Study of Power Factor in SRM Drives under Current Hysteresis Chopping Control

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***Abstract* -- Based on the simulation and experimental analyses, this paper investigates the effects of the control parameters and outputs upon the power factor in switched reluctance motor (SRM) drives under the current hysteresis chopping control. The control parameters include the reference current, hysteresis band, turn-on angle, turn-off angle and input ac voltage. The outputs consist of the speed and average torque. The relations between the power factor and the above variables are shown. The conclusions given in this paper will be used conveniently by fellow researchers as a useful tool to design SRM drive controllers that operate with good power factor.**

***Index Terms* – Power factor, switched reluctance motor (SRM) drives.**

I. INTRODUCTION

Power factor is one of the important performances for electrical equipments. It is well known that SRM drives exhibit many desirable features including simple construction, high reliability and low cost. Thus, SRM drives are ideal for many industrial applications. However, SRM drives suffer from poor operating power factor, which will result in more losses in power distribution systems. Therefore, improving the power factor is very beneficial to enhancing commercial competition of SRM drives. Furthermore, investigating the effects of the control parameters and outputs on the power factor is much helpful for developing control strategies to improve the power factor in SRM drives.

Reference [1] presented an algorithm to compute the power factor in SRM drives and thus provides an effective approach to study the power factor in SRM drives. The authors in [2] studied the effects of the freewheeling angle upon the power factor in SRM drives and proposed a novel strategy to improve the power factor by adjusting the freewheeling angle. For the single-pulse and voltage PWM operations, the effects of the control parameters and outputs on the power factor in SRM drives are investigated in [3]. Those control parameters and outputs are the turn-on angle, turn-off angle, duty cycle of PWM, chopping mode of PWM, input ac voltage. The outputs consist of the speed and torque. Based on [3], a new control strategy was proposed in [4], which is to improve the power factor in SRM drives through changing the turn-on angle and turn-off angle under the single-pulse voltage and voltage PWM controls.

SRM drives operate at low speed under the current hysteresis chopping control except under the voltage PWM control [5]. This study extended the initial research findings of [3] and [4]. The effects of the control parameters and outputs on the power factor in SRM drives under the current hysteresis chopping control were investigated in this paper. The control parameters include the reference current, hysteresis band, turn-on angle, turn-off angle, and input ac voltage. The outputs have the speed and torque. The measured and simulated current waveforms and power factor values were used to validate the proposed simulation modeling. The effects of the above parameters and outputs on the power factor in SRM drives were investigated and analyzed by using the demonstrated analytical approach. Furthermore, some ideas to improve the power factor were suggested. The simulation results and the analyses serve to give a solid foundation for researchers to understand how the power factor changes with the control parameters and the motor outputs under the current hysteresis chopping control. Hence the findings would facilitate the designers to design a good current hysteresis chopping controller with the high power factor in SRM drives.

II. ANALYTICAL APPROACH

A. Simulation Modelling

It is assumed that (a) SRM drives with the current hysteresis chopping control operate at steady state, and (b) the mutual coupling is ignored. The voltage differential equation of SRM drives can be given by

$$\frac{d\psi}{d\theta} = \frac{1}{\omega_r}(v_w - r_a i_w)\,. \tag{1}$$

where ψ denotes the phase flux linkage, θ denotes the rotor position, ω_r denotes the angular velocity of the rotor, v_w denotes the phase winding voltage, i_w denotes the phase winding current, and r_a denotes the resistance of a phase winding.

In the meanwhile, the flux linkage, phase current and rotor position must satisfy the magnetic characteristics of SRM drives, which are determined accurately from the following bicubic spline interpolation [6]:

The authors gratefully acknowledge the support of the Research Committee of the Hong Kong Polytechnic University.

$$\psi(\theta, i_w) = \begin{pmatrix} 1 & (\theta-\theta_k) & (\theta-\theta_k)^2 & (\theta-\theta_k)^3 \end{pmatrix} \boldsymbol{A} \begin{pmatrix} 1 \\ (i_w - i_j) \\ (i_w - i_j)^2 \\ (i_w - i_j)^3 \end{pmatrix} . \quad (2)$$

where θ_k and i_j are the known position and current values, respectively, and $\boldsymbol{A}$ is the 4×4 coefficient matrix that is computed from the known data [6].

In general, input ac voltages of SRM drives are symmetrical three-phase sinusoidal voltages and input ac currents are asymmetrical three-phase non-sinusoidal currents. Hence, the power factor in SRM drives is computed from

$$PF = \frac{P_a + P_b + P_c}{S_a + S_b + S_c} , \quad (3)$$

$$P_l = \frac{1}{T}\int_0^T v_l(t) i_l(t) dt , \quad (4)$$

and

$$S_l = V_{rmsl} I_{rmsl} . \quad (5)$$

where PF represents the power factor of SRM drives; P_a, P_b and P_c are the three-phase real powers; S_a, S_b and S_c are the three-phase apparent powers; T represents the period of ac supply; $v_l(t)$ and $i_l(t)$ are the ac phase voltage and current, respectively; t denotes the time; V_{rmsl} and I_{rmsl} are the effective values of the phase voltage and current, respectively; and $l = a, b, c$. The more detailed description of the simulation modelling is seen in [1].

In addition, the control of SRM drives under the current hysteresis chopping operation must satisfy

$$v_w = \begin{cases} +V \quad , \quad (i_w \le (i_{ref} - 0.5 i_b)) \\ -V \quad , \quad (i_w \ge (i_{ref} + 0.5 i_b), \quad for \quad hard \quad chopping) \\ 0 \quad , \quad (i_w \ge (i_{ref} + 0.5 i_b), \quad for \quad soft \quad chopping) \\ v_w \quad , \quad ((i_{ref} - 0.5 i_b) < i_w < (i_{ref} + 0.5 i_b)) \end{cases} . \quad (6)$$

where V denotes the net voltage applied to the phase winding, i_{ref} the reference current, and i_b the current hysteresis band.

Equation (6) indicates that when the rotor position changes from the turn-on angle to the turn-off angle, (a) the phase winding is charged if the phase current is not larger than (i_{ref} - 0.5i_b), (b) the phase winding discharges if the phase current is not smaller than (i_{ref} + 0.5i_b) and SRM drives operate under the hard chopping, (c) the phase winding freewheels if the phase current is not smaller than (i_{ref} + 0.5i_b) and SRM drives operate under the soft chopping, and (d) the state of the phase winding is not changed when the phase current is larger than (i_{ref} - 0.5i_b) and smaller than (i_{ref} + 0.5i_b).

B. Modelling Validation

Using the above simulation modelling described, a prototype of the four-phase SRM drive is simulated and tested, to validate this proposed analytical approach of the power factor in SRM drives. The schematic diagram of the control of the prototype with the current hysteresis chopping control is shown in Fig. 1. DAC denotes the D/A converter, PSC the position/speed converter, ADC the A/D converter, θ_{on} represents the turn-on angle, and θ_{off} the turn-off angle.

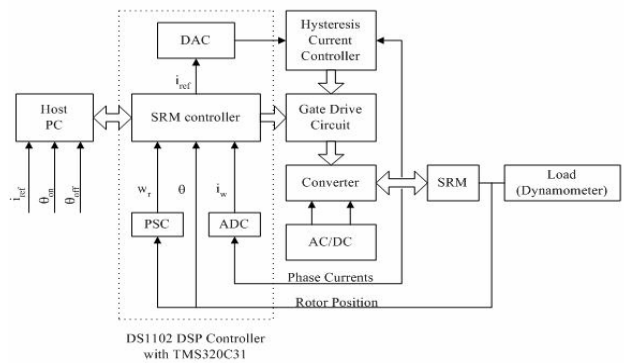
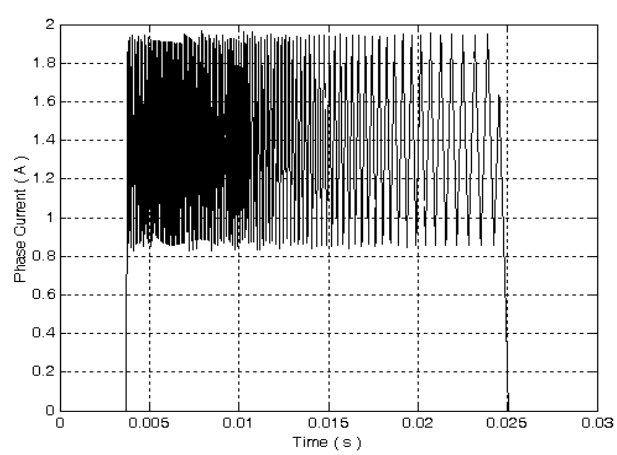
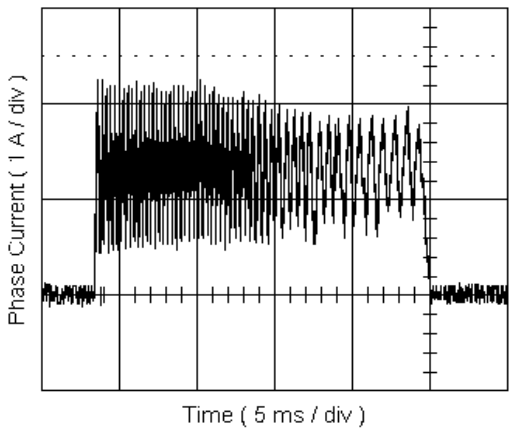


Fig. 1 Schematic diagram of the current hysteresis chopping control

Fig. 2 illustrates the simulated and measured current waveforms under the hard chopping, whereas Fig. 3 depicts the simulated and measured current waveforms under the soft chopping. It can be seen from Fig.2 and Fig. 3 that the simulation waveforms agree well with the measured waveforms under such two operations, respectively.

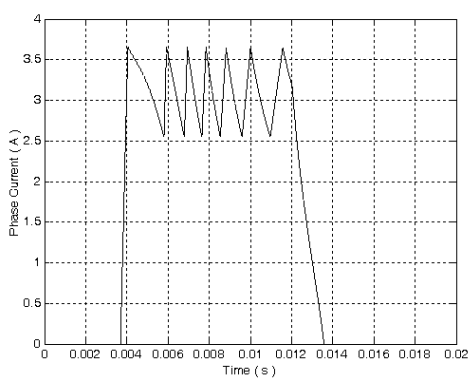


(a) Simulation

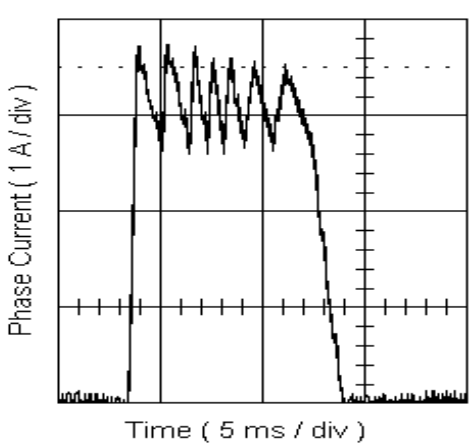


(b) Experiment

Fig. 2 Phase current waveforms with the hard chopping (Turn-on angle = 0°, turn-off angle = 15°, peak line voltage = 122.5 V, reference current = 1.4 A, hysteresis band = 1.1 A, and speed = 120 rpm)



(a) Simulation



(b) Experiment

Fig. 3 Phase current waveforms with the soft chopping (Turn on-angle = 0°, turn-off angle = 15°, peak line voltage = 73.5 V, reference current = 3.1 A, hysteresis band = 1.1 A, and speed = 300 rpm)

The computed and measured power factor values can be found in Fig. 4 and Fig. 5. The comparisons between the computations and experiments show that the computed power factor values are consistent well with the measured values. As a result, the illustrations as given from Fig. 2 to Fig. 5 serve as a good validation of the modelling and the simulation algorithm in this study. Therefore, the proposed analytical approach can be employed to accurately investigate the changes of the power factor in SRM drives under the current hysteresis chopping control.

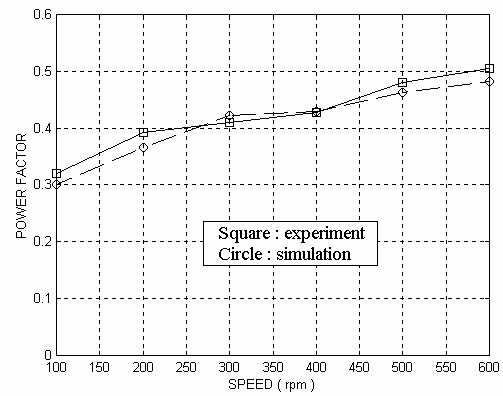


Fig. 4 Comparison of the power factor between the simulation and experiments with the hard chopping (Turn-on angle = 0°, turn-off angle = 15°, peak line voltage = 73.5 V, reference current = 3.0 A, and hysteresis band = 1.1 A)

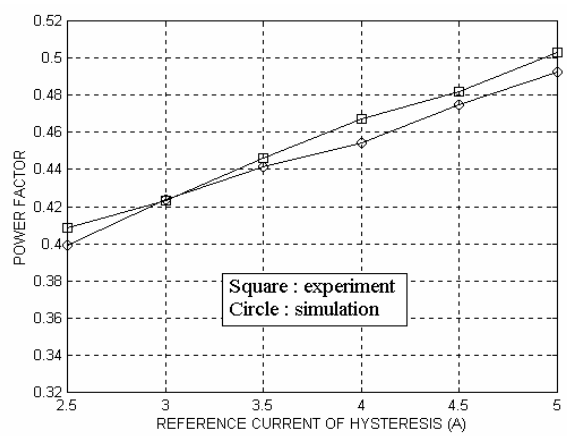


Fig. 5 Comparison of the power factor between the simulation and experiments with the soft chopping (Turn on-angle = 0°, turn-off angle = 15°, peak line voltage = 73.5V, hysteresis band = 1.1 A, and speed = 400

III. INVESTIGATION OF POWER FACTOR

The simulation modelling demonstrated in the last section is selected as an analytical approach to study the power factor in SRM drives. Unless otherwise stated, the analyses are obtained from the simulation with the hard chopping in this section.

A. Effect of the Reference Current

Fig. 6 illustrates the relation between the power factor and the reference current. It indicates that the power factor increases when the reference current goes up. In other words, the SRM drive has the high power factor if it operates under the current hysteresis chopping control with the large reference current. It is worth noting that discontinuous input current and pulsation of phase currents in SRM drives gives rises to the poor power factor [2]-[4]. Because the large reference current is helpful for enhancing the input current continuity, it is logical that the power factor should be improved as the reference current increases.

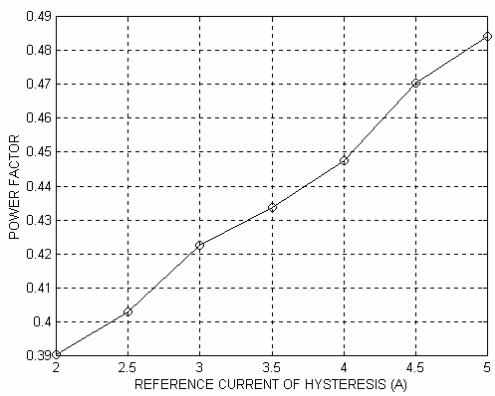


Fig. 6 Change of the power factor with the reference current (Turn-on angle = 0º, turn-off angle = 15º, peak line voltage = 73.5 V, hysteresis band = 1.1 A, and speed = 300 rpm)

B. Effect of the Average Torque

The relation between the average torque and the power factor is depicted in Fig. 7. It can be found that the power factor increases with the increase in the average torque. In fact, this analytical result is the same as that obtained in the last section, since the increment of the reference current must result in a higher average torque under the same operating condition.

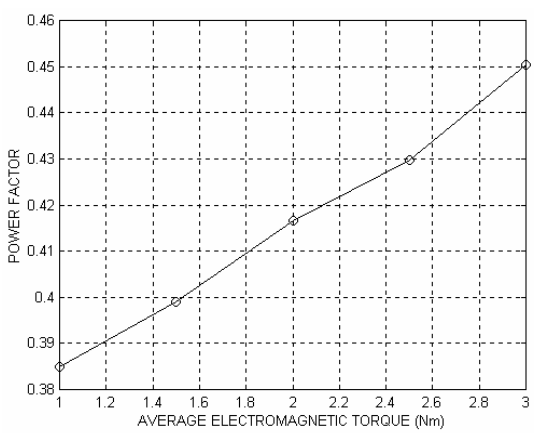


Fig. 7 Change of the power factor with the average torque (Turn-on angle = 0º, turn-off angle = 15º, peak line voltage = 73.5 V, hysteresis band = 1.1 A, and speed = 250 rpm)

C. Effect of the Current Hysteresis Band

The change of the power factor with the hysteresis band can be observed in Fig. 8. It can be seen that the power factor will become high if the hysteresis band increases. With a constant reference current, a constant conduction angle, a constant dc link voltage and a constant speed, a large hysteresis band will lead to a reduction in the phase current pulsation. Again, this helps to improve the power factor.

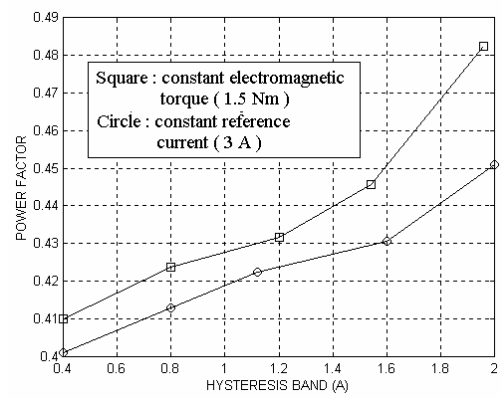


Fig. 8 Change of the power factor with the hysteresis band (Turn-on angle = 0º, turn-off angle = 15º, peak line voltage = 73.5 V, and speed = 300 rpm)

D. Effect of the Input AC Voltage

The effect of the input ac voltage on the power factor can be observed in Fig. 9, which is that the power factor decreases with increasing the ac input voltage. With a constant reference current, a constant conduction angle, a

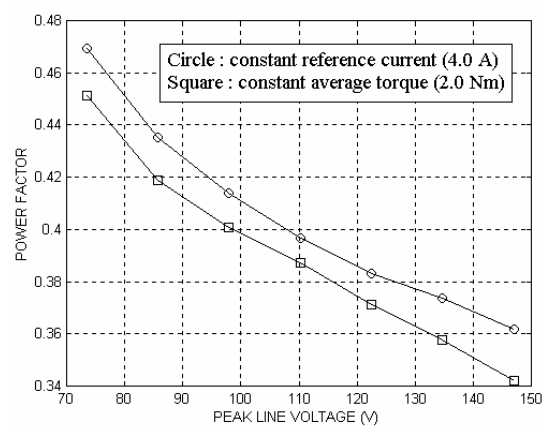


Fig. 9 Change of the power factor with the ac input voltage (Turn-on angle = 0º, turn-off angle = 15º, hysteresis band = 1.1 A, and speed = 300 rpm)

constant hysteresis band and a constant speed, the large peak line voltage (dc link voltage) will result in the increment of the phase currents pulsations, thereby resulting in a poor power factor. In other words, the power factor will become low if the ac input voltage increases.

E. Effect of the Speed

Fig. 10 depicts the change of the power factor with the speed. It can be found that the power factor increases with increasing the speed at constant torque. In fact, when the torque of the SRM drive is maintained constant, the reference current must increase if the speed goes up. Hence the power factor will become large.

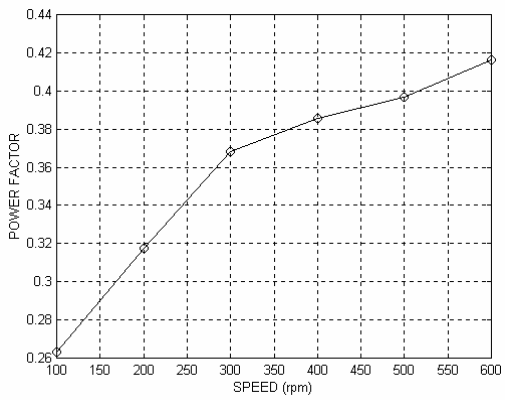


Fig. 10 Change of the power factor with the speed (Turn-on angle = 0°, turn-off angle = 15°, peak line voltage = 122.5 V, average torque = 2.0 Nm, and hysteresis band = 1.1 A)

F. Effect of the Turn-on Angle

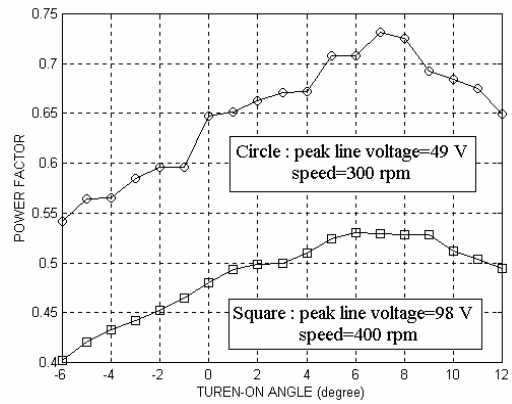
Fig. 11 shows the change of the power factor with the turn-on angle. Fig. 11(a) is obtained with the constant conduction angle whereas Fig. 11(b) is obtained with the constant turn-off angle. It can be seen that the turn-on angle affects the power factor very strongly. There is a specific turn-on angle at which the power factor of the SRM drive reaches a maximum value. In other words, the high power factor can be obtained through optimizing the turn-on angle.

G. Effect of the Hysteresis Chopping Modes

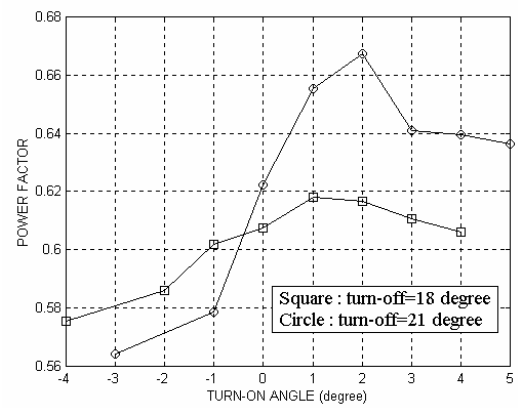
Fig. 12 shows the change of the power factor with the speed under the soft and hard chopping controls, obtained experimentally. It can be seen that the hysteresis chopping modes affect the power factor much weakly.

H. Effect of the Turn-off Angle

Fig. 13 illustrates the changes of the power factor with the turn-off angle with the constant reference current in Fig. 13(a) and the constant torque in Fig. 13(b). Similarly to the turn-on angle, it can be observed that the turn-off angle also affects the power factor strongly. Furthermore, it can be found that there is a specific turn-off angle that the SRM drive has a maximum power factor. Consequently a high power factor can also be obtained through optimizing the turn-off angle.



(a) Constant conduction angle = 18° (Reference current = 4.0 A, and hysteresis band = 1.1 A)



(b) Constant turn-off angle (Peak line voltage =49 V, torque = 2.0 Nm, hysteresis band = 1.1 A, and speed = 400 rpm)

Fig. 11 Change of the power factor with the turn-on angle

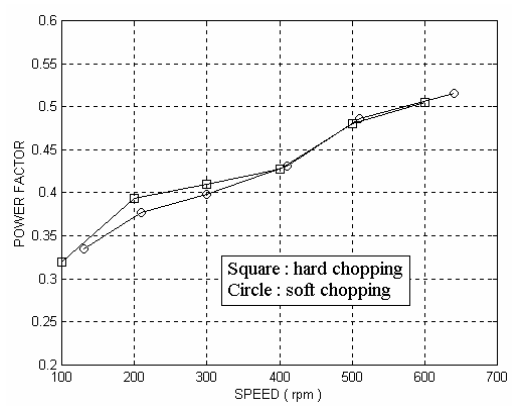
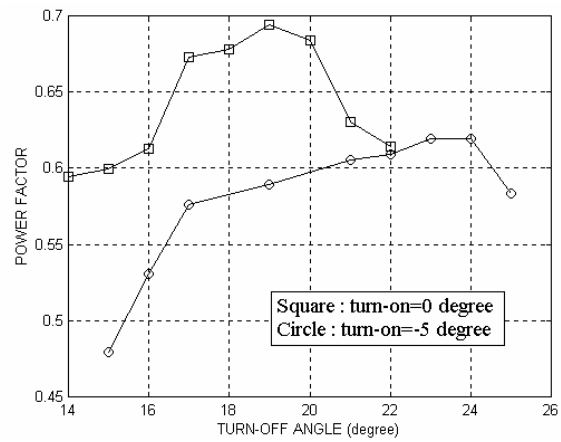
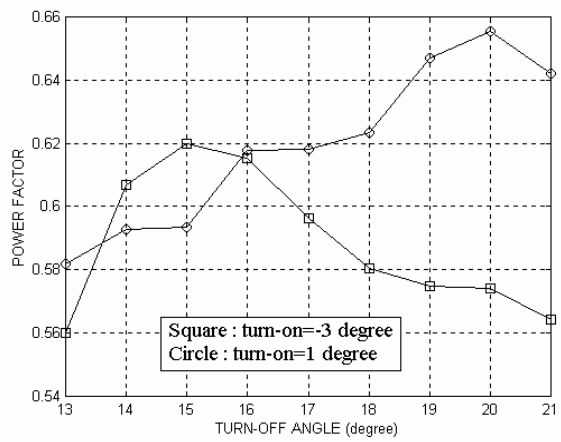


Fig. 12 Comparison between the soft chopping and hard chopping (Turn-on angle = 0°, turn-off angle = 15°, peak line voltage = 73.5 V, reference current = 3.0 A, and hysteresis band = 1.1 A)



(a) Constant reference current (Peak line voltage = 49 V, reference current = 4.0 A, hysteresis band = 1.1 A, and speed = 400 rpm)



(b) Constant torque (Peak line voltage = 49 V, average torque = 2.0 Nm, hysteresis band = 1.1 A, and speed = 400 rpm)

Fig. 13 Change of the power factor with the turn-off angle

IV. CONCLUSIONS

The investigation in this paper indicates that the control parameters and outputs under the current hysteresis chopping control can affect the power factor in SRM drives. These effects are:

- The reference current has significant effect on the power factor in SRM drives. Increasing the reference current will result in a high power factor.
- The hysteresis band affects the power factor in SRM drives considerably. The power factor increases with increasing the hysteresis band.
- The hysteresis chopping modes affect on the power factor in SRM drives much weakly.
- The input ac voltage or dc link voltage influences the power factor in SRM drives. The higher input ac voltage will result in the lower power factor.
- Both the turn-on angle and the turn-off angle affect the power factor in SRM drives strongly. There are such turn-on angles and turn-off angles at which SRM drives run with the high power factor.
- The average electromagnetic torque has a pronounced effect on the power factor in SRM drives as the power factor increases with an increase in the average torque.
- The speed has an effect on the power factor in SRM drives. To be specific, the power factor will become large if the speed goes up.

Current hysteresis controllers should incorporate the following features in the design in order to have the high power factor in SRM drives: (a) the low input ac voltage, (b) the large reference current, (c) the large hysteresis band, and (d) the optimized turn-on angle and turn-off angle.

The current hysteresis chopping control is one of the important control methods for SRM drives. It is often used during low speed operation of SRM drives. Therefore, this study is a systematic and comprehensive investigation to help the readers to understand clearly the relationships between the power factor and those factors that affect the power factor. Moreover, it serves as a useful guideline for designers attempting to obtain the high power factor of SRM drives.

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