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Flywheel Energy Storage System with an Improved C-Dump Converter applied to BLDC Motor

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Abstract:

The permanent magnet brushless DC machine (BLDCM) is one of the suitable motors for the flywheel energy storage system (FESS). In this paper brushless DC (BLDC) machine interfaced with an improved C-dump converter used in the flywheel energy storage system. A bidirectional converter is designed for recovery of energy extracted from the turn-off phase of BLDC machine. The proposed converter can realize the energy flowing from source to BLDC machine flywheel and BLDC machine with fly wheel to load. The PI control technique is used for designing of control system. The system operational principle, modeling of the system, and control technique has been mentioned in this paper. The performance of the proposed technique is verified by MATLAB/simulink software and Simulation and experimental results of the proposed system are described.

Index terms : Brushless DC (BLDC) machine, energy bidirectional flowing, flywheel energy storage system.

I.INTRODUCTION:

In a modern flywheel for storage of electrical energy there is also a rotating mass. Its purpose is to maintain the voltage of the attached lines at a constant value. This rotating mass is made of metal or composite, and it is spun up by being part of an electrical motor [1]. To charge the flywheel with energy, pulses of electrical current are fed sequentially to fixed coils called the stator, and the magnetic fields from these currents exert forces on the rotor to spin it up, as the potter's kicking speeds up her flywheel. The main parts of the modern flywheel are a power converter, a controller, a stator, bearings, and a rotor. The rotor includes the rotating part of the motor generator, and the rotating part of the bearings. The stator is also a part of the motor generator [2]. Figure 1 shows this schematically:

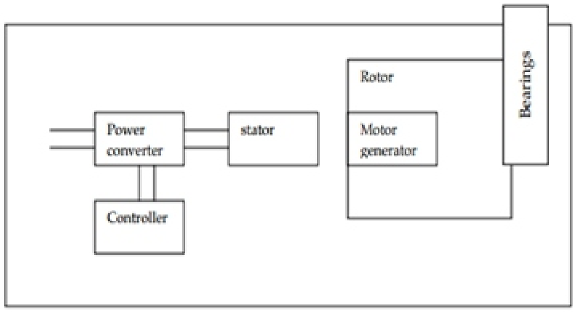

Fig.1. Schematic Diagram of Flywheel Subsystems

The power converter connects to a source of Direct Current (DC). It provides the current pulses to speed up the rotor. This is a current with variable frequency and variable voltage. The controller determines the frequency so that the flywheel receives the "kick" at just the right moment.

The AFS Trinity flywheel uses a permanent magnet motor generator. The permanent magnets are embedded in the rotor. The bearings support the rotor with minimal drag. The stator is fluid-cooled. The entire system is contained in one cabinet, along with the necessary fuses, contactors, and cooling fans to support safe operation.

Generally, BLDC drives employ current control, which essentially assumes that the torque is proportional to the phase current. Since, in practice, the relationship is nonlinear, various current control strategies have been adopted to minimize torque pulsations, by employing pre-optimized waveforms for the reference current, for example. Such an optimal current excitation scheme was proposed in [3], which resulted in minimal copper loss and ripple-free torque from a BLDC drive.

The common half-bridge topology for high-speed BLDCM is shown in Fig. 2. 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.

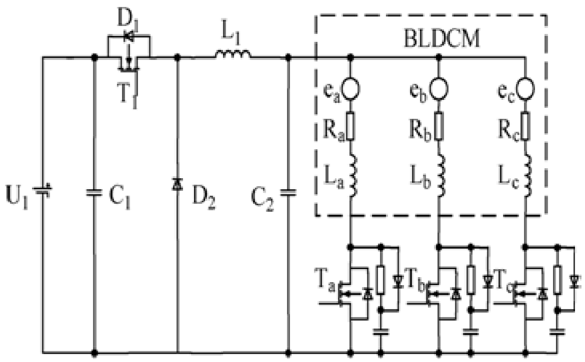

Fig.2. Common half-bridge topology for high-speed BLDCM.

In order to overcome these drawbacks, an improved 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.

This paper is organized as follows; In Section2, the proposed converter design structure and operational principle improved C-dump converter for BLDCM is presented. Section 3 describes the proposed modeling analysis and control technique. In section 4 the simulation results of the proposed converter are described. Finally, in section 5 the conclusion is presented.

CONVERTER DESIGN AND OPERATION:

The proposed converter includes a half-bridge converter (switchesT_a,T_b,T_c), an energy recovery chopper (switch T_r ; D_1,) D_2 D_3,D_4 diodes; inductance L_r and capacitorC_o), a bidirectional DC–DC converter (switchesT_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_1stands for the load. Fig. 3 shows the improved C-dump converter for BLDCM used in the FESS.

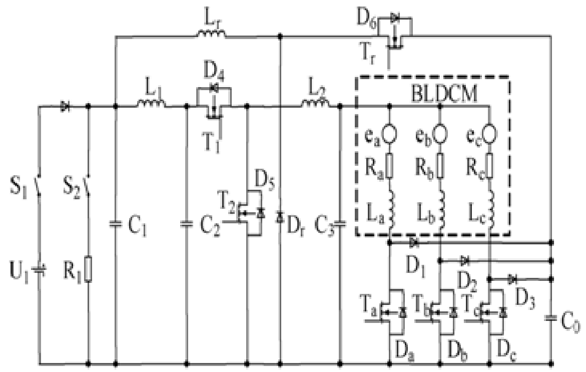

Fig.3. Improved C-dump converter for the FESS.

The improved converter has two working modes: the FESS charging mode and the FESS discharging mode.

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]-[5].The bidirectional DC–DC converter works in buck operation mode (T_1works in PWM operation mode and T_2 is off.) to control the motor speed. Fig.4 illustrates the improved converter for the FESS working in the charging mode.

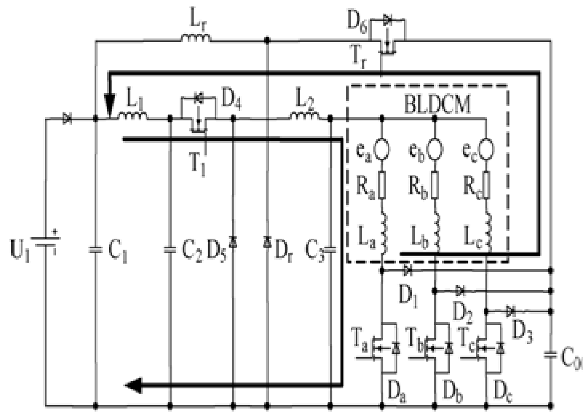

Fig.4. Improved converter working in the charging mode.

FESS discharging mode:

The BLDCM (with flywheel) acts as a generator to discharge the kinetic energy of the flywheel into the load, thereforeS_1 is off and S_2 is on. In this 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 andD_a,D_b,D_c forms a diode rectifier. With the speed of flywheel 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. 5 illustrates the improved converter for the FESS working in the discharging mode.

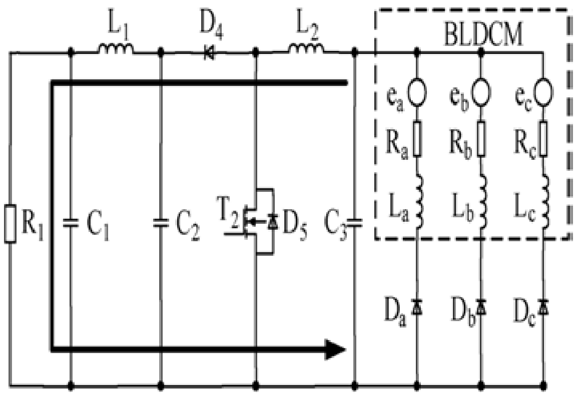

Fig.5.Improved converter working in the discharging mode.

III. MODELINGANALYSIS AND CONTROL TECHNIQUE:

The dynamic modeling analysis and controlling technique is described in this section.

Dynamic modeling:

The proposed converter in the charging mode is operated in four different modes of operations. The switch voltage drop and diode, resistance and mutual inductance of motor phases are negligible.

1)T_s on, T_r on

$$V_{dc} = L_S \frac{di_S}{dt} + e_s + R_s i_s \quad - 1$$

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

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

$$V_{dc} = k_0 V_{in} \quad - 4$$

2)T_s on, T_r off

$$V_{dc} = L_S \frac{di_S}{dt} + e_s + R_s i_s \quad - 5$$

$$V_{in} = -L_r \frac{di_r}{dt} \quad - 6$$

$$V_{c0} = \text{constant} \quad - 7$$

$$V_{dc} = k_0 V_{in} \quad - 8$$

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

$$V_{dc} = L_S \frac{di_S}{dt} + e_s + R_s i_s + V_{c0} \quad - 13$$

$$V_{in} = -L_r \frac{di_r}{dt} \quad - 14$$

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

$$V_{dc} = k_0 V_{in} \quad - 16$$

Here

T_s Considers as T_a, or T_b, or T_c 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,
is is the motor phase current,
V_{co} is the capacitor C_o 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_o is the buck factor.

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.

$$W_{LS} = \frac{1}{2} L_s i_{sMAX}^2 \quad - 17$$

Where
W_{LS} The energy is extracted from the turnoff phase.
i_{sMAX} Is the motor phase current in commutation moment.
The power extracted from the turnoff phase is

$$P_{LS} = \frac{W_{LS}}{t} = 3 * \frac{1}{2} L_s i_{sMAX}^2 \quad - 18$$

$$\frac{1}{T} = \frac{3}{2} L_s i_{sMAX}^2 \frac{np}{60} \quad - 19$$

Where N is the sped of the motor and p is the pairs of poles

Control technique:

The control technique of the improved converter working in the charging mode is shown in fig 6.

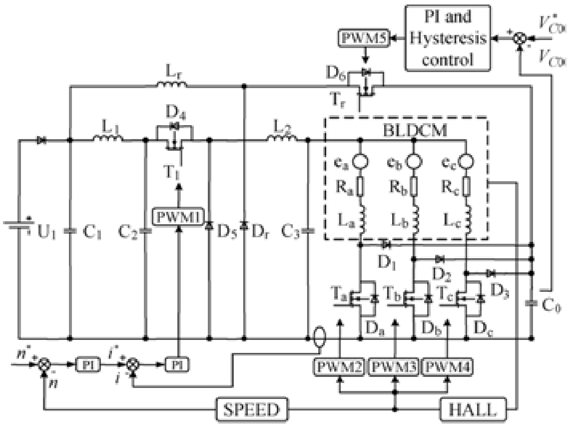

Fig.6. Control scheme of the converter in the charging mode.

The control scheme is designed for speed control of motor and voltage control of the recovery capacitor [6]. The speed control motor is having two loops. They are inner current loop and outer speed loop. The phase commutation is done by hall-effect sensors. Over current protection method is done for motor phases. Simple circuit

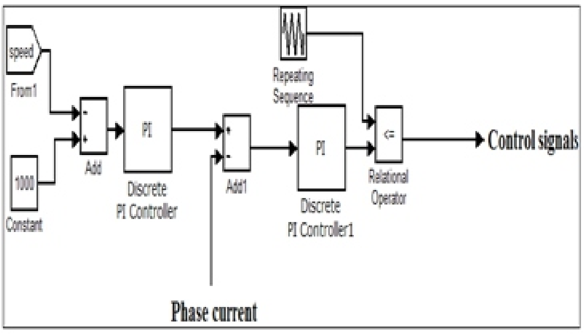

Fig.7. proportional–integral (PI) with PWM control diagram

IV.SIMULATION RESULTS:

The performance of the proposed converter is verified by using MATLAB simulation test results. The testing of converter is done by interfacing with the BLDC motor.

The designing parameters of the BLDC motor are described in table 1. And converter designing parameters of converter are described in table 2.

Parameter	Rating
Rated voltage	125 v
Rated current	20 A
Rated power	2.5 kW
Frequency	5333 HZ
Phase inductance	0.04 mH
Phase resistance	0.1 ohm

Table 1: parameters of BLDCM

parameter	Value
C_0	36 μF
C_1	530 μF
C_2	530 μF
C_3	1500 μF
L_1	0.31 mH
L_2	0.7 mH
L_r	0.6 mH

Table 2: converter parameters

The simulation circuit of the improved C-dump converter interconnected with the BLDC motor is shown in fig 8.

The simulations results are obtained for the proposed C-dump converter interconnected with the BLDC motor are obtained. The converter is operated in both charging and discharging condition. Simulation results are mentioned separately for both operations.

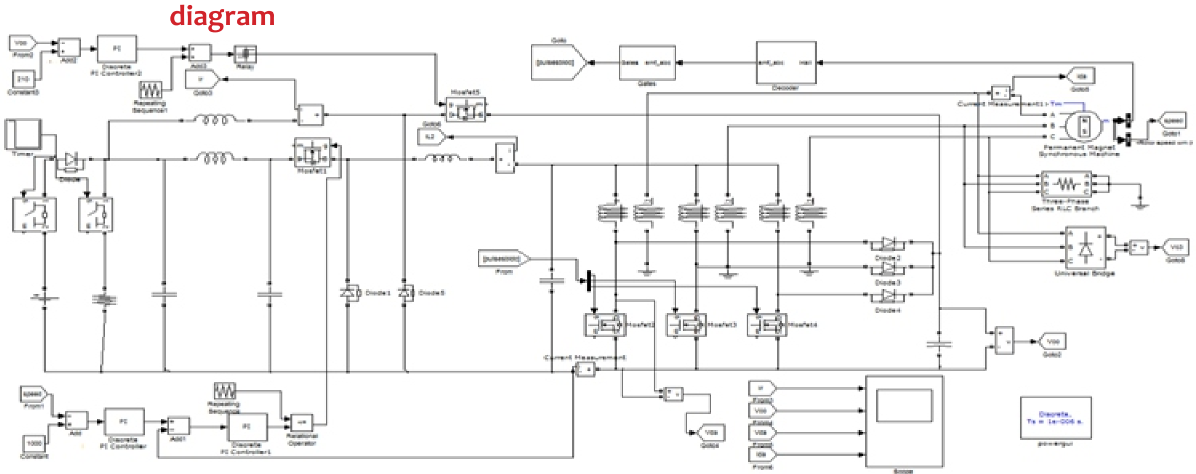

Fig 8. Simulation circuit of improved C-dump converter interconnected to BLDC motor

The simulation results of proposed converter working in the charging mode are described as follows. The simulation result of phase current is shown in fig 9, the recovery current ir is shown in fig 10, the voltage of energy recovery capacitor Co is shown in fig 11, and the voltage between the drain and source of MOSFET simulation result is shown in fig. 12.

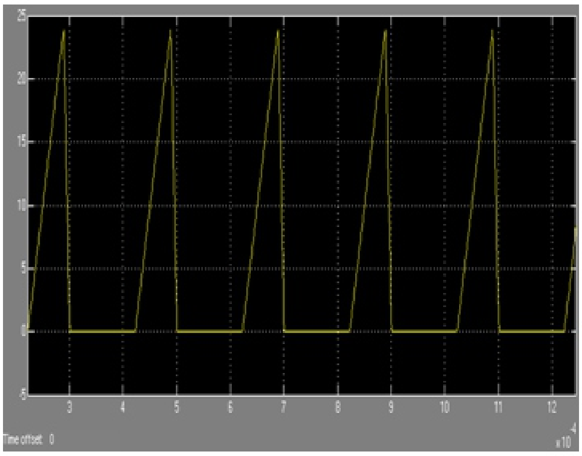

Fig 9. Simulation wave form of phase current (ia).

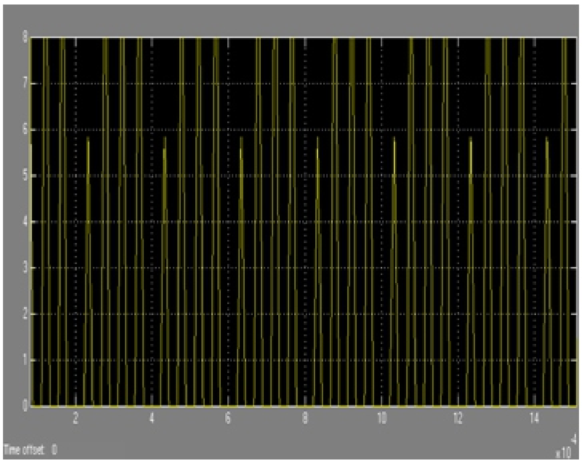

Fig 10. Simulation result of recovery current (ir)

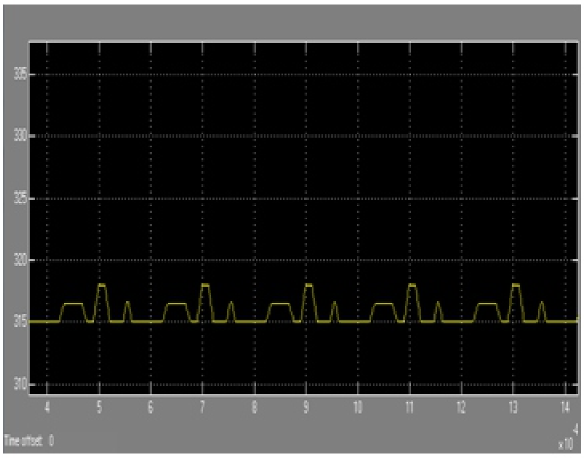

Fig11. Simulation wave form of capacitor voltage (Vco)

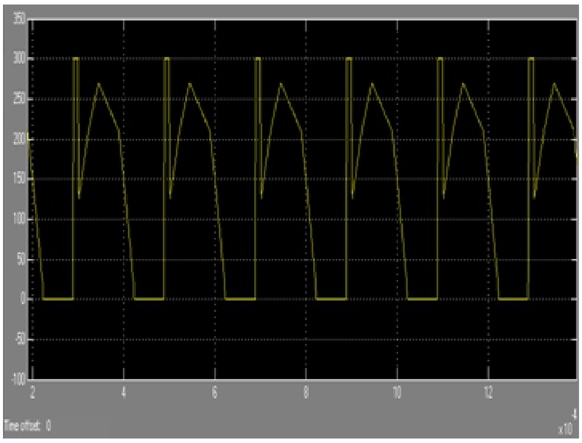

Fig 12. Voltage across drain and source of MOSFET (Vds) of phase A.

The proposed C-dump converter is operated in discharging mode. The simulation results are described as follows: the current through the inductance L2 is shown in fig 13, fig 14 shows the output voltage of converter (across C1) and output voltage of BLDC machine is shown in fig 15.

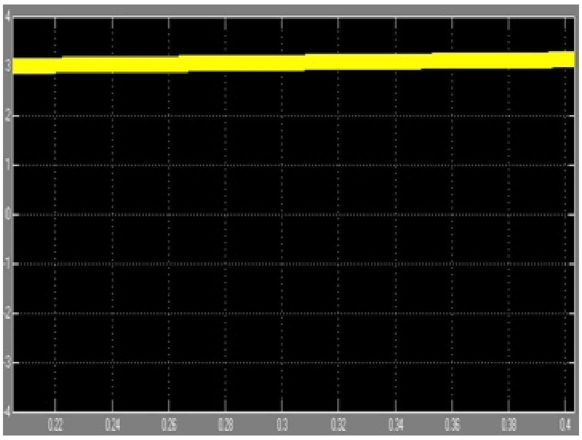

Fig13. Simulation waveform of Current of inductance L2 (iL2).

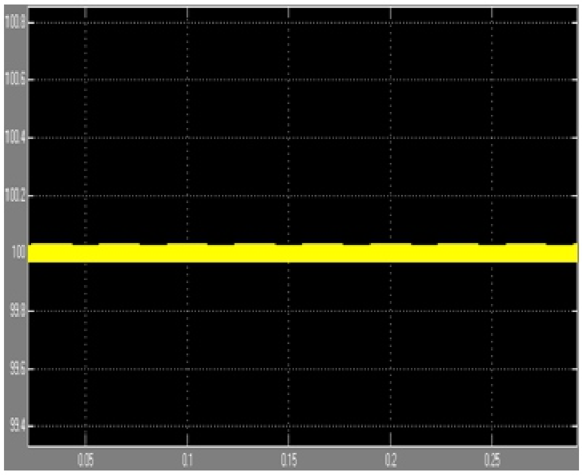

Fig14. Output voltage of converter (across C1)

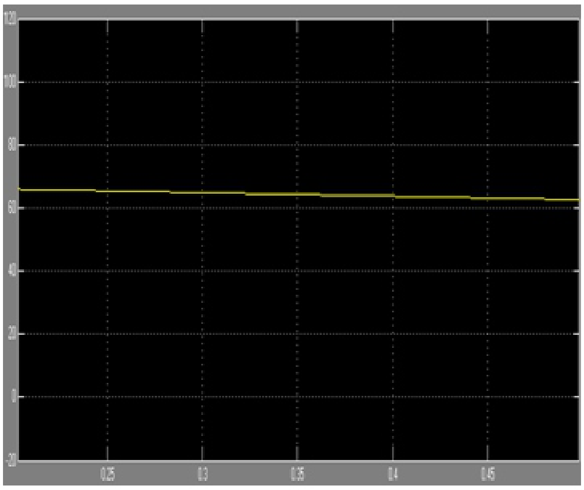

Fig 15. Output voltage of the BLDCM

CONCLUSION:

Fly wheel energy storage systems are having increase in application of large energy storage devices. In this paper an improved C-dump converter BLDC motor used in FESS. The converter presented in this paper is having bi-directional operation. It is having advantage of recovery of energy from the turn-off phases; this is best suitable for fly wheel energy storage systems.

The c-dump converter of half-bridge type is used for reduction of the number of switching devices.The dynamic model of the proposed converter and control technique of pulse width modulation (PWM) are presented.

The proposed converter is having advantage of higher energy extraction then previous systems. The performance of the proposed system is verified with MATLAB software and characteristics are described in results section.

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