Non-isolated Bidirectional DC-DC Converter for BLDC Motor in Electric Vehicle Applications

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***Abstract* — This paper proposes a Bidirectional DC-DC converter (BDC) that interfaces a battery pack and motor load for Electric Vehicle (EV) applications. The proposed converter is capable of operating in two distinct modes i.e. (i) Battery charging mode with boost operation and (ii) Battery discharging mode with Buck operation, and with the features of bidirectional power flow control. The system model has been simulated in MATLAB/SIMULINK software to validate the performance of the proposed bidirectional DC-DC converter. Moreover, a PI controller has been incorporated for controlling the DC link voltage so that the input voltage for the motor controller is maintained. A simple three-phase inverter powered the motor with the help of Hall sensor signals to generate the gate pulses and the findings are reported well at the end with the concluding remarks.**

Keywords—Bidirectional DC-DC converter, Electric Vehicle, PI Controller.

I. Introduction

In recent years, Electric vehicles (EVs) are getting more attention because of less running costs, less pollution to the environment, shortage of fuel, and cost of fuel (petrol/diesel). Electric vehicles have emerged as an innovative and sustainable solution to the environmental and new energy challenges posed by the transportation sector including in the battery industries. As the global automotive industry changes its attention towards electrification, plug-in electric and hybrid electric vehicles have gained interest as possibilities to reduce Carbon Dioxide (CO_2) emissions and protect the environment from air pollution with renewable energy resources. Electric vehicles are known for their low-carbon electricity and high energy efficiency of electric motors, contributing significantly to energy saving and environmental protection when compared to traditional internal combustion engine vehicles. The major parts of an EV, first the motor with a controller is one of the most essential components that ensure its performance and functionality, and secondly battery type and its technology. There are different kinds of motors used in electric vehicles, each with distinctive features in how it operates for the vehicle types. The selection of a suitable motor for electric vehicles is influenced by several factors, such as high efficiency, torque density, constant power at high speeds, smoothness, and ease of control [1]. Currently, the most commonly used motor types in electric vehicles are Brushless DC (BLDC) motors, AC Induction motors, Permanent Magnet Synchronous motors (PMSM), and Switched Reluctance motors (SRM). Direct Current (DC) motors are commonly found in early models of EVs since they provide high starting torque and easy control. Nevertheless, DC motors have lower efficiency and less power at high speeds than other motors. Therefore, the DC motor's attraction in electric vehicle applications vanished after the rise of Induction and Synchronous motors. AC induction motors have emerged as a prominent candidate owing to their reliability, robustness, fewer maintenance requirements, and ability to work in harsh environments. Among all, Induction motors are mature technology due to their ruggedness less cost, and less maintenance compared to other AC competitors.

In recent days, Switched Reluctance Motors have gained much popularity in Electric vehicle applications due to their superior efficiency and lower cost. These motors exhibit a number of benefits in terms of simple construction and control, fault tolerance, and excellent torque speed characteristics. However, there is a need to eliminate the torque ripple and noise which are the two major drawbacks. PMSM drives are also widely used in electric vehicles due to their high-power density and efficiency [2]. These motors use permanent magnets in the rotor, generating torque when the stator magnetic field interacts with it. Therefore, it is mostly opted for electric and hybrid EVs like Cars and Buses. However, the use of a permanent magnet increases its cost and is competitive with BLDC motors in traction applications [3]. The absence of commutators and brushes in brushless motors also reduces their maintenance. Moreover, the BLDC motor owns the merits of high starting torque and efficiency of 95-98%, which is essential for EVs competitive to ICEs and to meet the characteristics of traction properties.

One of the key components that make electric vehicles possible is their batteries. EV batteries store and provide the necessary energy for these vehicles to operate. These batteries are specifically designed to power electric vehicles and are typically made using lithium-ion technology due to their high energy density, long cycle life, and relatively low weight. The development of effective and efficient batteries for electric vehicles is crucial to maximizing the potential of these vehicles in reducing emissions and transitioning to a sustainable transportation system. Lithium-ion batteries are most opted one EVs due to their inherent capabilities of constant power, long life, less weight, fast and safe charging compared to lead acid, nickel-cadmium, and nickel-metal hybrid batteries. This will reduce the overall weight of the vehicles is an added advantage for EVs and can enhance the travel distance.

However, a critical component of the electric vehicle is a converter to power the electric motor and facilitate efficient energy transfer from the battery to the motor with controlled parameters for better performance. These different converter topologies are embedded in the powertrain of an electric vehicle and convert electrical energy stored in the battery pack into a form compatible with that required by the electric motor at rated values. The converter regulates the voltage, current, and frequency of the electrical power transmitted to the motor based on its operating condition requirement. Advanced technology vehicles such as hybrid electric vehicles (HEV), plug-in HEVs, fuel cell-based HEVs, and all-electric vehicles require these power electronics and electrical machines to function optimally. As a result, significant research efforts have been expended toward developing new and improved converters and inverters suitable for electric vehicle applications. In recent years, [4, 5] the various configurations of bidirectional DC-DC converters and their control scheme have been discussed by many investigators. A bidirectional DC-DC converter with the combination of Dual-battery arrangement for the HEVs is reported in [6]. The modeling and control of bidirectional DC-DC converters for EV applications are presented in [7]. Moreover, a half-bridge BDC without isolation and a regenerative braking facility for e-bikes is presented in [8].

The various contents of the paper are as follows. Section II presents the need for a bidirectional DC-DC converter for EV applications and its classifications. The circuit description and operating modes are analyzed in Section III. The controller operation using the PI controller is given in Section IV. Validation of the proposed converter using simulation results is illustrated in Section V. Finally, the overall discussion is concluded in Section VI.

II. BIDIRECTIONAL DC-DC CONVERTERS FOR EV APPLICATIONS

We can observe that more EVs are coming on the road in recent years, which demands reliable and efficient DC-DC converters for the transfer of power from the source to the load. Not only is powering the different loads of EVs at different capacities also challenging. Moreover, it acts as an interface between the battery and other components of electric vehicles. This is typically achieved through the use of high-frequency switching, which is facilitated by inductive and capacitive energy storage elements. The primary function of a converter is to transform the voltage level of a DC power source to a level that is more suitable for a particular application. The efficiency of the DC-DC converter is an important factor in the overall performance of the electric vehicle, as it directly affects the driving range and battery lifetime [9]. Therefore, the design and optimization of DC-DC converters are critical in the development of the electric vehicle industry. That's why this research area gained more attraction from many researchers. Basically, these converters can be classified according to the energy/power flow into two types. One is unidirectional and another is a bidirectional DC-DC converter. Fig. 1 illustrates the role of a Bidirectional DC-DC Converter in an EV powertrain.

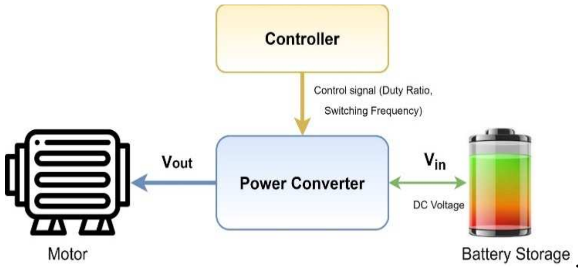

Fig. 1. Bidirectional DC-DC Converter in EV Applications

A unidirectional DC-to-DC converter is a device that enables the conversion of a DC input voltage to a distinct DC output voltage [10]. The converter operates in a unidirectional manner, meaning that the energy flows in a single direction from the input to the output. The boost/buck converters are power electronic device that is designed to step up/down the DC input voltage to another voltage level, which can be utilized to drive the electric motor and other electrical components at rated voltage values without causing any damage to the components. The boost/buck converters are the most prevalent type of unidirectional DC-to-DC converter. These kinds of converters are frequently used in electric vehicles to supply a regulated voltage to the electric motors and other electrical components. Bidirectional Converters have gained much popularity due to their ability to facilitate the transfer of energy/power for both sides (input and output) it means bidirectional, without the need for additional components [11]. These devices possess the unique capability to reverse the direction of current flow, which enables them to provide power while maintaining voltage polarity.

These Bidirectional Converters (BDCs) are categorized into two types: (i) isolated and (ii) non-isolated BDCs. The isolated Dual Active Bridge (DAB) with full bridge converters and high-frequency transformers is getting more attention due to its higher voltage gain, less weight, and higher efficiency. Other isolated topologies of dual push-pull, dual flyback, forward-flyback, dual half-bridge, half-full bridge, dual flyback, and so on are also preferred based on the requirement. Non-isolated BDCs can be used for light load applications with buck or boost operation features and to store energy during the regenerative braking period [12]. It also owns the merits of reduced size, weight, and cost compared to isolated BDCs. Moreover, it offers more efficiency due to reduced components and the absence of a transformer. Fig. 2 shows the classification of various BDCs.

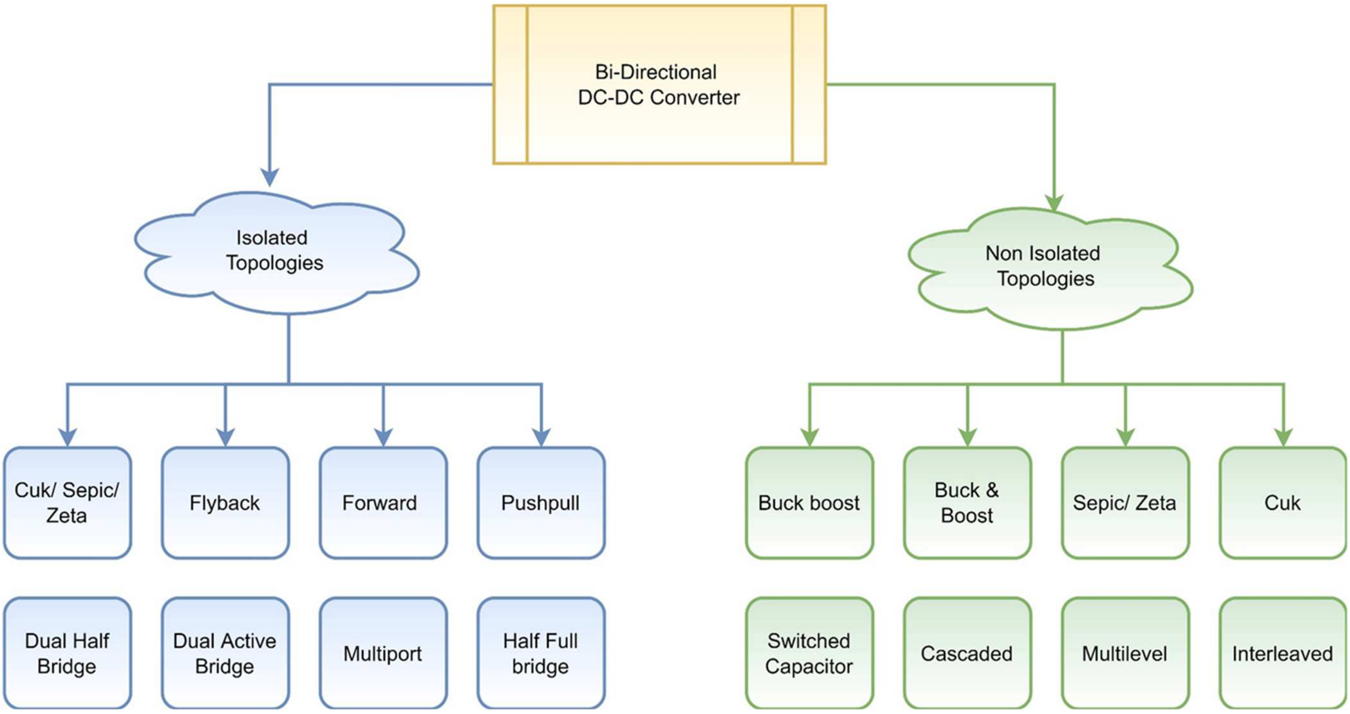

Fig. 2. Classification of Bidirectional DC-DC Converter

III. CIRCUIT DESCRIPTION AND OPERATION

The structure of the proposed design is illustrated in Fig. 3. In this topology, V_{bat} refers to the voltage of the battery pack and V_{dc} is the voltage of the DC link that will be given as the input for the three-phase inverter for the BLDC motor drive. The three-phase inverter pulse is generated from the Hall Effect sensor signal given from the BLDC motor. As can be seen, the circuit is composed of two switches, two capacitors, and one inductor with a simple PI controller to maintain the dc link voltage. According to the State of Charge (SOC) of the battery and motor torque input, the operating modes of the proposed bidirectional DC-DC converter can be categorized into two modes, which are discussed in the following. When power flows from the battery to the motor load, the converter works as a buck converter to draw energy from the battery. In the other power flow direction, the converter works as a boost converter to recharge the battery from the motor load. Table I shows the active devices in each mode of operation.

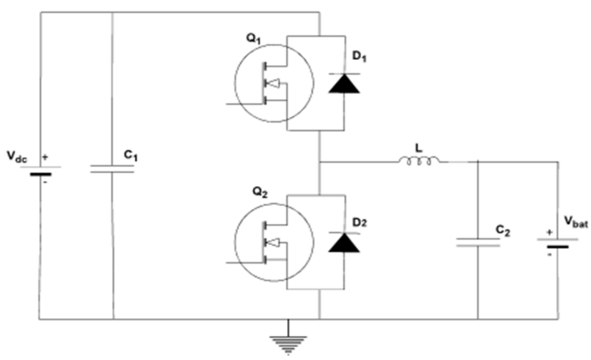

Fig. 3. Topology diagram of Bidirectional DC-DC Converter

A. Buck Mode 1: Battery Discharging Operation

In the buck mode of operation, the battery (V_{bat}=48V) discharges to the BLDC motor (rates V_{out}=24V) using DC-DC bidirectional converter with the current direction mentioned. During this mode of operation, switch Q_1 is turned on/off with a switching frequency of 5 kHz, and the circuit is operated as a buck operation of the converter. In this circuit operation, switch Q_1 is ON state (closed condition), and diode D_2 of switch Q_2 is in OFF state (open condition). Thus, switch Q_1 allows the current flows through the inductor to the BLDC motor while the torque input is positive (motoring mode).

B. Boost Mode 2: Battery Charging Operation

In this boost operation, the motor torque will be negative so that it acts as a generator and generated energy feedback to the battery. The three-phase inverter in rectification mode to charge the capacitor C_1 and the switch Q_2 is turned on/off with a switching frequency of 5 kHz. The switch Q_1 and diode D_1 is an off/on state and the energy stored in the inductor and capacitor C_1 voltage will charge the battery with the voltage of 48 V.

TABLE I. ACTIVE DEVICES IN DIFFERENT MODES OF OPERATION

Sl No.	Operation of switching devices		
	Modes	***Switches***	***Diodes***
1	Buck mode	Q_1	D_2
2	Boost mode	Q_2	D_1

IV. CONTROLLER OPERATION

In this work of bidirectional DC-DC converter, a PI controller has been implemented as the DC link voltage controller to recover the actual capacitor voltage to the reference value. The purpose of this implementation is to improve the performance of the electric vehicle and improve energy saving through the regenerative process. The PI controller is a widely used control strategy in various applications due to its simplicity and effectiveness [13]. The six-step inverter is coupled to the BLDC motor when the rotor position is detected by the hall sensor through which gate signals are generated to switch the inverter. Hall Effect sensors built within the stator of the BLDC motor are used to

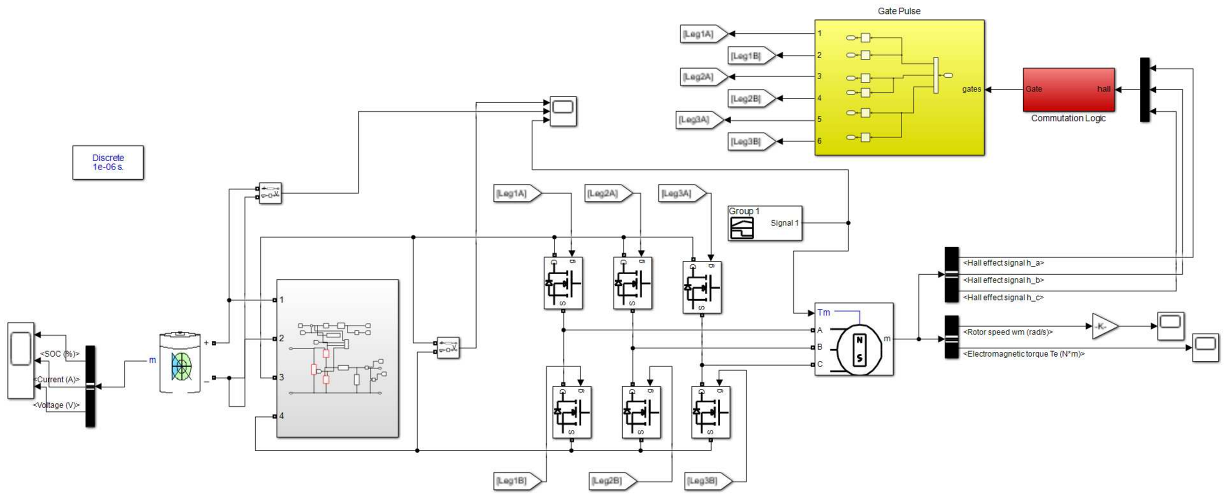

Fig. 4. Schematic of the proposed model realized in MATLAB/SIMULINK

determine the position of the rotor. This is identified with the strength of the signals either high or low which also indicates their corresponding position of the rotor magnet poles either north or south.

V. RESULTS AND DISCUSSION

In this section, to test the feasibility of the proposed system in various modes, the simulation has been carried out and presented in Figs. 4-6. The proposed converter is modeled in MATLAB/SIMULINK and the specifications of the different components used for the simulation are presented in Table II. From Fig. 4, it is observed that the study is performed with 48V battery as the input source and it delivers power to the bidirectional converter.

TABLE II. PARAMETERS FOR SIMULATION

Parameters	***Value***
Input battery voltage, V_{in}	48 [V]
DC link voltage, V_{dc}	24 [V]
Inductor, L	20 [mH]
Output capacitor, C	1000 [µF]
Switching frequency, f_s	5 [kHz]
BLDC motor controller	24 V, 32 Amps

Fig.5 illustrates the State of Charge (SOC) of the battery, output voltage, and current of the proposed bidirectional DC-DC converter. Initially, the motor is neither in motoring mode nor regeneration mode (up to 2s). Here we can find that the battery SOC is decreasing (after 2s) during the motoring mode since the battery is supplying power to the motor. After 4s, the converter is tested for the regeneration mode, we can notice that the SOC of the battery starts increasing.

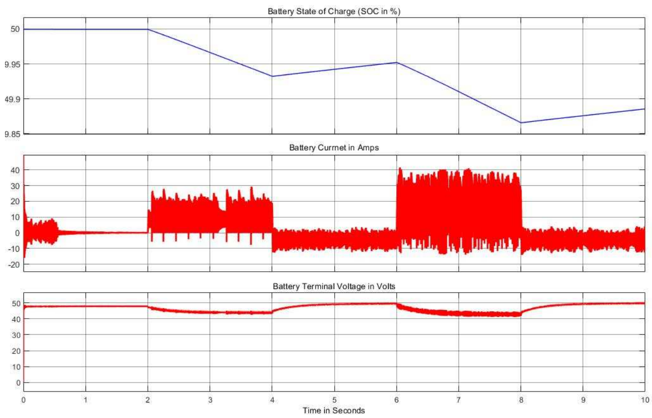

Fig. 5. Simulation result for SOC (%), Battery current (A), and Battery voltage

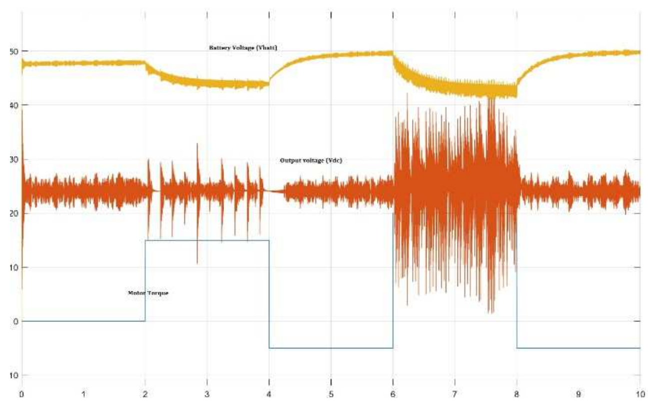

Fig. 6. Simulation result for Battery terminal voltage, DC link voltage, and Motor input torque.

Eventually, Fig. 6 represents the simulation results of Battery voltage (V_{bat}), output voltage (V_{dc}), and motor torque. From starting to 2s, the input torque is found to be zero and gradually it increases during the motoring mode of operation. From these simulation results, it is clear that when the SOC of the battery increases, battery voltage also increases and vice versa. From these results we can observe that the proposed converter can directly transfer the brake power to the battery source, thereby enhancing efficiency.

VI. CONCLUSION

In this study, a battery-based bidirectional DC-DC converter-fed BLDC motor for EV applications has been presented and evaluated. Detailed literature is provided in the introduction to highlight the importance of the work. The complete operation of the proposed topology is tested in MATLAB/SIMULINK environment. This power electronics interface is effective in transferring power from battery to load and load to battery vice versa. In addition, a simple PI controller has been implemented as the DC link voltage controller to recover the actual capacitor voltage to the desired reference voltage. The results findings shows the remarkable response in terms of battery SOC, current, voltage, and torque for various operating conditions. Therefore, the proposed topology may be a better alternate solution compared to the existing things as discussed in the introduction section.

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