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Suppression of Torque Ripple in Switched Reluctance Motors Which is Based on Synchronization Technology

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Abstract

The double salient pole structure of Switched Reluctance Motor (SRM) makes its electromagnetic field exist nonlinear saturation characteristics, resulting in its large torque pulsation in operation, so it is difficult to achieve speed regulation smoothly by traditional control methods. In view of this problem, a sliding mode control strategy which is based on synchronous transmission technology was proposed.Firstly, the basic structure of switched reluctance motor was analyzed, and the mathematical model of mechanical motion of switched reluctance motor was established. Secondly, an improved sliding mode controller which is based on synchronous signal transmission technology was designed by analyzing the reason of large torque ripple of switched reluctance motor, and the stability of the system was proved. Finally, simulation is used to verify the effectiveness of the control strategy.Compared with the traditional PID (Proportional Integral Differential) control algorithm, this control technology not only suppresses the SRM torque ripple effectively , but also makes the sliding mode controller output the precise target electromagnetic torque quickly by increasing the control variables. The results of research indicate that this design can not only restrain the torque ripple effectively, but also adjust the convergence speed and overshoot of the controller by adjusting the design parameters.

Keywords: Switched reluctance motor, Synchronization transmission, Sliding mode control, Torque ripple

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1. Introduction

As a stepless speed motor, switched reluctance motor has developed rapidly in recent years .This motor not only has simple structural design and low cost, but also has superior performance in speed regulation, so it has gained wide attention in the field of new energy electric vehicles .However, the problems of large torque ripple and strong buffeting of SRM limit the large-scale application of the motor in the field of new energy electric vehicles .Therefore, so far, how to effectively reduce SRM torque ripple and reduce system buffeting has become a hot issue in this field [1-2] .

The SRM adopts a double convex structure design, This design causes the SRM magnetic circuit to be seriously saturated, which makes the output torque, stator current and rotor rotation Angle present a nonlinear relationship, and with the structure changes with the change of control mode. The difference between the output torque and the target torque results in a relatively large torque ripple of the SRM. In view of the above problems, in order to effectively suppress the torque ripple of SRM, on the one hand, it can be solved by reforming the mechanical structure of the switched reluctance motor itself, and on the other hand, it can be solved by using advanced motor control algorithm [3-4].In order to restrain the torque ripple of switched reluctance motor, many scholars at home and abroad have made rich achievements in restraining the torque ripple through continuous research. For example, in literature [5], a fuzzy control algorithm is proposed to find the optimal combination of switching angles at different speeds, so as to suppress the torque ripple of SRM motor. Literature [6] proposes to use a new phase current waveform instead of the traditional square wave current to drive SRM motor, so as to solve the torque ripple problem caused by the commutation stage, and ultimately reduce the total torque ripple. Literature [7] proposed a method to reduce the torque pulsation and improve the average torque of SRM motor based on multistage ant colony optimization algorithm (MSCA). By optimizing the switching angle using multistage ant colony algorithm, the overall performance of

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the SRM motor is optimized, and ultimately the purpose of reducing the torque pulsation is achieved, and the operating efficiency of the motor is effectively improved. Literature [8] proposes a two-stator switched reluctance motor concept to save on the power converter by adding a stator to the motor, thus reducing the torque pulsations. Literature [9] reduces torque pulsations by using a buck converter to provide a suitable bus voltage for SRM motors, and realizes AC power factor correction while suppressing torque pulsations. It can be seen that the above studies are mature and effective. However, most of these research results are concentrated in the field of torque control, and there are fewer studies on the speed control loop of SRM.

Generally, the torque ripple is caused by the difference between the output torque and the target torque, and the target torque is determined by the output of the speed ring. It can be seen that the accuracy of the output of the speed ring has a great impact on the system torque ripple. The mainstream speed loop control in industry uses PID control, which is more sensitive to noise. If the SRM control requirements are low, the ideal output can be obtained by adjusting PID parameters. However, when the control requirements are high, it is difficult to use conventional PID to obtain good control performance. The sliding mode control [10] can overcome the uncertainty of the system, is not sensitive to noise, and can be well adapted to the SRM speed system. Based on these characteristics, the sliding mode variable structure control strategy is adopted to replace the traditional PID control. In addition, the synchronous transmission technology of signals has the advantage of controllable output. Applying the synchronous transmission technology of signals to the design of sliding mode controllers is equivalent to introducing control parameters into the system. By designing these control parameters, the system state variables can track the target signal quickly and accurately, thereby enabling the sliding mode controller to output the accurate target of electromagnetic torque, reducing SRM torque ripple and system chattering.

Based on the above discussion, in order to effectively control the torque ripple of SRM, this paper adopts the sliding mode variable structure control strategy to replace the traditional PID control strategy in the speed control ring. Meanwhile, the synchronization transmission technology of signal [11] is combined to obtain accurate target torque, so that the actual torque can accurately track the target torque, reduce system torque ripple and system buffeting. Finally, the correctness of the control strategy design will be verified by simulation experiments.

2. Basic structure of SRM system

2.1. Principle of system structure

When SRM works, it uses magnetic attraction to pull the rotor to rotate, at this time, the change in reluctance must be large, therefore, the SRM works according to the principle of minimum reluctance, that is, the flux closure path always flows in the direction of maximum permeability. Both the rotor and the stator of the SRM have protruding tooth poles, there are coils wound on the tooth poles of the stator, but there are no coils wound on the tooth poles of the rotor, the number of poles of the stator and the rotor is different, these characteristics make the SRM have the advantages of simple mechanical structure, large starting torque, fast speed regulation, etc.

The electrical schematic diagram of three-phase 12/8-pole SRM is shown in Fig.1.The stator and rotor teeth of A1, A2, A3 and A4 are aligned along the diameter direction, the pole coils A1, A2, A3 and A4 are connected in series to form A phase. Similarly, available BC phase. the three-phase of ABC has the same working principle and can work independently. As shown in Fig.1, when the positive and negative pole control switch S is closed, the current comes out of the US positive pole and returns to the US negative pole through windings A1, A2, A3 and A4,the magnetic field force generated in this process makes the rotor rotate. In order to make A phase off, the rotor polar axis YY 'must be rotated to the position of stator A1A3,phase A can be turned off and phase B can be turned on at the same time. At this point, because there are two freewheeling diodes D1D2 in the circuit, the current will not disappear immediately, but will freewheeling through the diode, so the direction will not change. If the conduction sequence of each phase is in accordance with the $A \rightarrow B \rightarrow C \rightarrow A$ sequence, the rotor rotates counterclockwise, otherwise it will rotate clockwise, independent of the current direction. Based on this, we can get that the electromagnetic torque is related to the current and switching time, and the direction of the electromagnetic torque can be changed by changing the winding power on sequence.

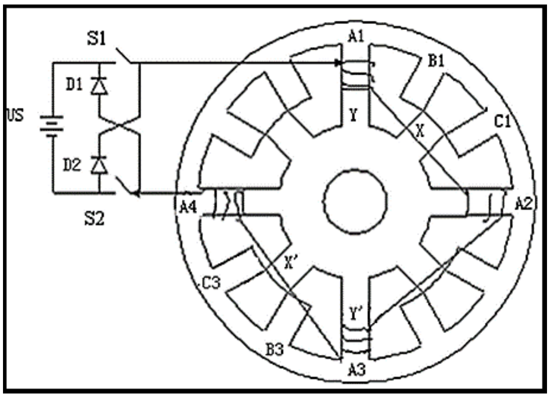


Figure 1. Electrical connection diagram

2.2. Establishment of mathematical model

The mechanical motion equation of SRM is based on Newton's law of motion, and its equation of motion can be expressed as equation (1) [12]:

$$J\frac{d\omega}{dt} = T_e - D\omega - T_L \tag{1}$$

where ω is the motor speed; J is the moment of inertia; $T_e = \sum_{i=1}^{m} T_i$, T_i is the i-phase electromagnetic torque, T_e is the number of motor phases, D is the sum of the electromagnetic torques of each phase; is the friction coefficient; T_L is the load torque.

For the convenience of calculation, it is assumed that the given speed is constant, that is $\frac{d\omega^*}{dt} = 0$,load torque is constant, $\frac{dT_L}{dt} = 0$ .At the same time, we conduct variable substitution, let's set:

$$x_1 = \omega^* - \omega \tag{2}$$

$$x_2 = \dot{x}_1 = \frac{d(\omega^* - \omega)}{dt} = -\frac{d\omega}{dt} \tag{3}$$

Substituting equation (2) into equation (3), we can get equation (4) :

$$\dot{x}_2 = -\frac{1}{J}\frac{dT_e}{dt} + \frac{D}{J}\frac{d\omega}{dt} \tag{4}$$

Setting $a = \frac{D}{J}$, $u = \frac{1}{J}\frac{dT_e}{dt}$, then the state equation of SRM system can be obtained as :

$$\begin{cases} \dot{x}_1 = x_2 \\ \dot{x}_2 = -ax_2 - u \end{cases} \tag{5}$$

It can be seen from equation (5) that the control quantity u is a quantity related to electromagnetic torque. Therefore, the design of u controller is to seek the optimal desired electromagnetic torque.

2.3. Torque analysis of SRM

Because the SRM winding current is non sinusoidal and the core reluctance is highly saturated, the mathematical model of SRM torque is also a highly nonlinear function, moreover, the function is related to the rotor position and current, and the current in the function drops and rises at different rates, resulting in the actual torque cannot follow the change of the expected torque during phase commutation, and the torque ripple is very large. It can be seen that it is very important for the actual torque to follow the expected torque. In traditional control, due to the PI controller with fixed parameters, the actual torque tracking expected torque effect of switched reluctance motor is not ideal, which will produce a large torque ripple. Based on the above analysis, in order to reduce torque ripple and obtain accurate expected torque T_e, the controller designed in this paper will adopt variable structure sliding mode control design and transmit synchronous signals at the same time to increase system practicability. The system block diagram is shown in Fig.2.

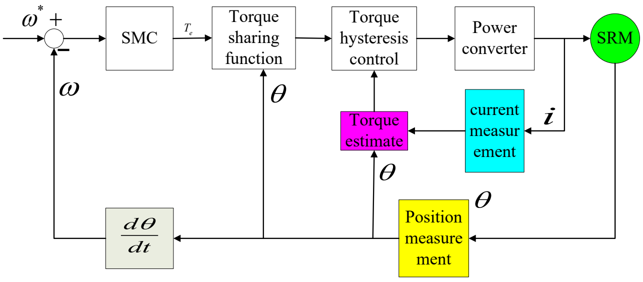


Figure 2. SRM control block diagram

The system block diagram is composed of sliding mode control, torque distribution function, torque hysteresis control, power converter, SRM and other modules. In Fig.2, ω^* is the given speed, ω is the actual speed, The difference between ω^* and ω is the system state variable x_1 .The design of sliding mode controller is actually a new sliding mode controller which combines sliding mode control technology and synchronous transmission technology. The controller not only enables SRM to track the given angular acceleration quickly, but also obtains the exact desired target torque Te as the objective function of the torque distribution function. The torque distribution function will be obtained by the output of the sliding mode controller, distributed by phase, and sent to the torque hysteresis control. The torque estimation unit provides the instantaneous torque value according to the detected current and position information. After comparing the expected torque distributed by each phase winding with the actual torque obtained by the torque estimation unit, the torque hysteresis unit controls the switching frequency of the power device to obtain the ideal rotor position θ and current value, and the instantaneous torque can follow the desired target torque. To achieve the purpose of reducing torque ripple, it can be seen that it is very important to obtain accurate target torque.

3. Sliding mode controller design which is based on signal synchronous transmission technology

Fast dynamic process response and good parameter robustness are the characteristics of sliding mode contro· Introducing sliding mode control into SRM control system has great effect on improving the rapidity and robustness of SRM. Although the sliding mode control can improve the robustness of the system significantly, it increases the system buffeting. In this paper, integral control is integrated into the design of the sliding mode surface. By the improved sliding mode surface design, the target electromagnetic torque can be quickly obtained, and the system buffeting can be reduced, and the inherent shortcomings of traditional sliding mode control can be overcome. On the other hand, synchronization transmission technology is used to obtain precise target torque by applying control parameters.

Therefore, the controller u with synchronous transmission signals is represented by symbol $\hat{u}$, and control input q_1 and q_2 are applied in equation (5), so that the system can simultaneously transmit target control signals. Then equation (5) is rewritten as equation (6):

$$\begin{cases} \dot{x}_1 = x_2 + q_1 + d_1 \\ \dot{x}_2 = -ax_2 - \hat{u} + q_2 + d_2 \end{cases} \tag{6}$$

In order to make the mathematical model more close to the actual system, perturbations d_1 and d_2 are added to the mathematical model (5).

As can be seen from Figure 2, when $\omega^* - \omega = 0$, The actual angular acceleration of SRM is fully synchronized with the feed quantity, that is, the target torque obtained at this time is the most accurate. Therefore take the objective equation (7):

$$y_d = 0 \tag{7}$$

Definition: If the angular acceleration output by the system is synchronized with the angular acceleration given by the system, the target signal will be transmitted synchronously, it must exist:

$$|x_i - y_d| = 0, (i = 1,2).$$

Theorem: When the controller output $\hat{u}$ and the control parameters q_1 and q_2 are expressed as equation (8), (9), and (10), the system can accurately predict the desired torque, and the target signal is transmitted synchronously.

$$\dot{\hat{u}} = ks_2 \tag{8}$$

$$q_1 = -x_2 - c_1e_1 - s_1 \tag{9}$$

$$q_2 = ax_2 + u - c_2e_2 - s_2 \tag{10}$$

Where c_1 and c_2 are any adjustment parameters greater than zero. By adjusting c_1 and c_2, the convergence rate of the sliding mode surface can be adjusted. k is any parameter greater than zero.

Proof: Define the error function $e_1 = x_1 - y_d$, $e_2 = x_2 - y_d$,taking into account equations (6) and (7), the following relation is easily obtained equation (11):

$$\begin{cases} \dot{e}_1 = x_2 + q_1 \\ \dot{e}_2 = -ax_2 - \hat{u} + q_2 \end{cases} \tag{11}$$

In order to obtain the control quantity $\hat{u}$ and transmit the target signal, we use sliding mode control technology to achieve. For this reason, we improved the conventional linear sliding surface, added the integral sliding surface part on the basis of retaining the linear sliding surface, and designed the following sliding surfaces:

$$\begin{cases} s_1 = e_1 + c_1\int_0^t e_1 d\tau \\ s_2 = e_2 + c_2\int_0^t e_2 d\tau \end{cases} \tag{12}$$

Note: The integrated sliding mode surface can realize continuous control of the controlled system, thus eliminating buffeting and ensuring the robustness and high precision of sliding mode control.

Based on equation (12) of sliding surface, it can be obtained that equation (13):

$$\begin{cases} \dot{s}_1 = \dot{e}_1 + c_1e_1 \\ \dot{s}_2 = \dot{e}_2 + c_2e_2 \end{cases} \tag{13}$$

We use Lyapunov function method to prove the above theorems. For this purpose, the following Lyapunov functions are constructed (14):

$$V(t) = \frac{1}{2}s_1{}^2 + \frac{1}{2}s_2{}^2 + \frac{1}{2k}(\hat{u} - u)^2 \tag{14}$$

Obviously, the derivative of Lyapunov function can be expressed as equation (15):

$$\begin{aligned} \dot{V}(t) &= s_1\dot{s}_1 + s_2\dot{s}_2 + \frac{1}{k}(\hat{u} - u)\dot{\hat{u}} \\ &= s_1(\dot{e}_1 + c_1e_1) + s_2(\dot{e}_2 + c_2e_2) + \frac{1}{k}(\hat{u} - u)\dot{\hat{u}} \\ &= s_1(q_1 + x_2 + c_1e_1) + s_2(q_2 - ax_2 - u + \\ &\quad c_2e_2) - s_2(\hat{u} - u) + \frac{1}{k}(\hat{u} - u)\dot{\hat{u}} \end{aligned} \tag{15}$$

Considering the expression of controller output $\hat{u}$ and control parameters q_1 and q_2 in the theorem, the above formula can be further expressed as:

$$\begin{aligned} \dot{V}(t) &= s_1\dot{s}_1 + s_2\dot{s}_2 + \frac{1}{k}(\hat{u} - u)\dot{\hat{u}} \\ &= s_1(\dot{e}_1 + c_1e_1) + s_2(\dot{e}_2 + c_2e_2) + \frac{1}{k}(\hat{u} - u)\dot{\hat{u}} \\ &= s_1(q_1 + x_2 + c_1e_1) + s_2(q_2 - ax_2 - u + \\ &\quad c_2e_2) - s_2(\hat{u} - u) + \frac{1}{k}(\hat{u} - u)\dot{\hat{u}} \\ &= -s_1{}^2 - s_2{}^2 \end{aligned} \tag{16}$$

Based on the stability theory,for the stabilize of the control system at the equilibrium point, $\dot{V}(t) \le 0$ is required . It can be easily seen equation (17) from equation (16):

$$\dot{V}(t) = -s_1{}^2 - s_2{}^2 \le 0 \tag{17}$$

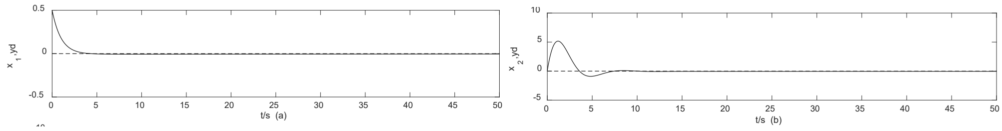
The condition of Lyapunov function is satisfied and the sliding mode surface is stable. Obviously, when $\dot{\hat{u}} = ks_2$, the system can output the target torque accurately and reduce the torque ripple to the greatest extent.

4. Simulation result and analysis

In order to verify the effectiveness of the sliding mode controller proposed in this paper, we use numerical simulation examples to simulate and analyze. The simulation system uses a three-phase 12/8-pole SRM as the object of study. The damping coefficient D of the motor is 0.01, and the viscous friction coefficient J is 0.005[13].SRM mechanical motion model (6), as a transmission system, obtains the desired electromagnetic torque value through sliding mode control. After sinusoidal signal of any target signal is taken, that is, $y_d = 0$, obtain equation (18):

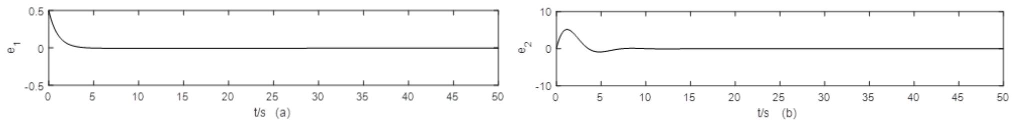
$$\begin{cases} \dot{x}_1 = -c_1 e_1 - s_1 + d_1 \\ \dot{x}_2 = -c_2 e_2 - s_2 + u - \hat{u} + d_2 \end{cases} \tag{18}$$

The error between SRM motor and target signal is: $e_1 = x_1 - y_d$, $e_2 = x_2 - y_d$, The sliding surface designed by Formula (12) is adopted. The parameters $c_1 = 0.01$, $c_2 = 0.005$, $k = 1$, $x_1(0) = 0.5, x_2(0) = 0.1,$ are taken in the simulation process,the perturbation signal in the system is assumed to be bounded and can be regarded as a superposition of sine or cosine functions.Therefore, set $d_1(t) = 0.1\sin t$, $d_2(t) = \sin t$, and obtain the synchronization process between SRM system state variables x_1, x_2 and the objective function, as shown in Figure 3(a),the synchronization of the target signal can be completed within 5s, that is, the system output ω is synchronized with the given ω^* in a very short time; the error curve of the system variables is shown in Figure 4.It can be seen from the figure, by adding control variables q_1, q_2 and SRM state variable x_1, x_2 can track the target function in a short time to complete synchronization transmission, and the state error signal of the system can steadily approach zero in a very short time. As time goes by, the error curve remains stable without jitter. The synchronization transmission objective function y_d can be arbitrarily selected, which is more beneficial to practical applications. Figure 5 shows the output of the sliding mode controller, and it can be seen that the output of the controller is smooth and continuous without jitter, which shows that the new sliding mode controller with integral control can eliminate the jitter problem inherent in the traditional sliding mode controller.



(a) Synchronization of x_1 and y_d (b)Synchronization of x_2 and y_d

Figure 3. Synchronization curve of SRM state variables and target signals



(a) Errors in x_1 and y_d (b) Errors in x_2 and y_d

Figure 4. Error curves of SRM system state variables

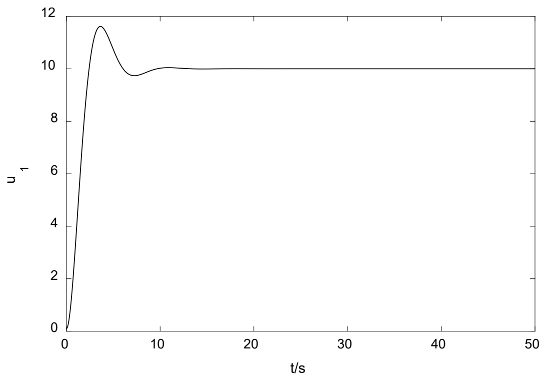


Figure 5. Output of the controller u

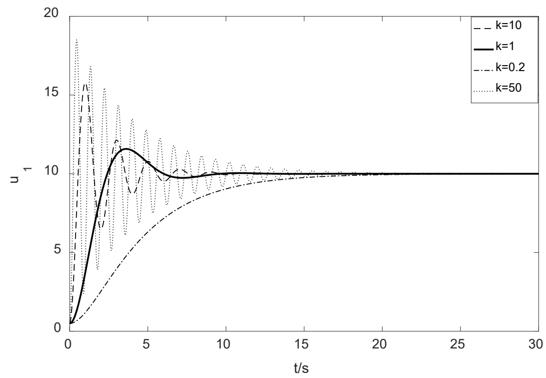


Figure 6. Output of controller when parameter k takes different values

In the simulation, we find that the rising time, adjusting time and overshoot of Controller $\hat{u}$ are different when the value of parameter k is different. When $k = 0.2$, as shown in Fig.6, the rising time and adjusting time are longer and the convergence speed is slower, which can not satisfy our control requirements. When $k = 1$, all three indexes can meet the control requirements When k =10 and $k = 50$, although the rising time and adjusting time of the controller can meet the requirements, the overshoot is too large. Obviously, if the value of k is small, the convergence rate of the system is relatively large. If the value of k is large, the overshoot is too large. Finally, we set $k = 1$, the convergence rate and system robustness can fulfill the design requirements.

5. Conclusion

Aiming at the problems of large SRM torque pulsation and strong vibration, this paper adopts the improved sliding mode controller and combines the synchronization transmission technology of the signal to obtain the accurate target torque and reduce the SRM torque pulsation. The simulation results show that increasing the control parameters in the synchronization transmission process can not only shorten the system response time, but also track the target signal accurately, so as to obtain the accurate target torque; in addition, the use of the integral sliding mode surface in the sliding mode control reduces the system chattering effectively, and the system robustness is good, which ultimately achieves the purpose of reducing the torque pulsation.

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