OPTIMUM DESIGN APPROACH OF SWITCHED RELUCTANCE MOTOR FOR ELECTRIC VEHICLE APPLICATIONS

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ABSTRACT

The shortage of energy and environmental pollution are considered as relevant problems due to the high amount of automotive vehicles with internal combustion engines. Electric vehicles (EV) are one of the solutions to localize the energy source and best choice for saving energy and provide zero emission vehicles. The key component of the Electric vehicles is the electric motor and, therefore, its choice is important. Many types of electric motors have been analyzed during last decades and evaluated for EVs. Switched reluctance motors (SRM) have a number of advantages in contrast with other electric motors due to their simple construction, flexibility of control, high efficiency, lower cost and robustness to run under failure conditions. The SRM rotor does not have any windings or permanent magnets, being suitable for very high speed drive application. The switched reluctance motors drives (SRDs) necessitate more advanced control technology than DC and AC motors drives. High torque ripple, acoustic noise and vibrations are the major drawbacks of the SRM. So to decrease the torque ripple and improve the electric efficiency is the main objective and can be achieved by optimization policy.

Keywords: *Switched reluctance motor, Torque ripple minimization, direct instantaneous torque control*

I. Introduction

Electric Vehicles will form an important part of the solution addressing the concerns of carbon emissions, energy security and the ongoing need for the personal transportation. The outcome of selecting the optimal drive for an Electric Vehicle application depends strongly on the application's requirements, i.e. torque and speed, and the design goals. Selecting a certain machine or designing an electrical drive is generally a compromise between technologically conflicting requirements, such as power density, efficiency (in a single operating point or over an entire load cycle), field-weakening potential, cost, employed materials, machine or drive volume, fault tolerance and maintenance cost. Switched reluctance drive (SRD) has become one of the most excellent choices for electric vehicle drive because it exhibit important advantages over other kinds of electric drive system. Switched reluctance motor drive system (SRD) is a new type of Ac speed regulating system with main advantages of both Dc drive and traditional Ac drive. Switched reluctance motor (SRM) has become one of the top measured schemes for electric vehicles (EV) drive system due to its important advantages such as low construction cost, simple manufacturing process, high fault-tolerant capability, wide speed range of operation etc. However, the more noticeable torque ripple of SRM can do harm to the transmission system of EV, in addition, the electric efficiency of SRM openly decides the travel distance of EV, so it is of enormous importance to reduce the torque ripple and improve the electric efficiency of SRM applied in EV [1–4] . Due to the high nonlinear characteristics and the unique pulse power supply mode of SRM, effective dynamic optimization methods of SRD for EV drive are difficult to design and realize. At the present phase, there are two main methods to realize the dynamic optimization of SRD for EV drive: one is aiming to optimize the structural parameters of the SRM to improve the dynamic performance of the SRD. Picodet al. [5] researched the influence of stator geometry on performances of the SRM based on a 6/4 SRM, a simultaneous analysis was performed and dynamic performance development was verified. In [6], a new rotor pattern is optimized and projected to reduce the vibration and noise. The FEM analysis and experimental verification were both developed to verify the affectivity of the structure. Wei et al. [7] examined the effects of the stator windings and end-bells on stator modal vibration frequencies. The numerical computations of the stator mode shapes and resonant frequencies were validated with experimental results. These methods can improve the active performance of the SRM. However, the combinations of key parameters are extreme and difficult, which will result in increasing the complexity to comprehend the optimization of comprehensive performance. Furthermore, these methods were implemented without considering the control variables of the SRD. The other method is aiming to develop the dynamic performance of the SRD with advanced control algorithms. Fuzzy compensation control [8], sliding mode control [9, 10], self-adaptive control [11, 12], artificial neural network control [13–15] were used to attain correct control for the torque or speed of the SRM in order to improve dynamic performance of the SRD. In addition, some other advanced algorithms including deep neural network [16], and convolution neural network [17] could be employed to obtained dynamic performance improvement of the SRD. The method is opportune and widely functional, however, most present research based on this are focused on the torque ripple suppression of SRM exclusively without the consideration of the electric efficiency of SRM. In this paper, based on the mathematical model of SRM, the effects on the torque ripple and the electric efficiency of SRM from load torque, opening angle and turn-off angle are simulated and analyzed, with the determined objective function of the minimum torque-ripple and the maximum electric efficiency respectively, opening angle and turn-off angle of SRM are optimized and analyzed adequately; with the determined objective function considering of both the torque-ripple reduction and the electric efficiency improvement, a novel double indicator synchronous optimization objective function is proposed, based on this, the mathematical relations among the synchronous optimization objective and opening angle, turn-off angle, load torque and speed are determined; with the introduced synchronous optimization weight coefficients, the control model of adjustable opening angle and turn-off angle based on load torque and speed is established. For the above three different optimization strategies, both simulation results and experiment results verify the usefulness and supremacy of the proposed double indicator synchronous optimization strategy..

II.Proposed Methodology

In this paper, based on the mathematical model of SRM, the effects on the torque ripple and the electric efficiency of SRM from load torque, opening angle and turn-off angle are simulated and analyzed, with the determined objective function of the minimum torque-ripple and the maximum electric efficiency respectively, opening angle and turn-off angle of SRM are optimized and analyzed adequately; with the determined objective function considering of both the torque-ripple reduction and the electric efficiency improvement, a novel double indicator synchronousoptimization objective function is proposed, based on this, the mathematical relationships among the synchronous optimization objective and opening angle, turn-off angle, load torque and speed are determined; with the introduced synchronous optimization weight coefficients, the control model of adjustable opening angle and turn-off angle based on load torque and speed is established.

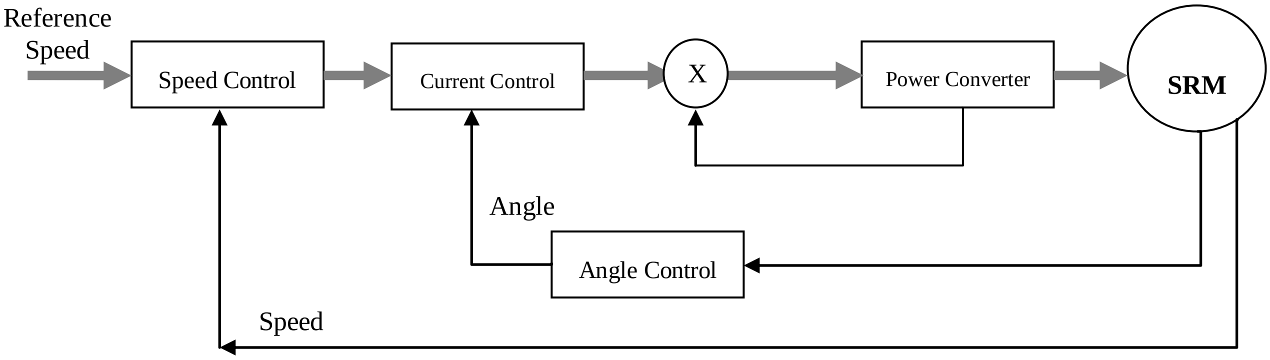

Figure 1. Block diagram of the SRD

Nonlinear model of SRM

Due to its highly nonlinear characteristics, nonlinear modeling of SRM is vital for both performance parameters calculation and dynamic characteristics analysis. At present, nonlinear modeling methods commonly used mainly include function analysis method [18, 19], neural network method [20,21] , experimental method and finite element analysis method (FEM) etc [22,23] .

Fundamental equations of SRM

According to the fundamental law of circuit, each phase flux linkage of SRM can be calculated by integrating Eq. (1).

$$\Psi j = \int (Uj - Rj\ ij)dt \qquad (1)$$

ψj is the flux linkage, Uj is the voltage of winding, Rj is the resistance of winding, ij is phase current, j is the phase number,.

Based on the principle of magnetism co-energy, the torque of SRM can be expressed by Eqs. (2) and (3) .

$$\mathrm{T}\ (\theta, \mathrm{i}) = \frac{\partial \mathrm{W}'(\theta,\mathrm{i})}{\partial \theta} \mathrm{T}\ (\theta, \mathrm{i}) = \frac{\partial \mathrm{W}'(\theta,\mathrm{i})}{\partial \theta} \qquad (2)$$

$$\mathrm{W}'\ (\theta,\mathrm{i}) = \int_0^1 \psi\ (\theta, i\ ) di \qquad (3)$$

T (θ,i) is electromagnetic torque, W' (θ,i) is magnetism co-energy, θis the position angle of rotor. According to the principle of dynamics, the mechanical movement equation of SRM can be expressed by Eq. (4) .

$$J \frac{d\omega}{dt} = \sum_{j=1}^{Nph} T\mathrm{j} - \mathrm{TL} - \mathrm{B}\omega \qquad (4)$$

J is rotary inertia, B is frictional coefficient, ω is angular velocity of rotor, TL is load torque, Tj is the torque of phase, and Nph is the total of phases.

Nonlinear model of SRM

As discussed earlier, it has been observed that flux values under different rotor position angle and phase current can obtained by finite element method (FEM). Based on mathematical model, SRM ontology module, power converter module, angle control module, current control module and switch control module are established respectively. Among them, the speed loop adopts PI control. Figure1 shows the control system block diagram of the 4 kW SRD.

Dynamic indicators analysis of SRM

Although SRM has many unique advantages, its inherent torque ripple greatly increases the noise of the vehicle system and reduce the comfort and reliability inevitably, so the torque ripple reduction is of great significance to improve the overall performance of EV. This paper introduces both the torque ripple coefficient (TR) defined by Eq. (5) and the torque smooth degree coefficient (TS) defined by Eq. (6) .

$$\mathrm{TR} = \left[\frac{3}{\pi} \int_0^{\pi/3} Te^2\,(i, \theta) d\theta\right] \qquad (5)$$

$$\mathrm{TS} = \sqrt{\frac{\pi}{3\ \int_0^{\pi/3} Te^2\,(i,\theta) d\theta}} \qquad (6)$$

T e (i, θ) is output torque. In addition, improving the electric efficiency of SRD is vital to increase the travel distance of EV.

The equivalent power factor (PF) can reflect the real-time power output characteristics of SRD effectively [24] and it can be expressed by Eq. (7) .

$$\mathrm{PF} = \frac{Ta\omega}{UIrms} \qquad (7)$$

U is input voltage of power supply, ω is the angular velocity of rotor, I rms is the root-mean-square (RMS) currentFor the SRM applied to EV drive, the greater value of TS and PF means the lower torque ripple and the higher electric efficiency of SRD. For the optimization control, the values of TS and PF are expected to be as bigger as possible.

Problem Formulation

Noise and vibrations are one of the major concerns in the design process of SRMs [1]-[4]. Studies show that proper selection of conduction angles, i.e., turn-on and turn-off angles, can significantly affect the magnitudes of torque ripple. Studies show that proper selection of conduction angles, i.e., turn-on and turn-off angles, can significantly affect the magnitudes of torque ripple [6]-[8]. Major techniques used for improving SRMs' efficiency, improving their torque quality, eliminating position sensors, etc, for SRMs' automotive applications are presented in [9]. Optimizations can be used to determine the conduction angle. In [10], a 4-phase 8/6 SRM is used in the optimization of conduction angles for maximizing efficiency. A control algorithm is developed in [11], which uses maximization of torque per Ampere as an objective for conduction angles for automatic adjustment of turn-on angles for an SRM. In [12], two controllers are proposed to optimize conduction angles for improving motor efficiency and reducing torque ripple.

Three objectives used in the optimization of conduction angles for an SRM in [13] are motor torque, copper loss, and torque ripple. The three objectives are combined into one objective using three weight factors and three groups of base values. An analytical method proposed in [14] is used in the optimization of conduction angles for improving an SRM's efficiencies based on a non-linear inductance model. However, this method is not suitable for the voltage pulse width modulation mode. A sliding mode controller proposed in [15] shows some advantages compared with a hysteresis controller in terms of torque ripple, current ripple, etc. However, in this paper, the hysteresis controller is used for its simplicity. On the other hand, the effects of different objective functions on the turn-on and turn-off angles, output torque, torque ripple, and the ratio of average torque to RMS value of phase current, have not been comprehensively studied. Furthermore, the correlation between these objectives is not well explored. Requirements for specific operating points also need to be considered in balancing objectives, such as maximizing output torque and maximizing torque ripple.

Therefore, an effort for a fast optimization-based procedure for automatically characterizing switched reluctance motor performances is proposed. For each selected operating point of one specific motor geometry, as shown in Fig. 2. θon and θoff need to be optimized for balancing output torque and torque quality, which is time-consuming if done manually. This can be even more laborious when there are a group of SRM geometries that need to be characterized.

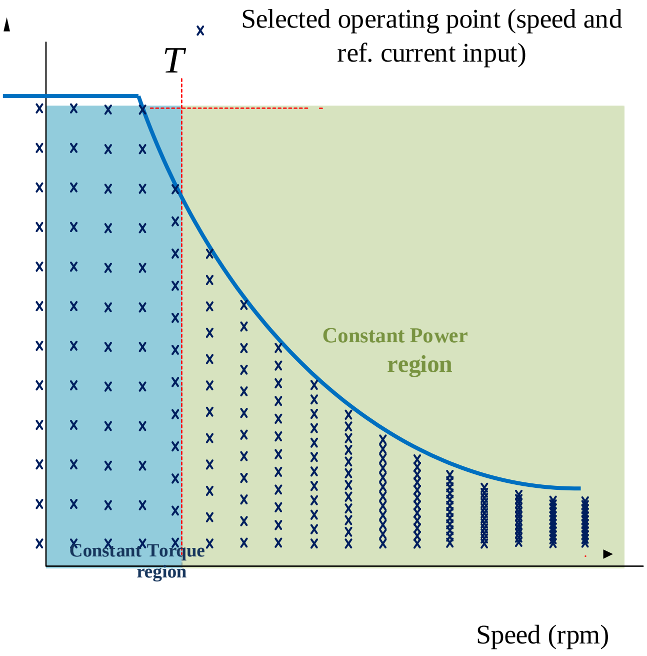

Fig. 2. Torque Speed Relation of SRM Drive

Here single optimizers are used in the optimization of conduction angles. Further, this procedure does not stop at the optimized θon and θoff lookup tables over the entire operating range. The lookup tables are then used in obtaining the motor performances, such as torque-speed profile, torque ripple map, copper loss map, rotor iron loss map, stator iron loss map, motor efficiency map, etc. This procedure can be very helpful in the SRM design stage, because it accelerates the characterization of design candidates. An 8/6 SRM is used to verify the results from the procedure. Fig. 2 Selected operating points used to characterize SRM over the entire operating range.Another aim is to understand the relationship between conduction angles and optimization objectives, and the objectives themselves. In addition, a decision- making processto balance between objectives is designed. A number of objectives can be used in the optimization: (1) maximizing average output torque, (2) maximizing the ratio of average output torque to RMS value of phase current, and (3) maximizing RMS value of net torque ripple. Using these objectives, four different optimization problems, two single- and two multi-objective, can defined and will compared based on criteria such as output torque, torque ripple, and efficiency for the selected operating points, i.e. 1000, 2000, and 4000 rpm. In addition to the four main optimization problems, another case can be defined where maximizing RMS value of the phase can employed current as an objective together with maximizing RMS value of net torque ripple. In high-speed operation of SRM, maximum torque can be achieved with a lower current than the maximum RMS value. This can pose a challenge in determining the current constraints at high-speeds. By using the desired output torque at different speeds as a constraint, this optimization problem helps determine the phase current constraints for the four main optimization problems.

Case I: max. Tave (f1), IRMS constraint; and

Case II: max. Tave/IRMS (f3), IRMS constraint. Two multi-objective optimization problems are:

Case III: max. Tave (f1), max. ΔTRMS (f2), IRMS constraint, and

Case IV: max. Tave/IRMS (f3), max. ΔTRMS (f2), IRMS constraint.

A few objectives are identified and used in the optimization problem. The objective f1 is used to evaluate the average torque:

$$f1 = Tave = \frac{1}{\theta 1-\theta 2}\int_{\theta 1}^{\theta 2} T(\theta)d\theta \qquad (8)$$

WhereT(θ) is the continuous torque waveform over rotor position and (θ1–θ2) is equal to a complete electrical cycle. The objective f2, which is the RMS value of net torque ripple, addresses the concern over the quality of output torque:

$$f2 = \Delta TRMS = \sqrt{\frac{1}{\theta_2-\theta_1}\int_{\theta_1}^{\theta_2}\left(T(\theta)-T_{ave}\right)^2 d\theta} \qquad (9)$$

One of the challenges in the control of SRMS is to minimize the torque ripple to improve the output torque quality. The objectives f1 and f2 need to be balanced over the entire operating range. For instance, in the high-speed region, the objective f1 is weighed heavily which means that the motors are required to output as much torque as possible. The objective f3 can be used as an indicator of the efficiency for the SRM running at a specificoperating point [21]:

$$f3 = = \frac{Tavg}{IRMS} = \frac{\frac{1}{\theta 1-\theta 2}\int_{\theta 1}^{\theta 2} T\,(\theta)d\theta}{\sqrt{\frac{1}{\theta 2-\theta 1}\int_{\theta 1}^{\theta 2} I^2\,(\theta)d\theta}} \qquad (10)$$

The method of transforming objectives into one single objective, for instance, by summing them up with assigned weights, is not recommended because the range of each cost functions may not be well known beforehand and the correlations between objectives and variables are ignored.

In the optimization problems, the first set of constraints used is the conduction angles. The turn-on angle θon and the turn-off θoff need to be selected within a range:

$$\begin{pmatrix} 1 & -1 \\ -1 & 1 \end{pmatrix}\begin{pmatrix} \theta 1 \\ \theta 2 \end{pmatrix} < \begin{pmatrix} -\frac{360}{m} \\ \frac{360k}{m} \end{pmatrix} \qquad (11)$$

Where m is the number of phase, and k is a constant value, determining the upper boundary of the conduction angle. The value for k is set to be 1.4 in the chapter. Another nonlinear constraint used in this chapter is the RMS value of phase current:

$$IRMS = \sqrt{\frac{1}{\theta 2-\theta 1}\int_{\theta 1}^{\theta 2} I^2\,(\theta)d\theta} \leq IRMS\_constraint \qquad (12)$$

In paper, IRMS is employed as the nonlinear constraint in the four main optimization problems. The value of IRMS varies as the rotational speed changes. An additional optimization problem was also defined to determine the IRMS constraints. In this added optimization problem, required Tave at different speeds is used as a constraint. On doing this simulation we observe that the efficiency has been improved and torque repulsion in the SRM drive has also been reduced and make it suitable for EV application.

III. Experiment and Result

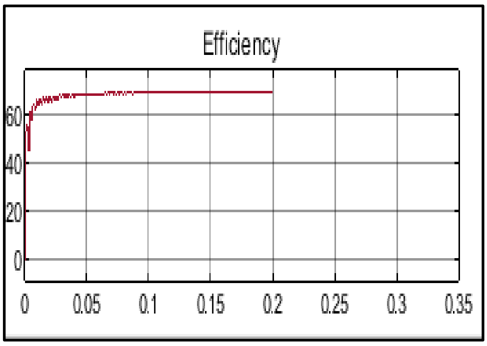

Fig. 3 Efficiency

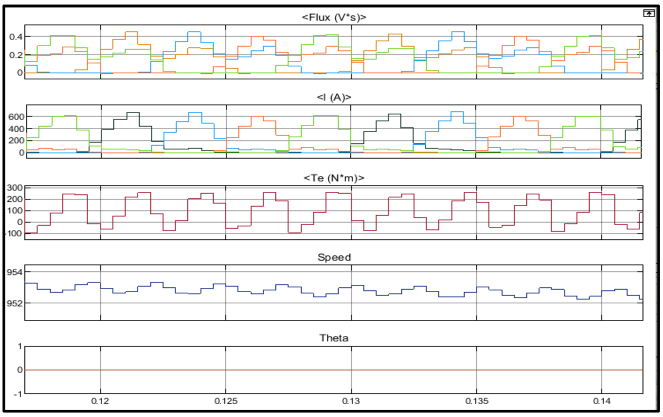

Fig. 4 Variation in the flux, Current. Torque, Speed

Fig. 3 clearly shows that by varying the turn on angleθon and turn off angle θoff efficiency actually affected. With the optimum angle 20.369 the maximum efficiency is found to be 68.466

Fig.4 also shows the variation in the flux, conduction current, Torque and the speed. Also with the application of DITC (Direct Instantaneous Torque Control) technique there is improvement in the torque and torque ripple minimizes.

IV.Conclusion

In this paper, the motor performances, such as the torque-speed profile and the motor efficiency, of the 8/6 SRM motor is discussed. The maximum output torque is 207 Nm. The maximum speed for the SRM is 953 rpm. The SRM is expected to achieve the same torque-speed envelope and competitive efficiency. In the optimization of conduction angles, two optimizations, Case I to Case II in the optimization of conduction angles for the 8/6 SRM are compared at three selected speeds (1000, 2000, and 4000 rpm). Two single-objective, (Case I & II), optimization problems, are formulated. In Case I, maximizing average output torque (Tave) is used as the only objective. For Case II, the single-objective optimizer employs maximizing the efficiency by reducing torque ripple. It has been observed this optimization technique along with DITC gives the optimization of the motor over the entire operating range, because it balances amplitude of Tave and torque quality and highly competitive performances in motor efficiency as well. The correlations between these two objectives are explored and solutions at different operating points can be selected from other advance optimization methods also.

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