Performance Analysis of Bi-Directional DC-DC Converters for Electric Vehicles

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Abstract: The paper presents the performance analysis and comparison of two types of bidirectional dc-dc converters - cascaded buck-boost-capacitor in the middle (cbb-cim) and cascaded buck-boost-inductor in the middle (cbb-iim) for use in plug-in electric and hybrid electric vehicles. The comparison of the two converters is based on device requirements, rating of switches and components, control strategy and performance. Each of the converter topologies has some advantages over the other in certain aspects. Efficiency analysis has been carried out for specific scenarios in vehicle applications. The simulation and experimental results are provided for both converter types.

Keywords: Bidirectional, DC-DC converter, Comparison, Electric vehicle, Cascaded Buck-Boost.

I. INTRODUCTION

The DC-DC converter between the energy storage device and the inverter in an electric power train of an electric and hybrid electric vehicle (EV/HEV) is used to condition the voltage levels and provide stable DC bus voltage [1]. Furthermore, the DC-DC converter needs to have bi-directional power flow capability so that regenerative energy can be captured and stored in the energy storage. In addition, some applications may require overlapping input-output voltage ranges. The two DC-DC converters analyzed and compared in this research can be used for DC fast charging in EV/HEVs to extend the all-electric drive range. A municipal parking deck charging station with DC power distribution bus can employ bi-directional DC-DC charger to allow Vehicle to Grid (V2G) operation [3]. V2G operation can be useful to inject real or reactive power to the grid to ensure current harmonic filtering or load balancing. A bi-directional converter with overlapping input output voltage range would enhance the operational flexibility for G2V or V2G applications. Several different types of bi-directional DC-DC converters along with their comparison appear in the literature [2-4]. Most of them require fewer components and simple control techniques but cannot provide bi-directional buck-boost power flow capability. In [3], R. M. Schupbach addressed the active and passive component’s stress issues due to the wide input voltage range of hybrid electric vehicle power management converters. Different non-isolated bi-directional DC-DC converters have been analyzed and compared for PHEV charging applications in [4]. Three-level bi-directional DC-DC converters have been found to be more efficient than other converters. The output voltage is smoother with these three level converters having three possible values of the output voltage. These converters have low switch voltage stress and smaller energy storage devices. The comparison of two bi-directional buck-boost converters analyzing the benefits and drawbacks of the topologies for electric vehicle applications is presented in [5]. The comparison is based on system stability, and component sizing and ratings. One of the converters is the Cascaded Buck-Boost Inductor in the middle (CBB-IIM) converter proposed in [6]; the converter topology is shown in Fig.1. The other converter topology, shown in Fig.2, was introduced in [7] and is called the Cascaded Buck-Boost Capacitor in the middle (CBB-CIM) converter. This paper presents the analysis of those two converters including experimental evaluation of the converters with multiple input and multiple output considerations.

II. THE NEED FOR A BIDIRECTIONAL DC-DC CONVERTER IN THE HEV IS DUE TO THE FOLLOWING REASONS

1. The system is operating at the high power and low voltage making the current to rise too high, which causes high electrical and thermal stresses in the passive as well as the active components of the system, also it increases the ohmic losses and hence decrease efficiency.

2. Device voltage and current stresses is even further increased up by the wide variation in the input voltage range of the system. Since device stresses depends on the output to input voltage ratio, input voltage variation further increases the components ratings to be used.

3. Further along with the above two factors, the parasitic ringing due to the parasitic components causes EMI emission and therefore the proper shielding has to be provided. All above three factors makes the converter packaging bulky, heavy and expensive. Thus there is a need for an efficient DC-DC converter to deal with this issue.

4. To be able to recharge the electrical energy storage system during the re-generative braking, and hence therefore there should be the provision of bidirectional power flow.
Some of the requirements for the Bidirectional DC-DC converters design for the HEV applications are as follows:

- High efficiency
- Lightweight & compact size
- Lower electromagnetic Interference
- Lower input and output current ripple
- Controlled power flow in spite of wide input voltage variation

III. BIDIRECTIONAL DC-DC CONVERTER WITH BATTERY AND DC MOTOR

In this topology, boost converter operation is achieved by modulating $Q_2$ with the anti-parallel diode $D_1$ serving as the boost-mode diode. With the direction of power flow reversed, the topology functions as a buck converter through the modulation of $Q_1$ with the anti-parallel diode $D_2$ serving as the buck-mode diode. It should be noted that the two modes have opposite inductor current directions. A new control model is developed using PI controller to achieve both motoring and regenerative braking of the motor. A Lithium-ion battery model has been used in this model to verify the motor performance in both motoring and regenerative mode. This controller shows satisfactory result in different driving speed commands.

A. Converter Operating Modes:

The MOSFETs $Q_1$ and $Q_2$ are switched in such a way that the converter operates in steady state with four sub intervals namely interval 1($t_0$-$t_1$), interval 2($t_1$-$t_2$), interval 3($t_2$-$t_3$) and interval 4($t_3$-$t_4$). It should be noted that the low voltage battery side voltage is taken as $V_1$ and high voltage load side is taken as $V_2$. The gate drives of switches $Q_1$ and $Q_2$ are shown in Figure. The circuit operations in steady state for different intervals are elaborated below. Interval 1($t_0$-$t_1$): At time $t_0$, the lower switch $Q_2$ is turned ON and the upper switch $Q_1$ is turned OFF with diode $D_1$, $D_2$ reverse biased as shown in Figure 2(a). During this time interval the converter operates in boost mode and the inductor is charged and current through the inductor increases.

Interval 2($t_1$-$t_2$): During this interval both switches $Q_1$ and $Q_2$ is turned OFF. The body diode $D_2$ of lower switch $Q_2$ starts conducting. Interval 3($t_2$-$t_3$): At time $t_3$, the upper switch $Q_1$ is turned ON and the lower switch $Q_2$ is turned OFF with diode $D_1$, $D_2$ reverse biased as shown in Figure 2(c). During this time interval the converter operates in buck mode.

IV. CONTROL STRATEGY

The control circuit of the bidirectional converter is shown in Fig. to control the speed of the dc drive; one possible control option is to control the output voltage of the bidirectional converter. To control the output voltage of the bidirectional converter for driving the vehicle at desired speed and to provide fast response without oscillations to rapid speed changes a PI controller is used and it shows satisfactory result. In this control technique the motor speed $\omega_m$ is sensed and compared with a reference speed $\omega_\text{ref}$. The error signal is processed through the PI controller. The signal thus obtained is compared with a high frequency saw tooth signal equal to switching frequency to generate pulse width modulated (PWM) control signals.

Fig. 3. Control strategy of the bidirectional dc-dc converter.
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The block diagram of feedback speed control system for DC motor drive is shown in Figure; the control objective is to make the motor speed follow the reference input speed change by designing an appropriate controller. The proportional-integral (PI) controller is used to reduce or eliminate the steady state error between the measured motor speed (ωmotor) and the reference speed (ωref) to be tracked.

B. Parameter used in the Simulation

The Separately excited DC motor rated at 5HP, 240V, 1750RPM Bidirectional converter parameters are: L=1600 μH, CH =470 μF, CL =470 μF, fSW =20 kHz. Battery voltage = 48V. Battery capacity = 16Ah, SOC= 88%

V. EXPERIMENTAL RESULTS

Fig. 5 shows the setup experimental set-up developed for evaluating the CBB-CIM and CBB-IIM converter topologies. Interleaved converters were developed for both topologies. For CBB-CIM, 450μH inductance was used both at the input and output sides. Intermediate stage capacitor, CM is 3300μF. Microchip dSPIC33 was used for the controller implementation. For the CBB-IIM, a larger unit was built with 4950 μF capacitors at both input and output terminals. 800 μH inductance was used as the center inductor while TI2812 processor was chosen for controller implementation. Experimental results for CBB-CIM and CBB-IIM are given in Fig. 6 and Fig. 7, respectively. Steady state and transient responses are provided for both topologies. Fig. 6(a) shows steady state output voltage (Ch2) for CBB-CIM at 68.1 V while supplying a 1 kW load with 14.2 A current (Ch4). The converter was operated in buck mode with 123 V intermediate stage voltage (Ch1) across the center capacitor. Another test run performed to observe the transient response is presented in Fig. 6(b). In Fig. 6(b), intermediate stage voltage (Ch1) changes from 80V to 100 V, while output voltage (Ch2) changes from 0V to 50 V.

Fig. 6. Experimental results for CBB-CIM. (a) Results for steady state (Ch1- intermediate stage voltage, Ch2- output voltage, Ch3- input current, Ch4- output current). (b) Experimental result shows the initial transient response of voltages and current (Ch1- intermediate stage voltage, Ch2- output voltage).

Fig. 5. Experimental Set up
Efficiency of CBB-CIM for multiple inputs with load variation in the experiments is shown in Fig. 11. It is observed that the efficiency increases with the increased load.

The multiple output case for CBB-CIM was experimentally evaluated with two output ports. Fig. 8 shows the gate signals and currents of output inductors where input voltage is 330 V, intermediate stage voltage is 400 V, load1 voltage is 170 V and load2 voltage is 150 V, load1 is 4.1 kW and load2 is 1.1 kW.

Efficiency of CBB-CIM topology for multiple output with load variation in the experiments is shown in Fig. 17. It is observed that the efficiency increases as load is increased.

The multiple input case for CBB-CIM was also experimentally evaluated with two input ports. Fig. 10 shows the gate signals and currents of input inductors where input1 voltage is 250 V, input2 voltage is 150 V, and output voltage is 170 V. Experiment has been completed up to 5.2 kW.
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VI. CONCLUSION

The performance analysis and comparison for two bi-directional DC-DC converters for EV/HEV applications are presented. Both the converters have their own advantages and disadvantages. The appropriate converter can be chosen based on the specific application. For EV charging station, multi-input and multi-output case, CBB-CIM can have better performance since input side and output side controls are independent. System control flexibility and reliability is better with CBB-CIM. CBB-IIM on the other hand requires fewer components.

V. REFERENCES


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