Improved Torque Ripple of Switched Reluctance Motors using Sliding Mode Control for Electric Vehicles

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ABSTRACT

This study describes the direct torque control-DTC approach, based on the Sliding Mode Control (SMC) technology with chattering reduction, for reducing the torque ripple of the Switched Reluctance Motor (SRM). The SRM torque control loop has been given the SMC treatment to account for the low-frequency fluctuations in the torque output. To maintain a consistent motor speed, the sliding mode controller modifies the value of the reference current. The findings demonstrate that the constant sliding mode controller is superior to PI controllers at lowering the motor's torque ripple, compensating for its nonlinear torque characteristics, and rendering the drive insensitive to parameter changes. MATLAB/SIMULINK simulation has been used to show how well this SMC performs. The performance of the proposed SMC method has been demonstrated by simulation in MATLAB/SIMULINK with a three-phase 8/6 pole, and a 2kW SRM.

Keywords-switched reluctance motor; Sliding Mode Control (SMC); PI; EV; torque ripple

I. INTRODUCTION

Switched Reluctance Motors (SRMs) have become a viable electrification option for the military, civic, agricultural, mining, and transportation industries, due to their low prices, high efficiency, and ability to run in hostile settings [1-3]. However, the fact that SRMs are vulnerable to torque ripple, which makes noise and shortens the motor's life, has been a problem [4-6]. The primary explanation is that SRMs align with magnetic fields using low-reluctance materials like iron and steel. The stator of the SRM features phased windings, while the rotor has low and high reluctance areas. The magnetic flux and materials' resistance creates a force that pushes the rotor pole into alignment with the closest stator pole when power is applied to the stator windings. The SRM control algorithms sequentially turn the stator windings on and off to change the magnetic field, which forces the rotor to revolve. The problem is that because of structural deformations and magnetic torque harmonics that cause the stator and rotor to interact, this process also generates vibration and noise. As a result, noise is produced, and the motor's lifetime is shortened by the interactions and oscillations that alter the torque or torque ripple [7-13]. This SRM torque ripple limits the possibility of their direct-drive applications in the industry. Significantly, the fastness and accuracy of the torque response the engine needs to mobilize during driving are affected considerably. Therefore, structure and control strategy optimization consist the primary aim of research on torque ripple reduction. In terms of structural optimization, the torque ripple was reduced by optimizing the pole shape [14-16] and stepper air gap [17] using the Finite Element Modeling (FEM) in conjunction with optimization techniques. The improvement in control is often more flexible than the optimization in construction since SRMs have a straightforward structure. Numerous studies use sophisticated control techniques to reduce torque ripple [18], such as optimal harmonic current injection and current waveform tuning. In [19, 20], a PID fuzzy logic controller with the integration of the speed error, the sum of the speed error, and the derivative of the speed error are presented to decrease the torque ripple of SRM with two inputs.

A comparison of SMC and fuzzy-neural network approaches was reported in [21]. SMC is comparable to other popular nonlinear control techniques, including adaptive input-output feedback linearization [17] and adaptive back stepping techniques [22]. Multiple industrial control systems have been used to study the development of SMC approaches [23-26]. Minimization of torque ripple in switched reluctance motor based on Model Predictive Control (MPC) and Torque Sharing Function (TSF) was conducted in [27]. A novel continuous terminal SMC technique has been devised to ensure that the system states reach the sliding surface in a finite amount of time. The suggested controller certifies robustness and continuity, making the control algorithm better suited for mechanical servo systems.

In this study, the speed loop is controlled by an SMC and a PI controller to enhance the performance of the DTC system by adequately determining the reference torque, further achieving accurate control, minimizing torque ripple, and improving the dynamic performance of the SRM.

II. MODELING OF AN SRM MOTOR

The nonlinear, switching currents are used in the SRM to drive the phases. By correctly modeling the nonlinear flux-current-angle (λi-θ) characteristics of the machine, the magnetic nonlinearities of an SRM may be taken into consideration [25]. The three – phase 8/6 SRM is shown in Figure 1.

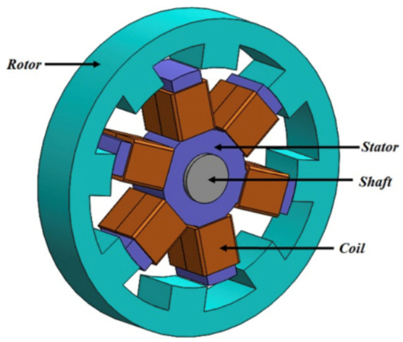

Fig. 1. The three – phase 8/6 SRM.

$$\frac{di}{dt} = \left(u - Ri - \frac{d\lambda(\theta,i)}{d\theta}\frac{d\theta}{dt}\right)\left(\frac{d\lambda(\theta,i}{dt}\right)^{-1} \quad (1)$$

The nonlinear torque dynamics are described by:

$$\frac{dT_e}{dt} = m + nu \quad (2)$$

where:

$$n = \left(\frac{dT_e}{di}\right)\left(Ri - - \frac{d\lambda(\theta,i)}{d\theta}\frac{d\theta}{dt}\right)\left(\frac{d\lambda(\theta,i}{dt}\right)^{-1} + \left(\frac{dT_e}{d\theta}\frac{d\theta}{dt}\right) \quad (3)$$

$$m = \left(\frac{dT_e}{di}\right)\left(\frac{d\lambda(\theta,i}{dt}\right)^{-1} \quad (4)$$

where T_e is the torque SRM motor, $\lambda(\theta, i)$ is the nonlinear function of phase flux linkage, θ is the rotor position, and i is the stator current.

The rate of energy change with rotor position may be used to express the SRM torque.

$$T_e(\theta, i) = \frac{1}{2} i^2 \frac{dL}{d\theta} \quad (5)$$

where L is the inductance at a position, θ_r is the rotor position, $\theta_1, \theta_2, \theta_3, \theta_4$ are the rotor positions at a phase (A, B, C, and D phases), L_{min} and L_{max} represent the minimum/maximum phase inductance with none aligned / aligned position.

$$L(\theta) = \begin{cases} L_{min} & if\ \theta_r < \theta_1 \\ L_{min} + \frac{dL}{\theta}(\theta_r - \theta_1) & if\ \ \theta_1 < \theta_r < \theta_2 \\ L_{max} + \frac{dL}{\theta}(\theta_r - \theta_1) & if\ \ \theta_2 < \theta_r < \theta_3 \end{cases} \quad (6)$$

III. SLIDING MODE CONTROLLER DESIGN FOR SPEED CONTROL

The technique used in SMC is intrinsically resistant to changes in parameters, nonlinear models, outside disturbances, and uncertainty. Therefore, it is employed when the robustness requirement is crucial for in-vehicle applications, and there are significant uncertainties [22]. The following procedures are part of the torque controller design by the sliding mode controller.

- Step 1: Select the sliding surface function:

$$S = e_{Te}(t) + P_t \int_0^t e_{Te}(t)dt = 0 \quad (7)$$

where $e_{Te}(t) = T_e^* - T_e$ is the error torque and P_t is a positive gain coefficient.

- Step 2: Taking the derivative of (7) and substituting from (2). The result of the sliding surface is expressed as:

$$\frac{dS}{dt} = -(m + nu) + P_t e_{Te} \quad (8)$$

- Step 3: The Lyapunov technique is often utilized to determine the conditions on the control rule that will cause the state to circle the equilibrium in SMC.

$$W = \frac{1}{2} S^T S \geq 0 \quad (9)$$

Then, the derivative of (8) and W is definitely negative without the sliding surface S=0. Therefore, the control law is:

$$u = n^{-1}\{-m + P_t e_{Te} + \gamma sgn(S)\} \quad (10)$$

where γ is the positive gain coefficient and $sgn(S)$ is the switch function. It is selected as:

$$sgn(S) = \begin{cases} 1, & \text{if } S > n \\ \frac{S}{n}, & \text{if } |S| \leq n \\ 1, & \text{if } S < -n \end{cases} \quad (11)$$

- Step 4: Based on (5) and (10), the control law is:

$$u = \frac{L_{min}+P_t\theta}{P_t}\left\{-\frac{P_t i}{L_{min}+P_t\theta}\left(-Ri - P_t i\frac{d\theta}{dt}\right) + P_t e_{Te} + \gamma sgn(S)\right\} \quad (12)$$

Equation (12) has the *sgn* function which causes system chattering. Therefore, the main disadvantage in conventional SMC is chattering. Chattering adversely affects the performance of system significantly. The chattering in the sliding mode controller can be reduced by modifying the control law in as $u = ksat(\frac{s}{\theta})$ and constant factor θ defines the thickness of the boundary layer around the switching surface. The $sat(s/\theta)$is the saturation function that is defined as:

$$sat\left(\frac{s}{\theta}\right) = \begin{cases} \frac{s}{\theta} & if \left|\frac{s}{\theta}\right| \leq 1 \\ sgn\left(\frac{s}{\theta}\right) & if \left|\frac{s}{\theta}\right| > 1 \end{cases} \qquad (13)$$

IV. SIMULATION RESULTS

Simulations of the DTC system were conducted to check the proposed SMC controller's accuracy and efficacy. Figure 2 depicts the block diagrams of the SMC controller and the DTC system. MATLAB/Simulink was used to model the SRM drive's DTC system with a three-phase, 2-kW SRM. Simulations were run in the 2022 version of MATLAB/SIMULINK. The closed-loop SRM drive speed controller based on SMC in Figures 2, 3, and the SRM motor have the parameters shown in Table I.

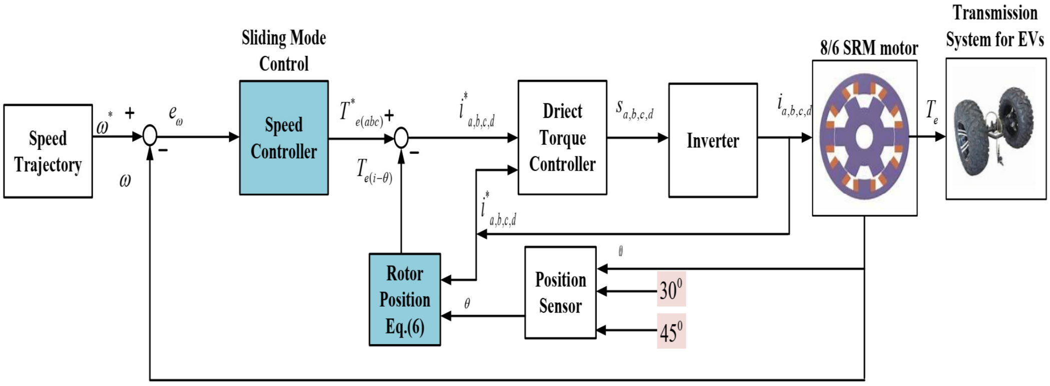

Fig. 2. Structure control of an improved torque ripple of an SRM for electric vehicles.

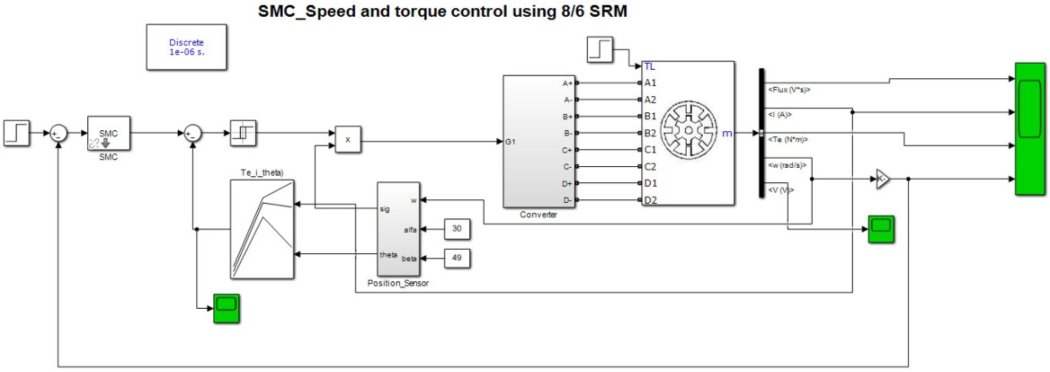

Fig. 3. Structure control reducing the torque ripple of the SRM motor in MATLAB/SIMULINK.

TABLE I. SRM MOTOR PARAMETERS

Parameters	Unit
Stator resistance (Ω)	2
Inertia (kg.m.n)	0.082
Frication (N.m.s)	0.01
Inductance *Lmin*	11
Inductance L_{max}	50
Stator pole number	8
Rotor pole number	6
Maximum current (A)	120
Maximum flux linkage (V.s)	0.486

The electromagnetic torque of the SRM with the classical PI controller and the proposed SMC for 1000 and 4000rpm are shown in Figure 4. The most significant advantage of the proposed SMC is its constant electromagnetic torque. Figure 4 shows the simulation results of the SRM at rotational speeds of 1000 and 4000rpm and a reference torque of 38Nm.

In addition, the SRMs have a significant ripple of electromagnetic torque. However, the average torque fluctuation is within 2.5%. Therefore, the speed ripple of the proposed SMC is smaller than that of a PI controller. Furthermore, the suggested SMC's electromagnetic torque is more uniform than the PI's. Therefore, reducing the electromagnetic torque ripple is the essential advantage of the proposed controller.

Figures 5 and 6 show the change of the flux linkage which should be made as smooth as possible when designing the torque, enhancing the movement following the ability of the SMC controller.

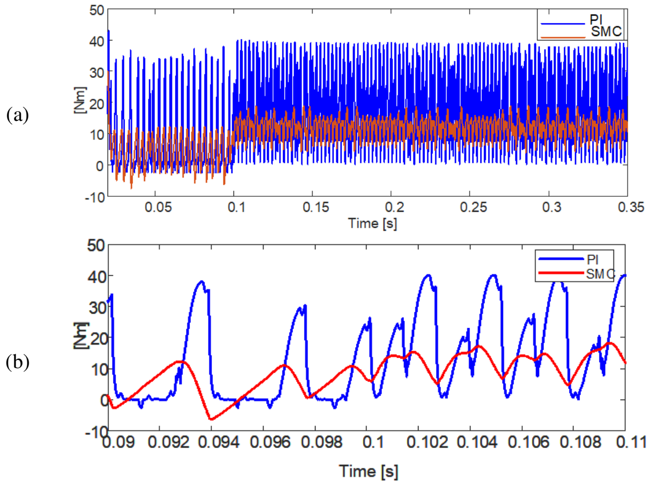

Fig. 4. Torque comparison, SMC and PI controllers. (a) 1000rpm, (b) 4000rpm.

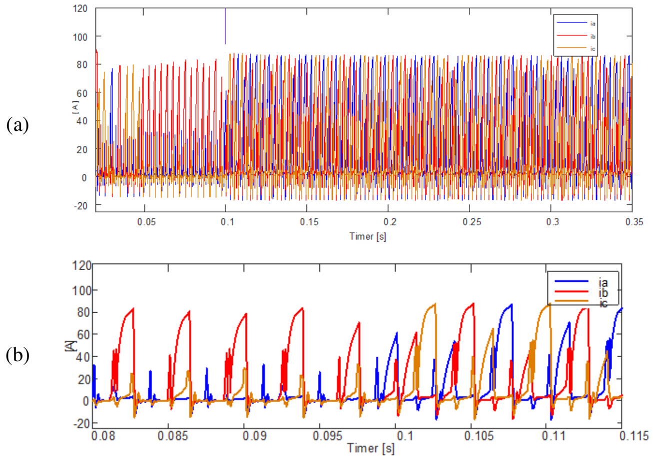

Fig. 5. The three-phase current response. (a) 1000rpm, (b) 4000rpm.

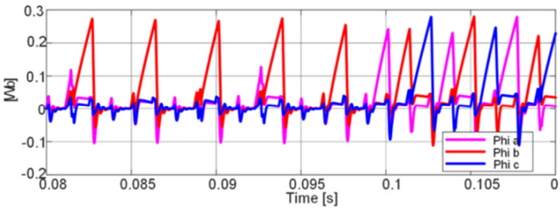

Fig. 6. The flux response.

Figure 7 shows that the actual speed response follows the set value. The short time is fast with $t = 0.025$s, and the static deviation is slight with $\pm 1\%$. Therefore, the proposed SMC method has the advantage of very small speed error of the SRM motor. Let's consider the case where the inductance parameter changes by 50%. The torque response is shown in Figure 8 and it does not change at 1000 and 4000rpm. Again, the short time is fast with $t = 0.025$s, and the static deviation is slight with ±1%. In contrast, the increased torque response of the PI control method is 23%, and the setting time is slower than that of the SMC controller.

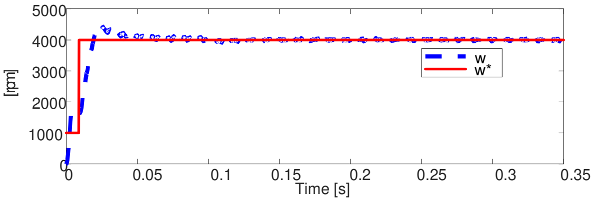

Fig. 7. Simulation results of the SRM control speed using SMC.

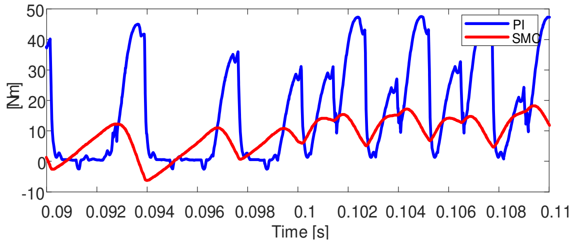

Fig. 8. Torque response when the stator resistance is increased by 50%.

V. CONCLUSIONS

This paper proposes a torque ripple minimization of switched reluctance motors using direct torque control based on the sliding mode. The proposed torque control method combines DTC with the SMC controller. The stability of the proposed system is verified through the Lyapunov function. In addition, this control method has reduced the chattering of the torque response by using a saturation part in the control signal. As a result, the proposed control method performs better than the PI controller and it is robust to parameter changes.

To improve the torque ripple reduction in future research, a sliding controller combined with a fuzzy logic controller or connected with a neural network or a model predictive control, will be considered to optimize the duty ratio and to minimize the torque ripple. In addition, this control method should be tested experimentally in the future to prove its correctness.

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