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Study of Motoring Operation of In-wheel Switched Reluctance Motor Drives for Electric Vehicles

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Abstract–Based on the requirements of electric vehicles on electric motor drives, this paper presents three criteria to evaluate motoring operation of in-wheel switched reluctance motor drives for electric vehicles. They are the average torque, the average torque per rms current, and torque smoothness factor. They indicate the motoring torque, copper loss and torque ripple, respectively. The model of motoring operation under the current hysteresis control is developed to investigate the effects of the turn-on angle, the turn-off angle, and the current reference on these criteria. The simulated and measured current waveforms verify the proposed model. The simulated results show that the turn-on angle and the turn-off angles have considerable effects on motoring operation of switched reluctance drives. The optimal turn-on angle and the optimal turn-off angle can be optimized in order to maximum the average torque, the average torque per rms current, or the torque smoothness factor. In addition, the larger current reference results in the larger average torque, average torque per rms current and torque smoothness factor. Thus, this study is helpful for developing new control method to implement the best motoring operation of in-wheel switched reluctance motor drives in electric vehicles.

Keywords–Electric vehicles, in-wheel, motoring operation, switched reluctance motor drives

I. Introduction

The requirements of electric vehicles on electric motor drives can be summarized as: i) a high instant power and a high power density; ii) a high torque at low speed for starting and climbing, as well as a high power at high speed for cruising; iii) a very wide speed range with constant-power region; iv) a fast torque response; v) a high efficiency over the wide speed range; vi) a high efficiency for regenerative braking; vii) compact size, low weight, and lower moment of inertia; viii) a high reliability and robustness for various vehicle operating conditions; ix) a reasonable cost; x) a fault tolerance [1]. Therefore, switched reluctance motor drives are found to be much suitable for electric vehicle applications due to simple and rugged motor construction, low weight, potentially low production cost, easily cooling, excellent power-speed characteristics, high torque density, high operating efficiency, and inherent fault tolerance.

Traction performances of electric vehicles depend on the ones of switched reluctance motor drives. Hence, efficient motoring operation of switched reluctance motor drives is important for electric vehicles with high performances. Some attempts were made to find best motoring operation of switched reluctance motor drives [2]-[5]. The systematic investigation on characteristics of motoring operation of switched reluctance motor drives is indispensable in order to implement the best motoring operation of switched reluctance motor drives in electric vehicles. This study aims at this issue.

The organization of this paper is described as follows. At first, the model of motoring operation of in-wheel switched reluctance motor drives will be proposed in the section II. Next, three criteria will be defined to evaluate motoring operation of switched reluctance motor drives in the section III. In the section IV, then, the effects of the turn-on angle, the turn-off angle and the current reference on motoring operation will be discussed. Finally, the section V will summarize this study.

II. Model of In-wheel Switched Reluctance Motor Drives under Motoring Operation

In general, motoring operation of SRM drives include two modes. One of which is the constant torque operation at low and medium speed, and the other is the constant power one at high speed. The in-wheel switched reluctance motor drives are used to directly drive vehicle wheels in this study. For direct drive, in-wheel switched reluctance motor drives run at low and medium speed generally. Thus, the motoring operation of the in-wheel switched reluctance motor drives is regarded as the constant torque operation. In this study, the current hysteresis control is selected to implement the constant torque operation. The proposed control scheme of motoring operation of in-wheel switched reluctance motor drives is shown in Fig. 1.

For SRM drives, the phase flux linkage and phase current must satisfy the equation, given as

$$V_{ph} = \frac{d\psi(\theta,i)}{dt} + i r_{ph} \quad (1)$$

where V_{ph} represents the voltage applied to a phase, ψ represents the phase flux linkage, θ represents the rotor position, i represents the phase current, t represents the time, and r_{ph} represents the phase resistance.

For the specified SRM drives, the flux linkage and torque characteristics can be given by using the finite element analysis or the experiment, which are expressed as

$$\psi(\theta,i) = f_{\psi}(\theta,i) \quad (2)$$

and

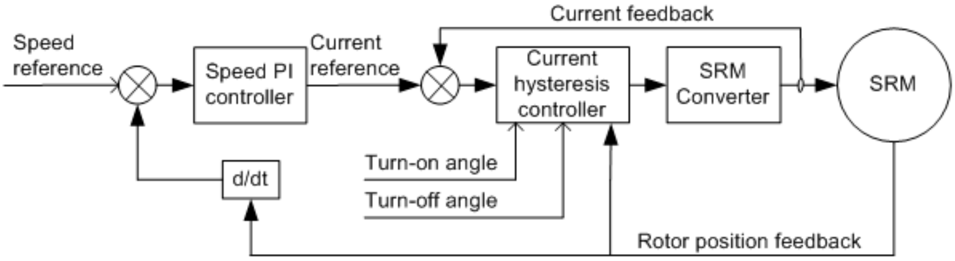


Fig. 1: Control schematic of motoring operation of in-wheel switched reluctance motor drives

$$T_{ph}(\theta,i) = f_T(\theta,i) \quad (3)$$

where T_{ph} represents the torque produced by one phase.

Neglecting on-state drop of power switches, the relationships between the DC link voltage, phase voltage, turn-on angle, turn-off angle, rotor position, current reference, and phase current, based on the control schematic shown in Fig. 2, can be expressed as

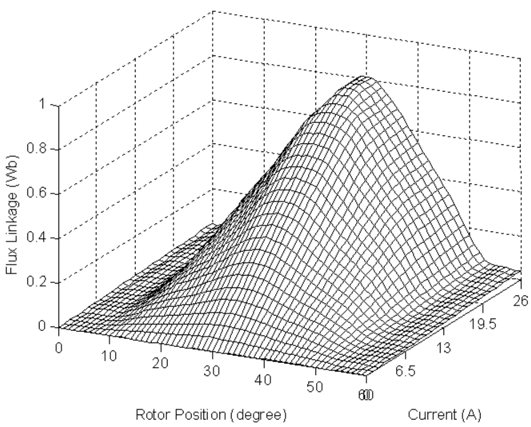
$$\begin{array}{ll} V_{ph} = V_{dc} & (i \le I_{ref} - 0.5I_b) \\ V_{ph} = 0 & (i \ge I_{ref} + 0.5I_b) \end{array} \quad (\theta_{on} \le \theta < \theta_{off}) \quad (4)$$

and

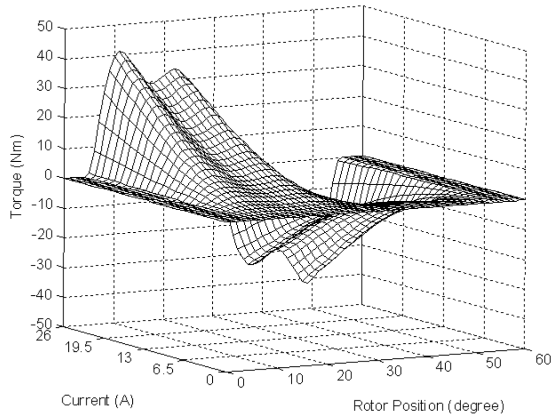
$$V_{ph} = -V_{dc} \quad (\theta_{off} \le \theta \le \theta_e) \quad (5)$$

where V_{dc} denotes the DC link voltage, I_{ref} denotes the current reference, I_b denotes the hysteresis band, θ_{on} denotes the turn-on angle, θ_{off} denotes the turn-off angle, and θ_e denotes the extinguishing angle.

In this paper, the developed prototype of the four-phase 5 kW in-wheel SRM drive is used to investigate characteristics of the motoring operation. The rotor position is defined as 0 degree when the stator pole is fully unaligned with the rotor pole and the rotor position is defined as 30 degree when the stator pole is completely aligned with the rotor pole. The characteristics of the flux linkage and torque of the prototype are illustrated in Fig. 2 and are computed by using the finite element analysis. Consequently, the developed model can be solved [6]-[7].



(a) Flux linkage



(b) Torque

Fig. 2: Given characteristics of the in-wheel SRM

Fig. 3 shows the developed in-wheel SRM, which is mounted on the rim.

Fig. 3 Prototype of the in-wheel SRM

III. Criteria to Evaluate Motoring Operation

From the aforementioned requirement of EVs on electric motors, three criteria of motoring operation are proposed as the average torque, the average torque per rms current, and the torque smoothness factor. They imply the magnitudes of motoring torque, operating efficiency and torque ripple, respectively.

The computation of the average torque in SRMs is given as

$$T_{ave} = \frac{1}{\theta_p} \int_{\theta_{on}}^{(\theta_{on}+\theta_p)} \sum_{k=1}^{N_{ph}} T_{phk}(\theta, i) d\theta \tag{6}$$

where θ_p denotes the period of the phase current, θ_{on} denotes the turn-on angle, N_{ph} denotes the number of phases, T_{phk} denotes the phase torque, i denotes the phase current and θ denotes the rotor position.

Consequently, the average torque per rms current is expressed as

$$TC = \frac{T_{ave}}{I_{rms}} \tag{7}$$

where I_{rms} denotes the rms value of phase current.

In this paper, the torque smoothness factor is defined as

$$TSF = \min\left\{ \frac{T_{ave}}{T_{\max} - T_{ave}}, \frac{T_{ave}}{T_{ave} - T_{\min}} \right\} \tag{8}$$

where T_{max} represents the maximum value of instantaneous torque, and T_{min} represents the minimum value of instantaneous torque.

For in-wheel SRM drives in EVs, the values of three criteria are desired to be as large as possible because large average torque , large average torque per rms current, and large torque smoothness factor indicate high motoring torque, low copper loss (high operating efficiency), and low torque ripple, respectively.

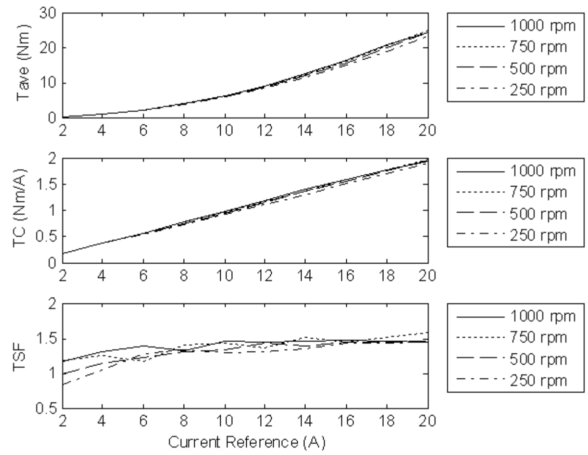
IV. Characteristics of Motoring Operation

1. Effects of current reference

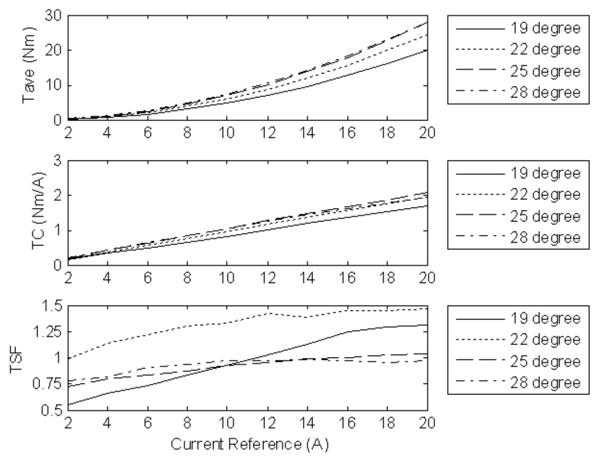
The current reference can be used to adjust the motoring torque. Fig. 4a illustrates the effects of the current reference, which are obtained when the turn-on angle is equal to 0 degree and the turn-off angle is equal to 22 degree. For various motor speeds, it can be observed that (i) the average torque becomes large if the current reference increases; (ii) the average torque per rms current increases if the current reference goes up; and (iii) the torque smoothness factor increases with increment in the current reference.

For various turn-off angles, the effects of the current reference are shown in Fig. 4b when the SRM is running at the turn-on angle of 0 degree and the motor speed of 500 rpm. It can be seen for various turn-off angles that (i) large current reference results in large average torque, (ii) the average torque per rms current changes with the current reference, and (iii) the torque smoothness factor goes up with increase in the current reference.

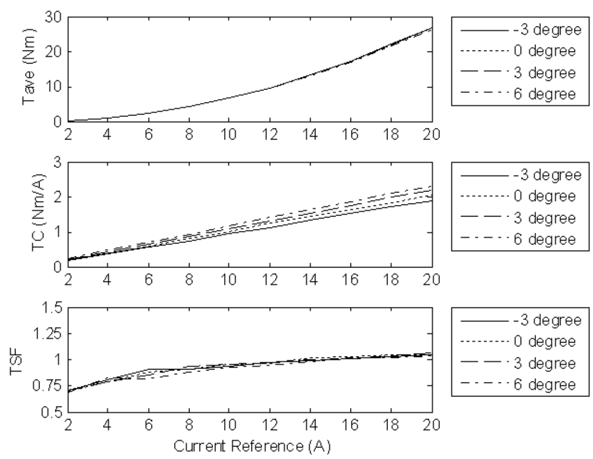
For a series of given turn-on angles, Fig. 4c illustrates the effects of the current references at the turn-off angle of 24 degree and the motor speed of 500 rpm. It can be observed that the average torque, the average torque per rms current, and the torque smoothness factor augment with increase in the current reference.



(a) Various motor speeds



(b) Various turn-off angles



(c) Various turn-on angles

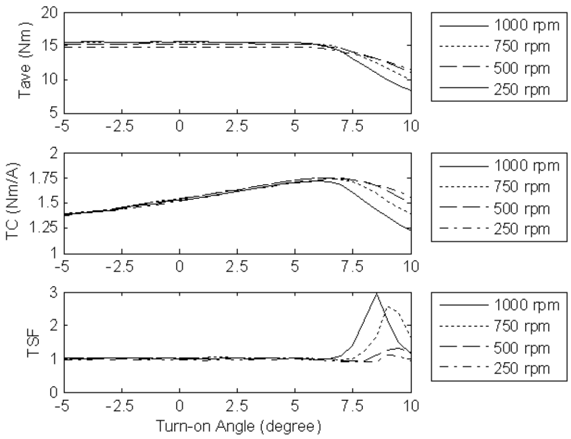
Fig. 4: Effects of the current reference

Therefore, the large current reference is beneficial to the desired motoring operation of SRM drives in EVs.

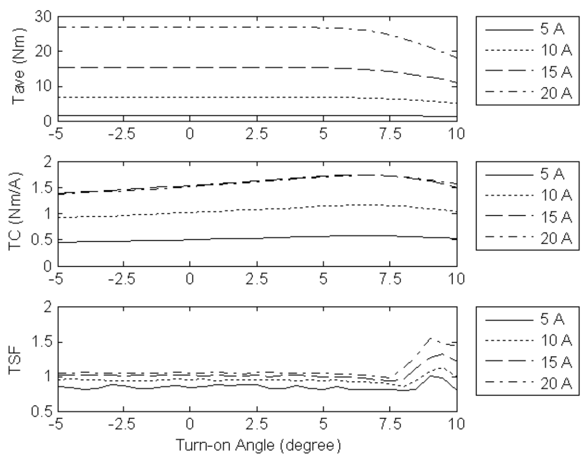
2. Effects of turn-on angle

The turn-on angle can be control the time when the phase starts to be excited. Fig. 5a illustrates the effects of the turn-on angle for various motor speeds when the SRM is running at the turn-off angle of 24 degree and the current reference of 15 A. It can be observed at various motor speeds that (i) the average torque has the similar values if the turn-on angle is smaller than 6 degree and the average torque goes down with increase in the turn-on angle if the turn-on angle is larger that 6 degree, (ii) there are the optimal turn-on angle such that the average torque per rms current reaches the maximum values, and (iii) the optimal turn-on angles can be found to obtain the maximum torque smoothness factors.

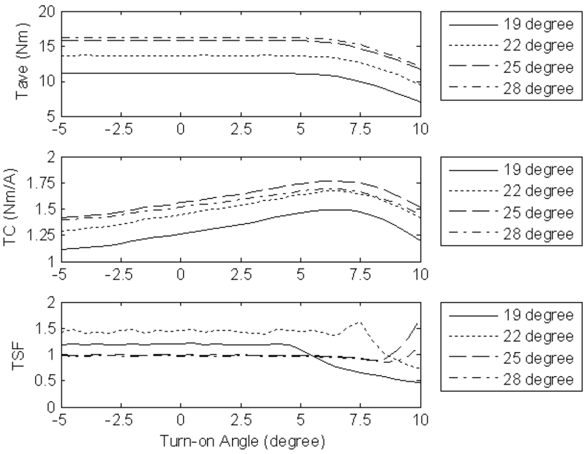
The effects of the turn-on angle for various current references are depicted in Fig. 5b when the SRM is working at the motor speed of 500 rpm and the turn-off angle of 24 degree. It is clear for various current references that (i) the average torque has the similar values if the turn-on angle is smaller than 6 degree and the average torque becomes small with increase in the turn-on angle if the turn-on angle is larger that 6 degree, (ii) the average torque per rms current leads to the maximum value if the turn-on angle is the optimal value, and (iii) the optimal turn-on angles can be determined to have the maximum torque smoothness factors.



(a) Various motor speeds



(b) Various current references



(c) Various turn-off angles

Fig. 5: Effects of the turn-on angle

The effects of the turn-on angle for various current references are depicted in Fig. 5b when the SRM is working at the motor speed of 500 rpm and the turn-off angle of 24 degree. It is clear for various current references that (i) the average torque has the similar values if the turn-on angle is smaller than 6 degree and the average torque becomes small with increase in the turn-on angle if the turn-on angle is larger that 6 degree, (ii) the average torque per rms current leads to the maximum value if the turn-on angle is the optimal value, and (iii) the optimal turn-on angles can be determined to have the maximum torque smoothness factors.

For various turn-off angles, the effects of the turn-on angle are illustrated in Fig. 4c when the SRM is operating at the motor speed of 500 rpm and the current reference of 15 A. It can be seen for different turn-off angles that (i) the average torque has the similar values if the turn-on angle is smaller than 6 degree and the average torque becomes small with increase in the turn-on angle if the turn-on angle is larger that 6 degree, (ii) there are the optimal turn-on angles to obtain the maximum average torque per rms current, and (iii) the optimal turn-on angle can be determined to yield the maximum torque smoothness factor.

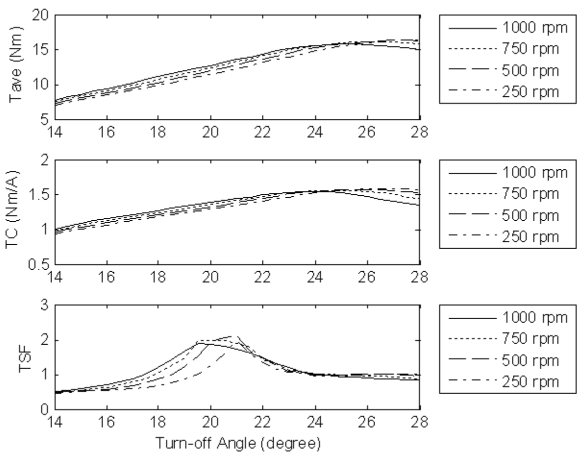
Therefore, the turn-on angle has considerable effects on motoring operation of SRM drives. The optimal turn-on angle can be found to have the maximum average torque, the maximum average torque per rms current, or the maximum torque smoothness factor.

3. Effects of turn-off angle

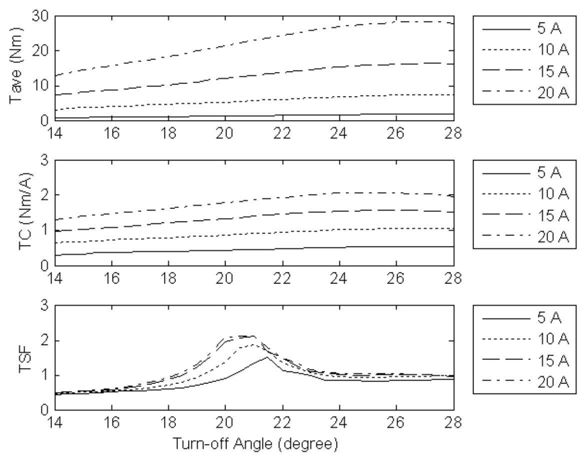
The turn-off angle can be used control the time when the excitation of the phase winding is terminated. When the SRM is operating with the turn-on angle of 0 degree and the current reference of 15 A, the changes of the average torque, average torque per rms current and torque smoothness factor with the turn-off angle are depicted in Fig. 6a. It can be seen that (i) there are the optimal turn-off angles for various motor speeds so that the average torque leads to the maximum values, (ii) there are the optimal turn-off angles and the maximum average torque per rms current for different motor speeds, and (iii) the turn-off angle can be found the optimal values for various motor speeds in order to obtain the maximum torque smoothness factor.

Fig. 6b shows the effects of the turn-off angle at various current references when the SRM is running at the motor speed of 500 rpm and the turn-on angle of 0 degree. It can be observed that (i) the optimal turn-off angles can be determined for various current references to have the maximum average torque, (ii) the maximum average torque per rms current can be obtained when the optimal turn-off angles for different current references are found, and (iii) there are the optimal turn-off angles for various current references to obtain the maximum torque smoothness factor.

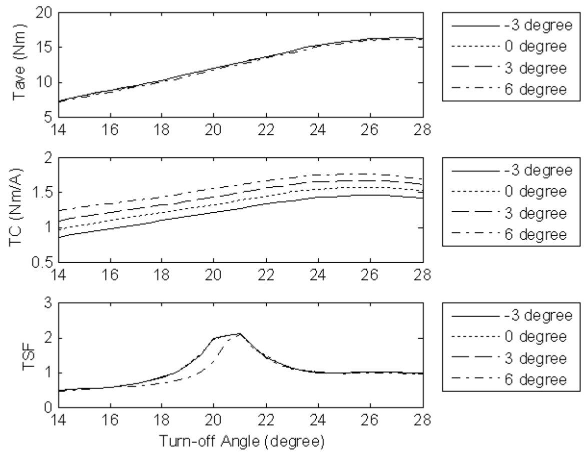
The effects of the turn-off angle for various turn-on angles are illustrated in Fig. 6c when the SRM is working at the motor speed of 500 rpm and the current reference of 15 A. It can be found for different turn-on angles that (i) there are the optimal turn-off angles to have the maximum average torque, (ii) the maximum average torque per rms current can be obtained when the turn-off angles are equal to the optimal values, and (iii) there are always the optimal turn-off angles such that the torque smoothness factor reaches to the maximum values for various turn-on angles.



(a) Various motor speeds



(b) Various current references



(c) Various turn-on angles

Fig. 6: Effects of the turn-off angle

As a result, the turn-off angle has significant effects on the motoring operation of SRM drives. The turn-off angle can be optimized to obtain the maximum average torque, the maximum average torque per rms current, or the maximum torque smoothness factor.

V. CONCLUSION

This study has presented three criteria to evaluate motoring operation of in-wheel switched reluctance motor drives in electric vehicles. They are the average torque, the average torque per rms current, and the torque smoothness factor. It can be seen that they indicate the motoring torque, copper loss, and torque ripple, respectively. Three maximum criteria mean the best motoring operation of in-wheel switched reluctance motor drives for electric vehicles.

The effects of control parameters on three criteria, which are used to evaluate the motoring operation of in-wheel SRM drives, have been studied systematically. The simulated results under the current hysteresis control shows that (a) the large current reference is beneficial for desired motoring operation of in-wheel SRM drives, (b) the optimal turn-on angles can be found to maximize the average torque, the average torque per rms current, or the torque smoothness factor, (c) the turn-off angles also can be optimized to obtain the maximum average torque, the maximum average torque per rms current, or the maximum torque smoothness factor, and (d) at the given motor speed and current reference the turn-on and turn-off angles can be optimized to obtain the maximum average torque, the maximum average torque per rms current, or the maximum torque smoothness factor.

Therefore, it can be inferred from this study that the optimal control method can be developed through optimizing the control parameters to implement the best motoring operation of in-wheel switched reluctance motor drives for electric vehicles. The authors will report the optimization results in the other paper.

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