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High Performance Switched Reluctance Motor Drive for Automobiles using C-dump Converters

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Abstract

Small electric motors in an automobile perform various tasks such as engine cooling, pumping, and in heating, ventilating, and air-conditioning (HVAC) system. At present, most of dc motors are supplied by 12V or 24V batteries. However, DC motors surfer from lack of efficiency, low life cycles and unreliability. Therefore, there is a growing interest in substituting DC motors for advanced AC motors including switched reluctance motors. Although there are several other forms SRM converters, they are either unsatisfactory to the control performance or unsuitable for the 12V-battery powered 3-phase SRM drives. Taking into account the requirement for effective operation and simplicity structure of converter in the limited internal environment of automobiles, the author inclines toward selecting the modified C-dump converter as well as the energy efficient C-dump converter. This is so that more economical and efficient converter topology in automobile industries can be utilized. This paper describes the foundation for the design and development of a 12V-250W-3000rpm SRM drives for automobiles. Furthermore, complete circuit, computer simulation and experiment results are presented to verify the performance of the C-dump converters.

1. Introduction

With some relatively simple converter and control requirements, the SRM is gaining an increasing attention in the drive(power transmission) industry. Conventional SRM converters, in particular, provide the most flexible and effective control of the current waveforms of SRM, but they use the most number of switches and produce conducting voltage drops across two power switches during SRM operation. An important factor in the selection of a motor and a drive for an industrial application is cost. For automotive applications with a 12V battery supply, this type of circuitry unfavorable. Taking into account the requirements of effective operation and simplicity in the structure of converters at the limited internal environment of automobiles, 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, and could reduce the overall cost of the SRM drive systems. They likewise provide some additional advantages. The topologies having single switch per phase are compared respectively in a point of dump capacitor voltage, speed response, drive characteristic according to the variation of advance angle and efficiency for the overall system as the radiator cooling-fan drive of an automobile. The voltage equation of the SRM is given as

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

In this equation labeled(1), the three on the right-hand side represent the resistive voltage drop, inductive voltage drop, and induced emf respectively. SRM torque T equation can be determined from the co-energy (Wc) as

$$W_C = \frac{1}{2} i(\theta)^2 \cdot L(\theta) \quad (2)$$

$$T = \frac{\partial W_C}{\partial \theta} = \frac{1}{2} i(\theta)^2 \frac{dL(\theta)}{d\theta} \quad (3)$$

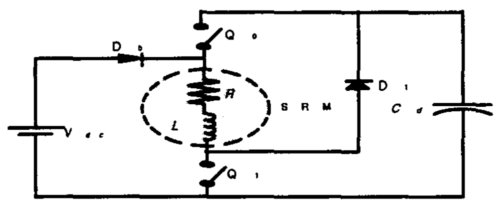

Fig. 1. The structure of SRM and C-dump converter drive system

Note that the torque is proportional to the square of the phase current and the slope of the inductance. [1] The $dL/d\theta$ term in equation 1 reduces current at positive torque in the positive direction.

2. Modified C-dump Converter

The modified C-dump converter is shown in Fig. 2. It is derived from the C-dump converter circuit with eliminating the inductor of the buck converter. The energy again is 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.3 represents the operating mode of modified C-dump converter topology.

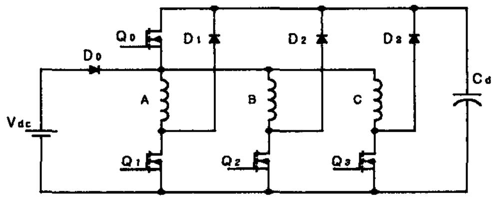

Fig. 2. Modified C-dump converter.

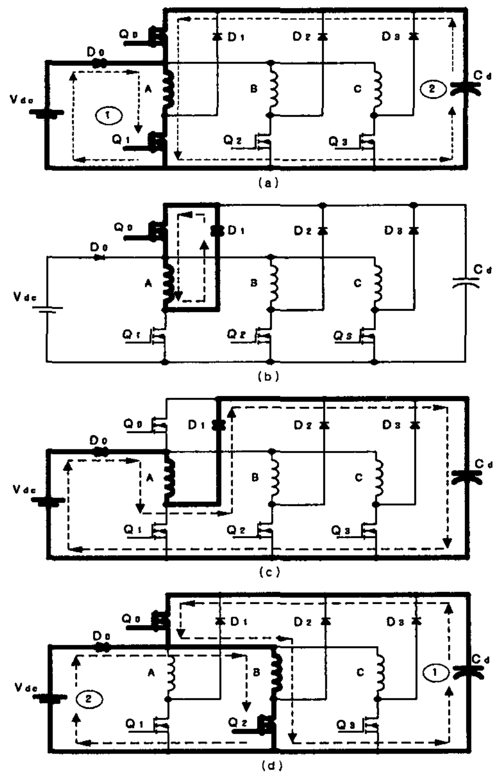

Fig. 3. Operating mode of modified C-dump

In Fig. 3(a), both Q_1 and Q_0 are closed. With the capacitor voltage V_{cd} being larger than the V_{dc}, phase A is magnetized by V_{cd}. Corollarily, for other case, Q_1 is on and the phase A winding is connected to the DC link voltage V_{dc}. During the conduction mode in Fig. 3(b), phase A is demagnetized through free-wheeling D_1. Q_0 and D_1 are conducted, short-circuiting the winding. The magnetic energy is discharged by a free-wheeling current, but the demagnetization is very slow, depending entirely on the circuit resistance. Q_1 has to withstand V_{cd}.

Both Q_0 and Q_1 are turned off (see Fig. 3 (c)), Phase A is demagnetized through D_1, capacitor C, and the input source, which provides the free-wheeling path. The capacitor is charged by energy transfer from the winding and by the DC link.[2] Fig. 3(d) shows that transfer of a magnetized phase, the operation characteristic is equivalent to Fig. 3 (a).

3. Energy Efficient C-dump Converter

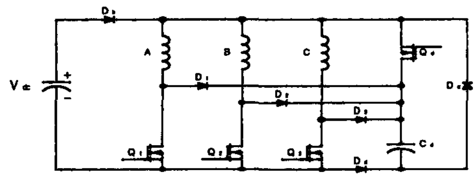

Fig. 4. Energy -efficient C-dump converter.

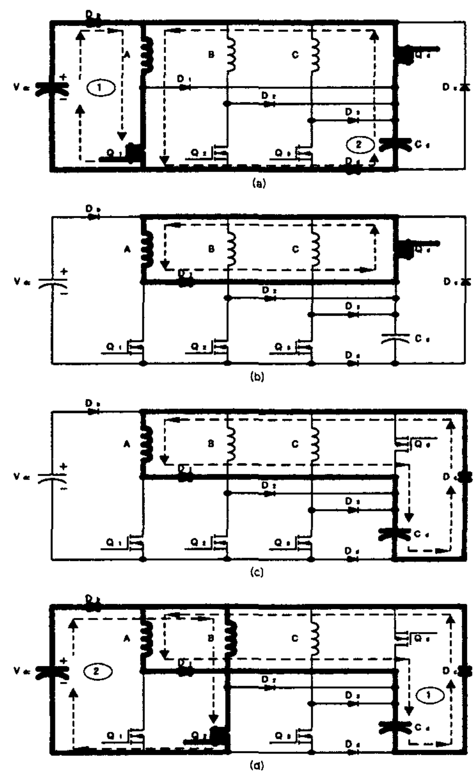

Fig. 5. Operating mode of energy-efficient C-dump
(a) Conduction mode (b) Free-wheeling mode
(c) Commutation mode-I (d) Commutation mode-II

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 V_{dc}

rather than $2V_{dc}$ and control of the dump capacitor voltage is simplified and duplication of the phase currents is enabled in an Energy efficient C-dump converter. Fig.4 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 (V_{dc}) level compared to twice the supply voltage ($2V_{dc}$) in the conventional C-dump converter.

In addition, the converter has simple control requirements, and allows the motor phase current to free-wheel during chopping mode. The converter has four modes of operation as shown in Fig. 4.

During the conduction mode, shown in Fig. 5(a), phase A starts to magnetize with both Q_1 and Q_d 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). Then 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 Q_1 on and off. The phase current free-wheels through diode D_1 and Q_d when Q_1 is "off"as shown in Fig. 5(b). The current commutates from Q_1 and Q_d "off" and charges the dump capacitor. Diode D_d blocks the demagnetizing current which flowed through the source. While phase A is being demagnetized, phase B can be magnetized by turning Q_2 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. [3]

4. Simulation

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

4.1 Modified C-dump Converter

Fig. 6 shows the simulated step change of the speed, phase current and dump capacitor voltage at 500-1000rpm.

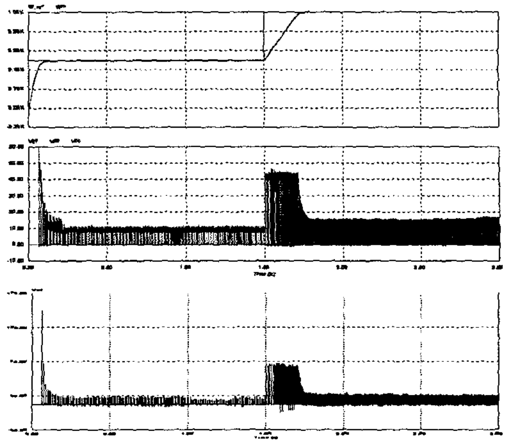

Fig. 6. Simulation results at 500-1000rpm. (200rpm/div, 10A/div, 50V/div 1s/div)

4.2 Energy Efficient C-dump Converter

Fig. 7 shows the simulated step response on the speed, phase current and dump capacitor voltage at 500-1000rpm.

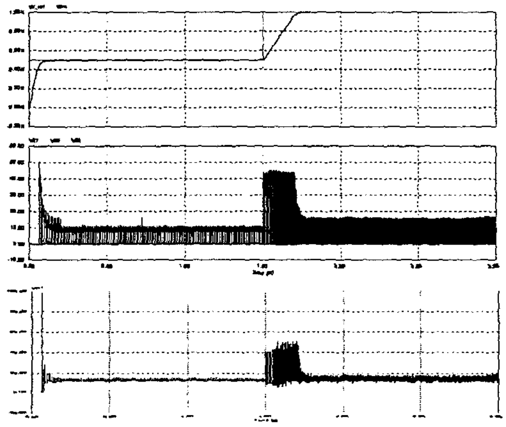

Fig. 7. Simulation results at 500-1000rpm. (200rpm/div, 10A/div, 20V/div, 1s/div)

5. Experimental Results

Fig. 8 shows the block diagram of SRM drive system. This control algorithm is implemented by an 80c196KC.

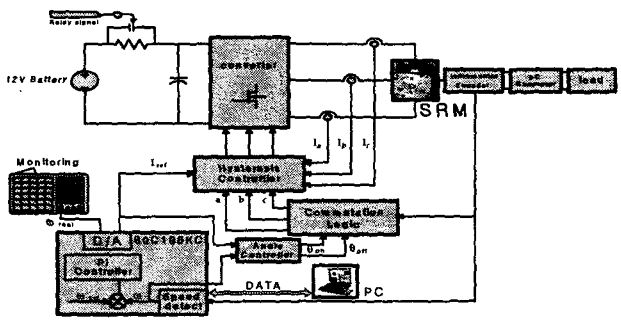

Fig. 8. Block diagram of SRM drive system.

It receives position signals from an encorder and calculates real speed values. 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 hysteresis 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. With the 12V battery for the car, we tested respectively the whole system performance at a point of view dump capacitor voltage, speed response, drive characteristic according to the variation of advance angle and efficiency for overall system as the radiator cooling-fan drive of automobile.

5.1 Modified C-dump Converter

Fig. 9, 10 show the experimental results of the modified C-dump converter.

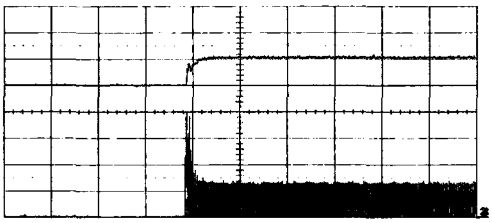

Fig 9. Waveform of speed and phase current (0.5s/div, 10A/div)

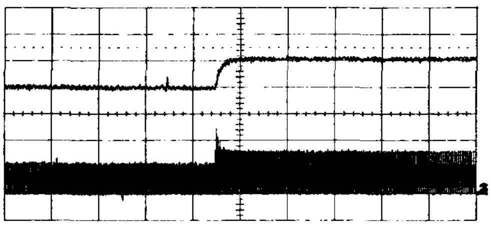

Fig 10. Waveform of speed and phase current (0.5s/div, 10A/div)

Fig. 9, 10 are waveforms of the step response for acceleration speed and phase current. Finally, to examine the performance of the SRM with the modified C-dump converter, The SRM is loaded with a permanent magnet dc generator, rated 250W with a base speed of 3000rpm. The road to dc generator is varied by connecting a rheostat at the motor terminal.

5.2 Energy efficient C-dump Converter

Fig. 11, 12 show the experimental results of the energy efficient C-dump converter.

Fig. 11, 12 are waveforms of the step response for acceleration speed and phase current.

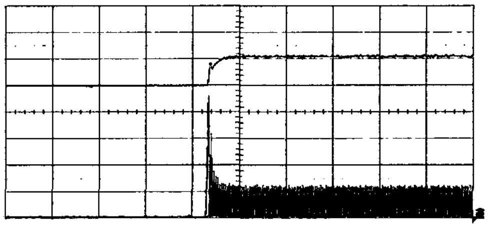

Fig. 11. Waveform of speed and phase current (0.5s/div, 10A/div)

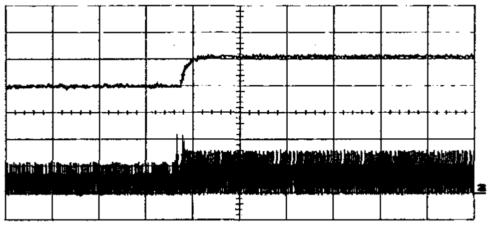

Fig. 12. Waveform of speed and phase current (0.5s/div, 10A/div)

Under same condition as a modified C-dump converter for the load test, we examined. 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]

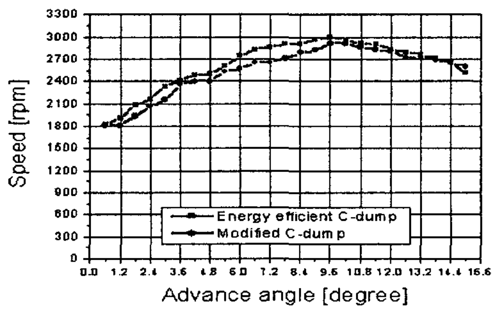

Fig. 13. Advance angle speed curves.

Fig. 13 shows the speed curves according to changing advance angle for two kinds of converters. These advance angles were adjusted to EPROM data. This graph illustrates that 9.6degree is an appropriate angle to get the rating speed of motor. And 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. 14 is the block diagram for measuring efficiency.

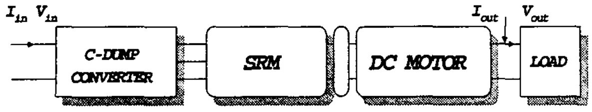

Fig 14. SRM system block diagram for measuring efficiency

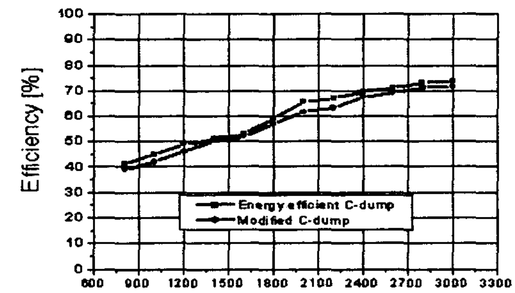

Fig 15. Speed-efficiency curves.

The DC source is considered as an overall system's input power and the output of DC generator is calculated as system's output power. It is neglected the loss of DC generator.

On measuring the speed efficiency, maximum figure for the load value is chosen to enable to follow the reference speed.

Fig. 15 shows the efficiency for speed of modified C-dump converter and energy efficient C-dump converter with an advance angle 9.6degree, selected through experiment.

We know also energy efficient C-dump converter is superior to modified C-dump converter.

6. Conclusions

Recently SRM used in automobiles of power assistant steering, accessory motion control and traction drives. In the motion control and traction drives especially, under the same performance, efficiency and cost, simple structure is of important factors. So the most optimal motor drive is needed. When C-dump converter is compared with asymmetric bridge converter, it has a benefit from cost and has more simple structure. To improve the weakness of the conventional SRM converter (Asymmetric bridge converter) in the limited internal environment of automobiles, we tested two kinds of C-dump converters respectively in terms of the operating system and high performance control. This paper presents the suitability in designing and constructing drive circuits for SRM in the limited internal environment of automobiles.

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