A battery integrated multiple input DC-DC boost converter

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ABSTRACT
In this paper, the proposed single boost converter aims to harness more than one renewable energy (RE) input source and achieve a high voltage gain. The interleaved technique combined with voltage multiplier (VM) cells, reduced inductor current and attained high voltage transfer ratio. The boost converter possesses two unidirectional input ports and a bidirectional input port that is connected to a battery storage. The duty ratios of the power and interleaving switches are used to regulate the output voltage of the proposed converter. Three operation modes are identified, and steady state analyses of the converter are presented and discussed. The converter can store excess energy in the battery during periods of abundance and deliver power to the loads when the RE sources are low or unavailable. In addition, the output voltage is higher than that of the conventional boost converter. The converter delivered 278 V from 12 V and 24 V dual input sources. The converter operation is simulated and verified using MATLAB/Simulink.

Keywords:
DC-DC converter
Interleaved
Multiple input
Renewable energy
Voltage multiplier

1. INTRODUCTION
Environmental degradation and predicted depletion of fossil fuels have been a source of concern about employing sustainable and clean energy sources for power generation. The quest for clean energy resources extends to the transportation sector [1]. Electric cars are expected to summarily replace gasoline or diesel-powered cars soon as a way to mitigate environmental pollution [2]. Recently, renewable energy (RE) sources like fuel cells (FC), wind turbines and photovoltaic (PV) cell have been utilized in hybrid electric vehicles [3], microgrids [4], traffic lights [5], or telecommunication/satellite systems [6].

The RE sources fall short in performance due to occasional unavailability, low output voltage levels, and limited slew rates [7]. The limited slew rate is common with FC and some storage devices like supercapacitors and batteries. An example of the stochastic nature of RE sources is the inability of PV cells to deliver at night or during low irradiance [8]. Other examples are wind turbines and hydrokinetic turbines that may experience insufficient wind speed and low water velocity respectively.

An approach to solving the problems of irregularity and slew rate posed by RE sources is to combine two or more of these energy sources to deliver regulated output to the load. Traditionally, separate DC-DC converters have been used for each RE source with outputs connected to a common DC bus [9]. This configuration is bulky and expensive with complex communication control requirements. Contemporary multiple input converters have advantages of reduced size, easier control and lower number of components thereby being cheaper [10]. A group of RE sources serving a load via a single multiple input converter. In this case, the respective RE sources are routed to the multiple input converter [11]. This converter can
process and regulate the source voltages thus delivering power to the load. In this way, the restrictions posed by the traditional multiple input converter are successfully eliminated.

General methods of synthesizing non-isolated multi-input converters (MICs) have been proposed [12], [13]. Liu and Chen [12] used an approach based on using appropriate connections to add extra pulsating voltage or current source to the pulse width modulation (PWM) converter. Li et al. [14] developed a set of rules based on the breakdown of the prime converter pulsating current source cells (PCSC). These rules lead to two families of MICs. The low voltage gains of the converters proposed in these papers imply their poor performance in systems that require high voltage.

A multi input switched capacitor based converter is introduced [15]. This topology eliminates the need for the inductor. The energy transfer is done by the capacitors and switches. This configuration suffers from high output ripple and output leakage voltage. Coupled inductor have been used to achieve high gain in [16], [17]. The coupled inductors suffer from some leakage inductance. High voltage gain has been achieved by using voltage multiplier (VM) cells [18]. The VM stages are positioned after a primary boost converter. The design lacks a bidirectional function for a storage element. The large number of passive components result in the high dissipation loss.

A modular non-coupled inductor based bidirectional multi input converter is proposed [19]. Several SISO converters with non-coupled inductors can share a common filter and bidirectional switch. The non-coupled converters are positioned in an interleaved structure. Reduced normalized voltage stress and very high voltage gain are the advantages of this converter. However, the aim of sharing components is not achieved. The driving circuits for control imply are complex. In addition, the component count increases with the addition of an extra input source.

The modified single-ended primary-inductor converter (SEPIC) converter [20] has a third energy storage input. In this converter, the input sources can charge the battery and at the same time, deliver power to the load in one operation mode. The battery can also complement the input sources when there is insufficient power to the load. The major weakness of this converter is the low voltage gain. The three input DC-DC converter has been adapted for PV, fuel cell and battery inputs [21], [22]. There are two unidirectional ports and one bidirectional port. The duty rations of switches are used to control the converter to give power to the load, and charge or discharge the battery simultaneously or individually. The voltage gain is slightly more when compared to conventional converters. There is a high number of passive elements. This reduces efficiency due to dissipation loss.

A dual input interleaved converter was proposed [23]. High efficiency is achieved by implementing zero voltage switching (ZVS) through an auxiliary circuit. Low voltage gain and high number of power switches stand as disadvantages to this converter. Another interleaved topology has two inputs, one PV source and a battery storage [24]. The converter can be extended to multiple outputs by using parallel switches. Although there is a bidirectional port, the voltage gain of the converter is low, and it cannot accommodate more than one RE source. A multiple input multi-level output converter was proposed in [25]. The simple configuration boasts of low number of passive elements and high voltage gain. However, this converter has an unusually high number of switches. This short coming has been tackled by inserting diodes in [26] thereby achieving lower switch count.

In this paper, a battery integrated interleaved multiple input DC-DC boost converter is proposed. The state of the art presented so far shows that there is need to accommodate more RE sources as well as achieve higher output voltage. The proposed converter can interface two RE sources and an energy storage device. The converter can reduce the inductor current as well as delivering a high step up to the input voltage. This paper is organized as follows. The first section provides the background and literature review. The second section presents the proposed converter, operation modes and circuit analysis. Simulation results and comparisons are presented and discussed in the third section. Conclusions are drawn in the fourth section.

2. CONVERTER TOPOLOGY

In this section, the proposed converter topology is introduced along with the operation modes and circuit analysis. The proposed structure is presented in Figure 1. Three distinct sections of the converter can be identified. The input section, interleaving section and the VM section. The input section has three input sources, $V_1$, $V_2$ and $V_6$. $V_1$ and $V_2$ are unidirectional ports. $V_6$ is a bidirectional port hence it is ideal for connection to a storage element. The converter has $n + 3$ power switches. A pulsating voltage source cell (PVSC) is formed by $V_1$, switch $S_1$ and diode $D_1$. Two additional PVSCs are formed by $V_2$, $S_2$, $D_2$ and $V_6$, $S_3$, $D_3$ respectively. Control of the unidirectional ports $V_1$ and $V_2$ can be done by manipulating the duty ratios, $d_1$ and $d_2$, of switches $S_1$ and $S_2$. Switches $S_3$ and $S_4$ facilitates the bidirectional capability of $V_6$. Battery discharging can be done by controlling the duty ratio $d_3$ of $S_3$ while the duty ratio $d_4$ of switch $S_4$ controlled the charging of the battery. In the interleaving section, inductors, $L_1$ and $L_2$, are connected in an interleaved
manner with switches $S_4$ and $S_6$. The VM section has a combined single stage of VM cell with capacitors $C_1$, $C_2$ and diodes $D_4-D_6$. $C_{out}$ and $D_{out}$ are the respective output capacitor and diode. $R_L$ is the load served by output voltage, $V_o$.

![Image](image_url)

Figure 1. Proposed battery integrated multiple input boost converter

2.1. Operation mode one

In this mode, the battery state of charge is optimal and the power of input sources $V_1$ and $V_2$ can sufficiently serve the load. During this operation mode, the battery neither charges nor discharges. This is the default operation mode. In this mode $S_3$ and $S_4$ are permanently turned off. The switching sequence in this operation mode is explained as follows:

a. Switching mode 1 $[0 < t < D_1 T]$; the circuit is represented in Figure 2(a). Switches $S_1$, $S_2$, $S_5$, and $S_6$ are turned on. Input source, the sum of $V_1$ and $V_2$ charges inductors $L_1$ and $L_2$. Diode $D_3$ is forward biased and all other diodes are reverse biased. Capacitors $C_1$ and $C_2$ are idle. $C_{out}$ delivers power to the load.

b. Switching mode 2 $[D_1 T < t < D_3 T]$; the circuit is illustrated in Figure 2(b). During this switching interval, switch $S_3$ continues conducting while $S_1$ is turned off. Only $V_2$ can deliver energy at this time. Similarly, interleaving switch $S_6$ is turned off and $S_3$ continues conducting. $D_6$ is forward biased. $L_1$ and $C_2$ charge capacitor $C_1$. $C_{out}$ serves the load.

c. Switching mode 3 $[D_3 T < t < D_5 T]$; the circuit is shown in Figure 2(c). $S_2$ is turned off and $S_4$ is turned on. $S_5$ and $S_6$ are turned on. $V_1$ charges $L_1$ and $L_2$. $C_1$ and $C_2$ are idle. $C_{out}$ services the load.

d. Switching mode 4 $[D_5 T < t < T]$; $S_1$ and $S_2$ are turned on. $S_5$ remains on. $S_6$ is turned off. $L_1$ continues charging by $V_1$ and $V_2$. $L_2$ and $C_1$ discharge to the load. $C_2$ is charging. Figure 2(d) depicts the circuit. Based on Figures 2(a)-(d) and applying the voltage-second balance principle on the inductors and the ampere-second balance principle on the capacitors, in (1)-(4) can be obtained.

\[
\begin{align*}
L_1: (V_1 + V_2)D_1 T + (V_2 + V_{c2} - V_{c1})(1 - D_3)T &= 0 \\
L_2: (V_1 + V_2)D_1 T + ((V_1 + V_2) + V_{c1} - V_0)(1 - D_3)T &= 0 \\
C_1: (iL_1 + iC_2)(D_2 - D_4)T - (iL_2 - i_0)(1 - D_3)T &= 0 \\
C_2: iL_2(1 - D_3)T - (iL_1 - i_{c1})(D_2 - D_4)T &= 0 \\
i_{batt} &= 0, P_{batt} = 0
\end{align*}
\]
2.2. Operation mode two

This operation mode occurs when the RE sources are incapable of servicing the load optimally. In this condition, the attached battery storage device, \( V_b \), steps in to augment the power delivery from the RE sources to the load. Switch \( S_3 \) plays the role of allowing or disallowing the battery to deliver power to the load. \( S_4 \) remains turned off during this operation mode. The respective switching modes are described as:

a. Switching mode 1 \([0 < t < D_1T]\): the circuit is represented in Figure 3(a). Switches \( S_1, S_2, S_3, S_5 \) and \( S_6 \) are turned on. Input sources, \( V_1, V_2 \) and \( V_b \) charge inductors \( L_1 \) and \( L_2 \). Capacitors \( C_1 \) and \( C_2 \) are idle and all diodes are reverse biased. \( C_{\text{out}} \) delivers power to the load.

b. Switching mode 2 \([D_1T < t < D_2T]\): this switching mode is the same as switching mode 2 of the first operation mode.

c. Switching mode 3 \([D_2T < t < D_3T]\): the circuit is shown in Figure 3(b). \( V_1 \) and \( V_b \) charge \( L_1 \) and \( L_2 \) though the conduction of the \( S_1, S_2 \) and \( S_5 \) and \( S_6 \) respectively. \( C_{\text{out}} \) serves the load.

d. Switching mode 4 \([D_3T < t < T]\): \( V_1, V_2 \) and \( V_b \) deliver power to the converter through \( S_1, S_2 \) and \( S_3 \) respectively. \( L_1 \) is charged through \( S_1 \). \( C_2 \) is charging and \( C_1 \) discharges. \( L_2 \) delivers power to the load. The circuit is illustrated in Figure 3(c).

By applying the voltage-second balance principle on the inductors, in (6)-(9) can be obtained. The ampere-second balance principle on the capacitors gives the same as in all operation modes. This is because the switching pattern exist for all conditions of the interleaving switches.

\[
\begin{align*}
L_1: (V_1 + V_2 + V_b)D_2T + (V_1 + V_2 + V_b)(1 - D_3)T &= 0 \\
L_2: (V_1 + V_2 + V_b)D_1T + ((V_1 + V_2 + V_b) + V_c - V_0)(1 - D_3)T &= 0 \\
in_{\text{batt}} &= (iL_1 + iL_2)(1 - D_3) \\
P_{\text{batt}} &= V_b(iL_1 + iL_2)(1 - D_3)
\end{align*}
\]
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2.3. Operation mode three

During this operation mode, the battery state of charge is depleted and the RE sources can service the load in addition to charging the battery. Switch $S_4$ plays the role of allowing charging current to the battery. $S_3$ remains turned off during this operation mode. The respective switching modes are described as:

a. Switching mode 1 [$0 < t < D1T$]: the switching mode is the same as the first switching mode of the first operation mode. Switch $S_4$ is turned off hence the battery is not charging.

b. Switching mode 2 [$D1T < t < D2T$]: $S_2$, $S_4$, and $S_6$ are turned on. $L_1$ is charged by $V_2$. The battery is charged from $L_2$ at this time. $C_2$ is charged through $D_6$ by $L_1$ and $C_1$. The output capacitor delivers power to the load. This is illustrated in Figure 4(a).

c. Switching mode 3 [$D2T < t < D3T$]: the circuit is shown in Figure 4(b). $S_1$, $S_4$, $S_5$, and $S_6$ are turned on. $L_1$, $L_2$ and $V_b$ are charged by $V_1$. The capacitors are idle. $D_5$-$D_6$ are reverse biased. Power is delivered to the load by the output capacitor, $C_{out}$.

d. Switching mode 4 [$D3T < t < T$]: $S_4$ is turned off. This switching mode is the same as the switching mode of the first operation mode. No charging current enters the battery.

The switching patterns and inductor waveforms for the first operation mode, second operation mode and third operation mode are presented in Figures 5(a)-(c) respectively. It reveals that the same switching pattern are maintained for the respective switches, $S_1$, $S_4$, $S_5$, and $S_6$ in all the operation modes. It is different for switches, $S_3$ and $S_4$ because they function only during battery charging and discharging operation as can be seen from Figure 5(b) and Figure 5(c). In compliance with the switching pattern, the inductor current $i_{L1}$ rises during the first three switching periods, $t_0$-$t_3$, and falls during the fourth switching period $t_3$-$t_4$. This is different for the current waveform of inductor $i_{L2}$ which rises in the first switching period, falls during the second switching period, and resumes rising during the third and fourth switching periods. By applying the voltage-second balance principle on the inductors, in (10)-(13) can be obtained.
\[ L_1: (V_1 + V_2)D_3T + (V_1 + V_2)(1 - D_3)T = 0 \]  
\[ L_2: (V_1 + V_2)D_1T + (V_1 + V_2 + V_c1 - V_o)(1 - D_3)T = 0 \]  
\[ i_{\text{batt}} = i_{L_2}(D_3 - D_1) \]  
\[ P_{\text{batt}} = V_b((D_2(D_3 - D_1)) \]  

Figure 4. Current paths for the third operation mode of proposed converter (a) switching mode 2 and (b) switching mode 3

Figure 5. Switching pattern and inductor current waveform for operation modes (a) operation mode one, (b) operation mode two, and (c) operation mode three

2.4 Converter analysis and design

In analysis of the steady-state obtained for the proposed converter, the voltage of the capacitors, \( C_1 \) and \( C_2 \) can be obtained. Based on the switching mode of the upper interleaving switch, \( S_5 \) in Figure 2(b), the capacitor voltages can be expressed as (14):

\[ V_{c1} - V_{c2} = \frac{V_2}{(1 - D_3)} \]  

\[ (14) \]
Referring to the circuit for the lower interleaving switch, \( S_6 \) in Figure 2(d), the voltage across the capacitor \( V_{c2} \) is (15) and (16):

\[
V_{c2} = \frac{V_1 + V_2}{1 - D_3}
\]  

(15)

\[
V_o - V_{c1} = \frac{V_1 + V_2}{1 - D_3}
\]  

(16)

Substituting the duty ratio of the interleaved switches, the voltage across the capacitor, \( V_{c1} \) can be derived as (17) and (18):

\[
V_{c1} = \frac{V_1 + 2V_2}{(1 - D_3)^2}
\]  

(17)

from (2),

\[
V_o = \frac{V_{c1} d_1}{1 - D_5}
\]  

(18)

Combining (17) and (18), and including the duty ratios of the respective voltage sources, the output voltage of the first operation mode is calculated by (19):

\[
V_o = \frac{V_1 d_1 + 2V_2 d_2}{(1 - D_{5,6})^3}
\]  

(19)

The output voltage of the second operation mode is given by (20):

\[
V_o = \frac{V_1 d_1 + 2V_2 d_2 + V_b d_3}{(1 - D_{5,6})^3}
\]  

(20)

where, \( D_{5,6} \) is the duty ratio of the interleaved switches, \( S_5 \) and \( S_6 \), \( d_1 \), \( d_2 \), and \( d_3 \) are the duty ratios of \( S_1 \), \( S_2 \), and \( S_3 \) respectively.

For component selection, the interleaved inductors have the same inductance. The inductance can be calculated by (21):

\[
L_1 = L_2 = \frac{V_{\text{total}} D_{5,6}}{f_{\text{sw}} \Delta i_L}
\]  

(21)

Where \( f_{\text{sw}} \) is the switching frequency; \( V_{\text{total}} \) is the sum of all input voltages; and \( \Delta i_L \) is the change in inductor current.

The design of the capacitors is dependent on the tolerable AC ripples for the respective capacitor voltages. Hence the capacitor value can be calculated by (22):

\[
C = \frac{I_c}{f_{\text{sw}} \Delta V}
\]  

(22)

3. RESULTS AND DISCUSSION

In this section, the parameter selection of the simulated converter will be presented. In addition, graphical illustrations of the results for specific operation modes and parameters will be presented and discussed. These will verify that the proposed converter meets the objective of accommodating more than one RE source alongside an energy storage device. In the latter part, some properties of proposed converter will be compared with other similar works. The properties to be compared include the number of input ports, bidirectional capability, number of semiconductor devices, and total number of components. Such comparisons will highlight the suitability of the proposed converter among other converters.

3.1. Simulation results

In a bid to confirm the compliance of the proposed converter with the discussed operation and characteristics, it has been simulated on the MATLAB/Simulink environment. The component sizes and other parameters are presented in Table 1. The values of the input voltages are 24 V, 12, and 12 V for \( V_1 \), \( V_2 \) and \( V_b \) respectively. The inductor value of 360 µH for each inductor are obtained using (19) with the desired current ripple. The switching frequency is 50 kHz. The duty ratio of the interleaving switches, \( S_5 \) and \( S_6 \) is 0.5 while
0.75 is used for the individual power switches, $S_1$ and $S_2$. In the first operating mode, the maximum input voltage delivered by $V_1$ and $V_2$ is 33 V. Figure 6 shows the state-of-charge (SOC) of the battery and the voltage levels of $V_1$ and $V_2$ during this operation mode. The battery SOC is 100% and does not deplete while $V_1$ and $V_2$ are 24 V and 12 V. The output voltage is 278 V with a load resistance of 500 Ω. The average values of the inductor currents, $i_{L1}$ and $i_{L2}$ are 5.1 A and 3.5 A respectively. The inductor current ripple, $\Delta i_L$ is set at 1 A.

The inductor currents are illustrated in Figure 7. It can be observed that $i_{L2}$ is higher than $i_{L1}$. This is because the number of VM is even and more current is drawn during the charging and discharging stages in $L_2$. Also, the waveforms of $i_{L2}$ and $i_{L1}$ appears inverted to relative to one another because there exists a phase delay between the switching signals. The voltage across the capacitors is shown in Figure 8. The maximum voltage across $V_{c1}$ is 192 V while that of $V_{c2}$ is 85.42 V. The voltage stress on the interleaving switches at 250 W is shown in Figure 9(a). The maximum voltage stress on $S_5$ and $S_6$ was 109.25 V and 86.82 V respectively. This brings to the fore, one advantage of VM cells being their ability to reduce voltage stress on the switch.

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input voltage</td>
<td>$V_1=24$ V, $V_2=12$ V, $V_b=12$ V</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>$F=50$ kHz</td>
</tr>
<tr>
<td>Load resistance</td>
<td>$R=500$ Ω</td>
</tr>
<tr>
<td>Duty ratio</td>
<td>$d_1, d_2, d_3=0.75$, $d_4, d_5, d_6=0.5$</td>
</tr>
<tr>
<td>Inductors</td>
<td>$L_1=L_2=360$ µH</td>
</tr>
<tr>
<td>Capacitors</td>
<td>$C_1=C_2=20$ µF, $C_{out}=220$ µF</td>
</tr>
</tbody>
</table>

Figure 6. Input voltage and battery SOC levels during operation mode one

Figure 7. Inductor currents

The voltage stress of the VM diodes and the output diode are shown in Figure 9(b). $D_4$ has the highest stress 278 V. This is equivalent to the output voltage and is because it is always in blocking mode.
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during the entire operation of the converter. $D_5$ and $D_6$ have a voltage stress of 192 V. This implies that the voltage stress on $D_5$ and $D_6$ is $V_{c1}$.

Figure 8. Maximum voltage across VM capacitors

Figure 9. Voltage stress (a) switches and (b) diodes

In the simulation of the second operation mode, input sources $V_1$ and $V_2$ are assumed to be depleted hence the battery is called into action. The values for $V_1$, $V_2$ and $V_b$ are 18 V, 6 V, and 12 V respectively. The maximum input voltage from all three supplies is 33 V. Since the interleaved switches adopt the same switching pattern in all the operation modes, the inductor currents, voltage stress and capacitor voltage and waveforms are almost the same as the first operation mode. Figure 10(a) shows the voltage output of $V_1$, $V_2$ and the SOC of the battery. The battery SOC reduces in the process of complementing $V_1$ and $V_2$. The output voltage is 275.5 V.

The input voltage levels, battery SOC, and converter output voltage in the third operation mode is presented in Figure 10(b). $V_1$ and $V_2$ are 24 V and 12 V respectively. The initial battery SOC is 50%. This SOC, slowly increased during operation to indicate battery charging in this mode. The output voltage of the third operation mode is 278 V. This is less than the first and second modes because the battery draws current for charging. The duty cycle of switch $S_4$ determine the charging rate of the battery. Increasing this duty cycle implies less power delivery to the converter and more charging current to the battery.

3.2. Comparison with other works

Comparing the proposed converter with previous works, the converter in [24] has lower voltage gain than this converter. In addition, the proposed converter has one more unidirectional input than [24]. While the converter in [27] boasts of high output voltage, the proposed converter has an advantage of capacity to
accommodate multiple input sources. This is an important factor in RE applications. The converter in [18] can function in RE applications because it has two unidirectional inputs and high output voltage. However, the proposed converter has an advantage of a bidirectional input that can store excess energy. It should be noted that the converters in [18], [27] have higher output voltage because they have greater number of VM cell than the proposed converter. Table 2 shows comparisons between the properties of the proposed converter and other structures.

![Figure 10. Input voltage and battery SOC levels (a) operation mode two and (b) operation mode three](image)

<table>
<thead>
<tr>
<th>Property</th>
<th>This work</th>
<th>[18]</th>
<th>[24]</th>
<th>[25]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of input ports</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>Number of switches</td>
<td>6</td>
<td>2</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>Inductor count</td>
<td>2</td>
<td>5</td>
<td>7</td>
<td>2</td>
</tr>
<tr>
<td>Diode count</td>
<td>7</td>
<td>5</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Capacitor count</td>
<td>3</td>
<td>5</td>
<td>2</td>
<td>5</td>
</tr>
<tr>
<td>Total component count</td>
<td>18</td>
<td>14</td>
<td>15</td>
<td>14</td>
</tr>
<tr>
<td>Bidirectional port</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>Output voltage, Vo</td>
<td>(V_1d_1 + 2V_2d_2) (1 - d_1)</td>
<td>(3V_1) (1 - d_1)</td>
<td>(2V_2) (1 - d_2)</td>
<td>(V_m - 5V_m) (1 - D)</td>
</tr>
</tbody>
</table>

4. CONCLUSION

In this paper, the proposed multi-input converter achieved high output voltage in an interleaved inductor topology by taking advantage of two VM cells placed after the interleaving stage. The converter can provide energy from three sources. There are two unidirectional input ports and a bidirectional input port that is suitable for a battery storage. The individual energy sources can be controlled by their respective power switches. The battery storage port is a major advantage of the proposed converter. Excess energy from RE sources can be stored in the battery. On occasions of inadequate power, this stored energy can be channeled to satisfy the power requirements. The charge and discharge rate of the bidirectional port is dependent on the duty ratio of the power switch. Thus, the proposed converter is appropriate for use in RE applications. Future work will focus on developing an optimal control strategy for the converter.

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