Unity Power Factor Control of SRM Drive

Sung-Jun Park, Dong-Hee Lee, Jin-Woo Ahn and Cheul-U Kim

Abstract - This paper suggests a novel single-stage drive for a switched reluctance motor (SRM) to achieve sinusoidal, near unity power factor input currents. The proposed drive is very simple without additional active switch. As a single-stage approach, which combines a DC link capacitor used as dc source and a drive used for driving the motor into one power stage, a simple structure and low cost drive is implemented. A prototype drive for an 8/6 pole SRM equipping a suitable encoder is designed to evaluate the proposed topology. Also subscription control algorithm is presented. The characteristics and validity of the proposed circuit will be discussed in depth through the experimental results.

Keywords - SRM (Switched Reluctance Motor), Unity Power Factor

1. Introduction

In recent years, a number of home appliance and low power electrical drives equipped with DC or universal AC motors are being redesigned in order to comply with new standards on electric power quality that heavily limit line current harmonics and distortions.

The switched reluctance motor (SRM) is a simple, low-cost, and robust structure suitable for variable-speed as well as servo-type applications. With relatively simple converter and control requirements, the SRM is gaining increasing attention in the drive industry. The conventional SRM drive usually includes a simple diode rectifier with a filter capacitor. Although this structure is simple, it draws a pulsating ac line current, resulting in a low power factor and high harmonic line current. With the increasing demand for better power quality, this approach is no longer suitable for high performance SRM drives. The best way to obtain a high power factor is the use of a power factor correction circuit with SRM drive [1].

In order to achieve sinusoidal input currents and to improve the low power factor in SRM drive system, several approaches are introduced [2]-[5]. The proposed approach in reference [2] consists of the cascaded power stages of a boost and a buck eliminating PWM control in the machine-side converter while delivering sinusoidal ac input current. This converter topology has high power factor and improved input current waveform. However, this approach is not a suitable choice in practical applications, because of complexity and high cost due to the cascaded power stages.

The SRM driver employing a half-wave ZCS quasi-resonant boost converter [3] obtained better performances and higher power densities using high quality rectifier with capacitive energy storage. Line current pollution generated by electric drives, was reduced by addition of both passive input filters and active input current shapers. However, adding an active switch has disadvantages since it increases drive cost and switching loss.

An SRM drive system using SPC-PFC was investigated in reference [4], this approach is sufficient to improve the power factor and to reduce the harmonics. However, due to the two power stages, double energy conversion is needed; therefore, overall efficiency may be decreased. And also, a complexity and a cost problem are still not solved.

To solve the complexity problem with a high power factor, a simple SRM drive converter in which PWM switches can be used to draw near sinusoidal current is proposed in reference [5]. The used power electronics componens used are kept low, but control complexity is increased. Since the operation of phase is not completely independent, at least two phases are required. Most of all, this method of improving the power factor of the SRM drive is suitable only for a limited range of output power.

In this paper, a novel single-stage power factor corrected SRM drive system is presented to achieve a unity power factor and to improve the input current waveforms. The proposed SRM drive is simple compared with the conventional approaches employing a power factor correction circuitry. The switches for SRM drive are also used for power factor correction. Therefore, near unity power factor can be achieved without any additional active switches; moreover, there is no additional switching losses. From the experimental results, the validity and the performance of the proposed single-stage PFC SRM drive system is verified.

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2. Operational Principles of SRM & Proposed PFC Drive

2.1 Operational Principle of SRM

In the SRM drive, the reluctance of the flux path between two diagonally opposite stator poles varies depending on the relative positions of rotor poles. Because inductance is inversely proportional to reluctance, when the rotor is in the aligned position, the inductance of the phase is maximized, and it is minimized in the unaligned position [6]-[9].

Due to the double salient structure, the stator and rotor poles tend to align together while offering minimum reluctance path to the main flux due to the excitation of stator phase. Thus, a unidirectional torque can be generated by sequential exciting of the stator phases, and it can be written as the following.

$$T = \frac{1}{2} i^2 \frac{\partial L(\theta, i)}{\partial \theta} \tag{1}$$

Inductance period of the SRM is determined by the combination of rotor and stator pole pair, and its mechanical angle can be expressed as;

$$\theta_T = 2\pi / P_r \tag{2}$$

where, P_r: the pole number of rotor

At this time, a mechanical phase angle between phases, θ_p is given as.

$$\theta_P = 2\pi / qP_r \tag{3}$$

where, q : the pole pair of rotor

After the pole number of rotor and stator of the SRM is determined and then it can be worked by forming sequential phase current using the mechanical phase angle satisfying (3). In this case, if a phase current waveform is equal to that of a rectangular form, ignoring magnetic saturation of inductance, a total torque will be flat-topped. The approach mentioned above, forming a flat-topped current in order to control the SRM, is the most general method. When the SRM is driving with sequential flat-topped currents, the voltage equation is written by:

$$V = Ri + \frac{dL(\theta, i)i}{dt} \tag{4}$$

Since the inductance of phase winding is expressed as a function of the position angle of the rotor according to the rotor position, it is difficult to describe using a single function in (4). Therefore, in the phase current analysis using inductance profile of the SRM, modes separation method may be useful.

First, in excitation mode the flat-topped current is settled via supplying the dc source voltage at the phase during an unaligned period that has no overlap between a rotor and a stator pole. At this period, a voltage equation per a phase is expressed as the following.

$$V = Ri + L_u \frac{di}{dt} \tag{5}$$

where, L_u: the minimum inductance

According to time constant of the circuit, switching currents are steeply increased. If the winding resistance is neglected, their amplitude depends on the minimum inductance value and the excited voltage. In the SRM drives, a method that increases the rate of output power is to set during minimum inductance periods. However, this is not sufficient to settle the flat-topped current in the case of conventional SRM drives; therefore, higher voltage is essential to minimize the settling time.

Second, in a driving mode that a rotor and a stator are overlapped, flux is increased and electric magnetic forces are much influenced. At this time, the circuit equation is written as the following.

$$V = Ri + L(\theta)\frac{di}{dt} + i\frac{dL(\theta)}{d\theta}\omega \tag{6}$$

where, $\omega = \frac{d\theta}{dt}$: rotor angular speed [rad/s]

This equation can be rewritten as;

$$V - E_S - Ri = L(\theta)\frac{di}{dt} \tag{7}$$

where, $E_S \equiv i\frac{dL(\theta)}{d\theta}\omega$

Now, if a supply voltage (V_i), speed emf (E_S), and voltage drop due to resistances are equally calibrated, the value of left term in (7) becomes zero and then di/dt also be zero. As a result, a flat-topped current is obtained. However, in the condition mentioned above, even if the advance switching angle is fixed, the settling current value is changed by the amplitude of the supplied voltage.

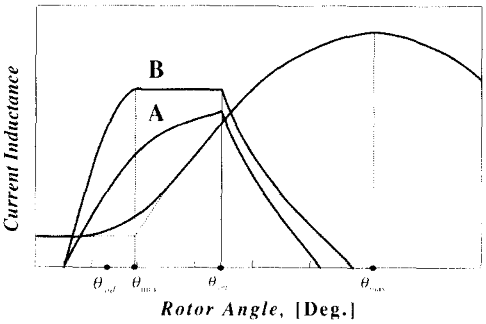


Fig. 1 Phase current waveforms with on-switching angles

θ_{min} and θ_{max} in Fig. 1 show the rotor angles, when each pole of a rotor and a stator is starting to overlap and is completely overlapped, respectively.

Fig. 1 shows the phase current waveforms when the excited voltage is controlled for settling flat-topped current under fixing on/off angles of the switch. The waveform A in Fig. 1 shows the amplitude of current in an intermediate region of inductance that the supplied voltage is higher than that of back-emf generated from the rotation speed angle. This appears when the current is insufficiently settled in a minimum inductance region. Because the variation rate of current is positive during a torque generation region, the phase current has a large amount of torque ripple due to the inconstant torque generation. When the higher excited voltage is applied in order to settle the current as the waveform B in Fig. 1, the phase current is constant at the torque generation period. In this case, once the rate of inductance variation is constant, a flat-topped torque is generated with reduced torque ripples; therefore, it can be a reference current for an effective motor driving.

At a demagnetizing mode, a magnetic energy in a magnetic circuit is transferred to the source; therefore, the current is decreased. Of course, the phase switch is in off condition. If this mode is implemented on the overlap period between a rotor and stator angle, dL(θ)/dθ and speed emf, Es becomes positive. The circuit equation can be written as;

$$-V - E_S - Ri = L(\theta)\frac{di}{dt} \tag{8}$$

In the phase winding at this demagnetizing mode, the current is dynamically decreased because of the high reverse voltage that is the sum of a reverse voltage and its speed emf. As a result, the accumulated magnetic energy in phase windings is recovered to the source.

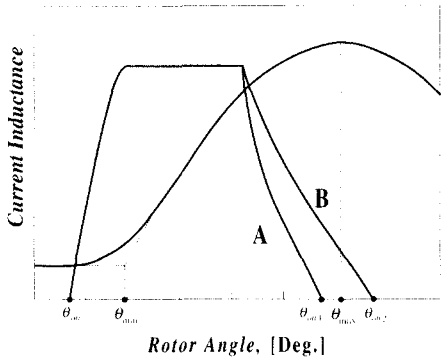
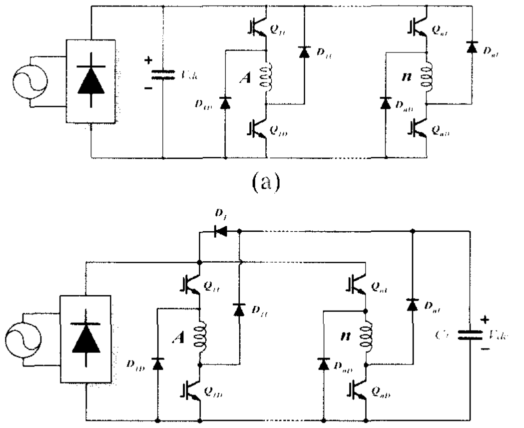


Fig. 2 Phase current waveforms with off switching angles

Fig. 2 shows the phase current waveforms when a demagnetizing voltage of the switch is changed under the fixed condition of switch on/off angles. When a high demagnetizing voltage is supplied, there is no negative torque as the waveform A, but in case of waveform B because of a tailing current, the negative torque is generated. In the turn-on and/or turn-off angle controls of the SRM, it is essential that the switching angles must be carefully scheduled and controlled to obtain the desired speed and torque.

In particular, the phase current should be controlled and not existe beyond θ_{max}, because it generates the negative torque and is the origin of the reduction of the mechanical output power and torque pulsation. As a result, For an effective utility of the reluctance torque, a higher voltage is necessary.

2.2 Proposed Single-Stage PFC Drive for SRM



(a)

(b)

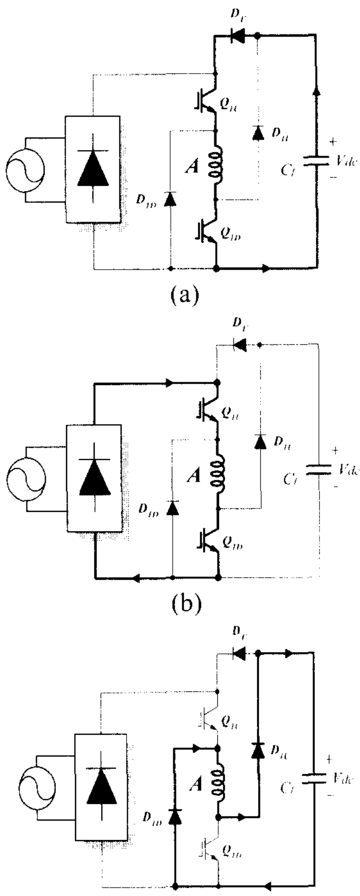
Fig. 3 Conventional and proposed PFC drives
(a) conventional drive (b) proposed PFC drive

In the SRM drive, DC source is essential. In general, SRM drive includes a simple diode rectifier with a filter capacitor in order to obtain dc source voltages. Although this structure is simple, it draws a pulsating ac line current, resulting in a low power factor and high harmonic line current. With the increasing demand for better power quality, this approach is no longer suitable for a high performance SRM drive. In the viewpoint of energy saving, to improve the power factor and to sustain the input current sinusoidally is very important. To solve the problems, power factor correction circuitry is often added in front of the conventional driver. However, this two-stage approach has several disadvantages such as complexity of circuit composition, additional control loop, and high cost, etc. An important factor in the selection of a driver for the SRM may be the cost. Therefore, a single-stage power factor corrected drive is suitable for a practical SRM drive.

Fig. 3 shows the classic converter and the proposed PFC drive for the SRM drive.[10] Fig. 3(a) illustrates the conventional drive. Generally, this is equipped with a bulk capacitor in the end of a diode rectifier. It can reduce the voltage ripple and store the recovered energy; however, it draws a pulsating ac line current, resulting in a low power factor and high harmonic line current. Fig. 3(b) shows the proposed single-stage PFC drive. The most remarkable characteristic of the proposed drive, there is no bulk capacitor in the end of the diode rectifier. Due to this fact, it can control the input current covering all ranges of the input power. To recover and store the energy, when the phase switch is turned off, capacitor C_f is necessary. And it works separately with the input part.

2.1.1 Operational Modes

To simplify the operation analysis of the proposed drive, the modes are devided into three i.e, discharging, input, and charging modes, respectively.



(a)

(b)

(c)

Fig. 4 Operational modes (a) Mode 1: Discharging mode (b) Mode 2: Input mode (c) Mode 3: Charging Mode

With turning on the phase switch, discharging mode starts. At this time, a higher voltage that is recoverd and stored at mode 3, is applied to a phase winding for a faster settling a flat-topped current. The phase current flows through C_F, D_F, Q_{IU} and Q_{ID}. Input mode starts when an absolute value of the recovered capacitor voltage is equal to that of input voltage. From this mode, input power is transfered to the motor. The phase current flows through rectifier diodes, Q_{IU} and Q_{ID}. Charging mode begins when the phase switch is turned off. In this mode, a reactive power of the phase winding is recovered through freewheeling diode, D_{ID} and D_{IU}.

2.1.2 Encoder for Position Sensing

Fig. 5 shows an encoder to control phase switches in 8/6 poles SRM drive. In this case, a period of encoder (θ_T) is 60°, and a displacement of photo interrupter (θ_p) to turn on/off each phase switch is 15° in mechanical degree from (2) and (3), respectively.

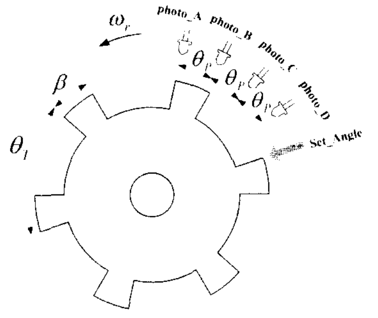


Fig. 5 Configuration of encoder for driving 8/6 poles SRM

An on angle displacement of phase switch (β) is determined by the experiment considering pole arc of a rotor and a stator of the SRM and magnetic saturation of inductance. In this experiment, it is 18° in mechanical angle; therefore, phase switches of the SRM can be controlled by each signal of photo interrupter. If phase switches are controlled by the signals of encoder in the Fig. 5, the on/off of switch is fixed; hence a current level controller is necessary in order to control the speed of the SRM. However, it increases the switching frequency. To solve the problem, switching time subscription method is used to speed control by switching angle control of encoder in the SRM.

2.1.3 Subscription Control Method

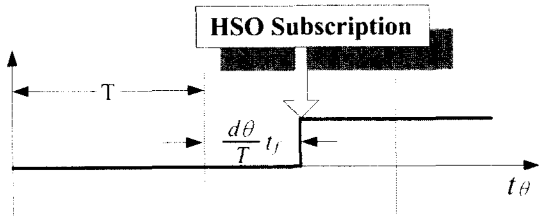


Fig. 6 A concept of switching time subscription

Fig. 6 illustrates a concept of the switching time subscription method. In phase switching angle control, sampling influence is unavoidable because it compares with each sampling time of microprocessor. In order to overcome this, the following solutuons are presented. If we assume that there is no variation of speed during the displacement of phase angle, speed term in (9) becomes a constant.

$$d\theta = \omega_r T \tag{9}$$

Based on (9), position information of the next sampling time can be obtained to the overall ranges as the following.

$$\theta_f = \theta_b + \frac{d\theta}{T} t_f \tag{10}$$

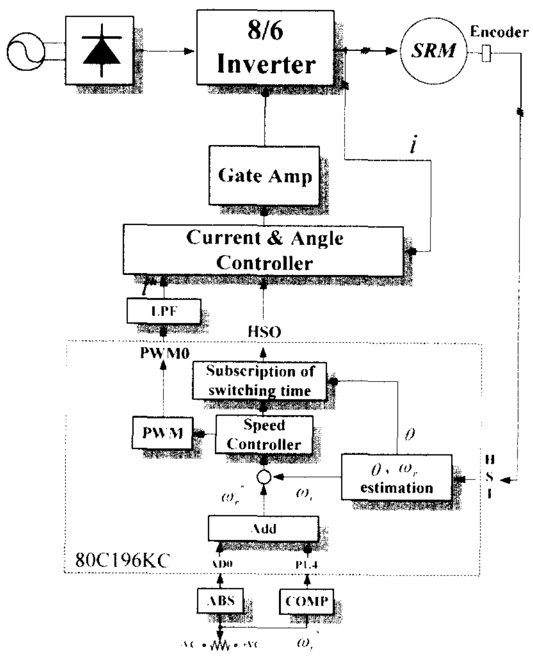


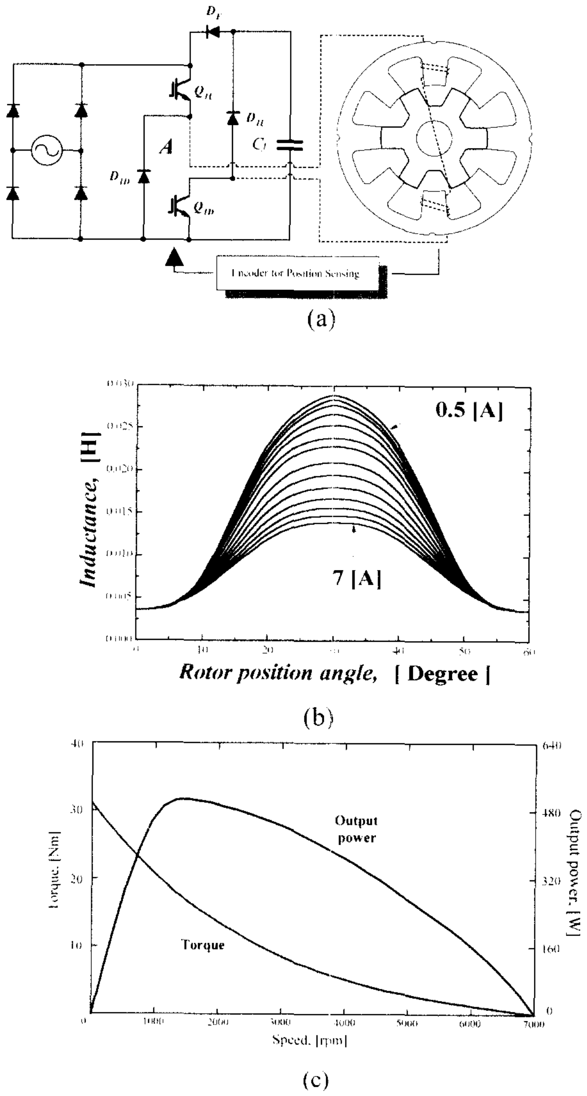
Fig. 7 Block diagram of the controller

With the position information, switching time is reserved to turn on/off phase switch at the preset position during the next sampling time. In this paper, this is done by HSO function of the 80c196kc. When (10) is satisfied, the subscription time is reserved to the HSO, and then to control phase switch on or off, setting the command resister of the HSO is needed.

Fig. 7 shows the block diagram of the controller to control of phase switch. The controller is used the microprocessor, 80c196kc. For starting, the phase signal of the encoder from the speed controller is the output of the HSO. At this time, in order to have a soft-start function the PWM part generates the PWM signal up to the amplitude of current limitation using a linear function. The command value of speed obtains 11bits information from an external variable resister due to a combination of AD and IO port of the output from an absolute circuit and comparator. The actual speed is obtained by CAM value recording the phase signal of encoder that is linked to the HSI. The speed controller controls the on angle displacement due to the difference between command value and actual one.

3. Experimental Results

The motor used in this experiment is 8/6 poles, 400 [W], 200 [V] SRM. A configuration of control block diagram is shown in Fig. 8(a). The inductance profile used for the implementation is as shown in Fig. 8(b). This is calculated by voltage and current data considering the winding resistance after measuring the current waveform by oscilloscope by adding the voltage pulse until the current approaches to the limit value 7 [A] changing the rotor by 1° in mechanical degree. Therefore, the inductance profile is a relatively accurate value that can indicate the dynamic driving characteristic of the SRM. Fig. 8(c) shows torque and output power vs. speed characteristics of an 8/6 SRM.



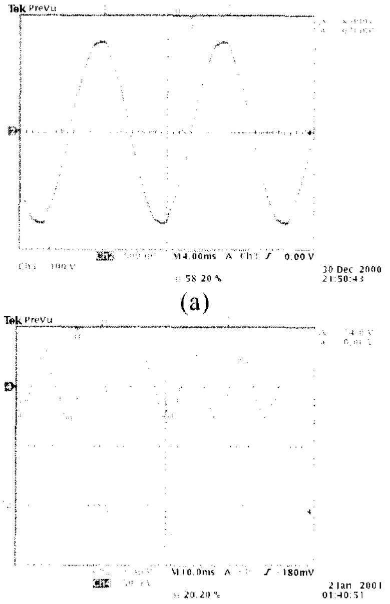
(a)

(b)

(c)

Fig. 8 Configuration and characteristic of the SRM (a) SR drive system (b) inductance (c)torque and output power vs. speed characteristics

Fig. 9(a) shows the experimental waveform of input voltage and current of the classical SRM drive. Although the structure is simple, it draws a pulsating ac line current, resulting in a low power factor and high harmonic line current. Fig. 9(b) shows the experimental waveform of input voltage and current of the proposed drive. The switches for SRM driving are also used for power factor correction. As a result, near unity power factor can be achieved without any additional active switches; moreover, there exists no additional switching losses. From the experimental results, the validity and the performance of the proposed single-stage PFC SRM drive system is verified.



(a)

(b)

Fig. 9 Experimental waveforms of input voltage and current (upper trace:input voltage, lower trace: current) (a) conventional drive (b) proposed PFC drive

4. Conclusion

In this paper, a single-stage power factor corrected drive for a switched reluctance motor is presented. The proposed drive has no additional active switch. Thanks to the single-stage approach, this drive has a simple structure and low cost. A prototype to drive an 8/6 pole SRM equipping a suitable encoder is used to evaluate the proposed topology. As a results, sinusoidal input currents and improved power factor are obtained by the proposed PFC drive. With the increasing demand for better power quality, this approach is suitable for high performance SRM drive.

Acknowledgments

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