스위치드 릴럭턴스 전동기 구동을 위한 히스테리시스 전류 제어형 공진형 C-Dump 컨버터

論 文
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A Hysteresis Current Controlled Resonant C-Dump Converter for Switched Reluctance Motor

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Abstract - The speed variation of SRM is fulfilled throughout a transition from chopping control to single pulse operation.(i.e., low speed to high speed operation). It is unsatisfied with performance at all operational regimes. In this paper, the operational performance of SRM can be improved by using current hysteresis control method. This method maintains a generally flat current waveform. At the high speed, the current chopping capability is lost due to the development of the back-EMF. Therefore SRM operates in single pulse mode. By using zero-current switching and zero-voltage switching technique, the stress of power switches can be reduce in chopping mode. When the commutation from one phase winding to another phase winding, the current can be zero as fast as possible in this period because several times negative voltage of DC-source voltage produce in phase winding. This paper is compared to performance based on conventional C-dump converter topology and the proposed resonant C-dump converter topology. Simulation and experimental results are presented to verify the effectiveness of the proposed circuit.

Key Words : SRM, Hysteresis Current Control, Zero-Current Switching, Zero-Voltage Switching, Resonant C-Dump Converter

1. Introduction

The Switched Reluctance Motor(SRM) can be applied to electric vehicle properly due to its simplicity, wide speed operation and wide environment. However, the non-linearity in the operation of the SRM complicates the analysis as well as the control of this motor. The non-linearity arises due to its design, saturation region of operation in almost all of its entire operational regimes[1-3]. High efficiency characteristics and lower EMI need to SRM in electric vehicle application. Reduction of power loss in switching devices can be established by using resonant type converter for operating motor and also needs minimize of switching devices in converter in the side of manufacturing cost[4-7]. Recently, torque output of SRM has been studied that it can be increased by operating with high demagnetization voltage, especially for high speeds[8].

In this paper, we used a prototype SRM with resonant C-dump converter for electric vehicle application. The proposed converter topology is compared with the conventional C-dump converter topology at the switching loss side. And we review the improvement of performance by add to current hysteresis control technique in low operational region from already presented resonant C-dump. During operation, when the effective voltage across the phase winding (that is, the dc-link voltage less than the back EMF) is too high, chopping mode is needed to regulate the phase current. This is normally the case for low-speed operation with a fixed dc-link voltage.

At high speed, current chopping may not be required because the dc-link voltage may not be much greater than the back EMF[4][5]. Fig. 2 shows waveforms in hysteresis current control mode. hysteresis Current control maintains a generally flat current waveform due to bandwidth of the current-regulator for determinable ripple.

At high speed, the back-EMF may prevent the current from ever reaching a high-band of current-regulator and then the current waveform is naturally determined by inductance and back-EMF as the rotor rotates. This is called single pulse mode[1]. Therefore, hysteresis current control technique is suitable for the proposed converter topology.

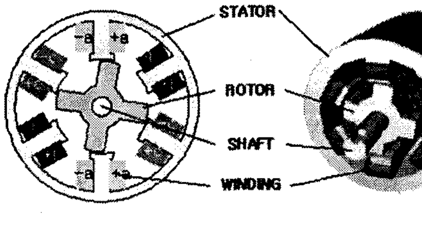

Fig. 1 Switched reluctance motor

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In the chopping method, hard chopping method that is applied to operate SRM is generally avoided due to high EMI and high switching loss. But this method has rapid demagnetization of phase current in commutation mode. In this paper, this method is applicable to SRM by zero-current switching (ZCS) and zero-voltage switching (ZVS) of switching device.

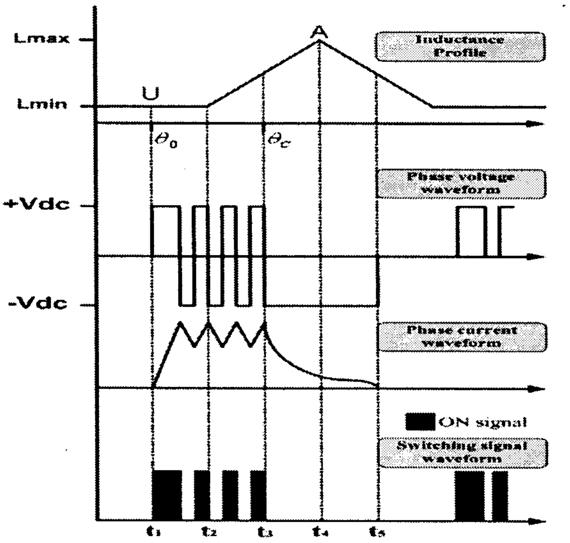

Fig. 2 Waveforms in case of hysteresis current control

2. Analysis and operational principles of the proposed Resonant C-dump Converter Topology

Fig. 3 shows the circuit of proposed resonant C-dump converter topology. This circuit is just use three switches. This is the reduced parts of converter devices as compared with the conventional C-dump converter topology. And also the proposed circuit eliminated three diode devices in addition when this is compared with presented resonant C-dump converter. The following operational mode divided into four steps for one cycle period. As power switching device S_a is operated, analysis of operational mode for each device is shown in Fig. 4.

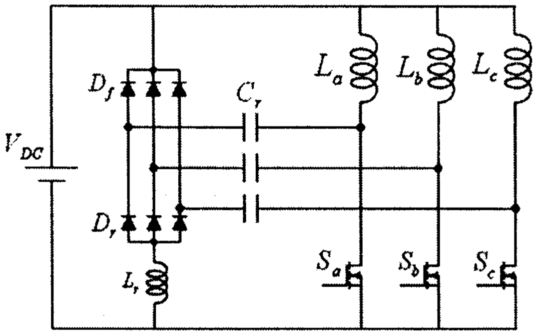

Fig. 3 The proposed resonant C-dump converter

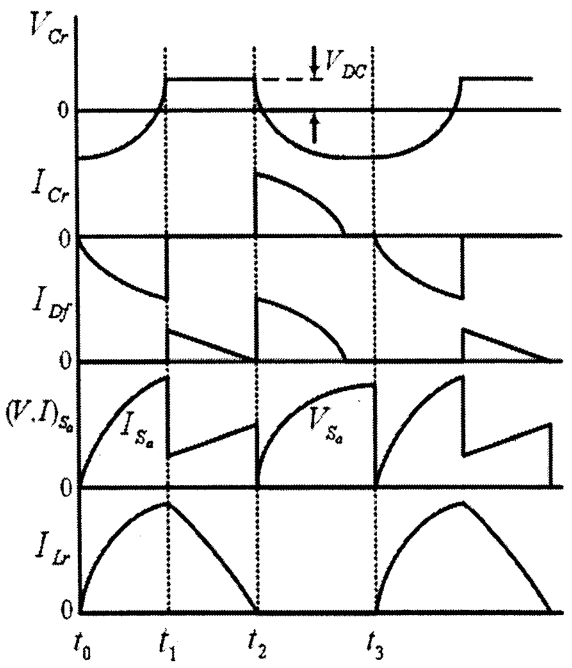

Fig. 4 Analysis of operation mode.

A. Mode 1 ($t_0 \sim t_1$)

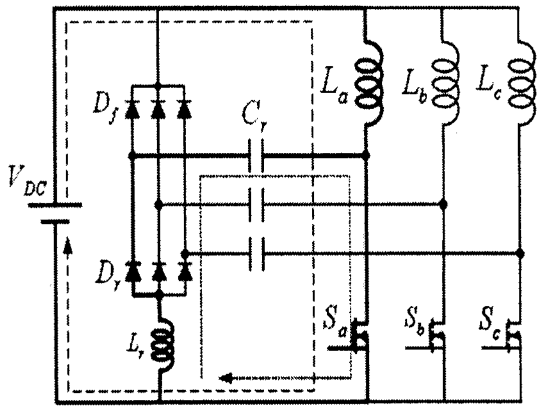

Fig. 5 Operation mode 1

Assume a finite capacitor capacity is full. In Fig. 5, A phase switch S_a is turn on and then resonant capacitor C_r is discharged. S_a, L_r, and D_r are formed series resonant circuit. A phase switch S_a is turn on with Zero Current Switching. And then total current flows in S_a

$$I_{S_a} = I_{C_r} + I_{L_a} \tag{1}$$

Voltage balance equation is in this period ($t_0 \sim t_1$)

$$L_r \frac{di_{L_r}}{dt} + V_{C_r} = 0 \tag{2}$$

Resonant Inductor current

$$i_{L_r}(t) = L_r C_r \frac{d^2 i_{L_r}}{dt^2} \tag{3}$$

where, initial value is $i_{L_r}(t_0) = I_{L0}$, $V_{C_r} = (t_0) = V_{C_{r0}}$ the equation can be expressed as

$$i_{L_r}(t) = I_{L_{r0}} \cos \omega_0 (t - t_0) \tag{4}$$

$$V_{C_r}(t) = V_{C_{r0}} \cos \omega_0 (t - t_0) \tag{5}$$

$V_{C_{r0}}$: initial resonant capacitor voltage, $I_{L_{r0}}$: initial resonant inductor current, t_0: start time, Angular resonance frequency is $\omega_0 = 1/\sqrt{L_r C_r}$, Characteristic impedance is $Z_0 = \sqrt{L_r / C_r}$

B. Mode 2 $(t_1 \sim t_2)$

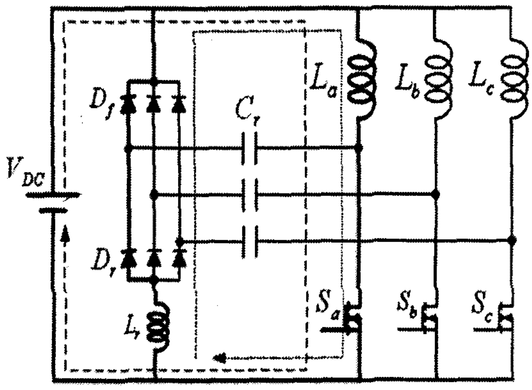

Fig. 6 Operation mode 2

In Fig. 6 resonant capacitor voltage V_{C_r} is discharged completely and $V_{C_r} = V_{DC}$, $I_{C_r} = 0$, and then phase current is $I_{L_a} = I_{DC} + I_{L_r}$ resonant inductor voltage V_{L_r} is expressed as

$$\frac{V_{L_r}}{L_r}(t - t_1) = i_{L_r}(t) - i_{L_r}(t_1) \tag{6}$$

Therefore resonant inductor current $i_{L_r}(t)$ is can be expressed as

$$i_{L_r} = \frac{V_{L_r}}{L_r}(t - t_1) + i_{L_r}(t_1) \tag{7}$$

C. Mode 3 $(t_2 \sim t_3)$

In Fig. 7, A phase switch S_a is turn off, a phase winding is demagnetizing and V_{C_r} is charging throughout D_f again. The freewheeling of a phase winding is formed in this period $(t_2 \sim t_3)$ with zero voltage switching. And then voltage balance equation can be expressed as

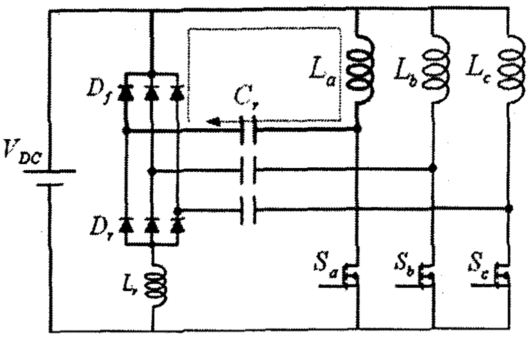

Fig. 7 Operation mode 3

$$L_a \frac{di_{L_a}}{dt} + V_{C_r} = 0 \tag{8}$$

Phase winding current equation can be expressed as

$$i_{L_a}(t) = I_{L_{a2}} \cos \omega_0 (t - t_2) \tag{9}$$

Where initial value is $i_{L_a}(t_2) = I_{L_{a2}}$, $V_{C_r}(t_2) = V_{C_{r2}}$

$V_{C_{r2}}$: initial resonant capacitor voltage $I_{L_{r2}}$: initial resonant inductor current, t_2 : start time, Angular resonance frequency $\omega_0 = 1/\sqrt{L_a C_r}$, Characteristic impedance $Z_0 = \sqrt{L_a / C_r}$

D. Mode 4 (Commutation mode)

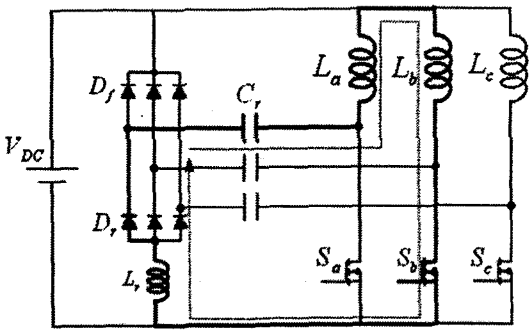

Fig. 8 Operation mode 4

In Fig. 8 commutation is formed from one phase to another after one cycle period $(t_0 \sim t_3)$. A phase switch S_a is turn off and B phase switch S_b is turn on. And then V_{C_r} of A phase is discharged throughout L_a, L_b and B phase winding is conducted in initial loop. After V_{C_r} of A phase is discharged completely, source voltage V_{DC} is conducted B phase. A phase current can be zero as fast as possible in this period because several times negative voltage of DC-source voltage produce in phase winding. Therefore, the maximum output torque increases by means of short current pulse tail-length[2].

3. Simulation results

Fig. 9 shows the overall block diagram of the developed model for SRM Motor drive system that is performed using the PSIM software. The system above is composed of SRM Motor, C-dump converter, current control block (hysteresis current control) and speed control block (PI speed control).

Fig. 10 shows conventional C-dump 3 phase current waveforms and Fig. 11 shows enlargement of A phase current and voltage waveforms. Phase current and phase voltage are overlapped when switch S_a turn on from turn off, that is, during switching transition switching loss brings out at switching device.

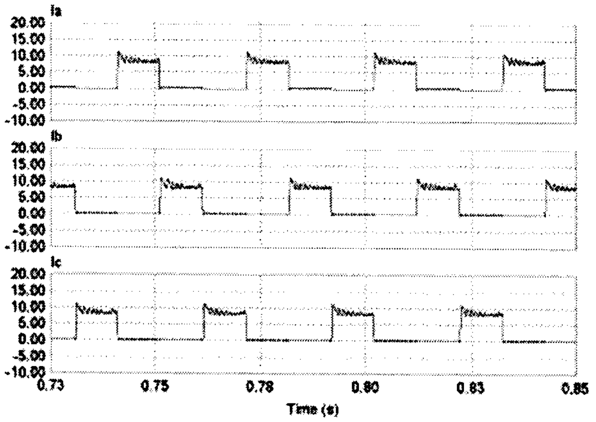

Fig.10 Conventional C-dump 3phase current (500rpm)

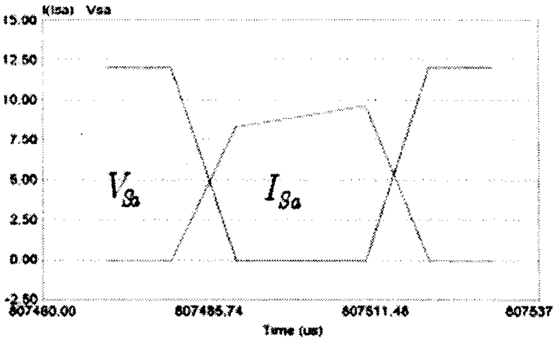

Fig.11 V, I in A phase switch

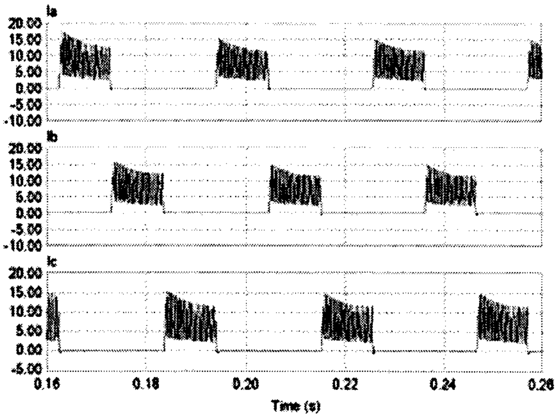

Fig.12 Proposed C-dump 3phase current (500rpm)

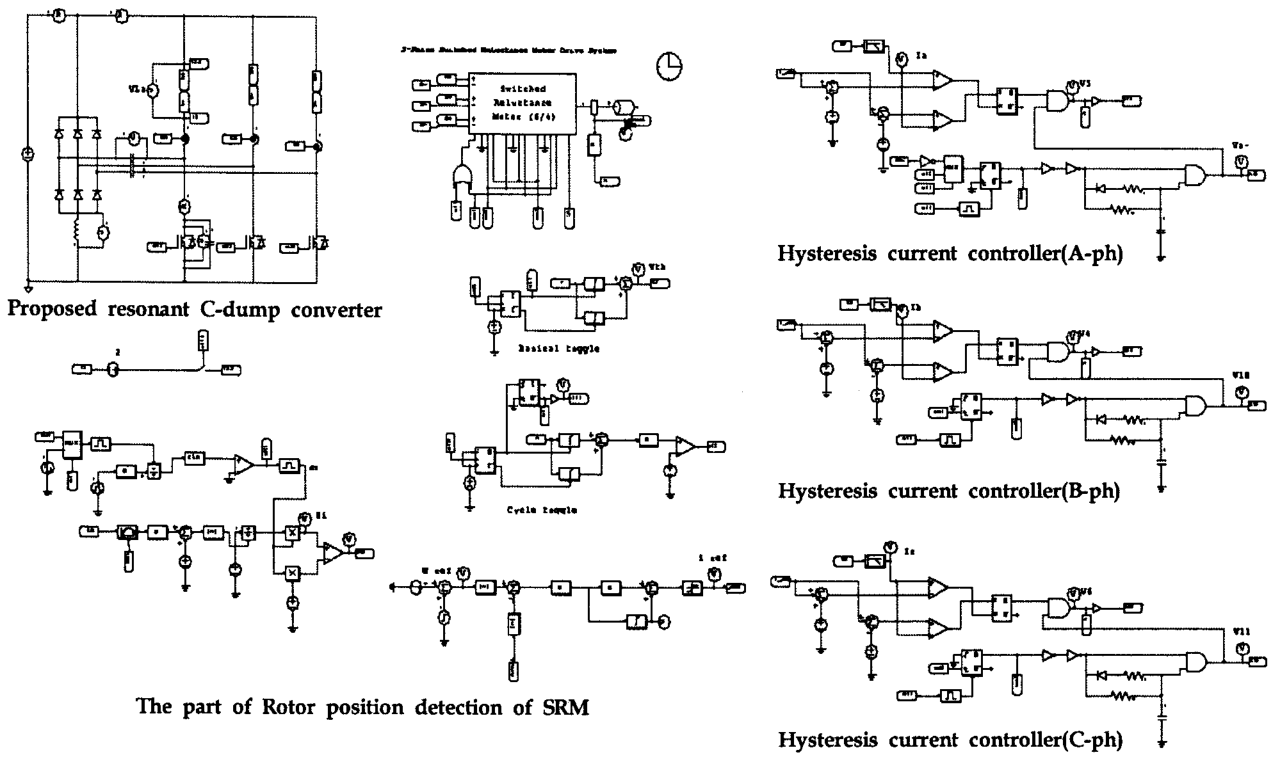

Fig. 9 The configuration of simulation for proposed SRM converter

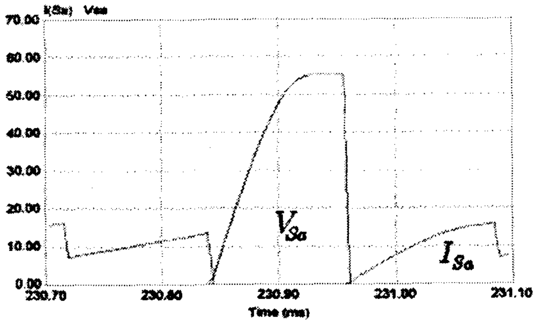

Fig.13 V, I in A phase switch by proposed resonant

Fig.12 shows three phase current waveforms on proposed converter topology and Fig. 13 shows enlargement of a phase current and voltage waveforms. As shown in Fig.13, Phase current and phase voltage are less overlap than Fig. 11. That is, the proposed resonant C-dump converter during switching transition switching loss is low.

4. Experimental Results

Fig. 14 shows the block diagram of SRM drive system. This control algorithm is implemented by a micro-controller, which is responsible for user interface and speed control. The sampling time of the speed control loop is 1[ms] and the shaft encoder has 600 pulses per revolution.

It receives position signals to calculate real speed values from an encoder. It produces PWM for power switches of converter and performs also the speed control.

The gate signals keep on and off maintaining the steady current between reference values and real current into the hystersis-band. The real speed value is calculated by using the M/T method. In the speed controller, the speed PI feedback loop compares the actual rotor speed ω with the command rotor speed ω_{ref} to produce the command of torque component current. The rated and associated parameters of the SRM are shown in the Table 1.

Table 1. Specification of SRM

Rated power	250 [W]
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]

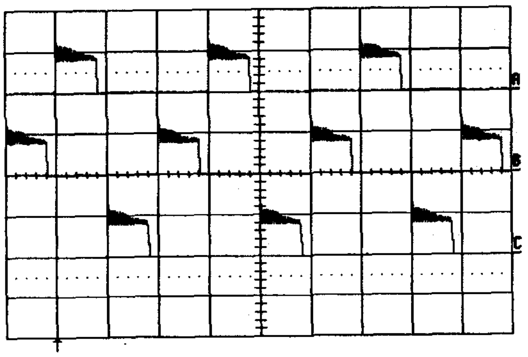

Fig.15 Conventional C-dump 3 phase current (10A/div, 10ms, 500rpm)

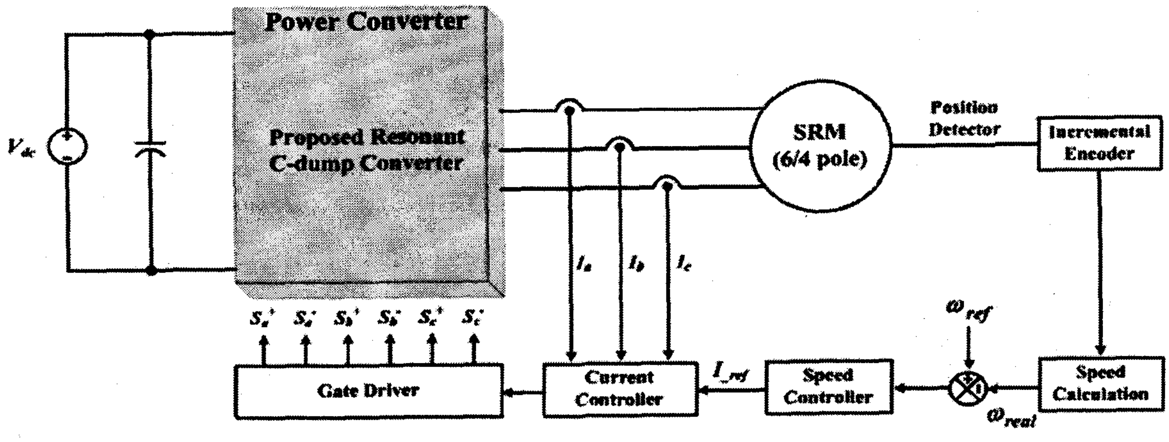

Fig.14 The configuration of overall experimental system

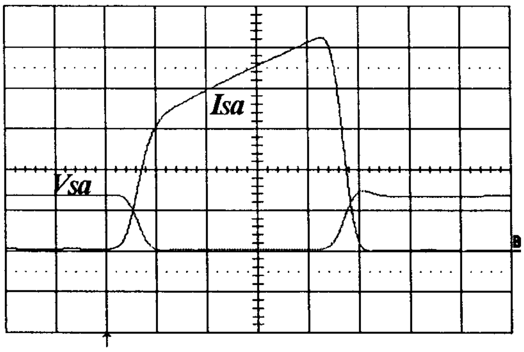

Fig.16 V, I in A phase switch (10V, 2A/div, 20μs)

The proposed converter topology is compared with the conventional C-dump converter topology from the switching loss side in Fig.15 ~Fig. 20. Fig. 15 shows each phase current at 500rpm with current hysteresis control in the conventional C-dump converter and Fig. 16 show voltage and current waveforms on the switch S_a when turn on and turn off. In transition switching, voltage and current waveforms are overlapped.

Fig. 17 ~ Fig. 20 show each waveform of the proposed C-dump converter. Fig. 17 represents 3 phase current at 500rpm.

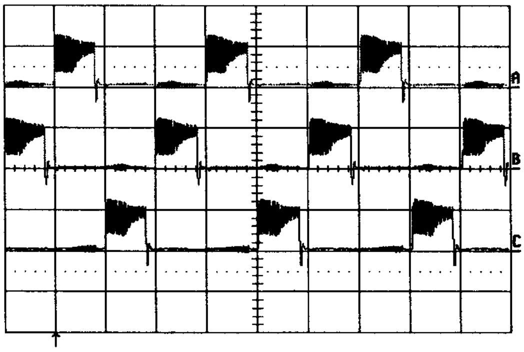

Fig.17 Proposed C-dump 3 phase Current (10A/div, 10ms, 500rpm)

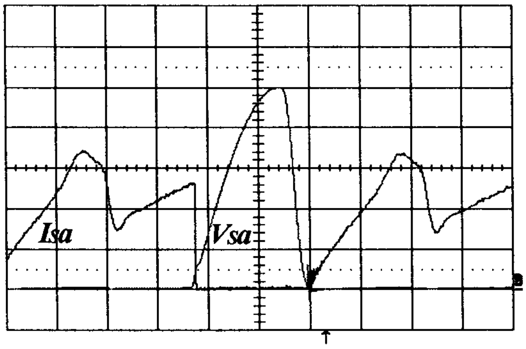

Fig.18 V, I in A phase switch (10V, 5A/div, 50μs)

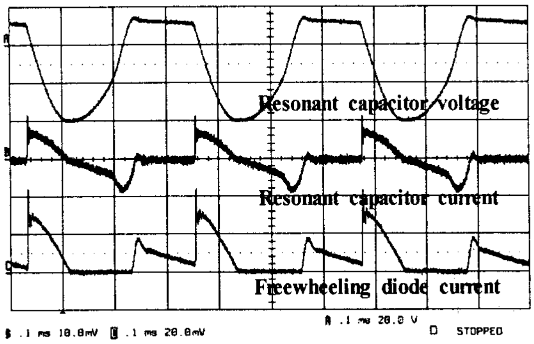

Fig.19 Waveforms of each device (0.1ms)

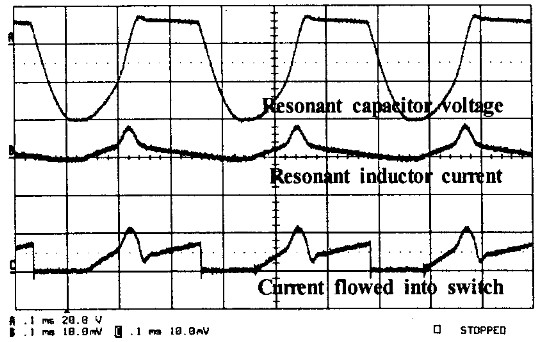

Fig.20 Waveforms of each device (0.1ms)

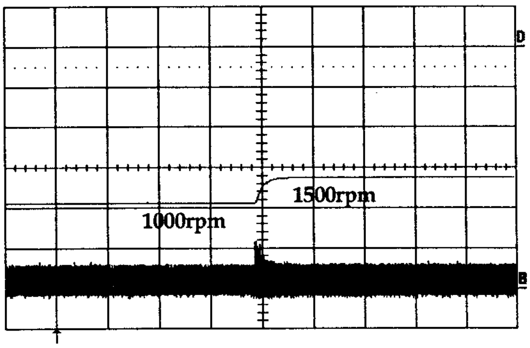

Fig.21 3-phase current and speed response for reference sped change (20A/div, 1s)

Fig. 18 shows the V-I waveform in A phase switch. So this part, we know that it is different to V-I waveform in A phase switch compared with the conventional C-dump converter in Fig.16. Fig. 19 and 20 show the waveforms of each device at the proposed C-dump converter. In order to demonstrate the speed dynamic response by the proposed algorithm, 3-phase current and the speed response characteristics is shown in Fig. 21 with the step change of reference speed.

5. Conclusion

By using hysteresis current control method improved torque ripple problem as single pulse mode in low speed regime. Power loss of three switches reduced with ZVS and ZCS by series resonant circuit.

The cost of manufacturing reduced by elimination of three diodes. And rapid demagnetization of phase current shows in entire operational regime by high negative phase voltage. Therefore performance of entire operation for SRM is improved than the conventional C-dump converter.

In the future, more specific experimental result should be implemented. (i.e. measurement of efficiency for full load at entire speed region) and modified whole system for obtaining higher efficiency.

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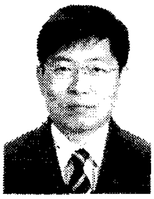

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