Bidirectional Power Conversion of Isolated Switched-Capacitor Topology for Photovoltaic Differential Power Processors

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Abstract

Differential power processing (DPP) systems are among the most effective architectures for photovoltaic (PV) power systems because they are highly efficient as a result of their distributed local maximum power point tracking ability, which allows the fractional processing of the total generated power. However, DPP systems require a high-efficiency, high step-up/down bidirectional converter with broad operating ranges and galvanic isolation. This study proposes a single, magnetic, high-efficiency, high step-up/down bidirectional DC–DC converter. The proposed converter is composed of a bidirectional flyback and a bidirectional isolated switched-capacitor cell, which are competitively cheap. The output terminals of the flyback converter and switched-capacitor cell are connected in series to obtain the voltage step-up. In the reverse power flow, the converter reciprocally operates with high efficiency across a broad operating range because it uses hard switching instead of soft switching. The proposed topology achieves a genuine on–off interleaved energy transfer at the transformer core and windings, thus providing an excellent utilization ratio. The dynamic characteristics of the converter are analyzed for the controller design. Finally, a 240 W hardware prototype is constructed to demonstrate the operation of the bidirectional converter under a current feedback control loop. To improve the efficiency of a PV system, the maximum power point tracking method is applied to the proposed converter.

Key words: Bidirectional converter, Differential power processor, Integrated inductor, Interleaved energy transfer

I. INTRODUCTION

Renewable energy resources are a promising solution to the future energy crisis and climate change. However, solar energy, one of the most promising energy sources, exhibits a fluctuating power generation profile because its generation is dependent on external environmental factors, such as temperature and radiation. A power conditioning converter is necessary in achieving a stable power generation with maximum energy efficiency. Differential power processing (DPP) converters are regarded as a novel architecture of next-generation power conditioning systems for the individual maximum power point tracking (MPPT) of multiple photovoltaic (PV) modules through a bidirectional power flow. Individual MPPT controllers for PV modules provide high MPPT efficiency even under partial shading. DPP [1] is an alternative power conversion method that passes most of PV-generated power directly to the next inverter, processing only the partially shaded mismatch to achieve local MPP with small capacity converters. Various converter topologies have been proposed for DPP architecture; examples include DPP converters, PV balancers, and PV equalizers [1]-[5]. Figure 1 shows an example of the PV-to-bus DPP architecture. A relatively high efficiency can be achieved because the converters only process the PV power necessary to compensate for the differences associated with the power generation mismatch among modules [6]. The PV-to-bus DPP architecture is considered an ideal converter architecture for distributed power sources, such as rooftop and building-integrated PV modules.

However, the high performance of DPP schemes requires the installation of distributed power converters for every PV module, as shown in the figure. Therefore, the manufacturing costs of these schemes proportionally increase with the number of PV modules. This characteristic hinders the wide use of distributed PV power systems. Converters have an
intermediate connection between the individual PV modules and DC links; hence, the voltage gain should be extreme. Moreover, converters should be isolated because of the ground difference among DPP converters. Converters also require a circuit topology to achieve a high efficiency and low manufacturing cost while satisfying extreme conditions. To reduce costs for the DPP scheme, the research on topology and control parts must be coordinated efficiently.

As conventional bidirectional buck-boost converters should achieve an extremely high duty cycle to obtain the input–output voltage gain, the power stresses of switches and diodes are increased significantly, followed by an increase in the switching losses caused by reverse recovery characteristics [7]-[9]. This condition results in the need for a new topology that operates under a lower voltage or current stress in comparison with existing topologies for bidirectional voltage step-up and down operations. The current work aims to find a high-efficiency, low-cost bidirectional converter topology with isolation that provides extreme voltage ratios for PV differential power processors.

Conventional research has put forward bidirectional topologies with high efficiency using soft-switching or multi-module parallel operations [10]-[16]. However, these power converters belong to non-isolated, bidirectional circuit topologies. A recent paper, which utilized zero-voltage transition and a bidirectional buck-boost topology to achieve 97% efficiency, is unsuitable for ground separation [17]. A comparative study shows current advancements in non-isolation bi-directional topologies [18]. Several high-power topologies have also been reported for isolated bidirectional applications. A combination scheme using two full-bridge converters with nine power switches has been proposed, but such scheme is unsuitable for small power applications of DPP [19]. Another bidirectional, isolated, full-bridge DC–DC converter also comprises nine power switches and two transformers, but it is too complicated for practical applications [20]. A recent achievement shows an almost optimal design comprising SiC devices for efficiency purposes, but such design require a large number of components [21].

High step-up and high efficiency requirements have also been addressed using a novel naturally clamped zero-current commutated soft-switching bidirectional current-fed full-bridge isolated DC–DC converter [22]. However, this combination scheme also comprises two full-bridge converters and eight additional power switches. Most isolated bidirectional power flow converter topologies are designed for high power applications. A recently presented bidirectional topology for multiple energy storage has one (extendable) bidirectional output, whereas another topology shows an auxiliary unidirectional output [23]. The topology remains complicated with four active switches and two magnetic devices under 10 step-up modes and 9 step-down modes satisfying the soft-switching condition, which is unsuitable for multiple-DPP architecture. Another topology for battery–DC bus applications employs a bidirectional push-pull structure with four switches and three magnetic devices under soft-switching conditions, but it only has 10 operating modes, which limit its operating range [24].

The present study proposes a simply structured bi-directional converter topology composed of a bidirectional flyback and an isolated switched-capacitor cell. In step-up mode, the output voltages of the flyback and switched-capacitor are connected in series to obtain a high gain with a high conversion efficiency even under hard-switching mode. These features broaden the operating range of the proposed topology. In step-down mode, the converter naturally undergoes an extremely low voltage step-down operation through a reciprocal operation. In addition, this converter is simple to implement under high power density with continuous energy transfer from a primary transformer to a secondary one via the ultimate interleaved operation between the flyback and switched-capacitor outputs both in the transformer core and primary and secondary copper windings. Furthermore, the converter has two operating modes under hard-switching conditions. Such characteristic contributes to a broad range of operation and simple control of bidirectional power flow. A detailed description of the operating principles and a dynamic characteristic analysis of the proposed converter topology are presented in the following sections.

II. BIDIRECTIONAL ISOLATED SWITCHED-CAPACITOR FLYBACK (BISCF) CONVERTER

A. Bidirectional Isolated Switched-Capacitor Cell

In realizing a high step-up for the input voltage, a charge pump circuit or a switched capacitor is commonly considered. Recently, an isolated switched-capacitor circuit was
presented in [7], but the charge–pump circuit could only operate under a unidirectional power flow and not under a bidirectional one. To rectify this disadvantage, a modified switched-capacitor circuit with a synchronous rectifier is introduced (Fig. 2). The circuit diagram is similar to that of a conventional bidirectional flyback converter. However, the dot of the transformer is on the other side, which critically determines the operation principle [7]. The circuit achieves high step-up/step-down ratios, as well as isolation capability, through the use of a high turn-ratio transformer. If the transformer is ideal, its operating performance is similar to that of conventional switched capacitors, except the voltage conversion ratios can be continuously changed according to the winding number.

**B. Proposed BISCF Converter Topology**

A prototype circuit of the proposed bidirectional converter is shown in Fig. 3(a). The secondary side of the transformer comprises an isolated switched capacitor and a bidirectional flyback converter employing two active switches. The cell and converter outputs are connected in series to interface with the high DC-link voltage. The proposed converters deliver the required energy to the load through the transformer core(s) whenever the main switch is turned on and off. Hence, more power is supplied to the load than any other single-ended isolation schemes at the same volume [25]-[29]. However, as secondary windings remain separate from one another, the converter is not a circuit version of a genuine interleaved power transfer. The topology is thus improved by sharing the secondary coils between the outputs of the switched capacitor and those of the flyback (Fig. 3(b)). One secondary winding $N_{s2}$ is utilized during on and off states to improve the utilization ratio of the transformer. The details of the operating modes are described in Section II.C.

To analyze the steady-state operation of the proposed converter, we present the DC-link voltage as separate equivalent circuits (Fig. 4).

The steady-state gain of the isolated switched-capacitor cell is only related to the transformer’s turn ratio such that

$$M_{VDC,sc} = \frac{V_{DC,sc}}{V_{pp}} = \frac{N_{s2}}{N_p}$$

The steady-state gain of the flyback under continuous conduction mode is

Finally, the gain of the BISCF converter under continuous conduction mode is

$$M_{VDC, fb} = M_{VDC,sc} + M_{VDC,fb} = \frac{N_{s2}}{N_p} + \frac{D}{1-D} \frac{N_{s1} + N_{s2}}{N_p}$$

**C. Operating Principle**

The proposed converter topology under the step-up/step-down modes has two operating modes (power flow opposite for each mode), as shown in Fig. 5. Each mode has a different switching state. This simple principle contributes to the simple controller design and wide operating ranges.

Mode 1: $Q_p$ and $Q_{sc}$ are turned on. The path of the current conduction is shown as a solid line in Fig. 5(a). $Q_{sc}$ operates as a synchronous rectifier with a small conduction loss and conduction path $N_{s2}$.

Mode 2: $Q_{fb}$ is turned on. The path of the current conduction is shown as a solid line in Fig. 5(b). $Q_{fb}$ operates as a synchronous rectifier with a small conduction loss and conduction path $N_{s2}$.

The step-down operation is exactly the same as the step-up
operation shown in Fig. 5, except that the direction of the average inductor current is reversed by the duty-cycle transient and the actions of the main switches and synchronous rectifiers are swapped, as in a conventional bidirectional buck-boost converter. Fig. 6 shows the pulse width modulation (PWM) operation of the switches and the detailed description of the operating principles, along with the key waveforms of the proposed converter. Fig. 7 also presents the primary and secondary switch current waveforms under the step-down mode.

D. Device Stress Analysis and Design Guidelines

This section analyzes the device stress for the proposed converter. A design example of the specification of the input and output voltage/power, such as 50 V and 400 V/200 W, is shown.

The switch voltage stresses are

\[ V_{pk} = V_{pp} + \left( \frac{N_p}{N_{s1}+N_{s2}} \right) V_{DC,fb} = 90 \text{ V} \]  
(4)

\[ V_{pk-sc} = \frac{N_{s2}}{N_{s1}+N_{s2}} V_{DC,fb} + V_{DC,sc} = 360 \text{ V} \]  
(5)

\[ V_{pk-fb} = V_{pp} \left( \frac{N_{s1}+N_{s2}}{N_p} \right) + V_{DC,fb} = 450 \text{ V} \]  
(6)

where \( V_{pk}, V_{pk-sc}, \) and \( V_{pk-fb} \) are the respective voltage stresses of the main switch, switched capacitor, and flyback switch.

The switch current stresses are

\[ I_{sw-avg} = N_{VT} I_o \left( \frac{N_{s2}}{N_p} \right) \left( \frac{D}{1-D} \right) \left( \frac{N_{s1}+N_{s2}}{N_p} \right) = 4 \text{ A} \]  
(7)

\[ I_{sc-avg} = I_o = 0.5 \text{ A} \]  
(8)

\[ I_{fb-avg} = I_o = 0.5 \text{ A} \]  
(9)

where \( I_{sw-avg}, I_{sc-avg}, \) and \( I_{fb-avg} \) are the average current stresses for the main switch, switched capacitor, and flyback switch, respectively. The turn ratios should be considered to
satisfy the reasonable duty-cycle ranges, such as 0.2–0.8, under the input and output voltage variations. The analysis results show that the number of device parts for the main and secondary switches affects the stresses.

The transformer winding numbers are determined with the conventional magnetic design equation and the required turn ratios such that

\[
\frac{N_p}{B_{\text{max}}/\mu} = \frac{10^{4} \cdot 50 \cdot 0.3}{0.3 (2.47)} = 8.1 \tag{10}
\]

where \(B_{\text{max}}\) is the maximum allowable magnetic flux density, \(L\) is the magnetizing inductance, \(I_{\text{pk}}\) is the peak current, and \(A_e\) is the effective area of the core. The current stress of each winding is the same as that of the corresponding switch in the conduction path (Fig. 5). The present study uses a highly coupled coaxial-cabled transformer to reduce leakage inductances.

III. Dynamic Characteristic Analysis

A. Control Configuration

Fig. 8 shows the structure of the proposed non-isolated DC–DC circuit diagram of the proposed converter under MPPT control. For the perturb-and-observe algorithm in the MPPT controller, the PV voltage and current from each module are observed. The MPPT controller then updates the proportional–integral (PI) controller reference \(V_{\text{ref}}\) given to the inner loop controller. Hence, the duty cycles of the converter are generated through the inner voltage feedback loop. To show the current regulation capability of the proposed converter topology, we implement a bidirectional current control loop that is independent from the MPPT controller. Fig. 9 shows the bidirectional power flow control configuration of the proposed converter. The PI controller in a current feedback loop senses a switching current \(I_{\text{pv}}\) or \(I_{\text{sw}}\) from the primary side, produces a control voltage comparable to the reference, and then makes the duty cycle through the PWM generator. The PI controller reference \(I_{\text{ref}}\) in Fig. 9 is given by a controller that provides a step-changed bipolar signal to show the bidirectional power flow operation. The experimental results are given in Section IV.

B. Small Signal Models of the BISFC

When the controller of the proposed converter is designed for MPPT, the control-to-PV voltage transfer function must be derived. The switched-capacitor cell is considered a proportional gain in the transfer function derivation because
Fig. 10. Small-signal parameters for the control-to-PV voltage transfer function (Zcc is the interaction from the other PV modules).

Fig. 11. Small-signal parameters for the control-to-current transfer function.

of the rapid dynamic response. The major concern is the dynamic characteristic of the flyback converter part (Fig. 10).

The control-to-PV-voltage transfer function is derived as

\[
\frac{\Delta V_{PV}}{\Delta I_{PV}} = \frac{-sL_L + nDV_{PV} + DV_{DC,FB} + nZ_T R_L I_L}{Z_T^2} + \frac{Z_T D^2 + nZ_T D' - R_L}{Z_T L_m C_{pp}}
\]

\[\text{(n = } N_{s1} + N_{s2})\]  

(11)

where \( Z_T = R_{sa} || Z_{cc} \), \( R_L \) is the parasitic resistance of the primary winding, \( R_{sa} \) is the equivalent output resistance of the PV sources, and \( Z_{cc} \) is the equivalent input resistance of the main string converter and other modules.

When the current controller is designed for power flow regulation, the control-to-input (DPP) current \( I_{dpp} \) is derived by the state-space averaging of Fig. 11. Analysis shows that the transfer function of the control-to-DPP current is derived as follows.

From \( I_{dpp} = I_{sa} - I_{cc} \), the result is

\[
\frac{\Delta I_{dpp}}{\Delta I_{PV}} = \frac{\Delta I_{sa}}{\Delta I_{PV}} - \frac{\Delta I_{cc}}{\Delta I_{PV}}.
\]

Then, from Fig. 10,

\[
\frac{\Delta I_{dpp}}{\Delta I_{PV}} = \frac{V_{PV}}{R_{sa} Z_{cc}} - \frac{V_{PV}}{Z_{cc}} = \frac{1}{R_{sa}} - \frac{1}{Z_{cc}}
\]

(13)

The final form can be derived by merging (13) with (11).

C. Simulation Results of MPPT Control and Bidirectional Power Flow

Fig. 12 shows the simulated PV voltage and current waveforms under the proposed MPPT controller. The MPP voltage is 45 V, which indicates that the controller tracks MPP well using the perturb-and-observe algorithm.

To verify the current regulation, we check the transient response of the 1A bipolar step-change in the DPP current. The switch current in Fig. 13 shows that the bidirectional power flow is regulated, as confirmed in Fig. 18.

IV. EXPERIMENTAL RESULTS

A hardware prototype of the proposed scheme was built and tested according to the design parameters in Table I. Fig. 14(a) illustrates the hardware efficiency of the proposed converter in accordance with the input voltage variation in step-up mode. The results show that the proposed converter achieves a maximum efficiency of 96%. The input voltage from 30 V to 48 V maintains efficiency at over 94% because of the simple operating principle. Fig. 14(b) also shows the measured efficiency according to the secondary voltage variation in step-down mode. The experimental results show that the proposed converter is 96% efficient, even at the maximum voltage of 460 V. Fig. 14(c) also shows the measured efficiency according to power variation. The proposed converter is over 96.2% efficient at maximum, and
TABLE I
DIODES AND MOSFET UTILIZED IN THE CSFTI HARDWARE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Parameter (part number)</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_{pv}$</td>
<td>PV voltage</td>
<td>30–48VDC</td>
</tr>
<tr>
<td>$V_{dc\text{-link}}$</td>
<td>DC-link voltage</td>
<td>340–460 VDC</td>
</tr>
<tr>
<td>$P_{out}$</td>
<td>Output power</td>
<td>240 W</td>
</tr>
<tr>
<td>$f_s$</td>
<td>Switching frequency</td>
<td>44 kHz</td>
</tr>
<tr>
<td>$L_m$</td>
<td>Magnetizing inductance</td>
<td>50 µH</td>
</tr>
<tr>
<td>$Q_p$</td>
<td>Primary switch</td>
<td>IRFP4568</td>
</tr>
<tr>
<td>$Q_{sc}$</td>
<td>Secondary switched capacitor switch</td>
<td>IRFP21N60L</td>
</tr>
<tr>
<td>$Q_{fb}$</td>
<td>Secondary flyback switch</td>
<td>IRFP21N60L</td>
</tr>
<tr>
<td>$N_p$ : $N_{s1}$ : $N_{s2}$</td>
<td>Turn ratio</td>
<td>1 : 1 : 4</td>
</tr>
<tr>
<td>$C_{sa}$</td>
<td>PV module capacitor</td>
<td>4700 µF</td>
</tr>
<tr>
<td>$D_p$</td>
<td>Primary anti-parallel diode</td>
<td>MBR10250</td>
</tr>
<tr>
<td>$D_{fb}$</td>
<td>Flyback anti-parallel diode</td>
<td>SF18</td>
</tr>
<tr>
<td>$D_{sc}$</td>
<td>Switched capacitor anti-parallel diode</td>
<td>SF18</td>
</tr>
</tbody>
</table>

the overall efficiency remains over 95% at an output of 100 W to 240 W.

The temperature distribution measurements of the hardware prototypes for topology validation are presented in Figs. 15(a) and (b). The temperature distributions of the proposed hardware show identical operating conditions, with the exception of the varying input voltage. Temperature distributions were measured with a DM-60 thermal imaging camera [30–33]. The experiment was conducted at ambient temperature, and the MOSFETs operated without any heat sinking devices. The main heat sources, such as the transformer winding (S1), core (S4), primary switch (S2), and secondary flyback switch (S3), are indicated in the figure.

The temperatures of the secondary MOSFETs are not significantly different, thus indicating that the loss changes in the secondary MOSFETs are minimal despite the voltage gain. The temperature of the main switch increases from 50.4°C to 70.1°C, whereas the primary winding temperature of the transformer increases from 38.7°C to 46.4°C. The primary switch and winding loss component are dominant factors in the efficiency variation depicted in Fig. 14. Moreover, the proposed topology effectively reduces severe power stress in extreme step-up-isolated applications.

Fig. 16 shows the PWM switching waveforms of the MOSFETs in the hardware, which are consistent with the simulation results in Fig. 6. The drain-source voltages have negligible voltage spikes even without a snubber circuit because of the high coupling of the coaxial-cabled transformer. Fig. 17 shows the experimental PV voltage and current waveforms under the MPPT controller. A dual PV-array simulator was used (TerraSAS) to emulate the PV panel.

Fig. 17(a) shows the V-I and V-P curves of the panel in the

(a) Step-up mode ($V_{dc\text{-link}} = 400$ V, $P_{out} = 200$ W).
(b) Step-down mode ($V_{pv} = 45$ V, $P_{out} = 200$ W).
(c) Power variation ($V_{pv} = 45$ V, $V_{dc\text{-link}} = 400$ V).

Fig. 14. Prototype efficiency of the proposed converter.

Fig. 15. Comparison of the thermal distributions of the hardware prototypes ($V_{out} = 400$V), with the MOSFETs operating without a heat sink.

(a) $V_{in} = 36$ V.
(b) $V_{in} = 46$ V.
Fig. 16. $V_{ds}$, $V_{ds_fb}$, and $V_{ds_{sc}}$ of the proposed converter in the hardware experiment (Channel 1: drain-source voltage of main switch [50 V/div.], Channel 2: flyback drain-source voltage [200 V/div.], Channel 3: switched-capacitor drain-source voltage [200 V/div.], time: 10 µs/div.)

Fig. 17. MPPT control of the proposed converter in the hardware experiment (Channel 1: solar panel voltage [20 V/div.], Channel 2: solar panel current [2 A/div.], time: 1 s/div.); the rightmost bar in the upper figure refers to the current operating MPPT efficiency.

MPPT control test. The MPP is 45 V. Thus, Fig. 17(b) shows that the controller tracks MPP well because of the PV voltage operating near the MPP.

The input current ($I_{dpp}$) waveform was measured with the bipolar 1A step-change of the reference to validate the bidirectional operation of the proposed topology. Fig. 18 shows that the bidirectional power flow is regulated well, even with step responses. Fig. 19 shows the switch current waveforms of the hardware prototype. Fig. 19(a) is the primary switch current in step-up mode, whereas Fig. 19(b) is the current in step-down mode. The plateau and ringing, unlike $I_{sw}$ in Fig. 7(b), are caused by the leakage inductance of the layout and transformer resulting from the absence of snubber circuitry.
V. CONCLUSIONS

This study proposed a low-cost, high-efficiency, bidirectional DC–DC power conversion circuit topology comprising of an isolated-type switched-capacitor cell and a flyback converter. The proposed topology is suitable for step-up and step-down voltage gains for DPP PV conditioning systems. Extreme step-up/step-down ratios were achieved by connecting the output terminals of the bidirectional flyback converter and the isolated bidirectional switched-capacitor converter in series. The topology structure is highly efficient, even with hard-switching action, under a broad range of operations.

The operating principle of the BISCF converter was presented with an analysis of the operating mode. Hardware experiments with a 240 W converter verified that the proposed converter could operate well in MPPT mode and bidirectional power-flow regulation mode. Moreover, the proposed converter achieves an efficiency of over 95%, even with a broad input voltage and output power variation under 400 V output operating conditions. The topology comprises only a few parts and is thus competitively affordable. The main switch should be carefully selected, as high power devices are often expensive.

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