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Novel Topologies Implementation for SRM Drive with Conventional Type Structure

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Abstract

This paper presents novel topologies implementation for Switched Reluctance Motor (SRM) drive used in commercial applications. For effective utilization of the developed system, a novel direct current controlled PWM scheme is designed and implemented to produce the desired dynamic speed characteristic. In comparison to conventional asymmetric converter topology, it can minimize entire system costs by reducing numbers of power semiconductors. Therefore, it may open up investigation of a new way for SRM to compete with other ac motors such as induction motors, brushless dc motors, etc. The validity of the proposed method is verified through theoretical explanation and experimental results.

Key Words : SRM, Asymmetric bridge converter, Six-switch converter, Four-switch converter

1. Introduction

Due to its advantages over other ac motors in terms of simple structure, robust performance, and simple control, the switched reluctance motor (SRM) has been considered in industry applications such as electric vehicles and home appliance systems. However, SRM has also suffered from high torque ripple and acoustic noise problems that cause SRM to be limited in commercial markets. Until now, in order to resolve the problems of SRM, much research has been carried out with respect to motor structure and control algorithm [1-5].

In general, due to the inherent torque generating mechanism in SRM, unipolar current pulses are applied to each phase to generate electromagnetic torque during positive slope of inductance profile. It results in independent control of each phase and causes asymmetric converter topology to be used which consists of two semiconductor switches and two external diodes for each phase. As a result of that, six discrete IGBT switches and six discrete diodes are required to drive three-phase SRM, so that the converter topology becomes greatly complicated and bulky.

For other ac motor drives such as induction motors, synchronous motors, and brushless dc motors, the converter can be realized by using a compact six-switch IGBT intelligent power module (IPM). However, only SRM needs a unique converter topology, which prohibits unification of

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power conversion systems. Consequently, even though the amount of iron and copper can be reduced in motor fabrication, the amount of silicon increases so that it is difficult to claim that SRM drives have advantage over the other ac motor drives with respect to the entire system cost and efficiency.

However, currently the SRM is attracting much interest due to its high torque density, robust performance, simple control, and lower maintenance. Thus, we have been investigating the possibility of novel topologies implementation for effective SRM drive with advanced control techniques.

In reference [6], the authors tried to use a six-switch converter by changing the stator and rotor shapes to get a proper inductance profile for bipolar switching scheme. However, in this study, it is difficult to ensure the advanced control angles from the modified motor structure.

In this paper, based on the conventional type of SRM structure, control schemes on novel topologies are presented in order to pave a new way for SRM drives to be applied to various industry applications.

2. BASIC Principles of SRM drives

2.1 Asymmetric bridge converter

Fig. 1 shows the conventional power circuit which is called an asymmetric bridge converter. An asymmetric bridge converter consists of two power switches and two freewheeling diodes per phase. The characteristics of this converter are 1) high efficiency, 2) various controls, and 3) two-phase current overlap due to independent control of each phase. Also, even if breakdown happens to one phase, it does not influence other phases. The rated voltage of the element is relatively low, and control performance is known as the most superior factor. However, the main disadvantage of this topology is that the use of a number of switches are required in each phase. Also, for low voltage applications, the forward voltage drops in two devices may be significant compared to the available dc bus voltage. In addition, the control and driver circuit become complicated due to the split configuration of each device [3].

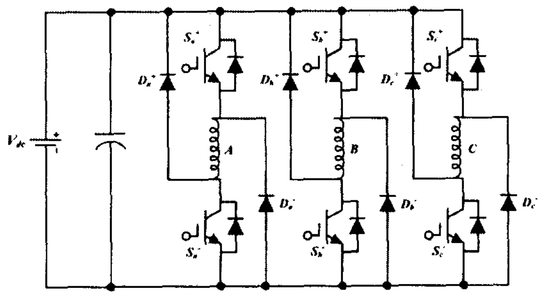


Fig. 1. Conventional asymmetric converter topology for SRM drive

Excitation of a phase produces an electro-magnetic torque which causes the rotor to align its poles with those excited on the stator. The equation for the torque is given by Eq. (1)

$$T = \frac{1}{2} i^2 \frac{dL}{d\theta} \tag{1}$$

Where i, L and θ are phase current, phase inductance, and rotor position angle, respectively.

We know that torque can generate independently from phase current's direction. The direction of the torque is controlled by varying the placement of the current pulses with respect to rotor position. This paper represents attempts to drive SRM by profiling the phase inductance as shown in Fig. 2.

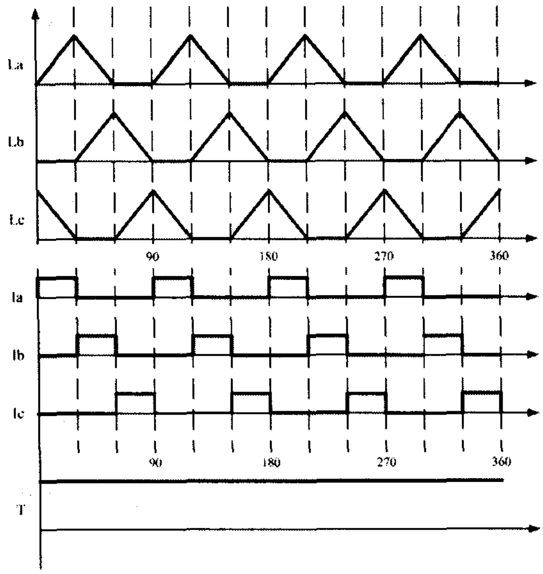


Fig. 2. Conventional inductance profile and current excitation scheme

2.2 Proposed six-switch SRM drives

The phase independence and unipolar current requirement have generated a wide variety of converter topologies for SRM drives. Converter topology is also closely related to the motor winding connections and numbers of phases. Fig. 3 shows the proposed converter circuit by using a six-switch IGBT module with Y-connected SRM. Compared with the asymmetric bridge converter, the proposed circuit reduces all additional freewheeling diodes. We found that torque production of the proposed converter circuit is the same as that of the asymmetric bridge converter as shown in Fig. 5. It results in the possibility of the six-switch configuration instead of the asymmetric bridge converter for SRM drives. As a result of that, proposed six-switch SRM drives can minimize the entire system size by reducing numbers of components.

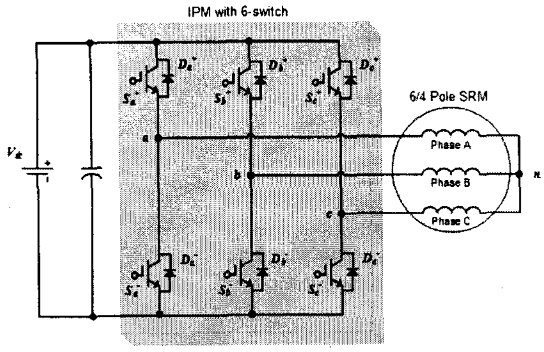
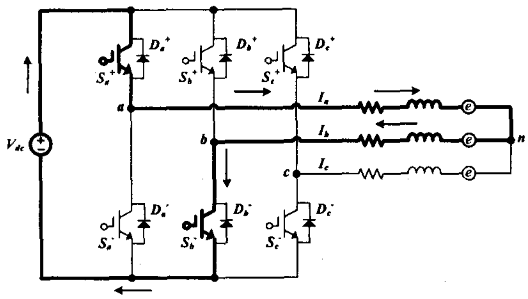


Fig. 3. Proposed six-switch IGBT module for SRM drive

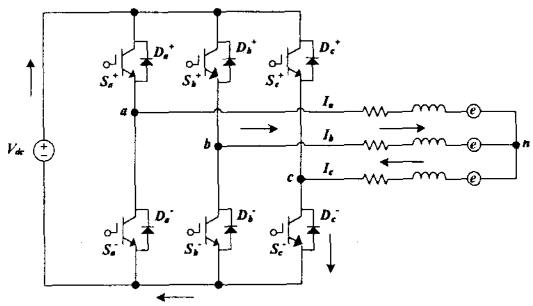
The entire operational modes of the proposed converter can be divided into three modes which are depicted in Fig. 4. In Fig. 4(a), S_a^+ and S_b^- are turned on and phase A and phase B are connected through DC-link voltage. In this proposed converter circuit, because the center node is not connected outside the motor, current flowing into one phase must flow out of the other phase.

In mode 2, S_b^+ and S_c^- are turned on and the current is flowing through phase B and phase C. In the same way, in mode 3, the current is flowing through phase C to phase A by turning on S_c^+ and S_a^-. Compared with the phase independence and one-phase excitation of the asymmetric bridge converter, it is noted that the two-phase excitation method for the SRM drive is applied to the proposed six-switch converter from the modes 1, 2, and 3. It makes possible the utilization of a conventional ac converter to drive the SRM which makes it easy to apply to commercial applications.

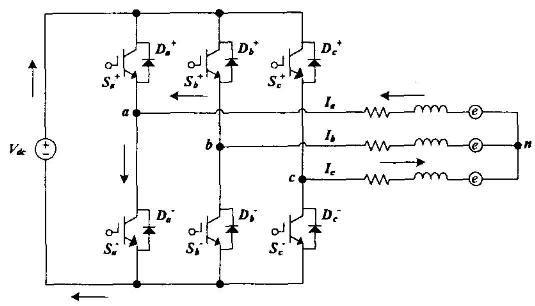
According to the operational modes, the three-phase current can be described in Fig. 5 with the inductance profile. As shown in Fig. 5, it is noted that the negative current is applied during the flat period of the inductance profile, which can make bipolar switching possible. Also, the negative current that causes the iron loss of the motor cannot contribute to the torque generation, so that the proposed six-switch converter can be considered for cost effective SRM drives.



(a) Mode 1



(b) Mode 2



(c) Mode 3

Fig. 4. Operational modes of the proposed six-switch SRM converter

1) Mode 1-1($t_o \sim t_1$)

In Fig. 6(a), the switches S_a^+ and S_b^- are turned on simultaneously, and phase A and phase B are connected through dc-link voltage. In this mode, I_a and I_b currents ($I_a > 0$, $I_b < 0$) flow and I_c is zero. Until I_a (I_b) reaches the upper (lower) limit, S_a^+ and S_b^- are turned on for supplying dc-link energy to increase the current. Let us consider the motor equations for the on interval with S_a^+ and S_b^-, the voltage equation during this stage is

$$\frac{V_{dc}}{2} = Ri + L(\theta)\frac{di}{dt} + e_L \tag{2}$$

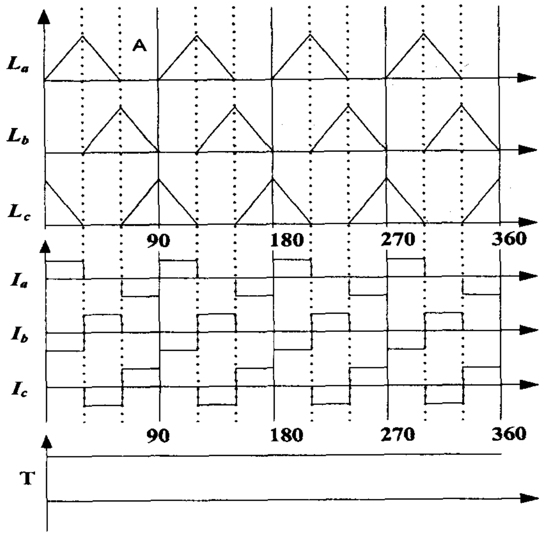


Fig. 5. Proposed bipolar current control scheme of the six-switch converter

2) Mode 1-2 ($t_1 \sim t_2$)

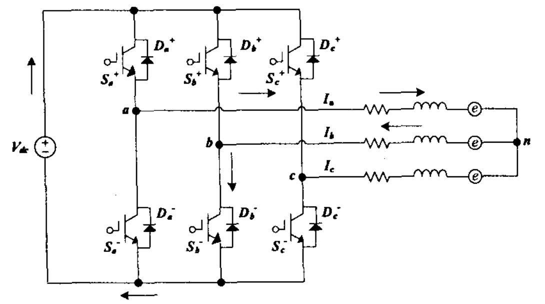
The phase current freewheels through S_b^- and D_a^- when S_a^+ is "off" as shown in Fig. 6(b). The voltage equation is the same as in Eq. (2) in which the voltage equation results in zero.

$$0 = Ri + L(\theta)\frac{di}{dt} - e_L \tag{3}$$

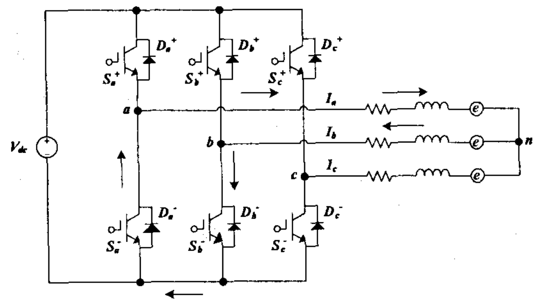
3) Mode 1-3 ($t_3 \sim t_4$)

When the current reaches the upper limit, S_a^+ and S_b^- are turned off to decrease the current through the anti-parallel diodes D_a^- and D_b^+. At that time, the reverse bias (negative dc-link voltage) is applied to the phases, resulting in decreasing the current. The voltage equation during this stage is

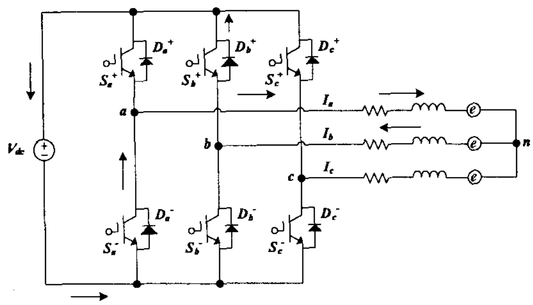
$$-\frac{V_{dc}}{2} = Ri + L(\theta)\frac{di}{dt} - e_L \quad (4)$$



(a) Mode 1-1



(b) Mode 1-2



(c) Mode 1-3

Fig. 6. Detailed switching operation on Mode 1 of Fig. 4

The detailed waveforms and switching sequences of mode 1-1, 1-2, and 1-3 as shown in Fig 6 and are described in Fig. 7. The switching frequency and torque ripple are the main considerations for setting the upper and lower limits. It means that a smaller band causes higher switching frequency, but lower torque ripple [5].

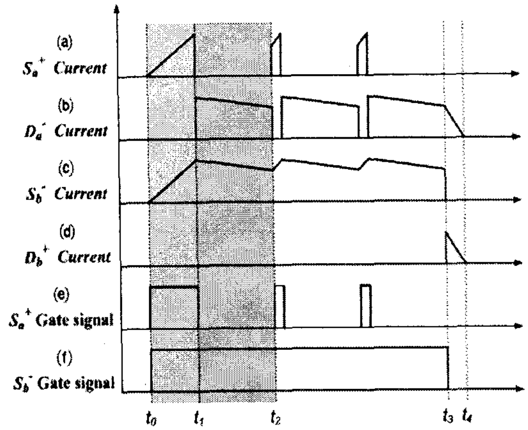


Fig. 7. Detailed current and switching waveform of Fig. 6 according to the operation modes

3. Experimental Results

In order to verify the proposed six-switch SRM drives using bipolar switching sequence, an experimental test-bed is developed with 250[W], three-phase 6/4 SRM. The detailed parameters of SRM are summarized in Table 1. Also a permanent magnet dc machine, rated 250[W], 12[V], 3000[rpm], is used as a constant torque load. The load is changed by varying the value of the resistor R_{load}.

A schematic diagram of the proposed drive system of SRM, which corresponds to the experimental system is designed, developed and presented in Fig. 8. In this system, position signal is provided from an incremental encoder and is calculated into the real speed. It produces commutation positions and executes speed control and current control.

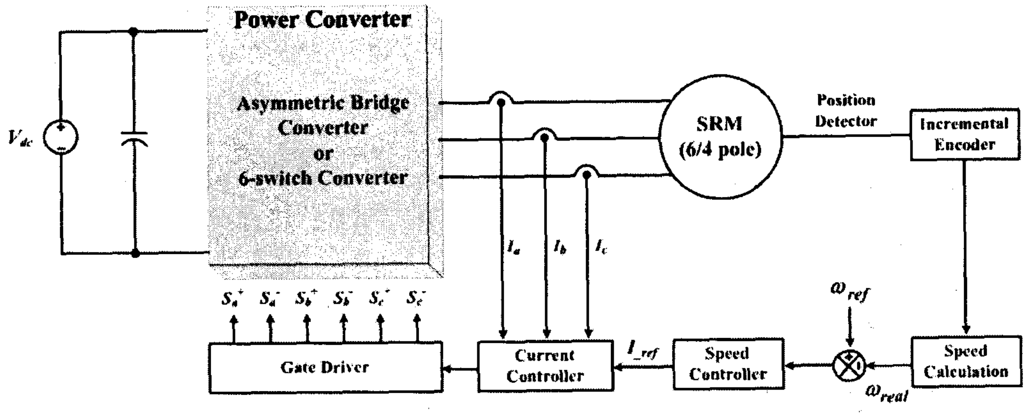


Fig. 8. Block diagram of experimental system

Table 1. Specification of SRM

Rated power	250[W]
Number of stator poles	6
Number of rotor poles	4
Aligned phase inductance	1.332[mH]
Unaligned phase inductance	0.241[mH]
Phase resistance	0.02166[Ω]
Rated speed	3,000[rpm]

3.1 Asymmetric bridge converter

First of all, the asymmetric bridge converter was built and tested.

Fig. 9 shows the experimental phase current waveforms, using hysteresis current control with 12V dc-link voltage at 1,000[rpm]. The current command is set at desired value and the actual current is compared with the command value and determines which switches should be turned on or off. Fig. 10 depicted the motor speed control when the speed command is changed from 1,000[rpm] to 2,000[rpm].

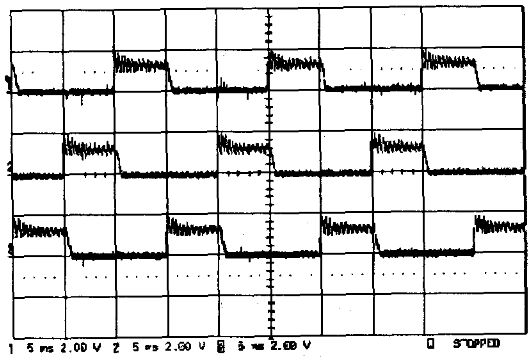


Fig. 9. Phase current waveforms when speed command is 1000[rpm](10[A/div.], 5[ms/div.])

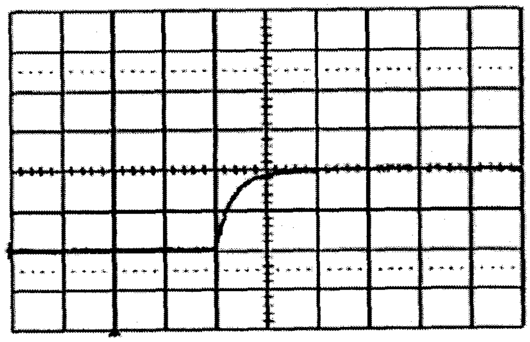


Fig. 10. Speed response characteristic in case of 1000 → 2000[rpm](500[rpm/div.], 0.2[ms/div.])

3.2 Proposed six-switch converter

Fig. 11 shows the phase current waveforms at 1,000[rpm] and from the result of this, it is certified that the phase currents are successfully controlled. At this point, it is noted that the proposed six-switch converter has the negative current which is produced during the flat period of the inductance profile. Consequently, the negative current that causes the iron loss of the motor cannot contribute to the torque generation, also bipolar switching of the proposed six-switch scheme can be possible at the SRM drive compared to that of the asymmetric bridge converter.

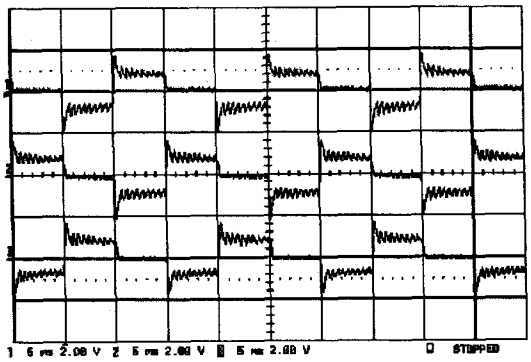


Fig. 11. Phase current waveforms when speed command is 1000[rpm](from top to bottom: I_a, I_b, I_c , 10[A/div.], 5[ms/div.])

The overall operating modes of the six-switch SRM drive use half dc-link voltage ($1/2V_{dc}$) because of two phases excitation as shown Eq. (2)~(4). According to the voltage utilization, voltage utilization distinguishes the six-switch converter from the asymmetric bridge converter in terms of current dynamics, slow di/dt, and speed limitation: Because of the two phases excitation, the motor phases are energized by half value of the full dc-link voltage, so that it produces the slower di/dt. The other effect of half dc-link voltage utilization is speed limitation. In the case of the asymmetric bridge converter, the full dc voltage (V_{dc}) excites all motor phases. However, in the case of the proposed six-switch converter, mainly only half dc voltage is utilized through all operations. This voltage utilization makes the six-switch SRM drive to have speed limitation. The above mentioned two problems such as slow di/dt and speed limitation are the inherent characteristics and main drawbacks of the proposed six-switch configuration. However, those problems can be overcome in conjunction with voltage-doublers and another proposed 4-switch for SRM drive as explained later--the four-switch converter for three-phase SRM drives.

To demonstrate the speed dynamic response using the six-switch control algorithm, the speed response characteristics are presented in Fig. 12 with the step change of reference speed from 1,000[rpm] to 2,000[rpm]. From the experimental results, it can be verified that the proposed six-switch converter with bipolar switching can drive SRM successfully.

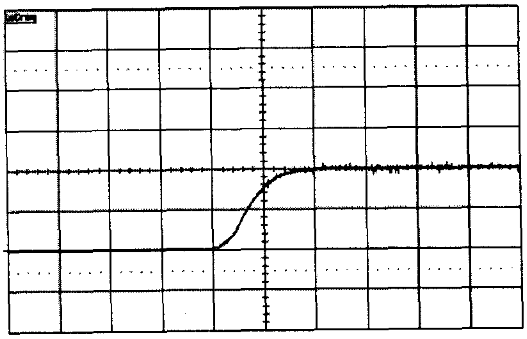


Fig. 12. Speed response characteristic in case of 1000 → 2000[rpm](500[rpm/div.], 0.2[ms/div.])

3.3 Another proposed four-switch converter

To overcome the aforementioned two problems of the proposed six-switch converter such as slow di/dt and speed limitation, this paper also proposed a four-switch type converter of SRM drives. The four-switch type topology which included active voltage doubler is studied to provide a possibility for the realization of low cost three-phase SRM drive system as shown in Fig. 13.

The first part is an active voltage doubler powered from single phase supply. The single-phase ac input which is of fixed frequency is rectified by the active voltage doubler switches T_1 and T_2. The split capacitor bank in the dc link is charged through the diodes associated with T_1 and T_2. The switches T_1 and T_2 are operated on a PWM pattern synchronized to the ac mains to shape input current to be sinusoidal. The inductor L helps in filtering the higher order current harmonics.

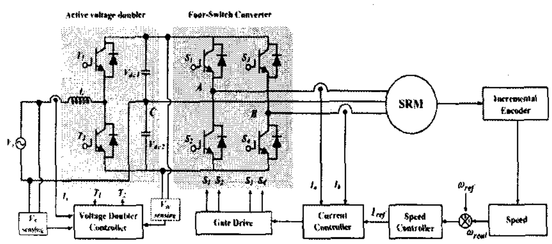


Fig. 13. The proposed four-switch type configuration of SRM drives

The active voltage doubler is also controlled to ensure unity input power factor at the supply side. Using the half-bridge configuration of the diode rectifier, one can obtain double value of the dc voltage from the same ac source and additional advantage, such as unity power factor correction. Therefore, this four-switch type configuration can solve the drawbacks of the proposed six-switch converter effectively [7-8].

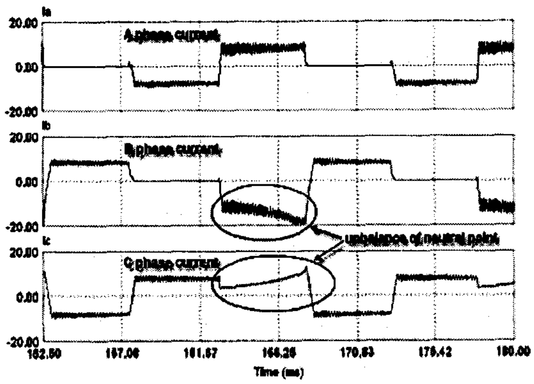
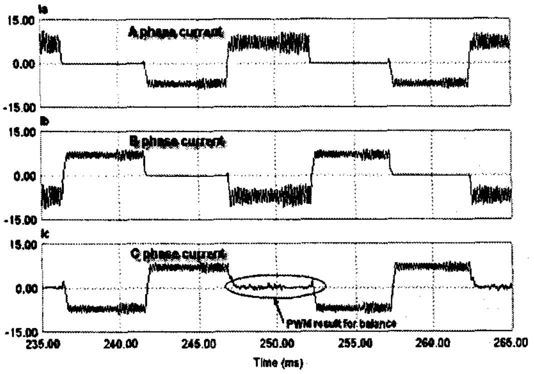


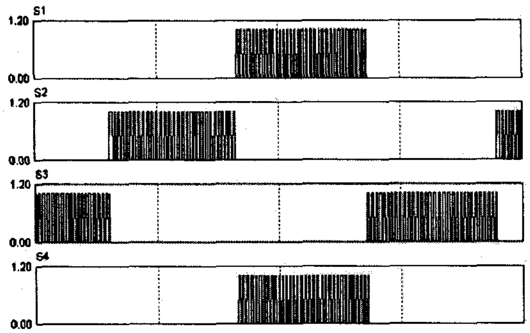
Fig. 14. Problems of unbalanced neutral point at four-switch converter

Firstly, the configuration incorporates an active voltage doubler structure that provides an active input current wave shaping feature and allows bidirectional power flow with four switches. A four-switch converter with the split capacitors in the dc link provides balanced three-phase output to SRM at adjustable voltage and frequency. An ac input is then connected to the two PWM voltages of rectifier and the center point of two split capacitors.

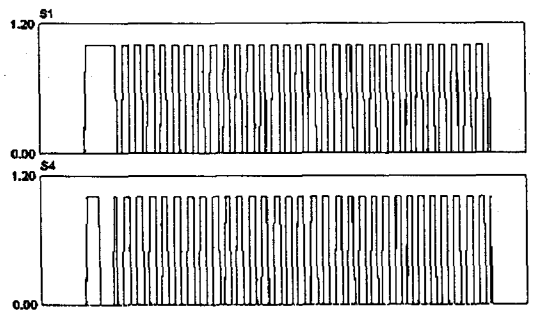
The three-phase SRM is also connected to the output converter and the same center point. Consequently, in this structure, only six power switches are required to provide single-phase to three-phase power conversion with the capability of bidirectional power flow with balanced three phase output voltages for SRM drives. Secondly, compared with the six-switch current excitation of SRM, bipolar current switching method is also implemented with Y-connected SRM in the four-switch converter. Especially phases A and B conduct the current, and phase C is regarded as being unexcited; it is expected that there is no current in phase C.



(a) Phase current (from top to bottom: I_a, I_b, I_c, 15[A/div.], 5[ms/div.])



(b) Each phase switching signal (from top to bottom: S_1, S_2, S_3, S_4)



(c) Expanded waveform of switching signal of S_1 and S_4

Fig. 15. Voltage and current waveforms of the developed four-switch three-phase SRM drives

However, the back EMF of phase C can cause an additional and unexpected current, resulting in current distortion in phases A and B as shown in Fig. 14. Therefore, the back-EMF compensation problem should be considered in the four-switch converter.

In order to solve this problem, phase A and phase B currents are sensed to generate the control signals independently. As a result of that, the neutral point voltage of the motor is controlled in a simple way. If phases A and B are regarded as independent current sources, the influence of the back-EMF of phase C can be blocked and cannot act as a current source, so that there is no current in phase C.

The phase current and each phase gate signal waveforms are displayed in Fig. 15. As phases A and B are controlled independently, one can obtain the successful current profile as shown in Fig. 15(a), and it is noted that the current can be controlled properly to drive three-phase SRM. From this result, some current ripples exist in phase C when the current is flowing through phase A to phase B.

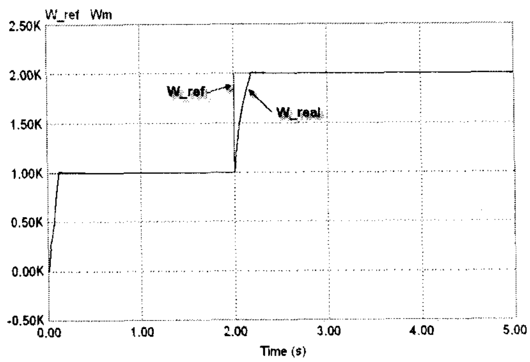


Fig. 16. Speed response with step change from 1,000[rpm] to 2,000[rpm]

Fig. 15(b) shows each gating signal of the proposed four-switch converter. Also, the enlarged waveform of gating signals S_1 and S_4 are shown in Fig. 15(c). From this result, it is noted that S_1 and S_4 are controlled independently. Moreover, the speed response characteristic of the proposed converter is shown in Fig. 16.

4. Conclusion

In this paper, novel bipolar current control topologies scheme of the three-phase SRM drive are studied to provide a possibility for the realization of low cost and high performance qualities. The operational principles of a converter are explained, and the performance of the proposed SRM drive system is examined via experimental results.

From the detailed investigation of the experimental results, it is noted that one can successfully utilize the six-switch converter topology to drive the three-phase SRM, and the validity of the developed control system is fully verified. Also, to counter some drawbacks such as voltage utilization and speed limitation of the proposed six-switch converter, the four-switch type converter which includes an active voltage doubler is also proposed in this paper. Therefore, it can be expected that one can realize a cost effective SRM drive.

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Biography

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