Design Optimization of Switched Reluctance Motor Torque Controller in Electric Vehicles

Yueying Zhu[1], Guifan Zhao[1], Dafang Wang[1], Dongyu Yang[1], and Takao Ito[2]

1 School of Automobile Engineering, Harbin Institute of Technology, Weihai 264209, Shandong Province, China
(Tel : 86-631-567-2276; Fax : 86-631-568-7523)
(hityueying929@163.com, zgf7071@163.com)

2 Dept. of Business Administration, Ube National College of Technology, Yamaguchi, Japan
(Tel : 81-836-35-7115; Fax : 81-836-35-7115)
(ito@ube-k.ac.jp)

Abstract: The drive performance of Switched Reluctance Motor (SRM) used for electric vehicles is one of the important issues for improving the stability and comfortable operation of the vehicle. This paper introduces a study of design optimization of the SRM torque controller. The purposes of the SRM nonlinear dynamic model established with the MATLAB/Simulink are to reduce the torque ripple and increase the average torque. The torque ripple and average torque, as functions of turn-off angles and rotor speed, are developed by simulation in this paper. The optimized torque controller is designed based on the changeable turn-off angles. The simulation results show that the proposed optimization of the torque controller has strong impact on the improvement of the torque ripple and the average torque.

Keywords: Electric vehicle, switched reluctance motor, torque control, optimization, computer simulation**.**

I. INTRODUCTION

We have to find the way to save our energies and protect our environment for the energies short. The development of the electric vehicles (EV) will contribute to save our energies and realize the zero emission in automobile industry.

Compared to other motors, the switched reluctance motor (SRM) used in the EV has some advantages, such as simple structure, low cost and flexible control, etc [1-3]. Therefore, the SRM has lately drawn considerable attention in the automobile drive system. However, the SRM suffers from a major drawback for its torque ripple which is harmful to the motor and the vehicle drive system [1, 4]. In order to obtain good drive performance of the EV, it is very significant to design a high torque controller for reducing the torque ripple and increasing the average torque of the SRM.

There are two ways to control the torque of the SRM as a whole now. One is to optimize and control the torque in changing phase condition, such as hysteresis current control [5], PWM voltage control [6] and direct instantaneous torque control [1,7,8]. The other is to control the torque by using modern intelligent control strategy, such as fuzzy logic control [9], sliding mode control [10] and artificial neural network control [11, 12]. With the development of control strategies, SRM has a good improvement in reducing the torque ripple.

The main contribution of this paper is to design a torque controller used in the EV and optimize it for reducing the torque ripple and increasing the average torque. Compared with the fixed turn-off angle controller, the optimized controller has great advantage to reduce the torque ripple and increase the average torque.

This paper is organized as follows. Section 2 introduces the main structure and characteristics of the SRM. The nonlinear dynamic model of the SRM using the MATLAB/Simulink is built under hysteresis current control strategy. In Section 3, the torque ripple and average torque as functions of turn-off angles and rotor speed are obtained by simulation. In order to reduce the torque ripple and increase average torque, the optimized controller based on turn-off angles and rotor speed is proposed in Section 4. In Section 5, the simulation results are presented, and the performance of the optimized controller is also discussed.

II. SRM NONLINEAR MODEL

1. The Structure of the 8/6 SRM

There are four parts for the SRM drive system, SRM, converter, controller and detection sensor. An 8/6 SRM matching with the four phase asymmetrical converter is chosen in this paper. Obviously the asymmetrical converter can manage the phase singly by controlling the switches and reduce the torque ripple by overlapping appropriately between on-going and off-going phase. In addition, the driving range is very important for electric vehicle, which can be extended by using this converter because of the ability of energy recovery. That is the reason why this converter is chosen.

2. Mathematical Model of SRM

The flux linkage in each phase can be calculated with phase voltage across the winding by Faraday's law as Eq. (1).

$$\psi_k(i,\theta) = \int (u_k - R_k i_k)dt \qquad (1)$$

where ψ_k is the phase flux linkage, u_k is the phase voltage, R_k is the electrical resistance of the winding, i_k is the phase current, θ is the angle of rotor.

The magnetic torque generated by the SRM is obtained by co-energy in the magnetic circuit using Eq. (2).

$$T_e(i,\theta) = \frac{\partial}{\partial\theta}W'(i,\theta) = \frac{\partial}{\partial\theta}\int_0^i \psi(i,\theta)di \qquad (2)$$

where T_e is the magnetic torque generated by the motor, $W'(i, \theta)$ is the co-energy.

The torque and load mechanical dynamic is presented in Eq. (3) based on mechanical principle.

$$T_e(i,\theta) = J\frac{d\omega}{dt} + B\omega + T_L \qquad (3)$$

where J is the inertia of the SRM system, B is the total friction coefficient, ω is the angular velocity of the rotor, T_L is the load torque.

The average torque is very important for the dynamic output of motor. As a four phase SRM, the average torque is determined using Eq. (4).

$$T_a = \frac{12}{\pi}\int_0^{\pi/3} T_e(i,\theta)d\theta \qquad (4)$$

The SRM suffers from a major disadvantage which is the torque ripple. The ripple affects not only the SRM dynamic performance, but also increases the inside noise and reduces the driving stability when the SRM is used to electric vehicle. So it is greatly significant for the vehicle to minimize the torque ripple. Literature [13] defines the motor ripple coefficient as Eq. (5).

$$T_r = \frac{T_{\max} - T_{\min}}{T_a} \qquad (5)$$

where T_r is the SRM torque ripple coefficient, $T_{\max}$ is the torque maximum value, $T_{\min}$ is the torque minimum value.

3. Implementing Flux and Torque in Simulink

The magnetization characteristic is basal for evaluating the SRM dynamic performance. And the flux linkage as a function of the current and turn-on angle is very important for establishing the nonlinear model of SRM. So the function $\psi(i, \theta)$ is needed to obtained before founding the SRM model in the MATLAB /Simulink environment.

There are many approaches found in literatures to determine the SRM magnetization characteristic, such as using mathematical model [14, 15], establishing neural network model [16, 17], making experiment and analyzing by finite element method (FEM) [18]. An 8 kW 8/6 SRM is chosen in this paper and the experimental data which is SRM phase fluxes relating to phase currents and rotor angles is obtained from FEM.

The flux data $\psi(i, \theta)$ at different currents i and rotor angles θ can be changed to the function $i(\psi, \theta)$ which is the phase current as a function of the flux and rotor angle. The Lookup Table among the phase current, rotor angle and flux which is presented in Fig.1 is established using the function $i(\psi, \theta)$ in Simulink environment, and the corresponding current value will be obtained when the flux and rotor angle value input to the Lookup Table.

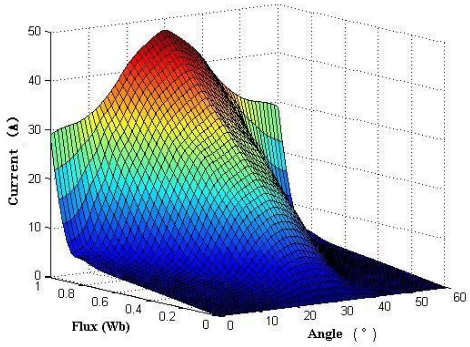


Fig.1. Lookup table of current versus flux and rotor angle.

The phase torque can be calculated using Eq. (2) when the inputs are phase currents and rotor angles. In order to improve the execution speed of the simulation system, the phase torque function $T(i, \theta)$ is pre-calculated and stored in a Lookup Table as shown in Fig.2. With the phase current and rotor angle as inputs, the Lookup Table produces the corresponding torque value.

4. Modeling the SRM Drive

With the phase voltage and the rotor angle as inputs and the phase current and total torque as the outputs, the SRM model is established with the MATLAB/Simulink in terms of the Eq. (1) and the two Lookup Tables.

The power converter model which is required to commutate the SRM phases is determined as asymmetrical converter. The motor and load mechanical dynamic model is governed by Eq. (3) and the hysteresis current controller model is established to avoid higher current which is harmful to the system. Fig.3 shows a Simulink diagram presenting a model of the current controlled SRM drive described above.

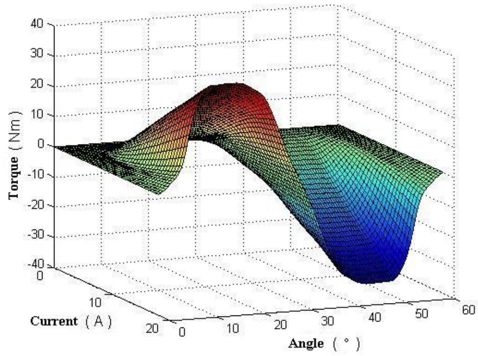


Fig.2. Lookup table of torque versus current and rotor angle.

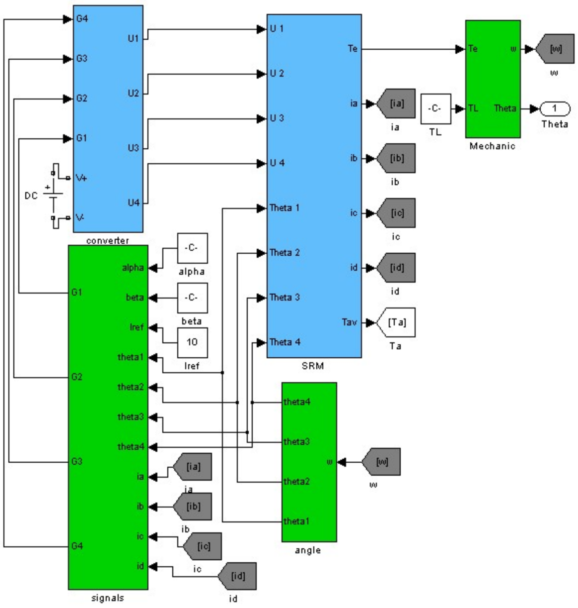


Fig.3. Simulink diagram of the 8/6 SRM drive.

III. SIMULATION OF SRM DRIVE

The SRM considered in the paper 8/6 motor with the following parameters, rated voltage U is 150V, reference current I_{ref} is 10A, armature resistance R is 1.3Ω, moment of inertia is J is 0.0013kg.m^2, and rated speed n is 300rad/s.

The purpose of the simulation is to obtain the SRM torque characteristic over the phase current and speed when the turn-off angles vary in appropriate ranges. With the simulation for the torque characteristic, the torque and torque ripple as functions of turn-off angles and output speed are obtained. According to the SRM rated speed is 300rad/s, so the speed will vary from 0-3300 rpm by steps of 300 rpm. With simple consideration and analyses, the changeable range of turn-off angles is 20°-30° and the turn-on angle is fixed on 0°.

In order to obtain the intuitionist numerical relation among torque ripple, speed and turn-off angle, the torque ripple data in simulation is presented in the form of 3-D surface chart as shown in Fig.4. The turn-off angle value which minimizes the torque ripple in given speed can be obtained by the simulation data and the function relation between optimizing turn-off angle and speed $\theta_{op}=f(\omega)$ is determined to achieve the optimization torque controller.

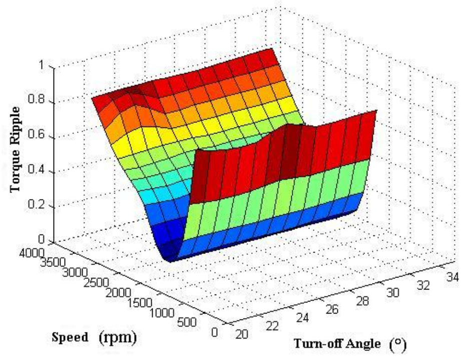


Fig.4. Torque ripples vs. speeds and turn-off angles.

IV. DESIGN OPTIMIZATION TORQUE CONTROLLER

It is very significant to select appropriate turn-off angles in SRM drive for improving dynamic performance of the motor and good drive performance of the EV as the turn-off angle value of SRM drive directly affect the average torque and torque ripple of the motor.

In this paper, the optimizing turn-off angles in different speeds is selected in the objective of reducing torque ripple and increasing average torque based on the torque function and torque ripple function established in Section 3. And the function relation between optimizing turn-off angle and speed $\theta_{op}=f(\omega)$ is determined by fitting data from simulation as shown in Fig.5.

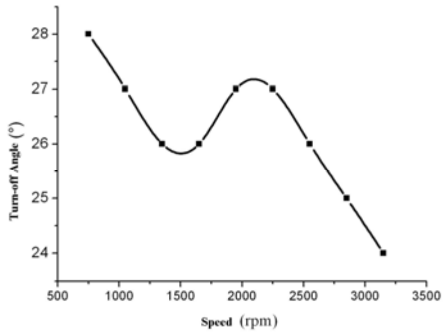


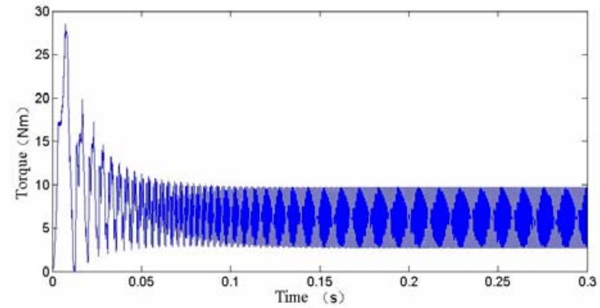
Fig.5. Turn-off angles versus speeds.

The variable turn-off angle model which is changing with the speed is established using the curve described in Fig.5. The model is imported to the simulation system using a Lookup Table in MATLAB/Simulink environment.

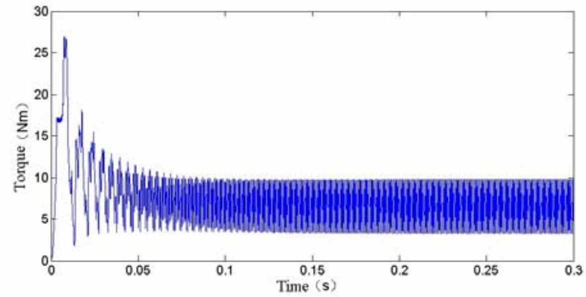
IV. SIMULATION RESULTS AND ANALYSIS

The simulation of 8 kW 8/6 SRM drive selected in this paper is carried on based on the SRM nonlinear dynamic model described above. With the fixed turn-on angle α=0°, the variable turn-off angle founded in Section 4 and fixed turn-off angle θ=25° are determined respectively to the SRM drive model. And the voltage U is 150V, the reference current I_{ref} is 10A.

The torque ripple and optimizing one can be obtained respectively by giving a steady speed to the SRM by simulation, which can be directly compared the two results from normal torque controller and optimization torque controller. The optimizing torque ripple and average torque performance are improved seen intuitively from Fig.6 which shows the normal average torque and optimizing one when the speed is about 2000rpm.



(a) Normal torque.



(b) Optimizing torque.

Fig.6. Total torque when speed is 2000rpm.

In order to present an easier comparison between the two drive systems, the SRM torque ripple coefficient data in different speeds from simulation results is described in the form of curve as shown in Fig.7 where the black square curve and the red round one respectively denote normal and optimizing results.

By comparing results from the two drive systems, the torque ripple reduces about 16.95% from 0.59 to 0.49 when the speed is imposed 375rpm. With the imposed speed 2300rpm, the optimizing torque ripple reduces 13.61% from 0.955 to 0.825 comparing with the normal ripple, and reduces 7.69% from 0.65 to 0.60.

In addition, it can be seen by comparing the results that the reduction effect of SRM torque ripple is very obvious as the SRM drive operating at low or high speed and the maximum reduction value can achieve 16.95%. While the reduction value falls a little when the drive runs at medium speed, and the value keeps around 7.7%.

When we reduce the torque ripple, the impact to average torque will directly determine the effect of the optimization controller designed in this paper as the purpose of optimization controller is to reduce the torque ripple without decreasing the average torque. In order to show an easier comparison, the SRM average torque data in different speeds from simulation results is described in the form of curve as shown in Fig.8 where the black square curve and the red round one respectively denote normal and optimizing results.

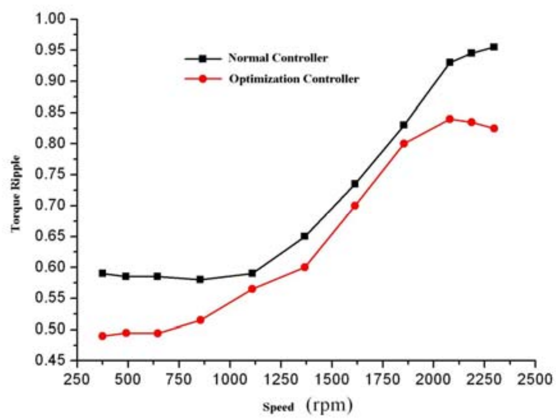


Fig.7. Comparison of the torque ripple.

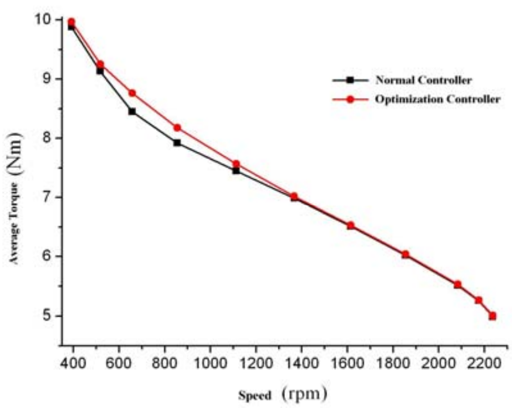


Fig.8. Comparison of the torque.

By comparing, the average torque is also improved at low and medium speed. It increases about 3.2% when the speed ranges from 500rpm to 1200rpm and about 1.0% at low speed. At high speed, there isn't a notable factor of two between the average torque curves.

In total, the power performance and driving stability of the EV will be improved greatly as the optimization controller can greatly reduce torque ripple over a wide speed range and appreciably increase average torque at low and medium speed.

VI. CONCLUSION

Considering the SRM flux linkage characteristic, a nonlinear dynamic model is established for 8 kW 8/6 SRM used in electric vehicles in this paper. With the hysteresis current control strategy, the optimization torque controller is designed based on the variable turn-off angle.

By the simulation on dynamic model established in the MATLAB/Simulink environment according to the SRM flux linkage characteristic, the torque ripple and average torque as functions of turn-off angles and speeds are determined using the simulation results. In order to reduce the torque ripple and increase the torque, the optimizing turn-off angles as a function of speed is obtained to achieve the optimization controller. Then the optimization torque controller is designed based on the variable turn-off angle.

The simulation results show that the nonlinear dynamic model of SRM established in this paper is good at robustness and dynamic performance, and the optimization torque controller based on the variable turn-off angle can effectively reduce the torque ripple and increase the ripple. Meanwhile the simulation results have a good reference value for designing EV and improving the performance.

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