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Design of an H-Bridge Bidirectional DC–DC Converter with LCL Filter for High Power Battery Applications

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***Abstract*—This paper provides an H-Bridge embedded bidirectional DC–DC converter with LCL filter for high power energy storage applications. Low current ripple is critical in sensitive electric devices such as batteries, two-stage photovoltaic systems and fuel cells connected at DC-bus in power electronics applications. Unlike, classical DC–DC converter, the proposed topology uses LCL filter instead of an input inductance to reduce the battery ripple current. It also reduces the value of total filter inductance, which leads to a significant reduction in copper materials, power losses, implementation cost and physical design. This study founds potential application to charge/discharge battery in high power applications, i.e., electric transportation (fast charging electric vehicles, ships) with a pre-defined reference current. Simulations and right half-plane zero analysis are performed to show the effectiveness of the proposed topology over the classical DC–DC converter**

Keywords—Bidirectional DC-DC converter, LCL-Filter, H Bridge, RHPZ, Battery charging

I. Introduction

Power Electronics technology has found its way in an extensive range of industrial, commercial, transportation and residential applications. Among the power electronics applications, DC-DC power converters have been the subject of considerable interest due to its significant involvement in renewable energy systems, micro-grids, electric transportation, smart grid, electrical drives and fast switching power supplies, etc. [1-3]. It is always vital to design highly efficient DC–DC converters to charge and discharge sensitive energy storage devices (i.e., battery, fuel cells and electrolytic capacitors) with low input current ripples. However, ripples in the input (battery) current appeared in DC-DC converters due to switching operation of power electronics switches.

There are several methods to address this problem. One way is to achieve a low input current ripple by using an extra high capacitor at the input side of converter [4-5]. Though, adding an extra capacitor at the input causes additional cost and space constraints. Other methods are to increase the value of inductance or to use passive filters. The increased of inductance provides a rapid solution, but extra copper materials, cost and bulky physical design are some of the concerns associated with it. In addition, high inductance value is mostly no preferred situation for high power systems.

Similarly, the use of passive filters causes some extra power losses and may generate a resonant behavior due to the coupling of inductors and capacitors. Some researchers have proposed interleaved operation of DC-DC converter as in [6-8]. The interleaved operation reduces output ripple due to ripple cancellation at some level among the phases, however, but a bulky inductor requirement is still a remaining concern [9]. Further, interleaved operation needs a high number of semiconductor devices. Some authors have recommended the use of tapped inductor to reduce the input current ripple [10-11], but the failure rate of inductor is high with it.

This paper proposes a new H bridge bidirectional DC–DC converter with LCL filter for high-current battery applications. LCL filter is used instead of L filter in the classical DC-DC converter. In this way, the total inductance requirement is reduced for a given constraint of a battery ripple current. As a result, the reduction of copper material occurs, which yields a light design of the circuit with low cost. Right Half-Plane Zero (RHPZ) analysis is performed for the proposed boost converter as well as for the classical DC-DC converter. It must be noted that the RHPZ leads to a high recoil in the output voltage and avoids increasing the voltage controller bandwidth, in the classical bi-directional DC-DC converter [12]. If the bandwidth is increased beyond the critical limit, instability will occur [13]. This implies that a sluggish control performance of the output voltage is an inevitable result, in the classical bi-directional DC-DC converter [14]. In the proposed converter, the RHPZ is far from the origin thanks to the LCL filter. Therefore, it is possible to increase the bandwidth of the voltage control loop much more than the conventional converter with the proposed converter, without causing the instability. Besides, the proposed topology here reduces the output voltage recoil by more than 75% as compare to the classical DC-DC boost converter.

This research is arranged as follows. Section II provides a description of the proposed converter. Section III describes the RHPZ analysis about the proposed and classical DC-DC converter. Section IV explains simulation results. Finally, conclusions are presented in Section V.

II. Description of Proposed converter

The proposed converter is recommended for high-current/power battery applications. Figs. 1 and 2 illustrate the proposed and classical DC-DC converter, respectively. The proposed DC-DC converter is obtained through modification in classical DC-DC converter. The modification is performed by replacing L of the classical converter by LCL filter at the output to suppress the battery current ripple. The new DC-DC converter consists of an H bridge, LCL filter, an output capacitor Cbus, and a load resistor RL. An H-bridge converter is a non-inverting highly efficient buck-boost DC-DC converter which is appropriate for battery powered applications because it operates as a bidirectional converter through a controlling double pair of switches. The LCL filter is constructed from two inductors L1 and L2, and a capacitor C. Normally, L1 and L2 are placed in the same core for a compact size. Similarly, a low value film capacitor for C is preferred for an optimum design.

III. Theoretical Verification of RHPZ of the Proposed and Classical DC-DC Converter

A. *Theoretical verification of RHPZ of the classical DC-DC converter*

Applying the small signal analysis to classical DC-DC converter, the following RHPZ analysis is obtained for a classical DC-DC converter as [7-14]:

$$\frac{V_c(s)}{d(s)} = \frac{\dfrac{V_{in}}{LC_{bus}} - \dfrac{V_{in}}{(1-D)^2 R_L C_{bus}} s}{s^2 + \dfrac{1}{R_L C_{bus}} s + \dfrac{(1-D)^2}{LC_{bus}}} \tag{1}$$

$$s_{RHPZ} = \frac{(1-D)^2 R_L}{L} \tag{2}$$

It can be seen from the above equations, the RHPZ is interpreted as follows. The RHPZ approaches to zero point when the value of load resistance decreases. In other words, as the load current increases, the RHPZ approaches to zero, i.e., higher backlash occurs at higher load currents. Roughly speaking, the higher the output voltages, the higher the recoil for the constant load resistance. When the duty cycle (D) increases, the RHPZ approaches to the zero point. Therefore, the recoil at higher D values is higher. Similarly, the RHPZ approaches to the origin as L increases. In other words, higher inductance values increase the recoil. The recoil caused by the RHPZ decreases as the poles increase to zero, i.e., the poles approaching the zero-point becomes dominant in the output response and suppress the behavior of the right half-plane zero. Thus, Cbus has a suppressing effect on the RHPZ [12-14]. All these situations are proved later in the simulations in Figs. 3 and 4.

As a result of the RHPZ, the bandwidth of the voltage control loop of the classical DC-DC converter cannot be increased very much. This causes poor performance. In applications such as marine power systems, an oscillating DC bus voltage is a concluding concern.

B. *Theoretical verification of RHPZ of the proposed DC-DC converter*

Similarly, using small signal analysis the following the theoretical verification of RHPZ for the H-bridge DC-DC converter with LCL filter.

It can be seen from Eq. (4), the RHPZ of the proposed H-bridge DC- DC converter with the LCL filter and classical DC-DC converter are found by the same equation. But, the difference between them is the inductances, L2 = 100 uH in the proposed converter but L = 14 mH in the classical converter.

$$\frac{V_c(s)}{d(s)} = \frac{V_{in}}{(L_1 C s^2 + 1)} \frac{\dfrac{1}{L_2 C_{bus}} - \dfrac{1}{(1-D)^2 R_L C_{bus}} s}{s^2 + \dfrac{1}{R_L C_{bus}} s + \dfrac{(1-D)^2}{L_2 C_{bus}}} \tag{3}$$

$$s_{RHPZ} = \frac{(1-D)^2 R_L}{L_2} \tag{4}$$

Thanks to these inductance values selected, the same battery ripple current is obtained for two cases. Consequently, the RHPZ of the H bridge DC-DC converter with the LCL filter is far from the zero at the origin. Therefore, as aforementioned, it is possible to increase the bandwidth of the voltage control loop much more than the classical DC-DC converter. As seen from the proposed topology in Fig. 2, there is the proposed H bridge converter with the LCL filter. For switching, unipolar PWM is employed to make the switching frequency doubled at the output. This enables LCL filter to perform a very better filtering than that with the bipolar PWM. In such way, LCL filter size further decreased, and thus, L1 and L2 are further reduced.

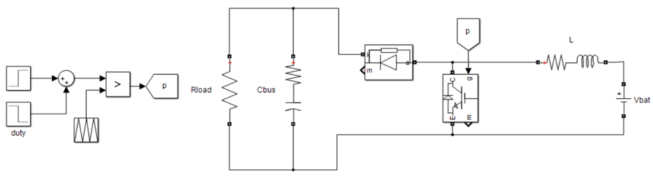

Fig. 1. Classical DC-DC converter with an open loop control

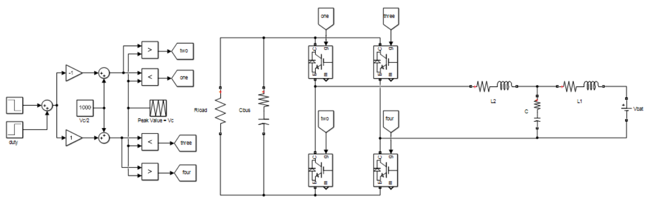

Fig. 2. Power scheme and open loop control of the bidirectional proposed DC-DC converter

IV. Simulation Results and Discussion

In this section, MATLAB/Simulink simulations have been performed to show the effectiveness of the H-bridge DC-DC converter with the LCL filter. The simulations are performed in the continuous conduction mode considering 1e-6 step time with ode23tb solver. The input voltage source Vin has assigned a value of 500 V, and the switching frequency is selected as 2 kHz. Other parameters including passive elements which are used during the modeling of the circuit are given in Table 1. The performance of both H-bridge DC-DC converter with the LCL filter and classical DC-DC converter is measured and compared in terms of recoil in the DC bus voltage Vbus, battery current Ibat, and ripple of the battery current against same D, and the bandwidth of the system.

Fig. 3 shows the graphs of the classical DC-DC converter. The RHPZ analysis is performed in an open loop operation by changing the duty cycle through step by step. For example, the output DC bus voltage for a load resistance of 1 ohm increases from 702.3 V to 1000 V at a step change, i.e., 0.3025 to 0.5235 at t = 0.5 s. During the change, the rebound value of the output voltage is observed as 103.9 V. Similarly, the response of DC bus voltage is checked at t= 1.5 s, it can be seen in Fig. 3 that D is reduced back to the past value of 0.3025, and the output voltage is about 700 V at the steady state again. During this change, the rebound value of the output voltage is seen as 207 V. The value of the recoil increases as the load current increases, because the right half plane zero approaches the origin.

Similarly, the performance of bi-directional DC-DC converter is checked for the same boost operation. This mode of operation refers to meeting the power demand at the DC bus from the battery. The response to step inputs of D is obtained in the graphs as shown in Fig.4. The recoil is close to zero. This is because, the LCL filter inductances are too small and the right half-plane zero is shifted far from the origin. The dynamic response of the proposed converter is oscillating, because the LCL filter has a transfer function with an open loop control, without a damping method.

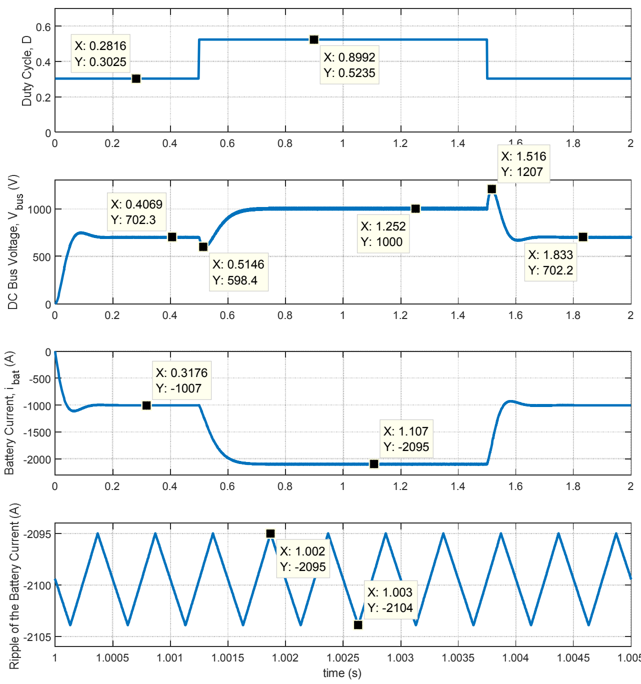

Fig. 3. Performance of a classical DC-DC converter

In the current case, the resonance of the LCL filter is damped on the parasitic resistors, and hence an oscillating behavior appears. It should be noted that a well-designed closed loop control system can easily damp the oscillations and provide a high-performance response along with a damping method if necessary.

It is important to state, the inductors of the LCL filter are 100 µH, while the coil of the classical DC-DC converter is 14 mH. In both cases, the battery current ripple value is 9 A. From this point of view, it is understood that the classical boost converter is not suitable for high power circuits. Because of LCL filter structure and the doubled switching frequency at the output, the RHPZ is so far away from the origin that there is about zero recoil in the response of the output voltage, as seen from Fig. 4. For example, when the battery current value is very high such as 1000 A, the recoil is close to zero, the exact value is 2.8 V.

The simulation results given in Figs. 3 and 4 confirm the above theoretical analysis. The recoil is reduced by more than about 98,0 %, which was aimed in this study, by the proposed converter. To be able to clearly demonstrate the effect of the RHPZ on the recoil, simulations were performed for 1.0 MW power value. As a result, the RHPZ analysis is performed for a worse condition and, even in the worst case approximately 98,0 % reduction in the recoil voltage is achieved.

TABLE I. SYSTEM PARAMETERS

Parameters	Classical DC-DC Amplifier Converter	Bidirectional H-Bridge with LCL Filter DC / DC Converter
Output capacity, Cbus	16800 uF, 0.01 Ω	16800 uF, 0.01 Ω
Δi_L (Battery current ripple value)	9 A	9 A
Load resistance	1 Ω	1 Ω
Operations	0 – 0.5 s output voltage 700 V, 0.5 – 1.5 s output voltage 1000 V, 1.5 – 2 s output voltage 700 V	0 – 0.5 s output voltage 700 V, 0.5 – 1.5 s output voltage 1000 V, 1.5 – 2 s output voltage 700 V
LCL filter	---	L1 = L2 = 100 uH, 0.001 Ω Cf = 1000 uF, 0.01 Ω
Classical boost converter inductance	14 mH, 0.01 Ω	---
Battery voltage	500 V, 0.1 Ω	500 V, 0.1 Ω

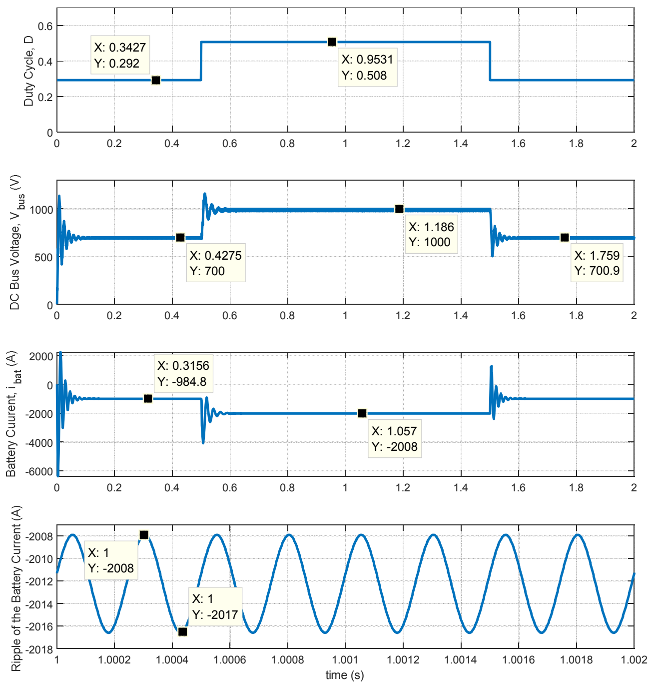

Fig. 4. Performance of H-bridge bidirectional DC-DC converter with LCL filter

V. CONCLUSIONS

A DC-DC H-bridge bi-directional converter with an LCL filter for high power battery applications was developed in this paper. The proposed converter shows same average current and/or voltage values in steady-state as the classical DC-DC converter, while attaining a very low battery ripple current. The proposed converter requires a lesser filter inductance totally, and hence a lesser copper material, because of a benefit from the LCL filter. Technically, the difference between the proposed and classical DC-DC converter is the extra film capacitor with low capacitance value in the LCL filter. The value of the film capacitor is normally very low which yields a cheap physical design. Thanks to the RHPZ far from the origin, it is very possible to increase the bandwidth of the closed loop control system, without leading to the instability. The proposed topology is highly recommended for high power battery applications, especially in discharging regime. The others can be fuel cells and photovoltaic systems. The simulation studies performed; show that the proposed converter is feasible in design and implementation.

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