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Four quadrant operation of bidirectional DC-DC converter for light electric vehicles

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ABSTRACT

This paper discusses the closed-loop control of a bidirectional full bridge DC-DC converter which aids in the four-quadrant operation of an electric vehicle (EV). Several topologies of bidirectional converters have been recently investigated for optimizing vehicle performance. The bidirectional converters with buck and boost modes of operation aid the four-quadrant operation of drives. The proposed bidirectional converter aids buck and boost modes of operation in both forward and reverse directions of the drive. The buck/boost operation in the forward direction is suitable to operate the traction drive in motoring mode. Also, the buck/boost operation in the reverse direction aids the drive to operate in charging mode. The performance analysis of the bi-directional converter-fed EV drive is done using MATLAB/Simulink software. The different modes of operation of the converter which is utilized for the four-quadrant operation of the drive are validated using a 12-60V hardware prototype. DSP TMS2837D controller is used to control the bi-directional converter and the code generation for the controller is done in MATLAB-DSP integrated platform. The hardware results validate theoretical analysis and simulation studies.

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1. INTRODUCTION

In recent decades, electric vehicles (EVs) have gained attention in the automotive industry due to their attractive features like zero carbon emission and noiseless operation. Emerging technologies in EVs are leading to the development of smart and sustainable transportation systems in the upcoming smart cities [1]. Widespread research is undergone in emerging technologies like vehicle-to-home (V2H), vehicle-to-grid (V2G) [2], [3], smart power distribution and autonomous driving [4]. Although trending investigations are undergone in battery technology, EV drive trains, energy management systems and charging infrastructures [5], there is still more work to be done for the widespread commercialization of EVs especially in developing countries.

EV drive train comprises energy sources, different power electronic converters and electric motors to drive the vehicle. Power electronic converters has a key role in the vehicle drive train as it is responsible for controlling the power flow from the energy sources to the motor and vice versa [6]. Advanced researches are carried out in power electronic converters to improve conversion efficiency, provide precise power flow control, and reduce the drive train's size and weight [7]. Different controlled power electronic converters like rectifiers, DC-DC converters, and inverters can be used in the EV drive train [8]. Among these, DC-DC converters are used mainly between the energy source and the inverter to control the DC link voltage. Also, bidirectional property incorporated in the DC-DC converters aids in feeding back power to the energy source.

For the proper utilization of EV drive train, widespread research is undergone on optimal DC link voltage, and generally, half-bridge DC-DC converters and full-bridge DC-DC converters [9] are used for this purpose. Also, bidirectional transfer of power between the battery and the motor drive is essential, which brings the bi-directional converter into action. The bidirectional DC-DC converter is used in applications where there is a power flow in forward and backward requirements. It can also perform stepping down and stepping up of voltage levels. It provides control of motoring and regenerative braking operation which increases the efficiency and boosts the voltage level of the electrical energy storage system (EESS) to a higher level, thereby reducing the current and associated losses.

This paper explores the design and closed-loop control of a bidirectional full-bridge converter-fed brushless DC (BLDC) drive for EVs. Closed loop control is achieved using Texas Instruments LAUNCHXL-F28379D C2000 Delfino Launchpad interfaced with MATLAB/Simulink. C2000 controllers have several attractive features like high resolution, highly flexible PWMs, and high switching frequency which makes them suitable for EV drive applications [10], [11].

2. BIDIRECTIONAL DC-DC CONVERTERS FOR EV

Recently, widespread research is undergone in bidirectional DC-DC converters' control, design and modelling [12]-[14] especially for EV applications. Bidirectional DC-DC converters can control both motoring and regenerative braking operations, resulting in a significant increase in overall efficiency. Bi-directional converters are classified as isolated converters and non-isolated converters [9], [15]-[17]. The basic working of bi-directional DC-DC converters is based on unidirectional converters such as buck-boost and buck-boost circuits, but additionally bidirectional current flow path is provided [18]. Several isolated structures are available such as push-pull converter, flyback converter, half-bridge converter, and full-bridge converter which are recommendable for high-power applications. Even though flyback converters are a good choice because of their simple form, low cost and strong response characteristics, they are subjected to significant voltage oscillation and switching stress due to transformers' leakage inductance. Push-pull DC-DC converters require two switching semiconductor switches in comparison to flyback converters and the system frequency is doubled. Bidirectional full-bridge DC-DC converters [19] are preferred for medium and high-power applications since they ensure the consistency of the bridge arm's on-off eliminating the bias problem. Since the working current of a full bridge DC-DC converter is double that of a half bridge converter, it is widely used in high power supplies.

Conventional non-isolated half-bridge converter combines step-up converter connected anti-parallel with step-down converter. The circuit operates either in a buck or boost mode providing bi-directional power flow [20]. However, in the bidirectional full-bridge converter, more switches are added to the circuit which allows the drive to operate in all four quadrants. In EV, four quadrant operation [13] primarily has the advantage of utilizing the braking energy,to charge the vehicle battery. The proposed converter operates either in a buck or boost mode to charge the battery effectively.

3. WORKING PRINCIPLE OF THE BIDIRECTIONAL FULL BRIDGE DC-DC CONVERTER

3.1. Design steps

The bi-directional converter is designed for 2kW with input and output voltage range of 12-60 V [9]. Design specifications are shown in Table 1. The switching frequency is assumed to be 25 kHz. Figure 1 shows the 2 kW bidirectional full bridge converter circuit diagram designed for EV drive.

Table 1. Design specifications of bi-directional full bridge DC-DC converter

Parameters	Specifications
Input voltage, V_{in}	12 V-60 V
Output voltage, V_o	12 V-60 V
Output power	2000 W
Switching frequency	25 kHz

Output voltage, $V_0 = V_{in} \frac{D}{1-D}$ (1)

for V_{in}=12 V and V_o=60 V, D=0.833.
where V_o, D and V_{in} are the output voltage, duty cycle and input voltage respectively.

Assuming resistance to be 100 Ω by (2):

$$L_{min}=\frac{(1-D)^2\times R}{2f}=0.05\text{ mH} \quad (2)$$

where L_{min}, R and f are minimum inductance, resistance and switching frequency respectively.

Assuming output voltage ripple to be less than 0.05 V by (3):

$$C_{in}=C_0=\frac{D\times V_0}{\Delta V_0\times R\times f}=468.7\ \mu F\approx 470\ \mu F \quad (3)$$

where C_0 and C_{in} is the output capacitor.

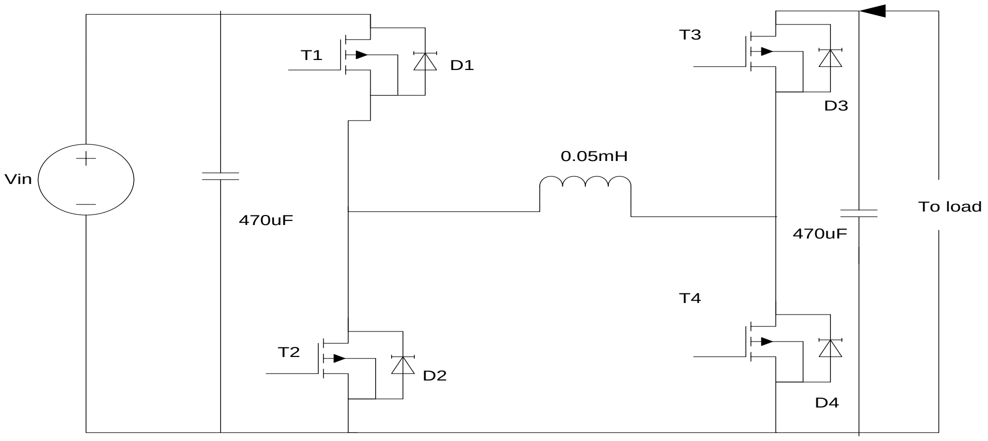


Figure 1. A 2 kW Bidirectional full bridge DC-DC converter for EV drive

3.2. Modes of operation

This section describes the different modes of operation of the bidirectional full bridge DC-DC converterin Figure 2, namely forward buck, forward boost, reverse buck and reverse boost mode. In the forward mode, power flows from energy source to load. In the reverse mode, power flows from the load to source.

3.2.1. Forward buck mode

In this mode, switch T1 is operated in PWM mode. When T1 is turned ON and since diode D3 is also forward biased, current follows the path as shown in Figure 2(a). Power flows from source to load, ie. in forward direction. When T1 is turned OFF, freewheeling happens through D3 and D2 as shown in Figure 2(b).

3.2.2. Forward boost mode

In this mode, switch T1 is in ON state and T4 operates in PWM mode. When T1 and T4 are turned ON, inductor current increases and energy gets stored in the inductor as shown in Figure 2(c). When T4 is turned OFF, energy stored in the inductor together with the supply flows to load as shown in Figure 2(d) and thus a boosted voltage is obtained across the load.

3.2.3. Reverse buck mode

In this mode, switch T3 is operated in PWM mode. When T3 is turned ON and diode D1 is also forward biased, the current flow path is as shown in Figure 2(e). Power flows from load to source, ie. in the reverse direction. When T3 is turned OFF, freewheeling happens through D1 and D4 as shown in Figure 2(f).

3.2.4. Reverse boost mode

In this mode, switch T3 is in ON state and T2 operates in PWM mode. When T3 and T2 are turned ON,inductor current increases and energy gets stored in the inductor. When T2 is turned OFF, energy stored in the inductor together with the load flows to the source, current flow path for this mode is as shown in Figures 2(g) and 2(h).

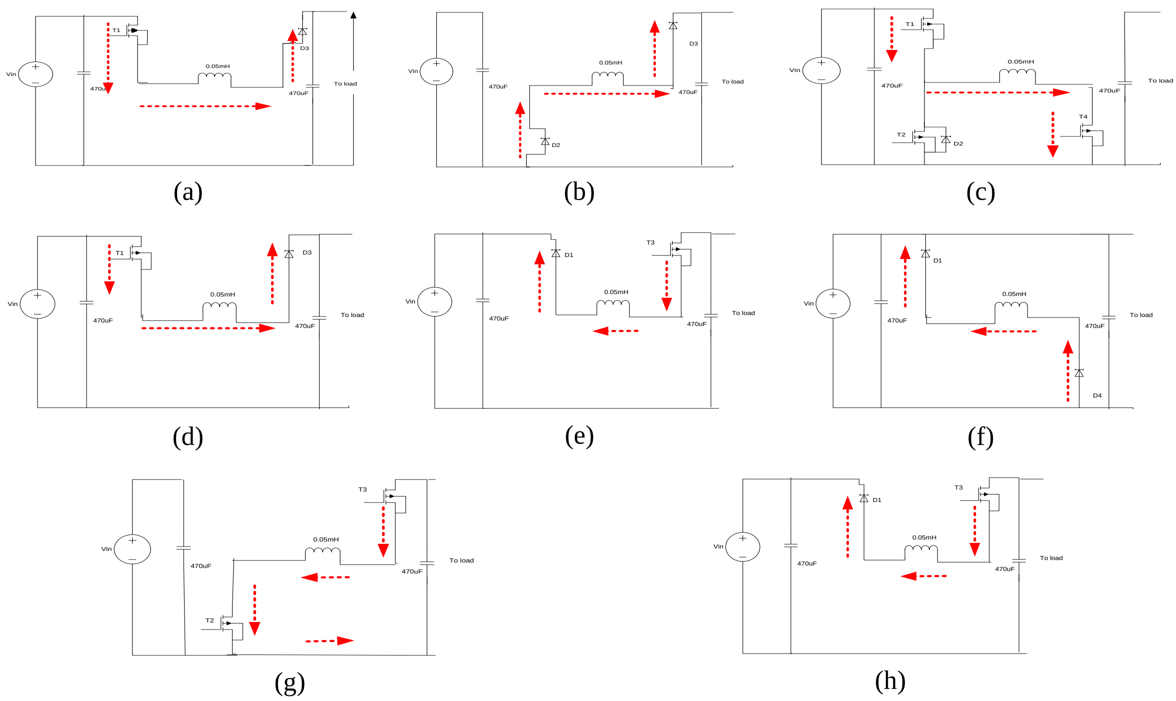


Figure 2. Modes of operation of the bidirectional full bridge DC-DC converter; (a) forward buck mode-T1 ON, (b) forward buck mode-T1 OFF, (c) forward boost mode-T1, T4 ON (d) Forward boost mode-T4 OFF (e) reverse buck mode-T3 ON, (f) reverse buck mode-T3 OFF, (g) reverse boost mode-T2, T3 ON and (h) reverse boost mode -T2 OFF

3.3. Control strategy for the bidirectional DC-DC converter

The different modes of operation of bidirectional converter for EV drive is demonstrated using a bidirectional DC-DC converter fed BLDC drive. The control strategy for the mode selection of the drive is explained as flowchart in Figure 3. Depending on the direction command, the corresponding sequence table is loaded as the commutation sequence for the BLDC inverter. Also, depending on the buck-boost action, the corresponding switching signals are generated for the bidirectional DC-DC converter. The closed-loop speed control [21] with an inner current controller is realized using PI controllers as shown in Figure 4 which provides a fast response to the rapid changes in the motor speed.

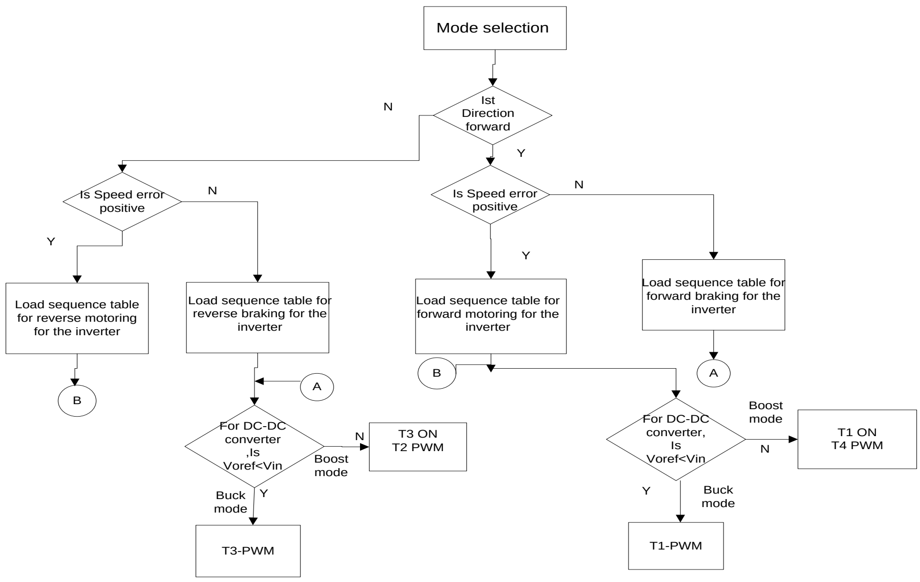


Figure 3. Program flow of the bidirectional full bridge converter-fed BLDC drive

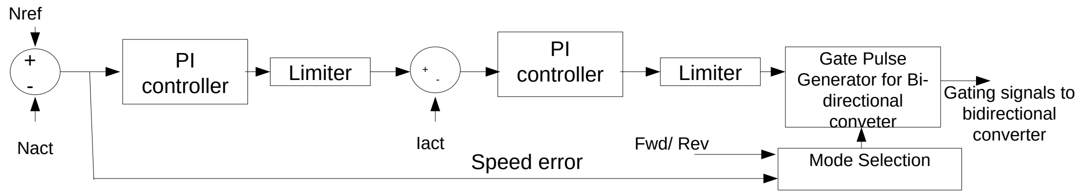


Figure 4. Closed loop control of bidirectional converter-fed BLDC drive

4. SIMULATION STUDIES OF BIDIRECTIONAL FULL BRIDGE DC-DC CONVERTER-FED BLDC DRIVE

Simulation studies of the bidirectional full bridge DC-DC converter fed BLDC drive is done using MATLAB/Simulink software. Figure 5 shows the simulation diagram of bi-directional full bridge converter fed BLDC drive with its buck/boost operation in both directions. Motoring operation in both forward and reverse direction is achieved by operating the bidirectional converter in forward buck and forward boost mode. Regenerative braking operation in both forward and reverse direction is achieved by operating the bidirectional converter in reverse buck or reverse boost mode.

Selection of buck/boost mode depends upon the reference speed given to the BLDC drive. If the voltage corresponding to the reference speed is greater than the actual input voltage of the drive, the converter operates in boost mode and vice versa. In this simulation, a voltage of 51.66 V corresponds to a speed of 3154 rpm. Switching pulses are generated using outer speed control closed loop operation with inner current control loop.

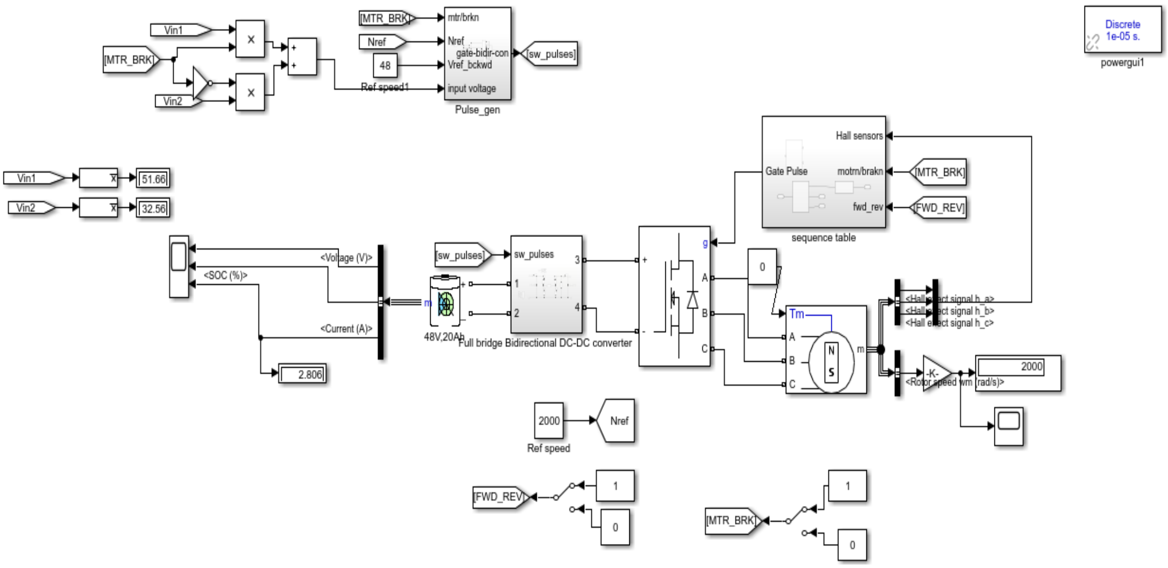


Figure 5. Simulation diagram of bi-directional full bridge DC-DC converter using MATLAB/Simulink software

5. HARDWARE DEMONSTRATION OF BI-DIRECTIONAL FULL BRIDGE DC-DC CONVERTER

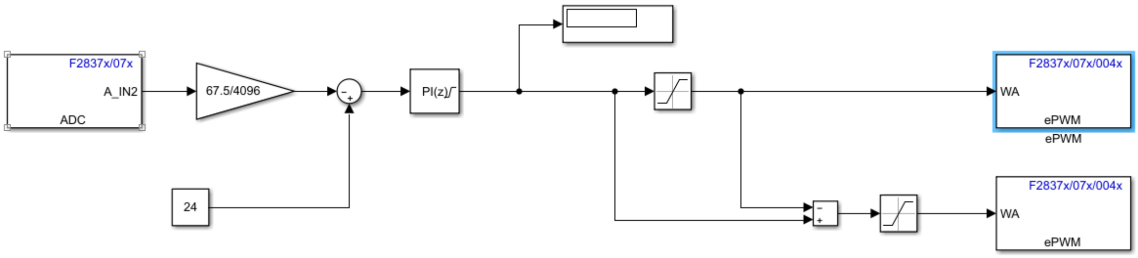
The hardware prototype of the bidirectional full bridge converter is realized and the pulse generation of the switches is done using DSP controller TMSF2837D. PC is connected to C2000 Launchpad and the simulation model for pulse generation is converted into DSP controller code and it is executed. The DSP controller code generation happens through automatic code generation [22]. DC supply is connected to the input1 terminals and load is connected across the input2 terminals for the forward direction and vice-versa for the reverse direction. Output voltages and their waveforms are observed for different input values of input voltages.

Table 2 lists the hardware setup components with their speciation. Code generation for the DSP controller is done using MATLAB-DSP integrated platform [23]. This integrated design environment is developed by Mathworks and TI company joint development toolkit. Researchers can use Simulink algorithm to build up the logic and then generate code automatically which can run on the DSP target board [24], [25].

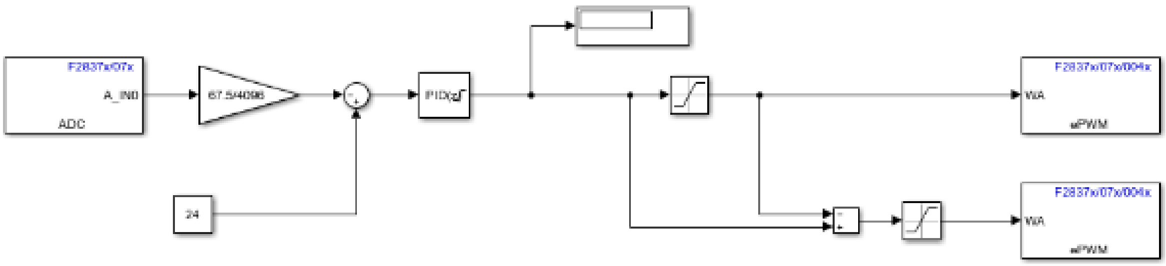
Figure 6 shows the simulation diagram in MATLAB/Simulink platform corresponding to the code generation for the closed loop control. This Simulink model uses ADC block and ePWM blocks corresponding to DSP controller F2837x and a PID controller with Kp=0.1 and Ki=10. The load voltage is read from ADC block with module A, channel: ADCIN2 for forward direction in Figure 6(a) and module B, channel:ADCIN0 for reverse direction in Figure 6(b). The actual load voltage read from ADC pin is compared with the input reference voltage (eg:24 V) and the PID controller output is used as the input to ePWM block which adjusts the duty ratio. The load voltage is made equal to the reference voltage by adjusting the duty ratio of switching pulses. Figure 7 shows the photograph of the hardware setup of closed-loop control of the bidirectional DC-DC converter for EV onboard chargers.

Table 2. Hardware components specification of bidirectional full bridge DC-DC converter

Sl No	List of components	Specifications	Quantity
1	TMS320F2837D C2000 Launchpad		1
2	DC supply	0-30 V,2A	2
3	Capacitor	470 uF	2
4	Inductor	0.05 mH	1
5	MOSFET	P80NF10	4
6	Load Resistor	$100\ \Omega, 20A$	1



(a)



(b)

Figure 6. Simulink model for DSP code generation for closed-loop control of DC-DC converter (a) forward direction and (b) reverse direction

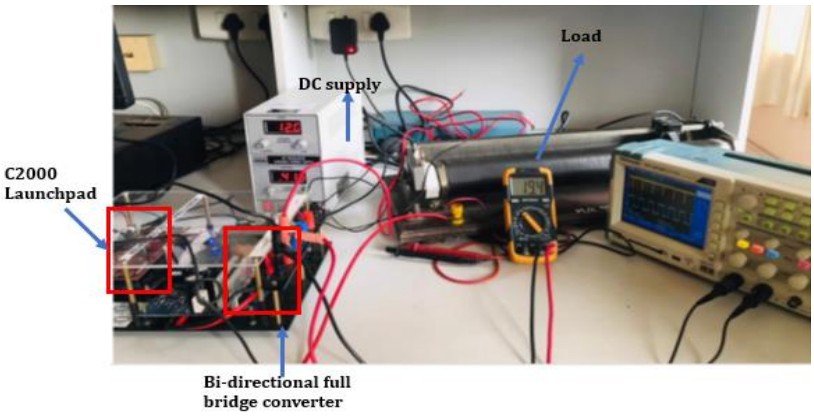
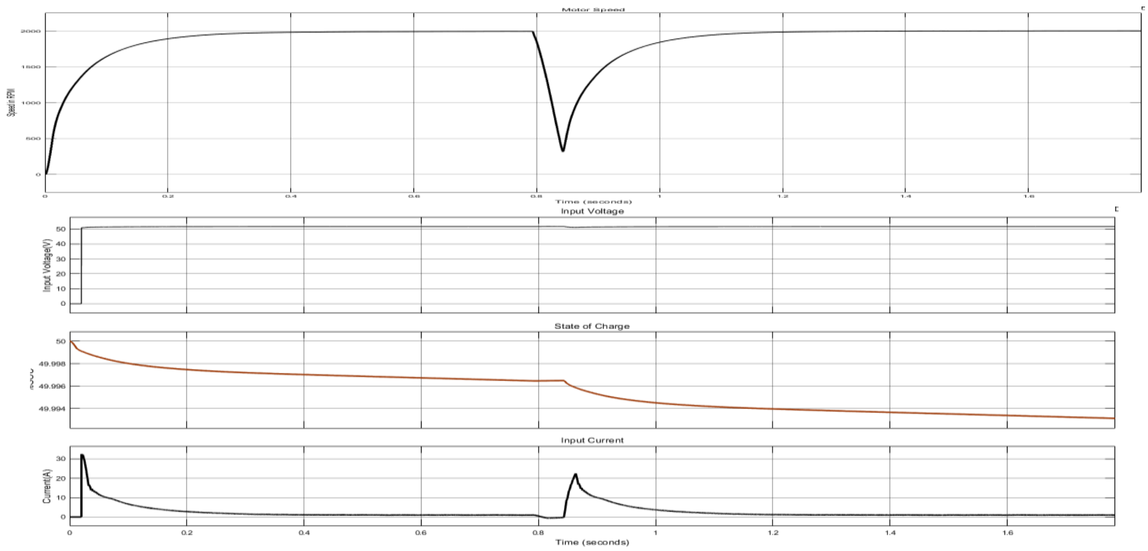


Figure 7. Experimental setup of closed-loop control of bi-directional full bridge converter

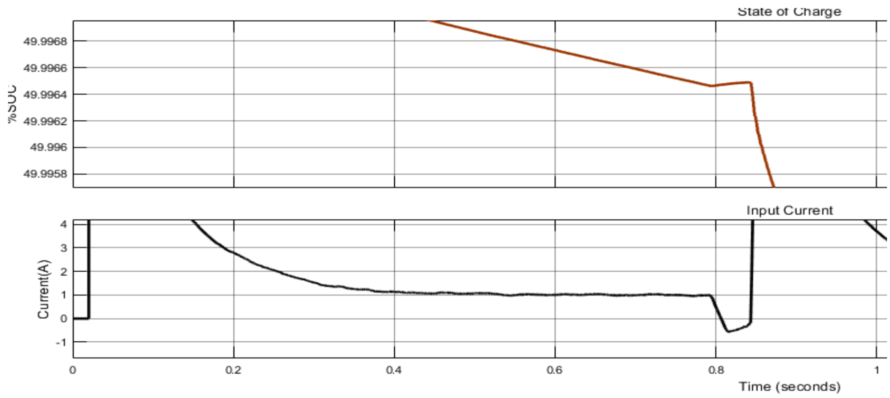
6. RESULTS AND DISCUSSION

The simulation results of the four quadrant operation of the bidirectional converter fed BLDC as shown in Figure 8 drive are tabulated in Table 3. If the reference speed is set below 3154 rpm, the converter operates in buck mode in both forward and reverse directions. If the reference speed is set above 3154 rpm, the converter operates in boost mode for both directions as well. Figure 8(a) shows the output waveforms of motor speed, battery voltage, battery state of charge (SoC) and battery current at a reference speed of 2000 rpm in forward direction. Command for braking is applied at 0.794 seconds till 0.84 seconds. As a result, speed starts to reduce from 2000 rpm to 317 rpm. During this time, battery current is negative and battery SoC is also increasing which indicates the regeneration mode as shown in Figure 8(b).

From the observations and output waveforms, it is clear that the closed loop speed control of bi-directional full bridge DC-DC converter fed BLDC motor is achieved in both forward and reverse directions. Also, energy regeneration is demonstrated through battery charging, in the braking mode for both directions. Load voltage values obtained for different reference voltages from the hardware setup are recorded in Table 4 and indicate that output voltages are almost equal to the reference voltages.



(a)



(b)

Figure 8. Simulation output waveforms of bidirectional full bridge DC-DC converter fed BLDC drive; (a) input voltage, SoC, input current of source battery and motor speed waveforms and (b) expanded view of battery SoC and current waveform indicating forward motoring and braking conditions

Table 3. Simulation results of bi-directional full bridge DC-DC converter

Sl No	Mode	Reference speed (RPM)	Actual speed (RPM)	Input voltage (V)	Output voltage (V)
1	Forward-buck	1000	1019	20.45	16.37
2	Forward-boost	1500	1505	12.9	24.33
3	Reverse-buck	1000	-1018	20.45	16.37
4	Reverse-boost	1500	-1507	12.9	24.37

Table 4. Observations of output voltages in the hardware setup for different reference voltages

Sl No	Mode	Reference voltage (V)	Input voltage (V)	Load voltage (V)
1	Forward-boost	24	10	24.5
2	Forward-boost	24	12	24.9
3	Forward-buck	24	28.4	25.1
4	Forward-buck	12	20	12.1
5	Reverse-boost	24	12	21.4
6	Reverse-boost	24	15	22.7
7	Reverse-buck	12	23.3	12.1
8	Reverse-buck	12	6.7	12

7. CONCLUSION

This paper discusses the closed-loop control of bi-directional full bridge DC-DC converter, proposed for the onboard charges of EVs. Based on the EV drive requirements, the converter operates either in buck or boost mode in both forward and reverse directions. Forward mode is selected for motoring mode and reverse mode is opted for regenerative braking mode of EV drive. Switching strategy for the converter is developed to obtain closed-loop voltage control with inner current control in all the modes of operation Simulation studies for the bidirectional converter-fed BLDC drive is done in MATLAB/Simulink software. A 2 kW hardware prototype of the converter is realized and the switching pulse is generated using the DSP TMSF2837D controller. The design and switching strategy of the converter is validated using simulation and hardware studies. The developed bidirectional converter can be utilized in the 2 kW light EV drive train to obtain four-quadrant operation. The control algorithm for the converter can be modified for a smoother transition between the four quadrants.

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