Investigation on Characteristics of Braking Operation of Switched Reluctance Motor Drives for Electric Vehicles

X. D. Xue, K. W. E. Cheng, T. W. Ng, and N. C. Cheung
Department of Electrical Engineering, the Hong Kong Polytechnic University
Hung Hom, Kowloon
Hong Kong, China

***Abstract*-Three criteria are proposed to evaluate braking operation of switched reluctance motor drives for electric vehicles. They are the average torque, the average torque per average excitation power and the average torque per phase rms current. They imply the braking torque, the efficiency of braking operation and the copper loss. Thus, the effects of the turn-off and turn-on angles on these criteria are investigated in detail. The investigation results are very beneficial to develop the new control method for best braking operation of switched reluctance motor drives in electric vehicles.**

I. INTRODUCTION

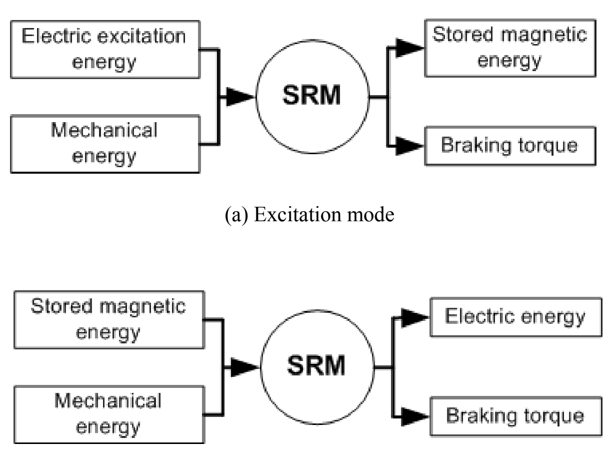
The electro-brake is one of advantages of electric motors in EVs. During braking operation, mechanical (kinetic) energy of electric motors can be converted to electric energy to generate braking torque. Clearly, it is helpful to that hydraulic brake systems stop EVs fast and its dynamic performance is better than conventional hydraulic brake systems. In addition, in stead of conventional hydraulic brake systems, electro-mechanical systems employing an electric motor that drives the brake caliper through a gear assembly are also developing [1].

Comparing with the motoring operation of electric motors in EVs, the braking operation is just the generating operation and it lasts by a short time in EVs. However, the braking operation of electric motors in EVs occurs frequently. The requirement of EVs on the braking operation of electric motors can be summarized as follows: (a) high braking torque, (b) little excitation energy, (c) low copper loss, and (d) controlled braking torque.

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, inherent fault tolerance, direct-drive, high transmission efficiency, highly reliable and simple drivetrain system, SRM drives are much suitable for EV applications [2]. Effective braking operation of SRMs is important for EVs with high performances. This paper is focused on this challenging issue.

II. MECHANISM OF BRAKING OPERATION OF SRM DRIVES

Different from other motors, SRMs have the particular braking mechanism. The braking operation of SRMs includes two modes. One of which is named as the excitation mode and the other is named as the generation mode. In a period, the excitation mode is active firstly. During the excitation mode, both electric energy and mechanical energy are needed to excite the SRM to set up stored magnetic energy. At the same time, the SRM also generates braking torque. Electric excitation energy is turned off when stored magnetic energy reaches to the specified value. Consequently, the excitation mode of the braking operation is inactive and the generation mode is active. During the generation mode, the SRM takes in mechanical energy and outputs electric energy. Clearly, the SRM generates braking torque. These two modes occur alternately in every a period until the braking operation terminates. Fig. 1 illustrates the schematic of the braking operation of an SRM.



(b) Generation mode
Fig. 1. Mechanism of braking operation of an SRM

The authors gratefully acknowledge the financial support of the Innovation and Technology Fund of Hong Kong Innovation and Technology Support Programme and The Automotive Parts and Accessory Systems R&D Centre, Hong Kong (Project code: ITF//013/07AP; PolyU ref: ZS01).

III. Characteristics of Braking Operation of SRM Drives

A. Model

The control schematic for braking operation of SRM drives is proposed as shown in Fig. 2. The turn-on angle and the turn-off angle are defined to generate braking torque. The current reference with the hysteresis current controller is used to adjust the average value of braking torque. Thus, the controlled parameters of SRM drives under braking operation have three ones, which are the current reference, turn-on angle and turn-off angle.

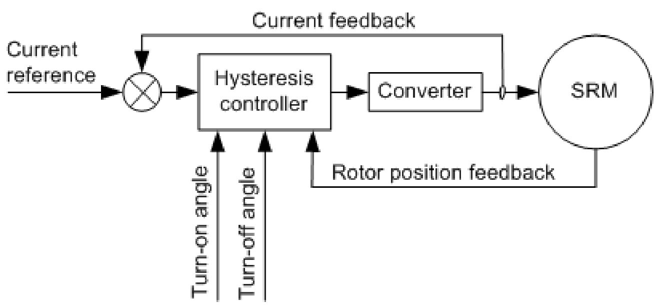


Fig. 2. Control schematic of braking operation in SRM drives

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

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

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

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

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

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

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.

The above model can be solved if the flux linkage and torque characteristics of an SRM are given [3] [4] [5].

B. Criteria of Braking Operation

From the aforementioned requirement of EVs on braking operation of electric motors, the criteria of braking operation for SRM drives are proposed as the average torque, the average braking torque per average excitation power, and the average braking torque per rms current. They imply the magnitude of braking torque, efficiency of braking operation and copper loss, respectively.

The average torque of an SRM is computed as

$$T_{ave} = \frac{1}{T_p}\int_0^{T_p} \sum_{k=1}^{N_{ph}} T_{phk}(\theta,i)dt \quad (6)$$

where T_p denotes the time value of an electrical period, N_{ph} denotes the number of phases, T_{phk} denotes the instantaneous torque produced by a phase. The positive torque represents the motoring torque and the negative torque represents the braking torque.

The average excitation power under braking operation is expressed as

$$P_{ae} = \frac{N_{ph}}{T_p}\int_0^{T_p} iV_{ph}dt \quad (iV_{ph} > 0) \quad (7)$$

The positive power indicates that the SRM takes in electric power from the DC link and the negative power indicates that the SRM output electric power to DC link.

The rms value of the phase current is determined as

$$I_{rms} = \sqrt{\frac{1}{T_p}\int_0^{T_p} i^2 dt} \quad (8)$$

Consequently, the average braking torque per average excitation power is expressed as

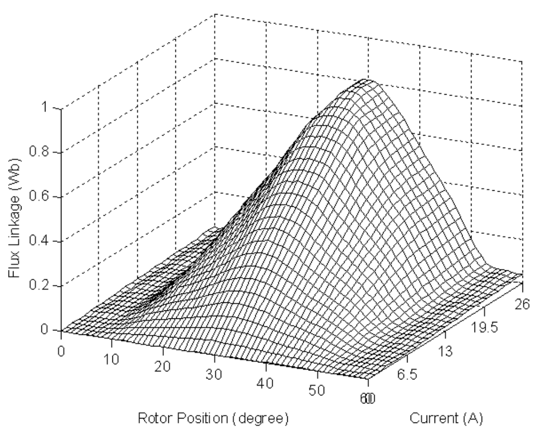
$$TP = \left|\frac{T_{ave}}{P_{ae}}\right| \quad (9)$$

The average braking torque per rms current is defined as

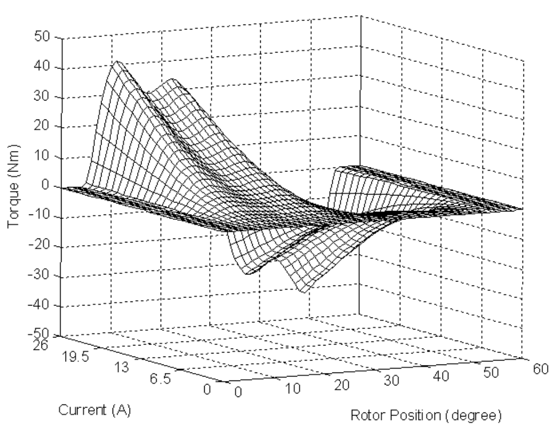
$$TC = \left| \frac{T_{ave}}{I_{rms}} \right| \tag{10}$$

It can be seen that large *TP* means that unity average excitation power can result in larger braking torque, and that large *TC* implies that unity copper loss can bring about larger braking torque. Obviously, it is desired that three above criterion values are as large as possible.

Investigating effects of the controlled parameters on the criteria is mush helpful to develop an optimal control method for braking operation of SRM drives. In this study, the prototype of a four-phase in-wheel SRM drive is simulated to accomplish the investigation. The rotor position angle is equal to 0 degree when the stator pole is fully unaligned with the rotor pole and the rotor position angle is equal to 30 degree when the stator pole is completely aligned with the rotor pole. The characteristics of the phase flux linkage and torque are illustrated in Fig. 3 and are computed by the finite element analysis.



(a) Flux linkage

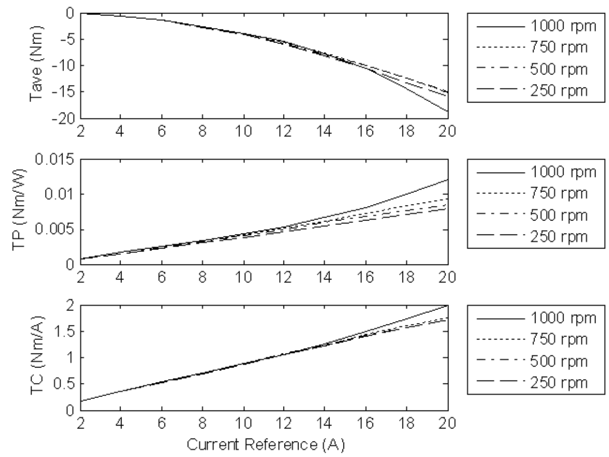


(b) Torque

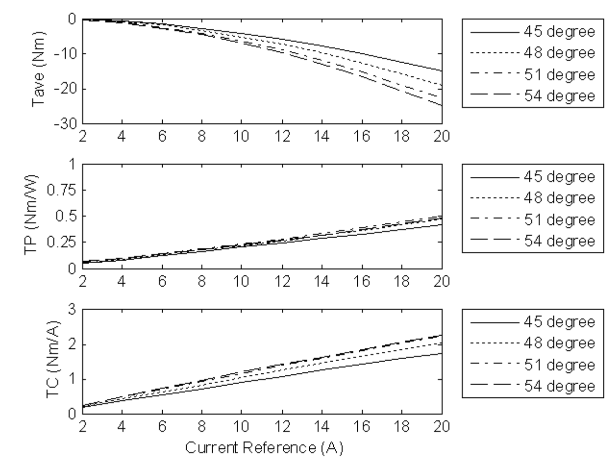
Fig. 3. Magnetic characteristics of the prototype

C. *Effects of Current*

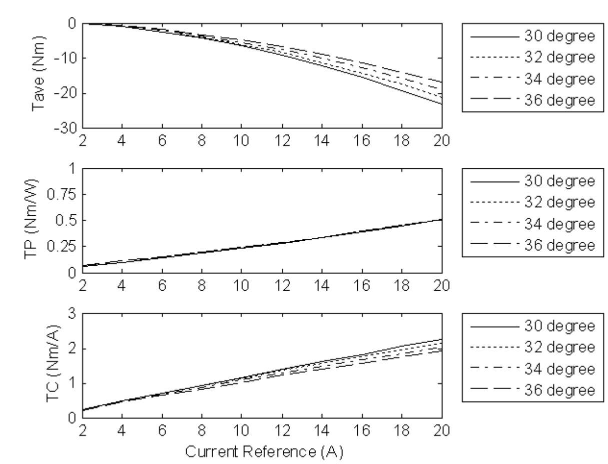
Fig. 4a illustrates the effects of the current reference, which are obtained when the turn-on angle is equal to 30 degree and



(a) Various motor speeds



(b) Various turn-off angles



(c) Various turn-on angles

Fig. 4. Effects of the current

equal to the optimal values, and (iii) there are always the optimal turn-off angle such that the average braking torque per rms current value reaches to the maximum value.

the turn-off angle is equal to 45 degree. For various motor speeds, it can be observed that (i) the braking torque becomes large if the current reference increases, (ii) the braking torque per excitation power increases if the current reference goes up, and (iii) the braking torque per rms current changes with the current references.

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 30 degree and the motor speed of 500 rpm. For various turn-on angles, the effects of the current reference are shown in Fig. 4c when the SRM is running at the turn-off angle of 45 degree and the motor speed of 500 rpm. It can be seen for various turn-off and turn-on angles that (i) large current reference results in large average braking torque, (ii) the average braking torque per average excitation power changes with the current reference, and (iii) the average braking torque per phase rms current goes up with increase in the current reference.

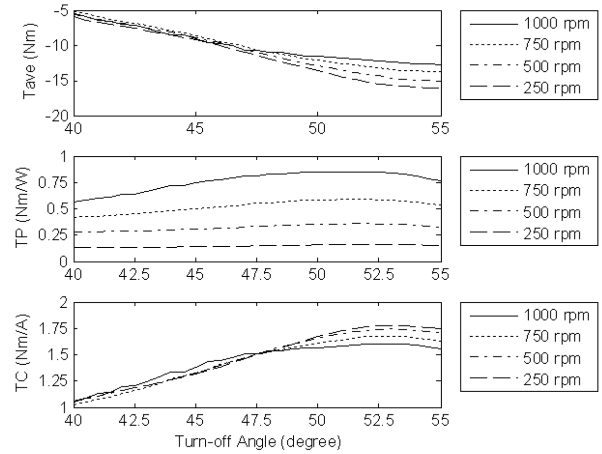
Therefore, the large current reference is beneficial to the desired braking operation of SRM drives in EVs.

D. Effects of Turn-off Angle

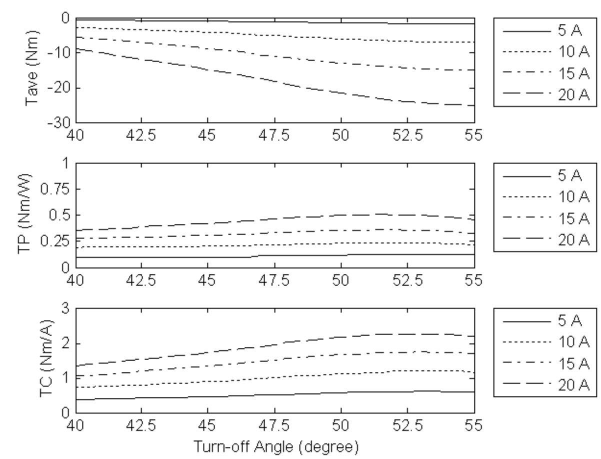
When the SRM is operating with the turn-on angle of 30 degree and the current reference of 15 A, the changes of the average braking torque, average braking torque per average excitation power and average braking torque per phase rms current with the turn-off angle are depicted in Fig. 5a. It can be seen that (i) the average braking torque does not change with the turn-off angle monotonously and there are the optimal turn-off angles for various motor speeds so that the average braking torque leads to the maximum values, (ii) there are the optimal turn-off angles and the maximum average braking torque per average excitation power 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 average braking torque per rms current values.

Fig. 5b 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 30 degree. It can be observed that (i) the optimal turn-off angles can be determined for various current references to have the maximum average braking torque, (ii) the maximum average braking torque per average excitation power 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 average braking torque per rms current values.

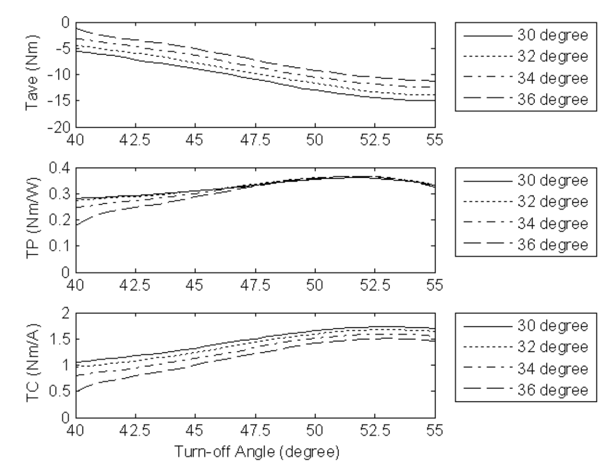
The effects of the turn-off angle for various turn-on angles are illustrated in Fig. 5c when the SRM is working at the motor speed of 500 rpm and the current reference of 15 A. It can be found for different turn-on angles that (i) there are the optimal turn-off angles to have the maximum average braking torque, (ii) the maximum average braking torque per average excitation power can be obtained when the turn-off angles are



(a) Various motor speeds



(b) Various current references



(c) Various turn-on angles

Fig. 5. Effects of the turn-off angle

As a result, the turn-off angle has significant effects on the braking operation of SRM drives. The turn-off angle can be optimized to obtain the maximum average braking torque, the maximum average braking torque per average excitation power and the maximum average braking torque per phase rms current.

E. Effects of Turn-on Angle

Fig. 6a illustrates the effects of the turn-on angle for various motor speed when the SRM is running at the turn-off angle of 51.5 degree and the current reference of 15 A. It can be observed at various motor speeds that (i) the larger turn-on angles will result in the smaller average braking torque, (ii) change in the turn-on angle has little effect on the average braking torque per average excitation power, and (iii) the average braking torque per phase rms current decreases if the turn-on angle becomes large.

The effects of the turn-on angle for various current references are depicted in Fig. 6b when the SRM is working at the motor speed of 500 rpm and the turn-off angle of 51.5 degree. It is clear for various current references that (i) the average braking torque decreases with increase in the turn-on angle, (ii) the average braking torque per average excitation power change little if the turn-on angle is varied, and (iii) the larger turn-on angle gives rise to the smaller average braking torque per phase rms current.

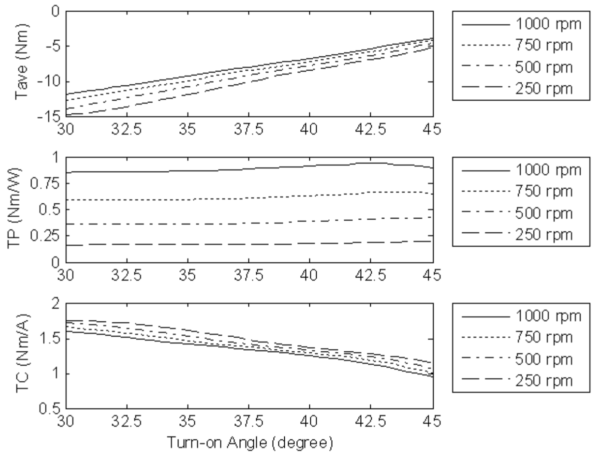
For various turn-off angles, the effects of the turn-on angle are illustrated in Fig. 6c when the SRM is operating at the motor speed of 500 rpm and the current reference of 15 A. It can be seen for different turn-off angles that (i) the average braking torque becomes small if the turn-on angle increases, (ii) variation in the turn-on angle result in little effect on the average braking torque per average excitation power, and (iii) the average braking torque per phase rms current decreases with increase in the turn-on angle.

Therefore, the turn-on angle has considerable effects on braking operation of SRM drives. The small turn-on angle is advantageous for braking operation of SRM drives.

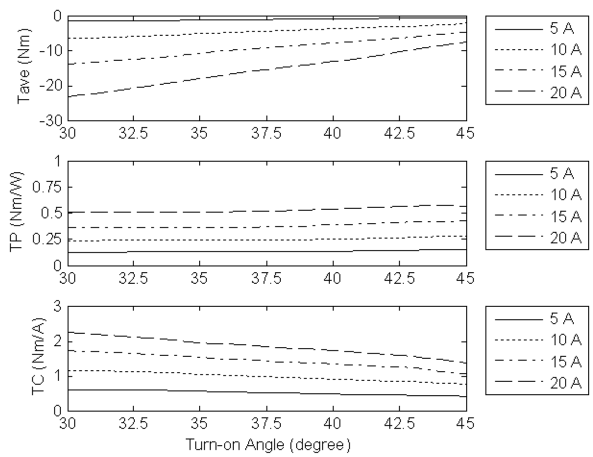
IV. Discussion

It can be seen from the investigation in the last section that the turn-on angle, turn-off angle and current have noticeable effects on the average braking torque, average braking torque per excitation power, and average braking torque per rms current. In other words, these three parameters affect the braking torque, efficiency of braking operation, and copper loss obviously. The turn-on angle and the turn-off angle can be optimized to implement the maximization of the braking torque, maximization of the braking torque per excitation power, maximization of the braking torque per rms current. Furthermore, the current can be used to control the magnitude of the braking torque.

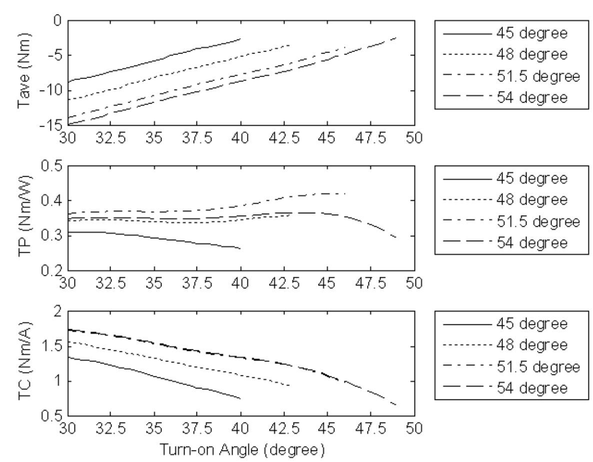
Thus, a novel control method for best braking operation of SRM drives in EVs is suggested as follows: i) the current with hysteresis current controller can be utilized to adjust the braking torque, ii) the optimal turn-on angle and turn-off angle are found from the motor speed and current to accomplish the



(a) Various motor speeds



(b) Various current references



(c) Various turn-off angles

Fig. 6. Effects of the turn-on angle

best braking operation of SRM drives in EVs. The authors' future study will aim at this issue.

V. Conclusions

In this paper, three criteria have been proposed to evaluate braking operation of SRM drives in EVs. They are the average torque, the average braking torque per average excitation power, and the average braking torque per phase rms current. These three criteria imply braking torque, excitation energy and copper loss.

The investigation in this paper indicates that (i) the large current reference is beneficial to the desired braking operation of SRM drives in EVs; (ii) the turn-off angle has significant effects on the braking operation of SRM drives, and the turn-off angle can be optimized to obtain the maximum average braking torque, the maximum average braking torque per average excitation power and the maximum average braking torque per phase rms current; and (iii) the turn-on angle has considerable effects on braking operation of SRM drives and the small turn-on angle is advantageous for braking operation of SRM drives. Therefore, the turn-off and turn-on angles can be optimized to obtain maximum average braking torque, maximum average braking torque per average excitation power or maximum average braking torque per phase rms current. The current reference can be used to control the braking torque. In summary, the investigation in this paper is helpful to develop the control method for implementing best braking operation of switched reluctance motor drives in electric vehicles.

References

[1] Omekanda, A.M.; Gopalakrishnan, S.; Klode, H.; "Acoustic Noise of Switched Reluctance and Permanent Magnet Motors: A Comparison in the Context of Electric Brakes", *42nd IAS Annual Meeting*, 2007, pp. 2147 – 2153.

[2] X. D. Xue, K. W. E. Cheng, and N. Cheung, "Selection of Electric Motor Drives for Electric Vehicles", presented at AUPEC 2008, Sydney, Australia.

[3] X. D. Xue, K. W. E. Cheng, and S. L. Ho, "A Position Stepping Method for Predicting Performances of Switched Reluctance Motor Drive", *IEEE Transactions on Energy Conversion*, vol. 22, no. 4, Dec 2007, pp. 839-847.

[4] X. D. Xue, K. W. E. Cheng, and S. L. Ho, "Simulation of Switched Reluctance Motor Drives Using Two-Dimensional Bicubic Spline", *IEEE Transactions on Energy Conversion*, Vol. 17, No. 4, December 2002, pp471-477.

[5] X. D. Xue, K. W. E. Cheng, and S. L. Ho, "Correlation of modeling techniques and power factor for switched-reluctance machines drives", *IEE Proceedings Electric Power Applications*, Vol. 152, No. 3, MAY 2005, pp. 710-722.