Investigation of the Effects of the Control Parameters and Outputs on Power Factor of Switched Reluctance Motor Drive Systems

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Abstract – **In this paper, the authors study the effects of the control parameters and outputs of SRM drive systems on power factor through theoretical, simulation and experimental analyses. The control parameters and outputs include turn-on angle, turn-off angle, input voltage, duty cycle of PWM, speed and torque. The analyses are carried out at three operation modes of SRM drives with voltage source, i.e., single-pulse operation, voltage PWM with hard chopping and voltage PWM with soft chopping. This study reveals completely the relationships between power factor and the above parameters. Moreover, the authors propose the new ideas to improve power factor in SRM drives, based on the analysis results. This study is very important for understanding clearly the parameters to affect on power factor, and the conclusions is quite helpful in designing good controller to improve power factor of SRM drive systems.**

I. Introduction

It is known that SRM drive systems have low power factor. In general, single-pulse phase currents or discontinuous input ac currents in SRM drives is the crucial reason to cause poor power factor of SRM drive systems [1]-[8]. On the other hand, the control parameters and outputs of SRM drives can affect the phase currents with single pulse. The control parameters and outputs presented in this paper include the turn-on angle, turn-off angle, input voltages, duty cycle of PWM, speed, and torque. Improving power factor in SRM drives can be fulfilled only through adjusting these parameters according to the outputs of SRM, if it is known how these parameters and outputs affect power factor. But the issue on the above, up to now, have not been reported.

This study is focused on the above issue. The authors' intentions are to reveal relationships between power factor of SRM drive systems, the control parameters and the outputs. Through theoretical, simulation and experimental analyses, the effects of turn-on angle, turn-off angle, input voltages, duty cycle of PWM, speed and torque on power factor in SRM drive systems are investigated. These analyses include the three operation modes of SRM drives with voltage source, which are single-pulse operation, voltage PWM with hard chopping, and voltage PWM with soft chopping. This study shows what parameters in SRM drive systems will affect power factor and how these parameters affect power factor. In addition, the authors propose the new ideas to improve power factor of SRM drives, based on the analytical results. Thus, this paper is highly helpful to design good controller to improve power factor of SRM drive systems.

This work is supported by the RGC of Hong Kong under grant PolyU5085/98E and by RC of the Hong Kong Polytechnic University under grant G-W081.

II. Theoretical Analyses

Fig.1 shows a schematic diagram of a typical phase branch in SRM drive systems. Any phase winding in SRM drive systems has three basic operation states [9], which can be summarized as follows:

State1: Charging. Both the power component Q_1 and Q_2 are switched on. The winding W is applied to DC supply directly. The winding W takes in the electrical power from supply. Most of which is converted into mechanical power, and the other is converted into stored magnetic energy and losses.

State2: Freewheeling. Q_1 is switched off and Q_2 is still switched on. The winding W is short-circuited through Q_2 and the diode D_1. The winding W does not take in any power from supply but it releases energy that stored in it, which is converted into mechanical power and losses.

State3: Discharging. Both Q_1 and Q_2 are switched off. Some of the energy stored in the winding W is fed back to the supply through the diodes D_1 and D_2, while the other is converted into mechanical power and losses.

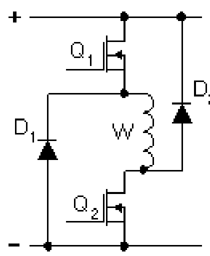


Fig. 1. Schematic diagram of a phase branch in topologies of SRM drives

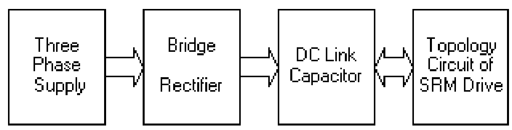


Fig. 2. Schematic diagram of power flows in SRM drives

From the above statement, the block diagram of power flow in SRM drives can be illustrated by Fig. 2. Power flow between DC link capacitor and circuit of SRM drive is bi-directional since the topology circuit of SRM drive can take in power from dc supply and feed back power to dc supply.

Referring to Fig. 2, the DC link capacitor takes in power from the last stage—the bridge rectifier if the topology circuit of SRM drive takes in power from the capacitor stage. Consequently the bridge rectifier has to take in power from the supply. Therefore, the three-phase supply outputs continuously electrical power to SRM drive through the rectifier and the capacitor. That is helpful to improving power factor in SRM drive systems.

Inversely, the capacitor will be charged if the SRM drive releases power to the capacitor, since the size of the DC link capacitor has a finite value. It is possible that it will result in that voltage across charged capacitor is larger than amplitude of input line-voltage and hence brings about discontinuous input currents. Apparently, the power factor in SRM drive systems would become poor.

In short, high power factor would be produced if SRM can take in electrical power from supply as continuously as possibly.

To summarize, the three operation states of a phase winding have effect on power factor in SRM drive systems. Charging is helpful to improve power factor, discharging makes power factor be low, and power factor at freewheeling operation is not good as at charging operation but better than at discharging.

III. ANALYSES AT SINGLE-PULSE OPERATION

A. Simulation Modeling

In the following simulation, it is assumed that (a) SRM drives with voltage source operate at steady state. (b) SRM drive operates at single-pulse mode. (c) The mutual coupling is ignored.

Fig. 3 shows the schematic diagram of SRM drive systems. It illustrates the typical construction of SRM drive systems. u_a, u_b and u_c represent three-phase sinusoidal voltages. i_a, i_b and i_c represent three-phase ac currents. i is dc current of the rectifier output. i_{cap} is the current of the capacitor. u_{cap} represents the voltage across the capacitor. i_{dc} is the dc input current of the topology.

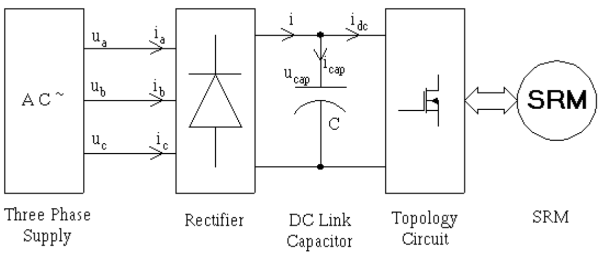


Fig. 3. Schematic diagram of SRM drive systems

Referring to Fig. 3, the modeling of SRM drive systems, which is used to compute power factor in this paper, should satisfy the following equations.

$$i = i_{cap} + i_{dc} \tag{1}$$

$$i_{dc} = k_p i_{wp} \tag{2}$$

$$\frac{d\psi}{d\theta} = \frac{1}{\omega_r}(u_w - r_a i_w) \tag{3}$$

$$u_w = \begin{cases} u_{dc} - 2*v_T & when: s_t = 1 \\ -(u_{dc} + 2*v_D) & when: s_t = -1 \\ -(v_T + v_D) & when: s_t = 0 \end{cases} \tag{4}$$

$$i_{cap} = C\frac{du_{cap}}{dt} \tag{5}$$

$$u_{cap}(t) = u_{cap}(t_0) + \frac{1}{C}\int_{t_0}^{t} i_{cap}(t)dt \tag{6}$$

$$u_{cap}(t) = u_{mn}(t) - v_R \quad if(u_{mn}(t) - v_R) > u_{cap}(t) \tag{7}$$

$$\theta = \omega_r t \tag{8}$$

$$pf = \frac{P_a + P_b + P_c}{S_a + S_b + S_c} \tag{9}$$

where k_p is a coefficient that would be equal to 1, -1 or zero and that depends on the structure of topology circuit, control strategy and switching angles, ψ denotes phase flux linkage, θ denotes rotor position angle, ω_r denotes angular velocity of rotor, i_{wp} represents phase currents in SRM, i_w represents the specified phase current and is equal to i_{w1} here, s_t is a coefficient that would be 1, -1 or zero and that depends on the work status of a winding, u_w represents winding voltage which depends upon s_t, v_T is the saturation voltage of power transistor, v_D is forward voltage drop of recovery diode, r_a is the resistance of winding, u_{cap} is the capacitor voltage, and u_{dc} is the dc voltage which should be equal to the average value of u_{cap}, u_{mn} represents line voltage of ac input, m and $n=a$, b, or c but $m \neq n$, v_R represents the forward voltage drop of bridge rectifier, P_a, P_b and P_c are the phase average power, S_a, S_b and S_c are the phase apparent power. Using Runge-Kutta method can solve (3). The more details about the modeling are seen in [1].

B. Experiment Set-up

In this study, the simulated and measured SRM drive system is a prototype. The data of this prototype are as follows. The typical on-state voltage v_T of IGBT is 1.65V. The forward voltage drop v_D of the recovery diode and the forward voltage drop v_R of the rectifier diode are 0.7V. The DC link capacitor C is 1000 μF. The resistance r_a of phase winding is 0.687 Ω. The stator poles are eight and the rotor poles are six. The number of phases is four.

The block diagram of the experimental system in this study is illustrated by Fig. 4. SRM is supplied by voltage source.

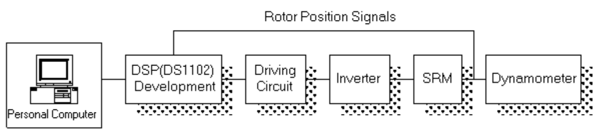
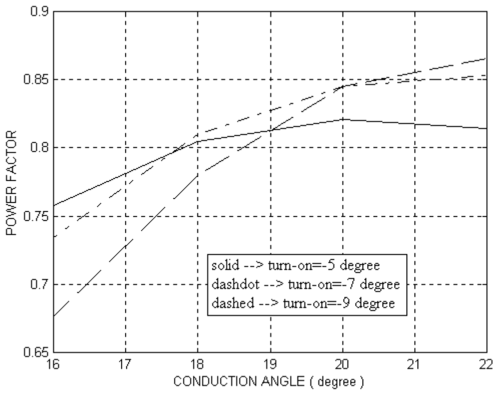


Fig. 4 Block diagram of the experimental system

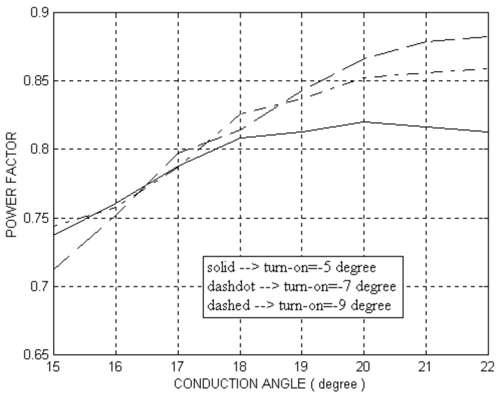
C. Simulation and Experimental Analyses

1) *Effect of turn-off angle on power factor*

In Fig. 5, the amplitude of the ac input line-voltage is equal to 24.5 V and speed is 600 rpm. Fig. 5 depicts changes of power factor with conduction angle, which is equal to the difference between turn-off angle and turn-on angle. Thus, Fig. 5 also illustrates changes of power factor versus turn-off angle. It is clear that the change tendencies of power factor from the simulation results agree with ones from the experimental results. Power factor increases with increasing conduction angle (i.e. turn-off angle) when turn-on angle is small value. However, power factor has maximum value when turn-on angle is large value. Therefore, turn-off angle has great effect on power factor in SRM drive system for a specified turn-on angle, regardless of speed. In other words, high power factor can be obtained through varying turn-off angle for a specified turn-on angle.



(a) Simulation results

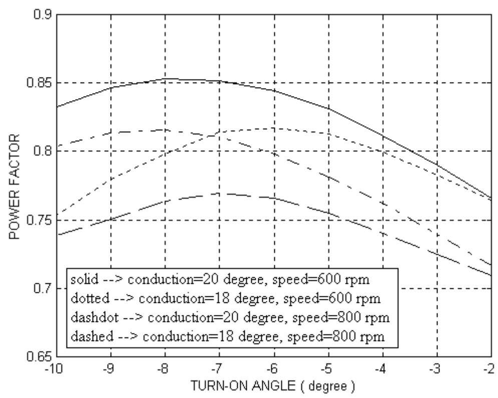


(b) Experimental results

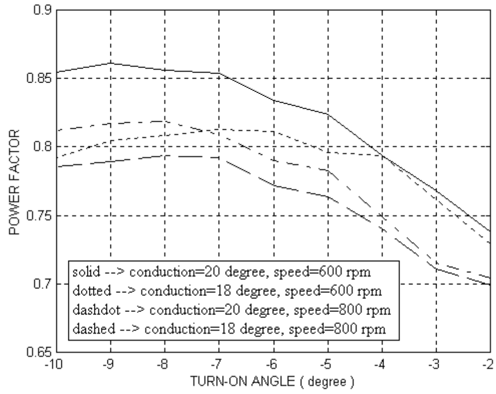
Fig. 5 Changes of power factor with conduction angle

2) *Effect of both turn-on angle and turn-off angle on power factor*

In Fig. 6, input peak line voltage is 24.5 V. It is seen that the illustration of power factor in Fig. 6(a) agrees with the one in Fig. 6(b).



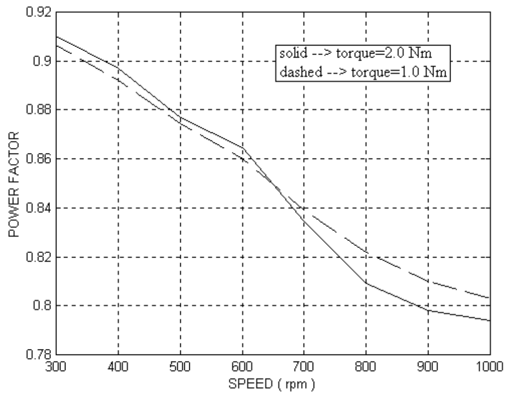
(a) Simulation results



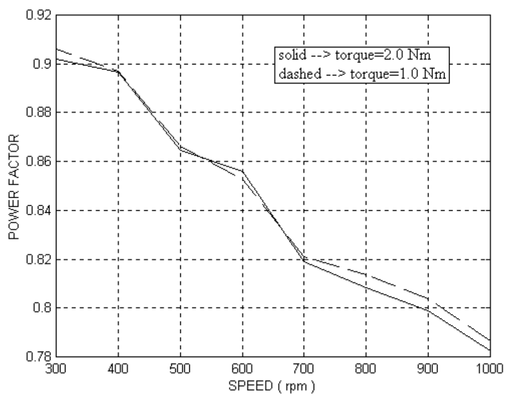
(b) Experimental results

Fig. 6 Changes of power factor with turn-on angle

Fig. 6 shows that turn-on angle have a great effect on power factor. It can be seen from Fig. 5 and Fig.6 that the power factor in SRM drive depends on both turn-on angle and turn-off angle. Moreover, there are such a turn-on angle and a turn-off angle at a constant conduction angle that power factor approaches to a maximum value. Therefore, choosing appropriate turn-on and turn-off angles, the maximum power factor of SRM drive can be obtained.



(a) Simulation results



(b) Experimental results

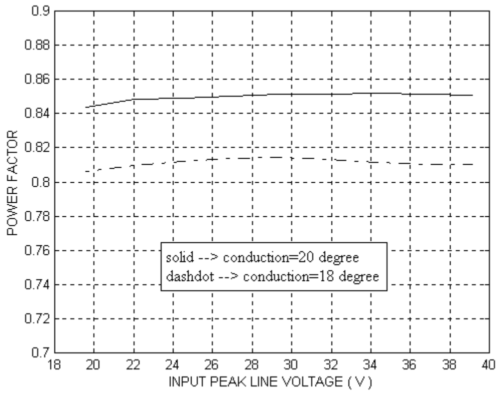
Fig. 7 Changes of power factor with speed

3) *Effect of speed on power factor*

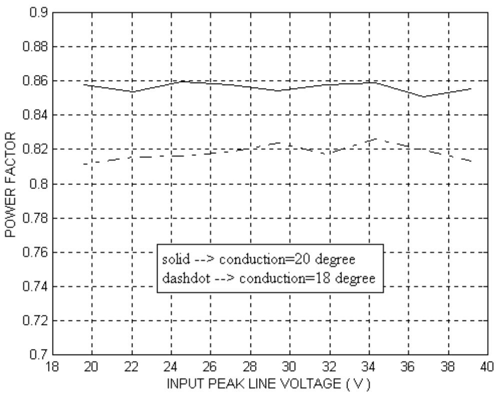
Turn-on angle is equal to -7^o and turn-off angle is 20^o in Fig. 7. It is seen that the changes of power factor from simulation and experiment are identical, and speed affects strongly on power factor in SRM drive system. To be specific, power factor decreases with increasing speed.

4) *Effect of input voltage on power factor*

In Fig. 8, the turn-on angle is –7^o and the speed is 600 rpm. It is seen that input voltage does not quite influence on power factor of SRM drive system. Both the simulation and experimental results confirm it.



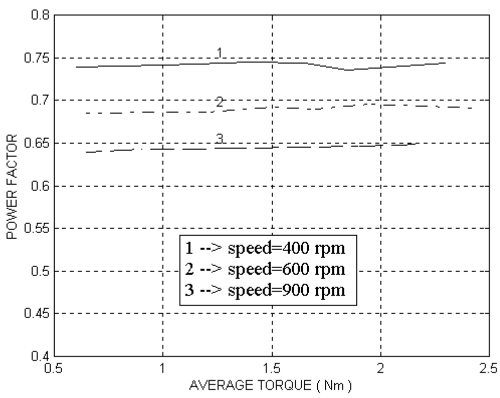
(a) Simulation results



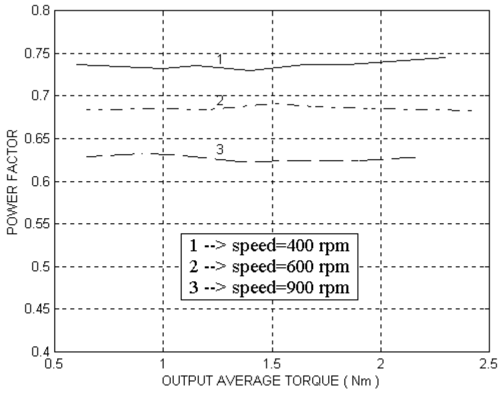
(b) Experimental results

Fig. 8. Changes of power factor with input voltage

5) *Effect of torque on power factor*



(a) Simulation results



(b) Experimental results

Fig. 9. Changes of power factor with average torque

Fig. 9 shows he condition of turn-on angle at 0^o and turn-off angle at 15^o It is seen from the simulation and experimental results that average torque has almost no effect on power factor in SRM drive system.

IV. ANALYSES AT VOLTAGE PWM OPERATION

A. Theoretical Analyses

The analyses in Section III are obtained at single-pulse operation. Except single-pulse operation, Voltage PWM operation is a common one in SRM drives. The analyses in Section III show that amplitude of input voltage almost has no influence on power factor of SRM drive. However, this cannot imply that voltage PWM does not influence on power factor in SRM drives, although PWM is used to change voltage. Voltage PWM in SRM drives has two modes. One of which is named as voltage PWM with hard chopping. The other is named as voltage PWM with soft chopping [9].

For voltage PWM with hard chopping, within one switching period, phase branch in SRM drives operates at two states. Referring to Fig. 1, Q_1 and Q_2 are switched on, phase winding takes in power, and phase winding is charged when $0 \le t \le DT_s$ where t represents time, D represents duty cycle of PWM, and T_s represents the switching period of PWM. When $DT_s \le t \le T_s$, Q_1 and Q_2 are switched off, phase winding feeds back magnetic stored energy to the capacitor, and phase winding discharges.

From the analyses in Section II, charging is helpful to improve power factor in SRM drive system, whereas discharging makes power factor be poor. At single-pulse operation, phase winding can operate at charging continuously within one switching period. However, it is impossible at hard chopping operation. As a result, voltage PWM with hard chopping results in enhancing discontinuities of input currents in SRM drive system in comparison with single-pulse operation. Moreover, it is clear that this effect is stronger if duty cycle of PWM decreases. Hence, power factor at hard chopping is smaller than at single-pulse operation. Furthermore, power factor decreases with decreasing duty cycle.

For voltage PWM with soft chopping, within one switching period, phase branch in the circuit of SRM drives operates at two states, too. Referring to Fig. 1, Q_1 and Q_2 are switched on and phase winding is charged when $0 \leq t \leq DT_s$. When $DT_s \leq t \leq T_s$, Q_1 is switched off and Q_2 is still switched on. Phase winding does not feed back magnetic stored energy to the capacitor. Magnetic stored energy is released via freewheeling.

Therefore, power factor at soft chopping is larger than at hard chopping. On the other hand, in comparison with single-pulse operation, phase winding at soft chopping cannot take in power from supply continuously within one switching period of PWM. Thus, power factor at single-pulse operation is larger than at soft chopping.

As a result, power factor at soft chopping is smaller than at single-pulse operation, but should be larger than at hard chopping. Moreover, power factor decreases with decreasing duty cycle.

B. Experiment Analyses

The experimental system is shown in Fig. 4. Switching frequency of PWM is 10 kHz. Turn-on angle is 0^o and turn-off angle is 15^o.

1) *Hard chopping*

In Fig. 10, SRM's speed is maintained at 600 rpm and the input peak line voltage is equal to 73.5 V. It is seen that the duty cycle of PWM at hard chopping influences on power factor strongly. More specially, power factor increases with increasing duty cycle. This agrees with the theoretical analysis in Section IV-A.

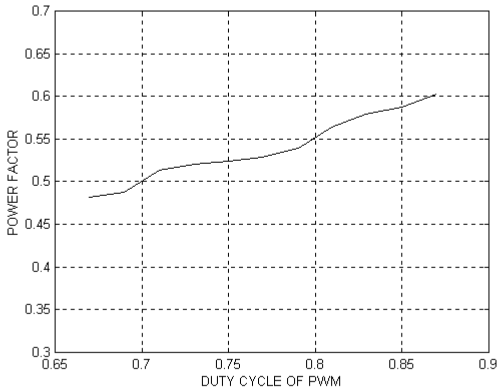
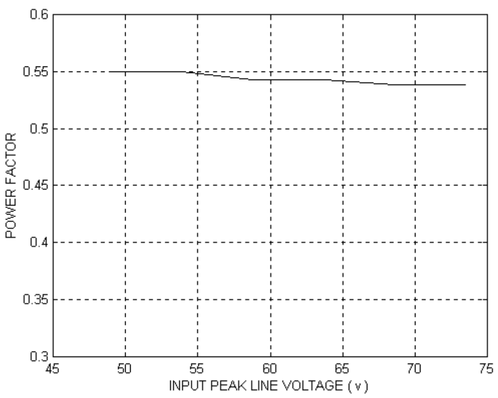
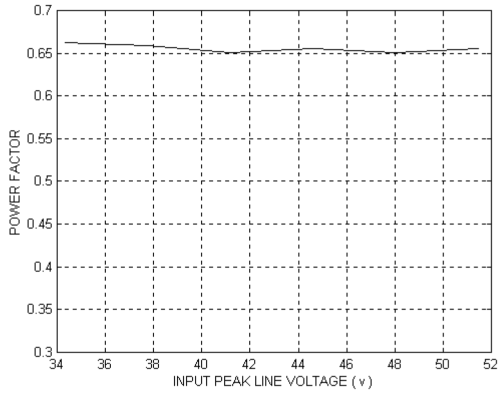


Fig. 10. Changes of power factor with duty cycle at hard chopping



(a) Duty cycle=0.85



(b) Duty cycle=1.0

Fig. 11. Changes of power factor with input voltage at hard chopping

In Fig. 11, speed of SRM drive system is maintained at 800 rpm. The duty cycle in Fig. 11(a) differs from in Fig. 11(b). However, the average voltage applied to phase winding in Fig. 11(b) is equal to the one in Fig. 11(a). It is seen that input voltage influences much weakly on power factor of SRM drive at a specified duty cycle. This result agrees with the analytical results in Section III. In addition, the power factor in Fig. 11(b) is larger than in Fig. 11(a) although their average voltages supplied to phase winding are the same. It indicates that power factor of SRM drive is affected by duty cycle of PWM, but not by changing voltage at PWM basically.

2) *Soft chopping*

In Fig. 12, input peak line voltage is equal to 49.0 V and speed is maintained at 600 rpm. Fig. 12 shows that power factor increases with increasing duty cycle. Consequently, it is seen from Fig. 10 and Fig. 12 that duty cycle of PWM has a great effect on power factor in SRM drive and power factor increases with increasing duty cycle, regardless of hard chopping and soft chopping. To compare Fig. 10 with Fig. 12, it is clear that power factor at soft chopping is larger than at hard chopping. These agree with the theoretical analyses in Section IV-A.

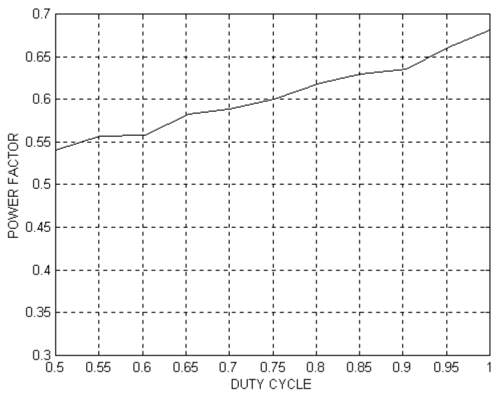
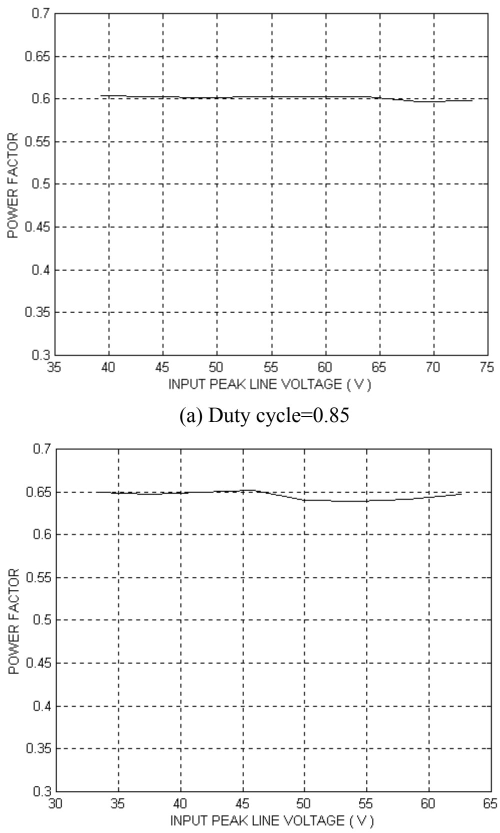


Fig. 12 Changes in power factor with duty cycle at soft chopping

Speed of SRM in Fig. 13 is maintained at 800 rpm. Similar to at hard chopping, the average voltage applied to phase winding in Fig. 13(b) is equal to one in Fig. 13(a). It is seen that input voltage influences much weakly on power factor of SRM drive at a specified duty cycle. Therefore, input voltage at voltage PWM operation influences much weakly on power factor in SRM drive, regardless of hard chopping and soft chopping.

Power factor in Fig. 13(b) is larger than in Fig. 13(a) although their average voltages supplied to phase winding are the same. It indicates that power factor of SRM drive is affected by duty cycle of PWM, but not by input voltage basically.



(a) Duty cycle=0.85

(b) Duty cycle=1.0

Fig. 13 Changes of power factor with input voltage at soft chopping

V. Conclusions

(a) This study reveals completely the relationships between power factor of SRM drive systems and turn-on angle, turn-off angle, conduction angle, input voltage, duty cycle of PWM, speed as well as torque. It is quite helpful to understand clearly the power factor in SRM drive systems and to design good controller of SRM with high power factor.

(b) The results of the theoretical, simulation and experimental analyses in this paper show that both the control parameters and outputs of SRM can influence power factor in SRM drive systems. For SRM drives supplied by voltage source, the effects are summarized as follows.

- Speed of SRM influences on power factor of SRM drive systems strongly. Power factor of SRM drive systems varies with speed. To be specific, power factor in SRM drive systems decreases with increasing speed at single-pulse operation.
- Torque of SRM and input voltage (or average voltage supplied to phase winding) have only a quite weak effect on power factor in SRM drive systems, which can be almost neglected.
- Turn-on angle and turn-off angle influences strongly power factor of SRM drive systems. An interesting result is that there is always such a turn-on angle and a turn-off angle that power factor of SRM drive systems can approach to a maximum value.
- Voltage PWM in SRM drive systems affects power factor. Power factor in SRM drive systems increases with increasing duty cycle of PWM.
- In general, the power factor under single-pulse operation is larger than that under the voltage PWM operation, and power factor at soft chopping operation is larger than at hard chopping operation.

(c) The analysis results in the paper show that the power factor of SRM drive systems will become much poor if the turn-on angle and the turn-off angle are not chosen properly. In other words, the higher power factor can be obtained through adjusting turn-on angle and turn-off angle. Based on the new idea, one can design good controller to improve power factor of SRM drive system.

(d) For SRM drives with voltage PWM, one should prefer voltage PWM with soft chopping, and duty cycle of PWM should be as large as possible within normal operation region of SRM drives, to obtain higher power factor of SRM drives.

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