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Control of C-dump Converters fed from Switched Reluctance Motors on an Automotive Application

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ABSTRACT

This paper deals with the analysis of switched reluctance motor drives for different drive circuit topologies used in automobile. So we attempt to improve the weaknesses associated with the asymmetric bridge converter in the limited internal environment of automotive application. Two kinds of c-dump converters are tested in terms of dump capacitor voltage, speed response according to the variation of advance angle and efficiency for the radiator cooling-fan drive of an automobile. They enable more economical and efficient converter topology for automobile industries. This paper describes the performance characteristics of 12V-250W-3000rpm SRM drives for automotive application. Computer simulation and experiment results are then presented to verify the performance of the two kinds of c-dump converters.

Keywords: SRM, Modified c-dump converter, Energy efficient c-dump converter

1. Introduction

Recently, switched reluctance motors have become popular for industrial applications, particularly for low medium drives. This is due to the advantage of SRMs: low manufacturing cost, good reliability, fault tolerance, a wide range of operational speeds and torque and efficient dynamic responses. In the last few years, many research results regarding the topologies of SRM driver circuits have been published. SRMs require power converters to control the conducting sequence of the stator winding. The asymmetric bridge converter has two switches per phase.

While this converter topology provides the most flexible and effective control to the current waveforms of SRM, it has the highest number of switches, and produces conducting voltage drops across two power switches during SRM operations [1,2]. For automotive applications with a 12V-battery supply, the high component cost and excessive heat generation make this circuit topology unfavorable. In the limited internal environment of automotive application, taking into account the requirements of effective operation and simplicity in the structure of converters, the author inclines toward selecting the modified c-dump converter and energy efficient c-dump converter. These two kinds of c-dump converters overcome the limitations of the conventional c-dump converter, with the potential to reduce the overall cost of the SRM drive systems. They also provide some additional advantages.

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Two converter topologies composed of single switch per phase are compared respectively in a point of dump capacitor voltage, speed response and drive characteristic according to the variation of advance angle and efficiency for the radiator cooling-fan drive of an automobile.

2. Recent Trends in Automotive Applications

The recent trend in the automotive industry is to exert new demands on small motors, such as SRM and BLDC motor. These demands may be summarized as follows:

(1) Low costs: As consumers demand lower prices for better products, auto-part manufactures are making efforts to cut production costs and to introduce cost-effective products.

(2) High reliability: As maintenance and repair services are becoming more expensive due to higher costs and complex auto-parts, highly reliable motors and drives are desirable.

(3) High efficiency: High efficiency motor drives are always desirable for saving energy and reducing battery/alternator rating.

(4) Variable speed control: in order to enhance performance, to save energy and to reduce noise level, variable speed control of automotive motors is desired.

(5) Long life cycle: Automobile motors should have a long life cycle in order to avoid replacements and repairs during the life span of automobiles.

SRM's offer many attractive features in certain aspects, such as high reliability, long life cycle, variable speed control, and high efficiency. As a result, automotive motors have undergone substantial changes. Alternative motors are entering the automotive market in replacement of the traditional dc motors [3].

Fig. 1 shows the engine cooling system demonstrating the flow of coolant between engine water jackets and the radiator. The radiator cools the engine by removing heat.

The liquid in the cooling system absorbs the heat, refracts it to the radiator and the radiator then dissipates it to the air.

Generally, dc motors and induction motors are used for driving at the radiator. However, these motors suffer from low efficiency, low life cycle and low reliability. It has therefore become a trend to replace these motors with advanced ac motors, including SRM.

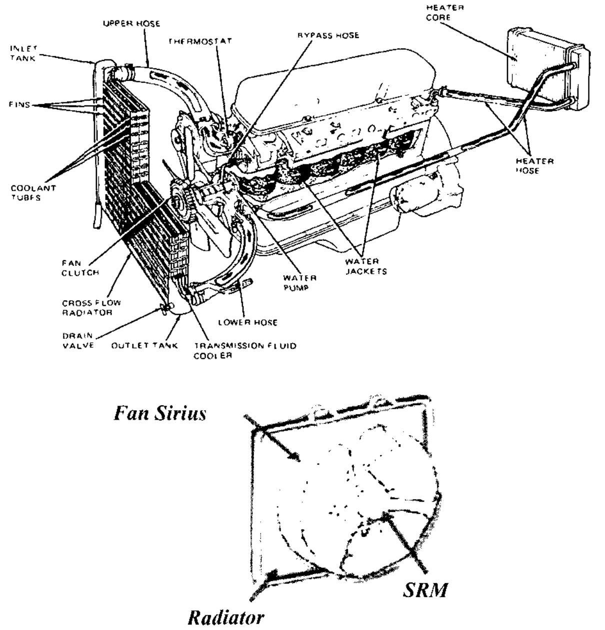

Fig. 1 Radiator engine cooling systems

3. SRM Converter Topologies

3.1 Modified C-Dump Converter and Energy Efficiency C-Dump Converter

The modified c-dump converter is shown in Fig. 2. It is derived from the c-dump converter circuit by eliminating the inductor of the buck converter. The energy is then dumped into the capacitor but is directly utilized by the next phase, rather than being returned to the DC supply as in the conventional c-dump configuration. Since the c-dump capacitor voltage is in the range of $2V_{dc}$, its proper utilization significantly improves the drive performance.

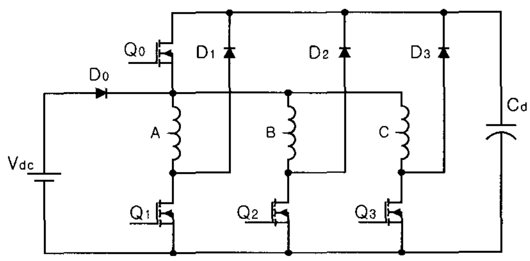

Fig. 2 Modified C-dump converter

Compared with a modified c-dump converter, we note that the energy in the dump capacitor is directly utilized to energize phase windings and maintain the dump capacitor voltage at Vdc rather than 2Vdc. Control of the dump capacitor voltage is simplified and duplication of the phase currents is enabled in an energy-efficient c-dump converter.

Fig. 3 shows the energy-efficient c-dump converter topology, derived from the conventional c-dump converter. The topology could reduce the overall cost of the SRM drive. The voltage ratings of the dump capacitor and some of the switching devices in the energy-efficient c-dump converter are reduced to the supply voltage(Vdc) level compared to twice the supply voltage(2Vdc) in the conventional c-dump converter. In addition, the converter has simple control requirements and allows the motor phase current to freewheel during chopping mode.

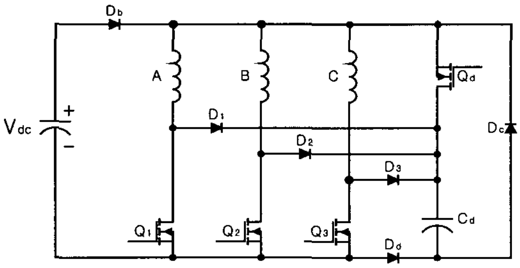

Fig. 3 Energy -efficient c-dump converter

3.2 Operation Mode

Fig. 4 represents the operating mode of the modified c-dump converter topology. In Fig. 4(a), both Q1 and Qo are closed. With the capacitor voltage Vcd being larger than the Vdc, phase A is magnetized by Vcd. Concurrently, for other cases, Q1 is on and the phase A winding is connected to the DC link voltage, Vdc.

During the conduction mode in Fig. 4(b), phase A is demagnetized through freewheeling D1. Qo and D1 are conducted, short-circuiting the winding. A freewheeling current discharges the magnetic energy yet the demagnetization is very slow and contingent entirely upon the circuit resistance. Q1 has to withstand Vcd. Both Qo and Q1 are turned off (see Fig. 4(c)), Phase A is demagnetized through D1, capacitor C, and the input source, which provides the freewheeling path. Energy transfer charges the capacitor from the winding and by the DC link [4].

Fig. 4(d) shows that transfer of a magnetized phase, the operation characteristic is equivalent to Fig. 4(a).

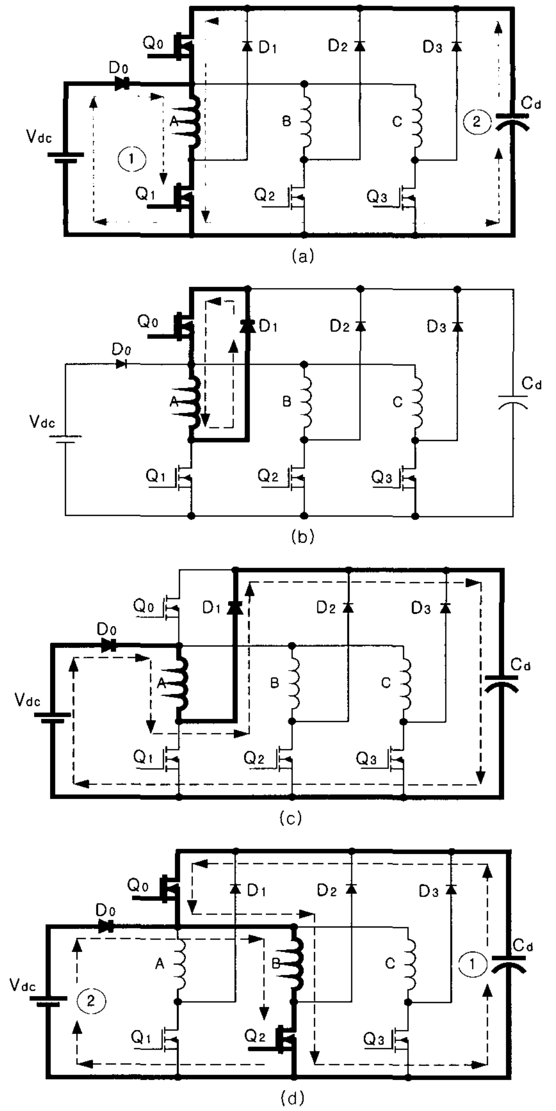

Fig. 4 Operating mode of modified c-dump converter

The energy efficient c-dump converter has four modes of operation as shown in Fig. 5.

During the conduction mode, shown in Fig. 5(a), phase A starts to magnetize with both Q1 and Qd on. The phase is energized from the capacitor that is transferred to the source until the capacitor voltage drops to the level of input voltage (②). At that point the blocking diode becomes forward biased and the source begins to feed energy to the phase (①). The current is maintained at the command level by switching Q1 on and off. The phase current freewheels through diode D1 and Qd when Q1 is "off" as shown in Fig. 5(b). The current commutates from Q1 and Qd "off" and charges the dump capacitor. Diode

Dd blocks the demagnetizing current, which flowed through the source.

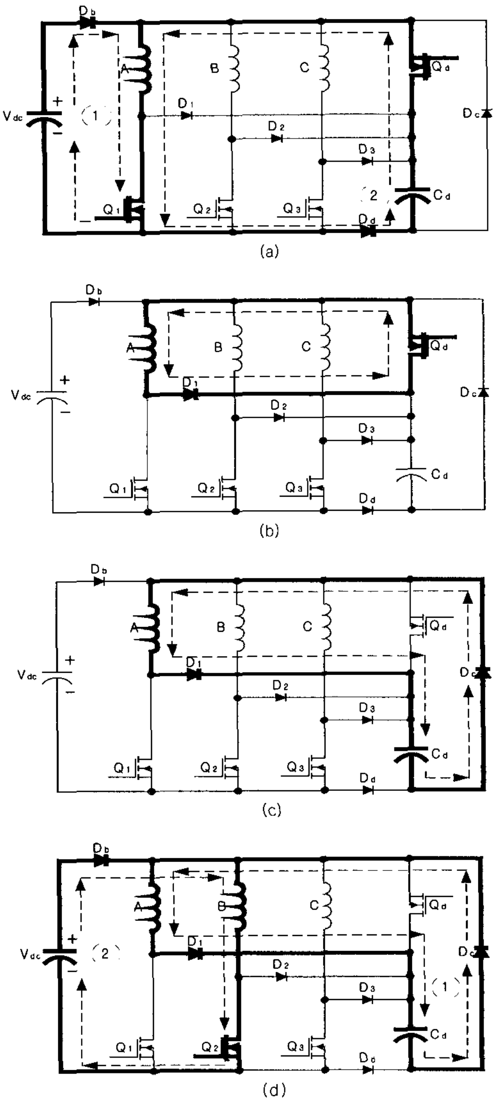

Fig. 5 Operating mode of energy-efficient C-dump converter
(a) Conduction mode (b) Freewheeling mode
(c) Commutation mode- I (d) Commutation mode- II

While phase A is being demagnetized, phase B can be magnetized by turning Q2 on, as shown in Fig. 5(d). During this period, the current through phase B is maintained at the command value by dumping any extra energy into the capacitor [5].

4. Simulation Results

To verify control of the performance in a point of dump capacitor voltage, speed response, according to the variation of advance angle, efficiency for overall system, simulation is implemented by using PSIM 6.0 software.

4.1 Simulation configuration

Fig. 6, 7, 8 show the each part of simulation configuration. In Fig. 6, the SRM used in the simulation is 6/4 and show the A, B, C phase and coupled load. To control SRM, the rotor position must be known, so Fig. 7 shows the rotor position detected by the A-phase. Fig. 8 represents hysteresis controller of the A-phase and gate signal controller(A, B, C-phase).

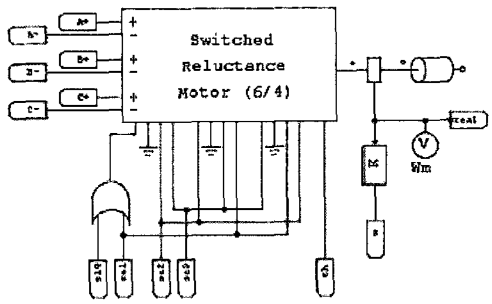

Fig. 6 The composition of SRM.

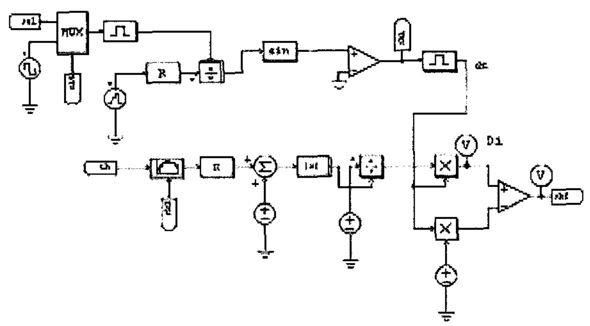

Fig. 7 Rotor position detect of A-phase

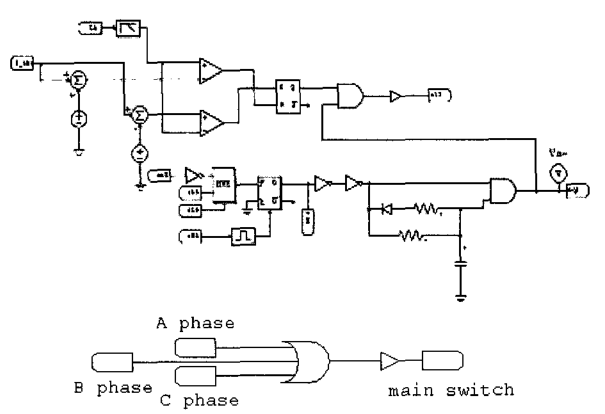

Fig. 8 Hysteresis controller and gate signal controller(A, B, C phase)

4.2 Modified C-dump converter simulation

Fig. 9 shows the simulated step change of the speed, phase current and dump capacitor voltage at 500-1000rpm.

Fig. 10 illustrates the detail waveform at 1000rpm for the phase current, dump capacitor voltage, and phase voltage. In the case of dump capacitor voltage, it is operated to charge and discharge from V_{dc} to $2V_{dc}$.

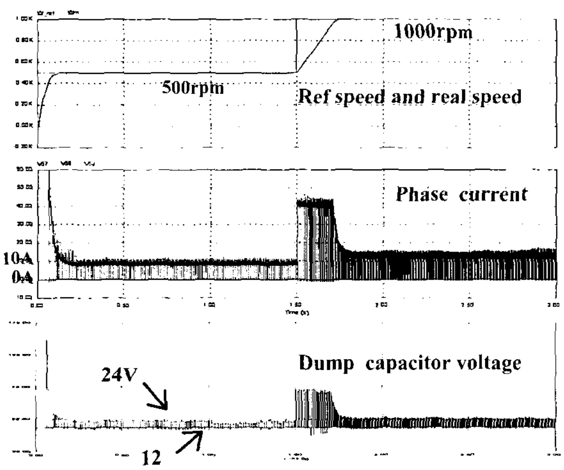

Fig. 9 Simulation results at 500-1000rpm (200rpm/div, 10A/div, 20V/div, 1s/div)

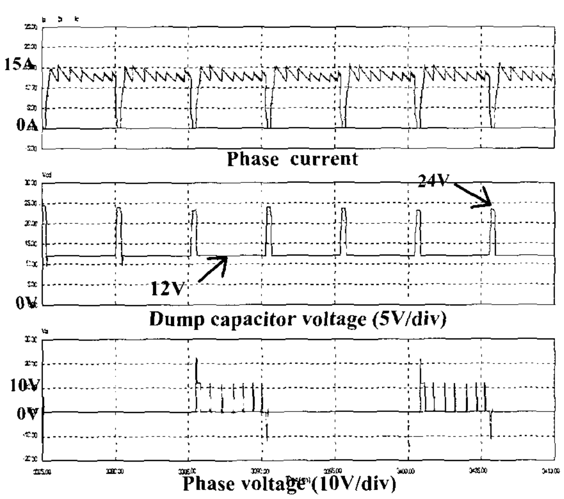

Fig. 10 Simulation results at 1000rpm

4.3 Energy efficient C-dump converter simulation

Fig. 11 shows the simulated step response on the speed, phase current and dump capacitor voltage at 500-1000rpm.

Fig. 12 illustrates the detail waveform at 1000rpm for the phase current, dump capacitor voltage, and phase voltage. The dump capacitor voltage is operated at a lower value than that of a modified c-dump converter.

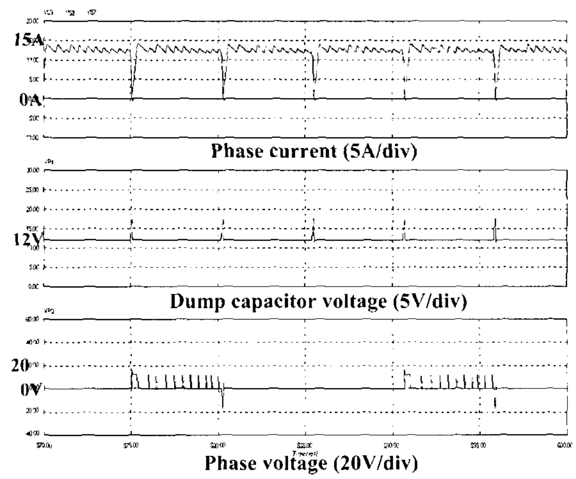

Fig. 11 Simulation results at 500-1000rpm (200rpm/div, 10A/div, 20V/div, 1s/div)

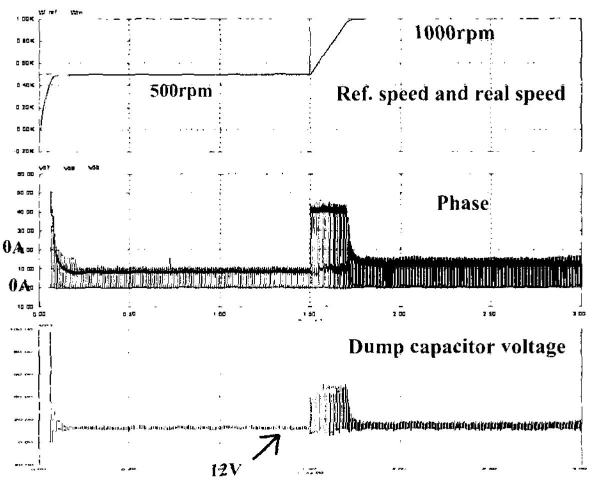

Fig. 12 Simulation results at 1000rpm

5. Experimental results

Fig. 13 shows the block diagram of SRM drive system. In order to verify the performance control, the system is implemented by software of INTEL 80C196KC micro -controller board. Converter input voltage is V_{dc} =12[V]. With the car's 12V battery we tested the whole system's performance from the dump capacitor voltage point of view, speed response, drive characteristic according to the variation of advance angle and efficiency for overall system as the radiator cooling-fan drive of automobile.

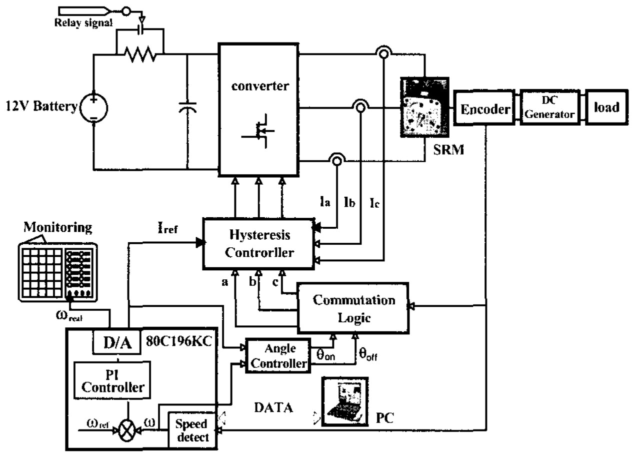

Fig. 13 Block diagram of SRM drive system

5.1 Modified C-dump converter

Fig. 14, 15, 16 and 17 show the experimental results of the modified c-dump converter.

Fig. 14 shows a phase current and the dump capacitor voltage at 1000rpm.

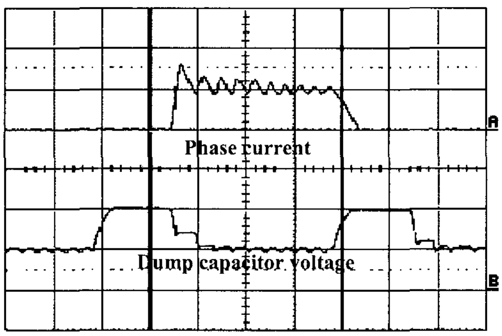

Fig. 14 Phase current and dump capacitor voltage at 1000rpm (10A/div, 12V/div, 1ms)

Fig. 15, 16 are waveforms of the step response for acceleration speed and phase current. In order to examine the performance of the SRM with the modified c-dump converter, it was tested on a permanent dc generator load (250W, base speed 3000rpm) which coupled the SRM. Connecting a rheostat at the motor terminal varies the road to dc generator. Fig. 17 shows the current of each phase with 100W load at 2500 rpm.

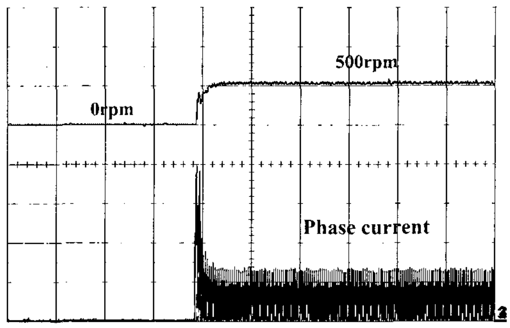

Fig. 15 Waveform of speed and phase current (0.5s/div, 10A/div)

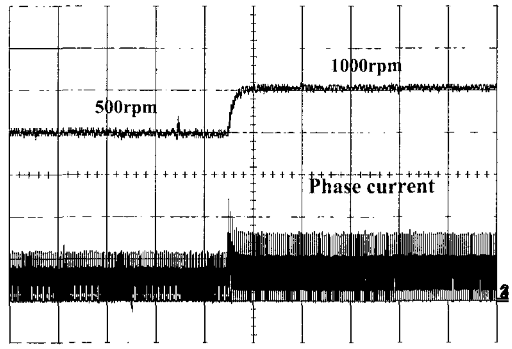

Fig. 16 Waveform of speed and phase current (0.5s/div, 10A/div)

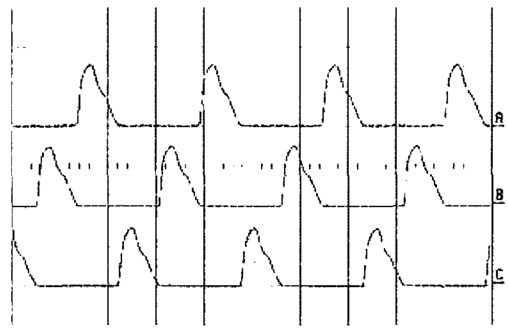

Fig. 17 Phase current according to load test (2500rpm, 100w, 20A/div, 2ms)

5.2 Energy Efficient C-dump Converter

Fig. 18, 19, 20 and 21 show the experimental results of the energy-efficient c-dump converter. Fig. 18 shows a phase current and the dump capacitor voltage at 1000 rpm.

Fig. 19, 20 are waveforms of the step response for acceleration speed and phase current. Under the same conditions as a modified c-dump converter for the load test, Fig. 21 shows the current of each phase with 100W load at 2500 rpm.

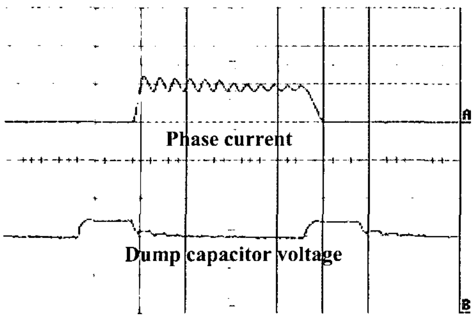

Fig. 18 Phase current and dump capacitor voltage at 1000rpm (10A/div, 6V/div, 1ms)

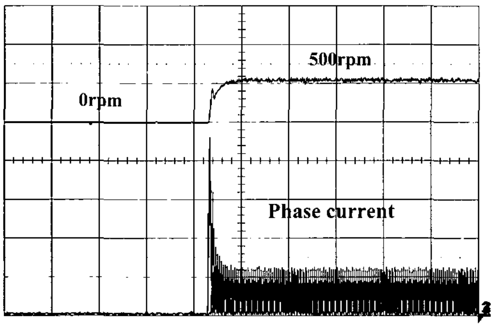

Fig. 19 Waveform of speed and phase current (0.5s/div, 10A/div)

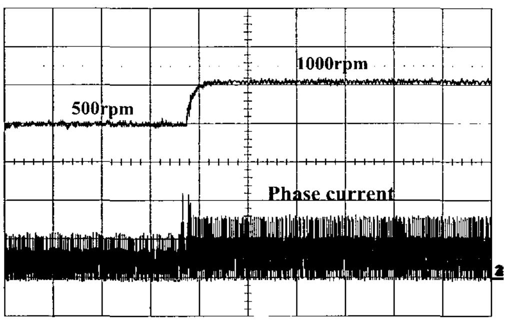

Fig. 20 Waveform of speed and phase current (0.5s/div, 10A/div)

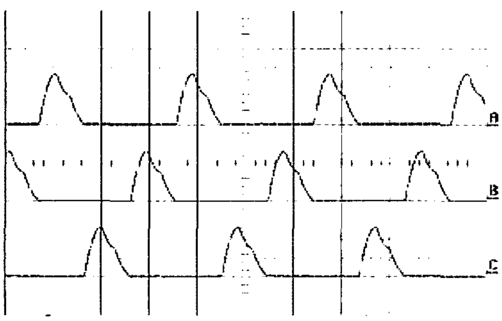

Fig. 21 Phase current according to load test (2500rpm, 100w, 20A/div, 2ms)

The rated and associated parameters of the SRM are shown in the Table 1.

Table 1 Specification of SRM

Rated output	250[W]
Rated voltage	12[Vdc]
Number of phase	3[phase]
Stator poles	6[pole]
Rotor poles	4[pole]
Phase resistance	0.02166[Ω]
Maximum inductance	332[mH]
Minimum inductance	241[mH]

Fig. 22 shows the speed curves according to the changing advance angle for two kinds of converters. These advance angles were adjusted to EPROM data. This graph illustrates that a 9.6degree is an appropriate angle to get the motor's rating speed. At this point, we know that the speed characteristic of the energy efficient c-dump converter is better than that of the Modified c-dump converter.

Fig. 23 is the block diagram for measuring efficiency. The DC source is considered as an overall system's input power and the output of DC generator is calculated as a system's output power. The loss associated with the DC generator is neglected. When measuring the speed efficiency, the maximum figure for the load value is chosen to enable and follow the reference speed.

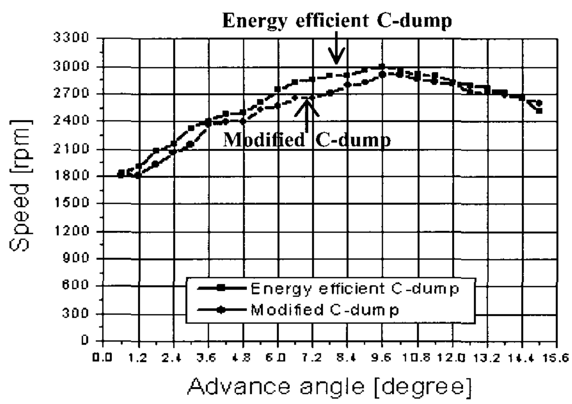

Fig. 22 Advance angle –speed curves

Fig. 24 shows the efficiency for speed of modified c-dump converter and energy efficient c-dump converter with an advance angle of 9.6 degrees, selected through experimentation. We also know that the energy efficient c-dump converter is superior to the modified c-dump converter.

Fig 25 shows the hardware used this experiment.

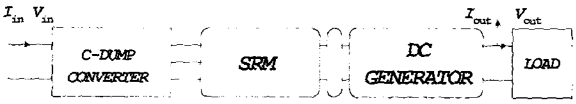

Fig. 23 SRM system block diagram for measuring efficiency

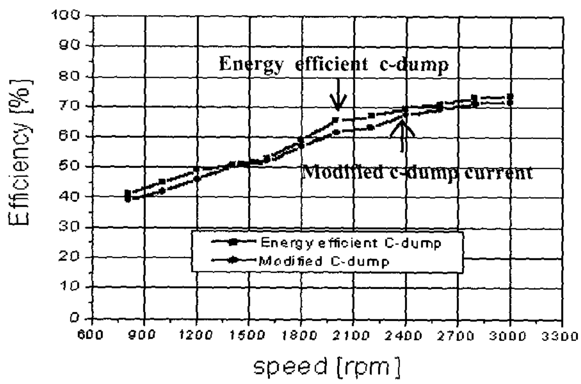

Fig. 24 Speed-efficiency curves

Fig. 25 Hardware overview

6. Conclusions

This paper has presented two types of converters for SRM drives that introduce modifications to the conventional c-dump converter configuration. To improve the weaknesses associated with the asymmetric bridge converter in the limited internal environment of the automotive application, two kinds of c-dump converters are tested in terms of dump capacitor voltage, speed response according to the variation of advance angle and efficiency for the radiator cooling-fan drive of an automotive application.

In particular, the energy- efficiency c-dump converter proved better than the modified c-dump converter in efficiency according to speed variation. Therefore, the laboratory testes confirmed the feasibility of the SRM drive as a candidate for advanced automotive applications, and verified its simplicity and low cost.

Acknowledgment

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