Development of a Switched-Capacitor DC–DC Converter with Bidirectional Power Flow

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Abstract—This brief presents a switched-capacitor dc–dc converter that offers features of voltage step-down, voltage step-up, and bidirectional power flow. Concept of energy transfer is achieved by using two current-controlled bidirectional converter cells, which are operating in antiphase. Good regulation capability and continuous input current waveform are other substantial advantages that facilitate practical realization and reduce electromagnetic interference with other circuits and supply networks. State-space averaging technique is applied to study the static and dynamic characteristics. A 20-W, 5-V–9-V prototype has been built and has an overall efficiency of over 80% in all operations.

Index Terms—Bidirectional converters, DC/DC power conversion, switched-capacitor circuits, switched circuits.

I. INTRODUCTION

Many of today’s very large scale integration (VLSI) chips operate at low voltages, ultimately requiring dc–dc converters that can be realized by integrated circuit (IC) technology. Recently, various switched-capacitor (SC) converters that contain semiconductor switches and capacitors to convert or invert dc voltages have been proposed [1]–[5] and are commercially available [6], [7]. As no magnetic devices are required, monolithic integration of this kind of converters is much more promising. Converters that are based upon improvements of switching techniques and circuit topologies have been intensively investigated and developed.

Topologies reported to date usually exhibit some of the following aspects:

1) weak regulation capability;
2) structurally defined voltage conversion ratio;
3) pulsating input current that generates electromagnetic interference (EMI) [8];
4) unidirectional power conversion for a circuit structure.

Recently, some techniques that solve 1) to 3) have been proposed in [4] and [5], having improved regulation capability and continuous input current waveform. The voltage conversion ratio is determined by a control voltage, which adjusts the charging profile of the capacitor. Concerning item 4), apart from converters with magnetic devices, the amount of literature that devotes to IC-based bidirectional power flow control is limited.

This brief presents a bidirectional SC converter, which is based on integrating the control features of [4] and [5]. A single circuit structure offers voltage step-down, voltage step-up, and bidirectional power flow capabilities. Section II gives the operating principles of the bidirectional converter cell and a complete realization. Section III shows the mathematical derivations of the static and dynamic behaviors. Section IV presents experimental results of a 20-W, 5-V–9-V prototype. Section V gives the conclusions.

II. OPERATING PRINCIPLES AND CONTROL PHILOSOPHY

Fig. 1 shows a single-capacitor bidirectional SC converter cell, consisting of one capacitor (C) with equivalent series resistance (ESR) $r_c$, three diodes (D1, D2, and D3), and four semiconductor switches (S1, S2, S3, and QS). The cell can convert electric energy between the high-voltage (HV) and the low-voltage (LV) sides. S1, S2, and S3 are operated as static switches with on-resistance $r_{on}$, while QS can be operated in cutoff, triode, or saturation modes. QS is used to control the charging current of C during the saturation mode. When a metal–oxide–semiconductor field-effect transistor (MOSFET) is operating in saturation mode, the relationship between the gate-source voltage $v_{GS}$ and the drain current $i_D$ can be expressed by a large-signal model [9]

$$i_D = K_1 (v_{GS} - V_T)^2, \quad K_1 = \frac{1}{2} k_1 k_2$$

$k_1$ is the process transconductance parameter, $k_2$ and $V_T$ are the aspect ratio and the threshold voltage of the MOSFET channel, respectively. The small-signal variation of $i_D$ with respect to the changes of $v_{GS}$ can be studied by introducing perturbations into (1) with $i_D = I_D + \dot{i}_D$ and $v_{GS} = V_{GS} + \dot{v}_{GS}$, thus

$$I_D = K_1 (V_{GS} - V_T)^2$$

and

$$\dot{i}_D = K_1 [2 \dot{v}_{GS} (V_{GS} - V_T) + \dot{v}_{GS}^2] \approx K_2 \dot{v}_{GS}$$

$$K_2 = 2 K_1 (V_{GS} - V_T).$$

The saturated MOSFET behaves as an ideal current source, whose value is controlled by $v_{GS}$ according to the square-law relationship in (2).

This cell has two modes of operation, namely, mode “A” and mode “B.” Mode “A” is a step-down operation. Electric energy is transferred from the HV side to the LV side. Mode “B” is a step-up operation. Electric energy is transferred from the LV side to the HV side. Each mode has two circuit topologies, which are operating for the same duration of half of the switching period $T_S$ (i.e., $T_S/2$). The circuit operation of each mode is described as follows.

A. Mode “A” Operation

In this mode, the two topologies are named as Topology AI and Topology AII, respectively, which are shown in Fig. 2. In the Topology AI [Fig. 2(a)], $S_1$ is closed and QS is in saturation mode. All other switches are open. C is linearly charged with a current of $I_{A,ch}$ from the HV side through $S_1$ and QS for a duration of $T_S/2$. The gate source voltage of QS determines the magnitude of $I_{A,ch}$. At the end of the Topology AI, C will be charged to a voltage slightly higher than the LV side (i.e., $v_{LV}$), in order to compensate the parasitic resistance and diode voltage drop in the Topology AI [Fig. 2(b)]. In the Topology AII, $S_2$ and $D_3$ are closed, while all other switches are open. C is then disconnected from the HV side and its stored energy is transferred to the LV side for $T_S/2$ through $S_2$ and $D_3$.

B. Mode “B” Operation

In this mode, the two topologies are named as Topology BI and Topology BII, respectively, which are shown in Fig. 3. In the Topology BI, $D_2$ is closed and QS is in saturation mode, while all other switches are open. $C$ is linearly charged from the LV side through $D_2$ and QS.
with current $I_{H,ch}$ for $T_s/2$. Again, the gate-source voltage of $QS$ determines the magnitude of $I_{H,ch}$. At the end of Topology BI, $C$ will be charged to a voltage slightly higher than the voltage difference between HV and LV sides (i.e., $v_{HV} - v_{LV}$), in order to compensate the parasitic resistance and diode voltage drop in Topology BII [Fig. 3(b)]. Theoretically, $C$ can be charged to a maximum voltage of $v_{LV}$ in Topology BI. Thus, the maximum value of $v_{HV}$ is $2v_{LV}$.

In the Topology BII, $D_1$ and $S_3$ are closed, while all other switches are open. $C$ is then connected in series with the LV side through $D_1$ and $S_3$ to supply energy to the HV side. The voltage at HV side will then higher than the LV side.

C. Complete Realization of a Bidirectional SC Converter

Complete realization of a bidirectional SC converter is achieved by using two converter cells, namely, “Cell 1” and “Cell 2” in Fig. 4. The HV and LV sides of each cell are correspondingly connected together with a capacitor in parallel, i.e., $C_{HV}$ for the HV side and $C_{LV}$ for the...
LV side with ESR $r_{C_{HV}}$ and $r_{C_{LV}}$, respectively, for smoothing the two terminal voltages. The two cells are operated in the same mode and antiphase. For instance, if the converter is in mode “A” operation, both cells will be in mode “A.” When “Cell 1” is in Topology Al, “Cell 2” will be in Topology AII, and vice versa. The principles of operation are similar in the step-up mode. Fig. 5 shows the theoretical circuit waveforms under the two modes. The input current of the converter at each side is equal to the sum of the input current of the two cells. For mode “A” operation, the HV side is connected to a voltage source and the LV side is connected to a load resistance. Thus

$$i_{HV} = i_{HV,1} + i_{HV,2} = I_{L,eh}$$

where $i_{HV,1}$ and $i_{HV,2}$ are the input currents of “Cell 1” and “Cell 2,” respectively, at the HV side. The current directions of $i_{LV,1}$ and $i_{HV,1}$...
of “Cell 1” in this mode are shown in Fig. 2. $i_{\text{HV}}$ is the input current of the whole converter at the HV side.

On the other hand, for mode “B” operation, the HV side is connected to a load resistance and the LV side is connected to a voltage source. Thus,

$$i_{\text{LV}} = i_{\text{LV},1} + i_{\text{LV},2} = -i_{\text{HV}} + I_{H,cb} \tag{5}$$

where $i_{\text{LV},1}$ and $i_{\text{LV},2}$ are the input currents of “Cell 1” and “Cell 2,” respectively, at the LV side. The current directions of $i_{\text{LV},1}$ and $i_{\text{LV},2}$ of “Cell 1” in this mode are illustrated in Fig. 3. $i_{\text{HV}}$ is the input current of the whole converter at the LV side.

As $I_{H,cb}, I_{L,sh}$, and $i_{\text{HV}}$ are relatively constant, the input current at both sides is constant and continuous, thus reducing EMI.

III. ANALYSIS OF THE SC STEP-UP DC–DC CONVERTER

By using averaging technique, the state equation sets are shown in the following. For mode “A,” if $R_{\text{LV}}$ is the load resistance at the LV side

$$\dot{x} = A_A x + B_A u_A$$
$$v_{\text{LV}} = C_A x \tag{6}$$

where $x = [v_{c1}, v_{c2}, v_{c3}]^T$, $u_A = I_{A,sh}$, [see (6a), at the bottom of the next page], and $r_D$ is the equivalent resistance of the diodes.

For mode “B” operation, if $R_{\text{HV}}$ is the load resistance at the HV side

$$\dot{x} = A_B x + B_B u_B$$
$$v_{\text{HV}} = C_B x + D_B u_B \tag{7}$$

where $u_B = [I_{B,sh}, v_{\text{HV}}]$ [see (7a), at the bottom of the next page].
Fig. 6. Experimental Waveforms. (a) Mode “A”—ChA: \(v_{LV} \) (5 V/div) and ChB: \(i_{HV} \) (2 A/div). (b) Mode “B”—Ch1: \(v_{HV} \) (5 V/div) and Ch2: \(i_{LV} \) (1 A/div).

The output current at HV side is equal to \(I_{HV, ch} \) and the conversion efficiency \(\eta_H \) can be shown to be

\[
\eta_H = \frac{\text{Output Power at HV side}}{\text{Input Power at LV side}} = \frac{v_{HV}I_{A, ch}}{v_{LV}(I_{A, ch} + I_{A, sh})} = \frac{v_{HV}}{2\eta_{LV}}.
\] (11)

Maximum \(\eta_H \) occurs when \(v_{HV} \) equals twice the voltage of \(v_{LV} \).

### B. Dynamic Characteristics

The small-signal dynamic behaviors of the converter around the operating point is studied by introducing a small-signal variation \(\tilde{v}_{con} \) on the steady-state value of \(v_{con} \), \(\tilde{v}_{LV} \), and \(\tilde{v}_{HV} \) on their steady-state value of \(v_{LV} \) and \(v_{HV} \), respectively, separating the small-signal component, and neglecting the infinitesimal terms of the second- and higher order disturbances. The open-loop input-to-output transfer function [i.e., \(\tilde{v}_{LV}(s)/\tilde{v}_{HV}(s) \) for mode

\[
\begin{align*}
A_A &= \begin{bmatrix}
-\frac{(R_{LV} + r_{c_{LV}})}{2C\beta_A} & 0 \\
0 & -\frac{(R_{LV} + r_{c_{LV}})}{2C\beta_A} \\
\frac{R_{LV}}{2C_{LV}\beta_A} & \frac{R_{LV}}{2C_{LV}\beta_A} \\
\frac{1}{2C} & \frac{1}{2C} \\
0 & 0
\end{bmatrix} \\
B_A &= \begin{bmatrix}
\frac{R_{LV}}{2C_{LV}} \\
\frac{R_{LV}}{2C_{LV}} \\
\frac{1}{2C} & \frac{1}{2C} \\
0 & 0
\end{bmatrix}
\end{align*}
\]

\[
C_A = \begin{bmatrix}
\frac{R_{LV}r_{c_{LV}}}{2\beta_A} \\
\frac{R_{LV}r_{c_{LV}}}{2\beta_A} \\
\frac{R_{LV}(r_c + r_D + r_{con})}{C_{LV}\beta_A}
\end{bmatrix}
\]

\[
\beta_A = r_c r_{c_{LV}} + r_{c_{LV}} r_D + r_c R_{LV} + r_{c_{LV}} R_{LV} + r_D R_{LV} + r_{c_{LV}} r_{con} + R_{LV} r_{con}
\] (6a)

\[
A_H = \begin{bmatrix}
-\frac{(R_{HV} + r_{c_{HV}})}{2C\beta_H} & 0 & \frac{R_{HV}}{2C\beta_H} \\
0 & -\frac{(R_{HV} + r_{c_{HV}})}{2C\beta_H} & \frac{R_{HV}}{2C\beta_H} \\
\frac{R_{HV}}{2C_{HV}\beta_H} & \frac{R_{HV}}{2C_{HV}\beta_H} & \frac{R_{HV} + r_c + r_D + r_{con}}{C_{HV}\beta_H}
\end{bmatrix} \\
B_H &= \begin{bmatrix}
\frac{1}{2C} \frac{r_{c_{HV}} + R_{HV}}{2C\beta_H} \\
\frac{1}{2C} \frac{r_{c_{HV}} + R_{HV}}{2C\beta_H} \\
0 & \frac{R_{HV}}{2C\beta_H}
\end{bmatrix}
\]

\[
C_H = \begin{bmatrix}
\frac{R_{HV}r_{c_{HV}}}{2\beta_H} & \frac{R_{HV}r_{c_{HV}}}{2\beta_H} & \frac{R_{HV}(r_c + r_D + r_{con})}{\beta_H}
\end{bmatrix}
\]

\[
\beta_H = r_c r_{c_{HV}} + r_{c_{HV}} r_D + r_c R_{LV} + r_{c_{HV}} R_{LV} + r_D R_{LV} + r_{c_{HV}} r_{con} + R_{LV} r_{con}
\] (7a)
Fig. 7. Frequency characteristics of the converter in mode “A” $G_{A,oc}$. 

Fig. 8. Frequency characteristics of the converter in mode “B”. (a) $G_{B,og}$. (b) $G_{B,oc}$.

“A” and $\dot{v}_{HV}(s)/\dot{v}_{LV}(s)$ for mode “B” and control-to-output transfer function [i.e., $\dot{v}_{LV}(s)/\dot{v}_{con}(s)$ for mode “A” and $\dot{v}_{HV}(s)/\dot{v}_{con}(s)$ for mode “B”] are as follows. For mode “A” 

\[
G_{A,og}(s) = \frac{\dot{v}_{LV}(s)}{\dot{v}_{HV}(s)} = 0
\]  

(12) 

and 

\[
G_{A,oc}(s) = \frac{\dot{v}_{LV}(s)}{\dot{v}_{con}(s)} = \frac{K_2 R_{LV} (C_{LV} r_{CLV} + 1)}{s^2 + a_{1}s + 1}
\]  

(13) 

where $a_0 = 2C_{LV}C$ and $a_1 = 2C(r_c + r_D + R_{LV} + r_{con}) + C_{LV}(r_{C_{LV}} + R_{LV})$.

For mode “B” 

\[
G_{B,og}(s) = \frac{\dot{v}_{HV}(s)}{\dot{v}_{LV}(s)} = \frac{2R_{HV}Cs (1 + C_{HV} r_{C_{HV}})}{b_0 s^2 + b_1 s + 1}
\]  

(14) 

and 

\[
G_{B,oc}(s) = \frac{\dot{v}_{HV}(s)}{\dot{v}_{con}(s)} = \frac{K_2 R_{HV} (C_{HV} r_{C_{HV}} + 1)}{b_0 s^2 + b_1 s + 1}
\]  

(15) 

where $b_0 = 2C_{HV}C$ and $b_1 = 2C(r_c + r_D + R_{HV} + r_{con}) + C_{HV}(r_{C_{HV}} + R_{HV})$. 
C. Selection of the Values of $C_{LV}$ and $C_{HV}$

After the value of $C$ is selected, the values of $C_{LV}$ and $C_{HV}$ are chosen such that the terminal voltage is less than a specified ripple voltage $\Delta V_{A,\text{max}}$ and $\Delta V_{H,\text{max}}$, respectively. For mode “A,” $C$ is connected in parallel with $C_{LV}$ and $R_{LV}$. Thus

$$\Delta V_{A,\text{max}} \geq \frac{v_{LV} T_s}{(C + C_{LV}) R_{LV}} \Rightarrow C_{LV} \geq \frac{v_{LV} T_s}{2\Delta V_{A,\text{max}} R_{LV}} - C. \quad (16)$$

Similarly, for mode “B”

$$\Delta V_{H,\text{max}} \geq \frac{v_{HV} T_s}{(C + C_{HV}) R_{HV}} \Rightarrow C_{HV} \geq \frac{v_{HV} T_s}{2\Delta V_{H,\text{max}} R_{HV}} - C. \quad (17)$$

In general, $C$, $C_{LV}$, and $C_{HV}$ are chosen to be the same value.

IV. Prototype

A 5-V–9-V, 20-W, bidirectional SC converter has been built in the laboratory. The component values of the converter are tabulated in Table I. The switching frequency is 180 kHz. The HV side is connected to a rechargeable battery and the LV side is connected to the supply rail, which is normally at a voltage of 5 V. In the normal operation, the battery is charged from the supply rail through the converter. When there is an outage in the supply rail, the converter will convert energy stored in the battery back to the supply rail. The overall efficiency, which includes the required power for the driving circuit, was found to be 85% in mode “A” operation and 80% in mode “B” operation.

Fig. 6(a) shows the experimental waveforms of $v_{LV}$ and $i_{HV}$ when the converter is in mode “A” operation. Fig. 6(b) shows the experimental waveforms of $v_{HV}$ and $i_{LV}$ when the converter is in mode “B” operation. It can be seen that the current is continuous and does not contain pulsating peaks. The waveforms are obtained from the oscilloscope—LeCroy 9304A and the current probe—Tektronix TM502A. Theoretical and experimental dynamic characteristics are shown in Fig. 7 for mode “A” operation and Fig. 8 for mode “B” operation. The experimental measurements are obtained by using a gain-phase analyzer HP4194A. The theoretical results agree well with the experimental ones at low frequencies. The converter can offer a maximum current of 4.5 A when the battery converts energy back into the rail. Moreover, it can also maintain an output voltage of 5 V when the terminal voltage of the battery is higher than 5.5 V.

V. Conclusion

A SC-based bidirectional converter is proposed. A single circuit structure can offer features of voltage step-down, voltage step-up, and bidirectional power flow. Concept of energy transfer is achieved by using two bidirectional SC converter cells that are operating in antiphase. Apart from the advantage of requiring no inductive elements, the converter hybridizes the advantages of previously developed SC-based power conversion technique, having good regulation capability and continuous input current waveform in both modes of operation. A 20 W, 5-V–9-V prototype has been built and tested. The experimental results are verified with theoretical predictions. Further research will be dedicated into the development of a generalized multistage bidirectional converter.

REFERENCES