3상 SRM 구동용 4-스위치 인버터 PWM 제어 알고리즘

논 문
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Control Algorithm for 4-Switch Inverter of 3-Phase SRM

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Abstract - Switched Reluctance Motor(SRM) has become popular for industrial application, particularly for low medium drives due to the advantages of SRM over the other ac motors: SRM can be manufactured with low cost because it has a simple structure. But, asymmetric bridge converter that generally is used for driving requires two discrete switching devices and freewheeling diodes per phase, and cause the SRM drives to be complicated and to increase the cost of overall system. Therefore, this paper suggests a new type of 4-switch converter for SRM. 4-switch converter topology is studied to provide a possibility for the realization of low cost 3-phase SRM drive system. For effective utilization of the developed system, a new current control algorithm is designed and implemented to produce the desired dynamic performance. With the developed power conversion circuit and control scheme, it is expected that the proposed system can be widely used in commercial applications with reduced system cost.

Key Words : 3-Phase SRM, AC Inverter, 4-Switch Converter, PWM Control Algorithm

1. Introduction

Recently, switched reluctance motor has become popular for industrial application, particularly for low medium drives due to the advantages of SRM over the other ac motors: SRM can be manufactured with low cost because it has a simple structure. Also, it is bearable high temperature because the rotor does not have winding and permanent magnet. Therefore, SRM has the advantage of high reliability, fault tolerance, a wide range of speed and fast dynamic responses. However, SRM has several problems, such of an exclusive driving converter and device for detecting position of the rotor. Because of these problems, there are many restrictions from the industrial application [1,2].

Fig. 1 shows the conventional asymmetric bridge converter for 3-phase SRM drives. The converter is the high efficiency and various controls. Also the current of each phase can be controlled independently. However, it requires two discrete switching devices and freewheeling diodes per phase, which causes the SRM drives to be complicated and to increase the cost of power conversion circuit. Compared with the other ac motors with the 6-switch converter as shown in Fig. 2, SRM only has unique power conversion circuit and it can be one of main reasons for SRM to be limited in industrial applications.

In order to apply the 6-switch converter to SRM drives, several attempts have been tried and the analysis of reliability and performance are still under examination [3]. From the informative results of these works, it gives promise of the possibility of using 6-switch converter for SRM drives.

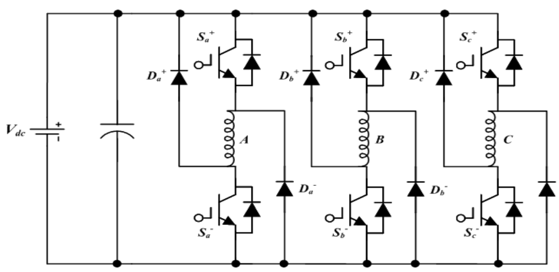

Fig. 1 Conventional asymmetric bridge converter for SRM drives

In this paper, much cost effective 4-switch converter, which is depicted in Fig. 3, is studied for 3-phase SRM drives. Even though the 4-switch converter has been applied to induction motors and brushless dc motors[4]-[6], it is regarded as the first try to use the 4-switch converter for the SRM application. In order to drive 3-phase SRM with 4-switch converter, a new control scheme is developed and tested. In the rest of this paper,

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the theoretical analysis of the proposed converter and control scheme is explained and the validity of the proposed converter is verified by simulation results.

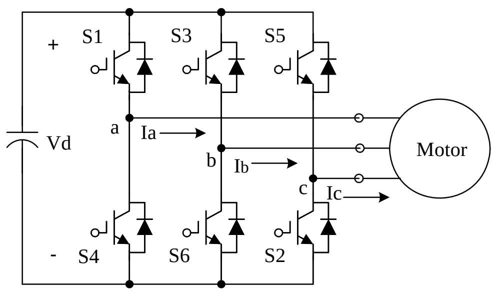


Fig. 2 6-switch converter for ac motor

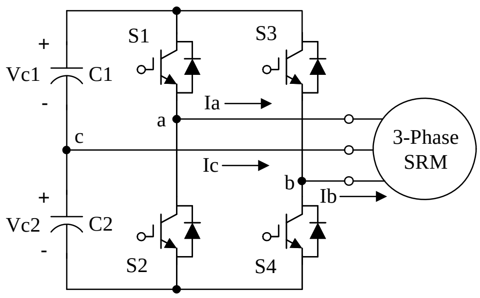


Fig. 3 Proposed 4-switch converter for 3-phase SRM

2. Operation Principle of SRM Drives

An electric circuit of SRM for one phase can be expressed as shown in Fig. 4 and the voltage and current equations can be derived in eq. (1).

$$V = Ri + L(\theta)\frac{di}{dt} + \omega i\frac{dL(\theta)}{d\theta} \tag{1}$$

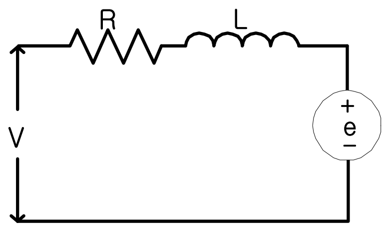


Fig. 4 Single-phase equivalent circuit of SRM

Fig. 5 shows inductance profile and torque production. The torque characteristics are dependent on the relationship between flux linkages and rotor positions as a function of current. The torque can be expressed as

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

From eq. (2), one knows that torque is proportional to the square of the current and change of inductance. This fact gives us freedom to flow the current.

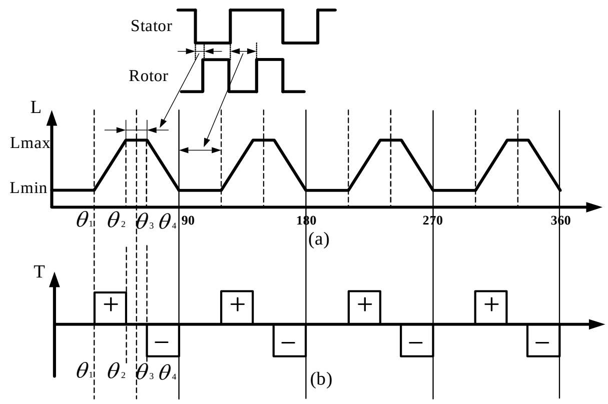


Fig. 5 Dynamic property of SRM
(a) Inductance profile and (b) Electromagnetic torque

3. Propose 4-Switch Converter for 3-Phase SRM Drives

3.1 Two-Phase Exciting Method

Compared with the conventional current excitation of SRM, such as unipolar method as shown in Fig. 6(a), in the 4-switch converter, bipolar current switching method is implemented with Y-connected SRM as shown in Fig. 6(b).

During 0°to 30°, phase A inductance is increased, phase B inductance is almost constant minimum value, and phase C inductance is decreased. Therefore, in case of excitation of phase A, the current can flow through phase A to phase B, so that positive torque can be generated in phase A.

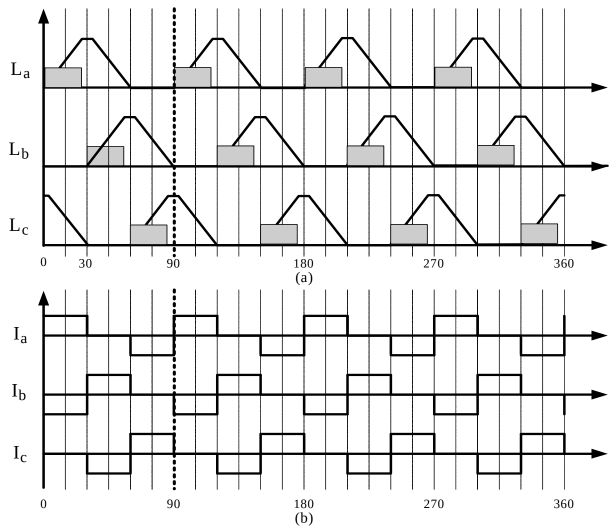
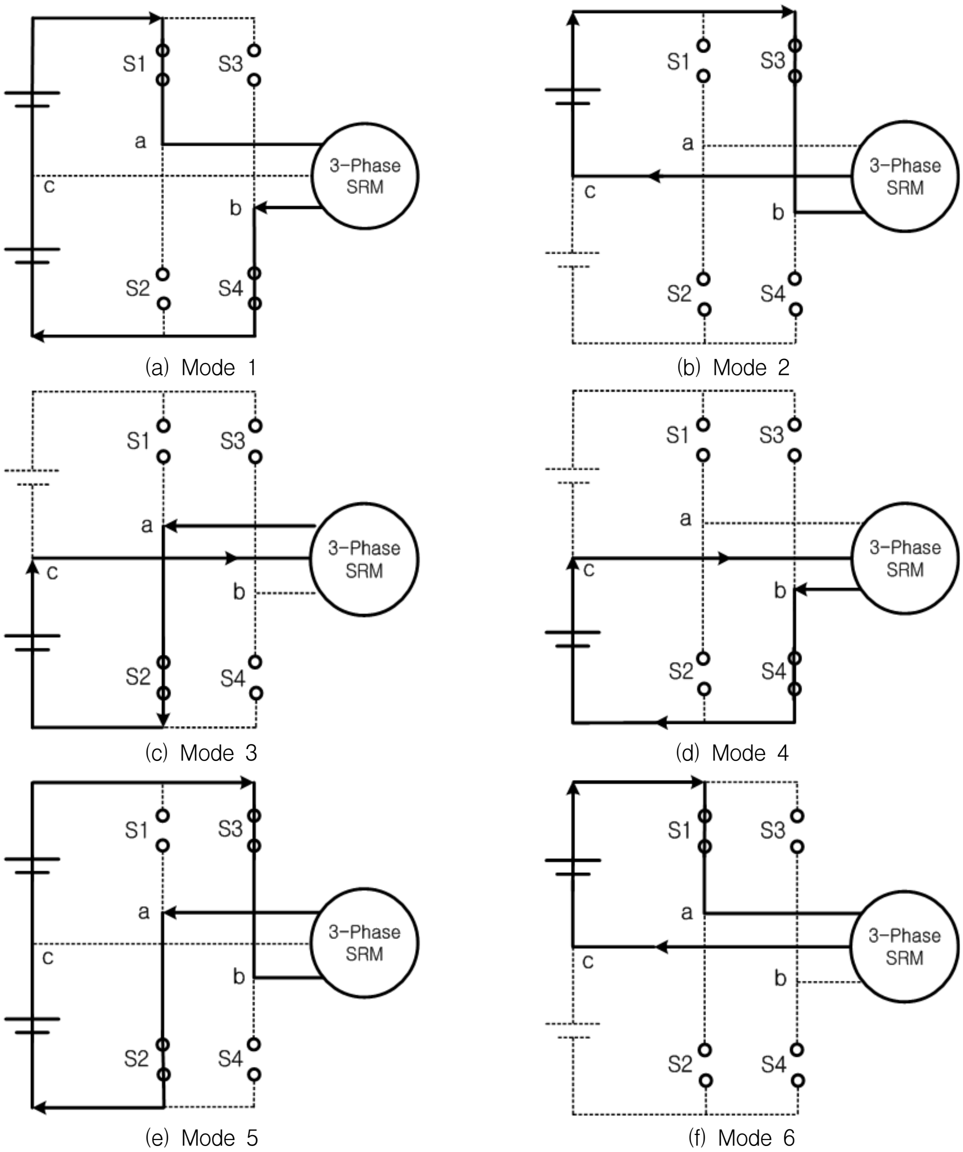


Fig. 6 Exciting method of 3 Phase SRM
(a) Inductance profile and conventional unipolar current exciting method and
(b) Bipolar current excitation for 4-switch 3-phase SRM drives



(a) Mode 1　(b) Mode 2　(c) Mode 3　(d) Mode 4　(e) Mode 5　(f) Mode 6

Fig. 7 Detailed operational modes of 4-switch 3-phase SRM drives

Table 1 Switching Sequences

Modes	Active Phases	Silent Phase	Switching Devices	Current of Neutral Point
Mode 1	Phase A, B	C	S1, S4	Ia + Ib = 0 and Ic = 0
Mode 2	Phase B, C	A	S3	Ib + Ic = 0 and Ia = 0
Mode 3	Phase C, A	B	S2	Ic + Ia = 0 and Ib = 0
Mode 4	Phase C, B	A	S4	Ic + Ib = 0 and Ia = 0
Mode 5	Phase B, A	C	S2, S3	Ib + Ia = 0 and Ic = 0
Mode 6	Phase A, C	B	S1	Ia + Ic = 0 and Ib = 0

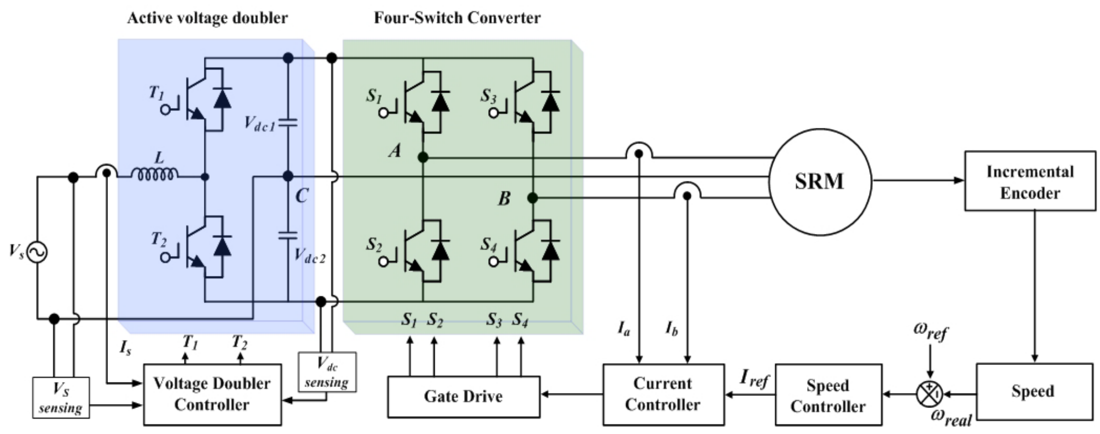


Fig. 8 The proposed four-switch type included active voltage doubler configuration of SRM drives.

In 4-switch converter configuration, when motor is driven forward and reverse directions, there are six switching status as shown in Fig. 7. Among of these six modes, only one switch is used to supply half of dc-link voltage to the motor when the current is flowing through phase A to phase C or phase B to phase C. On the other hand, when the current is conducted through phase A to phase B, two switches are used to supply full dc-link voltage to the motor. Therefore, it is noted that in 4-switch converters, it has low speed range with the same dc-link voltage of the conventional asymmetric converter, which is inherent problem of 4-switch converters. The other affect of the irregular voltage utilization is speed limitation. In case of the conventional converter, all motor phases are excited by the full dc voltage. However, in case of the 4-switch converter, mainly only half dc voltage is utilized through all operations. This voltage utilization makes the 4-switch SRM drive 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 4-switch configuration.
However, those problems can be overcome in conjugation with voltage-doublers. The detailed operational modes are summarized in Fig. 7 and each current equation according to the operational modes is summarized in Table 1.

To overcome the mentioned two problems of proposed four-switch converter, such as slow di/dt and speed limitation, this paper also proposed four-switch type converter of SRM drives. The four-switch type topology included active voltage doubler is studied to provide a possibility for the realization of low cost three-phase SRM drive system as shown Fig. 8.

The first part is a 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 T1 and T2. The split capacitor bank in the dc link is charged through the diodes associated with T1 and T2.

The switches T1 and T2 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.

The active voltage doubler is also controlled to ensure unity input power factor at the supply side. Using the half-bridge configuration of 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.

3.2 Current Control Algorithm

Special attention should be paid to mode 1 and mode 5. In these modes, phases A and B are conducting the current and phase C is regarded as being unexcited, so that it is expected that there is no current in the phase C.

However, the back EMF of phase C can cause an additional and unexpected current, resulting in current distortion in the phases A and B. Therefore, in the direct current controlled pwm, the back-EMF compensation problem should be considered. This phenomenon can be explained with the aid of the simplified equivalent circuit in Fig. 8. As an example of mode 1, in the ideal case, only one current (phase A or phase B) needs to be sensed and switching signals of S1 and S4 are identical.

In the case of sensing phase A current, the switching signal of S1 is determined independently and S4 depends on the S1signal, so that phase A current can be regarded as a constant current source. However, in this case, phase B current can be distorted by the phase C current. On the other hand, if phase B is controlled, phase B current can be a constant current source, and then the phase A current can be distorted.

The same explanation can be applied to mode 5. From the equivalent circuits of Fig. 9, one can come up with a solution. 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. It means that in the direct current controlled pwm, phase A and phase B currents should be sensed and controlled independently and the switching signals of S1 (S3) and S4 (S2) should be created independently, as shown in Fig. 10[7].

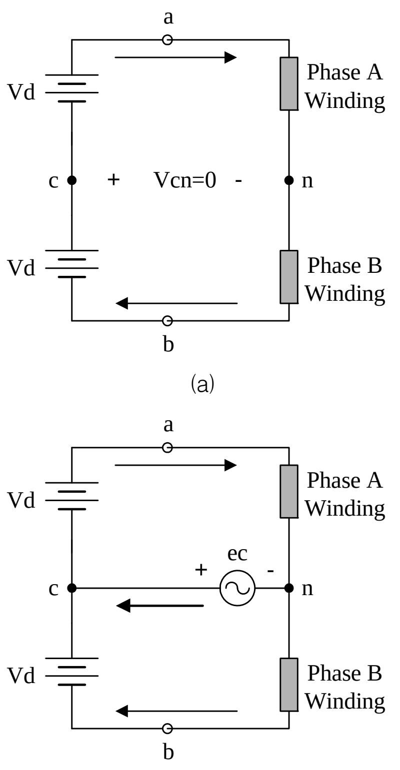


Fig. 9 Simplified equivalent circuits of modes II and V
(a) ideal case and
(b) actual case when the back EMF causes current in phase C.

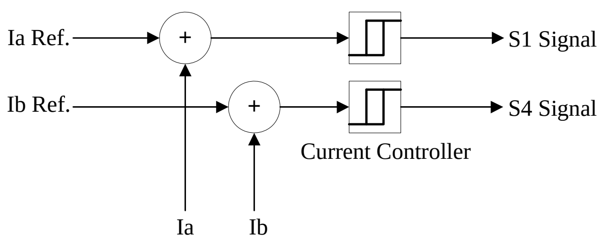


Fig. 10 PWM strategy for balancing the neutral point

4. Simulation Results

In order to examine the overall characteristics of the proposed 4-switch converter, simulation has been carried out by using PSIM software and the informative results are provided. The rated and associated parameters of the SRM are shown in the Table 2.

Table 2 Specification of SRM

Rated power	250 [W]
Rated voltage	12V
Number of stator poles	6
Number of rotor poles	4
Phase resistance	0.02166 [Ω]
Aligned phase inductance	1.332 [mH]
Unaligned phase inductance	0.241 [mH]

The summation of phase currents at the neutral point in Y-connection is zero. In mode 1 and mode 5, if each phase does not control independently, there is some current can be flowed through phase C. Therefore, the current in phase C during these modes should be blocked.

Fig. 11 illustrated this problem when only one of two phases currents is sensed and the control signals for each phase are generated in equal. It is clearly evident that current is flowing in phase C during the silent periods due to its back-EMF that are mode 2 and 5. In these cases, only positive current is sensed to generate pwm signal, so that the current distortion appears on the negative uncontrolled current. With the developed current pwm control strategy, considering back-EMF compensated solution.

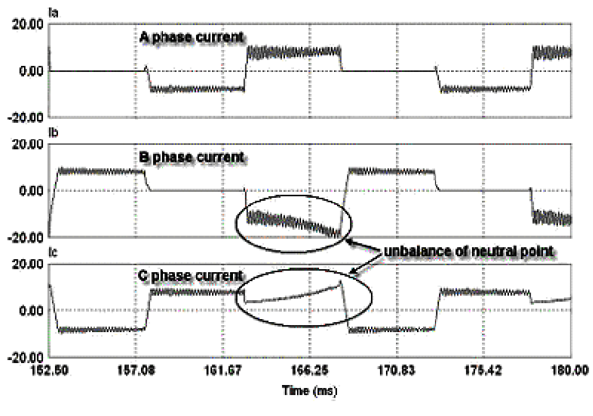


Fig. 11 Problem of mode 1 and mode 5

The phase currents waveforms are displayed in Fig. 12 and it is noted that the current can be controlled in proper to drive 3-phase SRM. From this result, one can note that some current ripples are existed in phase C when the current is flowing through phase A to phase B. It comes from the independent control of phase A and phase B during mode 1 and 5 to solve the neutral point balance problem and this ripple current can be minimized by PWM strategy and also can be reduced by controlling the hysteresis band size.

Fig. 13 shows each gate signal of 4-switch converter and it is noted that S1 and S4 are controlled independently. Also enlarged waveform of gate signals S1 and S4 are shown in Fig. 14. It is noted that the switching signals of S1 and S4 are not identical. It means that the phase A and B currents are controlled independently to prevent the effect of back -EMF of phase C during modes 2 and 5.

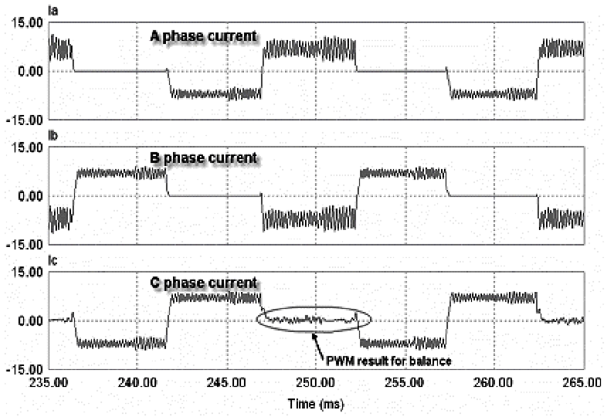


Fig. 12 Phase current waveforms

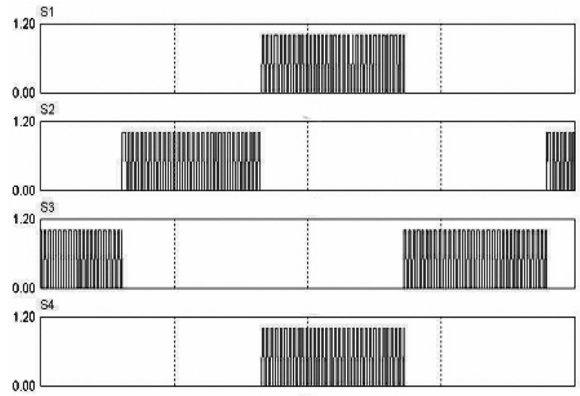


Fig. 13 Switching signals of each phase

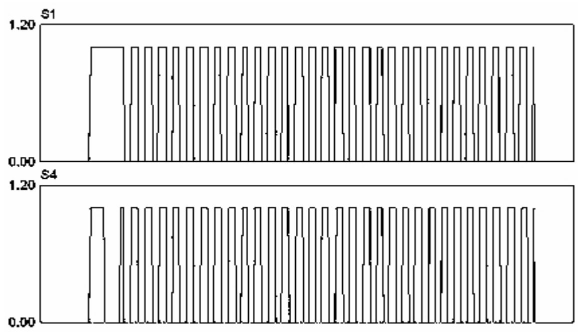


Fig. 14 Expanded waveform of switching signals of S1 and S4

Moreover, the speed response characteristic of the proposed converter is shown in Fig. 15 and Fig. 16.

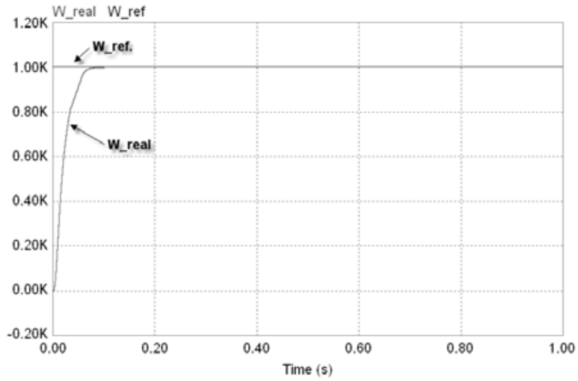


Fig. 15 Speed response with step change from 0rpm to 1,000rpm

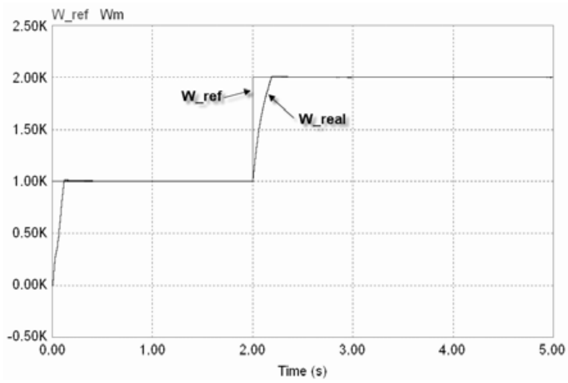


Fig. 16 Speed response with step change from 1,000rpm to 2,000rpm

5. Conclusion

An asymmetric bridge converter that generally is used for driving requires two discrete switching devices and freewheeling diodes per phase, and cause the SRM drives to be complicated and to increase the cost of overall system. Therefor in this paper, 4-switch converter is studied to provide a possibility for the realization of low cost of three-phase SRM drive systems. it is expected that the proposed system can be widely used in commercial applications with a reduced system cost.

Also we propose a new current control algorithm based on the current controlled pwm method, and this developed current controlled pwm method generates robust speed and responses and is simple to implement from the software points of view. Therefore, three-phase SRM drive with the 4-switch converter could be a good alternative to the conventional asymmetric bridge converter counterpart with respect to low cost and high performance.

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