High-Conversion-Ratio Switched-Capacitor DC-DC Converter with Bidirectional Power Flow

Yuen-Haw Chang and Kun-Wei Wu

***Abstract*—A closed-loop scheme of high-conversion-ratio switched-capacitor bidirectional (HSCB) DC-DC converter is proposed based on pulse-width-modulation (PWM) control for step-up/down conversion and bidirectional power flow. In the HSCB DC-DC converter, there are two 3-stage SC cells between HV bus (high-voltage DC side) and LV bus (low-voltage DC side), where each 3-stage SC cell has 3 pumping capacitors and 6 bidirectional switches. One SC cell can provide the voltage gain of 3 (or 1/3) at most via capacitors charging in parallel (series) and discharging in series (parallel) cyclically. Based on the connection of these two SC cells, plus control of bidirectional power flow, this converter is able to boost the voltage at HV side up to 3×3 times voltage of LV supply source (step-up mode), or convert the voltage at LV side into 1/(3×3) times voltage of HV supply source (step-down mode). In addition, the controller of HSCB converter contains HV/LV PWM block and phase generator. Here, PWM technique is adopted in order to enhance the output regulation for the different desired output. Finally, the closed-loop HSCB converter is designed and simulated by OrCAD Spice, and some cases are discussed as: operation of step-up mode and step-down mode, and HV/LV output ripple percentage. All the results are illustrated to show the efficacy of the proposed scheme.**

***Index Terms*—high-conversion-ratio, switched-capacitor, bi-directional converter, pulse-width-modulation, step-up/down**

I. Introduction

A bidirectional DC-DC converter is important for the electricity-supply applications of the multi-source and stand-alone system, such as photovoltaic (PV) systems, fuel cell systems, and hybrid electric vehicles (HEV). General speaking, the power converter module is always asked for a smaller volume, a lighter weight, a high efficacy, and a better regulation capability. But, the traditional converters have a larger volume and a heavier weight because of inductive elements, e.g., inductors and transformers. So, more manufactures and researchers pay much attention on this topic, and ultimately, they desire an integrated power module realized on a compact chip by mixed-mode VLSI technology.

An SC converter, based on the structure of charge pump, is one of the good solutions to low-power DC-DC conversion because it has semiconductor switches and capacitors only.

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Unlike traditional converters, it needs no magnetic element, so SC converter always has light weight, small volume, and low EMI. A charge pump SC converter is usually designed for an output higher/lower than times the voltage of supply or a reverse-polarity voltage. Up to now, various SC types have been suggested for power conversion. In 1976, Dickson charge pump was proposed based on a diode-chain structure via pumping capacitors [1]. It provides voltage gain proportional to the stage number of pumping capacitor, and the detailed dynamic model and efficiency analysis were discussed [2-3]. But, its drawbacks include the fixed voltage gain and the larger device area. In 1993, Ioinovici *et al.* suggested a voltage-mode SC with two symmetrical capacitor cells working complementarily [4], and PWM was used for output regulation enhancement [5-6]. Based on this, Chang proposed an integrated SC step-up/down DC-DC/DC-AC converter [7-8]. Nevertheless, some improvement space still exists. The development about bidirectional SC converters is not enough for now. In this paper, a closed-loop scheme of HSCB DC-DC converter is proposed with combining PWM for the bidirectional conversion with the step-up/down voltage gain reaching $(3\times3)/(3\times3)^{-1}$ at most.

II. Configuration Of HSCB Converter

A. HSCB Scheme

Fig. 1 shows the overall circuit configuration of HSCB converter, and it contains two parts: “power part” and “control part” for achieving the closed-loop step-up/down bidirectional conversion.

Firstly, the power part: HSCB converter is as shown in the upper half of Fig. 1. The converter is mainly composed of two SC cells (Cell A1 and Cell A2) between HV bus (high-voltage DC side) and LV bus (low-voltage DC side). For more details, it includes 6 pumping capacitors (C_{A11}~C_{A13}, C_{A21}~C_{A23}), 12 power CMOS transmission gates (S_{A11}~S_{A16}, S_{A21}~S_{A26}), and 4 MOSFET switches (S_{up}*, S_{down}*, S_{HV}, S_{LV}), where each capacitor has the same capacitance C (C_{A11}~C_{A13}= C_{A21}~C_{A23}=C). As show the right side in Fig. 1, the HV bus can be equivalent as including a source voltage V_{SH}, an internal resistance R_{SH}, and a rectifying diode D_{SH} (assume that bus has no reverse current to V_{SH}). Similarly, the LV bus contains a source voltage V_{SL}, an internal resistance R_{SL}, and a rectifying diode D_{SL}.

Secondly, the control part includes HV/LV PWM block and phase generator, where each PWM block is composed of low-pass filter (LPF), comparators, and integrator to aim at

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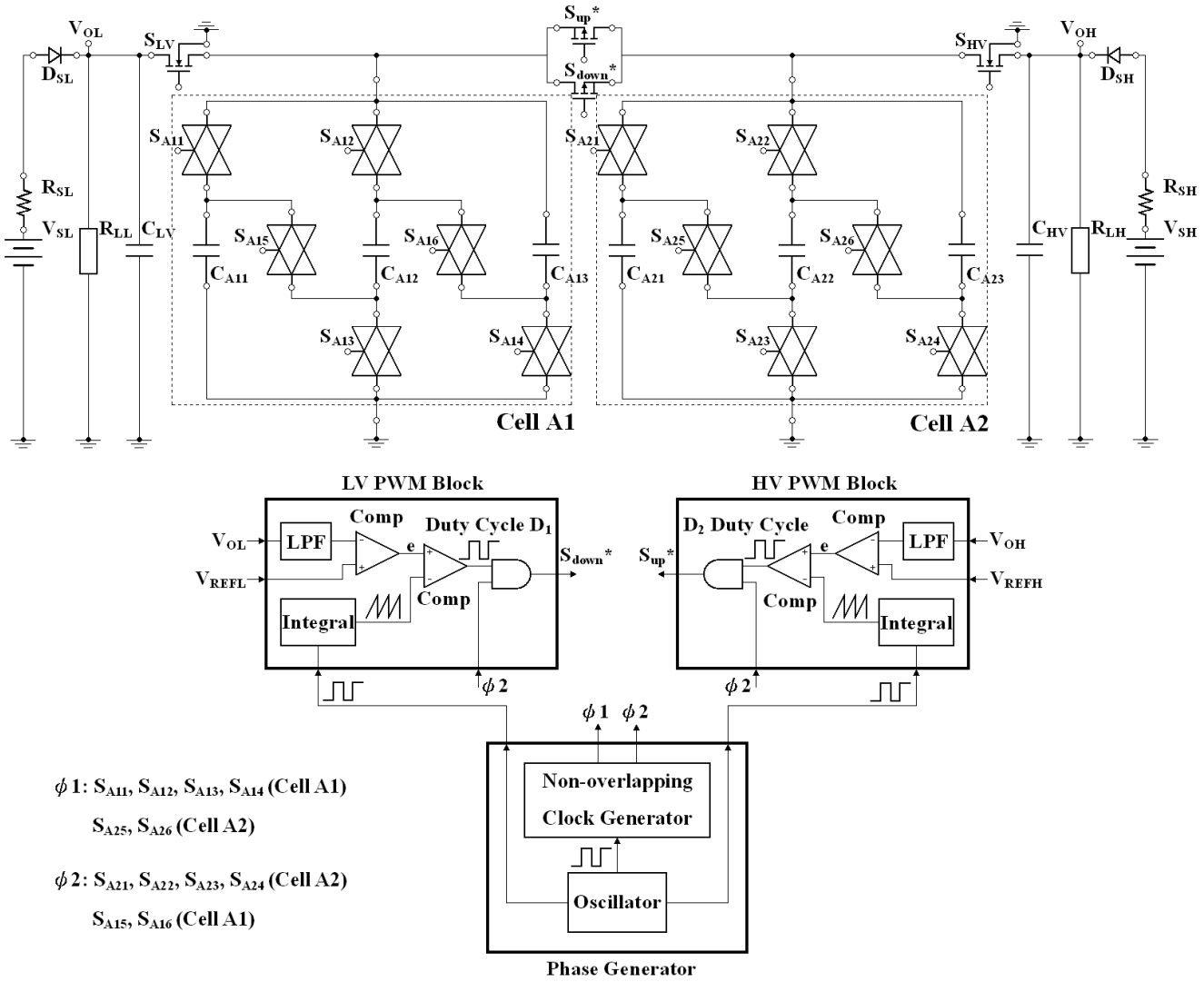

Fig. 1. Configuration of HSCB DC-DC converter.

TABLE I
OPERATING MODES OF HSCB

The V_{SH} compared with the V_{REFH}	The V_{SL} compared with the V_{REFL}	Operating modes
$V_{SH} \geq V_{REFH}$	$V_{SL} \geq V_{REFL}$	Individual mode
$V_{SH} < V_{REFH}$	$V_{SL} \geq V_{REFL}$	Step-up mode
$V_{SH} \geq V_{REFH}$	$V_{SL} < V_{REFL}$	Step-down mode
$V_{SH} < V_{REFH}$	$V_{SL} < V_{REFL}$	Bidirectional mode

duty-cycle generator. From the view of controller signal flow, the feedback signal: the attenuated output V_{OH}/V_{OL} is sent into the OP-amplifier LPF for high-frequency noise rejection. Next, the filtered VOH/VOL is compared with the desired output reference V_{REFH}/V_{REFL} so as to produce the duty cycle D_1/D_2 via the HV/LV PWM block. At the same time, a phase generator can be realized based on digital logic circuit to generate the MOSFET drive signals (S_{HV}, S_{LV} and S_{A11}~S_{A16}, S_{A21}~S_{A26}), where $\phi 1$ and $\phi 2$ are a set of non-overlapping two-phase clocks. In addition, S_{up}*/S_{down}* (step-up/down PWM control signal) can be generated via logic AND combination between signal $\phi 2$ and duty cycle D_1/D_2. In this paper, by using these two PWM control, the regulation capability of HSCB converter will be improved for different desired outputs.

B. Operating modes of HSCB

In order to handle the different voltage of V_{SH}, V_{SL}, V_{REFH}, and V_{REFL}, there are totally 4 operating modes as follows: individual mode, step-up mode, step-down mode, and bidirectional mode. These 4 modes are listed as in Table I and explained as follows.

1) Individual mode:
When $V_{SH} \geq V_{REFH}$ and $V_{SL} \geq V_{REFL}$, MOSFET switches S_{up}* and S_{down}* are OFF. In this case, this converter is not transferring any energy between HV and LV sides, i.e., HV side separates from LV side. HV/LV side has its own source voltage enough to supply the loading, so they are operating independently.
2) Step-up mode:
When $V_{SH} < V_{REFH}$ and $V_{SL} \geq V_{REFL}$, MOSFET switches S_{up}* is ON by PWM and S_{down}* is OFF. In this case, V_{SH} (HV voltage source) is lower than V_{REFH} (HV desired output), i.e., HV source can not supply the loading at HV bus for this V_{REFH}, Now by using the PWM-ON control of S_{up}*, this converter is transferring the energy from LV side to HV side, and is running at the step-up conversion with the voltage gain of 3×3 for the goal of buck-up.
3) Step-down mode:
When $V_{SH} \geq V_{REFH}$ and $V_{SL} < V_{REFL}$, MOSFET

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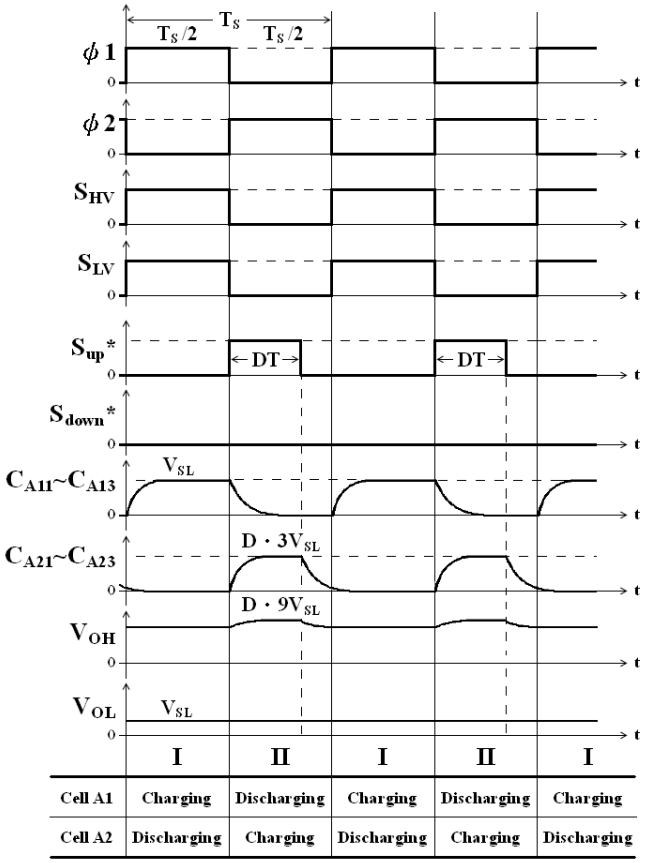

Fig. 2. Theoretical waveforms of HSCB DC-DC converter in step-up state.

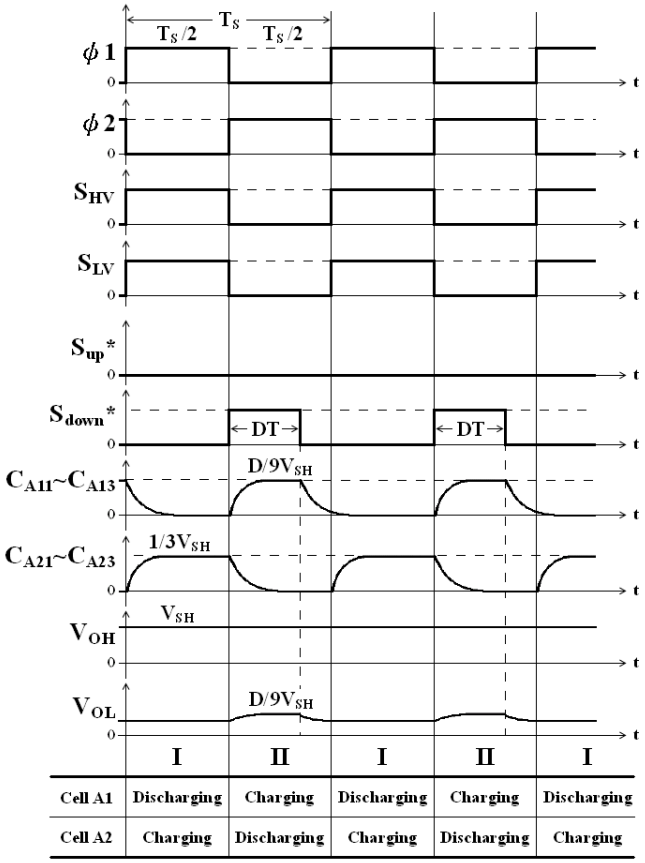

Fig. 3. Theoretical waveforms of HSCB DC-DC converter in step-down state.

switches S_{up}* is OFF and S_{down}* is ON by PWM. In this case, V_{SL} (LV voltage source) is lower than V_{REFL} (LV desired output), i.e., LV source can not supply the loading at LV bus for this V_{REFL}, Now by using the PWM-ON control of S_{down}*, this converter is transferring the energy from HV side to LV side, and is running at the step-down conversion with the voltage gain of 1/(3×3) for the goal of buck-up.

4) Bidirectional mode:

When $V_{SH} < V_{REFH}$ and $V_{SL} < V_{REFL}$, both MOSFET switches S_{up}* and S_{down}* are ON. In this case, V_{SH} (HV source voltage) is lower than V_{REFH} (HV desired output), and V_{SL} (LV source voltage) is also lower than V_{REFL} (LV desired output). Thus, the voltage sources at both sides are too small to supply the loading. Now, the bidirectional back-up operation is running: the energy can be transferred from LV side to HV side through PWM-ON control of S_{up}*, or from HV side to LV side through PWM-ON control of S_{down}*. Of course, the practical outputs at both sides can not be completely made up to the desired outputs, when the HV/LV source voltages are low now. But, the side with the smaller difference between source voltage and desired output (V_{SH} and V_{REFH}/V_{SL} and V_{REFL}) always helps the other side as more as possible, i.e., this side is transferring the energy by step-up or down conversion to the other side with the bigger difference between source voltage and desired output. However, when the source voltages (V_{SH}/V_{SL}) at both sides are much lower than desired references (V_{REFH}/V_{REFL}), this bidirectional converter is set to isolate the circuit of HV and LV bus for protecting the system.

C. Step-up/down modes of HSCB

According to the above descriptions, it is obvious that the basic modes of HSCB include: 1) step-up mode and 2) step-down mode. These two modes are discussed as follows.

1) Step-up mode:

Theoretical waveforms are shown in Fig. 2. Cleary, there are totally two phases (Phase I and II) in a switching cycle Ts. Fig. 4 shows the topology of Phase I and II. In Phase I, Cell A1 is running at capacitor-in-parallel-charging, and Cell A2 is running at capacitor-in-series-discharging.

a) Phase I:

S_{A11}~S_{A14}, S_{A25}~S_{A26}, S_{LV}, S_{HV}: ON, and
S_{up}*, S_{down}*: OFF.
C_{A11}~C_{A13} (Cell A1) are charged in parallel by the V_{SL},
C_{A21}~C_{A23} (Cell A2) are discharging in series to supply the load R_{LH}.

b) Phase II:

S_{A15}~S_{A16}, S_{A21}~S_{A24}: ON, S_{up}*: PWM-ON, and
S_{LV}, S_{HV}, S_{down}*: OFF.
C_{A11}~C_{A13} (Cell A1) are discharging in series to transfer the power to change C_{A21}~C_{A23} (Cell A2) in parallel via PWM control of S_{up}*.

2) Step-down mode:

Theoretical waveforms are shown in Fig. 3. Obviously, there are totally two phases (Phase I and II) in a switching cycle Ts. Fig. 5 shows the topology of Phase I and II. In Phase I, Cell A1 is running at capacitor-in-series-charging, and Cell A2 is running at capacitor-in-parallel-

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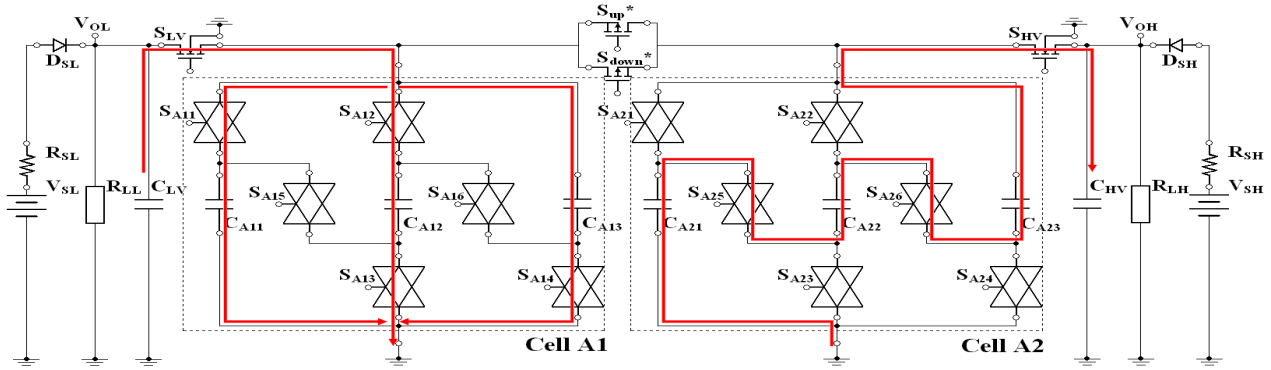
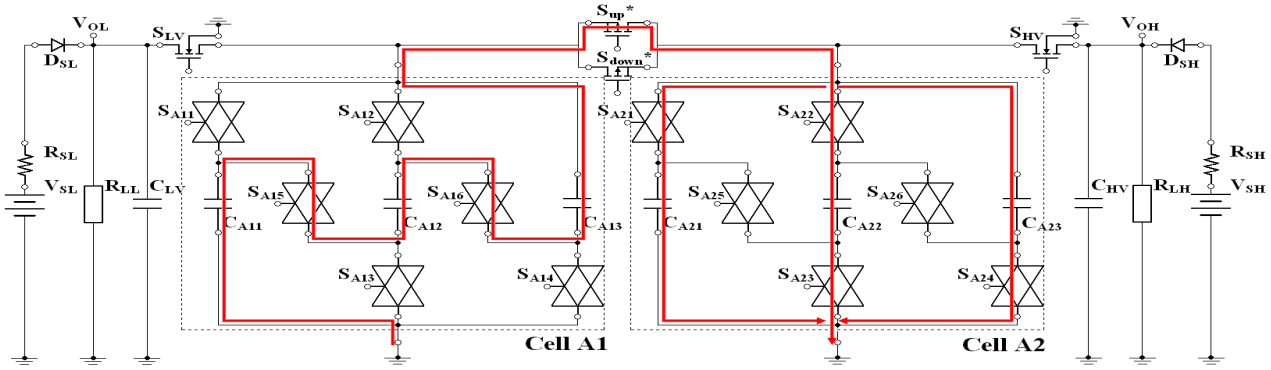
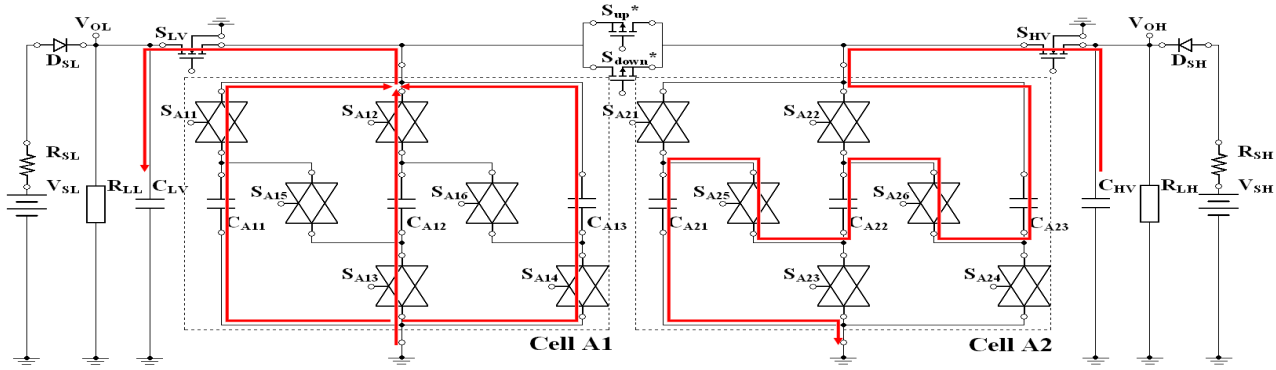


(a) Phase I-topology.

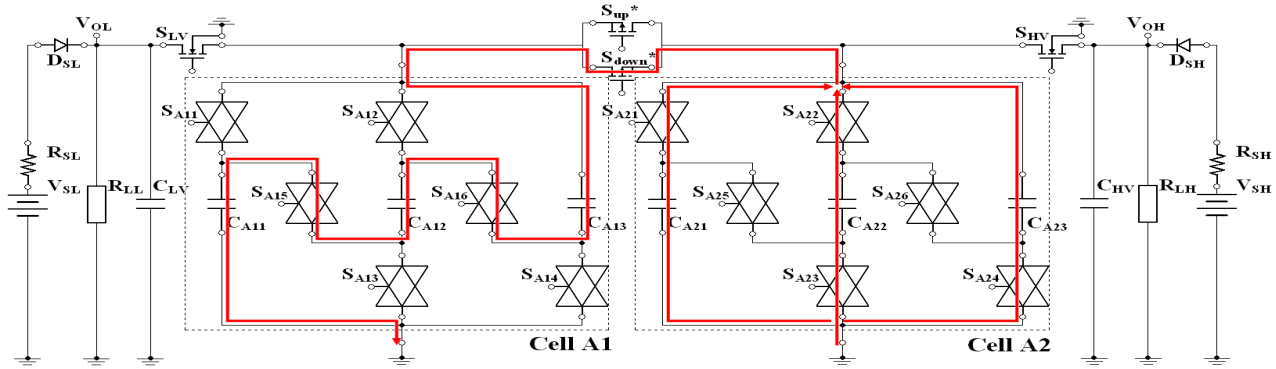


(b) Phase II-topology.

Fig. 4(a)-(b). HSCB DC-DC converter in step-up mode.



(a) Phase I-topology.



(b) Phase II-topology.

Fig. 5(a)-(b). HSCB DC-DC converter in step-down mode.

discharging.

a) Phase I:

S_{A11}~S_{A14}, S_{A25}~S_{A26}, S_{LV}, S_{HV}: ON, and
S_{up}*, S_{down}*: OFF.
C_{A11}~C_{A13} (Cell A1) are discharging in parallel to supply the load R_{LL}, C_{A21}~C_{A23} (Cell A2) are charged in series by the V_{SH}.

b) Phase II:

S_{A15}~S_{A16}, S_{A21}~S_{A24}: ON, S_{down}*: PWM-ON, and
S_{LV}, S_{HV}, S_{up}*: OFF.
C_{A21}~C_{A23} (Cell A2) are discharging in parallel to transfer the power to change C_{A11}~C_{A13} (Cell A1) in series via PWM control of S_{down}*.

III. Simulation Of HSCB Converter

In this section, this HSCB converter with PWM control is

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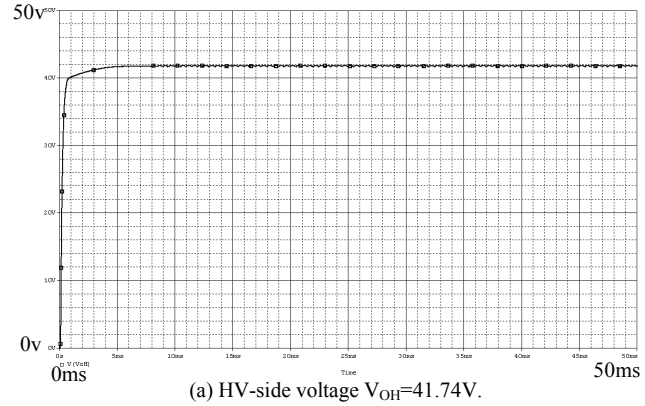
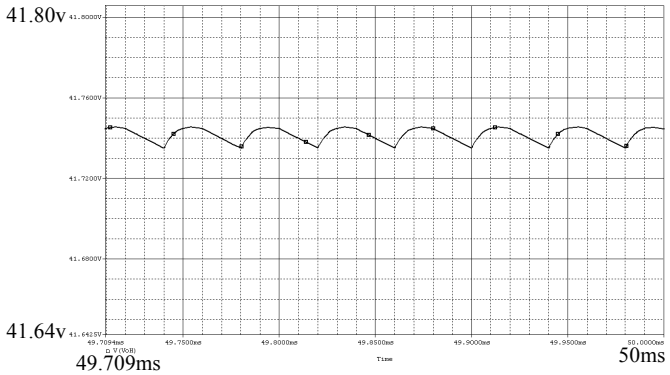
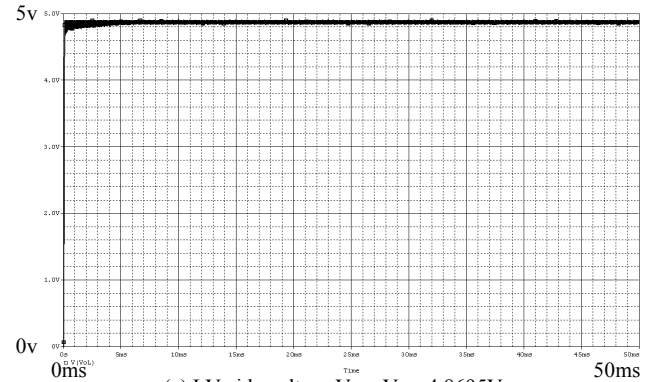


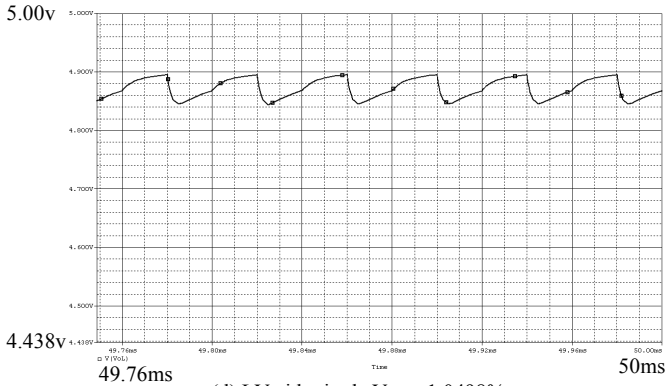
(a) HV-side voltage V_{OH}=41.74V.



(b) HV-side ripple V_{RPH}=0.0239%.

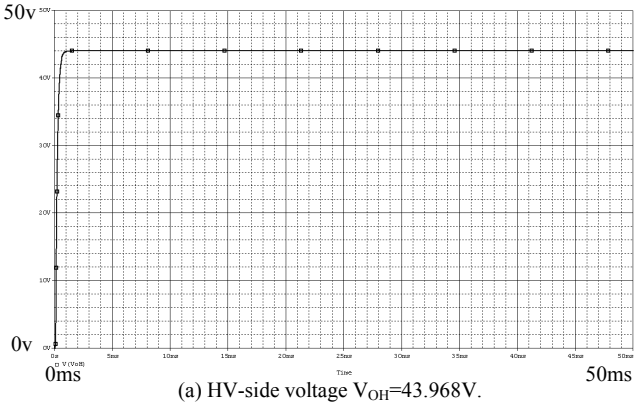


(c) LV-side voltage V_{OL}=V_{SL}=4.8695V.

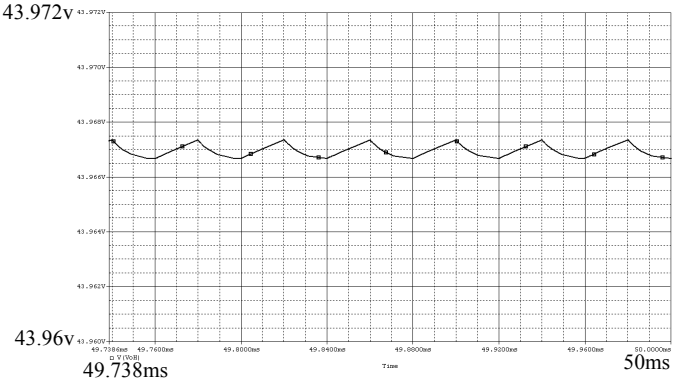


(d) LV-side ripple V_{RPL}=1.0498%.

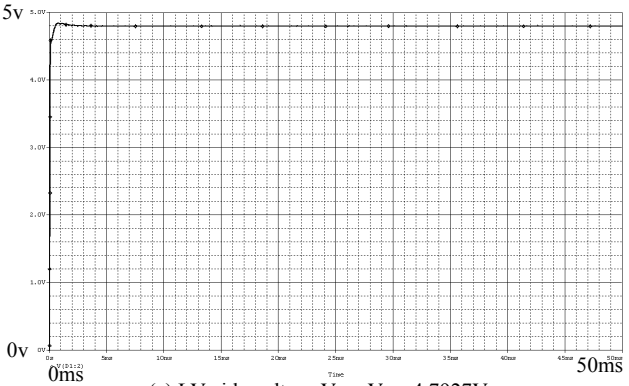
Fig. 6(a)-(d). HSCB DC-DC converter in Step-up mode.



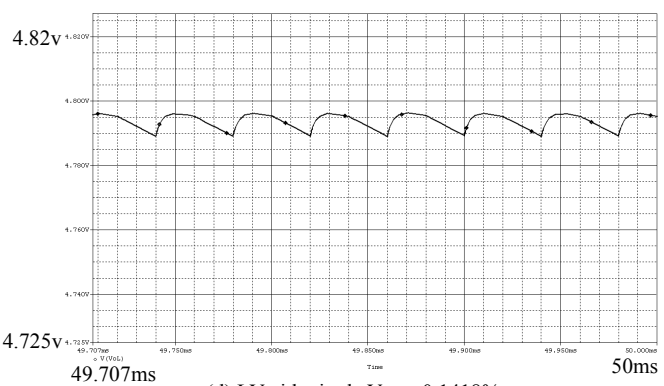
(a) HV-side voltage V_{OH}=43.968V.



(b) HV-side ripple V_{RPH}=0.0023%.



(c) LV-side voltage V_{OL}=V_{SL}=4.7927V.



(d) LV-side ripple V_{RPL}=0.1418%.

Fig. 7(a)-(d). HSCB DC-DC converter in Step-down mode.

made in circuit layout, and simulated by OrCAD Spice. The results are illustrated to verify the efficacy of the proposed HSCB converter. Here, all component parameters of the converter are listed in Table II. This converter is preparing to supply the loads R_{LH}=600Ω at HV side and R_{LL}=600Ω at LV side. For checking closed-loop performances, some topics will be simulated and discussed, including: voltage step-up/ down conversion and output ripple percentage.

1) Step-up simulation:

The HSCB converter is operated at V_{SL}=4.9V, V_{REFL}= 4.9V (LV side) and V_{SH}=40V, V_{REFH}=42V (HV side). It is clear that this converter is running in step-up mode because $V_{SH} < V_{REFH}$, and $V_{SL} \geq V_{REFL}$. The voltage and ripple waveforms of HV/LV sides are obtained as shown in Fig. 6(a)-(d), respectively. In Fig. 6(a), it can be found that the settling time is smaller than 10 *ms*, and the

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TABLE II
HSCB CIRCUIT PARAMETERS

HV source voltage (V_{SH})	42V, 44V
LV source voltage (V_{SL})	4.9V, 4.6V
pumping capacitors (C_{A11}~C_{A13}, C_{A21}~ C_{A23})	200uF
HV/LV capacitor (C_{HV}, C_{LV})	350uF
Resistance of capacitor (r)	35mΩ
MOSFET switches of HSCB (S_{A11}~S_{A16}, S_{A21}~S_{A26})	Power CMOS transmission gates
Channel resistance	0.05mΩ
Operation frequency of ϕ1and ϕ2	25KHz
Load resistance (R_{LH}, R_{LL})	600Ω

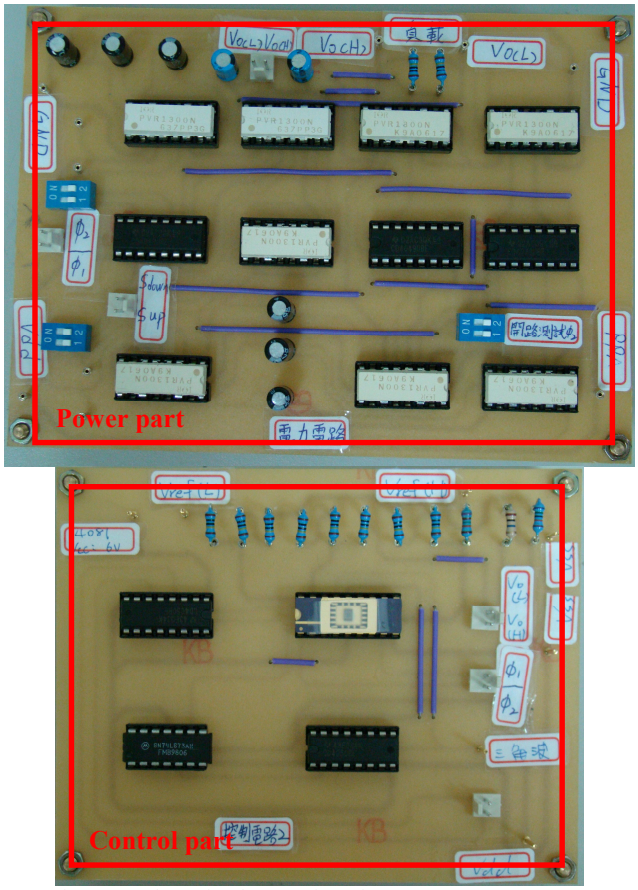

Fig. 8. Hardware implementation of HSCB DC-DC converter.

steady-state value of V_{OH} is really reaching 41.74V, and V_{SH} is following V_{REFH} now. In Fig. 6(b), the HV-side ripple percentage can be easily found as V_{RPH}= $\Delta V_{OH}/V_{OH}$=0.0239%. In Fig. 6(c), the LV-side voltage is V_{OL}=V_{SL}=4.8695V. In Fig. 6(d), the LV-side ripple is V_{RPL}=1.0498%. These results show that the converter has a pretty good steady-state performance in step-up mode, Obviously, when the HV-side source voltage is not enough to supply the HV-side loading, this HSCB converter can not only transfer the power from LV side to HV side, but also keep the HV-side output V_{OH} following the reference V_{REFH} via the HV-side PWM controller.

2) Step-down simulation:

The HSCB converter is operated at V_{SL}=4.6V, V_{REFL}= 4.8V (LV side) and V_{SH}=44V, V_{REFH}=44V (HV side). It is clear that this converter is mainly running in step-down mode, because $V_{SH} \geq V_{REFH}$, and $V_{SL} < V_{REFL}$. The voltage and ripple waveforms of HV/LV sides are obtained as shown in Fig. 7(a)-(d), respectively. In Fig. 7(a), the HV-side voltage is V_{OH}=V_{SH}=43.968V. In Fig. 7(b), the HV-side ripple is V_{RPH}=0.0023%. In Fig. 7(c), it can be found that the settling time is smaller than 5 *ms*, and the steady-state value of V_{OL} is really reaching 4.7927V, and V_{SL} is following V_{REFL} now. In Fig. 7(d), the HL-side ripple percentage can be easily found as V_{RPH}=$\Delta V_{OH}/V_{OH}$=0.1418%. These results show that the converter has a pretty good steady-state performance in step-down mode, Obviously, when the LV-side source voltage is not enough to supply the LV-side loading, this HSCB converter can not only transfer the power from HV side to LV side, but also keep the LV-side output V_{OL} following the reference V_{REFL} via the LV-side PWM controller.

IV. CONCLUSION

A closed-loop scheme of high-conversion-ratio switched-capacitor bidirectional DC-DC converter is proposed based on pulse-width-modulation control for step-up/down conversion and bidirectional power flow. The advantages of the proposed scheme are as: 1) The SC converter does not require any inductive element, so the I.C. fabrication is promising for realization. 2) This HSCB needs just 6 pumping capacitors to boost the HV-side voltage up to 3×3 times voltage of the LV-side supply at most (step-up mode), or convert the LV-side voltage into 1/(3×3) times voltage of the HV-side supply (step-down mode). 3) The PWM technique is adopted in order to enhance the output regulation for the different desired output, and future as well as robustness to source/loading variation. At present, we have implemented the hardware of HSCB DC-DC converter as shown the photo of Fig. 8. Next, some more experimental results will be obtained and measured for the verification of our HSCB DC-DC bidirectional converter.

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