Soft switching bidirectional DC–DC converter for ultracapacitor–batteries interface

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In this paper a new soft switching bidirectional DC–DC converter is introduced which can be applied as the interface circuit between ultracapacitors and batteries or fuel cells. All semiconductor devices in the proposed converter are soft switched while the control circuit remains PWM. Due to achieved soft switching condition, the energy conversion through the proposed converter is highly efficient. The proposed converter is analyzed and a prototype converter is implemented. The presented experimental results confirm the theoretical analysis.

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1. Introduction

The energy storage systems are designed to provide peak power demands. If only batteries or fuel cells are used in an energy storage system, their capacity should be over designed to provide the peak power stresses. By using ultracapacitor besides batteries or fuel cells, the peak power demands can be provided using ultracapacitors and therefore, the energy storage devices are designed to provide only the average power required. Therefore, by combining the ultracapacitors and batteries or fuel cells, the volume and cost of the energy storage elements can be decreased. The ultracapacitors are charged usually through the energy storage elements such as batteries and fuel cells when the power demand is low. At peak power, the stored energy in the ultracapacitor will support the energy storage devices to provide the required power.

Ultracapacitors are a new generation of capacitors that have extremely high capacity but the voltage they can tolerate is small. Although ultracapacitors have higher power density than batteries, their energy density is much lower. In order to combine the ultracapacitors and energy storage elements such as batteries and fuel cells, a bidirectional interface circuit is required. The interface circuit charges the ultracapacitor at low power demands and discharges the ultracapacitor at peak power demands. DC–DC converters are vastly applied in industry as interface circuits [1–3]. Usually buck and boost converter is used as the interface circuit of batteries and ultracapacitors [4,5]. The converter charges the ultracapacitors in buck mode since their voltage is low and discharges the ultracapacitors in boost mode to adapt the low capacitors voltage to higher voltage of batteries. In order to reduce the size and weight of this converter, high switching frequency is indispensable. However, at high frequencies the converter efficiency is reduced due to switching losses and thus, the energy is wasted while charging and discharging the ultracapacitors. Switching losses are produced at switching instances where both the voltage across the switch and the current through the switch have considerable value. By limiting the current or voltage at switching instant, switching losses are eliminated which is called soft switching. Therefore, soft switching techniques can be applied to the interface circuit to eliminate the switching losses and improve the converter efficiency while decreasing the Electro Magnetic Interferences (EMI) [6–10]. The introduced soft switching interface circuit in [9] is a bidirectional isolated converter. In many applications isolation is not necessary and only the total efficiency decreases due to isolation while no desirable benefit is achieved. Also, isolation increases the converter volume and weight. A ZVT PWM buck and boost converter is introduced in [10], however, in this converter the control circuit is complicated and the auxiliary circuit is used twice in every switching cycle. In soft switching converters the switching losses are recovered using additional circuit elements. In other words, in soft switching converters especially in ZVT and ZCT type converters, although the conduction losses of the auxiliary circuit are added, but the switching losses are recovered. Since the conduction losses of the auxiliary circuit are much less than the switching losses, the efficiency increases using these techniques. In the converter of [10], the auxiliary circuit is applied two times in a switching cycle. This means that in the
converter of [10], the additional conduction losses are almost twice the proposed converter for recovering the same amount of switching losses. Therefore, the proposed converter has better efficiency than converter of [10] while the required control circuit for the auxiliary circuit is much simpler.

In this paper a soft switching PWM buck and boost converter is introduced which uses an auxiliary circuit only once at switching instant in each switching cycle. Therefore, the control circuit is simple and also the auxiliary circuit losses are low. The proposed converter is introduced and analyzed in Section 2. Design considerations are discussed in Section 3. In Section 4, the experimental results are presented which confirm the validity of theoretical analysis.

2. Circuit description

The proposed interface circuit is shown in Fig. 1. The main bidirectional buck and boost converter is composed of two bidirectional switches S1 and S2 and filter inductor L. The auxiliary circuit is composed of a bidirectional switch Ss1, a unidirectional switch Ss2, two small resonant inductors Ls and Lr, and a small resonant capacitor Cs. The auxiliary circuit provides the soft switching condition for S1 and S2 while its semiconductor devices are also soft switched. In order to simplify the theoretical analysis, it is assumed that all semiconductor devices are ideal. Also, inductor L is large enough to assume its current is constant in a switching cycle. The converter operation is analyzed in both buck mode and boost mode.

2.1. Buck mode operation

The converter operation in buck mode is composed of six different operating intervals in a switching cycle. The converter theoretical waveforms are shown in Fig. 2 and equivalent circuit for each operating interval is shown in Fig. 3. Before the first interval it is assumed that Cs voltage is zero, D2 is conducting the current through Lr, and all other semiconductor devices are off.

Interval 1 [t0 − t1]: This interval starts by turning S1 on and since D2 is conducting, the battery voltage (Vbat) is placed across Lr and its current increases linearly. Therefore, this switch turns on under zero current (ZC) condition. Lr current equation during this interval is:

\[ I_{Lr} = \frac{V_{bat}}{L_r} (t - t_0) \]  (1)

At the end of this interval, Lr current reaches I0 and D2 turns off under ZC condition.

Interval 2 [t1 − t2]: In this interval, energy is transferred from battery to ultracapacitor. Also, a resonance starts between Ls and Cs and thus, Cs is charged to 2Vbat. The current equation for Ls during this interval is:

\[ I_{Ls} = I_0 + \frac{V_{bat}}{Z_0} \sin(\omega_0(t - t_1)) \]  (2)

2.2. Boost mode operation

The converter operation in boost mode has eight distinct operating intervals in a switching cycle. The converter theoretical waveforms are shown in Fig. 4 and equivalent circuit for each operating interval is shown in Fig. 5. Before the first interval it is assumed that D1 is conducting the current through Lr and L (Im) and all other semiconductor devices are off. Also, it is assumed that Cs voltage is Vbat/Z0.

Interval 1 [t0 − t1]: This interval starts by turning Sa1 and Ss2 on. Since Ss2 and D1 are on, Vbat − Vcap is placed across Lr and its current increases linearly to Im and D1 current reduces from Im to zero accordingly. Therefore, Ss2 is turned on under ZC condition and at the end of this interval D1 turns off under ZC condition. Ls current equation during this interval is:
Since the duration of this interval is small, it can be assumed that \( C_r \) voltage is almost constant during this interval.

Interval 2 \([t_1/C_0 t_2]\): In this interval a resonance occurs between \( C_r, L_r \) and \( L_s \) and thus, \( C_r \) discharges in a resonance fashion. \( C_r \) voltage equation is:

\[
V_{Cr} = (V_{bat} + Z_0 I_{in}/C_0 V_{cap}) \cos(\omega_1 (t - t_1) + V_{cap})
\]

where

\[
\omega_1 = \frac{1}{\sqrt{(L_r + L_s)/C_r}}
\]

\[
Z_1 = \sqrt{\frac{L_r + L_s}{C_r}}
\]

Interval 3 \([t_2/C_0 t_3]\): When \( C_r \) voltage reaches zero, \( D_2 \) starts to conduct under zero voltage condition and \( V_{cap} \) is placed across series combination of \( L_s \) and \( L_r \). Thus, the current in \( L_s \) and \( L_r \) decreases linearly to \( I_{in} \) where \( D_2 \) turns off under \( Z_C \) condition. During this interval \( S_2 \) is turned on under \( Z_V \) condition.

Interval 4 \([t_3/C_0 t_4]\): \( V_{cap} \) is still across \( L_s \) and \( L_r \) and their current continues to decrease from \( I_{in} \) to zero and \( S_2 \) current increases from zero to \( I_{in} \) accordingly. \( L_r \) current equation during this interval is:

\[
I_{lr} = I_{in} \frac{V_{cap}}{L_r + L_s} (t - t_3)
\]

Interval 5 \([t_4/C_0 t_5]\): \( S_2 \) is on and energy is being stored in \( L \) similar to a regular boost converter. Duration of this interval (converter duty cycle) is determined by control circuit according to control strategy.

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**Fig. 3.** Equivalent circuit for each operating interval of buck mode (a) \([t_0/C_0 t_1]\) (b) \([t_1/C_0 t_2]\) (c) \([t_2/C_0 t_1]\) (d) \([t_1/C_0 t_4]\) (e) \([t_4/C_0 t_5]\) (f) \([t_5/C_0 t_6 + T]\).

**Fig. 4.** Converter theoretical waveforms in boost mode.
Interval 6 \([t_5 - t_6]\): \(S_2\) is turned off and \(L\) current charges \(C_r\) through \(D_{a1}\). Since \(C_r\) voltage changes linearly from zero to \(V_{\text{bat}}\), thus, \(S_2\) is turned off under ZV condition. \(C_r\) voltage during this interval is:

\[
V_{C_r} = \frac{I_0}{C_r} (t - t_5)
\]

Interval 7 \([t_6 - t_7]\): \(C_r\) voltage reaches \(V_{\text{bat}}\), a resonance occurs between \(C_r\) and \(L_r\). Thus, \(L_r\) current increases from zero to \(I_{\text{in}}\) in a resonance fashion. Also, \(C_r\) voltage increases from \(V_{\text{bat}}\) to \(V_{\text{bat}} + Z_0 I_{\text{in}}\). The equations of \(C_r\) voltage and \(L_r\) current during this interval are:

\[
V_{C_r} = V_{\text{bat}} + Z_0 I_{\text{in}} \sin(\omega_0 (t - t_6))
\]

\[
I_{L_r} = I_{\text{in}} (1 - \cos(\omega_0 (t - t_6)))
\]

Interval 8 \([t_7 - t_8 + T]\): Diode \(D_1\) turns on under ZV condition and energy is transferred from ultracapacitors to batteries.

### 3. Design considerations

Inductor \(L\) is designed like filter inductor of a regular PWM buck and boost converter. According to (4), in order to achieve ZC condition at \(S_1\) turn off for the buck mode operation, the following condition should be achieved:

\[
\frac{V_{\text{bat}}}{Z_0} \geq I_{\text{omax}}
\]

where \(I_{\text{omax}}\) is the maximum ultracapacitors charging current in buck mode. In practice 20% over design is necessary, therefore:
\[ Z_0 < \frac{V_{\text{bat}}}{1.2 I_{0\text{max}}} \]  

(13)

\[ L_1 \text{ provides ZC condition for } S_{a2} \text{ turn on and } L_r \text{ provide ZC condition for } S_1 \text{ turn on. Thus, their values can be calculated like any turn on snubber. By calculating } L_r, \text{ the value of } C_r \text{ can be calculated using (13) and (3).}

According to (6), in order to achieve ZV condition for \( S_2 \) turn on for the boost mode operation, the following condition should be achieved:

\[ V_{\text{bat}} + Z_0 I_{\text{in, min}} \geq 2V_{\text{cap}} \]  

(14)

where \( I_{\text{in, min}} \) is minimum \( I \) current in boost mode. Since \( V_{\text{bat}} \) is usually more than twice the ultracapacitors voltage, the above condition is trivial.

4. Experimental results

In order to confirm the validity of theoretical analysis, a prototype converter is implemented. The batteries voltage is 48 V and the ultracapacitors voltage is 24 V. The converter operating power is 100 W and its switching frequency is 100 kHz. According to design procedure, a 200 \( \mu \)H inductor is used for \( L \), a 1.5 \( \mu \)H inductor is used for \( L_r \), a 1 \( \mu \)H inductor is used for \( L_s \), 18 nF capacitor is used for \( C_r \). IRF540 is used for all of the switches and for \( S_{a2} \), a MUR460 is used as the series diode. The converter experimental results for buck mode are shown in Fig. 6 and boost mode experimental results are illustrated in Fig. 7. According to Fig. 6a, after the main switch \( S_1 \) is turned on, its voltage decreases to zero and then its current increases first linearly to \( I_0 \) and then in a resonance.
fashion to its maximum value as it was predicted in the theoretical analysis. As it can be observed from the same figure, just before turning $S_1$ off, its current has decreased to zero. Therefore, zero current switching condition is achieved for $S_1$ that confirms the theoretical analysis and also the achieved soft switching condition for the auxiliary switch is apparent in Fig. 6b. As it can be observed in Fig. 7a, the $S_2$ voltage has decreased to zero and then this switch is turned on and the switch current increases to $I_{in}$. Furthermore, when $S_2$ is turned off, the voltage across it increases linearly to its final value as predicted in theoretical analysis. In addition, the presented experimental results in Fig. 7b, justify theoretical analysis of the proposed converter. The converter efficiency curve in buck mode and boost mode is compared with hard switching converters in Fig. 8.

5. Conclusions

In this paper a new soft switching buck and boost is introduced. The soft switching is achieved for full load range while the control circuit remains PWM. The converter is analyzed and its different operating modes are presented. Design considerations are discussed and a laboratory prototype is implemented. The presented experimental results confirm the validity of theoretical analysis.

References