Single-phase SRM Drive with Torque Ripple Reduction and Power Factor Improvement

D. H. Lee
Kyungsung Univ. Korea
E-mail : leedh@ks.ac.kr

J.W. Ahn
Kyungsung Univ. Korea
E-mail : jwahn@ks.ac.kr

Z. G. Lee
Shenyang Univ. of Tech. China
E-mail : leezhenguo@gmail.com

Abstract - In the single-phase switched reluctance motor (SRM) drive, the required DC source is generally supplied by the circuit consisting of bridge rectifier and large filter capacitor connected with DC line terminal. Due to the large capacity of the capacitor, the charged time of capacitor is very short from the AC source. Lead to the bridge rectifiers draws pulsating current from the AC source side, which results in reduction of power factor and low system efficiency. Therefore a novel single-phase SRM drive system is presented in this paper, which includes drive circuit realizing reduction of torque ripple and improvement of power factor with a novel switching topology. The proposed drive circuit consists of one switching part and diode, which can separate the output of AC/DC rectifier from the large capacitor and supply power to SRM alternately, in order to realize the torque ripple reduction and power factor improvement through the switching scheme. In addition, the validity of the proposed method is tested by some simulations and experiments.

1. INTRODUCTION

The switched reluctance motor (SRM) is a low cost, simple and has robust structure, high ratio of torque to rotor volume, reliability, controllability and high efficiency applications. Specially, single-phase SRM have simple drive circuit and high speed performance [1].

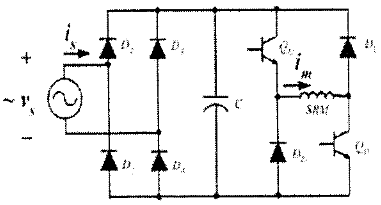
However, conversional converter uses the diode bridge rectifiers and large filter capacitor as the front-end, since the diode rectifiers draws pulsed current from the AC source side and results in low power factor and low system efficiency. So single-phase SRM drive system always has the disadvantage of low power factor and high current harmonic. With the increasing demand for better power quality, this approach is no longer suitable for high performance SRM drives. One of best way to obtain a high power factor is the use of a power factor correction (PFC) circuit with SRM drive [2].

In order to improve the power factor of the drive, many power factor correction approaches have been presented [3]-[6]. In this paper, a novel single-phase SRM drive system is presented for torque ripple reduction and power factor improvement. The proposed drive circuit consists of one switching part and diode, which can separate the output of AC/DC rectifier from the large capacitor and supply power to SRM alternately, in order to realize torque ripple reduction and power factor improvement through the switching scheme. In order to verify the proposed method, some computer simulations with MATLAB/Simulink have been done, and the phototype single-phase SRM drive system has been built up. The result is shown in this paper.

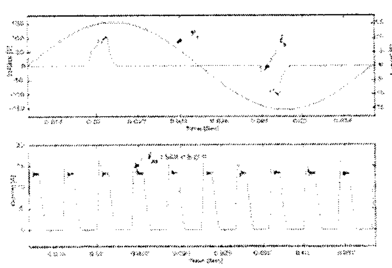
2. TORQUE RIPPLE REDUCTION DRIVE OF PFC SINGLE-PHASE SRM

2.1 Asymmetric converter of single-phase SRM

Fig. 1(a) shows a conventional asymmetric converter of single-phase SRM drive circuit. The drive circuit has a simple diode rectifier, a filter capacitor and asymmetric bridge converter. The rectifier and the filter capacitor supply the DC source. The filter capacitor reduces DC voltage ripple and stores the recovered energy from the motor.



(a)



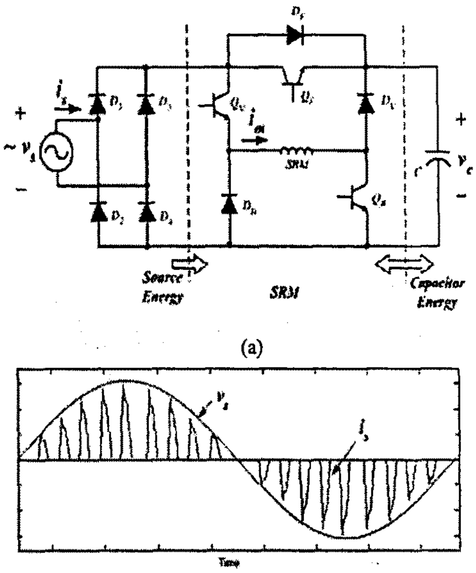
(b)

Fig. 1 Asymmetric drive circuit and waveform
(a) Asymmetric drive circuit
(b) AC voltage, AC current and Phase current of SRM

This structure is simple, but the capacitor charges and discharges the energy shown as Fig. 1(b), which illustrates a pulsating AC line current and results in the low power factor. At the same time, the reactive power makes the motor to be low efficiency in this drive circuit.

2.2 The proposed converter of single-phase SRM

Fig. 2 shows the proposed PFC SRM drive circuit, voltage and current waveform. The proposed PFC circuit is shown in Fig.2 (a). Different from asymmetric drive circuit, the capacitor appears at back-end of the proposed PFC circuit. The positive pulse output voltage of a full-wave bridge injects into SRM phase winding directly. On the other hand, the capacitor can supply input energy to phase winding, and store recovered energy from demagnetization state. Fig. 2 (b) shows the drive draws many smaller pulsating currents near sinusoidal variety, which replace a single big pulsating current from asymmetric drive. The magnitude of AC current has been reduced, so this proposed drive improve the crest factor (CF) and the power factor (PF) at the same time



(a)

(b)

Fig. 2 Proposed PFC circuit and waveform
(a) Proposed PFC circuit
(b) Voltage waveform and current

2.3 The operation mode of the proposed converter

To analyze operation of the proposed PFC drive, the modes are divided into four separated modes from different states of phase switch and discharge switch, i.e. discharging current excitation mode, input current excitation mode, energy feedback mode and source charging mode, respectively. The four modes are shown in Fig. 3.

Fig. 3(a) shows the discharging current excitation mode. In this mode, two phase switches (Q_{1U}, Q_{1D}) and discharge switch (Q_F) are turn on. The phase current i_1 flows C_f, Q_F, Q_{1U} and Q_{1D}. While this mode works on the exciting state, the higher voltage of discharge capacitor which is recovered during previous mode is applied to the phase winding for a faster build-up of flat-topped current. The phase voltage equation is obtained as (1):

$$v_c = R i_1 + L_{min} \frac{d i_1}{dt} = \frac{1}{C} \int i_1 dt \quad (1)$$

While this mode works on the torque produced state, stored energy of capacitor transforms to mechanical energy directly. The phase voltage equation is obtained as (2):

$$v_c = R i_1 + L(\theta) \frac{d i_1}{dt} + i_1 \frac{\partial L(\theta)}{\partial \theta} \omega = \frac{1}{C} \int i_1 dt \quad (2)$$

Fig. 3(b) is source current excitation mode. In this mode, two phases switches (Q_{1U}, Q_{1D}) are turn on, and source voltage flows to the phase winding. The phase voltage equation is changed to (3):

$$|v_s| = R i_2 + L_{min} \frac{d i_2}{dt} \quad (3)$$

In the torque produced case, source power can flow into motor directly, and transform into mechanical torque. It can contribute to improve power factor of proposed PFC drive. The phase voltage equation is given as (4):

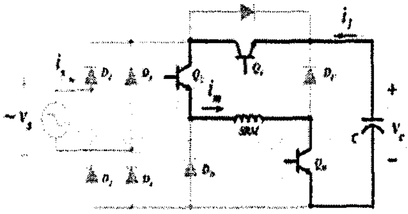
$$|v_s| = R i_2 + L(\theta) \frac{d i_2}{dt} + i_2 \frac{\partial L(\theta)}{\partial \theta} \omega \quad (4)$$

Fig. 3(c) is energy feedback mode. In this mode, the phase switch and discharge switch are turn-off. The phase current flows through two diodes, and reactive power recharges to the capacitor. The phase voltage equation is given by (5):

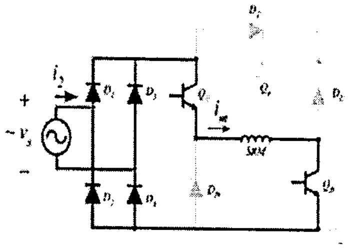
$$v_c = R i_3 + L(\theta) \frac{d i_3}{dt} + i_3 \frac{\partial L(\theta)}{\partial \theta} \omega \quad (5)$$

Fig. 3(d) is source charging mode. This mode is independent of switch states. While source voltage is greater than capacitor voltage, it will operate of itself. The capacitor voltage equation is (6):

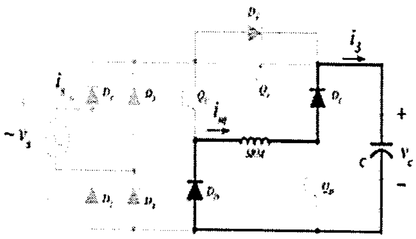
$$|v_s| = -V_c = -\frac{1}{C} \int i_1 dt \quad (6)$$



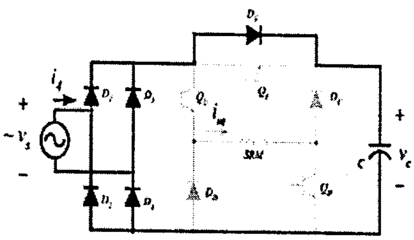
(a)



(b)



(c)



(d)

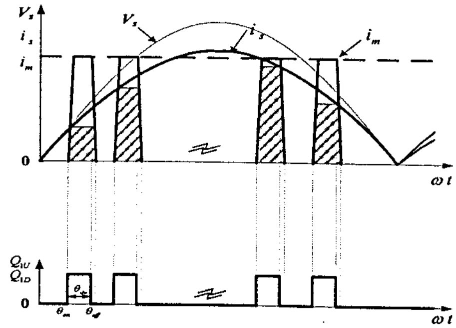
Fig. 3 Operation modes of the proposed PFC circuit
(a) Discharging current excitation mode
(b) Source current excitation mode
(c) Energy feedback mode
(d) Source charging mode

2.4 Switching topology for PFC and torque ripple reduction

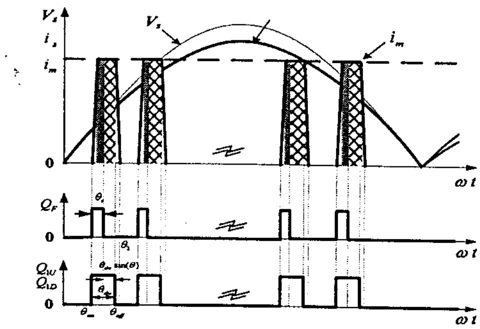
Fig. 4(a) shows a general PFC switching topology. The ideal phase current i_m is needed by single-phase SRM. As a result of sinusoidal voltage and fixed dwell angle, the phase current just can reach i_s . The power factor has great improved by using this method, but the bigger torque ripple is produced by this fluctuating current. It influences serious the single-phase SRM operating performance. In order to improve power factor and reduce the torque ripple together, the novel switching topology is proposed in the Fig.4 (b). The stored energy of capacitor compensates low source voltage, so the phase current could be close to i_m , and then the torque ripple can be reduced. When the area ⊠ of Fig. 4 (b) equates to the area ▨ of Fig. 4 (a), the power factor of the proposed switching topology will approach to general PFC switching topology. So the equation is given by(7):

$$\theta_x = \theta_{dw} \cdot \sin\theta \qquad (7)$$

where θ_x is the part of source input energy, θ_{dw} is current dwell angle and θ is source electrical degree.



(a)



(b)

Fig. 4 Switching topology for two control methods
(a) The general PFC switching topology
(b) The proposed switching topology

Furthermore, work region θ_F of discharging switch Q_F is given by(8):

$$\theta_F = \theta_{dw} \cdot (1 - \sin\theta) \qquad (8)$$

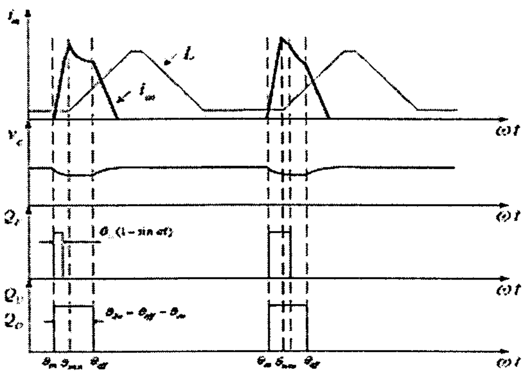


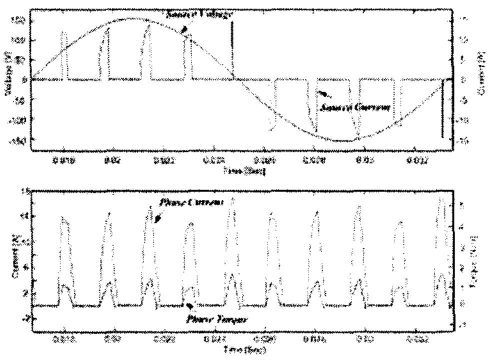
Fig. 5 Timing chart of gate signal, voltage and current of proposed converter

The stored energy of capacitor is discharging in this mode. From law of conservation of energy, all of the energy come from the source, so the current i_s^* which input from source side, must be bigger than current i_s . The proposed topology will output more power than general PFC switching topology at the same condition. The timing chart of gate signal, voltage and current for proposed converter is shown in Fig.5. The dwell angle of phase switches (Q_{1U}, Q_{1D}) are fixed by turn-on angle and turn-off angle. But the state of discharge switch Q_F is controlled by Eq.(8). So the stored energy of capacitor can be compensated the torque ripple which bring on pulsing voltage from AC source.

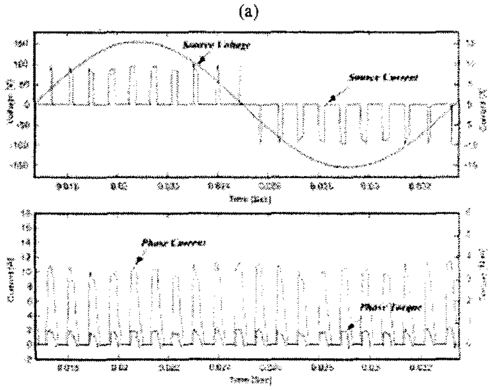
3. SIMULATION RESULTS

In order to verify the proposed PFC SRM drive has been simulated using MATLAB/SIMULINK. In the simulation, the 6/6 poles single-phase SRM is used. The rotor pole arc and the stator are 22 degrees. The maximum and minimum inductance is 5.31 and 1.055[mH], respectively. And the linear inductance profile is used in the simulation method. Otherwise, the voltage source parameter is single phase, 110V and 60Hz.

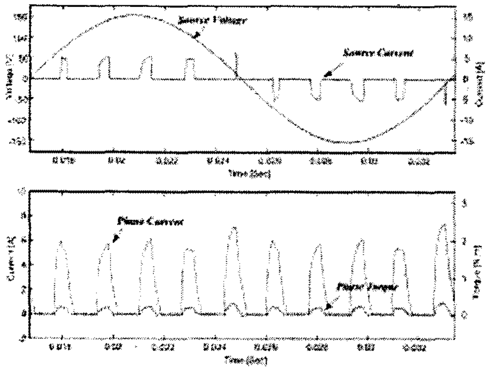
Fig. 6 shows simulation results of proposed PFC SRM drive. In the Fig. 6(a) and Fig.6(b), the same output power and same capacitor is used in the simulation. With the speed increasing, the phase current is more uniform than low speed condition. From the basic theory, the uniform phase current can easy to reduce the torque ripple. Compare with Fig. 6(a) and Fig. 6(c), the different load condition is considered in these two simulations. In a certain extent, with the load increase, the torque ripple will be reduced by the proposed converter. Fig. 6(a) and Fig.6(d) show that the size of capacitor is more larger, the torque ripple is more smaller.



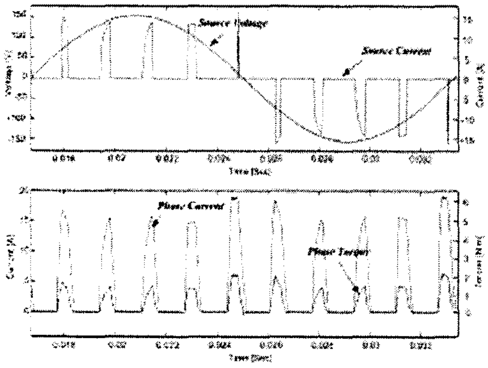
(a)



(b)



(c)



(d)

Fig. 6 Simulation result of the proposed PFC SRM drive

(a) 6000[rpm], 0.32[N.m], 470[μF]
(b) 12000[rpm], 0.16[N.m], 470[μF]
(c) 6000[rpm], no load, 470[μF]
(d) 6000[rpm], 0.32[N.m], 68[μF]

4. EXPERIMENTAL RESULTS OF PHOTOTYPE SRM

The Single-phase SRM drive system is shown in Fig.7. The experiment SRM drive system is a DSP-based control system. The control board based on the Texas Instrument TMS320F2812, and processor running at 150[MHz], and the sampling time of the program is 100[μs]. The experimental motor is 6/6 poles single-phase SRM. In order to testing the experimental result, the dynamometer, dynamometer controller and power analyzer were used.

Experimental waveform according to using switching topology for torque ripple reduction is shown in Fig.8. Result of general PFC switching topology is shown in Fig.8 (a). The pulsed AC current is close to sinusoidal current, but phase current of SRM is near to sinusoidal current, too. So disadvantage of switching topology is large torque ripple and low performance. From the Fig. 8 (b), the torque ripple reduction is obtained in proposed switching topology. Experimental waveform with 9000[rpm] is shown in Fig.9. The free load and fixed load experiment result is shown in Fig.9 (a) and Fig.9 (b), respectively.

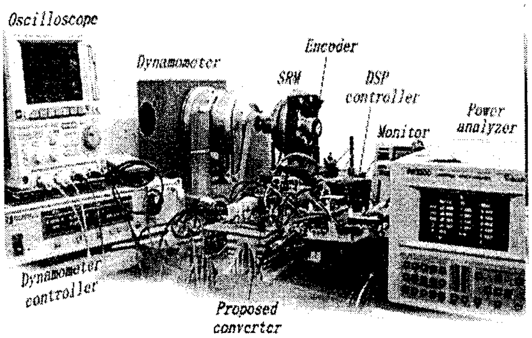
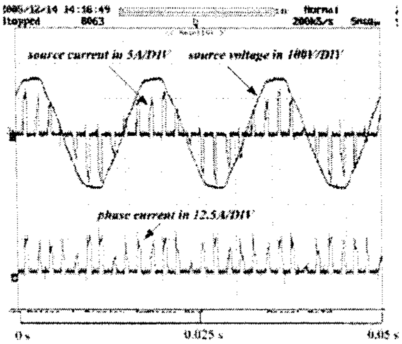
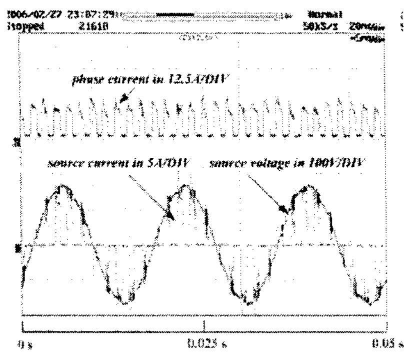


Fig. 7 Single-phase SRM drive system

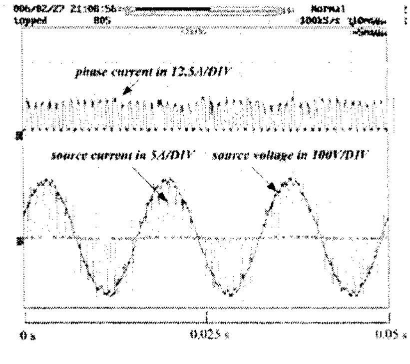


(a)

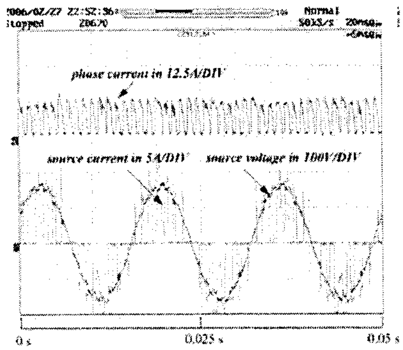


(b)

Fig. 8 Experimental waveform according to using switching topology for torque ripple reduction
(a) General one stage PFC circuit
(b) Proposed one stage PFC circuit



(a)



(b)

Fig. 9 Experimental waveform with 9000[rpm]
(a) free load (b) 0.21[N.m]

5. CONCLUSIONS

In this paper, a novel torque ripple reduction drive of single-phase SRM with PFC is presented. The operation principle has been discussed in detail. Also, a prototype to drive a 6/6-pole single-phase SRM has been built to verify the analysis and simulation results. The experimental results have been shown in previous section. As a result of the novel torque ripple reduction drive of single-phase SRM with PFC, not only the power factor has been improved, but also the torque ripple reduction has been achieved.

This work has been supported by KESRI(R-2005-B-109), which is funded by MOCIE(Ministry of commerce, industry and energy).

REFERENCE

[1] J. W. Ahn, B. C. Kim, "Drive Characteristic of Single-phase SRM for Fan Application." The Transactions of The Korean Institute of Power Electronics. Vol.8, No.5, pp. 450 - 454 , October 2003.
[2] Sung-Jun Park, Jae-Won Moon, Han-Woong Park, Jin-Woo Ahn, "Microcontroller Based Single-phase SRM Drive with High Power Factor." Proceedings of IEEE/ISIE 2002. Vol.3, pp:701 - 705 May 2002.
[3] Geun-Hie Rim, Won-Ho Kim, Eun-Soo Kim, Ki-Chul Lee,"A Choppingless Converter for Switched Reluctance Motor with Unity Power Factor and Sinusoidal Input Current." Proceedings of IEEE/PESC'94. vol.1 Page(s): 500 - 507, June. 1994
[4] Caruso L, Consoli A, Scarcella G, Testa A, "A Switched Reluctance Motor Drive Operating at Unity Power Factor." Proceedings of IEEE/IAS'96. Vol.1, Page(s):410 - 417 Oct. 1996
[5] Young Ahn Kwon, Kyoo Jae Shin, Guen Hie Rim, "SRM Drive System with Improved Power Factor." Proceedings of IECON'97, Page(s):541 - 545 vol.2. Nov. 1997
[6] Barnes, M.; Pollock, C.; "Power Factor Correction in Switched Reluctance Motor Drives." Proceedings of IEE/PEVSD'98, Page(s):17 – 21, Sept. 1.