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

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ABSTRACT

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.

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

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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 S_1 and S_2 and filter inductor L. The auxiliary circuit is composed of a bidirectional switch S_{a1}, a unidirectional switch S_{a2}, two small resonant inductors L_r and L_S, and a small resonant capacitor C_r. The auxiliary circuit provides the soft switching condition for S_1 and S_2 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 C_r voltage is zero, D_2 is conducting the current through L (I_0), and all other semiconductor devices are off.

Interval 1 [$t_0 - t_1$]: This interval starts by turning S_1 on and since D_2 is conducting, the battery voltage (V_{bat}) is place across L_r and its current increases linearly. Therefore, this switch turns on under zero current (ZC) condition. L_r current equation during this interval is:

$$I_{Lr} = \frac{V_{\text{bat}}}{L_r}(t - t_0) \tag{1}$$

At the end of this interval, L_r current reaches I_0 and D_2 turns off under ZC condition.

Interval 2 [$t_1 - t_2$]: In this interval, energy is transferred from battery to ultracapacitor. Also, a resonance starts between L_r and C_r through D_{a1} and thus, C_r is charged to $2V_{\text{bat}}$. The current equation for L_r during this interval is:

$$I_{Lr} = I_0 + \frac{V_{\text{bat}}}{Z_0}\sin(\omega_0(t - t_1)) \tag{2}$$

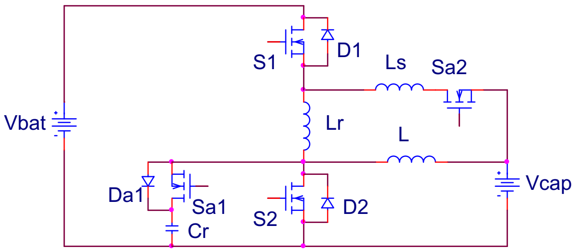

Fig. 1. Proposed soft switching interface circuit.

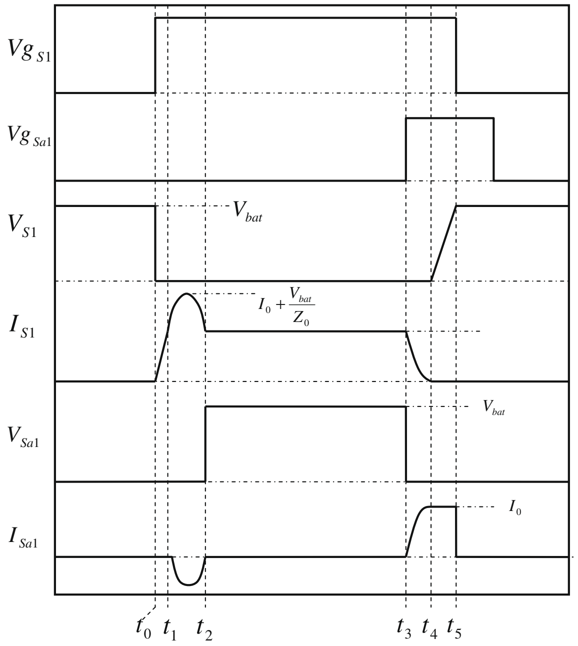

Fig. 2. Converter theoretical waveforms in buck mode.

where

$$Z_0 = \sqrt{\frac{L_r}{C_r}}, \quad \omega_0 = \frac{1}{\sqrt{L_r C_r}} \tag{3}$$

Interval 3 [$t_2 - t_3$]: In this interval, the energy is transferred from battery to ultracapacitor through S_1 and all other semiconductor devices are off.

Interval 4 [$t_3 - t_4$]: In this interval, S_{a1} is turned on and the difference between C_r voltage and the battery voltage is placed across L_r. Therefore, the current through L_r and S_1 is reduced to zero. At the end of this interval S_1 is turned off under ZC condition. L_r current during this interval is:

$$I_{Lr} = I_0 - \frac{V_{\text{bat}}}{Z_0}\sin(\omega_0(t - t_3)) \tag{4}$$

ZC condition for S_1 turn off is achieved if V_{bat}/Z_0 is greater or equal to I_0. Assuming V_{bat}/Z_0 is equal to I_0, C_r voltage is equal to V_{bat} at the end of this interval.

Interval 5 [$t_4 - t_5$]: During this interval, C_r is discharged by L current (I_0) until its voltage is reduced to zero and diode D_2 is forward biased.

Interval 6 [$t_5 - t_0 + T$]: Diode D_2 starts to conduct under zero voltage (ZV) condition and L current runs through this diode.

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 D_1 is conducting the current through L_r and L (I_{in}) and all other semiconductor devices are off. Also, it is assumed that C_r voltage is $V_{\text{bat}} + Z_0 I_{\text{in}}$.

Interval 1 [$t_0 - t_1$]: This interval starts by turning S_{a1} and S_{a2} on. Since S_{a2} and D_1 are on, $V_{\text{bat}} - V_{\text{cap}}$ is placed across L_S and its current increases linearly to I_{in} and D_1 current reduces from I_{in} to zero accordingly. Therefore, S_{a2} is turned on under ZC condition and at the end of this interval D_1 turns off under ZC condition. L_S current equation during this interval is: