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Research Paper

PERFORMANCE ANALYSIS OF A HIGH GAIN BIDIRECTIONAL DC-DC CONVERTER FED DRIVE FOR AN ELECTRIC VEHICLE WITH BATTERY CHARGING CAPABILITY DURING BRAKING

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Abstract: *This research presents a novel non-isolated high gain bidirectional DC-DC converter (BDC) and its application in integrating energy storage system with electric vehicle (EV). The proposed converter can provide high voltage gain with the help of two duty cycle operation by employing fewer components in its circuit design. The proposed topology makes use of dual current path inductor structures which reduces their size and eliminates the need for an additional clamping circuit to power the load. Without using voltage multiplier cells (VMC) or hybrid switched-capacitor approaches, the proposed converter can achieve a significant voltage gain. The simulation of the proposed converter-based drive is carried out using MATLAB/Simulink and OPAL-RT software in loop (SIL) system and the performance analysis is done for different driving conditions. The converter powers the motor through the battery during the forward motoring mode. The motor acts as a generator during regenerative braking and the energy is transferred back through the converter to the battery which stores the recovered energy.*

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1. Introduction

Governmental bodies and organizations are enforcing stricter limits for fuel consumption and emissions due to the rising rate of oil consumption in the transportation sector, as well as growing concerns over the impact of global warming and the depletion of energy resources. By 2040, it is predicted that the yearly sales of EVs and Hybrid Electric Vehicles (HEVs) would surpass those of petrol and diesel vehicles, with sales of over 48 million [1]. The automobile industry is concentrating on the development of new technologies for the power train, battery, and charging infrastructure in response to the rising demand for vehicles with better fuel efficiency and less impact on the environment. The installation of a high-energy battery pack and regenerative braking aid in extending the driving range and battery life of electric vehicles.

Power electronic converters find its application in drive train to modulate the power flow from battery to the propulsion motors and to facilitate regenerative braking in the reverse direction. To increase efficiency and power density, the drive train motor and propulsion inverter are made to operate at higher voltage [2]. To raise the battery voltage to the desired level, a boost converter is used. It also enhances the overall performance of the drivetrain by delinking the battery voltage and the inverter dc link voltage [3]. The DC DC converter must be bidirectional because the forward mode will face transient and overload conditions during which power gets transferred from the battery to load and during the reverse mode, the battery pack is to be charged. Some of the benefits derived by providing a BDC between the battery and the inverter [4], [5] are: a) It reduces the stress on the inverter with an additional DC stage b) It adjusts the inverter supply voltage to increase the motor output, c) The cost and size of the battery can be reduced because of lower cell count requirement and d) The system voltage and battery can be individually designed by the manufacturers. This architecture thus enables versatile system designs for vehicles with various output characteristics. For instance, the battery nominal voltage in the 2010 Toyota Prius is about 200 V, while the DC-DC converter raises the voltage of the dc bus to about 650 V [2].

The most common BDC is the one with an isolated framework [2], [6], [7], [8], [9], [10], [11]. These isolated converters employ the high frequency transformer throughout the operation, increasing its losses and volume. Transformer core saturation [25] is another issue with this kind of converter. Additionally, many isolated converter configurations, such as LLC converters, CLLC converters and dual-active bridge (DAB) converters, which are the most prevalent kind of isolated BDCs, call for a significant number of active switches [10], [11]. Therefore, non-isolated BDCs are typically preferred when isolation is not mandatory. This is due its simple structure and low component count, which draw the attention of several researchers. They are suitable for some applications, such as the drive train of an electric vehicle, where size and weight are crucial considerations.

To attain high conversion ratios, non-isolated BDCs employ many circuit principles, including SEPIC/Cuk/Zeta, voltage multiplier cells, switching capacitors, and linked inductors. Due to their cascaded construction, SEPIC/Cuk/ Zeta converters have a low efficiency and higher voltage stress. BDCs can be designed using voltage multiplier cells; however, this is restricted by the high voltage across switches. BDCs[12],[13],[14] utilizes witched capacitors that perform better, have a simpler construction, and require less control complexity. However, for high-gain applications, the circuit becomes progressively complex and is susceptible to losses with the growing number of switches and capacitors.

The system efficiency can be increased with hybrid topologies, but there is insufficient voltage gain and a greater ripple current [15] associated with few of these topologies. How ever, high conversion factors can be attained using hybrid architectures like SEPIC/quasi-Z source with switched capacitors [16], [17]. Conversion efficiency is nonetheless limited by a high component count and its inability to provide soft switching. Large ripple current at the LV side is a prevalent issue with all high gain non-isolated BDC circuits as it short ens the life and degrade the performance of the battery. Large capacitors can control input ripple current [18], but it is not the preferred option due to the added bulk and cost to the system. Interleaved DC-DC converter is a better option to reduce the input current ripple, but it has a lower voltage gain and more components [19].

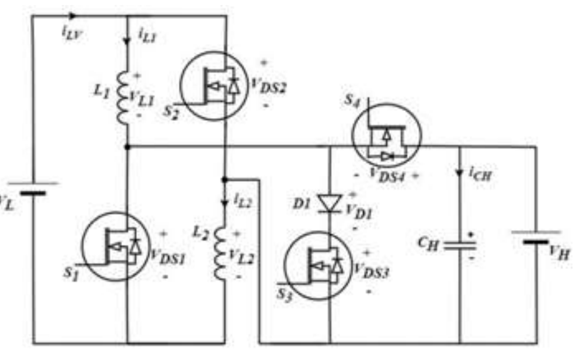
Another significant advancement in this regard is the coupled inductor-based bidirectional converter (CIBDC) architecture [20], [21], [22], [23], [24], [25] that aims to achieve ahigh voltage conversion ratio. Contrary to transformer-based topologies, these coupled inductor-based systems [20] allow energy exchange at several instants during the course of a single time period. By carefully planning the circuit, switch current and voltage stress can be reduced as well. Clamping the coupled inductor’s leakage energy and minimizing volt age spikes and stress across switches are major challenges in coupled inductor topologies. By raising the coupled inductance at the low voltage side, the CIBDC proposed in [21] could minimize the current ripple. But it restricts the number of turns of other windings and in turn the voltage transfer ratio of the BDC. The CIBDC suggested in [24] employs two secondary coupled inductor branches to obtain a greater voltage conversion ratio and current sharing features in addition to soft switching. A non-isolated high gain converter for micro grids is suggested in [26], where coupled inductor is substituted by a normal inductor to make the topology appropriate for high voltage conversion application. How ever, it is unidirectional. The proposed converter is a modified version of the converter in [26] with bidirectional capability for electric vehicle applications.

The proposed high gain bidirectional converter (HGBDC) utilizes only four active power switches which makes its con struction simple. High voltage gain is achieved by choosing the appropriate duty cycle and designing proper inductor and capacitor values. Operation of the converter at a lower duty ratio reduces the core saturation problem of the inductor. Furthermore, the input current is divided among the inductors, which reduces their size and eliminates the need for an additional clamping circuit to give energy to the load. The performance analysis of the converter fed drive has also been carried out using MATLAB/Simulink and OPAL-RT SIL system to prove the viability of the converter in interfacing energy storage device to the dc link in electric vehicles. The converter successfully controls the power flow from the energy source to the motor and vice versa during forward motoring and regenerative braking.

In Section II, the topology and operation of the proposed HGBDCis covered, and in Section III, the specification and design of the converter fed drive system are discussed. The modelling and simulation of the converter fed drive in MAT LAB/Simulink is given in Section IV. Section V describes the implementation of the proposed converter in RT-LAB real time simulation system. The summary of the work is presented in Section VI.

2. Proposed high gain bidirectional dc-dc converter (HGBDC)

The proposed HGBDC shown in figure 1 has four active power switches (S1, S2, S3, and S4), two identical inductors (L1 and L2), a diode (D1), and a capacitor (CH) at the high voltage side. Diode D1 helps in blocking the reverse voltage VL appearing across the MOSFET while the switches S1 and S2 are conducting in boost mode. A switching frequency of fs is used by the switches S1, S2, S3, and S4. During boost mode, switches S1 and S2 have a duty ratio of d1, and switchS3 has a duty ratio of d2. The duty ratio of the switch S4 is (1-d1-d2) during boost mode and it is db during buck mode of operation of the converter.



Proposed HGBDC

A. OPERATION OF THE HGBDC IN BOOST MODE

The boost operation of the converter is explained in three different phases namely, Mode I, Mode II and Mode III. The current flow path of the proposed HGBDC operating in boost mode is depicted in figure 2. During this mode, the energy is transferred from the low voltage side to the high voltage side of theconverterwiththehelpofcontrolledswitchesS1, S2,S3 and S4. The switches S1, S2 and S3 are operated through the PWM control. Typical wave forms of the proposed HGBDC in boost mode for continuous conduction are shown in figure 3.

Mode:1

The switches S1 and S2 are turned on in this mode (t0, t1), while the switches S3 and S4 are turned off for the duration of d1Ts. Energy flow is from the battery to the inductors L1, L2 which are connected in parallel, as shown in figure 2(a). The energy stored in the capacitor; CH is released to the load. The voltage across the inductors is expressed in (1) to (3).

$$v_{L1} = v_{L2} = V_L \quad (1)$$

$$L_1\frac{di_{L1}}{dt} = L_2\frac{di_{L2}}{dt} = L\frac{di_L}{dt} = V_L \quad (2)$$

$$\frac{di_L}{dt} = \frac{V_L}{L} \quad (3)$$

Where vl1 and vl2 are the voltages across inductors L1 and L2 respectively.

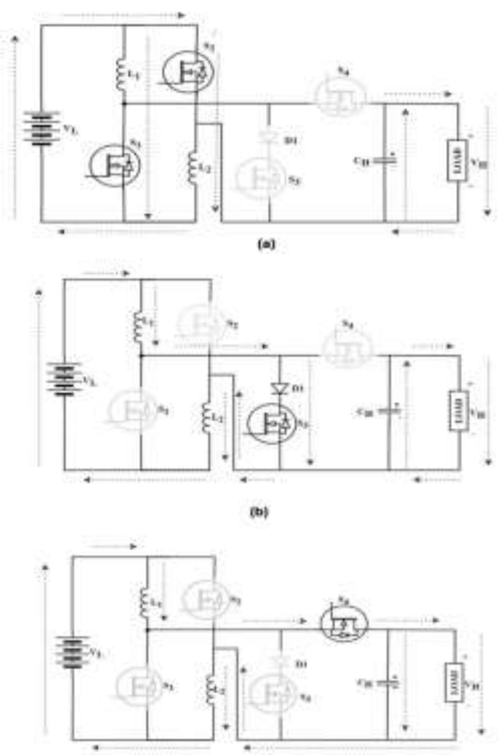


FIGURE 2. HGBDC in boost mode (a) Mode I (b) Mode II (c) Mode III.

Mode:2

Switch S3 is active for the duration of d2Ts, while switches S1 and S2 are turned off in Mode II (t1, t2). As displayed in f igure 2(b), current flow is through L1, D1, S3 and L2. The energy from the source is delivered to the inductors. The load receives the energy that is stored in the capacitor. Source is in series with the inductors in this mode. Equations (4) and (5) represent the currents flowing through and the voltages across the inductors.

$$i_{L1} = i_{L2} \quad (4)$$

$$v_{L1} + v_{L2} = V_L \quad (5)$$

$$v_{L1} = v_{L2} = L\frac{di_L}{dt} \quad (6)$$

$$\frac{di_L}{dt} = \frac{V_L}{2L} \quad (7)$$

Where il1 and il2 are the current through inductors L1 and L2 respectively.

Mode:3

The MOSFET switches S1, S2 and S3 are turned off in this mode (t2, t3), whereas the body diode of the MOSFET S4 conducts during (1-d1-d2)TS. Diode D1 is reverse biased. The load is supplied by both the source and the inductors as depicted in figure 2(c). The capacitor CH is in charging mode as the body diode of S4 is forward biased. The inductors are connected in series to the source. The current through and the voltage across the inductors are given in (8) to (10).

$$i_{L1} = i_{L2} \quad (8)$$

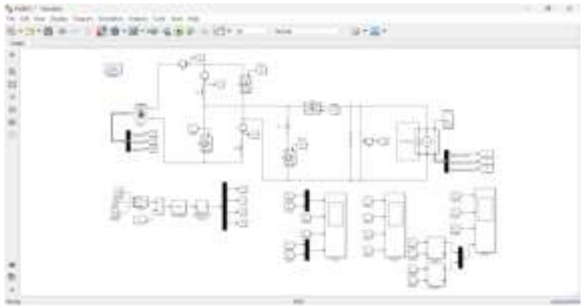
$$v_{L1} + v_{L2} = V_L - V_H \quad (9)$$

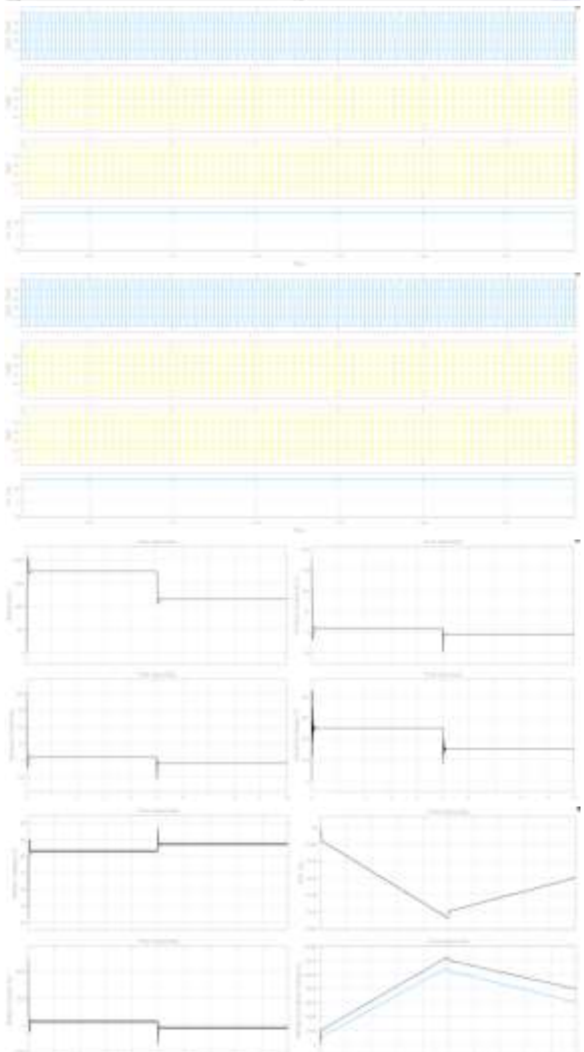
$$v_{L1} = v_{L2} = L\frac{di_L}{dt} \quad (10)$$

3. SIMULATION ANDRESULTS

Transition of the motor operation from forward motoring to regenerative braking

The converter is made to operate in boost (forward motoring) mode from 0-5 seconds and in buck (regenerative braking) mode from 5–10 seconds. Figure 12 shows the motor speed, armature torque, armature current, armature voltage (output voltage VH) of the converter, battery SoC and battery voltage for this case.



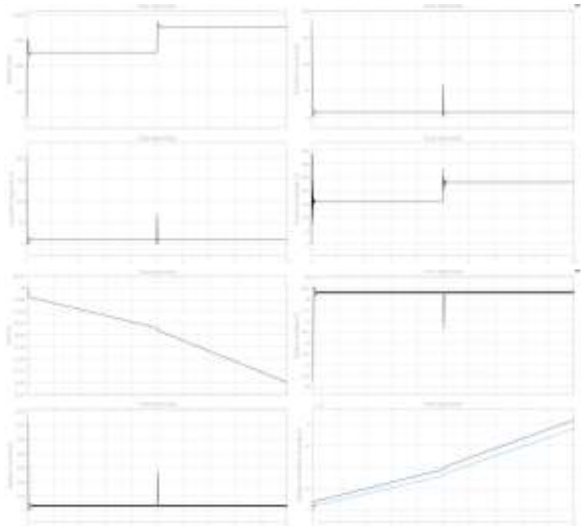


Simulation results for case1- transition of the motor from forward motoring to regenerative braking: (a) speed, (b) armature current, (c) armature torque, (d) armature (output) voltage of the motor, (e) battery voltage and (f) battery SoC (g) battery current (h) battery and motor energy.

Simulations are carried out for the brakingaction with a speed change from 1750 rpm to 1150 rpm when the motor current and torque exhibit a reversal characteris tic as shown in figure 12(a), 12(b) and 12(c) respectively. The change in directions of current and torque during the transition from motoring mode to regenerative braking mode indicates the reversal of power flow. As seen in figure 12(d) armature voltage decreases in proportion to the decrease inspeed. There is a dip in battery voltage and reduction in SOC of the battery during forward motoring (0 to 5 seconds). But the battery voltage and SoC of the battery increases during regenerative braking as observed in figure 12(e) and 12(f). The SoC of the battery increases by 0.02% from 79.95 to 79.97 during a short span of 5s in regenerative braking mode. The battery current and the energies of battery and motor areshown in figure 12(g) and 12(h) respectively. Around 5000J of energy is recovered during regenerative braking.

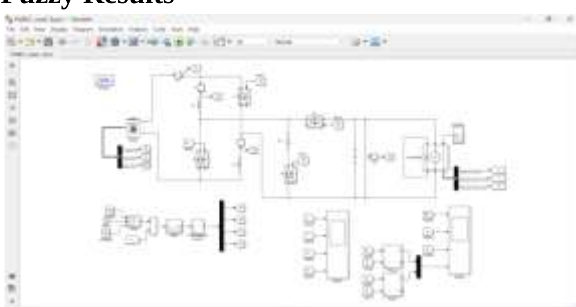
B. A STEP CHANGE IN SPEED DURING FORWARD MOTORING

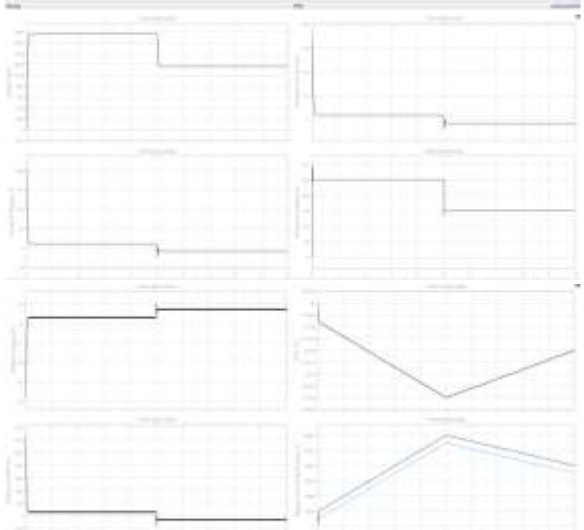
Astep change in motor speed from 1250 RPM to 1750 RPM at constant torque constitutes the second instance of transient operation. Figure 13(a) depicts the speed waveform for a duration of 10 seconds. It is observed that the system settles down at the new speed within 0.5 seconds. The momentary change in armature torque caused by a sudden alteration in the speed is seen in Figure 13(c). The characteristics of current that is identical to that of torque is shown in f igure 13(b). The change in armature voltage with respect to the change in motor speed is depicted in figure 13(d). As seen in figure 13(e), when the speed increases, the motor draws more energy from the source, resulting in a fall in the SoC ofThethe battery by 0.08%. The battery voltage and current during this phase are depicted in figures 13(f) and 13(g) respectively. battery and motor energy characteristics are shown in f igure 13(h).



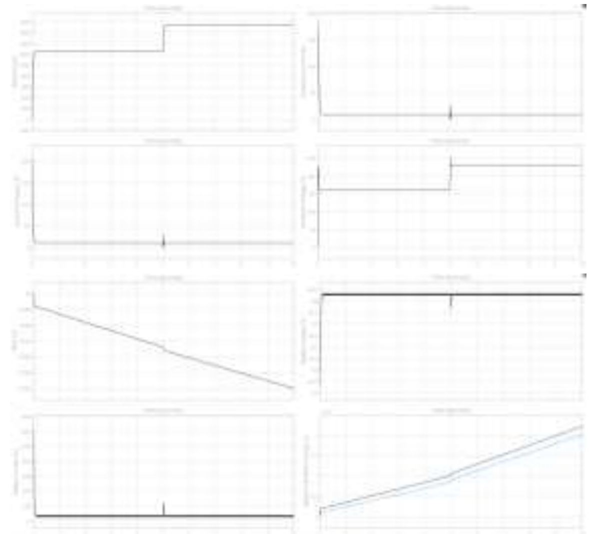
Simulation results for case 2- step change in speed during forward motoring: (a) speed, (b) armature current, (c) armature torque, (d) armature voltage, (e) battery SoC, (f) battery voltage, (g) battery current and (h) battery and motor energy.

Fuzzy Results





Simulation results for case1- transition of the motor from forward motoring to regenerative braking: (a) speed, (b) armature current, (c) armature torque, (d) armature (output) voltage of the motor, (e) battery voltage and (f) battery SoC (g) battery current (h) battery and motor energy.



Simulation results for case 2- step change in speed during forward motoring: (a) speed, (b) armature current, (c) armature torque, (d) armature voltage, (e) battery SoC, (f) battery voltage, (g) battery current and (h) battery and motor energy.

4. Conclusion

This paper focused on the design and development of a High Gain Bidirectional Converter (HGBDC) for electric vehicle applications with battery charging capability during regenerative braking. The performance analysis of the converter is carried out during motoring and regenerative braking modes in both MATLAB/Simulink and real time simulation environment with RT-LAB. The proposed method is simpler and the converter can attain high gain with the help of two duty cycle operation. It demonstrates a good balance among the voltage gain and the component counts which gives a viable solution to the application of interfacing storage devices to the DC link in electric vehicles which is the focus of the paper. The HGBDC also successfully controls the power flow direction by modifying the converter's working mode from motor ing to regenerative braking. The efficiency of the proposed converter can further be improved by selecting SiC based power switches. Further Soft switching can be implemented to reduce the switching losses when the converter operates at higher frequency, but it adds complexity and increases the number of components.

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