A NEW METHOD TO REDUCE TORQUE RIPPLE IN SWITCHED RELUCTANCE MOTOR USING FUZZY SLIDING MODE

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Abstract. This paper presents a new control structure to reduce torque ripple in switched reluctance motor. Although SRM possesses many advantages in motor structure, it suffers from large torque ripple that causes some problems such as vibration and acoustic noise. In this paper another control loop is added and torque ripple is defined as an objective function. By using fuzzy sliding mode strategy, the DC link voltage is adjusted to optimize the objective function. Simulation results have demonstrated the proposed control method.

1. Introduction

In recent years, Switched reluctance motor (SRM) has been focused on by many researchers. This motor has individual features than the others. These features such as simplicity, robust structure, low cost, high ratio of torque to rotor volume, reliability, high efficiency, suitability for variable speed application [14], brushless construction, controllability and many other features are the advantages of SRM presented in some papers. These advantages and inherent efficiency make it considerable for researchers. Besides these advantages, it has some problems [15]. The SR motor has a nonlinear model and torque ripple is a prevalent disadvantage resulting in acoustic noise and rotor vibration. Hence reduction of such problems is an important subject in SRMs [4, 7, 8]. Motor structure makes its characteristic nonlinear and the simulation results of linear control are not acceptable [13, 9], therefore nonlinear control strategy is used in the paper. Variable structure systems (VSS) in high speed control devices have a better performance as a nonlinear control. The most popular operation regime associated with VSS is sliding mode control (SMC) [1, 5, 12]. The advantage of this control algorithm is its robustness, simplicity and high accuracy. Although SMC has a good performance with respect to linear control such as PI, it has some disadvantages. High control activity makes chattering phenomenon. Oscillation of the control output to establish sliding mode is not desirable in practical application and may result in instability. Fuzzy logic is a flexible method of implementing nonlinear systems and useful in control strategies [16, 11] as well as fault detection and investigation [10, 6]. In this paper a new

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approach has been presented that deals with the torque ripple controller based on fuzzy SMC and used to control the torque ripple of SRM drive.

2. Mathematical Model of SRM

To properly evaluate the SRM performance and effectiveness of different schemes, a reliable model is required. SRM has salient poles on both stator and rotor. Only the stator poles carry windings, and there are no windings or magnetic materials on the rotor. The windings on the stator are particularly simple form, where each two opposite stator pole winding are connected in series to form one phase. Each phase has an ohmic winding resistance and a flux linkage which depends on excitation current and rotor angle. The most important properties of the SRM are its non-linear angular positioning parameters and nonlinear magnetic characteristic. An elementary equivalent circuit for the SRM can be derived by neglecting the magnetic hysteresis loss, the mutual inductance between the phases and eddy current loss. The applied voltage to phase 'j' is equal to the sum of resistance voltage drop and the rate of the flux linkages and is given as:

$$V_j = R_j i_j + \frac{d\varphi_j(\theta, i_j)}{dt} \tag{1}$$

where R_j is the resistance and φ_j is the flux linkage of phase 'j ' and is obtained as

$$\varphi_j = L_j(\theta, i_j) \cdot i_j \tag{2}$$

where L is the inductance depends on the rotor position and phase current. Then, the phase voltage is

$$V_j = R_j i_j + \frac{d(L_j(\theta, i_j) \cdot i_j)}{dt} = R_j i_j + L_j(\theta, i_j) \cdot \frac{di_j}{dt} + \frac{dL_j(\theta, i_j)}{d\theta} \cdot \omega_m i_j \cdot \tag{3}$$

In (3), three terms on the right-hand side represent the resistive voltage drop, inductive voltage drop and induced back-emf respectively. The induced back-emf, e, is expressed as

$$e_j = \frac{dL_j(\theta, i_j)}{d\theta} \cdot i_j \cdot \omega_m = k \cdot \omega_m \tag{4}$$

where k is the back-emf coefficient. The phase current is limited by back-emf and it depends on rotor speed, hence there are two basic control strategies; Current chopping control (CCC) at low speed and Angle position control at high speed [16]. The control strategy of this paper uses CCC mode and phase current is the control parameter. The produced torque on the shaft satisfies the following equation

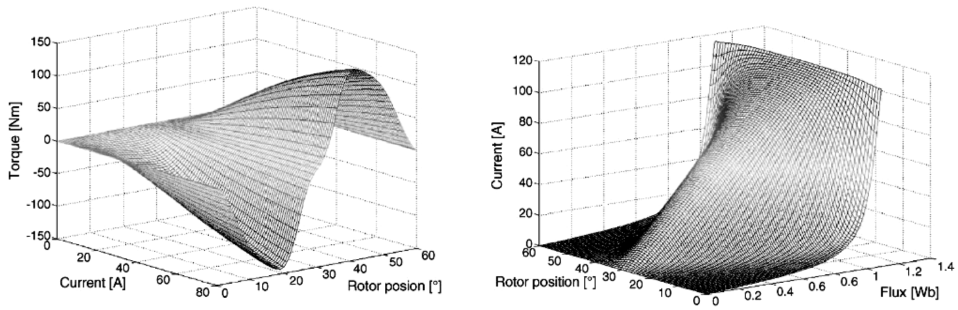
$$T(i, \theta) = \sum_{i=1}^{n} \left(\frac{\partial W_j}{\partial \theta} \right)_{i_j = cts} \tag{5}$$

$$W_j(i_j, \theta) = \int_0^{i_j} \varphi_j(i_j, \theta)\ di_j \tag{6}$$

where $W_j(i_j, \theta)$ is co-energy and finally the mechanical equation is as below

$$\frac{d\omega}{dt} = \frac{1}{J} \cdot (T(i,\theta) - T_L - B \cdot \omega), \qquad \frac{d\theta}{dt} = \omega \tag{7}$$

where ω stands for angular velocity, T_L for load torque, B for friction coefficient and J for the moment of inertia [11]. However, function for $T(i, \theta)$ and $i(\varphi, \theta)$ is very difficult to define as illustrated in Figure 1 [2].



(a) (b)

FIGURE 1. Lookup Table of (a) Torque-current-position and (b) Flux-current-position

3. **Fuzzy Sliding Mode Control**

The variable structure control systems (VSCS), as the name suggests, is a class of systems whereby the control law is deliberately changed during the control process according to some defined rules that depend on the nature of SRM drive. These rules are derived from the VSCS theory. The problem of doing set-point control for a system of the form (8) is considered

$$x^{(n)} = f(x) + b(x) \cdot u \tag{8}$$

where x is the state vector and $f(x)$, $b(x)$ are uncertain functions. The variable $\widetilde{x}$ (the error signal), is defined as the difference between x and x_d (set-point)

$$\widetilde{x} = x - x_d. \tag{9}$$

If it restricts the dynamics of the system to lie on a well behaved surface, then the control problem can be greatly simplified. The surface is called the sliding mode, and is defined in such a way that the error dynamics are exponentially stable when the system is restricted to lie on this surface. Therefore the control problem is reduced to driving the system to this surface, and then ensuring that it stays on this surface all the time. The sliding mode $S(t)$ is defined as follows

$$S(t) = \{x \mid s(x,t) = 0\} \tag{10}$$

where $s(x,t)$ is defined by

$$s(x,t) = (\frac{d}{dt} + \lambda)^{n-1} \cdot \widetilde{x}(t), \quad \lambda > 0. \tag{11}$$

On the surface $S(t)$, the error dynamics are governed by

$$(\frac{d}{dt} + \lambda)^{n-1} \cdot \widetilde{x}(t) = 0. \tag{12}$$

On this surface, the error will converge to 0 exponentially. This implies that if there exists a control input $u(t)$ such that $x(t)$ is in $S(t)$ it follows that $x(T)$ is in $S(T)$ for all $T > t$ and the error will converge exponentially to 0 for this control input. For example in an SRM, speed error between the desired speed and actual rotor speed is

$$\widetilde{x} = e = \omega_d - \omega. \tag{13}$$

Then the sliding mode is defined as

$$s(x,t) = (\lambda e + \dot{e}) \tag{14}$$

where λ is the design parameter and is selected such that ($\lambda > 0$) to ensure stability of the sliding mode. If the time derivative of (14) is computed and put equal to zero, the control law will be as below

$$u_{eq} = J \cdot ((\lambda + \frac{B}{J}) - cT_L). \tag{15}$$

The Lyapunov function is used to stable the control law [9]. This function is defined as

$$V(s) = \frac{1}{2} \cdot s^2. \tag{16}$$

Efficient condition for the stability of the system is described as

$$\dot{V}(s) = \frac{1}{2} \cdot \frac{d}{dt} s^2 \leq -\eta |s|, \quad \eta \geq 0. \tag{17}$$

The above condition makes the system stable and moves it towards the sliding surface and hits it. Thus

$$S\dot{S} \leq -\eta |s|. \tag{18}$$

To achieve the sliding mode, the controller output must be chosen as

$$u = u_{eq} - K \cdot sgn(S). \tag{19}$$

In (19), when the parameter K has a high value, the other terms can be neglected and Lyapunov condition is satisfied properly, then the system is robust. But low value of K may disturb the Lyapunov condition and robustness of system may be lost. However, high value of K could result in high activity and chattering problem. Fuzzy logic can be used to determine the proper value of K intelligently.

4. Torque Ripple Reduction Strategy

In the proposed strategy torque ripple is defined as an objective function and control must do in such a way that reduce this function. Torque ripple is not defined as the difference between maximum and minimum value of torque because this value is not a good signal to properly analyze and evaluate the motor torque. Harmonic analysis is implemented to produce a signal which can be used in fuzzy sliding control and can be proportional to motor torque ripple. Because torque ripple doesn't depend on the DC value of torque, this value is subtracted from the motor torque. At the next step, the RMS value of fundamental harmonic is extracted and used as a torque ripple factor. This factor is proportional to the motor torque ripple and can efficiently predict torque agitation, so it is used as an objective function in fuzzy sliding controller. According to equation (3), the motor current can be shown as

$$i_{ph} = \frac{V_{ph}}{\left(R + \omega\frac{dL_{ph}}{d\theta}\right) + L_{ph}s}, \quad K_1 = R + \omega\frac{dL_{ph}}{d\theta}, \quad K_2 = L_{ph} \tag{20}$$

and the motor torque is calculated according to the nonlinear equations (5) and (6). The torque ripple control loop is shown in Figure 2. The transform functions $B_0(s)$, $B_1(s)$ and $B_2(s)$ are uncertain or nonlinear enough that traditional PI cannot reduce error in the torque system. Therefore, SMC as a variable structure and robust controller was chosen.

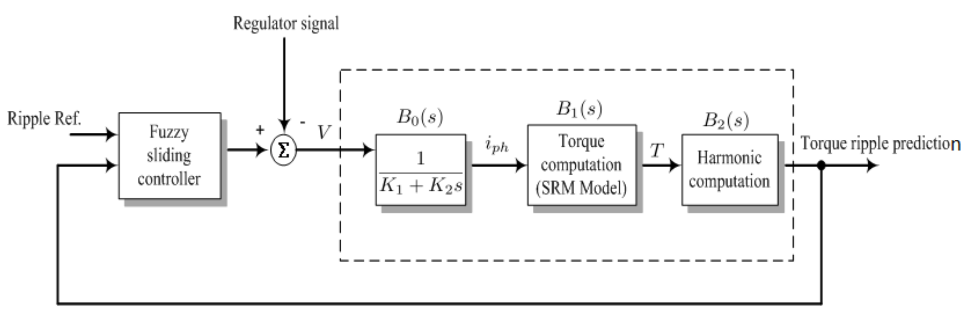


Figure 2. Block Diagram of the Torque Ripple Reduction Loop

In the ideal state, the motor torque ripple reference should be zero but always there is a difference between torque ripple and desired value of it. The objective function can be considered as the error between them. In the fuzzy sliding control, this error signal, e_{tr} is used in the sliding mode similar to speed error signal which is often used to control speed and mentioned in the section 3. Therefore, in the new control structure the sliding mode defined as

$$s_{tr}(t) = (\lambda e_{tr} + \dot{e}_{tr}) \tag{21}$$

and the torque ripple control output, u_{tr} must be chosen as

$$u_{tr} = u_{tr(eq)} - K \cdot sgn(s_{tr}). \tag{22}$$

Fuzzy logic is a procedure that is used in many applications, in particular for those fields that need linguistic tools instead of mathematical ones. In the proposed sliding control, the value of K in (22) is fuzzified based on the rules given in the Table 1.

$\dot{e}_{tr}, e_{tr}$	NB	NM	NS	Z	PS	PM	PB
PB	Z	PS	PM	PB	PB	PB	PB
PM	NS	Z	PS	PM	PB	PB	PB
PS	NM	NS	Z	PS	PM	PB	PB
Z	NB	NM	NS	Z	PS	PM	PB
NS	NB	NB	NM	NS	Z	PS	PM
NM	NB	NB	NB	NM	NS	Z	PS
NB	NB	NB	NB	NB	NM	NS	Z

Table 1. The Fuzzy Logic Rule Table

After evaluation of K using fuzzy method, it can be used in the SMC without causing chattering or instability, because the fuzzy method properly guides it in the sliding surface. Fuzzy membership functions and behavior of fuzzy method in the sliding mode surface are shown in Figures 3-4.

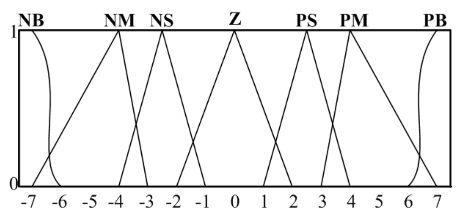


Figure 3. Membership Functions

Fuzzy strategy satisfies the followings in the sliding surface: (1) IF sliding is high THEN control activity must be increased and (2) IF sliding is low THEN control activity must be decreased. The performance of the fuzzy attempt is shown in Figure 5.

Different membership functions with the given rules approximately have the same result, so typical membership functions are selected as shown in Figure 3. In the proposed structure fuzzy logic control signal, is used to adjust DC link voltage that supplies motor drive. Figure 6 shows how the control procedures affect the motor phase. SMC is robust and fast, so it can efficiently govern the DC link voltage to reduce torque ripple, on the other hand, fuzzy method avoids control to become instable.

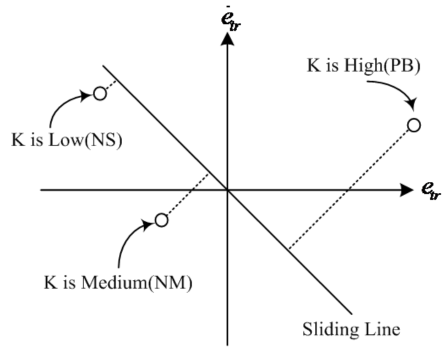
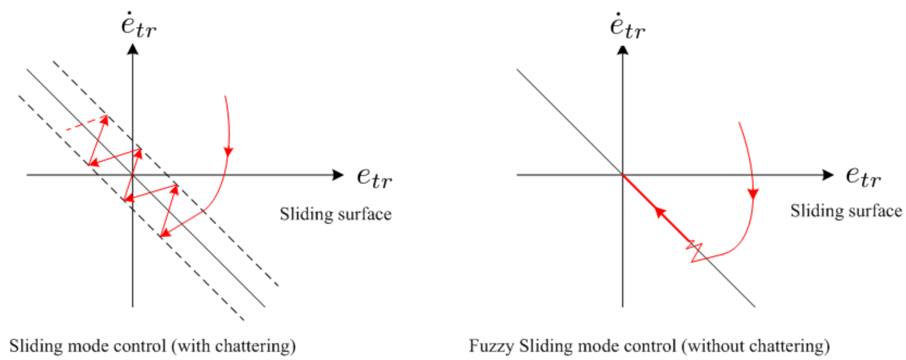


FIGURE 4. Determination of K Using Fuzzy Sets



(a) (b)

FIGURE 5. Trajectory of the Sliding State (a) without Using Fuzzy Method and (b) with Fuzzy Method

Total block diagram of the proposed control strategy is shown in Figure 7. To increase the reliability of fuzzy sliding method and prevent voltage control signal to become zero during starting stages, speed error signal has been used to regulate the output signal of fuzzy sliding controller and improve the torque ripple control loop. Beside these, the conventional PI is used to control motor speed. In the speed control loop, the control output defines the magnitude of instantaneous reference current which combined to the position sensor command to avoid negative torque production. Afterwards, hysteresis controller compares it with motor current to govern phase switches in the SRM drive. In early literatures, fuzzy sliding method was only used in speed control loop and slightly influenced on the torque ripple.

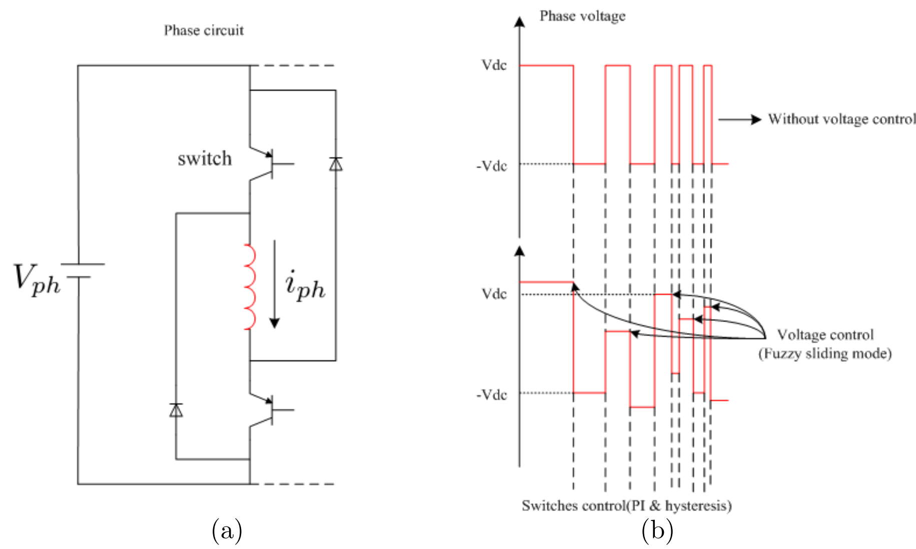


FIGURE 6. (a) Motor Phase Circuit and (b) Control Procedure Schemes

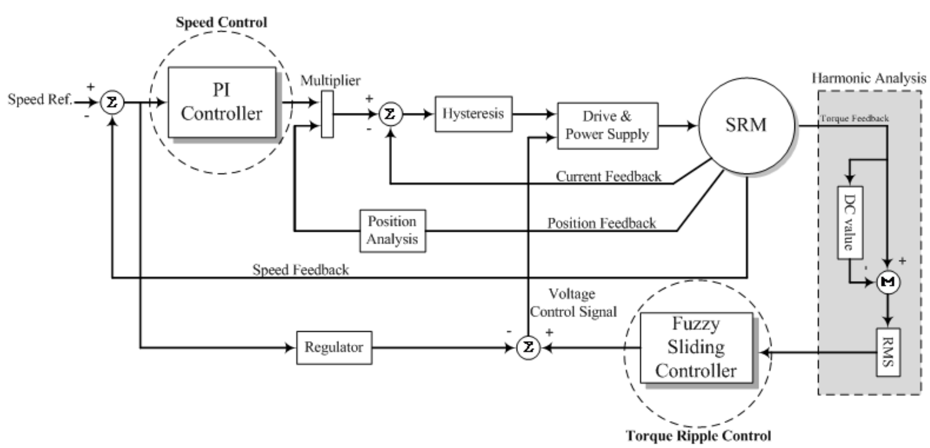
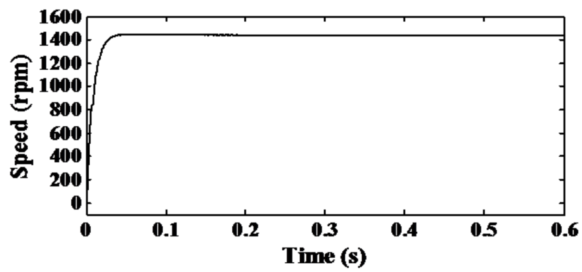


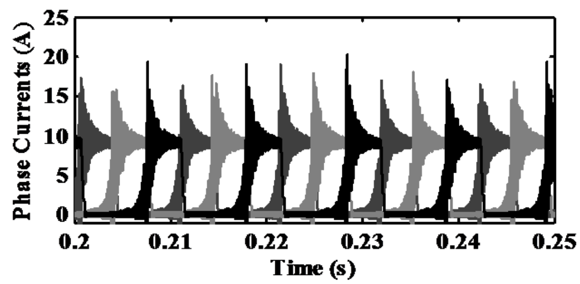
FIGURE 7. Block Diagram of SRM Drive with the Proposed Structure

5. **Simulation Results**

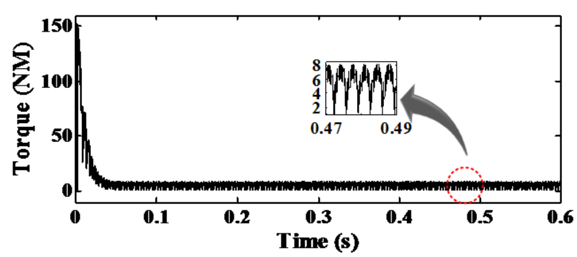
In order to verify the proposed control method, the drive has been simulated in MATLAB/Simulink software. At first, only speed control is used in SRM drive. Motor torque, speed and phase currents are extracted as shown in Figure 8. In the next step, the proposed torque ripple control has been employed in the SRM drive aiming at torque ripple reduction. As shown in Figure 9 torque ripple is highly reduced in this strategy.



(a)



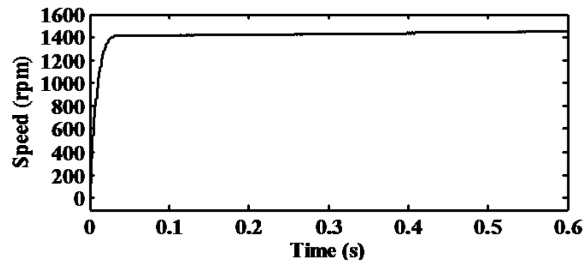
(b)



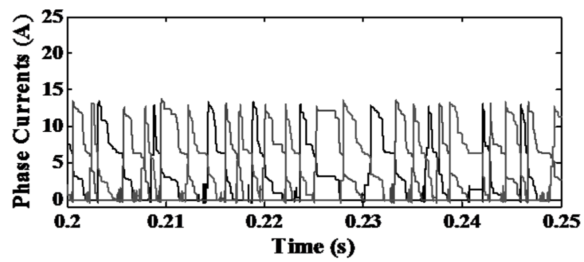
(c)

FIGURE 8. (a) Motor Speed, (b) Phase Currents and (c) Motor Torque without Torque Ripple Control

Figure 8c shows that torque ripple without the torque ripple control, is about 6 Nm, but with the torque ripple control it will be about 2.5 Nm as shown in Figure 9c. To evaluate and compare the proposed method with some other attempts [4, 13], the percents of torque ripple reduction have been calculated and summarized in the Table 2. As load torque is reduced, the motor torque ripple is also decreased so the torque ripple reduction should be compared with each other considering the average torque.



(a)



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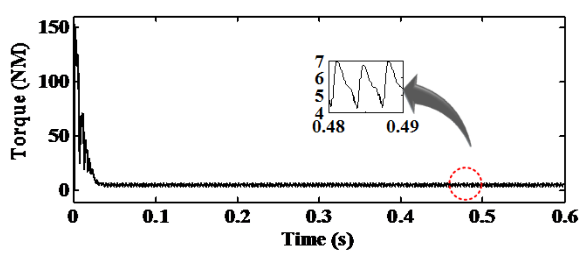

(c)

FIGURE 9. (a) Motor Speed, (b) Phase Currents and (c) Motor Torque with Torque Ripple Control

Control Strategies	Percent of Torque Ripple Reduction
SMC in [4]	36
SMC in [13] compared to PID	22
Fuzzy in [13] compared to PID	45
Proposed Fuzzy in SMC	61

TABLE 2. Composition of Methods in Torque Ripple Reduction

Finally, the response of speed reversal in the proposed strategy has been evaluated and is shown in Figure 10.

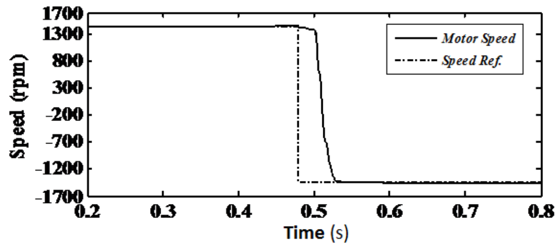

Figure 10. Response of Speed Reversal in the SRM

6. Conclusions

The application of torque ripple control loop using fuzzy sliding mode to an SRM drive has been proposed and simulated. The ripple of torque has been defined as an objective function and fuzzy sliding mode controller adjusted the DC link voltage based on this function. On the other side, the speed controller has been defined the reference current and governed motor phase switches. Although sliding mode strategy is robust and fast enough to adjust DC link voltage in order to reduce torque ripple, fuzzy procedure properly influenced state path in the sliding surface and avoided instability or chattering. In other words, mentioned fuzzy logic makes new structure practical and combines the robustness and efficiency, simultaneously. In this method, torque ripple is properly reduced and the speed response of motor is not changed considerably. Computer simulation results verified that the proposed control strategy decrease torque ripple and improve the performance of the SRM drive.

7. Appendix

Number of Rotor Poles: 4
Number of Stator Poles: 6
Rated Voltage: 280 V
Rated Current: 9 A
Rated Speed: 150 Rad/s
Moment of Inertia: 0.0082 kg.m^2
Stator Resistance: 0.5 Ω
Friction Coefficient: 0.004 N.m.s
Turn on Angle: 45°
Turn off Angle: 75°
Hysteresis Band Width: $\pm$ 0.1 A

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