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PERFORMANCE ANALYSIS OF C-DUMP CONVERTER FOR BLDC MACHINE APPLICATION IN A FLYWHEEL ENERGY STORAGE SYSTEM

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ABSTRACT

This paper presents a modified C-dump converter for brushless DC (BLDC) machine application in the flywheel energy storage system. The proposed converter can realize the energy flowing from source to BLDC machine flywheel and BLDC machine with fly wheel to load. The energy extracted from the turnoff phase of the BLDC machine is to be recovered by C-dump converter. The system principle of operation, modelling, and control strategy has been discussed in this paper. This paper also investigated Simulation and experimental results of the proposed system.

KEYWORDS

Brushless DC (BLDC) machine, c-dump converter, flywheel energy storage system.

1. INTRODUCTION

The flywheel energy storage system (FESS) is a suitable choice for temporary energy storage in high power utility applications and hybrid electric systems [1], [2].The permanent magnet brushless DC machine (BLDCM) is one of the fixed motor for the flywheel energy storage system [3]. The Fig. 1 describes the half-bridge topology for high-speed BLDC machine. The half-bridge topology consists of a half-bridge converter and buck chopper. The half bridge converter Compared with the full-bridge converter, the half bridge converter consist of half of the number of switches and also it avoids the short circuit across the phase segment in the full-bridge converter. However, this half-bridge topology contains two drawbacks for the flywheel energy storage system.1) the flow of energy is unidirectional and 2) the turnoff phase energy is consumed on the resistance which is waste of energy. This paper proposes C-dump converter for high-speed BLDC machine which is used to overcome these drawbacks. And also describes principle of operation and the analysis of the proposed converter.

2. STRUCTURE AND PRINCIPLE

Fig.2 illustrates the modified C-dump converter for BLDC machine used in the flywheel energy storage system. The proposed converter consists of a half-bridge converter (switches Ta, Tb, Tc), a bidirectional DC–DC converter (switches T1 ,T2 ; inductance L2 and capacitor C3), an energy recovery chopper (switch Tr ; diodes D1, D2, D3 Dr ; inductance Lr and capacitor C0), and a DC filter (inductance L1 and capacitors C1,C2 ,).where U1 indicates for the source and R1 indicates for the load.

The proposed converter works in two modes of operations: one is the FESS charging mode and another one is the FESS discharging mode.

In the charging mode of the FESS, the source U1 supplies energy to the flywheel, then switch S1 is on and switch S2 is off. In this mode, the half-bridge converter operates as the motor operation. The switches Ta, Tb, and Tc are operate with the duration of 120^0 degrees electrically.

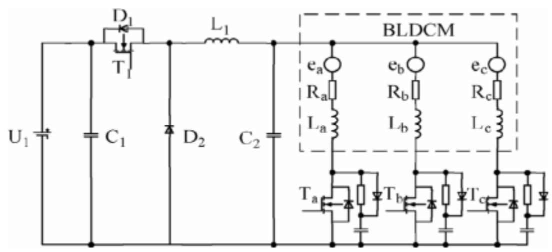

Figure1. Common half-bridge topology for high-speed BLDCM

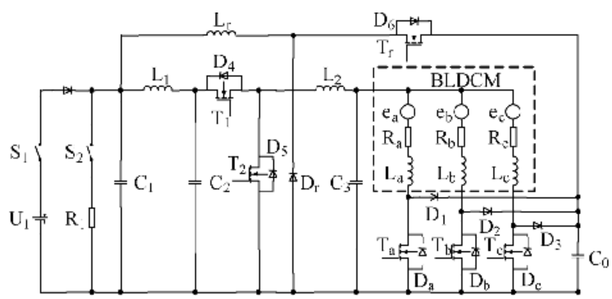

Figure.2. Modified C-dump converter for the FESS

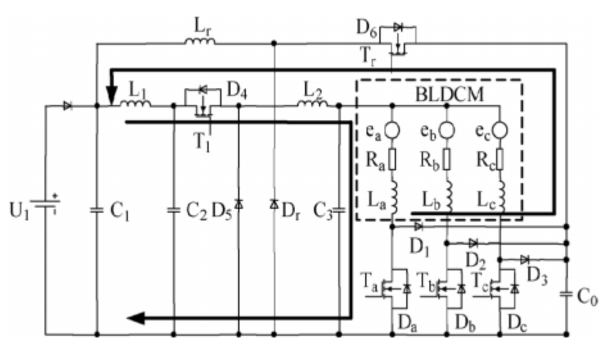

Figure.3 Modified converter working in the charging mode

T_r operates as the pulse width modulation (PWM) operation mode and the energy of the turnoff phase to the source recovered by Tr [4].The bidirectional DC–DC converter operates in the buck operation mode (T_2 is off and T_1operates in PWM operation mode.) to control the speed of the motor. Fig. 3 shows the proposed converter for the FESS which is in charging mode.

In the FESS discharging mode, the BLDC machine (with flywheel) works as a generator, the kinetic energy of the flywheel is discharged to the load, and then switch S_1 is off and switch S_2 is on

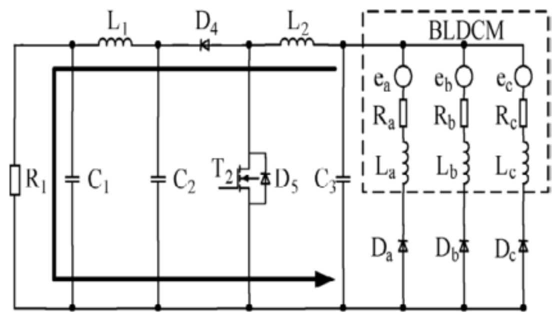

Figure 4.Proposed converter working in the discharging mode

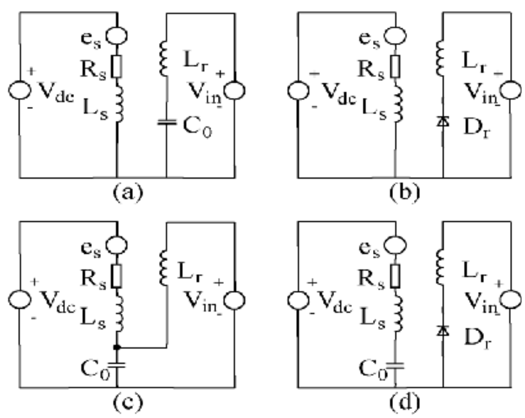

Figure 5.The equivalent topologies of the proposed converter in its switching operation.
(a) Switch T_s On; switch T_r on; (b) Switch T_s on, switch T_r off; (c) switch T_s off, switch T_r on;
(d) Switch T_s off, switch T_r off.

In this mode, the half-bridge converter operates as a diode rectifier which converts the high-frequency AC to the DC. Switches T_a, T_b, T_c &,T_r are all off mode and diodes D_a, D_b, D_c forms a diode rectifier. The output voltage is dropped Whenever, the flywheel speed is decreasing,. The bidirectional DC–DC converter operates in boost operation mode (switch T_2 operates in PWM operation mode and switch T_1 is turn off) in order to keep the output voltage stable. Fig. 4 describes the proposed converter for the FESS working in the discharging mode.

3. MODELLING AND CONTROL STRATEGY

The modelling and analysis of the proposed converter are presented in this part.

3.1 Dynamic Model

Four different modes of operation can be identified for the proposed converter working in the charging mode. Fig.5 describes the equivalent circuits of the converter in its switching operation. The switch voltage drop, the diode, the resistance of the inductance, and the mutual inductance of the motor phases are ignored. Switch T_s considers as T_a, or T_b , or T_c V_{dc} indicates the bus voltage (voltage of the capacitor C_3),e_s indicates the back-electromotive force (back-EMF) of the motor, R_s indicates phase resistance of the motor, L_s indicates phase inductance of the motor, i_s indicates phase current of the motor,V_{c0} indicates the capacitor C_0 voltage, V_{in} indicates the source input voltage (voltage of the capacitor C_1), L_r indicates the energy recovery circuit inductance, i_r indicates the current of the energy recovery inductance L_r , and k_0 is the buck factor.

1) T_s on, T_r on

$$V_{dc} = L_s \frac{di_s}{dt} + e_s + R_s i_s \tag{1}$$

$$V_{in} = V_{co} - L_r \frac{di_r}{dt} \tag{2}$$

$$C_0 \frac{dV_{c0}}{dt} = -i_r \tag{3}$$

$$V_{dc} = K_0 V_{in} \tag{4}$$

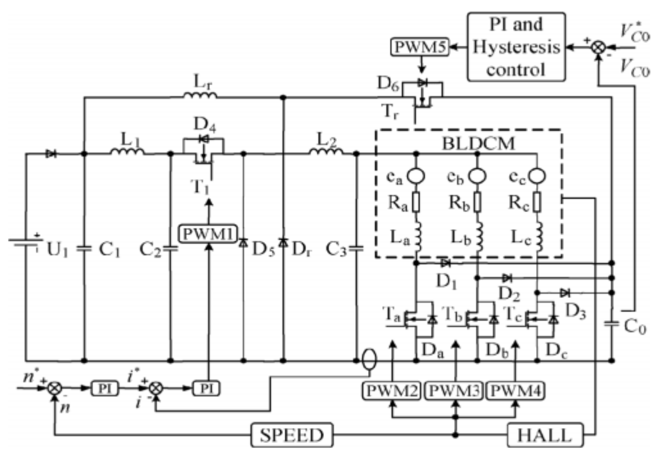

Figure.6. Control structure of the converter in the charging mode

2) T_s on, T_r off

$$V_{dc} = L_s \frac{di_s}{dt} + e_s + R_s i_s \tag{5}$$

$$V_{in} = -L_r \frac{di_r}{dt} (\text{if } i_r > 0) \tag{6}$$

$$V_{c0} = \text{constant} \tag{7}$$

$$V_{dc} = K_0 V_{in} \tag{8}$$

3) T_s off, T_r on

$$V_{dc} = L_s \frac{di_s}{dt} + e_s t + R_s i_s + V_{c0} \tag{9}$$

$$V_{in} = V_{c0} - L_r \frac{di_r}{dt} \tag{10}$$

$$C_0 \frac{dV_{c0}}{dt} = i_s - i_r \tag{11}$$

$$V_{dc} = K_0 V_{in} \tag{12}$$

4) T_s off, T_r off

$$V_{dc} = L_s \frac{di_s}{dt} + e_s + R_s i_s + V_{c0} \tag{13}$$

$$V_{in} = -L_r \frac{di_r}{dt} (\text{if } i_{r>} 0) \tag{14}$$

$$C_0 \frac{dV_{c0}}{dt} = i_s \tag{15}$$

$$V_{dc} = K_0 V_{in} \tag{16}$$

3.2. Design of Main Parameter

The c-dump converters of main parameters are derived as follows.

3.2.1. Energy Extracted From the Turnoff Phase

The system mechanism in stable state and the switching loss is ignored. The following describes the energy which is extracted from the turnoff phase.

$$W_{LS} = \frac{1}{2} L_s i_{s\,Max}^2 \qquad 17$$

Where W_{LS} indicates the energy extracted from the turnoff phase. i_{sMax} indicates the phase current of the motor in commutation moment; these can be obtained from table (1).

Table 1: Ratings of BLDCM

Rated Voltage(V)	100
Rated Stator Current(A)	20
Rated Power(KW)	2
Frequency in HZ	5333
Phase Inductance in mH	0.06
Phase Resistance in Ω	0.2

The power extracted from the turnoff phase is

$$P_{LS} = \frac{W_{LS}}{t} = 3 \times \frac{1}{2} L_s i_{s\,Max}^2 \times \frac{1}{2} = \frac{3}{2} L_s i_{s\,Max}^2 \frac{np}{60} \tag{18}$$

Where n is the motor speed and p is the pairs of poles.

3.2.2. Energy Recovery Capacitor C_0

The energy which is extracted from the turnoff phase is delivered to the energy recovery capacitor. Then

$$W_{LS} = \frac{1}{2} L_s i_{s\,Max}^2 = \frac{1}{2} C_0[(V_{c0} + \Delta V_{c0})^2 - V_{c0}^2] \qquad (19)$$

$$C_0 = \frac{L_s i_{s\,Max}^2}{(V_{c0}+\Delta V_{c0})^2 - V_{c0}^2} \qquad (20)$$

Where ΔV_{C0} is the voltage variation of the capacitor C_0. The voltage V_{c0} should be higher than $V_{dc}+e_s$

3.2.3. Energy Recovery Inductance L_r

According to energy conservation, the energy recovered to source can be described as

$$\frac{1}{2} L_s i_{s\,Max}^2 = \frac{1}{2} C_0[(U_c + \Delta U_c)^2 - U_c^2]$$

$$= \frac{1}{2} L_r i_{rMax}^2 - \frac{1}{2} L_r i_{r\,Min}^2 \qquad (21)$$

Where $i_{rMAX}(i_{rMin})$ is the maximum (minimum) current of the inductance L_r . In order to keep the energy recovery fast, the L_r should not be too large. Therefore, it is better for the L_r to work in discontinuous conduction mode $i_{MIN} = 0$

$$\frac{1}{2} L_s i_{s\,Max}^2 = \frac{1}{2} L_r i_{r\,Max}^2 \qquad (22)$$

$$L_r = \frac{L_s i_{s\,Max}^2}{i_{r\,Max}^2} \qquad (23)$$

3.2.4. Control Strategy

The modified proposed converter control structure working in the charging mode is shown in Fig. 6.The Figure includes control of the motor speed and also controls the recovery capacitor voltage. The control of the motor speed includes double loops: the inner loop is current loop and the outer loop is speed loop. The output of three Hall Effect sensors effects commutation among phases. The supply to the motor is protected against over current.

The proportional–integral (PI) control and hysteresis control are combined and it is used in capacitor C_0 voltage control. The capacitor C_0 voltage is recommended for the proposed converter due to its small voltage fluctuation of the energy recovery capacitor and current ripple of the motor.

4. SIMULATION AND EXPERIMENT

To verify the performance of the proposed converter, simulations and experimental tests have been performed. The ratings and parameters of the BLDCM are presented in Table I. Parameters of the converter are shown in Table 2

Table 2.Parameters of the converter

Capacitor	Value(μF)	Inductance	Value(mH)
C_0	33	L_1	0.24
C_1	470	L_2	0.2
C_2	470	L_r	0.4
C_3	1000		

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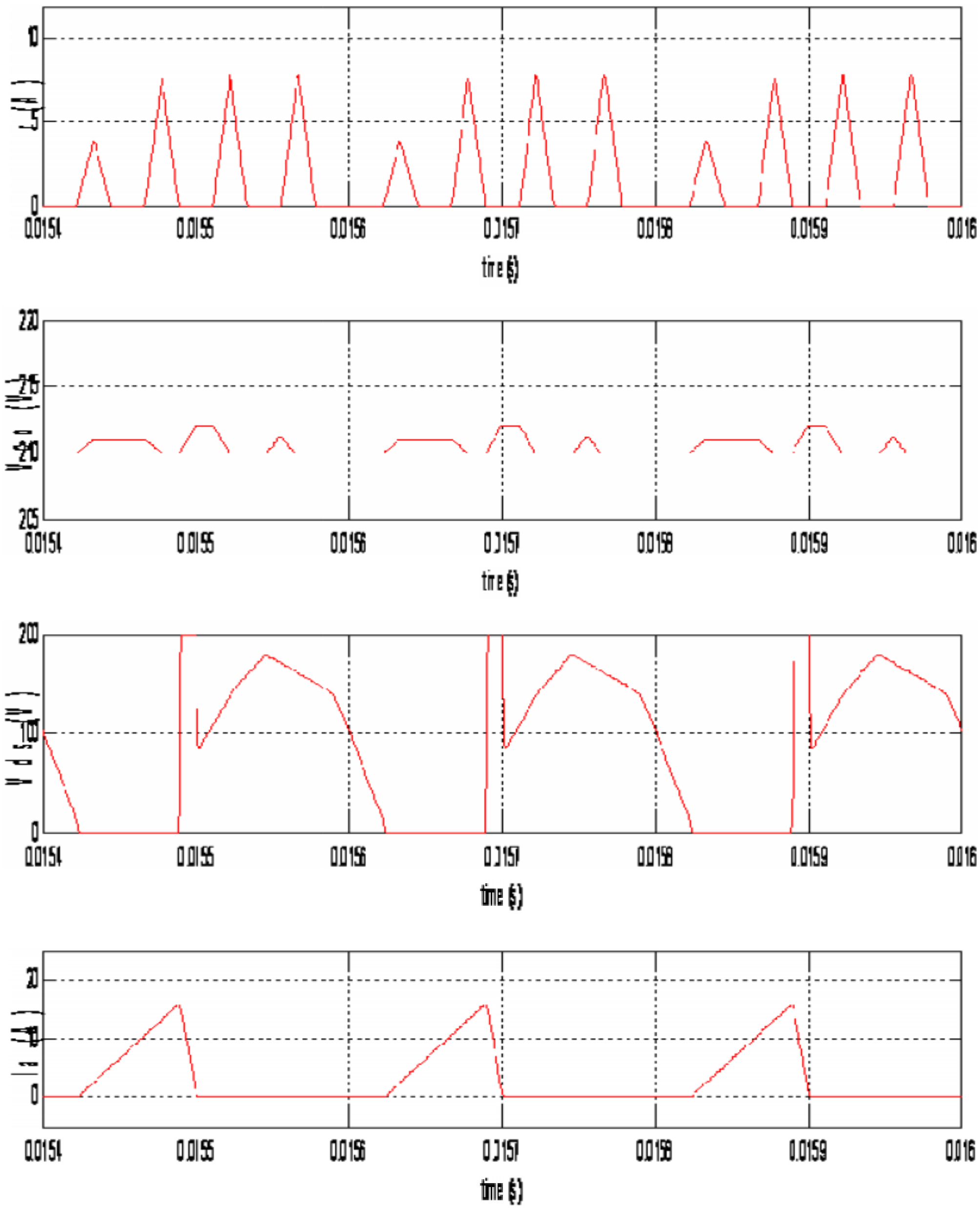

Figure7. Simulation results of the converter working in the charging mode. (a) Recovery current i_r. (b) Voltage of the capacitor C_0. (c) The MOSFET Voltage between the drain and the source terminals (phase A). (d) Current of the phase A.

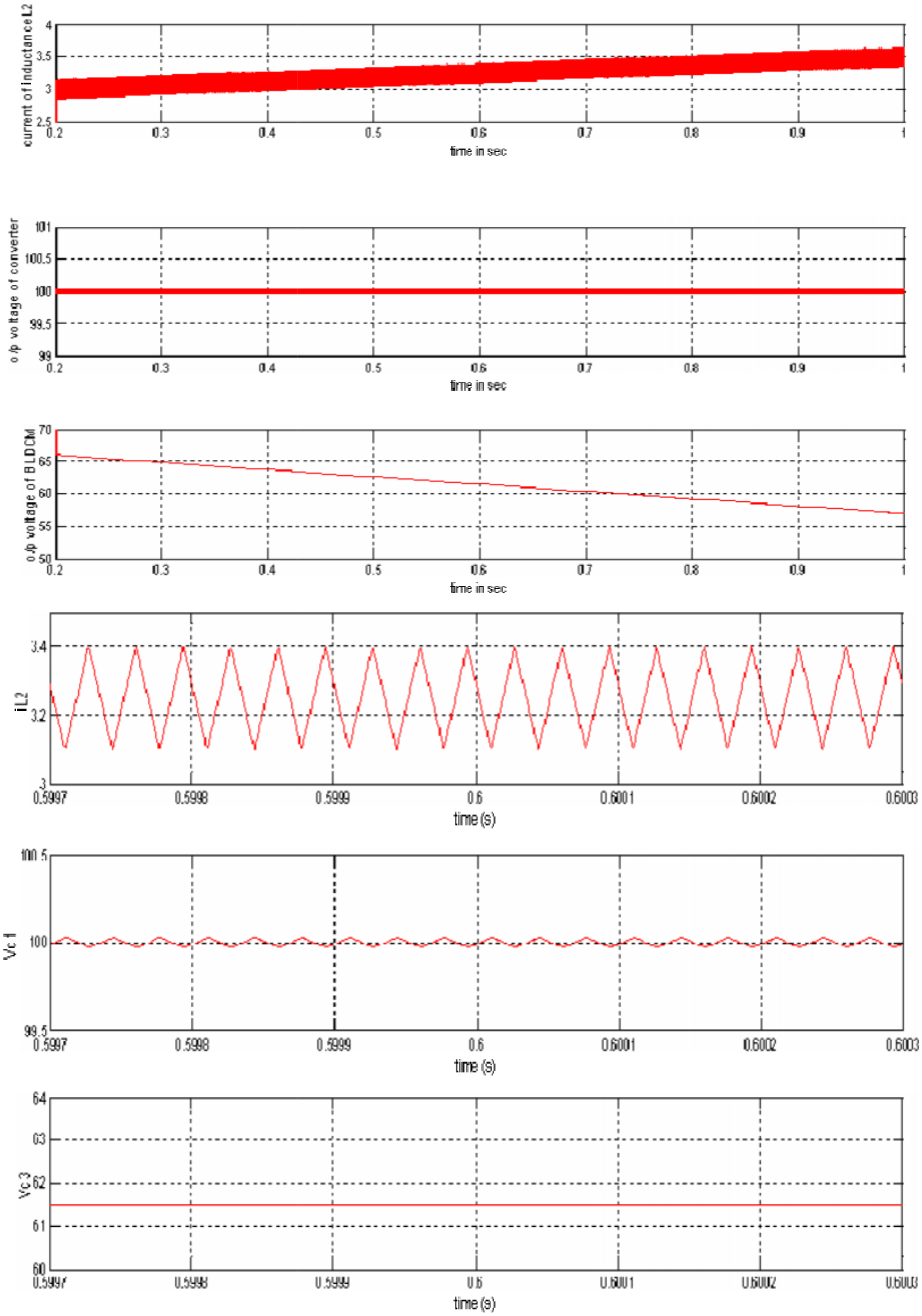

Figure 8.Simulation results of the converter working in the discharging mode. (a) Current of inductance L_2. (b) Output voltage of the converter. (c) Output voltage of the BLDCM rectified by the diode rectifier.

4.1 SIMULATION RESULTS

The simulation results of the proposed C-dump converter working in the charging mode describes in Fig7. At this range, the peak value of the phase current i_a is about 21 A, as shown in Fig. 7(d). Fig. 7(a) shows the recovery current i_r which is limited to a peak value of 9 A. Fig. 7(b) shows the voltage of energy recovery capacitor C_0 which stays around 210 V, and increases to 213 V during commutation when the capacitor starts to discharge into the source.

The voltage (Vds) between the drain and the source of the metal–oxide–semiconductor-field-effect transistor (MOSFET), which equals to the phase terminal voltage plus the bus voltage (Vdc) describes in Fig 7(c).

Fig. 8 shows the simulation results of the proposed converter working in the discharging mode .Fig. 8(a) shows the current of inductance L_2 .The output voltage of the converter (voltage of the capacitor C_1) which stays around 100 V describes in Fig 8(b).

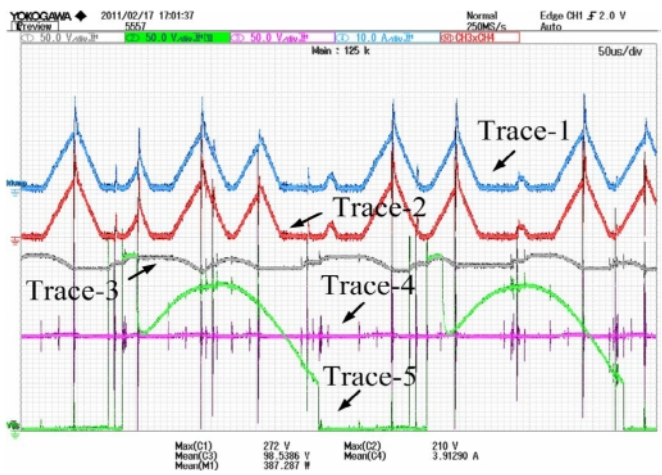

Figure 9 Experimental results of the converter working in the charging mode when the average bus current is 15.6 A.(1) Recovery current i_r (50 μs/div, 10 A/div). (2) Recovery power. (3) Voltage of C_0(50 μs/div, 50 V/div).(4) Source input voltage (50 μs/div, 50 V/div). (5) Voltage between the drainand the source of the MOSFET (50 μs/div, 50 V/div).

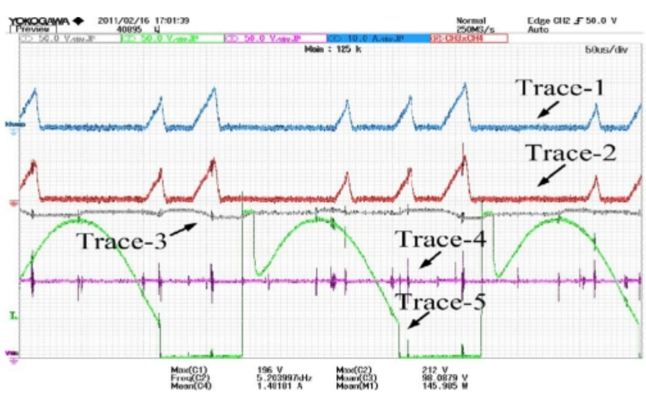

Figure10. Experimental results of the converter working in the charging mode when the average bus current is 8.2 A.(1) Recovery current i_r (50 μs/div, 10 A/div). (2) Recovery power. (3) Voltage of C_0 (50 s/div, 50

V/div). (4) Source input voltage (50 μs/div, 50V/div). (5) the MOSFET voltage between the drain and the source terminals (50 μs/div, 50 V/div).

Whenever, the speed of the flywheel decreases. Fig.8(c) shows the output voltage of the BLDCM rectified by the diode rectifier (voltage of the capacitor C_3).

4.2. EXPERIMENTAL RESULTS

Fig. 9 shows the experimental results of the converter working in the charging mode when the average bus current (current of the inductance L_2) is 15.6 A. the recovery current i_r which is similar to what was observed in simulation described in wave form 1. Waveform "4" shows the source input voltage (voltage of the capacitor C_1). Waveform "2" is the product of waveforms "1" and "4" which equals to the recovery power.

It is about 387 W. Waveform "3" shows the voltage of energy recovery capacitor C_0. A small charging and discharging action of the capacitor can be seen from the waveform, and the average

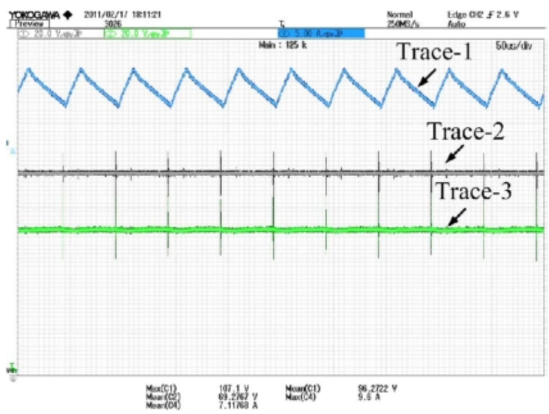

Figure11 Experimental results of the converter working in the discharging mode when the output voltage of the BLDCM is 70 V. (1) Current of inductance L_2 (50 μs/div, 5 A/div). (2) Output voltage of the converter (50 μs/div, 20 V/div).(3) Voltage of the capacitor C_3 (50 μs/div, 20 V/div).

Voltage of C_0 is 204 V. the voltage between the drain and the source of the MOSFET described in wave form 5. Fig. 10 shows the experimental results of the converter working in the charging mode when the average bus current is 8.2 A. With the phase current decreasing, the recovery energy reduces. The average recovery current is 1.48 A, and the average recovery power is about 145.9 W. Fig. 11 shows the experimental results of the converter working in the discharging mode when the output voltage of the BLDCM rectified by the diode rectifier is 70 V. Waveform "1" shows the current of inductance L_2 . Waveform "2" shows the output voltage of the converter which is stable, about 96.2 V. Waveform "3" is the voltage of the capacitor C_3.

5. CONCLUSION

The modified C-dump converter for BLDCM used in the flywheel energy storage system is described in this paper. The bidirectional energy flowing is realized by the proposed converter and also recovers the energy extracted from the turnoff phase. This energy is useful for the motor driver system especially for the flywheel energy storage system. The principle of operation, modelling, and control strategy of the System has been presented. Simulation and experiment confirm the theoretical results and shows the good performance of the proposed converter. The study indicates that the converter is suitable for the FESS applications.

6. REFERENCES

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