter to improve the overall performance of the SRM drive system. The simulation results, which consider changes in the setpoint of speed and variable load, demonstrate the excellent performance of the proposed controller in comparison to the backstepping sliding mode controller and the nonlinear H-infinity controller mentioned in [25]. These results indicate considerable potential for the future development and application of novel algorithms in SRM systems. Further research to enhance the overall performance through torque control and experimental testing on real hardware will be conducted by the authors in the future.

Appendix A. SRM and simulatuon parameters

Number of rotor poles 6	J=6.8x103 kg/m2
Number of stator poles 8	a=1.5x103 H
Number of phases 4	b=1.364x103 H
Power 5.5 HP	B=0.2
Peak current 9A	l=2 m
Stator winding resistance 0.72 Ω	c1=2
Aligned phase inductance 130 mH	c2=0.1
Unaligned phase inductance 12 mH	T=0.025

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