Design and Analysis of Bidirectional DC-DC Convertor

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Abstract : On-board bidirectional battery charger is a key component in a plug-in vehicle with vehicle-to-grid (V2G) capability. In a high-performance on-board battery charger, volume and weight should be minimized. Battery charger topologies are generally classified under the two main categories of single-stage and two-stages. Each category has its own merits and drawbacks. This paper attempts to make a review of the existing bidirectional battery charger topologies.

***IndexTerms* – State Space Model, Discrete-Time Analysis, Digital Control.**

I. INTRODUCTION

Bidirectional DC-DC converters serves the purpose of stepping up or stepping down the voltage level between its input and output along with the capability of power flow in both the directions. Bidirectional DC-DC converters have attracted a great deal of applications in the area of the energy storage systems for Hybrid Vehicles , Renewable energy storage systems, Uninterruptable power supplies and Fuel cell storage systems. Traditionally they were used for the motor drives for the speed control and regenerative braking. Bidirectional DC DC converters are employed when the DC bus voltage regulation has to be achieved along with the power flow capability in both the direction. One such example is the power generation by wind or solar power systems, where there is a large fluctuation in the generated power because of the the large variation and uncertainty of the energy supply to the conversion unit (wind turbines & PV panels) by the primary source. These systems cannot serve as a standalone system for power supply because of these large fluctuations and therefore these systems are always backed up and supported by the auxiliary sources which are rechargeable such as battery units or super capacitors. This sources supplement the main system at the time of energy deficit to provide the power at regulated level and gets recharged through main system at the time of surplus power generation or at their lower threshold level of discharge.

Buck or their derived topologies are popular for realizing lower voltages from higher input dc voltages. However, the basic buck circuits, such as simple buck converter, draw pulsating currents from the dc battery and hence reducing the life of the battery sources. In order to reduce the ripple currents drawn from the source and to enhance the battery life input filters need to be established in between the battery and the main power processing converter. In addition to these EMI filters are also needed to reduce the high frequency noise generated to high frequency switching. Embedding all different filters in the simple buck converter increases the number of energy storage elements, and results in the system whose dynamical behavior is different from simple 2nd-order buck topology [1-2].

To avoid some of these problems, existing in the conventional buck topologies, a 4th order step-down buck converter is proposed in the literature [3]. On account of inductance present on the input side of the 4th-order topology reported in ref[4] gives continuous input current, but there is no change in the bucking function like in conventional buck converter, $V_0=DV_g$. There are certain limitations with the conventional buck topologies exhibiting $V_0=DV_g$, which are:

(i) Extreme duty ratios are needed to realize excessive bucking
(ii) Poor switch utilization
(iii) Converter exhibits more loss at higher duty ratios.

A fourth-order buck converter with current control as well as load voltage regulation has been documented. These studies have demonstrated the salient feature of low source current ripple, but there is no change in voltage transformation like in conventional buck converter. Although, the reported buck topologies/ converters are exhibiting lower current ripple, but still they need to be driven at extreme duty ratio's from the view point of voltage transformations. To overcome some of these shortcomings, a new fifth-order buck converter (FBUC) is proposed in this paper. In analog or in digital control voltage-mode and current-mode control strategies are widely used to realize desired limits either on current or voltage. However, there is not enough literature dealing with such types of converter control strategies. To bridge this gap in this paper an attempt is made to get buck voltage transformations with moderate duty ratios together with lower source current ripple [4].

II. MODELING OF CONVERTER

A. Steady-state Analysis:

The proposed fifth-order buck converter (FBUC) contains two switching devices, one diode, and five energy storage elements (two inductive and three capacitive elements). This converter has two switching devices which are driven with complementary gating signals without any dead-band among them. In view of this single complementary PWM generator is sufficient enough drive the converter. As this converter gives buck conversion the current magnitude at the load side is high and hence the current status in the inductive elements is continues in nature. In view of this for most of the duty ratios it will operate in the continuous inductor current mode (CCM) of operation and hence the respective analysis is given in the following lines [5-7].

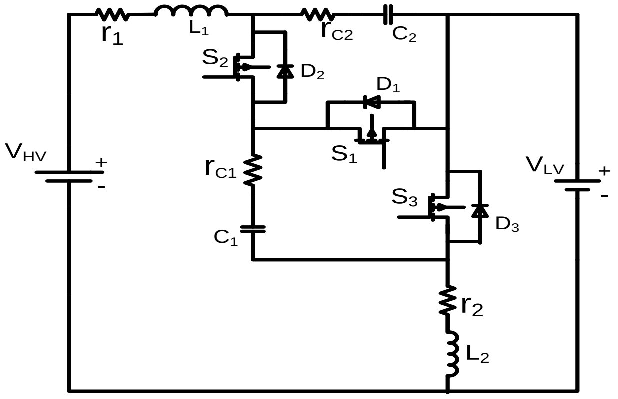

Figure 1: Buck Converter

The above expression clearly shows that the transformation ratios that it gives are different from the conventional buck converter. Conventional buck converter gain is going to increase almost linearly with ‘D’, while the proposed FBUC gives decreased values of gain, which just opposite to the conventional converter[8-9]. With lower duty ratio its gain is more, while exhibits lower values with increased values of ‘D’. In any case the maximum achievable is 0.5 and exhibits lower gains at higher duty ratios ($0<M<0.5$). Comparison of voltage bucking feature of this converter with conventional buck converter is shown in Fig.1.

B. State-space Analysis:

For the assumed switching sequence, continuous inductor currents, two operating modes are possible which are Mode-I: $0<t<DT_S$, mode-II: $DT_S<t<T_S$. By writing KVL/ KCL a set of first-order differential equations for inductor currents and capacitor voltages are formulated and then these are transformed into state-space models and its expression is given by

$$[x] = [A][x] + [B][u] \qquad (1)$$

III. CONTROLLER DESIGN AND IMPLEMENTATION

The main intention of using any control scheme in the dc-dc converters is essentially to regulate or track the desired quantity (current or voltage). Several voltage and current control schemes have been reported in literature [4]-[7]. In this paper a simple digital voltage-mode controller is designed to regulate the load voltage. Linear or small-signal models of the converter are required to design the digital voltage-mode controller[10-12].

For designing the controller the standard pole-placement technique is used here. Loopgain consists of '$G_{vd}(z)$' and '$G_c(z)$' transfer functions. For the given specifications the first transfer function '$G_{vd}(z)$' can easily be obtained, while controller transfer function '$G_c(z)$' need to be computed depending on the closed-loop system/ loopgain requirements. Here for designing the controller Matlab-Sisotool interactive platform is used, where-in the controllers pole, zero locations can easily be adjusted such that the final resulting loopgain must exhibit sufficient relative stability margins, which are: gain margin > *6 dB*, and phase margin: $45^{o} \sim 75^{o}$**.** The averaged state space model of the power stage developed above allows us to analyse the stability and the control issues related to the circuit. Generally the transfer function of the unidirectional power flow in normal buck or boost mode is easily known, but in the present case there is only one transfer function for the power flow in both the modes i.e. motoring as well as regeneration. Therefore the power flow depends upon the duty cycle and the instantaneous voltage across both the sides. Since the voltage of the battery is generally fixed, the voltage variation only exists at the input of the motor terminal i.e armature voltage and this depends on the back emf of the motor and the duty cycle[13-16].

The power can flow in both the directions in the bidirectional dc dc converter in all the three modes as discussed,. Voltage mode controller transfer function.

$$G=K(z-z1)(z-z1)/(z-p1)(z-p2) \qquad (2)$$

IV. SIMULATION RESULTS: STEADY-STATE AND CLOSED-LOOP PERFORMANCE

To demonstrate the effectiveness of proposed buck converter a 12 V, 60 Watt load is considered. it is assumed that the converter is driven at 50 kHz and is connected to 48 V dc-battery[17-20]. From the design expressions, obtained from steady-state analysis, energy storage elements are chosen to meet the current and voltage ripple requirements ($\Delta i<20\%$, $\Delta v<5\%$). The final design parameters are shown in table 1.

Table 1: Simulation Parameters

Power rating	60 W
DC grid voltage	48 V
Battery voltage	12 V
Current ripple	≤10%
Voltage ripple	≤5%
Switching frequency	50 kHz

With these parameters simulation studies are made initially and for illustration steady-state waveforms for nominal loading condition are shown in Fig. 3. These results shows the steady-state waveforms showing the ripple current magnitude both on source and load side. These steady-state waveforms are at nominal loading conditions and percentage of ripple current in the source current is ≈14% while in load current it is ≈4%. Ripple in load voltage is ≈ 0.2%. Now the digital controller performance is tested for its regulation feature. Several simulation cases have been studied and found that the above designed controller performing the desired task. To illustrate this feature sample dynamic response characteristics of the converter are given here for (i) sudden change in load *R: 7.0 - to- 5.0* Ω, (ii) sudden change in source voltage V_g: *48 -to - 42 V*, and (iii) gradual change in source voltage V_g: *48 -to- 42 V*. These responses are shown in Figs. 2 to 3. In all these dynamic conditions the load voltage is regulated in less than *5 msec*.

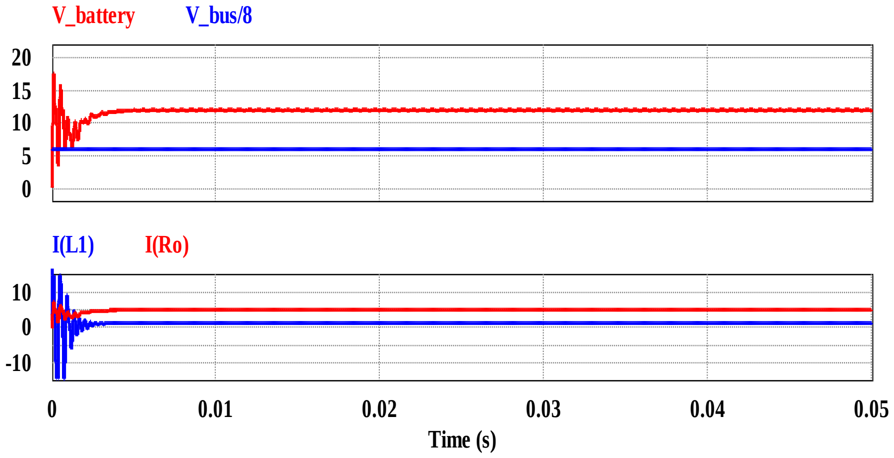

Figure 2: Simulated steady-state performance of charger.

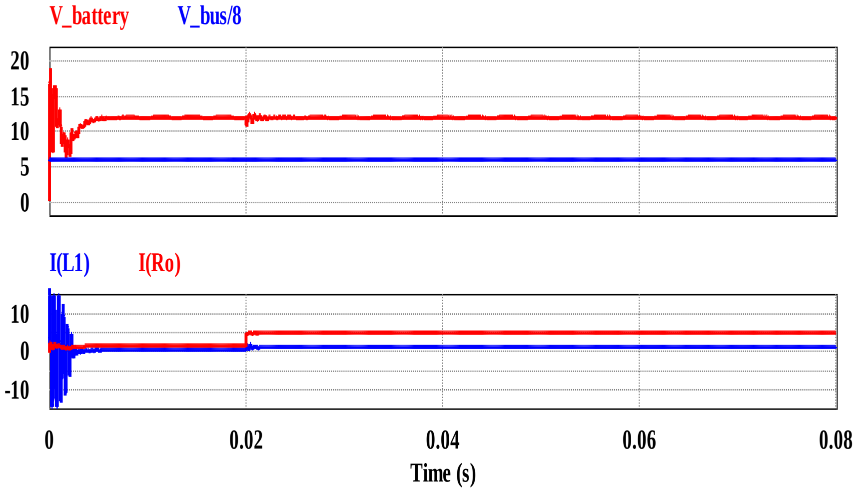

Figure 3: Simulated dynamic response of battery voltage against load variation.

V. CONCLUSION

The designed converter operating in the complimentary ZVRT switching has been simulated and the various current and voltage waveforms has been compared with the bidirectional DC DC converter without complimentary switching, which shows that the designed converter operates in the soft switching mode, and therefore the switching losses are reduced thereby increasing the efficiency[22-26].

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