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A Modified C-Dump Converter for BLDC Machine Used in a Flywheel Energy Storage System

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Abstract
This paper presents a modified C-dump converter for brushless DC (BLDC) machine used in the flywheel energy storage system. The converter can realize the energy bidirectional flowing and has the capability to recover the energy extracted from the turnoff phase of the BLDC machine. The principle of operation, modeling, and control strategy of the system has been investigated in the paper. Simulation and experimental results of the proposed system are also presented and discussed.
***Index Terms*—**Brushless DC (BLDC) machine, c-dump converter, flywheel energy storage system.

I. INTRODUCTION

THE flywheel energy storage system (FESS) is an attractive option 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 suitable motors for the FESS [3].The common half -bridge topology for high-speed BLDCM is shown in Fig. 1. It includes a buck chopper and a half-bridge converter. Compared with the full-bridge converter, the half-bridge converter has half the number of switches and avoids the short circuit across the phase leg in the full -bridge converter. However, this half-bridge topology has two disadvantages for the FESS: 1) the energy unidirectional flow, and 2) the energy of the turnoff phase is consumed on the resistance which means the waste of energy. In order to overcome these drawbacks, a modified C-dump converter for high -speed BLDCM used in the FESS is presented in this paper. The principle of operation and the analysis of the proposed converter are developed.

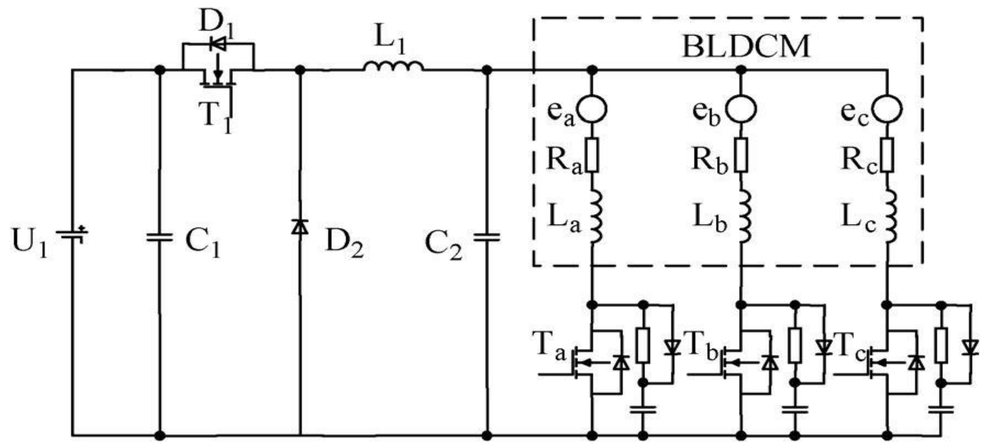


Fig.1. Common half-bridge topology for high-speed BLDCM

II. STRUCTURE AND PRINCIPLE

Fig.2 shows the modified C-dump converter for BLDCM used in the FESS. The proposed converter includes a half-bridge converter (switches T_a ,T_b ,T_c) an energy recovery chopper (switch T_r ; diodes $D1 D2 D3$ D_r ; inductance L_r and capacitor), a bidirectional DC–DC converter (switches T_1 , T_2 ; inductance L_2 and capacitor C_3), and a DC filter (inductance L_1 and capacitors C_1 , C_2). U_1 Stands for the source and R_1 stands for the load. The modified converter has two working modes: the FESS charging mode and the FESS discharging mode. In the FESS charging mode, the source supplies energy to the flywheel, therefore S_1 is on and S_2 is off. In this mode, the half-bridge converter works in the motor operation. T_a ,T_b and T_c are operated with the duration of 120 electrical degrees.

T_r works in the pulse width modulation (PWM) operation mode and recovers the energy of the turnoff phase to the source [4]. The bidirectional DC–DC converter works in buck operation mode (T_1 works in PWM operation mode and T_2 is off.) to con-trol the motor speed. Fig. 3 illustrates the modified converter for the FESS working in the charging mode.In the FESS discharging mode, the BLDCM (with flywheel) acts as a generator to discharge the kinetic energy of the fly-wheel into the load, therefore S_1 is off and S_2 is on. In this mode, the half-bridge converter acts as a diode rectifier to con-vert the high-frequency AC to the DC. $T_a T_b T_c T_r$ are all off and $D_a D_b D_c$ form a diode rectifier. With the speed of fly-wheel decreasing, the output voltage drops. In order to keep the output voltage stable, the bidirectional DC–DC converter works in boost operation mode (T_2 works in PWM operation mode and T_1 is off). Fig. 4 illustrates the modified converter for the FESS working in the discharging mode.

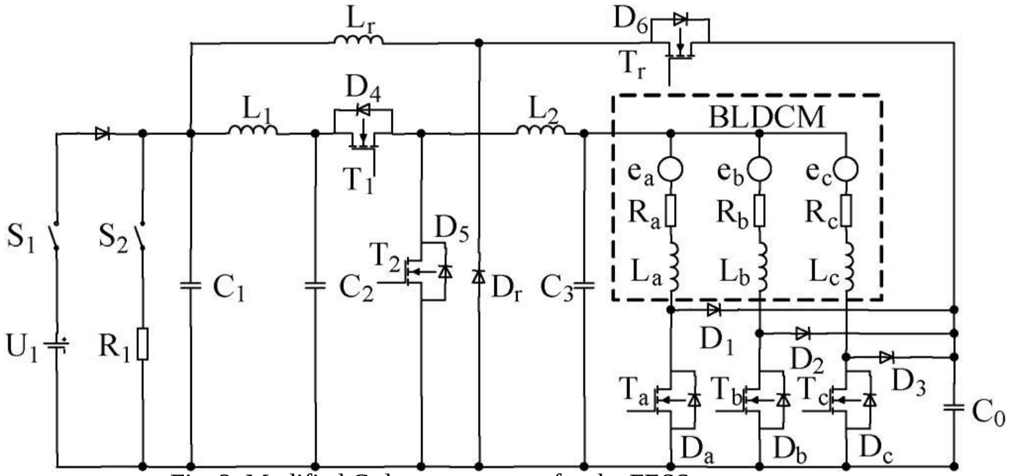


Fig. 2. Modified C-dump converter for the FESS.

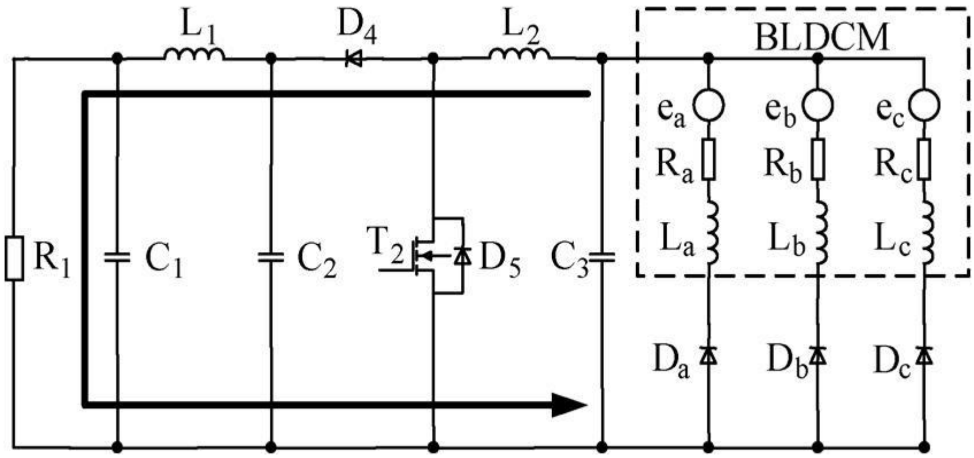


Fig. 4. Modified converter working in the discharging mode.

III. MODELING AND CONTROL STRATEGY

The modeling and analysis of the proposed converter are pre-sented in this part.

A) Dynamic Model:

Four distinct modes of operation can be identified for the pro-posed converter in the charging mode. The equivalent circuits of the converter in its switching operation are shown in Fig. 5. The voltage drop of the switch and the diode, the resistance of the inductance, and the mutual inductance of the motor phases are ignored. T_a considers as T_a or T_b ,or T_c V_{dc} is the bus voltage (voltage of the capacitor C_3), e_s is the back -electromotive force (back-EMF) of the motor, R_s is the motor phase resistance. L_a is the motor phase inductance, i is the motor phase current, V_0 is the capacitor C_0 voltage, V_i is the source input voltage (voltage of the capacitor C_1), L_r is the energy recovery circuit inductance i_s is the current of the energy recovery inductance L_r. and k_0 is the buck factor.

1) T_s on, T_r on

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

$$V_{in} = V_{c0} - L_r \frac{di_r}{dt} \tag{2}$$

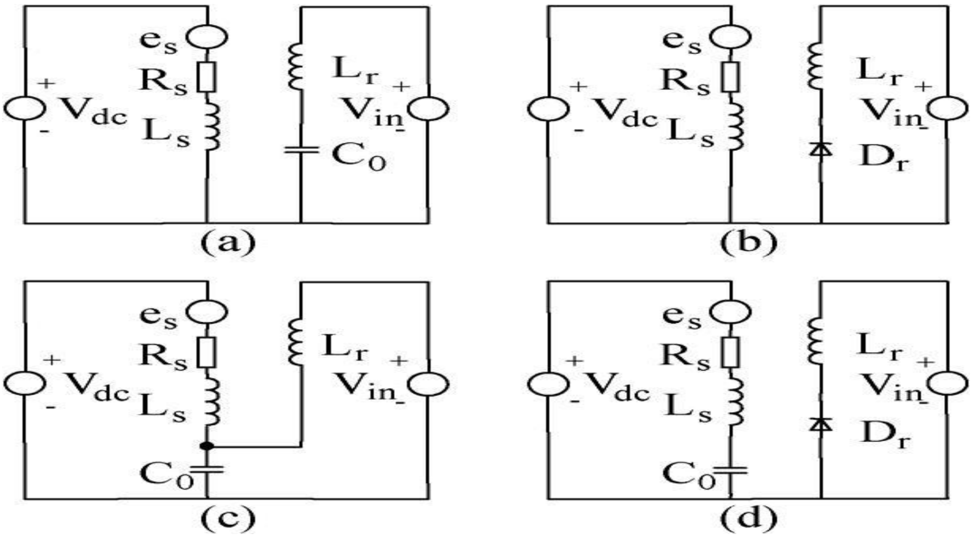


Fig. 5. The equivalent circuits of the converter in its switching operation.
(a) T_s on, T_r on; (b) T_s on, T_r off; (c) T_s off, T_r on; (d) T_s off, T_r off.

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

$$V_{dc} = k_0 V_{in}. \tag{4}$$

2) T_s on, T_r off

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

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

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

$$V_{dc} = k_0 V_{in}. \tag{8}$$

3) T_s off, T_r on

$$V_{dc} = L_s \frac{di_s}{dt} + e_s + R_s i_s + V_{c0} \quad (9)$$

$$V_{in} = V_{c0} - L_r \frac{di_r}{dt} \quad (10)$$

$$C_0 \frac{dV_{c0}}{dt} = i_s - i_r \quad (11)$$

$$V_{dc} = k_0 V_{in}. \quad (12)$$

4) T_s off, T_r off

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

$$V_{in} = -L_r \frac{di_r}{dt} \qquad (\text{if } i_r > 0) \quad (14)$$

$$C_0 \frac{dV_{c0}}{dt} = i_s \quad (15)$$

$$V_{dc} = k_0 V_{in}. \quad (16)$$

B. Design of the Main Parameter
The main parameters of the proposed converter are derived as follows.

1) Energy Extracted From the Turnoff Phase: The system works in steady state and the switching loss is ignored. The en-ergy extracted from the turnoff phase can be described as

$$W_{\mathrm{LS}} = \frac{1}{2} L_s i_{s\mathrm{Max}}^2 \quad (17)$$

Where W_{ls} is the energy extraxted from the turn off phase is the motor phase Is_{Max} current in commutation moment. It can be obtained (1). The power extracted from the turnoff phase is

$$P_{\mathrm{Ls}} = \frac{W_{\mathrm{LS}}}{t} = 3 \times \frac{1}{2} L_s i_{s\mathrm{Max}}^2 \frac{1}{T} = \frac{3}{2} L_s i_{s\mathrm{Max}}^2 \frac{np}{60} \quad (18)$$

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

TABLE I
RATINGS AND PARAMETERS OF BLDCM

Rated voltage (V)	100
Rated stator current (A)	20
Rated power (kW)	2
Frequency (Hz)	5333
Phase inductance (mH)	0.06
Phase resistance (Ω)	0.2

TABLE II
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		

2) Energy recovery capacitor C_0 *:* The energy extracted from the turnoff phase is delivered to the energy recovery capacitor. Therefore

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

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

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) Energy Recovery Inductance L_r *:* According to energy conservation, the energy recovered to source can be described as

$$\frac{1}{2} L_s i_{s\rm Max}^2 = \frac{1}{2} C_0 \left[(U_c + \Delta U_c)^2 - U_c^2 \right] = \frac{1}{2} L_r i_{r\rm MAX}^2 - \frac{1}{2} L_r i_{r\rm MIN}^2 \quad (21)$$

where $i_{r\rm MAX}(i_{r\rm Min})$ 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 $i_{\rm rMIN} = 0$

$$\frac{1}{2} L_s i_{s\rm Max}^2 = \frac{1}{2} L_r i_{r\rm MAX}^2 \quad (22)$$

$$L_r = \frac{L_s i_{s\rm Max}^2}{i_{r\rm MAX}^2}. \quad (23)$$

C. Control Strategy

The control structure of the modified converter working in the charging mode is shown in Fig. 6. It includes the motor speed control and the recovery capacitor voltage control.The motor speed control includes double loops: the inner cur-rent loop and the outer speed loop. The commutation of phases is decided based on the output of three Hall effect sensors. The motor phases are protected against over current.The proportional–integral (PI) control combined with the hysteresis control is used in capacitor C_0 voltage control. It is recommended for the converter due to its small voltage fluctuation of the energy recovery capacitor and current ripple of the motor.

IV. SIMULATION AND EXPERIMENT

To verify the performance of the proposed converter, simula-tions and experimental tests have been performed. The ratings and parameters of the BLDCM are presented in Table I. Param-eters of the converter are shown in Table II.

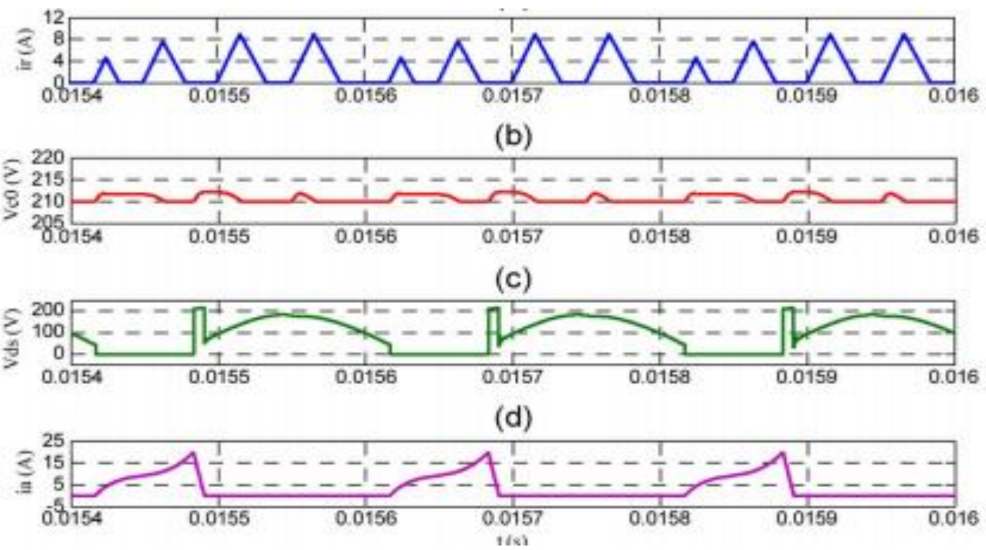


Fig. 7. Simulation results of the converter working in the charging mode.(a) Recovery current i (b) Voltage of the capacitor C_0 . (c) Voltage between the drain and the source of the MOSFET (phase A). (d) Current of the phase A.

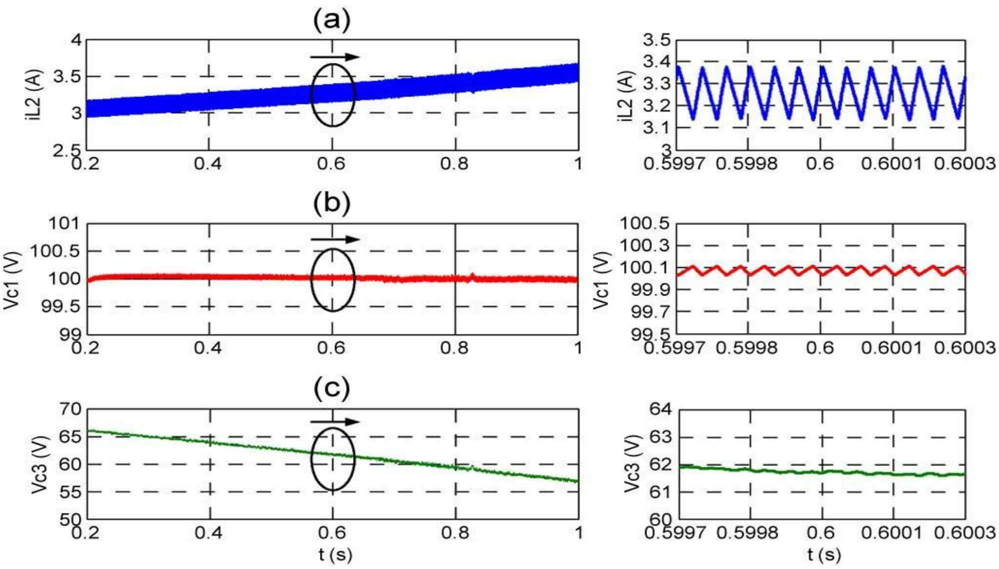
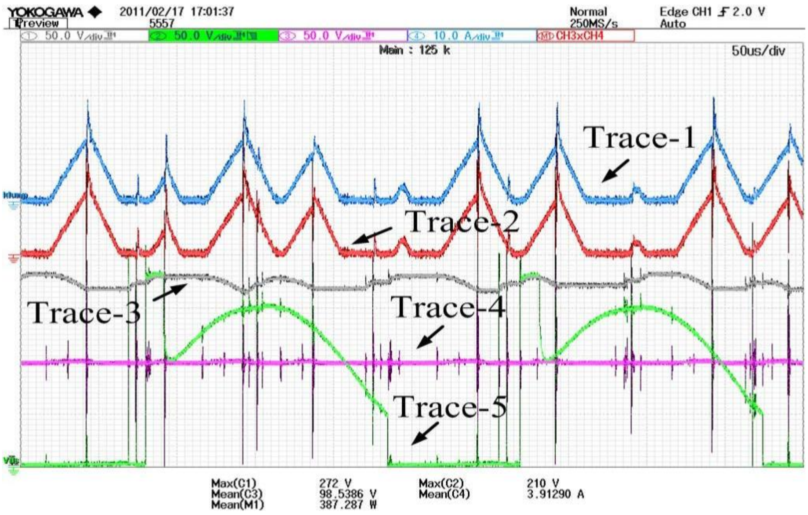


Fig. 8. Simulation results of the converter working in the discharging mode. (a) Current of inductance L_2 . (b) Output voltage of the converter. (c) Output voltage of the BLDCM rectified by the diode rectifier.

A. Simulation Results

Fig. 7 shows the simulation results of the proposed converter working in the charging mode. 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 re-covery capacitor C_0 which stays around 210 V, and increases to 213 V during commutation when the capacitor starts to dis-charge into the source. Fig. 7(c) shows the voltage (V_{ds}) be-tween the drain and the source of the metal–oxide–semicon-ductor field-effect transistor (MOSFET), which equals to the phase terminal voltage plus the bus voltage (V_{dc}) . 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 . Fig. 8(b) shows the output voltage of the con-verter (voltage of the capacitor C_1) which stays around 100 V.



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

B. 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. Waveform "1" shows the recovery current i_r which is similar to what was observed in simulation. 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 $C_{\bullet}$. A small charging and discharging action of the capacitor can be seen from the waveform, and the av- erage voltage of $C_{\bullet}$ is 204 V. Waveform "5" shows the voltage between the drain and the source of the MOSFET. 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.

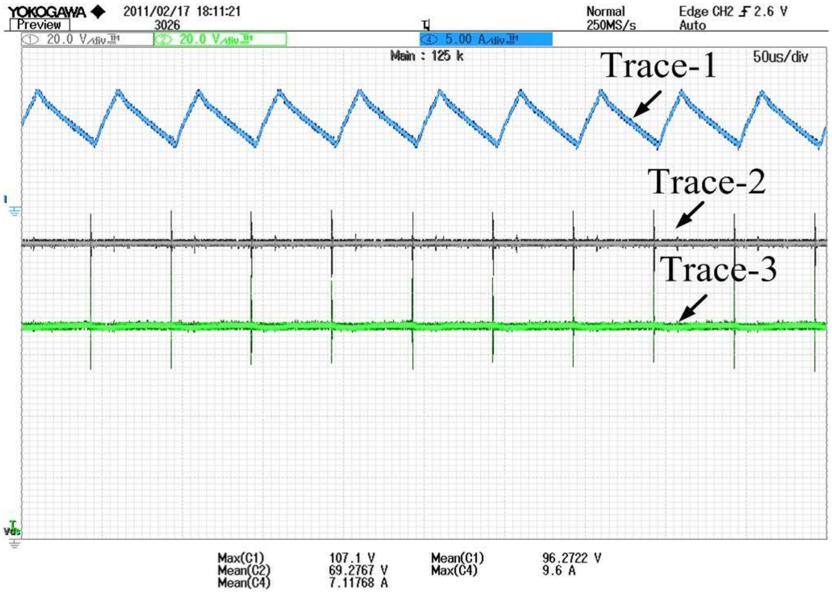


Fig. 11. Experimental results of the converter working in the discharging mode when the output voltage of the BLDCM is 70 V. (1) Current of inductance L_2 (50 μ s/div, 5 A/div). (2) Output voltage of the converter (50 μ s/div, 20 V/div).(3) Voltage of the capacitor C_3 (50 μ s/div, 20 V/div).

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 rectifi er 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.

V. CONCLUSION

This paper has presented a modified C-dump converter for BLDCM used in the FESS. The proposed converter can re-alize the bidirectional energy fl owing and has the capability to recover the energy extracted from the turnoff phase which is useful for the motor driver system especially for the FESS. The principle of operation, modeling, and control strategy of the system has been presented. Simulation and experiment validate the theoretical results and demonstrate the good performance of the converter. The study indicates that the converter is suitable for the FESS applications.

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