

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

Jibin Zou, Kai Liu, Jianhui Hu, and Junlong Li

Department of Electrical Engineering, Harbin Institute of Technology, Harbin 150001, China

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.

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 D_1, D_2, D_3, D_r ; inductance L_r and capacitor C_0), 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

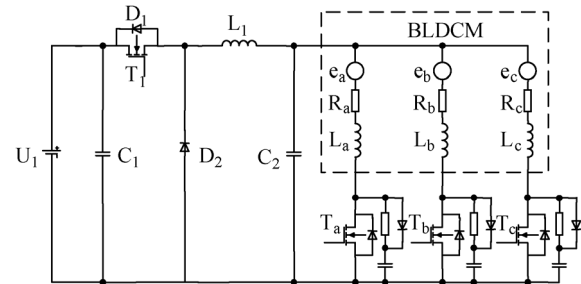


Fig. 1. Common half-bridge topology for high-speed BLDCM.

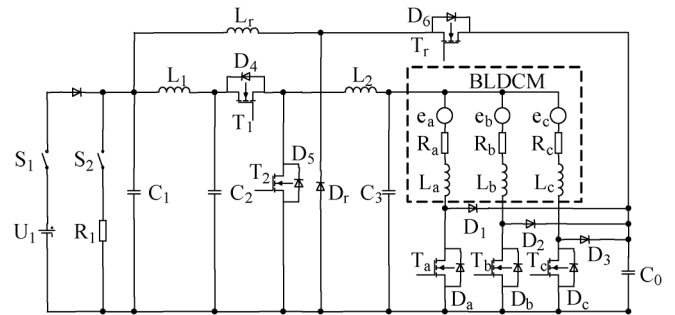


Fig. 2. Modified C-dump converter for the FESS.

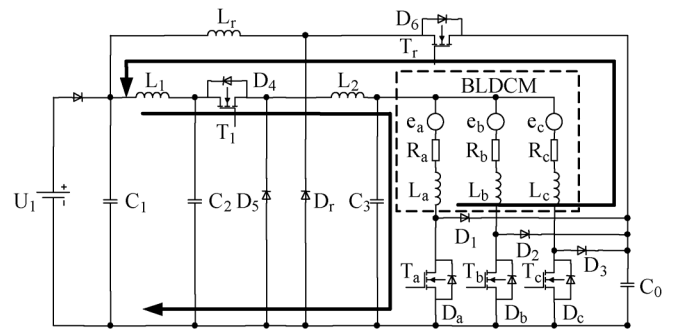


Fig. 3. Modified converter working in the charging mode.

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 control 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 flywheel into the load, therefore S_1 is off and S_2 is on. In this

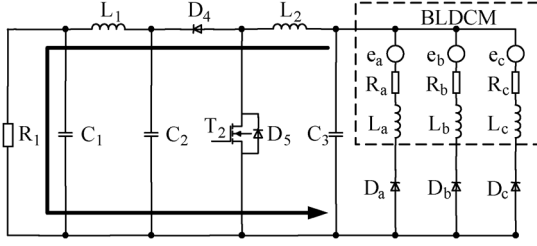
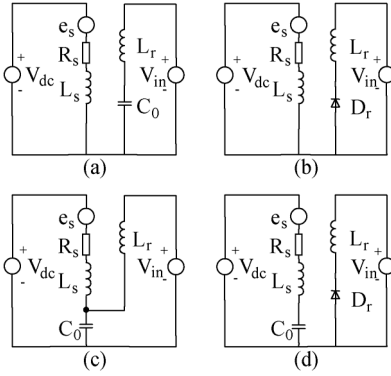


Fig. 4. Modified converter working in the discharging mode.

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.

mode, the half-bridge converter acts as a diode rectifier to convert 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.

III. MODELING AND CONTROL STRATEGY

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

A. Dynamic Model

Four distinct modes of operation can be identified for the proposed 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_s 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_s is the motor phase inductance, i_s is the motor phase current, V_{c0} is the capacitor C_0 voltage, V_{in} is the source input voltage (voltage of the capacitor C_1), L_r is the energy recovery circuit inductance, i_r is the current of the energy recovery inductance L_r , and k_0 is the buck factor.

1) T_s on, T_r on

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

$$V_{in} = V_{c0} - L_r \frac{di_r}{dt} \quad (2)$$

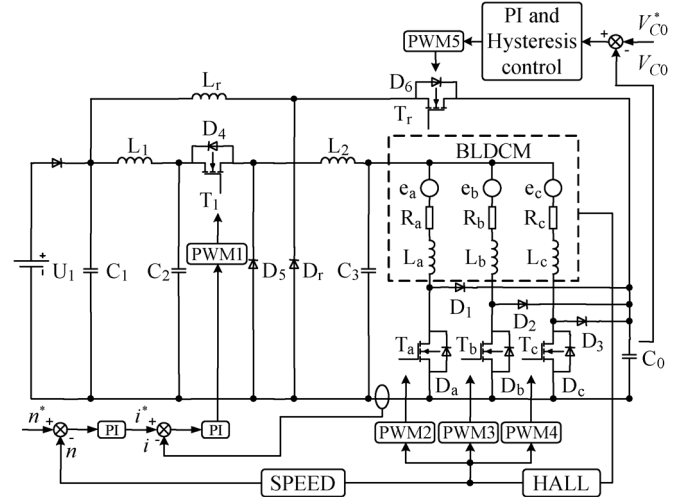


Fig. 6. Control structure of the converter in the charging mode.

$$C_0 \frac{dV_{c0}}{dt} = -i_r \quad (3)$$

$$V_{dc} = k_0 V_{in}. \quad (4)$$

2) T_s on, T_r off

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

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

$$V_{c0} = \text{constant} \quad (7)$$

$$V_{dc} = k_0 V_{in}. \quad (8)$$

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

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

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

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

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

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 energy extracted from the turnoff phase can be described as

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

where W_{LS} is the energy extracted from the turnoff phase. $i_{s\text{Max}}$ is the motor phase current in commutation moment; it can be

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

obtained from (1). The power extracted from the turnoff phase is

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

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

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

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

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

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

$$\begin{aligned} \frac{1}{2} L_s i_{s\text{Max}}^2 &= \frac{1}{2} C_0 [(U_c + \Delta U_c)^2 - U_c^2] \\ &= \frac{1}{2} L_r i_{r\text{MAX}}^2 - \frac{1}{2} L_r i_{r\text{MIN}}^2 \end{aligned} \quad (21)$$

where $i_{r\text{MAX}}$ ($i_{r\text{MIN}}$) 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 $i_{r\text{MIN}} = 0$

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

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

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 current 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, 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 II.

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		

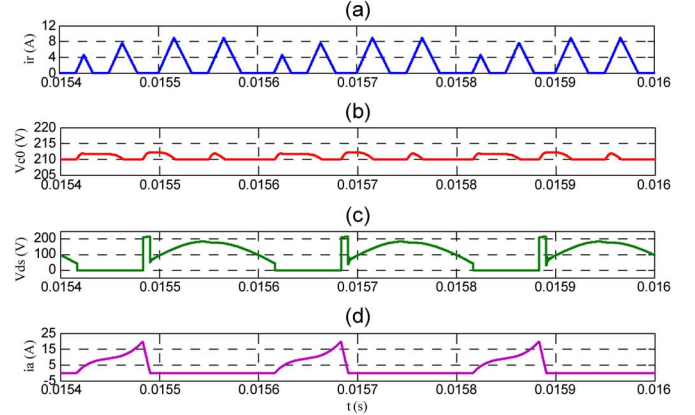


Fig. 7. Simulation results of the converter working in the charging mode. (a) Recovery current i_r . (b) Voltage of the capacitor C_0 . (c) Voltage between the drain and the source of the MOSFET (phase A). (d) Current of the phase A.

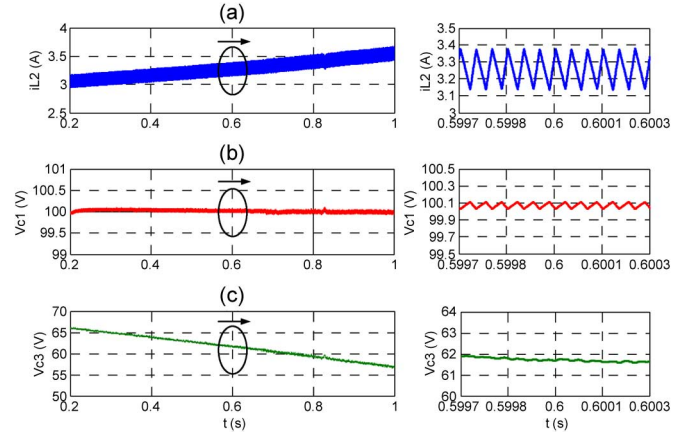


Fig. 8. Simulation results of the converter working in the discharging mode. (a) Current of inductance L_2 . (b) Output voltage of the converter. (c) Output voltage of the BLDCM rectified by the diode rectifier.

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 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. Fig. 7(c) shows the voltage (V_{ds}) 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 (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 converter (voltage of the capacitor C_1) which stays around 100 V

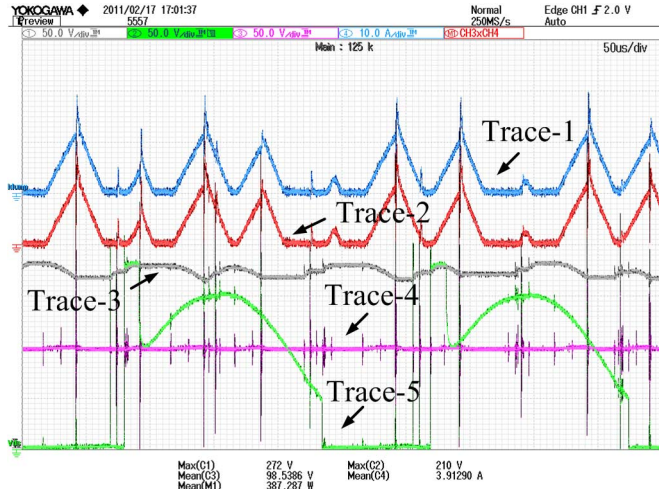


Fig. 9. Experimental results of the converter working in the charging mode when the average bus current is 15.6 A. (1) Recovery current i_r (50 μ s/div, 10 A/div). (2) Recovery power. (3) Voltage of C_0 (50 μ s/div, 50 V/div). (4) Source input voltage (50 μ s/div, 50 V/div). (5) Voltage between the drain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

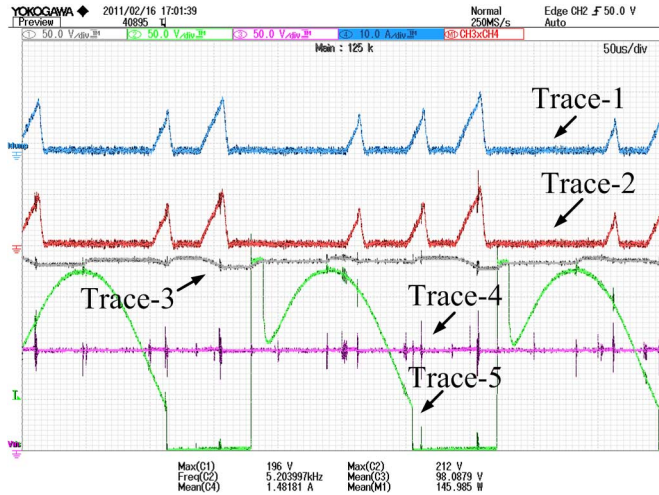


Fig. 10. Experimental results of the converter working in the charging mode when the average bus current is 8.2 A. (1) Recovery current i_r (50 μ s/div, 10 A/div). (2) Recovery power. (3) Voltage of C_0 (50 μ s/div, 50 V/div). (4) Source input voltage (50 μ s/div, 50 V/div). (5) Voltage between the drain and the source of the MOSFET (50 μ s/div, 50 V/div).

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_0 . A small charging and discharging action of the capacitor can be seen from the waveform, and the av-

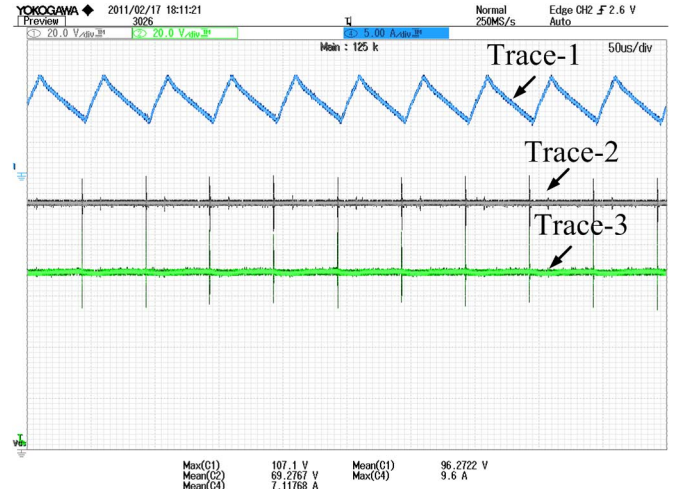


Fig. 11. Experimental results of the converter working in the discharging mode when the output voltage of the BLDCM is 70 V. (1) Current of inductance L_2 (50 μ s/div, 5 A/div). (2) Output voltage of the converter (50 μ s/div, 20 V/div). (3) Voltage of the capacitor C_3 (50 μ s/div, 20 V/div).

erage voltage of C_0 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 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 .

V. CONCLUSION

This paper has presented a modified C-dump converter for BLDCM used in the FESS. The proposed converter can realize the bidirectional energy flowing 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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