Novel Switched Reluctance Machines for Domestic Appliances

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Abstract. Switched reluctance motors (SRM) are the core components of household appliances, which directly affect the performance and quality of household appliances. We have studied the application of switched reluctance motors in the home appliance industry. The 12/8 pole three-phase switched reluctance motor with a new rotor structure was proposed for the performance of SRM and the performance is simulated by MATLAB tools. Besides, the control principle and the operating equations of the switched reluctance motor are also introduced and deduced in detail. For the further work, although the 12/8 pole switched reluctance motor can effectively reduce the torque ripple, it cannot be completely eliminated. Therefore, the next step should continue to explore ways to reduce torque ripple.

1. Introduction

With the rapid development of the economy and the increasing quality of people's lives, domestic appliances such as washing machines and food processors have become indispensable [1]. The core components of many household appliances are motors, and the performance of the motor directly affects the quality of household appliances. The advancement of motors and their control systems has played a very important role in the upgrading of home appliances. Taking the washing machine as an example, the hot-selling washing machines on the market are mainly divided into drum type and pulsator type. They are driven by a motor to rotate the drum and the pulsator, thereby driving the clothes and the water to rotate and rub [2]. Therefore, the quality of the washing machine depends on the performance of the motor and the performance of the motor affects the cleanliness of the washing.

Nowadays, common domestic appliances motors mainly include single-phase asynchronous motors, brushless DC motors, series-excited motors and switched reluctance motors [3]. Single-phase asynchronous motor is a small-power motor powered by a single-phase AC power supply. It has the characteristics of simple structure, mature process and low cost, but it has a narrow speed regulation range, large starting current and low working efficiency. The brushless DC motor replaces mechanical commutation with an electronic commutator, has no mechanical friction and a wide speed range. However, not only the complex and costly controller, but the commutation torque ripple and the cogging torque ripple affect its application in high-performance speed regulation applications [4]. The series excitation motor is also called AC/DC dual-purpose series excitation motor, which has large starting torque, convenient speed regulation, high efficiency and good load characteristics. This, however, involves carbon brush system and commutator, which easily produce mechanical wear and electromagnetic interference during operation.

Switched reluctance motor is a new type of controllable AC speed control system which has emerged with the rapid development of power electronics and microelectronics in the past decade [5].
The switched reluctance machine system consists of a doubly salient reluctance motor, a power converter, a position sensor and a controller [6].

However, the traditional switched reluctance motor speed control system has the drawback of low motor winding utilization, higher maximum inductance in the motor windings, large torque ripple and noise of the motor and the serious copper consumption of the motor.

2. Proposed methodology - 12/8 SRM based on Alloy 6B
The stator and the rotor of the switched reluctance motor are both salient pole structures, that is, the double salient pole structure, and the number of poles of the rotor and the stator are not equal. The rotor and the stator core are pressed by a silicon steel sheet with good magnetic permeability, the rotor core has no winding, and the stator has a concentrated winding on the salient pole. Like ordinary motors, there is a small air gap between the rotor and the stator, which allows the rotor to rotate freely in the stator. Switched reluctance motors can have a variety of different phase numbers depending on the number of poles and stators. Figure 1 shows a typical three-phase 12/8-pole structure switched reluctance motor. The following takes the 12/8 motor as an example to illustrate the working principle of a switched reluctance motor.

The switched reluctance motor operates in accordance with the principle of "minimum reluctance", that is, the magnetic flux selects the smallest reluctance to form a closed loop [7]. Switched reluctance motors have two typical characteristics including switchability and magnetoresistance, which means that the motor operates in a continuous switching mode, and it is a doubly salient motor with a variable magnetic resistance loop between the stator and the rotor [8].

A m-phase switched reluctance motor, assuming that the structure and parameters of each phase are the same or symmetrical, ignoring the core loss and not considering the mutual inductance between the phase windings, the motor can be regarded as an electromechanical system with m pairs of terminals, the schematic diagram of its electromechanical conversion energy is shown in Figure 1.

![Figure 1. Schematic diagram of electromechanical energy conversion](image)

In Figure 1, $T_e$, $T_L$, $D$, and $J$ represents electromagnetic torque, load torque, viscous friction coefficient and moment of inertia of the system respectively. The voltage balance equation for the kth phase winding in the diagram according to the basic law of the circuit can be written as:

$$U_k = R_k i_k - e_k = R_k i_k + \frac{d\psi_k}{dt}$$  \hspace{1cm} (1)

where $U_k$ is the voltage applied to the kth phase winding, $R_k$ is the resistance of the kth phase winding, $i_k$ is the current of the kth phase winding and $\psi_k$ is the flux linkage of the kth phase winding. The flux linkage $\psi_k$ of the phase winding is a function of $i_k$ and $\theta$ and is given as

$$\psi_k (\theta, i_k) = L_k (\theta, i_k) i_k$$  \hspace{1cm} (2)

According to Newton's law of motion, the differential equation of motion of the mechanical end rotor in Figure 2-3 can be written as
The switched reluctance motor converts electrical energy into mechanical energy to satisfy the principle of energy conservation, and its electromagnetic torque can be derived from the magnetic field energy storage expression:

$$
T_e = J \frac{d^2 \theta}{dt^2} + D \frac{d \theta}{dt} + T_L
$$

(3)

When ignoring core loss, $dW_f = dW_m$ and $W_m$ represents the magnetic field storage energy.

$$
dW_c = \sum_{k=1}^{m} e_i dt = \sum_{k=1}^{m} i_k d\psi_k
$$

(4)

When ignoring core loss, $dW_f = dW_m$ and $W_m$ represents the magnetic field storage energy.

$$
dW_m = \frac{\partial W_m}{\partial \theta} + \sum_{k=1}^{m} \frac{\partial W_m}{\partial \psi_k} d\psi_k
$$

(5)

$$
dW_{mev} = T_m d\theta
$$

(6)

$$
dW_m = -T_e d\theta + \sum_{k=1}^{m} i_k d\psi_k
$$

(7)

Winding magnetic common energy is expressed as:

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

(8)

Based on the above formulas, the electromagnetic torque expression can be written as:

$$
T_e = \frac{\partial W(i_k, \theta)}{\partial \theta}
$$

(9)

The combined torque is superimposed by the torque of each phase and can be written as:

$$
T = \sum_{k=1}^{m} T_k(i_k, \theta)
$$

(10)

Due to the stator and the rotor of SRM are double salient pole structure and the SRM always works in the switching mode, the electromagnetic characteristics of SRM are highly nonlinear, which makes the torque ripple of the SRM more serious than other rotating systems. Reducing torque ripple through structural optimization is the most cost-effective method. Compared to the 6/4 structure of the three-phase switched reluctance motor, the 6/8 and 12/8 structure of the motor has a smaller step angle, which is advantageous for reducing the torque ripple. However, since the space between the teeth and the grooves is small, the inductance ratio of the stator and the rotor at the aligned position and the misaligned position is lowered, resulting in an increase in the controller capacity. In addition, since the step angle is small, the number of steps per revolution increases, and the switching frequency also increases, eventually leading to an increase in core loss. In household appliances such as washing machines, switched reluctance motors are required to be frequently started and stopped and reversed, which also exacerbates the loss of core. In order to solve this problem, Alloy 6B material is used as the core of the switched reluctance motor in this article. Alloy 6B is a cobalt-based alloy used in abrasive environments to prevent seizure, wear and abrasion. The wear resistance of Alloy 6B is inherent, and it does not rely on cold working or heat treatment, so it can also reduce the heat treatment workload and the cost of subsequent processing.

3. Simulation results
In order to realize the rapid prediction and optimized design of SRM performance, this paper analyses the SRM mathematical model and uses the powerful simulation modelling capabilities of MATLAB to develop the SRM model. Simulink is a visual simulation tool in MATLAB and it provides an integrated environment for dynamic system modelling, simulation and comprehensive analysis utilizing the functional components contained in Simulink. Simulink is an extension of MATLAB software, which is mainly used for dynamic system simulation. In this environment, a complex system can be constructed without a large number of writing programs, but with a simple and intuitive mouse operation. The model of 6/4 three phase SRM was built by the modules in Simulink is shown in Figure 2.

![Figure 2. The model of 6/4 three phases SRM built in simulink](image)

Some modules in Figure 2 are not basic modules in the library of Simulink such as CONVERTER module, which is the ordered composition of some basic modules. This Simulink feature makes complex models look simply. The basic structure of the converter and its deep structure are shown in Figure 3. As we discussed above, the asymmetric half-bridge circuits consist the converter part of the SRM. It is worth noting that ITBL and TTBL are two-dimensional tables of current and torque, respectively. In the process of calculating the SRM model in MATLAB, the most important process is to calculate ITBL and TTBL according to the set alignment inductance, non-aligned inductance, saturation current, maximum current and maximum flux linkage.

The corresponding simulation curves can be obtained by running the SRM model as shown in Figure 4. The A phase, B phase and C phase is represented in green, red and blue curve, respectively.
Although the SRM model in Simulink can be used to simulate different operating conditions of the motor under the set conditions, the stator and rotor poles of the SRM model in Simulink are only 6/4, 8/6 and 10/8. In order to obtain the widely used SRM model with stator and rotor poles of 12/8, we modified the original SRM model. Compared with 6/4 poles SRM, the 12/8 poles SRM’s inductance cycle is different. The inductance cycle of 6/4 poles SRM is 90 degrees and the inductance cycle of 12/8 poles SRM is 45 degrees. Some parameter settings for the 6/4 poles SRM and the 12/8 poles SRM simulation models are shown in Table 1. In the case of ensuring that the values of inertia, stator resistance, friction are constant, we set the turn-on angle, turn-off angle and the rotation speed to half.

Table 1 Parameters setting during model verification

| Parameters | Inertia | Turn on angle | Turn off angle | Rotating speed |
|------------|---------|---------------|----------------|----------------|
| 6/4 poles SRM | 0.006   | 40            | 75             | 1000           |
| 12/8 poles SRM | 0.006   | 20            | 37.5           | 500            |

(a) The flux linkage curves of three phases of 12/8 poles SRM

(b) The stator currents of three phases of 12/8 poles SRM

(c) The electromagnetic torque of three phases of 12/8 poles SRM
4. Conclusion
This paper has analyzed the development of the SRM. Besides, the control principle and the operating equations of the switched reluctance motor are also introduced and deduced in detail. By analyzing the requirements of the home appliance industry for the performance of SRM, we discussed a 12/8 poles SRM with new rotor materials. And the simulation model was built in the Simulink simulation environment. In order to verify the correctness of the model, we compared the simulation data of the 6/4 poles three-phase SRM and the proposed SRM. For the further work, although the 12/8 pole switched reluctance motor can effectively reduce the torque ripple, it cannot be completely eliminated. Therefore, the next step should continue to explore ways to reduce torque ripple.

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