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Performance Analysis and Comparison 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 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 experimentalresults are provided for both converter types.

I.INTRODUCTION

The DC-DC converter between the energy storage device and the inverter in an electric powertrain 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 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 multipleoutput considerations.

II.CONVERTER TOPOLOGIES OF INTEREST

Fig.1 and Fig.2 show the two different converters of interest. Fig.1 presents the conventional Cascaded Buck Boost Inductor in the middle (CBB-IIM) having an interfacing inductor between the input and output sides [6]. Fig.2 on the other hand presents the Cascaded Buck Boost Capacitor in the middle (CBB-CIM) topology where the two half bridge converters are cascaded together with a common dc bus capacitor [7]. The DC bus voltage is typically higher than the battery voltage in electric vehicles with a boost stage, but depending on the characteristics of the batteries and design of the propulsion system the battery voltage may overlap with the nominal DC bus voltage. Therefore, the converter must have the capability to handle the input and output side voltages with overlapping ranges. Both the converters, CBB-IIM andCBB-CIM, have the input and output voltage overlap capability.

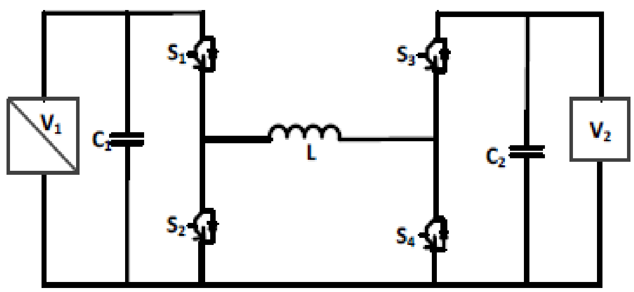

Fig.1: Cascaded Buck Boost Inductor in the middle (CBB-IIM)

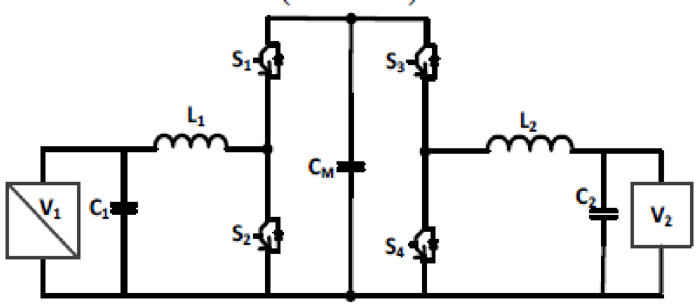

Fig.2: Cascaded Buck Boost Capacitor in the middle (CBB-CIM)

III.STABILITY ANALYSIS

System stability of high power converters should be considered during the design stage [8-10]. The stability analysis of the open loop system is provided in terms of state space model for the two converters. The basic CBB-CIM and CBB-IIM topologies with single-input, single-output case have the following transfer function containing unavoidable non-idealities.

$$\dot{x} = Ax + Bv_{in}$$
$$V_{out} = Cx + Dv_{in}$$

For CBB-CIM, the following state space matrix was developed considering the switching of S_2 and S_3 . D_2 and D_3 are the duty cycles of S_2 and S_3 respectively. The derivation of the equations is given in Appendix A.

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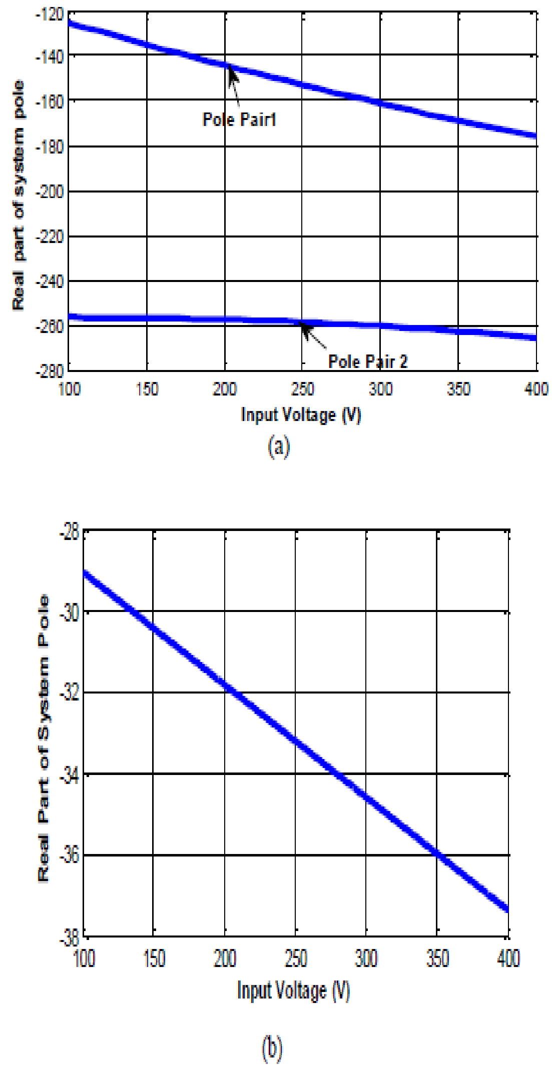

Fig. 3: Effect of input voltage change in system poles (a) Pole trajectories of CBB-CIM (b) Pole trajectory of CBB-IIM.

The sensitivity to load changes was also analyzed for the two converters. The converter output varies to meet the required power level, and the system must be robust over a wide range of power level. The load resistance was varied from 1Ω to 50 Ω with output voltage maintained at 300V, which corresponds to output power levels of 90 kW to 1.8 kW. The real part pole trajectories of CBB-CIM are shown in Fig. 4(a), while the real part pole trajectory for CBB-IIM is shown in Fig. 4(b). Both the converters have real poles in the negative *x*-axis at all power levels.

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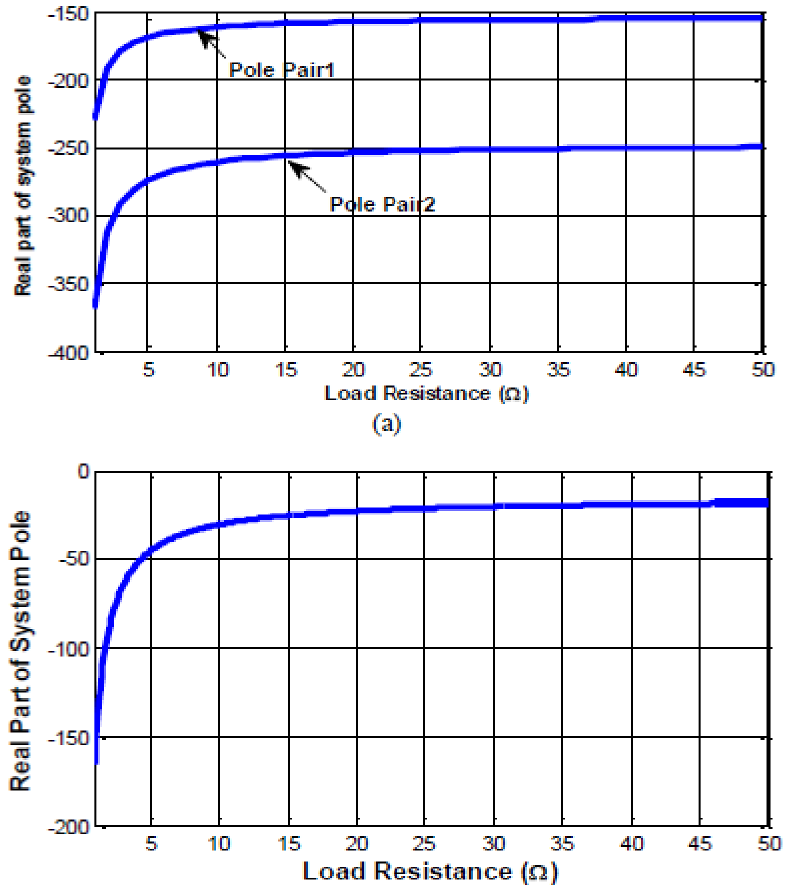

(b)

Fig. 4: Effect of output load power level in system poles (a) Pole trajectories of CBB-CIM (b) Pole trajectory of CBB-IIM.

IV.COMPARISON OF THE TWO TOPOLOGIES

Comparisons of the two converter topologies are done for the following aspects: i) Switching mechanism ii) Stresses on switches and diodes, iii) Ratings of the passive components, iv) Size of the passive components, v) Interleaving capability, and vi) Multi input, output capability.

VI.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, $450\mu H$ inductance was used both at the input and output sides. Intermediate stage capacitor, C_M 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. 14 and Fig. 15, respectively. Steady state and transient responses are provided for both topologies.

Fig. 14(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. 14(b). InFig. 14(b), intermediate stage voltage (Ch1) changes from 80V to 100 V, while output voltage (Ch2) changes from 0V to 50 V. Fig. 15(a) shows steady state response of CBB-IIM with 630 V input (Ch2) and 410V output (Ch1) voltage. The total output current of 174 A (ChM) was maintained which was measured using two separate current probes (Ch3, Ch4) as seen

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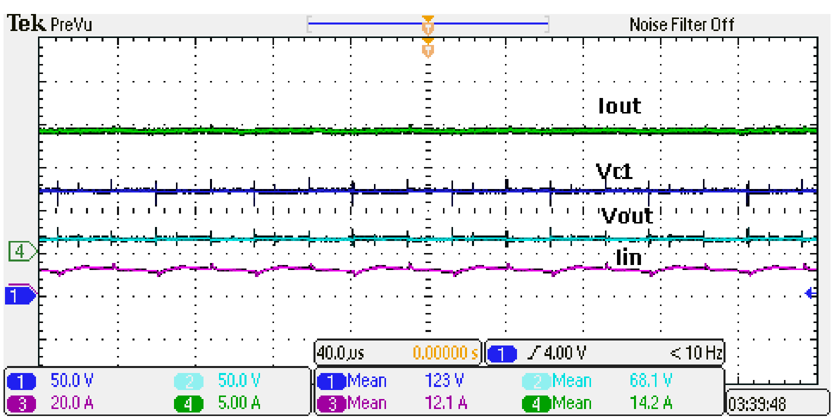
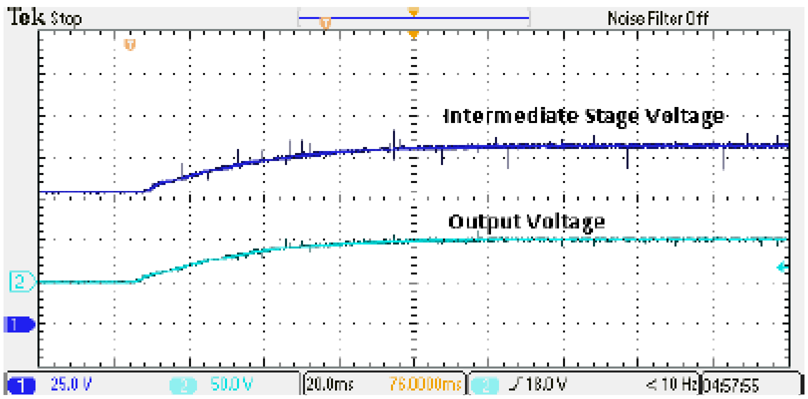
in the figure. Two separate signals I_{out1} and I_{out2} were added and shown in Fig. 15(a) indicated as 'M' and labeled $I_{charging}$.

Fig. 15(b) shows the transient response of the system while charging current (Ch3) was changed from 0 to 90 A and then from 90 A to 50 A while maintaining average output voltage (Ch1) close to 360 V. The battery voltage labeled as '*Vout*' in Fig. 15(b) was found to increase when 90 A current was flowing.

Fig. 5: Experimental Set up

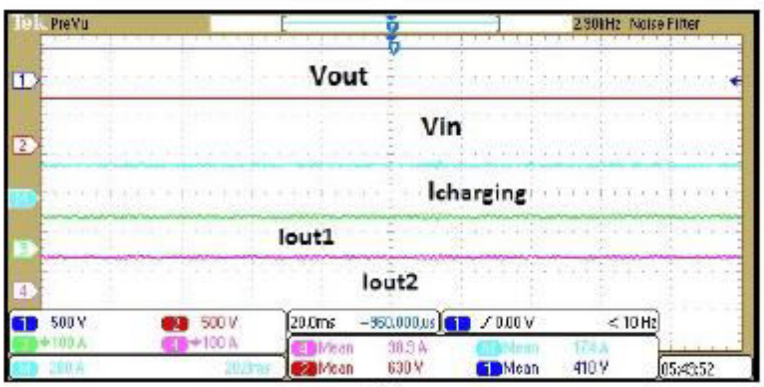


(a)

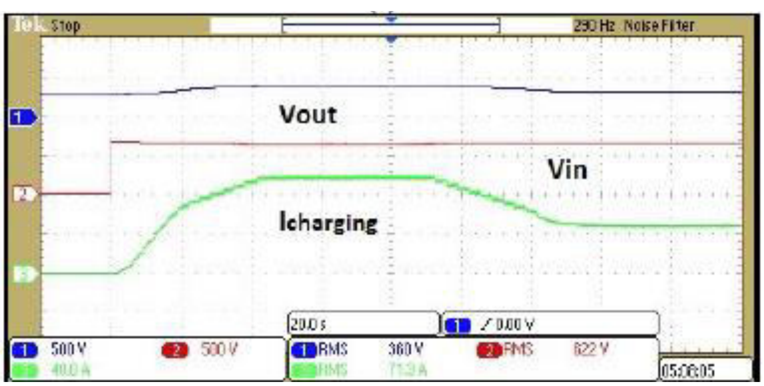


(b)

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).



(a)



(b)

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VII. CONCLUSION

The performance analysis and comparison for two bi-directional DC-DC converters for EV/HEV applications are presented. 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.

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