Review of Torque Ripple Reduction of Switched Reluctance Motor

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ABSTRACT

Switched reluctance Moto (SRM) has become one of the best choices for electric vehicle drive because it exhibits prominent advantages over other kinds of electric drive system. Nowadays, switched reluctance machines (SRM) are gaining interest in the scientific community due to the advantages they offer. The SRM offers an overall efficiency similar to an induction motor of the same rating, since the friction and windage losses are comparable. Many researchers have been done on SRMs, their related systems and challenges. This paper reviews the SRM structures, their advantages and disadvantages. Various SRM topologies are studied and their merits and limits are given. Additionally, the most common control strategies for SRM drives are categorized, which is followed by a summary of the researches on challenges in torque and vibration reduction.

Keywords— *Switched reluctance machine, direct and indirect control, torque ripple, vibration reduction*.

1. INTRODUCTION

The climate changes over the last few decades and the shortage of natural resources lead to introduction of the concept of sustainable development which aims to meet the actual human needs while preserving the environment such that the needs of future generations can be met. In terms of preventing global warming and conserving natural resources, vehicles are playing a critical role [12]. To reduce the greenhouse gases produced by automotive vehicles, fuel efficiency must be improved while cleaning exhausts gases as well as ensuring safety. World are making appeals to the manufacturers and researchers to be aware of the need for development of electric vehicles. The challenge is high due to ever increasing demand for mobility and transport of people and goods, in urban and rural regions. The principal task is to replace the fossil energy dependency and its environmental impact, with primary energy sources that are renewable, secure, sufficient, and environmentally compatible [12].

The paradigm shift in the auto industry, towards more energy efficient, more reliable and smarter vehicles [13] led to the development of electrified vehicles. The more electric vehicles (MEVs), hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs) and electric vehicles (EVs) are entering in the class of electrified vehicles. As for the energy, it can be drawn from multiple sources, such as: chemical batteries, fuel cells (FCs) or ultra-capacitors.

The key component of the EV is the electric motor and, therefore, its choice is very important. Many types of electric motors have been analyzed during last decades and evaluated for EVs. Switched reluctance motors (SRM) have some advantages in comparison with other electric motors due to their simple structure, flexibility of control, high efficiency, lower cost and robustness to run under failure conditions. The machine rotor does not have any windings or permanent magnets, being suitable for very high speed drive applications [2], [3]. The switched reluctance motors drives (SRDs) need more advanced control technology than DC and AC motors drives. High torque ripple, high noise and vibrations are the most important drawbacks of the SRM [1].

In order to produce maximum torque and reduce the torque ripple, many investigations have been done to design the SRM effectively, which needs the determination of a set of geometrical parameters. The influences of these geometrical parameters were also the topic of many investigations.

This paper is organized as follows. Section II describes the principles of of a SRM, including the SRD systems and its advantages and limitations. Section III presents the conventional and advanced SRM structures. Section IV introduces the common control strategies. Challenges to overcome SRM limitations are presented in Section V. Conclusions are given in Section VI.

1.1 PRINCIPLES OF SRM

A. Operation principles

The principle of SRM operation is to generate torque by varying magnetic reluctance. The SRM motor has double saliency, meaning it has a saliency in the stator as well as saliency in the rotor. Depending on the rotor and stator pole number, multiple SRM configurations can be constructed (figure 1). The basic electromagnetic equation that governs a SRM individual phase is the following:

$$V = iRm + L(\theta, i)\frac{di}{dt} + KB(\theta, i)\frac{d\theta}{dt} \quad (1)$$

where v is the phase voltage, i is the phase current, Rm is the phase resistance, L(_; i) is the instantaneous inductance and KB(_; i) is the instantaneous Back-EMF. At the excitation moment of each stator pole, the nearest rotor pole tends to come to the minimum reluctance position. In other words, the resultant torque due to the current flow in a phase prefers to move the rotor in a direction that leads to a decrease in the reluctance and, hence, an increase in the inductance [4]. Neglecting magnetic saturation, the torque produced by the machine can be expressed as:

$$T = \frac{i^2}{2}\frac{dL}{d\theta} \quad (2)$$

From (2), it is shown that torque does not depend on the polarity of the stator current (because of the square term) and can only be developed when the inductance changes. Thus, positive torque is produced on the rising inductance region, while negative torque is produced on the decreasing inductance region. When a pair of rotor poles is aligned to a pair of stator poles, the other pairs of rotor poles are out of alignment. Then, a pair of stator poles (which is the closest to any other pair of rotor poles) is excited to bring this rotor poles into alignment. Therefore, by such a sequentially switching and flowing current into the pairs of stator windings, the rotor can rotate continuously. These switching and their control are applied by SRDs [4]. If all pairs of stator poles were aligned with the rotor poles, the initial torque could not be produced. In order to avoid such a situation, the SRMs are usually designed to have unequal number of rotor and stator poles [4], as seen in figure 1. Comparing with other electric machines, SRM has high torque ripple due to the independent phases and discrete torque production. The main drawback of SRM is the torque ripple that causes restriction on their application in EVs [5]. To solve this problem, many control techniques have been investigated and proposed recently [3], [6].

Fig -1. Internal Structure of SRM

B. Advantages and limitations

Switched reluctance motors (SRM) have many advantageous characteristics comparing to those of the conventional AC and DC machines. The mechanical simplicity in construction of the SRM can be seen through their purely laminated-steel structure without permanent magnets, rotor windings and squirrel-cage bars. Thus, SR machines offer high reliability and robustness in operation. Due to their ruggedness, the SR motors are inherently suitable for high-speed drives and applications in high-temperature and hazardous environments. In addition, the SRM are efficient and suitable for some applications which required high torque and high dynamics. Consequently, the switched reluctance motors have recently gained a considerable attention from industries and researchers in the specific areas of high-performance and adjustable speed drives. Nevertheless, SRM are very nonlinear in nature due to their operations in high-saturation conditions. The highly non-uniform reluctance torque is produced from magnetic saliency between stator poles and rotor poles. Phase flux linkages and instantaneous phase torque are nonlinear functions of phase currents and rotor positions. Therefore, without proper control, the inherent torque ripples, vibrations and acoustic noise can become major problems of the SRM drives. For a century, such drawbacks have prevented the SR motors from being widely used in applications of high-quality and variable speed drives. With the view to achieve high-performance servo drives for SRM, several instantaneous torque control techniques including torque ripple minimization features have been successively proposed.

2. CONVENTIONAL AND ADVANCED METHOD FOR TORQUE RIPPLE REDUCTION

In the conventional scheme called indirect instantaneous torque control (IITC), SRM torque is regulated by controlling the instantaneous phase currents in a cascaded fashion. The reference torque is converted to equivalent reference phase currents so that they can be tracked in the inner current control loops. By using the phase current profiling technique, optimal phase torques corresponding to torque sharing functions can be generated and, ultimately, torque ripples can be minimized. Various methods of torque ripple-minimization using IITC have been successively proposed in the last three decades. [1]However, torque-to-current conversion in SRM is complex and becomes non-trivial due to their nonlinear relationship. Analytical expression of such conversion is complicated and leads to intensive on-line computation. On the other hand, the current profiles can be pre-calculated and pre-stored in the controller memory. Yet, this method requires large amount of on-line memory space. Concepts of direct instantaneous torque control (DITC) for SRM have been developed to overcome the mentioned drawbacks of the IITC. The main DITC characteristics are: the instantaneous torque (which can be estimated from motor terminal quantities) is considered directly as a control variable, torque-to-current conversion and closed-loop control of phase currents are no longer required. In other words, DITC does not use current or torque profiles. Therefore, DITC is expected to counteract the torque error instantaneously with fast dynamic response and effectively minimize the inherent torque ripple. A DITC for SRM using the concept of a short flux pattern that links two separate poles of the stator was already proposed. But this method was expensive and inconvenient, as it involved motor winding alteration and bipolar current requirement. The torque sharing function can be used to generate the reference values of phase torques from the required torque. The switching signals are directly generated from the comparison between the reference phase torques and the estimated phase torques using hysteresis controller. The hysteresis torque controller generates gating signals to the power converter. The instantaneous phase torques can be calculated from the phase currents and rotor position.

Equation (2) shows that the developed torque is independent of direction of current but only depends on magnitude of current & direction of dL/dΘ.

The Fourier Series of phase winding inductance is given by

$$L(\theta) = L_0 + \sum_{n=1}^{N}[Ln\cos n\,(Nr\,\theta - \varphi 0)] \tag{3}$$

$$L(\theta) = L_0 + (L_1 + L_3)[1-\cos(Nr\,\theta - \varphi 0)] + L_2[\cos 2(Nr\,\theta - \varphi 0)-1] + L_3[\cos 2(Nr\,\theta - \varphi 0)-1] \tag{4}$$

Where $L_0 = L_{min}$, L_{min} is the minimum phase winding inductance;

$L_1 = \frac{Lmax - Lmin}{2}$, L_{max} is the maximum phase winding inductance; L_2 and L_3 are the coefficients of absolute pole width and relative pole width of stator-rotor respectively.

$$U_k = R_k i_k + \frac{d\psi k}{dt} \tag{5}$$

$$T_{ek} = \frac{d}{d\theta} \int_0^i \psi k \, dik \tag{6}$$

$$T_e = \sum_{k=1}^{m} Tek \tag{7}$$

$$T = T_e - T_L = J\frac{d\omega}{dt} + D\omega \tag{8}$$

where U_k, R_k, i_k and ψ_k are voltage, resistance, current, and flux linkage of the phase winding respectively; θ is rotor position angle; ω is rotational velocity; T_{ek} and T_e are electromagnetic torque of phase winding and SRM respectively; m is the number of phase; T_L is load angular force; D is viscous friction coefficient; is moment of inertia of rotor and load of SRM.

$$T = T_e - T_L = J\frac{d\omega}{dt} + D\omega \tag{9}$$

$$\frac{d\omega}{dt} = \frac{1}{J}[Te - D\omega - TL] \tag{10}$$

$$\theta = \frac{d\omega}{dt} \tag{11}$$

Variation in rotor position with respect to time results in angular speed.

Hence theta is associated with ω as a function of time.

I. TORQUE SHARING FUNCTIONS

At any, time the resultant output torque of SRM is the summation of the torque in all phases. If the phase current is fixed, the torque of an 8/6 SRM will have a profile as shown in Fig.2

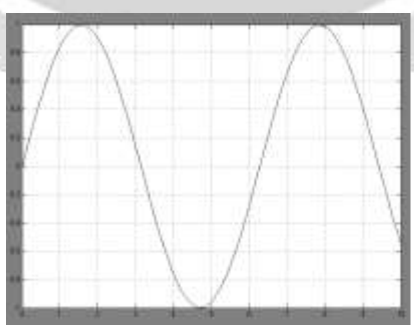

Fig -2 Phase torque profile under fixed current

From Fig.2, it is clear that high torque is not available near aligned/unaligned position even when high phase current is presented. To generate a ripple –free output torque, there must be overlapping between phases. During phase overlapping, the current in one phase is increasing. To obtain a constant torque, the summation of the torque generated in non-overlapping period. To determine the desired torque produced by each phase, torque sharing functions (TSFs) are introduced, which are defined as

$$T = \sum_{j=1}^{N} Tj \ = \ \sum_{j=1}^{N} TSFj\,(0)\,Tref \tag{12}$$

Where TSFj(θ) is the torque sharing function for phase j at rotor position θ, and T_{ref} is the reference torque.

For four phase 8/6 switched reluctance motor, to generate desired torque, the torque sharing functions must meet the following requirements:

$$\sum_{j=1}^{4} TSFj\,(\theta) = 1$$

$$TSFj\,(\theta) = TSF\,j\left(\theta \ + \frac{\pi}{3}\right) \tag{13}$$

$$TSFj\,(\theta) = TSF_{\,k}\left(\theta - \ (j-k\,)\frac{\pi}{12}\right) \tag{14}$$

For 8/6 SRM, the inductance increasing/decreasing period for each phase will be π/6 and the conduction angle to be selected as π/8. This means

$$\theta_{off} - \theta_{on} = \frac{\pi}{8} \tag{15}$$

so the phase overlapping for each two adjacent phase is π / 8 – π / 12 = π / 24.

For this work, a sinusoidal torque sharing functions can be used. The sinusoidal torque sharing functions means that the torque produced by the phases, during phase commutation, changes with the rotor position in terms of the sinusoidal functions. On the basis of the sinusoidal torque sharing function presented by Husain and Ehsani, the sinusoidal torque sharing function for phase j in a rotor period can be expressed as

$$Fact_j(\theta) = \begin{cases} \frac{1}{2} - \frac{1}{2}\cos 24\,(\theta - \theta onj\,)\ , & for\ \theta onj \ \le \theta < \left(\theta onj + \frac{\pi}{24}\right) \\ 1\ , & for\ \left(\theta onj + \frac{\pi}{24}\right) \le \theta < \left(\theta offj + \frac{\pi}{24}\right) \\ \frac{1}{2} + \frac{1}{2}\cos 24\left(\theta - \theta offj - \frac{\pi}{24}\right) & ,\ for\left(\theta offj - \frac{\pi}{24}\right) \le \theta < \theta offj \\ 0 & \text{otherwise} \end{cases}$$

The Fig.- 3 shows the sinusoidal torque sharing functions of all four phase in forward motoring operation.

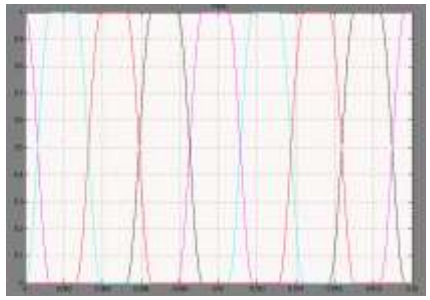

Fig -3 Sinusoidal TSFs current

3. DIRECT INSTANTANEOUS TORQUE CONTROL OF SRM

First, the phase torques are calculated from the measured phase currents and rotor position using the torque. The magnitude of the reference phase torques can be calculated using the torque sharing functions. The input reference phase torques will be compared with the feedback estimated phase torques using hysteresis controller. The hysteresis controller outputs three discrete voltage levels + V_{dc}, 0, - V_{dc} will be applied to the motor.

The justification of using applied phase voltage to directly control the instantaneous torque of switched reluctance motor is explained here.

The nonlinear instantaneous torque of SRM can be found co energy principal, as expressed in equation (2) earlier. For simplification, the torque equation becomes

$$T_{e,j} \approx \frac{\partial \lambda(\theta,i)}{\partial \theta} \int_0^i i\, di \approx \frac{\partial \lambda(\theta,i)}{\partial \theta}\, i \qquad (16)$$

Thus, the instantaneous torque of the saturated SRM can be found from the product of the flux linkage derivative (with respect to rotor position) and the phase current, as shown in equation (16).

The phase voltage equation of SRM is given by

$$\begin{aligned} V &= Ri + \frac{d\lambda(i,\theta)}{dt} \\ &= Ri + \frac{\partial \lambda}{\partial i}\frac{di}{dt} + \frac{\partial \lambda}{\partial \theta}\frac{d\theta}{dt} \qquad (17) \\ &= Ri + I(i,\theta)\frac{di}{dt} + \frac{\partial \lambda}{\partial \theta}\,\omega \end{aligned}$$

This incremental inductance I(i, θ) has significantly large value such that phase current can be assumed unchanged in one sampling period. Once the resistive drop is negligible and the current is considered constant, the phase voltage equation can be approximated as equation (18)

$$V \approx \frac{\partial \lambda}{\partial \theta}\,\omega \qquad (18)$$

Consequently, the instantaneous phase torque equation of SRM can be simplified to:

$$T \approx \frac{\partial \lambda}{\partial \theta}\, i \approx \frac{i}{\omega}\, V \qquad (19)$$

The rotor speed and the phase current are assumed constant during the control cycle. As a result, the torque expression has been linearized and the phase voltage V becomes an effective control variable for the DITC.

Many research effort is focused on overcoming different challenges in torque ripple and vibration reduction. In [20], a combination of multi-objective technique by using the FEM to optimize a 4/2 SRM is presented. In this proposed approach, the torque ripple reduction and the minimal degradation for the mean torque and starting torque are considered. In [21], it is mentioned that the general cause for the torque ripple that leads to make the current non-linear is the fringing flux. In this investigation, a new rotor shape with notched teeth in the forward rotating direction has been proposed to reduce the torque ripple by improving the inductance profile. Some different shapes of stator and rotor have been designed and analyzed to improve the torque and minimize the torque ripple [22]–[26].

In some researches, torque ripple reduction up to a certain range was achieved, where the upper speed limit, with accurate torque control, was decided by the controller bandwidth which in turn depends on the sampling frequency and DC link voltage. In [32], two improved torque sharing functions were proposed, dependent on turn on angle, overlap angle and the expected torque using genetic algorithm to optimize these torque sharing functions. Exponential torque sharing function is found to give better results if maximum speed with torque control is considered as the evaluating target. In [33], a family of TSFs by using different secondary objectives was introduced, such as power loss minimization and drive constraint consideration. However, the consideration of linear magnetic characterization and a simple torque equation may reduce drive efficiency and performance. In [34], a novel method of profiling the phase currents to minimize the torque ripple of a switched reluctance machine was proposed. The method is a combination of machine design and control algorithm designed to function from zero speed to the maximum speed for the application.

4. CONCLUSIONS

In this paper, some studies and researches about different SRM topologies and structures to improve their performance were presented. It was also shown that, by some optimizations in the design of SRMs, their efficiency can be improved by reducing their torque ripple. The results of such designs can be very helpful and important for the selection of a proper SRM structure for the particular applications, such as in EV applications. Regarding to conventional SRM structures, studies suggest that 8/6 and 10/8 configurations best suit for EV applications. The features of these conventional structures can be improved to a some extend using more advanced SRM topologies.

6. REFERENCES

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