Sensors & Transducers, Vol. 171, Issue 5, May 2014, pp. 15-19

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Sensors & Transducers

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The Control of Switched Reluctance Motor in Electric Vehicle

[1] Zheng Liu, [2] Miaoshan Lin

[1] School of Application and Technology, Hainan University, Danzhou, 571737, China

[2] School of Mechanics and Electronics Engineering, Hainan University, Haikou, 570228, China

Received: 5 March 2014 /Accepted: 30 April 2014 /Published: 31 May 2014

Abstract: The control of SRM was discussed: current chopping control, angle position control. This paper presents an inverter circuit and a fuzzy sliding mode control method to minimize the torque fluctuation and noise of the SRM. Based on the experimental results, Using the inverter circuit and fuzzy sliding mode control method can effectively minimize the torque fluctuation and noise of the SRM, For the switched reluctance motor applications in electric vehicles to provide a theoretical basis. *Copyright © 2014 IFSA Publishing, S. L.*

Keywords: Switched reluctance motor, Electric vehicle, Control introduction.

1. Introduction

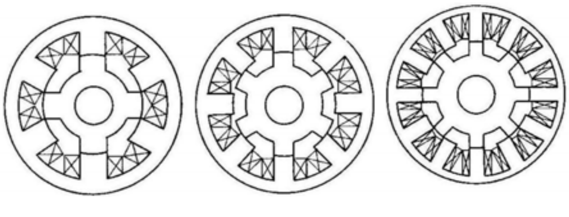
The electromotor drive system is the heart of electric car, and its task is to efficiently convert the energy of the battery into the kinetic energy of the wheel, or put the kinetic energy feedback of the wheel into the battery under the control of the driver. From the view of the function, the electromotor drive system of electric car can be divided into two large systems. The electric system is composed of three subsystems, electromotor, power converter and electronic controller; but the mechanical system mainly includes the mechanical transmission device (optional) and the wheel. The control objective is to drive electromotor, the electromotor is asked to be able to frequently start/stop, accelerate/decelerate, and it is requested to high torque when climbing or low speed, low torque and widely variable speed range when high speed.

The switch reluctance electromotor is directly derived from the variable reluctance stepper electromotor. Its advantage lies in which its torque/rotate speed characteristic is good, and it is suitable for electric car drive. Because of the serious magnetic saturation of magnetic end and the edge effect of magnetic pole and grooves, its design and control is very difficult and exquisite. It often causes noise problem in the testing process. The essay fully considers the limit of the pole arc, the height and the Maximum magnetic flux density by the optimization design for switch reluctance electromotor; it uses the finite element analysis method to make the loss of the whole electromotor be minimized. At the same time, it adopts fuzzy sliding mode control method, which can control the nonlinearity of the electromotor and make the noise be minimized. [1]

2. The Switch Reluctance Electromotor of Electric Car

2.1. The Structure of Switch Reluctance Electromotor

Switch reluctance drive electromotor is composed of four parts: switch reluctance electromotor, power converter, sensor and controller. The switch reluctance electromotor plays a key role-it transforms the electric energy into mechanical energy. At present, switch reluctance electromotor is classified according to the pole number of the different stator and rotor, the Fig. 1 shows the basic structure of three kinds of switch reluctance electromotor.



(a) 6/4 pole (b) 8/6 pole (c) 12/8 pole

Fig. 1. The basic structure of switch reluctance electromotor.

2.2. The Operating Principle of Switch Reluctance Drive Electromotor

As is shown in Fig. 2, the four-phase 8/6 pole switch reluctance drive electromotor is an example (lone one phase winding is drawn in the figure).

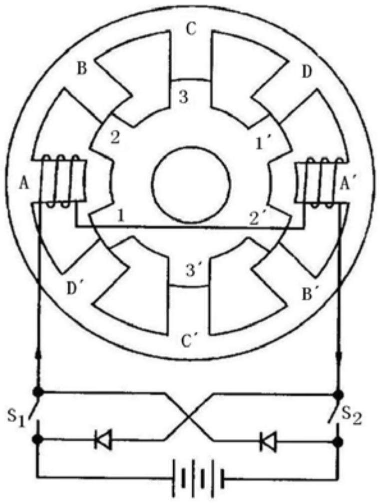


Fig. 2. Four-phase 8/6 pole switch reluctance drive electromotor.

Because the stator and rotor pole is salient pole structure, the inductance L of each phase winding varies with the change of the rotor position. The operating principle of switch reluctance electromotor follows the principle of minimum reluctance, when B phase winding is stimulated, the rotor needs clockwise rotation until the rotor pole 1 is opposite to stator pole B in order to reduce the magnetic resistance of magnetic circuit; this moment, the magnetic resistance of magnetic circuit is minimum (inductance is maximum). Then, the magnetic resistance torque makes rotor pole 1 is opposite to stator pole A by cutting off the stimulation of the winding B and inflicting the stimulation on the winding A. The torque direction often points to the opposite position of the pair of nearest poles. Therefore, according to the feedback signal of rotor position sensor, phase winding is conducted according to the order of B-A-D-C, which makes rotor continuous clockwise rotation [2].

According to the principle of magnetic energy in total, each phase rotor produces reluctance torque in the different position as follows:

$$T(\theta,i)=\frac{\partial W'(\theta,i)}{\partial\theta}$$

where θ is the rotor position angle; ί is the phase winding current; w'(θ, ί) is the magnetic energy in total.

The area under the magnetizing curve can be represented as:

$$W'(\theta,i)=\int_0^i \varphi(\theta,i)di$$

Flux linkage φ(θ, ί) is written as φ(θ, ί)=L(θ, ί)ί, therefore:

$$T\left(\theta,i\right)=\frac{1}{2}\frac{\partial}{\partial\theta}\int_0^{i^2} L(\theta,i)di^2$$

Under the specific circumstance, switch reluctance electromotor has no magnetic saturation, the inductance has nothing to do with the phase winding current, it can deduce reluctance torque as follows:

$$T\left(\theta,i\right)=\frac{1}{2}t^2\frac{dL}{d\theta}$$

Given the magnetic saturation, the inductance is the function of rotor position angle and phase winding current.

We can see from the above analysis that the switch reluctance electromotor has two obvious features. One is that the direction of torque isn't influenced by the direction of phase current; another is: when the inductance increases, it can produce electromotor torque (dL/dθ>0); on the contrary, it can produce minus torque, just braking torque. Therefore, each phase only produces positive torque within a half of polar distance so that it easily produces torque ripple, increasing the number of electromotor phase can reduce the torque ripple. [3]

The voltage formula of switch reluctance electromotor can be represented as:

$$u=Ri+L\frac{di}{dt}+i\frac{dL}{d\theta}\omega\,,$$

where u is the phase voltage; R is the winding resistance; ω is the rotor speed.

The corresponding phase current can be represented as:

$$i = \frac{u}{\omega} f(\theta)$$

where $f(\theta)$ is the structure parameters of the electromotor, the rotor position, triggering angle and the function of turn-off angle.

Therefore, the average torque of m phase switch reluctance electromotor is:

$$T = \frac{m}{\theta_{cy}} \int_0^{\theta_{cy}} \frac{1}{2} i^2 \frac{\partial L}{\partial \theta} d\theta = \frac{mu^2}{2\theta_{cy}\omega^2} \int_0^{\theta_{cy}} f^2(\theta) \frac{\partial L}{\partial \theta} d\theta$$

where θ_{cy} is the rotor pole pitch angle.

If the phase voltages of switch reluctance electromotor, triggering angle and turn-off angle have been given, the average torque and power are:

$$T_{av} = \frac{K}{\omega^2} \qquad P = \frac{K}{\omega}$$

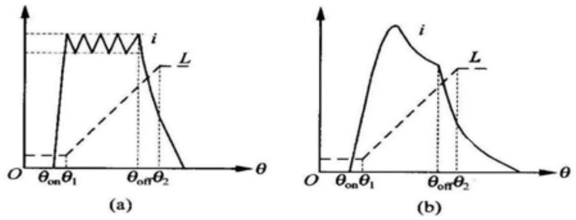
We can see from the formula that the torque of switch reluctance electromotor is inversely proportional to the square of the rotor speed; the power is inversely proportional to the rotor speed.

2.3. The Operating Method of Switch Reluctance Electromotor

Switch reluctance electromotor has two basic operating methods. When the rotor speed is lower than the base speed ωb, CHOP for the current is called as current chopping control. In the way of CCC, the triggering angle θ_{on} and turn-off angle θ_{off} are changeless; the triggering angle is only decided by speed. Changing current limit can control torque, so using CCC can get constant torque characteristic. In the high speed area, the peak current is limited by the induction electromotive force of phase winding. Its characteristic can be controlled by adjusting the switches that is corresponding to different rotor position; it is called as angle position control (APC). In the way of APC, it can get constant power performance. It reaches its limit value in the critical rotor speed ωsc, θ_o and θ_{off}. Later, switch reluctance electromotor doesn't keep constant power characteristic, but enters into the series characteristic region, at the moment, $\theta_c=\theta_{cy}/2$ (is conduction angle). In the way of CCC and APC, the typical waveform of the current and inductance is shown in Fig. 3.

3. The Inverter Circuit

To reduce the noise to the minimum, the chopping frequency of switch reluctance drive electromotor should be higher than 10 kHz. Reducing the number of power device and making fully use of unipolar work have to increase inverter circuit. But reducing the number of power devices brings many negative effects, for example, the control performance becomes poor, the reliability becomes low, the operating performance becomes bad, additional passive components need to be added, etc. The designed inverter circuit that is shown in Fig. 4 is suitable for the switch reluctance electromotor of electric car. It makes use of two power devices to respectively control phase current and two fly-wheel diodes, this give stored electromagnetic energy back to the accumulator of electric car. Because each phase in the topological structure of the kind of circuit needs two power devices, the cost of the inverter is relatively higher than the inverter of a power device, but the inverter bridge can control each phase winding, and it isn't influenced by other phase winding condition. Therefore, using phase overlap can increase the torque and widen the constant power range of the electric car drives, satisfy the use performance of electric cars.



(a) CCC mode (b) APC mode

Fig. 3. The current and voltage waveform in the CCC and APC mode.

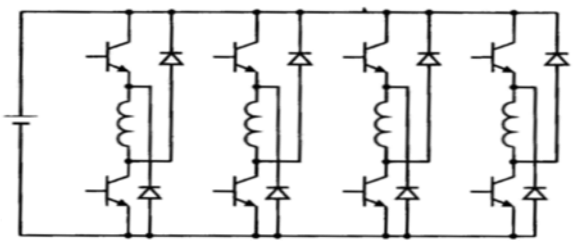


Fig. 4. The inverter circuit design of switch reluctance drive electromotor.

4. The Control of Switch Reluctance Electromotor

The control requirement of switch reluctance drive electromotor is unique, so the control method of induction electromotor and synchronous electromotor is no longer applicable. The traditional control method such as PID control is no longer suitable for electric cars. The essay develops a new fuzzy sliding mode (FSMC) control method for the switch reluctance electromotor of electric car drive, and this method comprehensively makes use of the fuzzy logic control (FLC) and sliding mode control (SMC).

Because FLC control is under the condition of not using control system's mathematical model and able to transform language control strategy for automatic control, it can deal with complex and uncertain system. But because the fuzzy control rule is decided by experience, the choice of its subordinate function mainly relies on trial-and-error method, the design of FLC elapses time, and the dynamic response of controlled system can't also determine in advance.

With the SMC method, control system has strong robustness for outside interference and parameter change. Therefore, reserving the ideal sliding mode of state trajectory can control the dynamic characteristic of the controlled system. But because of various non-ideal system such as switching hysteresis, control system and data sampling time delay, etc., the state trajectory usually shakes along non-ideal sliding mode surface, and the unexpected shake produces dynamic characteristic of high frequency non-model control in the control system.

FSMC method combines with the advantages of FLC and SMC, that is to say, it uses SMC to overcome the nonlinearity of switch electromotor, and uses FLC to reduce control vibration. The speed control system of electric car's switch reluctance electromotor; it is composed of two closed loops: one is internal current loop, and another is external speed loop. The input of FSMC is the difference of reference speed ω* and feedback speed ω, but the output is reference torque T*. Its reference current i＊ is represented by the nonlinearity torque corner characteristic of switch reluctance electromotor [4].

Designing the FSMC system needs to regard the speed error and speed derivative as state variable:

$$\begin{cases} x_1 = \omega - \omega^* \\ x_2 = \dot{\omega} = -\dfrac{B}{J}\omega + \dfrac{1}{J}T - \dfrac{1}{J}T_1 \end{cases}$$

where B is the viscous friction coefficient; J is the rotational inertia; T and T1 are the electromotor torque and load torque respectively.

As control variable, the state formula of u=T* is represented as:

$$\begin{pmatrix} \dot{x}_1 \\ \dot{x}_2 \end{pmatrix} = \begin{pmatrix} 0 & 1 \\ 0 & -B/J \end{pmatrix}\begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} 0 \\ 1/J \end{pmatrix} u + \begin{pmatrix} -\dot{\omega}^* \\ -\dot{T}_1/J \end{pmatrix},$$

where $\dot{\omega}^*$ and $\dot{T}_1$ are the system interference.

The sliding mode working has two switch sides, current control and speed control is defined as:

$$\begin{cases} s_i = i - i^* \\ s_\omega = x_1 + cx_2 \end{cases}$$

The system dynamic characteristic in the formula is controlled by parameter c. The sliding mode condition of current is just $s_i \dot{s}_i < 0$, controlling phase voltage can get:

$$u_i = \begin{cases} V_{dc} & s_i < 0 \\ -V_{dc} & s_i > 0 \\ ki\omega & s_i = 0 \end{cases},$$

where V_{dc} is the DC circuit voltage.

When the switch reluctance drive electromotor works in the way of chopping, it needs to meet this condition. In addition, giving the following sliding mode control law can meet speed sliding mode condition

$$s_\omega \dot{s}_\omega < 0$$

$$u_\omega = \begin{cases} \alpha & s_\omega < 0 \\ u_{eq} & s_\omega = 0 \\ -\alpha & s_\omega > 0 \end{cases}$$

Among them $\alpha = \eta J/c$, $u_{eq} = -Jx_2/c$.

In order to make sure the sliding mode condition, the parameter η must be large enough.

To reduce control vibration and the torque ripple, the switch rules of the fuzzy speed sliding mode condition are:

$$R_1 \quad if \quad s_\omega > 0 \quad then \quad u_1 = -\alpha$$
$$R_2 \quad if \quad s_\omega < 0 \quad then \quad u_2 = \alpha$$
$$R_3 \quad if \quad s_\omega = 0 \quad and \quad x_1 \neq 0 \quad then \quad u_3 = u_{eq1}$$
$$R_4 \quad if \quad s_\omega = 0 \quad and \quad x_1 = 0 \quad then \quad u_4 = u_{eq2}$$

The u_{eq1} and u_{eq2} are two kinds of different control functions; their switch line slopes $s_\omega = x_1 + c_i x_2 (i = 1, 2)$ are different.

Design and test a set of three-phase 4kw switch reluctance drive electromotor that adopts FSMC. It firstly optimizes design parameters (shown in Table 1), then adopts to compare the switch reluctance drive electromotor of FSMC and SMC in 1000 r/min torque waveform, and the result shows that adopting FSMC obviously reduces the torque waveform [5, 6].

5. Conclusion

The speed control system of switch reluctance electromotor has a series of advancements such as high density power, good control performance and good reliability; it better meets the power performance of the electric cars, and has broad application prospects.

Table 1. The technical parameter of some switches reluctance electromotor.

Rated power /kW	4
Rated voltage /V	240
Rated speed /($r \bullet \min^{-1}$)	3000
Number of phase	3
The stator	
Outer diameter /mm	175
Inner diameter /mm	110
Air gap/mm	0.5
The length of the core/mm	168
Pole height /mm	23
Pole arc	15.5º
The turn number of coil/ turn	11
The rotor	
Outer diameter /mm	109
Inner diameter /mm	38
Pole arc	17.5º
Pole height /mm	14

However, big noise of electromotor and torque ripple blocks the broad application of SRD system on the electric cars. Therefore, reducing switch reluctance electromotor torque ripple is the important way of increasing the speed control system performance of switch reluctance electromotor. The essay proposes a kind of method of inverter circuit and fuzzy sliding control (FSMC). The experimental result shows that adopting the inverter circuit and fuzzy sliding mode control method can effectively reduce the noise and torque ripple of switch reluctance electromotor; it provides support for further studying the control technology of switch reluctance electrometer's speed control system [7].

Acknowledgement

The work was supported by the Education Teaching Research Topic of Hainan University (hdjy1309).

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