# INTERLEAVED BIDIRECTIONAL DC-DC CONVERTER FOR REGENERATIVE BRAKING

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***Abstract:* A bidirectional DC-DC converter is a key device for interfacing an energy storage element with a motor. The voltage of a storage battery is typically 60V or lower, while the voltage of the motor is 24V. Thus, a bidirectional DC-DC converter with a wide voltage-gain range is desired for energy storage systems to connect a high-voltage battery with a low voltage motor. The interleaved switched-capacitor DC-DC converter is used to interface battery with the BLDC motor. The main components used are converter, battery, motor and an inverter. The interleaved structure is adopted in the low-voltage side of this converter to reduce the ripple of the current through the low voltage side, and the series-connected structure is adopted in the high-voltage side to achieve the high step-up/step-down voltage gain and the efficiency of the converter is improved. The converter is used to perform regenerative braking of BLDC motor. Converters HV side is connected to a battery and LV side connected to a BLDC motor. 2 modes of operation. Motoring mode and braking mode. During motoring mode motor is driven by the battery and during braking mode the battery is getting charged. The simulation is performed in MATLAB/SIMULINK. Hardware is made.***

***IndexTerms* - bidirectional DC-DC converter, BLDC motor, battery, regenerative braking**

## I. INTRODUCTION

The battery supply of inverter-fed motor drives devoted to the propulsion of EVs is accomplished generally at a low voltage level, and in a great number of applications the battery is used to supply directly the inverter input terminals. However, such an inverter supply arrangement affects negatively the motor drive efficiency, and it does not allow the control of regenerative braking operations, which can actually contribute to an increase of the vehicle overall efficiency only if the recovery in the battery of the vehicle energy is accomplished by means of a proper control of the motor braking current. In order to overcome the problems mentioned above a bidirectional dc-dc converter can be used in the dc link of battery-fed motor drives devoted to EVs applications. The bidirectional arrangement of the dc-dc converter allows the reversal of the power flow and the control of the motor braking current. Besides of that, the dc-dc converter used for the supply of the inverter input terminals can be operated in order to reduce the ripple of the motor current waveform.

The non-isolated converters include the Cuk, Sepic/Zeta, coupled-inductor, conventional buck-boost, three-level [11], multi-level and switched-capacitor. Due to the cascaded configurations of two power stages, conversion efficiencies of Cuk and Sepic/Zeta are lower. Though the conventional two-phase interleaved bidirectional DC-DC converter in can reduce low-voltage side current ripples, but this converter still has disadvantages including the narrow voltage conversion range and the high voltage stress for power semiconductors. The voltage stress of power semiconductors of the bidirectional three-level DC-DC converters in is half that of the conventional two-phase interleaved bidirectional DC-DC converter, but its voltage-gain range is still narrow. Besides, the low-voltage and high-voltage side grounds of this converter are connected by a power semiconductor, the potential difference between the two grounds is a high frequency PWM voltage, which may result in more maintenance issues and EMI problems. The low-voltage and high-voltage sides of the bidirectional three-level DC-DC converter [3] in share the common ground, but the voltage-gain of this converter is still limited. In addition, this converter requires the complicated control scheme to balance the flying-capacitor voltage. The converters in and can achieve a high voltage gain, and the low voltage stress of power semiconductors. However, these converters need more power semiconductors, and require additional hardware circuits and control strategies to maintain the balanced voltage stress of power semiconductors. The switched-capacitor converter structures and control strategies are simple and easy to expand. Different charging and discharging paths of the capacitors transfer energy to either the low-voltage or the high-voltage side to achieve a high voltage gain. Single capacitor bidirectional switched-capacitor converters were proposed in, but the converter efficiency is low. To reduce the input current ripple, interleaved switched-capacitor converters have been proposed in. However, the converter in needs more components, and the inductor currents of the converter in are unbalanced when Db is not equal to 2Da. Finally, the high voltage-gain converter needs more power components and fails to achieve bidirectional power flows. In addition, the balanced inductor currents just can be achieved when the number of the voltage multiplier stages is odd.

These non-isolated bidirectional DC-DC converters referred above cannot simultaneously achieve the low current ripple, the low voltage stress of power semiconductors and the wide voltage-gain range. In order to solve this problem, an interleaved switched capacitor bidirectional DC-DC converter is introduced in this paper. Comparing with the conventional two-phase interleaved bidirectional DC-DC converter and the bidirectional three-level DC-DC converter, the converter has advantages including low current ripple, low voltage-stress of power semiconductors and wide voltage-gain range. In addition, the connection between the low-voltage and the high-voltage side grounds of the converter is a capacitor rather than a power semiconductor. To achieve a high step up gain, the capacitors are charged in parallel and discharged in series in the step-up mode. Opposite to the step-up mode, the high step-down ratio can also be obtained because two capacitors are charged in series and discharged in parallel. Furthermore, the capacitor voltage of the converter is half of the high-voltage side voltage, and the efficiency is improved by synchronous rectification operation [1].

## II. INTERLEAVED BIDIRECTIONAL DC-DC CONVERTER FOR REGENERATIVE BRAKING

There are interleaved bidirectional converter, BLDC motor, Battery and an inverter. The system uses a battery which gives an output voltage of 60V. BLDC motor's rated voltage is 24V and rated speed is 4000rpm. The battery is connected to the HV side and the motor is connected to the LV side of the converter.

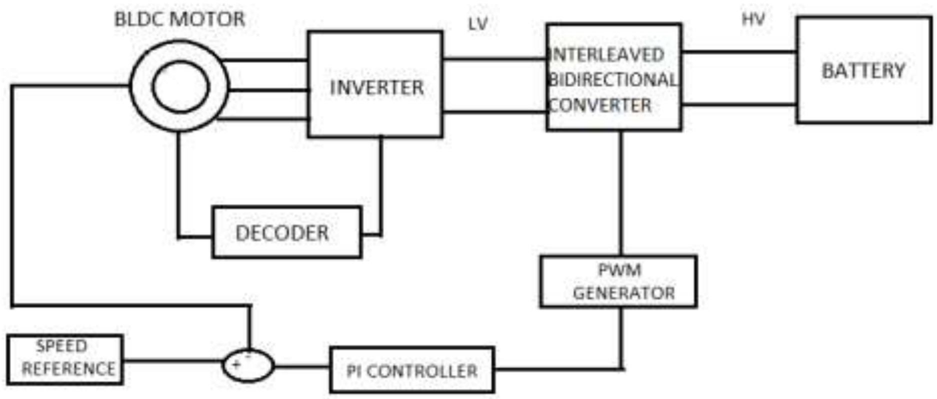


Fig 1. block diagram for regenerative braking

There are 2 modes of operation for the proposed system. Motoring mode and braking mode. During motoring mode, the battery drives the BLDC motor through the interleaved bidirectional DC-DC converter. During braking energy is fed back to the source and the battery is getting charged. For current to flow into battery, the bus voltage should be higher than the battery terminal voltage. Hence we have to boost the voltage developed from motor higher than the battery. The control pulse for the converter is generated according to the speed of the BLDC motor. By varying the duty cycle, the output voltage can be boosted to different magnitude.

In addition to this The speed control of BLDC motor is possible with the interleaved bidirectional DC-DC converter. The output voltage of the converter is controlled by the pulse given to the MOSFET switches. Thereby speed can be controlled.

### 2.1 Interleaved Bidirectional DC-DC Converter

Interleaved structure is adopted in the low voltage side. High voltage side of the converter is connected in series. This converter is composed of four modules. $C_{low}$ is the energy storage/filter capacitor of the low-voltage side. Module 1 includes switches $S_1$, $S_2$, and inductors $L_1$, $L_2$. In addition, $L_1$-$S_1$ and $L_2$-$S_2$ form the parallel structure of the low-voltage side. Module 2 is a switched-capacitor network, including switched-capacitor units $C_1$-$S_3$, $C_2$-$S_4$ and $C_3$-$S_5$. The low-voltage side, Module 1, Module 2 and the high-voltage side form the bidirectional DC-DC converter with the structure of the low-voltage-side in parallel and the high-voltage-side in series.

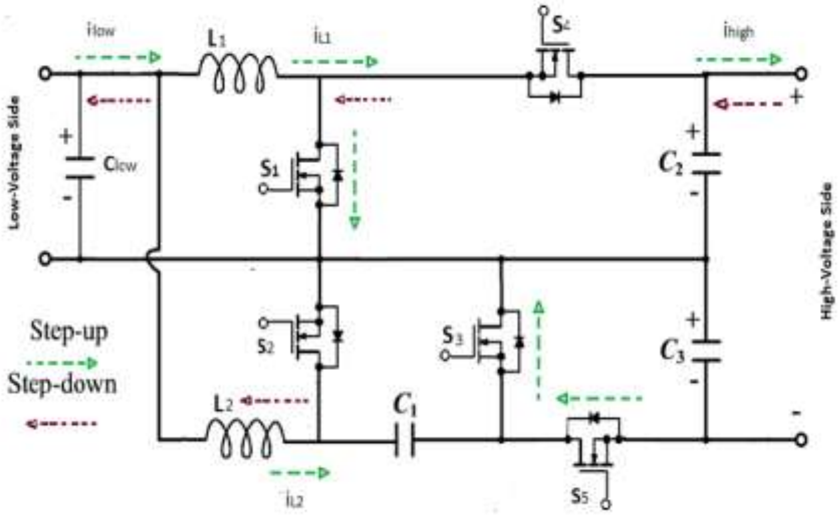


fig 2. interleaved bidirectional DC-DC converter

#### 2.1.1 Modes of Operation

There are 4 modes of operation for step-up and step-down operation. Modes of operation are similar for both operations. But the direction of operation is opposite for step-down mode.

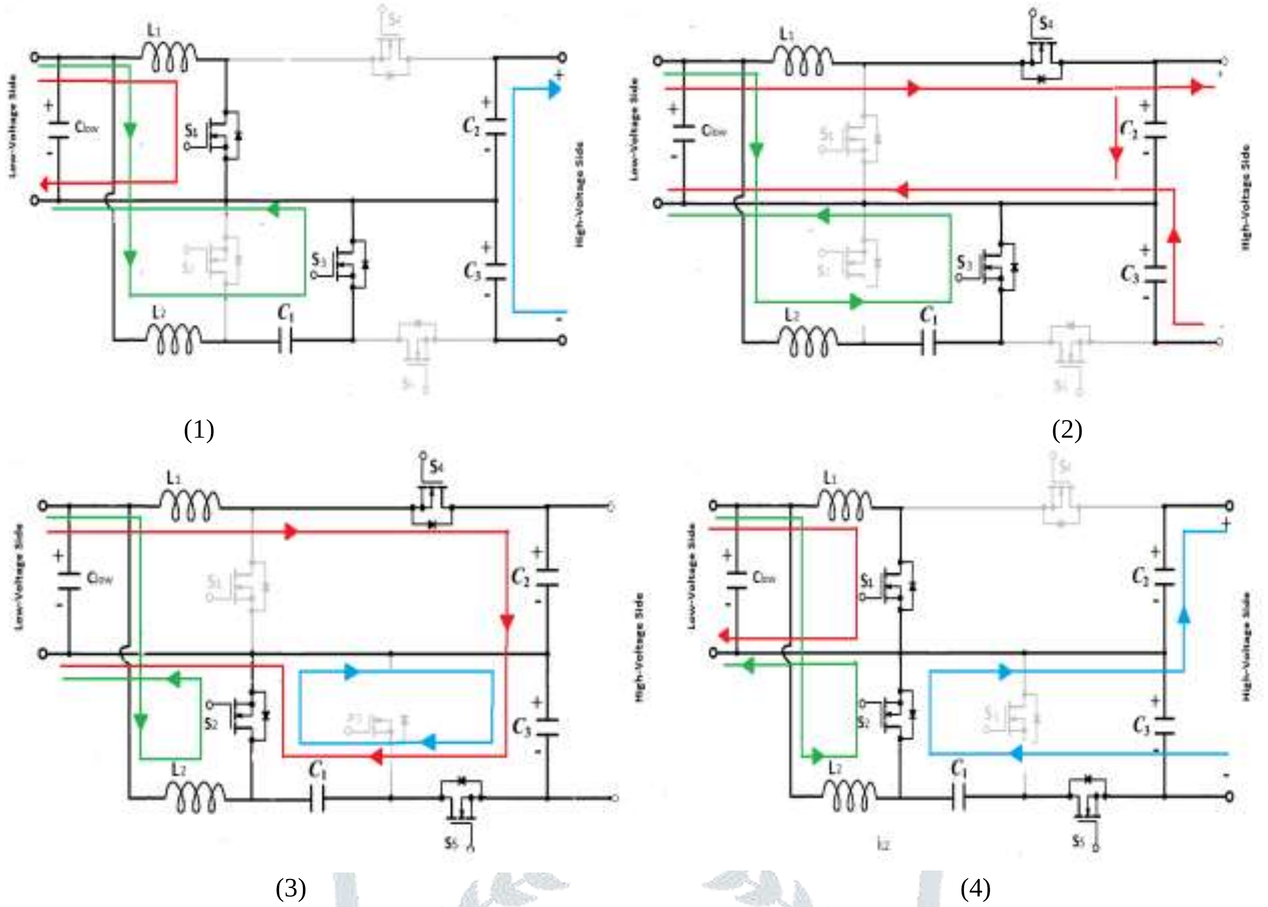


fig 3. modes of operation of the converter

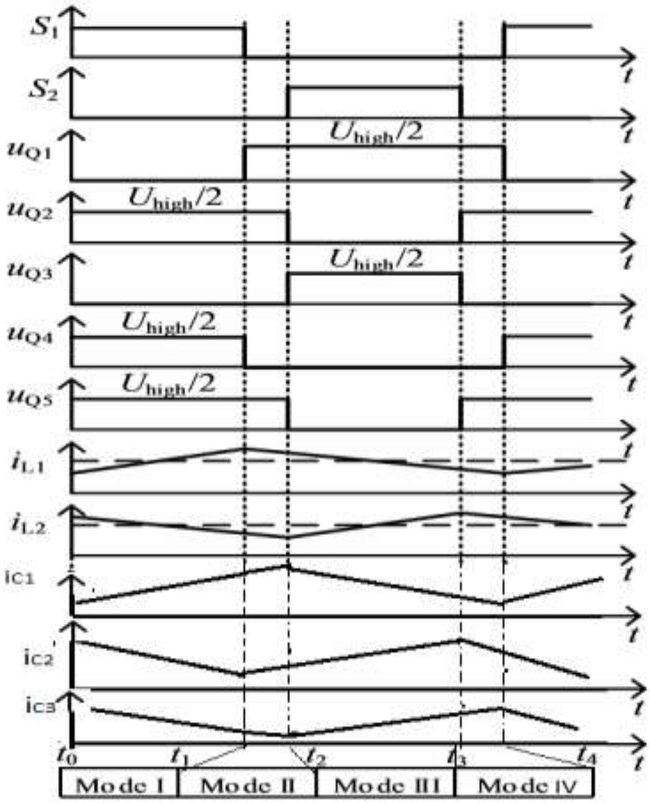


fig 4. modes of operation

## III. SIMULATION STUDIES

The simulation of interleaved switched capacitor bidirectional DC-DC converter is done in MATLAB R2014a/Simulink. The simulation parameters, simulation model and results of interleaved bidirectional DC-DC converter for regenerative braking are shown below. The input to the system is 60V.

### 3.1 Simulink Model and Simulation Results

The detailed MATLAB/Simulink model of interleaved bidirectional converter is made. The various parameters that has been considered for the simulation has been given in table 1 and table 2. Table 1 shows the simulation parameters for the converter and table 2 indicates motor parameters.

Table 1: Simulation parameters for the converter

| Parameters | Specifications |
|---|---|
| Storage/filter capacitor $C_{low}$ | 55.4µF |
| Switched-capacitors $C_1$, $C_2$ and $C_3$ | 55.4µF |
| Storage/filter inductor $L_1$ | 108µH |
| Storage/filter inductor $L_2$ | 108µH |
| Battery voltage | 60V |
| Low voltage side voltage | 24V |
| Switching frequency fs | 20kHz |

Table 2: Simulation parameters of BLDC motor

| Parameters | Specifications |
|---|---|
| Stator phase resistance $R_S$ | 0.01Ω |
| Stator phase inductance $L_S$ | 0.001115µH |
| Torque constant | 0.035 |
| Flux linkage | 0.004375 |
| Inertia | 0.0002kg.m$^2$ |
| viscous damping | 0.000303448 N.ms |
| pole pairs | 4 |

The system model and the implemented control strategy has been simulated in the simulink as shown in Fig 5. The main components in the system model are battery, interleaved bidirectional DC-DC converter, inverter finally a BLDC motor.

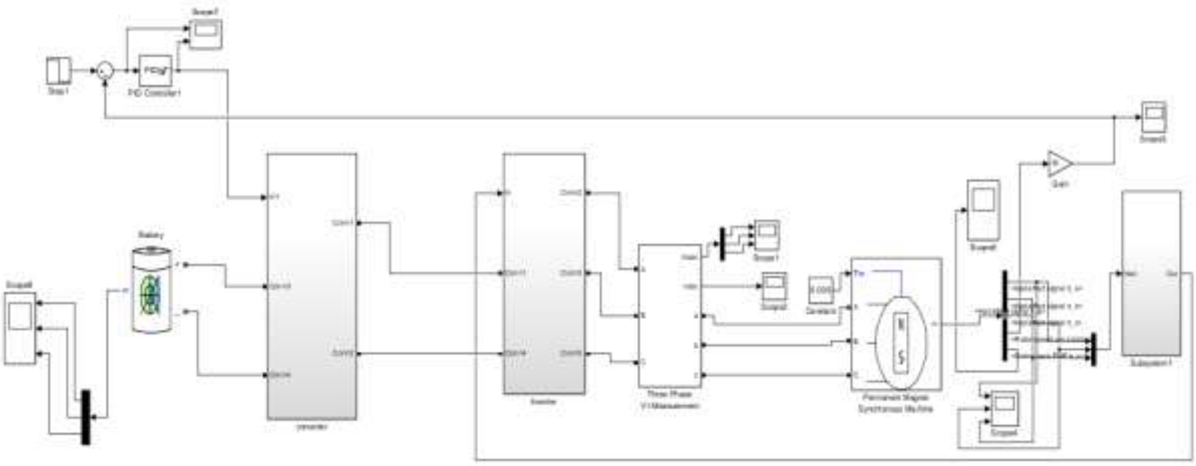

fig 5. Simulink model of interleaved bidirectional converter for regenerative braking

The interleaved bidirectional DC-DC converter is shown in Fig 6. The high voltage side of this converter is connected to the battery and low voltage side to the BLDC motor through a three phase inverter. The pulses for the inverter is given by the hall effect signals coming from the BLDC motor.

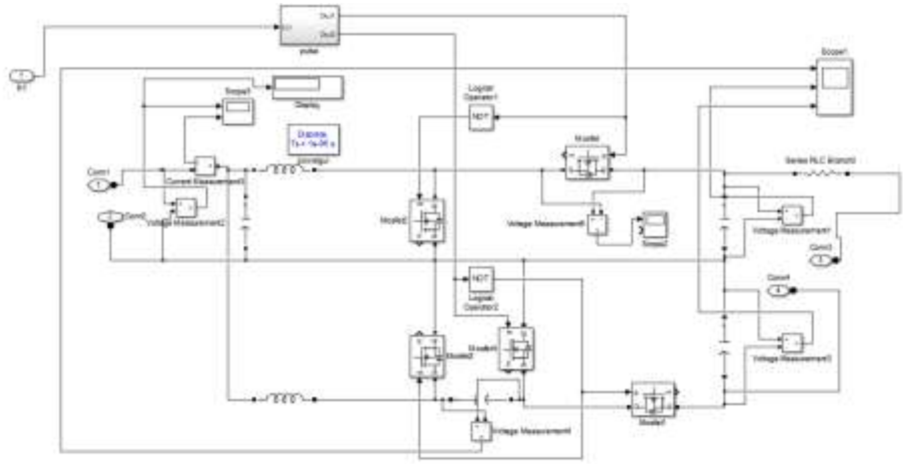

fig 6. Interleaved bidirectional converter

To illustrate the working of the system, the speed of the motor is varied using a step. Initial speed is 2000 rpm and after a 2 seconds the speed is reduced to 1000 rpm. Total simulation time is 4 seconds. Battery supplies the BLDC motor through interleaved bidirectional converter. At 2 second as the speed is reduced to 1000 rpm from 2000 rpm, regenerative action takes place and the battery is getting charged. Figure 9 shows the speed of the BLDC motor. Figure 10 shows the current, voltage and SOC of the battery.

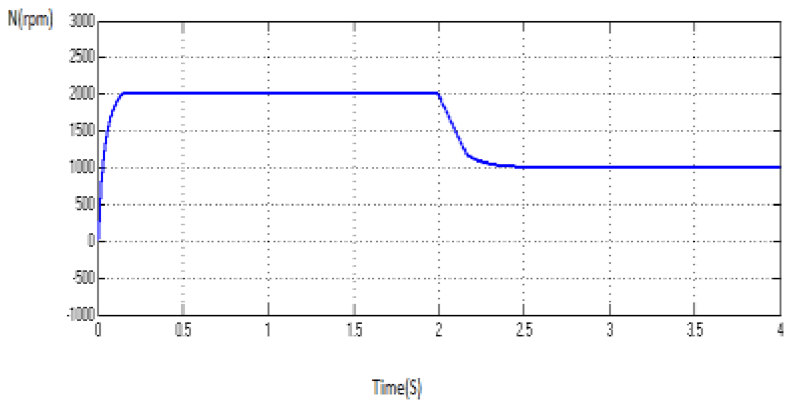


fig 9. Speed of BLDC motor

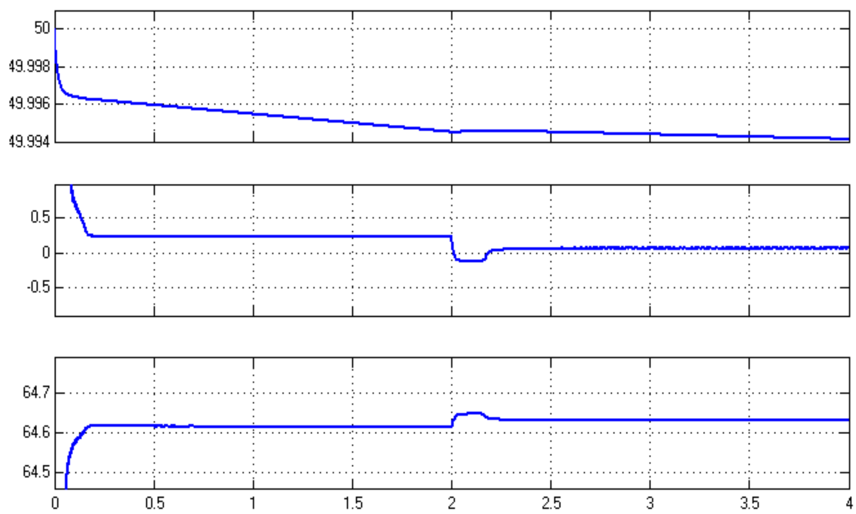


Fig 10. Battery SOC, current and voltage

Fig 11 shows the hall effect signals generated from the BLDC motor. The pulse for the inverter is given by this signals. Hall effect signals are generated by sensing the rotor position corresponding to each phase.

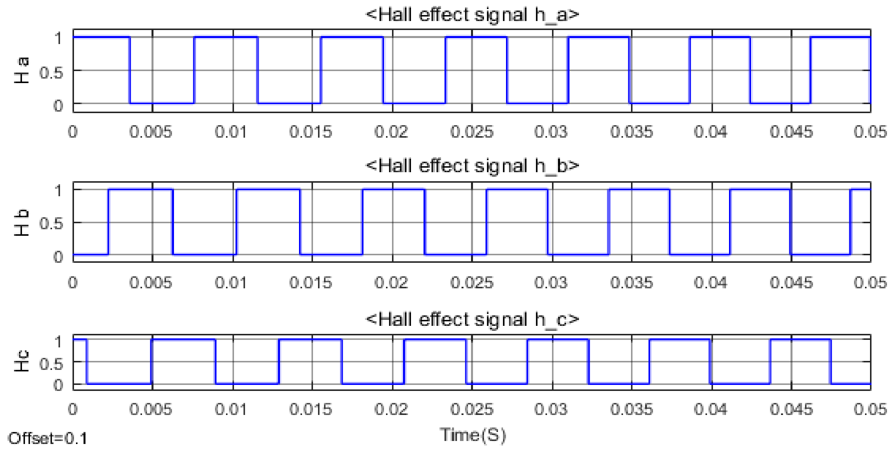


Fig 11. hall effect signals of BLDC motor

## IV. HARDWARE IMPLEMENTATION

The simulation results are verified experimentally by implementing the hardware, due to the lack of 60V battery and other availability of devices, the hardware is done by reducing the parameters of prototype to 24V as the input. Fig 12 shows the hardware setup of interleaved bidirectional converter for regenerative braking. Switching pulses for the converter is generated by TMS 320. Pulse for the inverter is obtained from dsPIC30f2010. Opto-coupler TLP250 provides the isolation between the driver and power circuits of the converter. Driver circuit of inverter mainly consist of MOSFET driver IR2110.

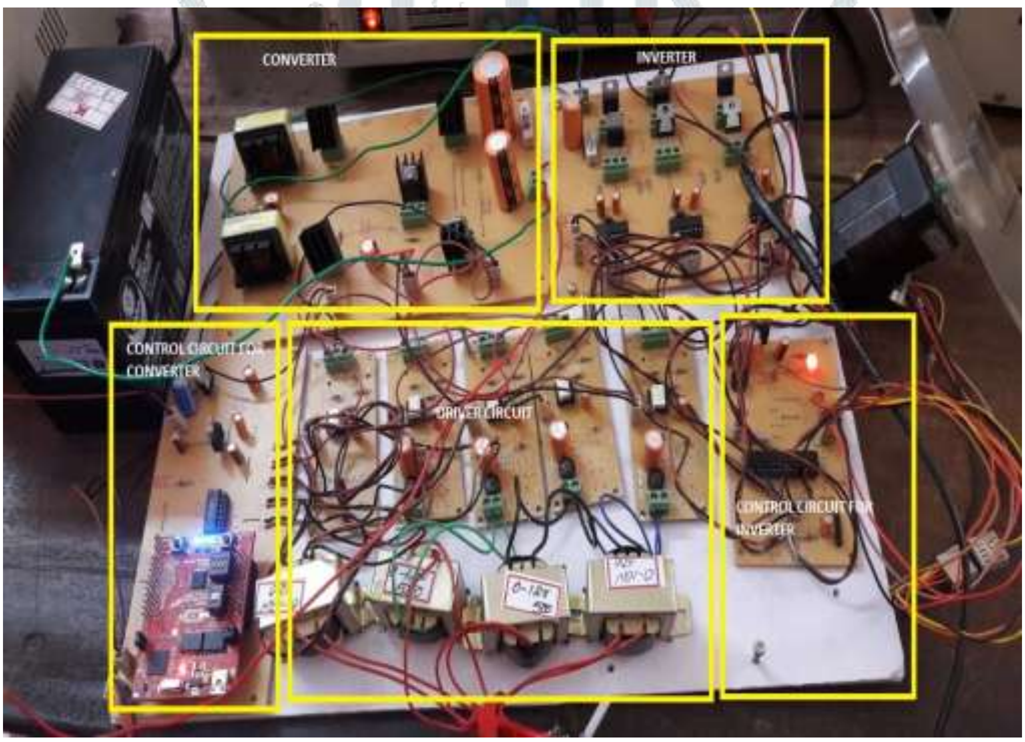


Fig 12. Experimental setup

From the experimental setup we can assure that the hardware setup is working and produces the desired output. At the time of speed reduction regeneration is taking place. The energy is fed back to the battery. Speed control of BLDC motor is achieved by adjusting the pot connected in ADC channel 2 of TMS 320. The regeneration output is shown in figure 13.

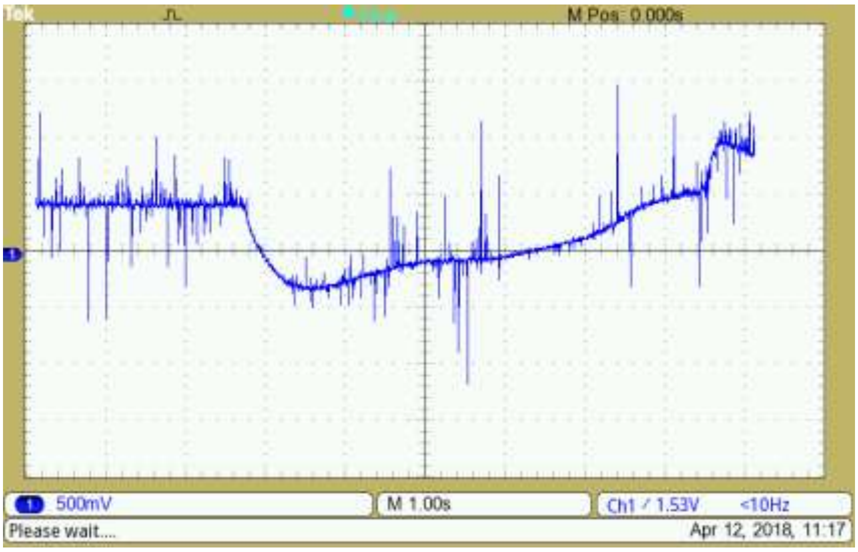


Fig 13. Battery current waveform

## V. CONCLUSIONS

In this paper, an interleaved switched-capacitor bidirectional DC-DC converter for regenerative braking has been introduced. It is suitable for battery charging of electric vehicle. Energy is regenerated in each braking. This energy can be stored in the battery. The proposed system has other industrial applications. During sudden power failure the motor speed suddenly reduces to zero. At that time energy can be regenerated for a particular duration. The bidirectional DC-DC converter has good dynamic and steady-state performance and is suitable for the power interface between the high-voltage battery pack and the low voltage motor for various new energy storage systems.

## REFERENCES

**[1]** Yun Zhang, yongping Gao, Jing Li, Mark Sumner, Interleaved Switched-Capacitor Bidirectional DC-DC Converter with Wide Voltage-Gain Range for Energy Storage Systems in Transactions on Power Electronics, 2017, pp. 16.

**[2]** Pragyan Priyanka Satapathy, Regenerative Braking Using Buck boost Converter, ethesis, 2014.

**[3]** K. Jin, M. Yang, X. Ruan, and M. Xu, Three-level bidirectional converter for fuel cell/battery hybrid power system, IEEE Transactions on Industrial Electronics, vol. 57, no. 6, pp. 19761986, Jun. 2010.

**[4]** W. Li, C. Xu, H. Yu, Y. Gu, and X. He, Analysis, design and implementation of isolated bidirectional converter with winding-cross-coupled inductors for high step-up and high step-down conversion system, IET Power Electronics, vol. 7, no. 1, pp. 6777, Jan. 2014.

**[5]** R.Y. Duan and J.D. Lee, High-efficiency bidirectional dc-dc converter with coupled inductor, IET Power Electronics, vol. 5, no. 1, pp. 115-123, Jan. 2012.

**[6]** M. Shah, J. Sutaria, and C. Chauhan, Design, simulation and implementation of two phase interleaved bi-directional DC-DC converter, in Proc. IEEE EESCO Conference Rec, 2015, pp. 16

**[7]** K. Sun, L. Zhang, Y. Xing, and J.M. Guerrero, A distributed control strategy based on DC bus signalling for modulator photovoltaic generation system with battery energy storage, IEEE Trans. Power Electron., vol.26, no.10, pp.30323045, Oct. 2011

**[8]** B. Wu, K. Smedley, and S. Sigmond, a new 3X interleaved bidirectional switched capacitor converter, in Proc. IEEE Appl. Power Electron. Conf. Expo., 2014, pp. 14331439.

**[9]** V. A. K. Prabhala, P. Fajri, V. S. P. Gouribhatla, B. P. Baddipadiga, and M. Ferdowsi," A DCDC converter with high voltage gain and two input boost stages," IEEE Transactions on Power Electronics., vol. 31, no. 6, pp. 4206-4215, Jun. 2016

**[10]** L. S. Yang and T. J. Liang, Analysis and implementation of a novel bidirectional DCDC converter, IEEE Transaction on Industrial Electronics., vol. 59, no. 1, pp. 422434, Jan. 2012.

**[11]** C.-C. Lin, L.-S. Yang, and G.-W. Wu, Study of a non-isolated bidirectional DCDC converter, IET Power Electronics., vol. 6, no. 1, pp. 3037, 2013.