A Control Scheme of Torque Ripple Minimization for SRM Drives Based on Flux Linkage Controller and Torque Sharing Function

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Abstract – This paper presents a new control scheme to implement the torque ripple minimization in switched reluctance motor drives. The proposed scheme uses the nonlinear torque sharing function in which two active phases contribute the torque during phase commutation and the torque at other time is produced by an active phase. The flux linkage controller with the hysteresis chopping is employed to trace the flux linkage reference computed from the torque sharing function. The simulations on a four-phase switched reluctance motor drive demonstrate that the proposed control scheme can be used to well implement the torque ripple minimization. Comparing with conventional current controllers, the limit on the proposed flux controller is easily determined and the saturation of the flux linkage controller may be avoided.

Index Terms – Flux linkage controller, switched reluctance motor drives, torque ripple minimization

INTRODUCTION

The torque ripple is an inherent drawback of switched reluctance motor (SRM) drives. The causes of the torque ripple include (a) the geometric structure (doubly salient motor, excitation windings concentrated around the stator poles) and (b) the working modes (necessity of magnetic saturation in order to maximize the torque/mass ratio and pulsed magnetic field obtained by feeding successively the different stator windings). The phase current commutation is the main cause of the torque ripple. Such a torque ripple is not necessarily detrimental for SRM drive systems. However, it is particularly intolerable in special applications of SRM drives, such as robot controls and servo-type systems. Hence, investigating control methods to minimize the torque ripple in SRM drives is a challenging issue.

Control methods to minimize the torque ripple have two types basically. One of which is named the method of the pre-computed current profiles, in which the current waveforms for the torque ripple minimization (TRM) are pre-computed off line and then these optimized current profiles are traced on line. The other is named the method of the direct torque control (DTC), in which the torque is controlled directly from the defined torque sharing function (TSF). The TSF may be classified into two kinds. The first one has the constant torque-change-rate, i.e., the torque changes linearly during phase commutation [1]. For the second one, the torque changes with the defined nonlinear function [2]. The nonlinear TSF is better than the linear TSF because the former produces more smooth torque and current profiles than the latter.

In meanwhile, two types of controllers are utilized to implement the torque ripple minimization. Both are the current controller [2] and flux linkage controller [3-4]. The former is popular with most of reported studies, as the current is measured easily. However, the change-rate of the current to the position is a nonlinear function of the current and position. This nonlinearity makes the generation of the phase current reference for minimizing the torque ripple not trivial. Inversely, the change-rate of the flux linkage is a linear function of the current. Thus, the limit on the flux linkage controller can be easily determined in contrast to the current controller.

This study describes a control scheme to implement the torque ripple minimization in SRM drives. The proposed scheme combines the flux linkage controller with the nonlinear TSF. In Section II, the flux linkage control, the TSF, and the design of the flux linkage controller will be discussed. The proposed control scheme is applied to an SRM drive in Section IV, where the simulation results will be shown. Finally, Section V concludes this study.

CONTROL SCHEME

A. Flux Linkage Controller

Neglecting the mutual coupling between phase windings and selecting the flux linkage as the controlled variable, it is well known that the rate of change of the flux linkage in SRM drives is computed from

$$\frac{d\psi}{dt} = V - ir \tag{1}$$

where ψ represents the flux linkage, t represents the time, V represents the voltage applied to a phase winding, i represents the phase current, and r represents the resistance of a phase winding.

At steady-state and in the case of non-zero speed, (1) can be changed into

$$\frac{d\psi}{d\theta} = \frac{V - ir}{\omega} \tag{2}$$

where θ denotes the rotor position and ω denotes the motor speed.

In general, the ohmic voltage drop is small compared with the DC link voltage. Neglecting the ohmic voltage drop, hence, (1) and (2) can be simplified into, respectively,

$$\frac{d\psi}{dt} = V \tag{3}$$

and

$$\frac{d\psi}{d\theta} = \frac{V}{\omega} \tag{4}$$

It is clear that the rate of change of the flux linkage to the time or the position basically depends on the DC link voltage or the DC link voltage and the motor speed. The effect of the current on the change of the flux linkage is much weak. The flux linkage varies approximately linearly with the position at the constant voltage and speed. For the flux linkage controller, thereby, the computation of the flux linkage reference values is simplified noticeably. Furthermore, it can be observed from these equations that there is only a simple limit on the rate of the flux linkage and hence the limit on the flux controller is easily determined and the saturation of the flux controller does not occur. The flux linkage references can be easily determined in order to achieve the torque ripple minimization.

For the current controller, however, the rate of change of the current is determined by

$$\frac{di}{dt} = \frac{V - ir - \omega\partial\psi/\partial\theta}{\partial\psi/\partial i} \tag{5}$$

At steady-state and in the case of non-zero speed, (5) can be changed into

$$\frac{di}{d\theta} = \frac{V - ir - \omega\partial\psi/\partial\theta}{\omega\partial\psi/\partial i} \tag{6}$$

Clearly, the change of the current with respect to the position is a highly nonlinear function even at the constant voltage and speed. For the current controller, thus, this nonlinearity makes the generation of the current references complicated and difficult, in order to minimize the torque ripple.

The drawback of the flux controller is that the flux linkage cannot be measured directly. Consequently, the flux linkage has to be acquired indirectly. In general, two approaches are utilized. One of which is the trapezoidal integration approach, which is given by

$$\begin{aligned}
&\psi_{k+1} = \psi_k + \frac{1}{2}t_s(V_{k+1} + V_k - ri_{k+1} - ri_k), \quad or \\
&\psi_{k+1} = \psi_k + \frac{1}{2}t_s(V_{k+1} + V_k) \\
&\psi_0 = 0
\end{aligned} \tag{7}$$

where ψ_{k+1} and ψ_k are the flux linkage values, V_{k+1} and V_k are the measured voltage values, i_{k+1} and i_k are the measured current values, respectively, at the sampling instants (k+1) and (k), and t_s is the sampling period.

The other is the interpolation or analytical computation approach, in which the flux linkage values may be determined from

$$\psi_k = f(\theta_k, i_k) \tag{8}$$

where $f(\theta_k,i_k)$ may be the interpolation function or the analytical function, such as the bi-cubic spline interpolation [5] or the 2-D least square polynomials [6].

For the proposed flux linkage controller, the hysteresis chopping is adopted. Hence, the flux linkage controller must execute

$$\begin{cases} V = -V_{dc}, & when \quad \psi > \psi_{ref} + 0.5\psi_b \\ V = V_{dc}, & when \quad \psi < \psi_{ref} - 0.5\psi_b \\ V = V & when \quad \psi_{ref} - 0.5\psi_b \le \psi \le \psi_{ref} + 0.5\psi_b \end{cases} \tag{9}$$

where V_{dc} represents the DC link voltage, ψ_{ref} represents the flux linkage reference, and ψ_b represents the hysteresis band.

B. Torque Sharing Function

To achieve the torque ripple minimization, the proposed commutation scheme is that (a) each phase winding only produces positive (motoring) torque, (b) at any time, only one phase winding or two adjacent phase windings are energized, and (c) the TSF is a nonlinear function with respect to the rotor position. For four-phase SRMs, thus, the TSF with respect to the rotor position can be defined by a cubic segment and constants [2] [4]. The rotor position is equal to 0 degree when the stator pole is just unaligned with the rotor pole. The rotor position is equal to half a rotor period (i.e., 30 degree for a four-phase SRM drive) when the stator pole is just aligned with the rotor pole. Within a rotor period, the TSF for the phase-1 can be expressed by

$$\begin{aligned}
&TSF(\theta) = \begin{cases} 0, & 0 \le \theta \le \theta_{on} \\ f_{up}(\theta), & \theta_{on} \le \theta \le \theta_{on} + \theta_{ov} \\ T_e, & \theta_{on} + \theta_{ov} \le \theta \le \theta_c + \theta_{on} \\ f_{dn}(\theta), & \theta_c + \theta_{on} \le \theta \le \theta_c + \theta_{on} + \theta_{ov} \\ 0, & \theta_c + \theta_{on} + \theta_{ov} \le \theta \le \theta_p \end{cases} \\
&\theta_c + \theta_{on} + \theta_{ov} \le 0.5\theta_p
\end{aligned} \tag{10}$$

where θ_{on} denotes the turn-on angle, θ_{ov} denotes the overlap angle, θ_c denotes the phase commutation angle that is 15 degree for a four-phase SRM drive, θ_p denotes the rotor period, T_e denotes the expected torque produced by the SRM, $f_{up}(\theta)$ and $f_{dn}(\theta)$ denote the rising portion and declining portion in the TSF, respectively.

A typical TSF profile for a four-phase SRM drive is shown in Fig. 1, where the variables in (10) are also given.

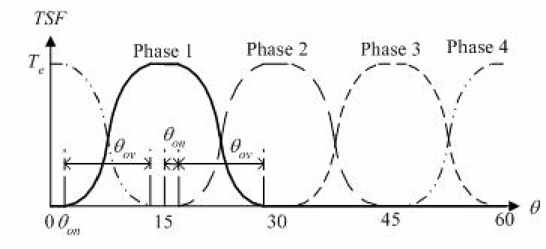


Fig. 1 Typical profile of the proposed TSF for a four-phase SRM drive

$f_{up}(\theta)$ is defined by the cubic segment and expressed by

$$f_{up}(\theta) = u_0 + u_1(\theta - \theta_{on}) + u_2(\theta - \theta_{on})^2 + u_3(\theta - \theta_{on})^3 \tag{11}$$

To determine the coefficients in (11), $f_{up}(\theta)$ must satisfy the constraints, which are

$$f_{up}(\theta) = \begin{cases} 0, & \theta = \theta_{on} \\ T_e & \theta = \theta_{on} + \theta_{ov} \end{cases} \tag{12}$$

$$\frac{df_{up}(\theta)}{d\theta} = \begin{cases} 0, & \theta = \theta_{on} \\ 0, & \theta = \theta_{on} + \theta_{ov} \end{cases} \tag{13}$$

Hence, the coefficients in (11) can be computed from (12) and (13). The computed results are

$$\begin{cases} u_0 = 0 \\ u_1 = 0 \\ u_2 = \dfrac{3T_e}{\theta_{ov}^2} \\ u_3 = \dfrac{-2T_e}{\theta_{ov}^3} \end{cases} \tag{14}$$

Consequently, (11) is changed into

$$f_{up}(\theta) = \frac{3T_e}{\theta_{ov}^2}(\theta - \theta_{on})^2 - \frac{2T_e}{\theta_{ov}^3}(\theta - \theta_{on})^3 \tag{15}$$

$f_{dn}(\theta)$ can be computed from

$$f_{dn}(\theta) = T_e - f_{up}(\theta - \theta_c) \tag{16}$$

The phase corresponding to $f_{up}(\theta)$ is named as the active or in-coming phase and the phase corresponding to $f_{dn}(\theta)$ is named as the active or out-going phase. Thus, two active phases occur simultaneously during phase commutation and only an active phase occurs during phase non-commutation. It should be noticed that the conduction angle is a constant value for the proposed TSF. For four-phase SRM drives, the conduction angle must be 15 degree.

C. Structure of Control Scheme

Fig. 2 illustrates the block diagram of the proposed control scheme for the torque ripple minimization based on the flux linkage controller. According to Fig. 2, the proposed control algorithm is executed as follows.

(a) The torque reference value (T_{ref}) at the rotor position (θ) is computed from the expected torque (T_e), and specified turn-on angle (θ_{on}) and overlap angle (θ_{ov}) by using the presented TSF.

(b) Using the given analytical flux linkage function with respect to the rotor position and the current as well as the given analytical torque function with respect to the rotor position and the current, the flux linkage reference value (ψ_{ref}) is determined from the computed torque reference (T_{ref}) and the measured position (θ).

(c) From the measured current (i) and the measured position (θ), the given analytical flux linkage function with respect to the rotor position and current is used to compute the actual flux linkage value (ψ_m).

(d) The flux linkage hysteresis controller is utilized to generate the control signals from the comparison between the flux linkage reference and the actual flux linkage value.

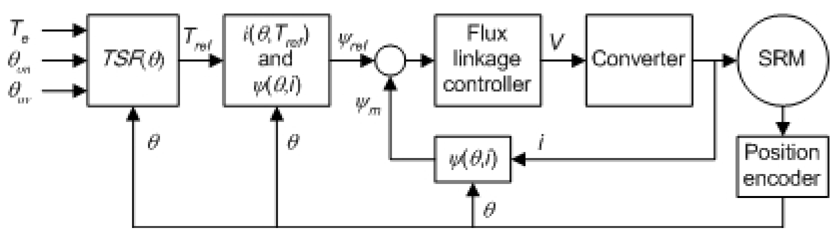


Fig. 2 Structure of the proposed control scheme of torque ripple minimization based on the flux controller

(e) The generated control signals are used to drive the converter to output the appropriate voltage applied to phase windings.

On the other hand, the flux linkage reference computed from the TSF must be limited by the constraint, which is described by

$$\left|\frac{d\psi}{d\theta}\right| < \frac{V}{\omega} \tag{17}$$

For the specified the voltage applied to the phase winding and the speed, (17) can be fulfilled through adjusting the turn-on angle and the overlap angle.

APPLICATIONS

A. Flux Linkage and Torque Characteristics

In order to validate the proposed control scheme, a four-phase SRM drive is simulated. It is well known that the flux linkage and static torque characteristics change periodically. To be specific, the flux linkage characteristics are symmetrical about the position that is equal to half a rotor period and the torque characteristics are anti-symmetrical about the position that equals to half a rotor period. Thus, the analytical expressions for computing the flux linkage characteristics and torque characteristics are defined within half a rotor period. Both are given by, respectively,

$$\psi(\theta,i) = \sum_{k=0}^{10}\sum_{j=0}^{10} p_{kj}(\theta-15)^k(i-6)^j \tag{18}$$

and

$$T(\theta,i) = \sum_{k=0}^{10}\sum_{j=0}^{10} q_{kj}(\theta-15)^k(i-6)^j \tag{19}$$

where coefficients p_{kj} and q_{kj} are determined by using the 2-D least square technique from the measured flux linkage data and static torque data, respectively [6].

The given and computed flux linkage characteristics with respect to the position and the current are shown in Fig. 3 and the given and computed static torque characteristics with respect to the position and the current are illustrated in Fig. 4. The solid curves denote the given values and the dotted curves are the computed values. It can be seen that the flux linkage characteristics computed by using (18) and the torque characteristics computed by using (19) are well consistent with the given data, respectively. Hence, the presented analytical model of the flux linkage or torque can be used to accurately compute the flux linkage characteristics or torque characteristics.

B. Torque Ripple Minimization

The proposed control scheme is applied to the four-phase SRM drive to implement the torque ripple minimization. The turn-on angle is selected as 6 degree and the overlap angle is also selected as 6 degree. Fig. 5 depicts the case in which the expected torque is 2 Nm. Fig. 5(a) shows the torque reference and flux linkage reference computed from the defined TSF. The actual phase voltage, actual phase flux linkage, actual phase current, torque produced by a phase, and total torque produced by the SRM are illustrated from top to bottom in Fig. 5(b) at the speed of 400 rpm and in Fig. 5(c) at the speed of 1000 rpm. Similarly, the case in which the expected torque is 4 Nm is depicted in Fig. 6.

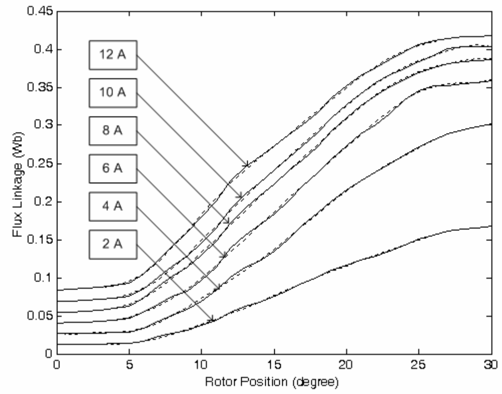


Fig. 3 Given and computed flux linkage characteristics for the four-phase SRM drive

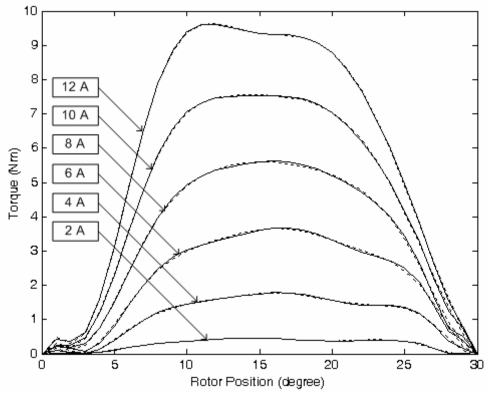
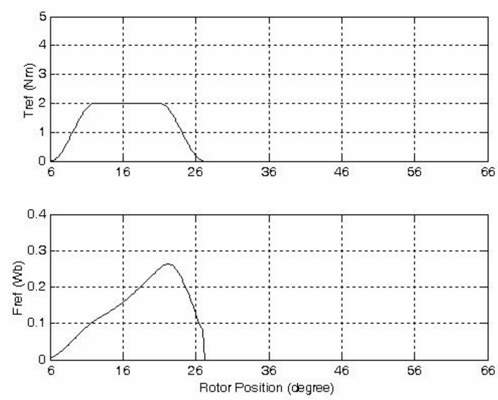
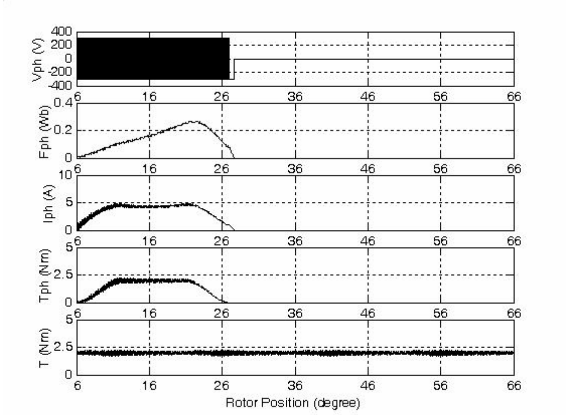


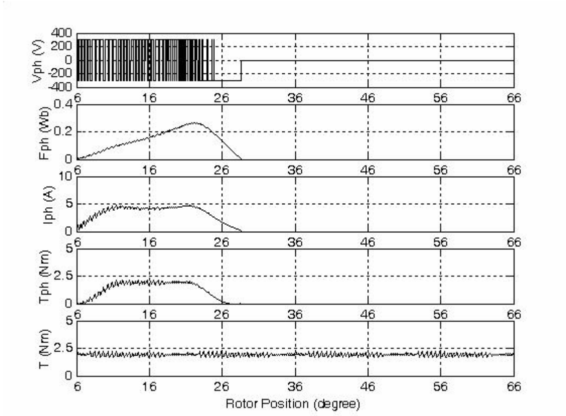
Fig. 4 Given and computed static torque characteristics for the four-phase SRM drive



(a) Torque and flux linkage references



(b) Actual waveforms at the speed = 400 rpm



(c) Actual waveforms at the speed = 1000 rpm

Fig. 5 Torque ripple minimization with the expected torque of 2 Nm

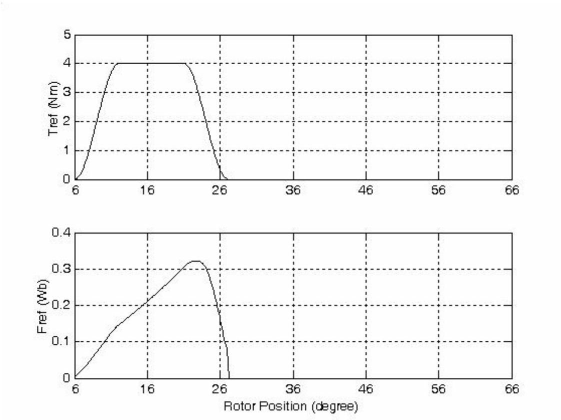
It can be observed from Fig. 5 and Fig. 6 that the proposed control scheme can be used to successfully implement the torque ripple minimization. Thus, these simulation results validate the proposed scheme for the minimizing torque ripple in SRM drives.

CONCLUSIONS

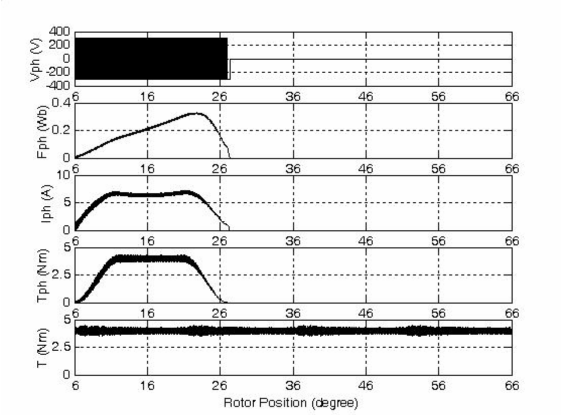
A control scheme to minimize the torque ripple in SRM drives has been presented in this paper. The flux linkage controller with hysteresis chopping is combined with the nonlinear TSF in the proposed control scheme. The simulations on the four-phase SRM drive have demonstrated that the proposed control scheme can be used to successfully accomplish the torque ripple minimization in SRM drives.

Under the specified DC link voltage and speed, the change-rate of the flux linkage to the position is a constant basically. The limit on the flux linkage controller mainly depends on the Dc link voltage and the speed. Hence, the flux linkage reference is determined easily for minimizing the torque ripple and the saturation of the flux linkage controller does not occur. However, the change-rate of the current to the position is the complicated and nonlinear function. The limit on the current controller is dependent on: (1) the DC link voltage and the speed, (2) the change-rate of the flux linkage to the current, and (3) the change-rate of the flux linkage to the position. Consequently, the saturation of the current controller often has to be encountered in order to minimize the torque ripple. It will lead to a harmful effect on the torque ripple minimization. Therefore, the flux linkage controller is better than the conventional current controller. On the other hand, the nonlinear TSF is beneficial to the generation of the smooth torque reference profiles and the torque ripple minimization.

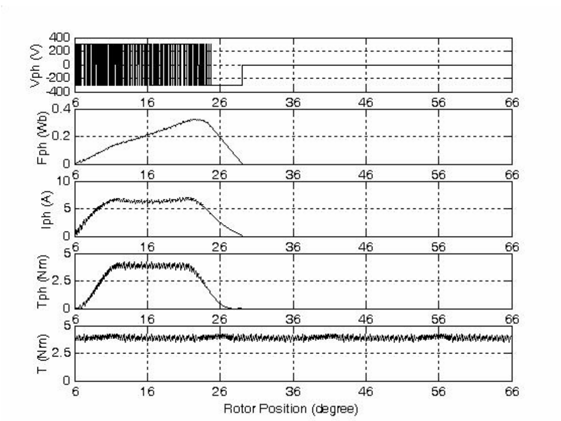
This study has shown that the nonlinear TSF can be well combined with the flux linkage controller. Hence, the proposed control scheme is a valuable approach to minimize the torque ripple in SRM drives.



(a) Torque and flux linkage references



(b) Actual profiles at the speed = 200 rpm



(c) Actual profiles at the speed = 800 rpm

Fig. 6 Torque ripple minimization with the expected torque of 4 Nm

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