Double-Input DC–DC Power Electronic Converters for Electric-Drive Vehicles—Topology Exploration and Synthesis Using a Single-Pole Triple-Throw Switch

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Abstract—Hybridizing energy systems using storage devices has gained popularity in transportation and distributed electric power generation applications. Traditionally, several independent power electronic converters (PECs) were utilized in such practices. Due to their reduced part count, double-input (DI) PECs prove to be a promising choice in hybridizing energy systems. A few topologies for multi-input converters have been reported in the literature; however, there is no systematic approach to synthesize them. Furthermore, all possible topologies are not completely explored, and it is difficult to derive new converters from existing topologies. Therefore, in this paper, a systematic approach to derive DI converters by using a single-pole triple-throw switch as a building block is presented.

Index Terms—DC–DC power conversion, energy storage, multiport converters.

I. INTRODUCTION

DOUBLE-INPUT (DI) converters have gained popularity in power electronic applications including electric, hybrid, and plug-in hybrid electric vehicles; fuel cell systems; photovoltaic systems [1], [2]; wind generation [3], [4]; and power factor correction [5]. In these applications, utilizing a short- or long-term energy storage device is inevitable since the instantaneous values of the input and output powers are not equal [6]–[11]. The energy storage unit can be comprised of batteries and/or electrochemical capacitors. In other words, the storage unit can be hybridized itself.

Electrochemical capacitors have been proposed to be utilized in the electrical distribution system of conventional and hybrid vehicles to serve applications like local energy cache, voltage smoothing, pseudo-42-V architecture, and service life of batteries extension. However, the high specific power of electrochemical capacitors is the major reason for having them used as an intermediate energy storage unit during acceleration, hill climbing, and regenerative braking. A hybrid energy storage unit comprising both batteries and electrochemical capacitors seems to be the promising choice for future electric drive vehicles. The basic idea is to realize the advantages of both batteries and electrochemical capacitors while keeping the weight of the entire energy storage unit minimized through an appropriate matching.

In order to combine the main source of power with the energy storage unit or in order to hybridize the energy storage unit, either two independent converters or a single DI converter is needed. The advantages of using a DI converter include reduced component count, lower cost, and control simplicity. These advantages can potentially improve the overall cost and efficiency of electric drive vehicles.

Magnetic coupling has been used to develop DI and, more generally, multi-input converters [12]–[17]. Combining the structure of independent power converters has also been proposed to make multiport converters [18]–[22]. These approaches do not systematically use building blocks to derive DI power electronic converters (DIPECs). Furthermore, all possible topologies have not been completely explored. In addition, it is difficult to derive new DI converters using existing DI topologies. Hence, in this paper, a single-pole triple-throw (SPTT) switch is used as a building block in creating DIPECs.

Three DI dc–dc converters are proposed in Section II. The operating modes of the new converters, as well as their voltage transfer ratios in the continuous conduction mode, are also described. In Section III, the switch realization of the converters is discussed. Simulation and experimental results to verify the converters’ characteristics are presented in Sections IV and V, respectively. Finally, Section VI draws the concluding remarks.

II. DERIVATION OF NEW DI CONVERTERS USING AN SPTT SWITCH

Fig. 1 shows a simple representation of an SPTT switch. At any given time, the pole is connected to one and only one of the throws. An SPTT switch can be realized by using three single-pole single-throw (SPST) switches, as shown in Fig. 2. It should be remarked that one and only one of the three SPST switches is on at any given time [23].
Figs. 3–5 show the circuit diagrams of the new DIPECs that can be synthesized using an SPTT switch. Here, these converters are named DI buck, DI buckboost, and DI buckboost-buck topologies, respectively. Although voltage sources are used for the graphic demonstration of these topologies, any stiff dc voltage source or storage mechanism can be used. It is worth mentioning that only one inductor is used in the structure of these converters. Therefore, they benefit from a higher power density. These converters are derived and will be analyzed using basic PEC topologies reported in the literature [12], [13], [19]–[21], [24]–[28]. Similar to classic power electronic approaches, parasitic components will be neglected in the analysis.

Fig. 6 shows the circuit diagram of the DI buck converter using three SPST switches instead of one SPTT switch. This replacement makes the switch realization easier. Voltage source $V_1$ delivers power when SPST switch $S_1$ is turned on. Similarly, voltage source $V_2$ is the source of power when switch $S_2$ is on. Finally, switch $S_3$ can be used for freewheeling purposes. Fig. 7 shows a typical switching pattern for the three SPST switches. This pattern can be applied to any of the DIPECs discussed here. Three modes of operation for a DI buck converter that occur under unidirectional power flow are described in Table I.

<table>
<thead>
<tr>
<th>Mode</th>
<th>ON Switch</th>
<th>$V_L$</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>$S_1$</td>
<td>$V_1 - V_o$</td>
<td>$V_f$ supplies energy</td>
</tr>
<tr>
<td>II</td>
<td>$S_2$</td>
<td>$V_2 - V_o$</td>
<td>$V_2$ supplies energy</td>
</tr>
<tr>
<td>III</td>
<td>$S_3$</td>
<td>$-V_o$</td>
<td>Freewheeling</td>
</tr>
</tbody>
</table>

Similarly, the modes of operation for the DI buckboost and buckboost-buck converters are shown in Tables II and III, respectively. It is worth mentioning that Mode III does not have to appear at the end of the switching period. All or parts of it can be placed between Modes I and II.
TABLE II
VOLTAGE ACROSS INDUCTOR FOR DIFFERENT MODES OF OPERATION OF DI BUCK CONVERTER

<table>
<thead>
<tr>
<th>Mode</th>
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<tr>
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<td>( S_2 )</td>
<td>( V_2 )</td>
<td>( V_2 ) supplies energy</td>
</tr>
<tr>
<td>III</td>
<td>( S_3 )</td>
<td>(- V_o )</td>
<td>Freewheeling</td>
</tr>
</tbody>
</table>

TABLE III
VOLTAGE ACROSS INDUCTOR FOR DIFFERENT MODES OF OPERATION OF DI BUCKBOOST-BUCK CONVERTER

<table>
<thead>
<tr>
<th>Mode</th>
<th>ON Switch</th>
<th>( V_L )</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>( S_1 )</td>
<td>( V_1 )</td>
<td>( V_1 ) supplies energy</td>
</tr>
<tr>
<td>II</td>
<td>( S_2 )</td>
<td>( V_2 - V_o )</td>
<td>( V_2 ) supplies energy</td>
</tr>
<tr>
<td>III</td>
<td>( S_3 )</td>
<td>(- V_o )</td>
<td>Freewheeling</td>
</tr>
</tbody>
</table>

One can observe in Fig. 7 that \( T_1 \) is the on-time of switch \( S_1 \), \( T_2 \) is the on-time of switch \( S_2 \), and \( T_3 \) is the on-time of switch \( S_3 \). Hence

\[
\begin{align*}
T_1 &= d_1 \cdot T \\
T_2 &= d_2 \cdot T \\
T_3 &= d_3 \cdot T
\end{align*}
\]

(1)

\[
T_1 + T_2 + T_3 = T
\]

(2)

where \( T \) is the switching period and \( d_1 \), \( d_2 \), and \( d_3 \) are the duty cycles of switches \( S_1 \), \( S_2 \), and \( S_3 \), respectively. Considering a DI buck converter, one can write the following equation based on Fig. 7, Table I, and the volt–second balance equation of the inductor:

\[
T_1 \cdot (V_1 - V_O) + T_2 \cdot (V_2 - V_O) + T_3 \cdot (-V_O) = 0. 
\]

(3)

This can be simplified to the following equation:

\[
V_1 \cdot T_1 + V_2 \cdot T_2 = V_O \cdot (T_1 + T_2 + T_3).
\]

(4)

Combining (1), (2), and (4), one can obtain the following equation which describes the relation between the input and output voltages:

\[
V_O = d_1 \cdot V_1 + d_2 \cdot V_2.
\]

(5)

Similarly, voltage transfer ratios of the DI buckboost and buckboost-buck converters can be described as

\[
V_O = \frac{d_1}{1 - d_1 - d_2} \cdot V_1 \quad \text{and} \quad V_O = \frac{d_2}{1 - d_1 - d_2} \cdot V_2.
\]

(6)

(7)

In employing (5)–(7), one should keep in mind that

\[
d_1 + d_2 \leq 1.
\]

(8)

For instance, in a DI buck converter, (8) indicates that \( V_o \) cannot exceed \( \max(V_1, V_2) \). Variations of the output voltage as a function of the duty ratios for a DI buck converter are shown in Fig. 8. In this figure, \( V_1 \) and \( V_2 \) are selected to be 80 and 60 V, respectively.

III. SWITCH REALIZATION FOR NEW DI CONVERTER TOPOLOGIES

In the DI buck converter shown in Fig. 6, SPST switches \( S_1 \), \( S_2 \), and \( S_3 \) can be realized using diodes and transistors. Switch realization depends on the input and output voltage levels as well as the power flow direction. Assuming that the power flow is from left to right (or \( i_L > 0 \)), one can argue

(If \( S_1 \) is on \( \rightarrow S_2 \) and \( S_3 \) are off)

\[
\Rightarrow (i_s1 > 0, V_{S2} = V_2 - V_1, \text{ and } V_{S3} = -V_1)
\]

(If \( S_2 \) is on \( \rightarrow S_1 \) and \( S_3 \) are off)

\[
\Rightarrow (i_s2 > 0, V_{S1} = V_1 - V_2, \text{ and } V_{S3} = -V_2)
\]

(If \( S_3 \) is on \( \rightarrow S_1 \) and \( S_2 \) are off)

\[
\Rightarrow (i_s3 > 0, V_{S1} = V_1, \text{ and } V_{S2} = V_2).
\]

Therefore, SPST switch \( S_1 \) conducts positive currents and has to block either a positive or a negative voltage depending on the magnitude of \( V_1 \) and \( V_2 \). Consequently, it should be replaced by a diode in series with a transistor. Similarly, switch \( S_2 \) should be a bidirectional voltage blocking switch. Switch \( S_3 \), which conducts positive currents and opposes negative voltages, should be replaced by a diode. Therefore, the final circuit diagram of the DI buck converter is shown in Fig. 9.

The structure of a DI buck converter can be simplified to Fig. 10 if \( V_1 \) is always greater than \( V_2 \) (\( V_1 > V_2 \)). Similarly, the structure of the DI buck converter can be further simplified if \( V_1 \) is always greater than \( V_2 \) (\( V_1 > V_2 \)) and Mode III never
Fig. 9. Switch realization for the DI buck converter (unidirectional power flow).

Fig. 10. Simplified DI buck converter (if $V_1 > V_2$).

Fig. 11. Further simplified DI buck converter with $V_1 > V_2$ and no Mode III occurs. The simplified converter in this case is shown in Fig. 11. This converter is similar to a two-input buck converter [5].

Similarly, the unidirectional switch realization for the DI buckboost and buckboost-buck converters results in the final circuits shown in Figs. 12 and 13, respectively. These two topologies may also be further simplified similar to the discussion presented for the DI buck converter.

In applications such as hybrid electric vehicles and photovoltaic systems, one of the dc sources noted by $V_1$ or $V_2$ is a battery. Hence, bidirectional power flow to and from one of the sources ($V_1$ in this paper) is required. In this case, switch realization will be slightly different

(If $S_1$ is on) $\Rightarrow$ ($i_{S1} > 0$ or $< 0$)

(If $S_2$ is on $\rightarrow S_1$ is off) $\Rightarrow$ ($V_{S1} > 0$ or $< 0$).

As switch $S_1$ conducts either a positive or a negative current and also blocks either a positive or a negative voltage, it must be replaced by a four-quadrant switch (see Fig. 14).

IV. SIMULATION RESULTS

Figs. 15–17 show the simulation results of the DI buck, buckboost, and buckboost-buck converters, respectively. Two dc voltage sources $V_1 = 100$ V and $V_2 = 150$ V are used as input voltage sources. The switching commands for $S_1$ and $S_2$ have fixed duty ratios of 0.3 and 0.4 at the switching frequency is 100 kHz. The inductor value was selected to be 200 $\mu$H, the capacitor value was 80 $\mu$F, and the load resistance was 5 $\Omega$. From top to bottom are the waveforms of the switch commands for $S_1$ and $S_2$, inductor voltage $V_L$, inductor current $i_L$, and the output voltage. One can observe from the waveforms that the average value of the output voltage for the DI buck converter is 90 V. This can also be obtained from the voltage transfer ratio described in (5). Similarly, the output voltages of the DI buckboost and buckboost-buck converters are regulated at 300 and 128.6 V, which can also be obtained by (6) and (7), respectively.
The peak-to-peak ripple of the inductor current in a DI buck converter is at its maximum level when \( V_1 = V_2 \) and Mode II occurs right after Mode I. Similar to a single-input buck converter, in order to make sure that the converter operates in the continuous conduction mode, one needs to make sure that the inductor value is greater than

\[
L_{\text{Critical}} = \frac{R(1 - d_1 - d_2)}{2f_s} \quad (9)
\]

where \( R \) is the load resistance and \( f_s \) is the switching frequency. Similarly, under the same conditions, one can describe the peak-to-peak ripple of the output voltage in a DI buck converter as \([29]\)

\[
\frac{\Delta V_o}{V_o} = \frac{1 - d_1 - d_2}{8LCf_s^2} \quad (10)
\]

where \( \Delta V_o \) is the peak-to-peak ripple of the output voltage and \( C \) is the output capacitor.

V. EXPERIMENTAL VERIFICATION

In order to verify the simulation results, a low-power laboratory prototype of a DI buck converter was built. Sources \( V_1 \) and \( V_2 \) were selected to be 80- and 60-V power supplies. Dual-pack IGBT switches were used for \( S_1 \) and \( S_2 \). The switching frequency was 50 kHz. A 50-\( \mu \)H inductor and a 150-\( \mu \)F capacitor were used as \( L \) and \( C \), respectively. The load resistance was about 4.5 \( \Omega \), and the output power was expected to be around 550 W.

Duty cycles \( d_1 \) and \( d_2 \) were selected to be 0.3 and 0.5, respectively. Mode II does not start immediately after Mode I. Mode III is placed before and after Mode II. The open-loop results are shown in Figs. 18 and 19. Fig. 18 contains the waveforms of output voltage \( V_o \) and inductor current \( i_L \). When both switches are off, the inductor is de-energized, and the power is dissipated through the load resistor. This process can be observed from the negative slope of the inductor current waveform. The output voltage was measured to be 50.5 V when the reading was taken by a multimeter. This is very close to 54 which \((5)\) predicts. The 6.5% difference is due to nonideal effects and parasitic components which were not included in the development of \((5)\). Fig. 19 shows the current waveforms of switches \( S_1 \) and \( S_2 \). It can be observed that experimental and simulation results agree with each other. Fig. 20 shows the transient response of the open-loop DI buck converter to a step change in the load resistance. The dynamic response is similar to that of a single-input buck converter. The variations of the
Three DI converters are developed in this paper using a SPTT switch as a building block. All of the proposed converters use only one inductor, which results in a reduced size and part count of the system. The proposed converters can be used in ultracapacitor enhancement of battery packs in automotive applications or hybridizing photovoltaic or fuel cell systems. Simulation and experimental results agree with the analytical results.

VI. CONCLUSION

efficiency of the DI buck converter versus the output power are shown in Fig. 21. The curve follows the efficiency curves of classic dc–dc converters.

REFERENCES


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