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Research on Torque Ripple for Switched Reluctance Motors Based on A Torque Distribution Function Considering Mutual Inductance

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Abstract. A torque control algorithm which adopts a two-excitation, which combines with PI controller, is proposed to improve the performance of the Switched Reluctance Motor (SRM) drive base on large torque ripple commutation. After the reference torque was given from the PI controller of speed error, the instantaneous torque of each phase was produced by the torque distribution function (TDF), distribute torque to two adjacent phase base on information of the rotor position, and compute reference current using Current Command Generation, then get the PWM voltages signals combines with feedback current through Current Controller to exciting two adjacent phase. In this paper, simulation model of the motor takes into account the impact of mutual inductance. To take the SRM in the promotion of low-power into applications, a torque control system model of a 220VDC, 2.2kW SRM is established, and the simulation results showed that this method could effectively reduce the torque ripple compared with the traditional means

Keywords: SRM; Torque Ripple; Torque Distribution Function; Mutual Inductance.

1. Introduction

Switched Reluctance Motor (SRM) is more popular in recent years because of its simple structure, high torque-to-mass ratio, high efficiency, and high reliability. Therefore, it has a very broad outlook in the aerospace, industrial and automotive system. However, applications of the SRM have been limited because of its large torque ripple, which causes noise and vibration problems.

Torque ripple is one of hot issues of SRM. The results show that: to achieve constant torque control of SRM, and only by controlling the instantaneous torque to reduce the torque ripple, rather than the traditional average torque control.[1-3] In order to solve these problems, a torque distribution function (TDF) method has been proposed, which is widely used as a torque control algorithm. The current pulse width modulation strategy in the low speed to reduce the torque ripple is proposed in reference [4], which the distribution of torque primarily depends on rotor position, and resulting in the phase current control signal. Seungho Kim and Changhwan Chio [5] proposed an optimal choice of the TDF based on additional control objective such as minimizing the power loss and voltage requirement. The TDF method proposed in the previous works defined the TDF only at a positive torque production region, as the speed increases, the positive torque near the unaligned position is reduced, and the negative torque near the aligned position is increased due to the delay of the current rising and falling times. The reference [6] defines the TDF in both positive and negative torque region, therefore, adequate current rising and falling times, and good mechanical characteristic in high speed.

The torque distribution function algorithm, which adopts a two-phase excitation, is proposed to improve the performance of SRM. By exciting two adjacent phases instead of single phase, the changing rate and the magnitude of the phase currents are much reduced. Therefore, existing problems caused by the single-phase excitation such as large torque ripple during commutation, increased audible noise. The torque is efficiently distributed to each phase by the TDF. Most of the existing literature ignore the mutual couplings between

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different phases, Han-Kyung has shown earlier through finite-element analysis that mutual coupling can cause errors in the flux-linkage characteristics as much as 6.4% [6]. However, actual test results on mutual flux were not reported in most of the existing literature, and also failed to identify the asymmetric nature of the mutual coupling on different phase. The effects of mutual coupling on different configurations such as for even and odd number phase motors and also their effect on position estimation almost no mention. Debiprasad Panda and V.Ramanarayanan [7] establish the asymmetry of mutual flux for even and odd number phase motors, and give experimental results, these experimentally measured mutual can be utilized for modeling the motor.

In this paper, to a four-phase 8/6 SRM for the study, the SRM model is implemented as a Simulink/SimPowerSystems block and based on two 3-D lookup tables: (a) current as a function of flux linkage and rotor position, (b) torque as a function of current and rotor position. Both tables consider the affect of mutual inductance, and can be computed from the magnetization characteristic of the SRM. This magnetization characteristic can be obtained by finite-element filed computation or experimental measurements. In addition to using TDF control algorithm, and single-phase excitation, direct torque control are compared.

2. Implementation of Control Strategy

2.1 Torque characteristics of SRM

According to SRM mechanical equation:

$$T_e = J\frac{d\omega}{dt} + B\omega + T_L \tag{1}$$

In equation (1), J is inertia, B is viscous coefficient. When the system is at a point of equilibrium, we can got $d\omega / dt = 0$, so:

$$T_e = B\omega + T_L \tag{2}$$

In the interval Δt is small enough, $B\omega$ and T_L as a constant, and $d\omega/dt \cong \Delta\omega/\Delta t$ so:

$$\Delta T_e = J\frac{\Delta\omega}{\Delta t} \tag{3}$$

Assumption $k = J\dfrac{1}{\Delta t}$, equation (3) can be rewritten as:

$$\Delta T_e = k \cdot \Delta\omega \tag{4}$$

Equation (4) shows that speed control can reduce the torque ripple..

2.2 Selection of TDF [6]

Two adjacent phases are considered simultaneously to include the effects of mutual coupling. As only two phases are excited, it is not necessary to consider all four phase equations at the same time, and the phase currents of other two phases are assumed to be zero, then two-phase equations as follows.

$$\left.\begin{aligned} v_x &= R_s i_x + \frac{d\lambda_x}{dt} \\ v_y &= R_s i_y + \frac{d\lambda_y}{dt} \end{aligned}\right\} \tag{5}$$

and

$$\left.\begin{aligned} \lambda_x &= \mathrm{L}_x i_x + M_{xy} i_y \\ \lambda_y &= \mathrm{L}_y i_y + M_{xy} i_x \end{aligned}\right\} \tag{6}$$

where the subscript x and y are the excited adjacent phase, such as (a, b), (b, c), (c, d), or (d, a). R_s is the winding resistance, L is the phase inductance, M is the mutual inductance, i is the phase current, Torque distribution function is :

$$\left.\begin{aligned} f_x(\theta) &= \frac{g_x^2}{g_x^2 + g_y^2 \pm 2 g_{xy}\sqrt{g_x g_y}} \\ f_y(\theta) &= \frac{g_y^2}{g_x^2 + g_y^2 \pm 2 g_{xy}\sqrt{g_x g_y}} \\ f_{xy}(\theta) &= \frac{2 g_{xy}\sqrt{g_x g_y}}{g_x^2 + g_y^2 \pm 2 g_{xy}\sqrt{g_x g_y}} \end{aligned}\right\} \tag{7}$$

The self torque function and mutual torque function are:

$$g_x = \frac{\partial L_x}{\partial \theta} 、 g_{xy} = \frac{\partial M_{xy}}{\partial \theta} \tag{8}$$

2.3 Calculation of mutual inductance flux

The mutual inductance between two adjacent phases is not more than 6.4% of the related self inductance and the mutual inductance between non-adjacent phase is not more than 0.07% of the related self inductance at any rotor position. Therefore, the mutual inductance between non-adjacent phase is negligible [7]. The mutual flux ψ_{xy} is computed through the numerical integration of the induced voltage V_{xy} in the x th phase due to the excitation in the y th phase and that is given by the following equation:

$$\psi_{xy} = \int \left(v_{xy}\right) dt \tag{9}$$

3. Design of a Torque Control System Model

3.1 SRM model in simulink

The SRM can be modeled in Simulink/SimPowerSystems as a nonlinear electric system followed by a mechanical system representing the mechanical dynamics of the motor and the driven load. Figure 1 shows the Simulink diagram that models a four-phase 8/6 SRM.

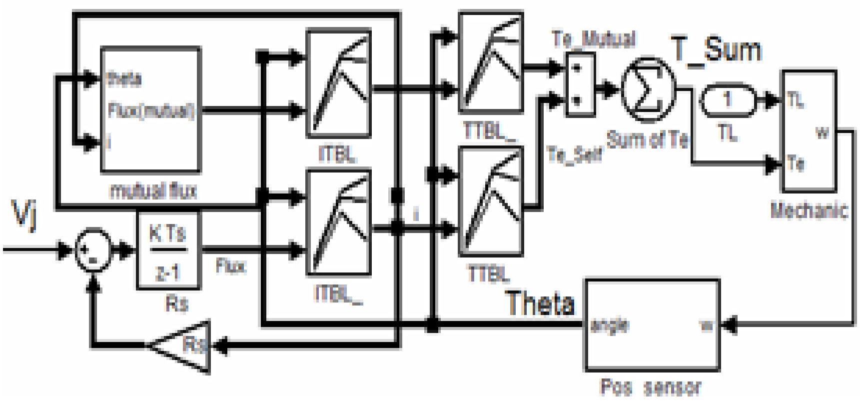


Fig.1 Simulation Model of Switched Reluctance Motor

The inputs of SRM model are the stator phase voltage measured at the input ports. Controlled current sources are used, in the input ports, to inject in the stator windings the currents produced by the nonlinear function $i(\psi, \theta)$ including the mutual inductance current generated by the mutual inductance flux, the electromagnetic torques produced by the stator phase are provided by the nonlinear function $T_e(i, \theta)$, which include the mutual inductance torque generated by mutual inductance current. The torques produced by all stator phase are then summed up to provide the total torque on the rotor shaft.[8]

3.2 Simulink diagram of the 8/6 SRM drive

Figure 2 shows a Simulink diagram of 8/6SRM which was used for torque control implementation based on TDF.

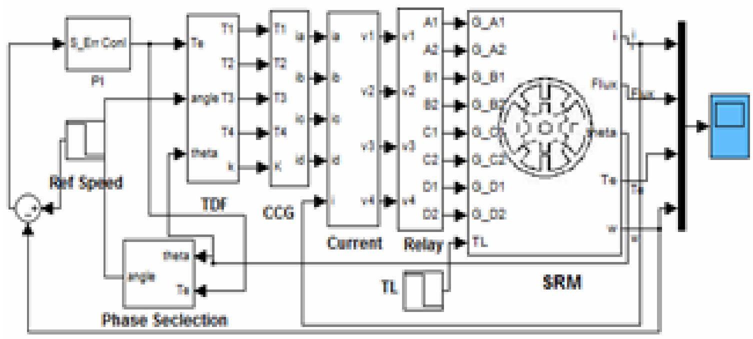


Fig.2 Simulink diagram of the 8/6 SRM

In this simulink setup, torque control signals generated after the speed deviation of PI controller, and calculated the desired torque of each phase by TDF, Current Command Generation (CCG) block is the current generator module which used to calculated the phase current according to the torque value, current value calculated compared with the feedback current through the Current Control block, finally, the phase control signals generated.[9]

3.3 Selecting adjacent phases

Two adjacent phases can produce the desired torque in the 15° electrical angle. In the 8/6 SRM, a cycle will be four different excitation regions, but only two-phase produce the desired torque is useful. Positive and negative torque, rotor position signals and selection of the adjacent in one cycle, shows in Table 1.

Table 1 Torque, rotor position and phase correspondence

Rotor Position	$T_e \geq 0$	$T_e < 0$
$0 \leq \theta < 15$	1 0 0 1	0 1 1 0
$15 \leq \theta < 30$	1 1 0 0	0 0 1 1
$30 \leq \theta < 45$	0 1 1 0	1 0 0 1
$45 \leq \theta < 60$	0 0 1 1	1 1 0 0

In Table 1, 1 represents the choice of the phase, 0 is the opposite.

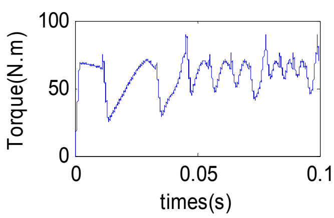
4. Comparison of Simulation Results

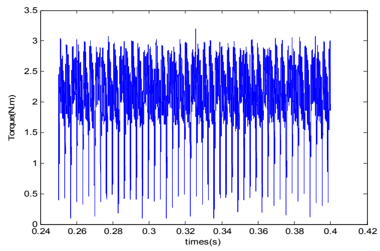
The parameters of motor shows in Table 2

Table 2 The parematers of srm

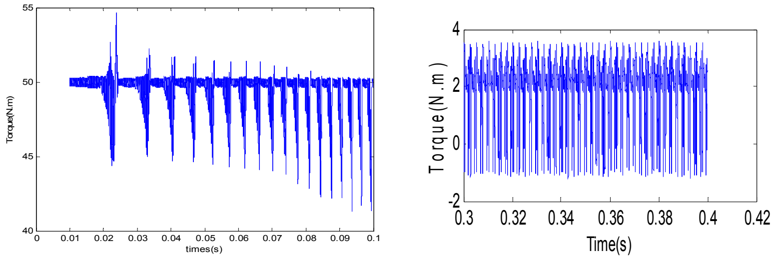
Parameters	Values
Voltage	220 VDC
Max. Inductance	23.6e-3 H
Min. Inductance	0.67e-3 H
System Inertia	0.05 kg.m.m
Phase Resistance	0.05 Ohm
System Friction coeff	0.02 N.m.s

In the simulation, single-phase control, direct torque control and TDF control were compared, simulation results are as follows Figure 3

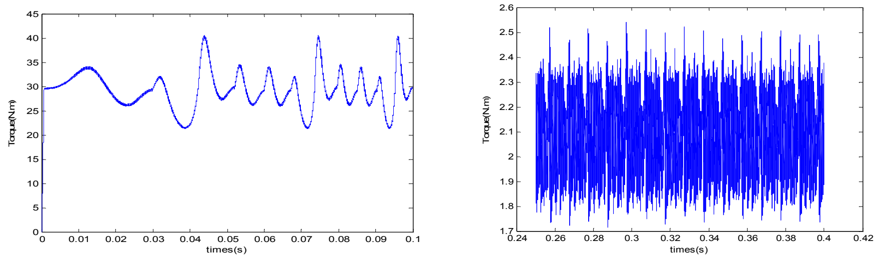




(a)



(b)



(c)

Fig.3 Three Control methods of torque waveforms. (a) single-phase control (b) direct torque control (c) TDF control

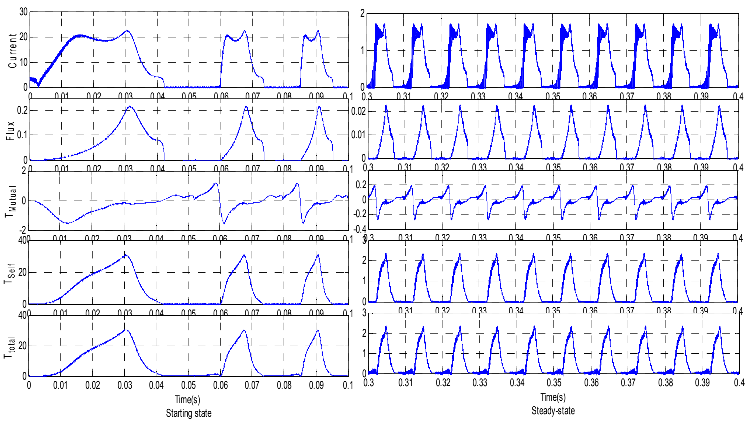
These control strategies are done for a rotor speed of 1000 rpm. The system is in start-up before the reference speed has not reached, PI controller will output upper limit. At this time, the current reaches the maximum value, resulting in the high torque, however, torque ripple is relatively large. When the speed reach the reference speed or near, torque will stabilize at a range.

Single-phase control: a turn-on angle of 32°, a turn-off angle of 47°, the torque peak and trough values obtained with the stable phase are respectively 2.5 N.m and 0.5 N.m, therefore, torque ripple range is 2 N.m.

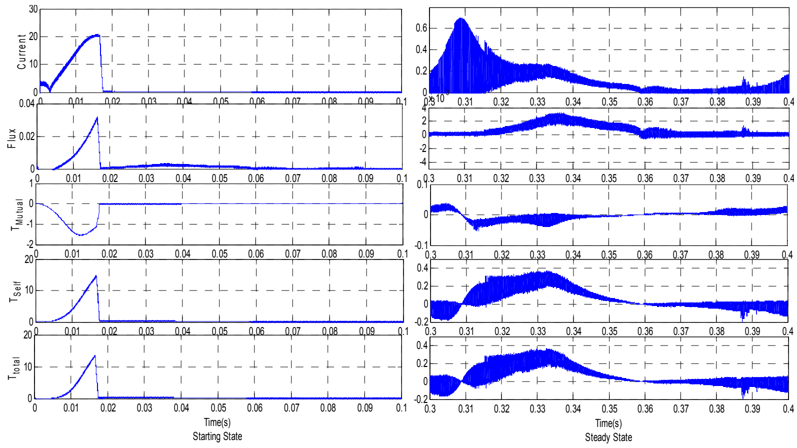
Direct torque control: (a) The stator flux linkage vector of the motor is kept at a constant (with amplitude hysteresis bands). (b) The torque can be controlled during accelerating or decelerating the stator flux vector. [10] The control objective a) is achieved by selecting an appropriate voltage vector. The control objective b) is also achieved by acceleration or deceleration of the stator flux vector relative to the rotor movement. Figure 3 (b) shows the waveforms obtained for DTC, the torque peak and trough values obtained with the stable phase are respectively 3 N.m and -1 N.m, therefore, torque ripple range is 4 N.m.

TDF control: The torque peak and trough values obtained with the stable phase are respectively 2.4 N.m and 1.8 N.m, therefore, torque ripple range is 0.6 N.m.

To further study, Figure 4 (a) shows the waveform of motor in the speed of 1000rpm, Figure 4 (b) shows the waveform of motor in the speed of 100rpm, which show parameters of phase A including phase current, phase flux linkage, phase mutual-torque, phase self-torque and total torque respectively from top to bottom, the left for the starting phase, the right for the stability phase, in which the right and the left vertical axis corresponds to the same.



(a)



(b)

Fig.4 Under the 1000 rpm and 100 rpm, A phase waveform (a) A phase waveform under 1000 rpm (b) A phase waveform under 100 rpm

When the motor be in the stating phase, output torque is relatively large, the single-phase torque can reach 20 N.m in the speed of 1000rpm and 100rpm, and current can track the change of flux. And can be seen, mutual-torque will affect the self-torque. In the current rising time, mutual-torque reaches the maximum which is almost 7% of the self-torque, therefore, we can not ignore the impact of mutual inductance.

5. Conclusion

It has been proved that at any position two adjacent phases contributing to generate desired torque and the excitation interval of a phase can be broadened to 30 degrees whereas it is 15 degrees in conventional drives. This reduces the rate of change of phase currents and the peak current. Simulation results of the proposed TDF have shown that the output torque has low ripple.

An accurate nonlinear model of switched reluctance motors has been developed and implemented as a Simulink/SimPowerSystems block, which considers the effect of mutual inductance. In this block, the user can take on the different control strategies of SRM to optimize torque ripple. With single-phase control, DTC control to comparison, the TDF control system can effectively reduce the torque ripple. As making the SRM in the promotion of low-power applications, a torque control system model of a 220VDC, 2.2kW SRM was established.

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7. References

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