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A Soft-Switched Bi-directional DC-DC Converter for a BLDC motor based Electric Vehicle

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ABSTRACT

In an Electric vehicle or Hybrid electric vehicle, the bi-directional DC-DC Converter (BDC) is an essential component for the control of the energy flow between the battery and the motor. A uni-directional dc-dc converter present inside the electric vehicle can allow energy flow only from battery to the motor. As many electric vehicles have a concept of regenerative braking, it has become necessary to have a BDC, allowing bi-directional energy flow. The main objective of this paper is to design, simulate and implement a soft-switched BDC with reduced number of components along with resonant inductor and a coupled inductor added to improve the gain of the BDC. Soft switching is applied to the BDC to minimize the switching losses though ZVS technique. There is no need of additional circuit to regulate the direction of power flow. This converter is integrated with a BLDC motor with the help of a voltage source inverter (VSI) and a battery.

Key words: Coupled inductor, Resonant inductor, DC-DC Converter, ZVS, Soft Switching

1. INTRODUCTION

In the world wide vehicle production, the demand for electric vehicles and hybrid electric vehicles is increasing due to environmental concerns and since the cost of the electric vehicles are now reducing. The major components required for designing of electric vehicles are available at reducing costs and components can be designed based on the requirement of power, type of usage and regional issues.

An electric vehicle generally draws power from an external supply through the charging port and stores it in a battery pack. For the vehicle accessories, a DC-DC converter is employed which converts the power from the battery to the low voltage auxiliaries. If the vehicle is driven by an induction motor or a BLDC motor, an inverter is required to interface the dc voltage with the motor load.

In an electric vehicle, the bi-directional dc-dc converter is a major component which is widely used for the energy flow in both the directions such that vehicles may have regenerative braking. When brake is applied in a vehicle, a certain amount of energy gets dissipated in the form of heat. This eventually causes wear and tear of brakes and at some point the brakes may even fail. So to avoid such failures and increase the life time of braking system and to avoid the power losses during braking, regenerative braking is employed in electric and hybrid vehicles. The concept of regenerative braking in electric vehicles is defined as the power flow from the motor to the battery and hence the vehicle can be braked without loss of energy. During the regenerative braking of the motor, deceleration takes place and the motor acts as a generator, where a large amount of energy is transferred to the battery through the converter which would otherwise be lost as heat if mechanically braked.

Plenty of literature is available for bi-directional converters used in electric vehicles which are isolated or non-isolated. A battery operated electric vehicle traction system with a bidirectional dc dc converter has been analysed [1]. In [2] is suggested a circuit with soft switching on a push-pull based converter converting solar PV power to the load through an ac module. A complete review of topologies for battery charging has been detailed in [3] for electric and hybrid electric drive applications. A quasi-switched capacitor based bidirectional converter using a SiC MOSFET is proposed [4]. [5] discusses an isolated bi-directional converter with multiple input sources. The converter has dual active bridges with a H-bridge on the LV and HV sides. The input sources need not have the same voltages and are connected in series.

To improve the efficiency of converters by reducing switching losses, many circuits have been suggested in literature. In [6] is suggested a boost converter with a coupled inductor which can achieve both zero current transition and zero voltage transition for the main switch during turn-on and zero voltage switching during turn-off. Three inductors are used which share a common core. In [7] is derived a family of non-isolated bidirectional converters and a topology is evolved which can achieve soft switching in both directions. The circuit makes use of an additional switch but however dispenses with the resonant inductor. Similarly a family of non-isolated bi-directional converters with zero voltage transition is derived in [8]. An auxiliary circuit with a coupled inductor and two auxiliary switches are made use of.

A converter with zero voltage switching over the entire range has been outlined in [9]. The converter makes use of a lagging leg and leading leg, symmetrical half bridge inverters and requires minimum filtering. The implementation of zero voltage switching for a buck converter using a coupled inductor has been illustrated in [10]. It is further elaborated for a bidirectional converter in [11]. [12] improvises this further with a simpler structure with an auxiliary circuit comprising only a coupled inductor, a resonant inductor and two diodes. ZVS is obtained for both the switches in both forward and reverse directions. In [13] is suggested a topology where a BLDC motor used in an electric vehicle is braked in a regenerative mode and the energy released is stored in a combination of battery and supercapacitor.

In the proposed system, the bi-directional dc-dc converter (BDC) is integrated with a battery bank and a voltage source inverter and drives an electric vehicle through a BLDC motor. For the bi-directional dc-dc converter, MOSFET switches are used along with a resonant circuit and a coupled inductor.

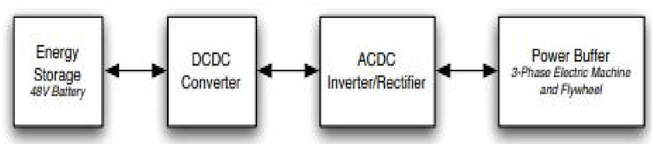

Figure 1: Block diagram of dc-dc converter with power buffer.

Since the converter is switched at high frequencies, switching losses take place due to the usage of the switches for power flow in both the directions. In order to reduce the switching losses, the bi-directional dc-dc converter uses a resonant circuit to achieve soft switching. A coupled inductor is used to obtain a high converter gain in the boost and buck modes. The coupled inductor also helps in releasing extra energy of the resonant inductor and freewheeling action and reduces the power losses in the switches. A typical block diagram of the power management system is shown in Figure 1.

2. PROPOSED BI-DIRECTIONAL CONVERTER

On the basis of power flow direction, the proposed bi-directional dc-dc converter has two operations: positive operation and negative operation. The power flow from high side to low side can be defined as positive operation which can be shown as a synchronous buck converter type of operation. The power flow from the low side to the high side can be defined as negative operation which can be shown as a synchronous boost converter type of operation. The main objective is to design a bi-directional dc-dc converter with less number of components that can be integrated with a BLDC motor through a three phase inverter powered by the battery.

The proposed bi-directional converter consists of MOSFET switches, resonant inductor and a coupled inductor. In high power applications, switching losses reduce the efficiency and reliability of the converter.

To overcome such switching losses, the soft switching is adopted. The soft switching characteristics can be achieved by zero voltage switching technique where the current flow through switches only after voltage becomes zero. In zero voltage switching (ZVS) technique, when the switches are engaged with pulse width modulation (PWM) operation at higher frequency, the soft switching takes place such that the voltage is made zero before the pulse is given such that the switch is turned on or off which eliminates the overlap of current and voltage in respective time frames.

In the proposed converter design the soft switching characteristics is employed with zero voltage switching for both synchronous buck mode of operation and synchronous boost mode of operation. The soft switching takes place with the help of the snubber capacitor parallel to the MOSFET switch and a resonant inductor which is in series with a coupled inductor, because of this LC resonance occurs and eventually switch voltage will become zero. The current through the switch flows only after the voltage is made zero. Hence during the synchronous buck and boost converter operation, the switching losses are reduced by this technique to improve the power flow and efficiency of the bi-directional dc dc converter and hence loss free power input can be given to the BLDC motor for operation.

Coupled Inductor is basically similar to a transformer but it has low coefficient of coupling and can store energy. The coupled inductor employed in the proposed converter consists of two coils where the energy is transferred from one coil to another with the principle of mutual inductance. The major advantage of using coupled inductor is to improve the gain of the converter and assist soft switching. Though the load current is uni-directional during either boost or buck modes of operation, the current through the resonant inductor is bi-directional which makes soft switching possible [11].A schematic of the bi-directional dc-dc converter with a coupled inductor and integrated with a BLDC Motor is shown in Figure 2. Depending upon the direction of power flow in the converter, the converter performs two modes of operation.

2.1 Positive operation

During the positive mode of operation, the energy flow from the high side to the low side. This can also be defined as the synchronous buck mode of operation. Hence in the proposed converter model the BLDC motor is integrated with the bi-directional DC-DC converter along with a 3 phase inverter to provide power to the motor from the battery. The motor side is the high voltage side where the power is developed as the motor acts as a generator due to the regenerative braking.

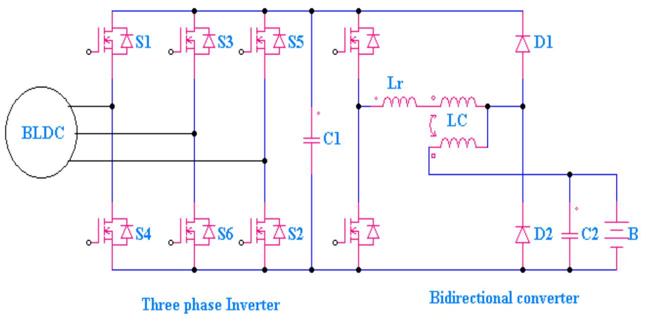

Figure 2: Bi-directional converter integrated with a BLDC Motor.

At this point, the motor develops negative torque, thereby the motor acts as generator and generates electricity. The energy produced flows through a 3 phase inverter which acts as a rectifier and gives a constant dc voltage. This DC voltage flows across the DC link capacitor to avoid voltage variations and then through the bi-directional converter, as the converter acts as step down chopper. This energy can be stored to the battery where the battery side is known as the low voltage side. Soft switching operating modes are described in [12].

2.2 Negative operation

During the negative operation, the energy flows from the low voltage side to the high voltage side. This can also be defined as the synchronous boost mode of operation. The energy stored in the battery flows through the bi-directional dc-dc converter to the motor through the inverter. Here the converter acts as a step up chopper and the generated high voltage flows across the DC link capacitor to an almost ripple-free constant voltage. The energy from DC link flows to a 3 phase inverter and the generated 3 phase voltage is applied to the motor. This operation is given as motoring action, where the BLDC motor is powered with the help of battery.

3. SIMULATION RESULTS

A Matlab simulation of the bi-directional dc-dc converter with soft-switching is shown in Figures 3 and 8 for the buck and boost modes of operation. The simulation results Figure 4 to Figure 7 illustrate the buck mode of operation and the zero voltage switching (ZVS) of the switches in this mode. Figure 4 illustrates the gate pulse given to switch 1, the voltage across switch 1 and the current through switch 1. It can be seen that the current starts rising after the switch voltage becomes zero. Similarly Figure 5 illustrates the switch voltage and current through switch 2. Figure 6 illustrates the main inductor current and the resonant inductor current. The output voltage is shown in Figure 7. Figures 9 to Figure 12 illustrate the waveforms in the boost mode of operation and the zero voltage switching that is happening in this mode. The control of the converter can be implemented using fuzzy logic control and for a typical wind application as outlined in [14] and [15].

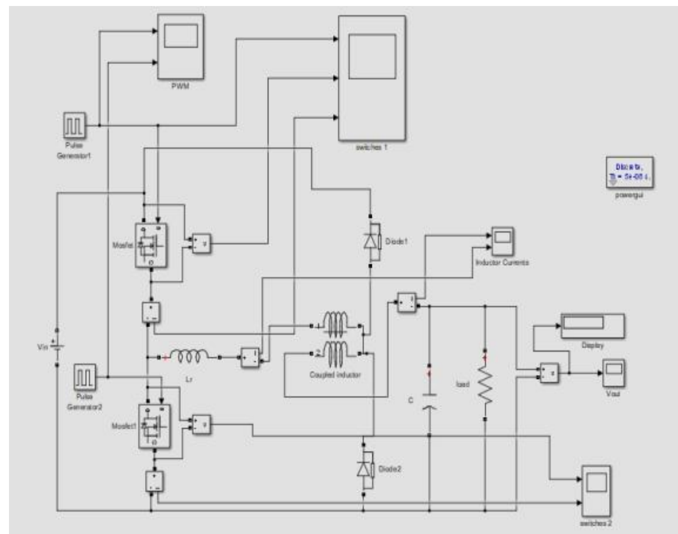

Figure 3: Simulation diagram (illustrating buck operation)

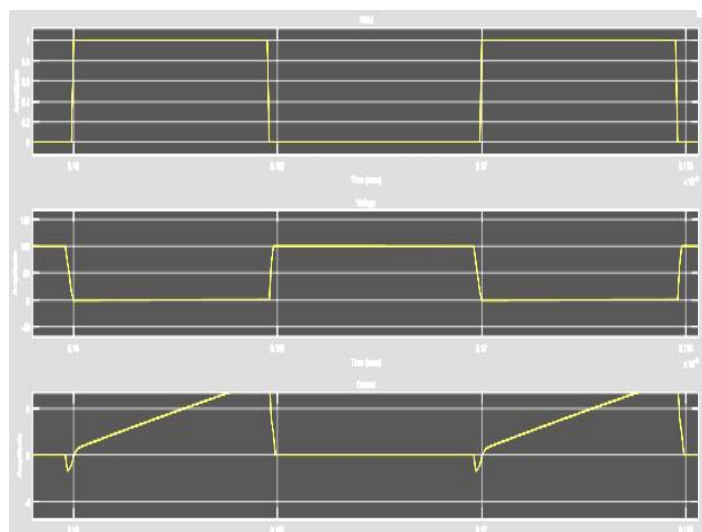

Figure 4: Switch 1 Parameters (Gate pulse, Voltage and Current)

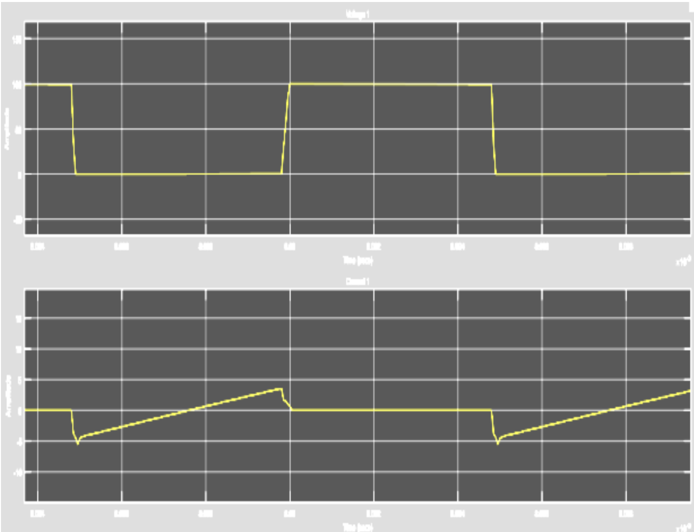

Figure 5: Switch 2 Parameters (Voltage and Current)

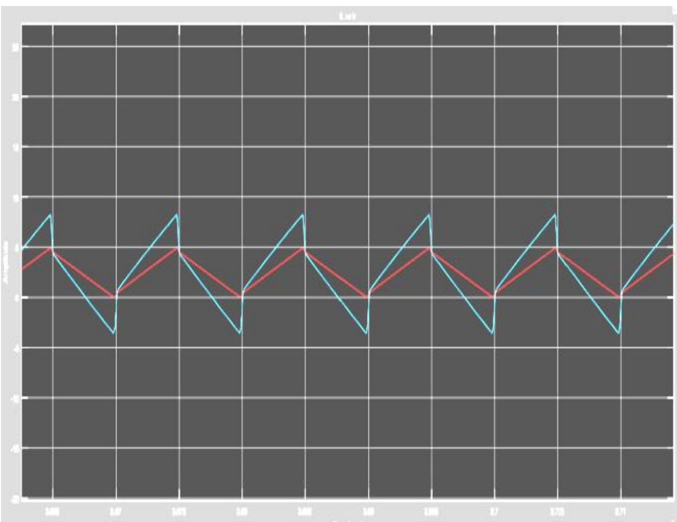

Figure 6: Inductor current Vs Resonant Current

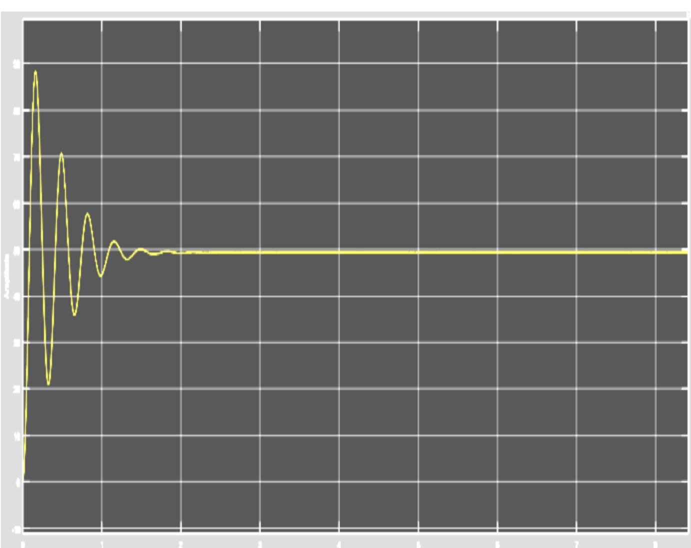

Figure 7: Output Voltage (Vout)

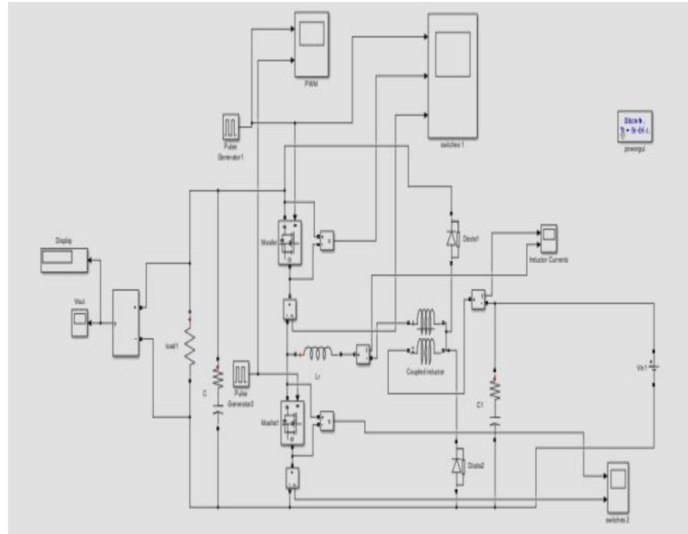

Figure 8: Simulation diagram (illustrating boost operation)

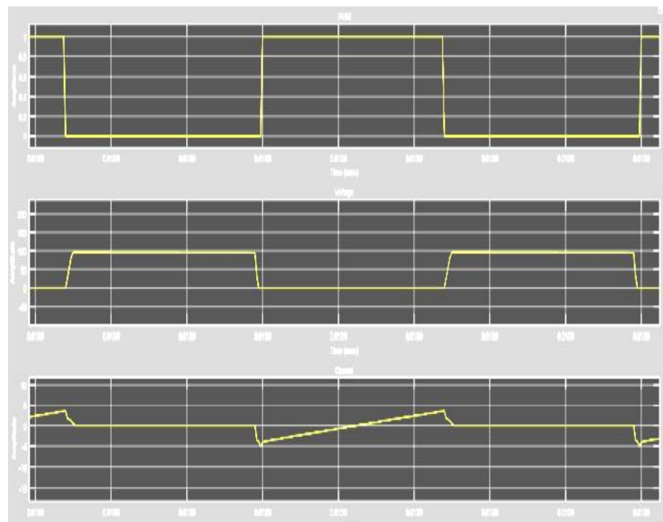

Figure 9: Switch 1 Parameters (Gate pulse, Voltage and Current)

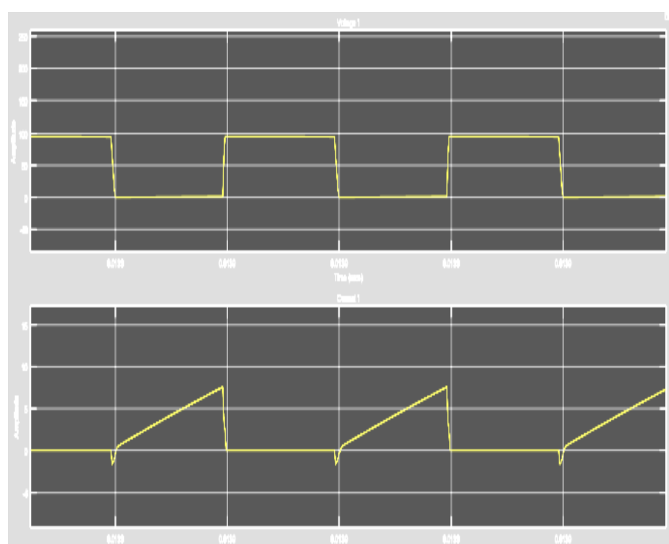

Figure 10: Switch 2 Parameters (Voltage and Current)

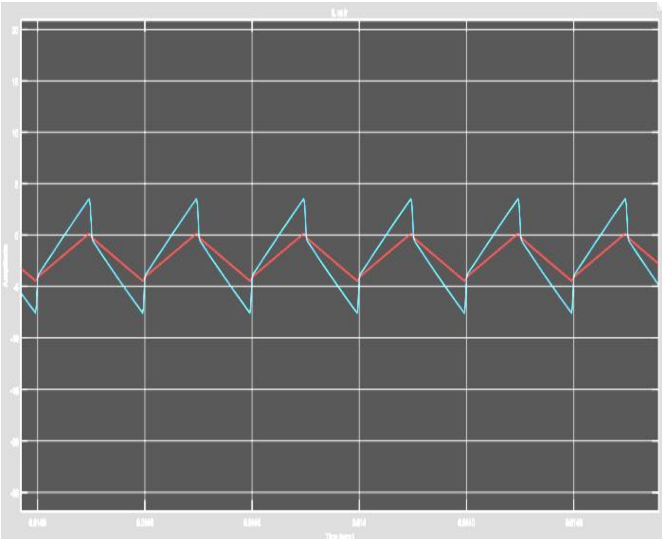

Figure 11: Inductor current Vs Resonant Current

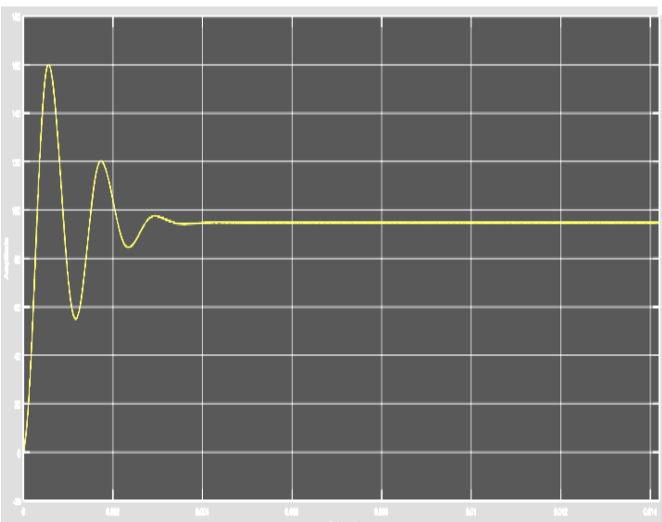

Figure 12: Output Voltage (Vout)

4. EXPERIMENTAL RESULTS

A hardware prototype of the proposed converter integrated with a 3 phase resitive load is shown in Figures. 13 and 14. The setup has 48V on the high-voltage side and 12V on the low-voltage side.The prototype consists of two high power MOSFET switches,a high capacity DC link capacitor, a resonant inductor,a coupled inductor and two freewheeling diodes.

Table 1: Power circuit paramaters

Capacitor(Dc Link) – 450 V, 22 µF
MOSFET - IRF840(500 V,8 A)
Diode - IN4007
Main Inductor (L) – 420 µH
Couped Inductor(Lc) - 50 µH
Resonant inductor- 30 µH
Battery – 12 V, 1.3Ah
Switching Frequency- 4 kHz

Table 2: Control circuit parameters

Voltage regulator - KA7805
Power supply capacitor – 25V, 1000µF
Microcontroller - PIC16F877A
Oscillator - MEC AH9HK
Optocoupler - TLP250H
Driver circuit IC - FAN7392N
Power capacitor - 63V ,47µF

The converter switches are controlled by a simple, low cost 16-bit PIC microcontroller 16F877A. The switchiong frequency is kept at a modest frequency of 4 kHz considering the limited processing capacity. A suitable driver circuit FAN7392N along with optocoupler TLP 250 is used to operate the high power MOSFET switches. The output voltage waveforms in buck and boost modes are shown in Figures.15 and 16. The parameters of the power and control circuits are as shown in Tables 1 and 2.

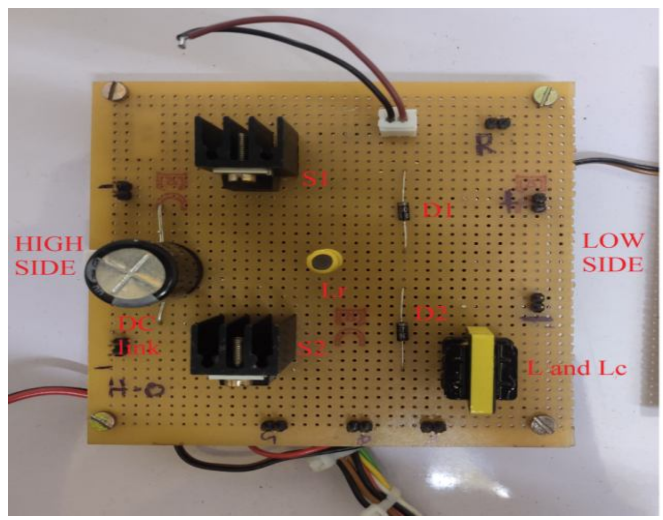

Figure 13: Power circuit

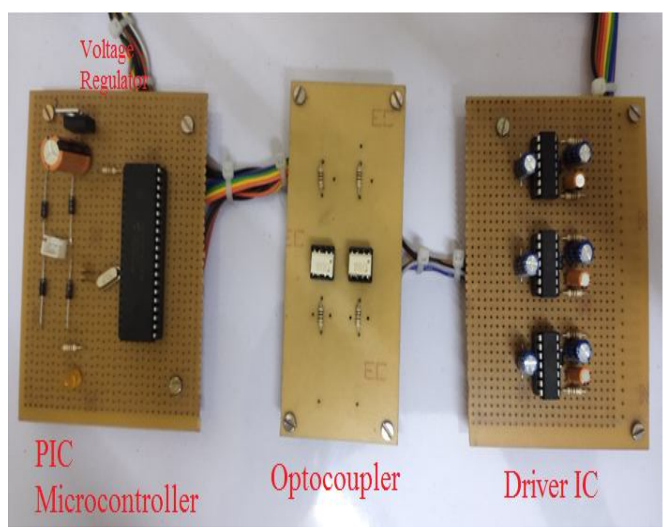

Figure 14: Control circuit

In buck mode of operation, the energy is developed from the motor by the method of regenerative braking where the motor acts as a generator and initiates power flow. In the prototype, the input to the high voltage side is given from a single phase supply through a single phase transformer and a rectifier and the power flow is directed towards the battery. The 230 volt supply from mains is stepped down to 48 V and is given to the dc-dc converter.

In boost mode of operation, the energy from the battery is transferred to the load which represents the power flow from the low side to the high side .The input to the low side in this mode is given by a 12 V battery which is stepped up by the converter. The converter is further integrated with a three phase inverter to give a 3 phase voltage of 48 V which can be given to the motor. Hence the low voltage 12 V from the battery is increased to 48V with the help of bi-directional DC DC converter and 3 phase voltage in each phase is shown in the oscilloscope.

Figure 15: Voltage in buck mode

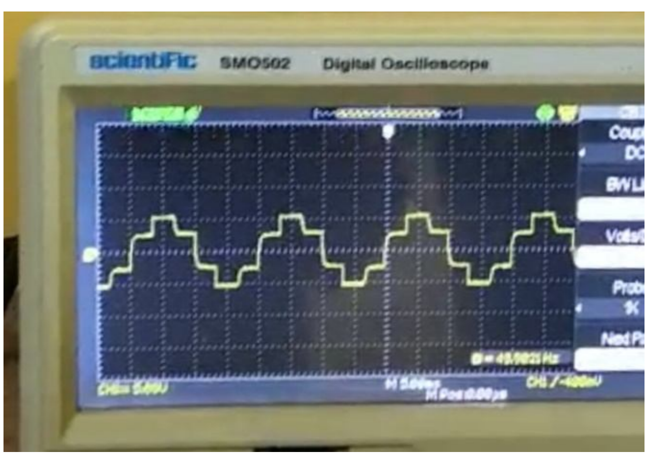

Figure 16: Voltage in boost mode

5. CONCLUSION

This paper outlines the operation of a bi-directional DC-DC converter integrated with a BLDC motor to drive an electric vehicle. Power flows in the converter is bi-directional. In the buck mode, power flow takes place from the high side to the low side that is from the motor to the battery and in the boost mode power flows from the battery to the load. The energy from the motor developed during regenerative braking is further stored in the battery. The bi-directional DC DC converter is designed with components such as power MOSFET switches, resonant inductor and coupled inductor. Since the MOSFET switches are employed in the converter operation, they are subjected to certain switching losses which are overcome by ZVS switching. Zero voltage soft switching operation is shown with simulation results in MATLAB/SIMULINK for buck and boost modes of operation. A hardware prototype is developed and some hardware results have been presented.

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