A family of non-isolated three-port converters based on H-bridge

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Abstract. In order to satisfy the charging and discharging circuits of energy storage element (ESE), a family of non-isolated three-port converter (TPC) by embedding a ESE-centric H-bridge cell into the classic buck, boost and buck/boost converters are proposed. There are two types of embedding method: (1) Without connecting with component of the classic converter, H-bridge is inserted into the classic converter directly. (2) Connected with component of the classic converter in a specific way, the H-bridge is connected with the rest part of the classic converter. The operating mode and port voltage restriction of the obtained TPCs are analyzed and summarized, which features high integration and compact size. Experimental results of one of the proposed TPCs, named LP-3-buck/boost, have been presented to verify the analysis results.

1. Introduction

Due to the instability of natural environment, the output powers of solar, wind and thermoelectric power generation equipment have the characteristics of intermittence and instability, the energy storage unit such as super capacitor or battery is mandatory for the stand-alone renewable power system to balance the input and output power. Compared with several independent two-port converters, an integrated three-port converter (TPC) can be a good candidate which shows the advantages of fewer components, more compact packaging, and more unified power management among the input port, energy storage port and the load port [1-3]. In general, topologies of the TPC can be classified into non-isolated and isolated topologies. With convenience to achieve up/down voltage and galvanic isolation, isolated TPCs are good choices for high-power applications. Fully isolated TPCs employ a high-frequency transformer to build the magnetic coupling among those ports [4-7]. The parasitized circuit in the primary-side circuit of an isolated two-port converter can be utilized to construct a partly isolated TPC [8-12]. However, in the low-power application where isolation is not necessary, a non-isolated TPC offers more benefits such as higher efficiency, higher power density, and lower cost. In [13], a systematic approach to generate TPC by adding an additional power flow path to dual-input and dual-output converter is provided. Based on this method, a family of TPCs with a unified bidirectional cell are derived [14]. However, the bidirectional cell is not applicable for buck converter. In [15], a non-isolated TPC family is constructed by inserting a general storage-switch-diode cell into the classic buck, boost, and buck/boost converter, which maximizes the usage of the control freedoms.
Besides, in order to adapt to the wide voltage variations of the renewable source, literature [16] proposes a TPC by coupling a transformer, a secondary rectifier and filter circuit with the inductor of a four-switch buck/boost converter. However, the introduction of the transformer increases the weight of the converter and the complexity of the control method. Generated from inserting the storage-switch-diode cell is proposed in [15] into the two-switch buck/boost converter, the TPC proposed in [17] loosens the port voltage restriction through the variable structures among ports, thus featuring wide operation range. In order to satisfy the charging and discharging circuits of energy storage element (ESE), a family of non-isolated TPCs by embedding a ESE-centric H-bridge cell into the classic buck, boost and buck/boost converters are proposed in this paper.

2. H-bridge cell

2.1. Power management requirements of a TPC
As shown in figure 1, a TPC includes an input port connected to a main source, an output port connected to a load, and a bidirectional port connected to the energy storage unit (a battery is used as an example). $V_{in}$, $V_b$ and $V_o$ are the voltages of input port, the energy storage port and the load port respectively. There are five energy management requirements that a TPC should try to satisfy. When the input power is sufficient, the battery absorbs the surplus power, the TPC is in dual-output (DO) mode, as shown in figure 1 (a); when the input power is inadequate, the battery supplements the deficient power, the TPC is in dual-input (DI) mode, as shown in figure 1 (b). Besides, according to the practical application, the power flow paths from $V_{in}$ to $V_o$, $V_{in}$ to $V_b$ and $V_b$ to $V_o$ could better be able to work individually, which is called source-only, charging-only and load-only mode, respectively, as shown in figure 1 (c)-(e).

![Figure 1. Power management requirements.](image)

**Figure 2.** The ESE-centric H-bridge cell.

![Figure 3. Power flow paths of H-bridge.](image)

2.2. The generation of H-bridge cell
To develop TPCs from classic two-port converters, a switching unit containing the battery should be added. As the bidirectional port of a TPC, the battery needs separate charging circuit for input port and discharging circuit for output port. From this point, we choose to embed the ESE-centric H-bridge into classic converter to generate TPC. The H-bridge is shown in figure 2. Suppose the battery is charged when $S_1$ and $S_3$ are turned on, as shown in figure 3 (a), the path formed can be applied to DO and charging-only mode; when $S_2$ and $S_4$ are turned on, the battery is discharged, as shown in fig 3 (b), this...
path can be applied to DI and load-only mode; when \( S_1 \) and \( S_2 \) or \( S_3 \) and \( S_4 \) are turned on, the inductor current takes \( S_1 \) and \( S_2 \) or \( S_3 \) and \( S_4 \) as path without following through the battery, as shown in figure 3 (c) and (d). These two paths preserve the original performance of the classic converter and can be applied to source-only mode.

3. The embedding method of H-bridge
For the simplification of control method, we choose an active switch and a diode located in the same side of the battery. When the switch is turned on, the diode is cutoff under reverse bias voltage. And the orientation of the diode should follow the original power flow of the branch in classic converter.

3.1. Without connecting with component of the classic converter
The H-bridge without connecting with component of the classic converter is shown in figure 4(a). The switches and diodes are denoted as \( S_{b1}, D_{b1} \) and \( S_{b2}, D_{b2} \), respectively. Classic buck, boost and buck/boost converters share the same structure shown in figure 4(b), where components \( C1\sim C3 \) are any combination of inductor, switch and diode. From figure 4(b), we can see that H-bridge can be inserted in each position of \( P1\sim P8 \). The positions of \( P1, P4 \) and \( P8 \) are taken as examples to construct the TPCs shown in figure 5 and the corresponding port voltage restrictions are obtained, where the TPC generated by embedding H-bridge into the position \( P1 \) of boost converter is named as \( P1\)-boost, and so on.

![Figure 4. Configuration of H-bridge without connecting with component.](image)

![Figure 5. Examples of TPCs without connecting with component of the classic converter.](image)

For \( P8\)-buck/boost, if the battery is discharged when \( S \) is off and charged when \( S \) is on, it can be simplified to the topology shown in figure 6 (a) [15]. On the other hand, if the battery is charged when \( S \) is off and discharged when \( S \) is on, it can be simplified to the topology shown in figure 6 (b), which loses the charging-only and load-only mode. The simplification will reduce the number of switches. However, for \( P8\)-buck/boost shown in figure 5(h), the charging and discharging state of the battery is free from the switching state of \( S \), thus the TPC can operate in a wider operational range.

3.2. Configurations of source or load connected with H-bridge
The connection of input source is taken as an example: If we select the negative electrode of the source as the breakpoint (marked as point B in figure 7 (a)) and the connecting method with H-bridge is shown in figure 7 (b). It should be noted that the input source, switch and load (the output capacitor
and the load are treated as a whole) are available for the connection with H-bridge except the inductor. This is because the current will not flow through the inductor when \( S_2 \) and \( S_3 \) are turned on and this operational mode is not allowed for the single-inductor feature of TPCs in this paper.

When the source or load is connected with H-bridge, there will be a loop composed of the source or load, battery, switch and diode. Appropriate port voltage restriction should be met to ensure the switch and diode conduct complementarily. Since the current flows in and out of the positive electrode of the load and source respectively, the orientation of H-bridge for the source and load is different.

![Figure 6. The simplification of P8-buck/boost TPC.](image)

![Figure 7. The method of H-bridge connected with component of the classic converter.](image)

For the input source connected with H-bridge, when the positive electrode is chosen as the breakpoint and the terminals of the source and battery with the same polarity are connected through the switches, there are two cases corresponding to figure 8 (a) and (b) referred as SP-1, SP-2, with ports’ voltage restriction \( V_b > V_{in} \) and \( V_b < V_{in} \), respectively, the source along with the battery delivers power to the load in the time-sharing way. When the terminals of the source and battery with the different polarity are connected through the switches as shown in figure 8 (c), referred as SP-3, there is no ports’ voltage restriction between the source and the battery. Here, in DI mode, the source and battery were connected in series offering power to the load simultaneously. Similarly, if we take the negative terminal of the source as the breakpoint, there are three cases shown in figure 8 (d) - (f) referred as SN-1, SN-2, SN-3 with ports’ voltage restriction \( V_b > V_{in} \), \( V_b < V_{in} \) and no ports’ voltage restriction respectively.

![Figure 8. Source connected with H-bridge.](image)

![Figure 9. Load connected with H-bridge.](image)

For the load connected with H-bridge, similar to the input source, there are three cases with positive breakpoint, corresponding to figure 9 (a)-(c) referred as LP-1, LP-2, LP-3, respectively. With respect to LP-1 and LP-2, the source supplies power to the load and battery in the time-sharing way with ports’ voltage restriction \( V_b > V_o \) and \( V_b < V_o \). On LP-3, the load and battery are connected in series powered by the source simultaneously with no ports’ voltage restriction between the load and the battery. Similarly, if we take the negative electrode of the load as the breakpoint, there are three cases...
shown in figure 9 (d) - (f) referred as LN-1, LN-2, LN-3 with ports’ voltage restriction $V_b>V_o$, $V_b<V_o$ and no ports’ voltage restriction, respectively.

We denote the TPC derived by the combination of SP-1 and the classic boost converter as SP-1-boost, and so on. In particular, when the battery of LP-1-boost is discharged, that is, $S_{b2}$ and $S_{b2}$ of the H-bridge are turned on simultaneously, for the ports’ voltage restriction $V_b>V_o$, there will be an undesired circuit formed by the anti-parallel diode of $S$, so that the topology can’t work properly. However, switches of the H-bridge can be controlled properly to replace the function of the switch and diode of the classic boost converter and thus LP-1-boost can be simplified to the topology shown in figure 10, which is similar with LP-3-boost, SP-1-buck, SP-3-buck. Although LP-2-boost doesn’t have the same problem with LP-1-boost, it can also be simplified with the above method. It should be noted that the simplification won’t change the operational mode of LP-2-boost. Though the number of switches is reduced, employing two switches controlling the three individual power flows in TPC increases the degree of control coupling [18]. Different breakpoint of the same component won’t affect the ports’ voltage restriction and operational mode of the formed TPCs. To prevent redundancy, we here provide the cases with positive breakpoint of the source or load, as shown in figure 11. Due to the embedding of H-bridge, the structures from $V_{in}$ to $V_b$ and from $V_{in}$ to $V_o$ can be varied [17]. The equivalent circuit among the ports of TPCs formed in this section has been summarized in table 1.

![Figure 10. Simplification of LP-1-boost TPC.](image)

![Figure 11. TPCs developed from classic converter with source or load connected with H-bridge.](image)

3.3. Configurations of switch or diode connected with H-bridge

The breakpoint of $S$ needs to be connected with the diode of the H-bridge as shown in figure 12 (a) and (b), referred as SS and SD, respectively. Taking SD as an example, the switching state in which $S_{b2}$ and $S$ turned off plays the same role as the turn-off of $S$ for the classic converter and $D_{b2}$ prevents short-circuit of the battery through the anti-parallel diode of $S$ when $S_{b2}$ is turned on. On the connection of the diode $D$ with H-bridge, since the anti-parallel diode of $S_{b1}$ and $S_{b2}$ have formed a path with opposite conducting direction to the diode of classic converter, the breakpoint of the diode $D$ should be connected with the switch of the H bridge to block this path, as shown in figure 12 (c) and (d), referred as DP and DN, respectively.

There are four configurations of switch or diode connected with H-bridge for the classic buck, boost and buck/boost converter and thus 12 TPCs are yielded. Similar to section 3.1, we here provide the cases with the configuration SS and DP as shown in figure 13. Compared with the TPCs in figure 5 with the corresponding embedding position, the TPCs in this section own the same operational mode...
and ports’ voltage restriction. However, less components in some power flow paths of the TPCs are needed, which means higher efficiency can be obtained.

3.4. Optimization of the generated TPCs
Without the changing of operating mode, some TPCs generated in section 3.2 can be connected with two components of the classic converter. Combining the afore-described principles of connection between H-bridge and the component of classic converter, some examples are given in figure 14.

| Table 1. The equivalent circuit among the TPC ports. |
|----------------------------------------------------|
| Topologies  | $V_{in}$-$V_o$  | $V_{in}$-$V_b$  | $V_b$-$V_o$  | Reported |
|------------|----------------|----------------|--------------|---------|
| SP-1       | two-switch     | boost          | two-switch   | [17]    |
|            | buck/boost     |                | buck/boost   |         |
| SP-2       | two-switch     |                | two-switch   | [17]    |
|            | buck/boost     |                | buck/boost   |         |
| SP-3       | two-switch     | buck/boost     |              |         |
| LP-1       | boost          |                | boost        |         |
| LP-2       | boost          |                | boost        |         |
| LP-3       | boost          |                |              |         |
|------------|----------------|----------------|--------------|---------|
| SP-1       | buck           |                | buck         |         |
| SP-2       | buck           |                | buck         |         |
| SP-3       | buck           |                |              |         |
| LP-1       | two-switch     | two-switch     | buck         | [17]    |
| LP-2       | two-switch     | two-switch     |              |         |
| LP-3       | two-switch     | two-switch     |              |         |
|------------|----------------|----------------|--------------|---------|
| SP-1       | buck/boost     | boost          | buck/boost   |         |
| SP-2       | buck/boost     |                |              |         |
| SP-3       | buck/boost     |              |              |         |
| LP-1       | buck/boost     | buck/boost     |              |         |
| LP-2       | buck/boost     |              |              |         |
| LP-3       | buck/boost     |                |              |         |

![Figure 12. Configurations of switch or diode connected with H-bridge.](image-url)
4. The operational principle of TPC and experimental results

Upon close inspection of the TPCs generated above, it’s difficult for a specific case to occupy all the merits such as variable operational modes, wide operational range and high efficiency. For example, the LP-1-buck reported in [17] loosens port voltage restrictions with variable structures, which is analyzed in terms of operational principles, control strategy and efficiency. However, the ports’ voltage restriction $V_o<V_b$ should still be met. Consequently, the LP-3-buck/boost is chosen as an example to analyze the performance of the proposed converter. It can be seen from LP-3-buck/boost that the sources and load are not common-ground, and the converter can be used for where the ports’ voltage restriction is the primary consideration. The analyses of other proposed converters are similar.

4.1. The Operational principle

The LP-3-buck/boost shown in figure 11(l) has three operational modes: dual-output (DO) mode, dual-input (DI) mode and load-only mode.

![Figure 13](image13) **Figure 13.** TPCs developed from switch or diode connected with H-bridge.

![Figure 14](image14) **Figure 14.** Examples of TPCs connected with two components of the classic converter connected with H-bridge.

1) DO mode: $S_{b1}$ is off when the TPC is in the dual-output mode. There are three switching states in a switching period. The equivalent circuits in each state and the key waveforms are shown in figure 15 (a)–(d) respectively. When $S$ and $S_{b2}$ are both turned on, $L$ is magnetized by $V_o$, as shown in figure 15 (a). When $S$ is turned off and $S_{b2}$ is turned on, energy stored in $L$ is released to the load and $L$ is demagnetized by $-V_o$, as shown in figure 15(b). When $S$ and $S_{b2}$ are both turned off, the energy from $L$...
is transferred to the battery and load simultaneously and \( L \) is demagnetized by \( - (V_o + V_b) \), as shown in figure 15 (c).

Suppose the TPC operates in the continuous conduction mode. In the steady state, according to the volt-second balance of \( L \), the relations among the three ports can be obtained as

\[
V_o = -\frac{V_o d - V_b (1 - d_{b2})}{1 - d}
\]

(1)

where \( d \) and \( d_{b2} \) are the duty cycles of \( S \) and \( S_{b2} \), respectively.

2) DI mode: \( S_{b2} \) is on when the TPC works in the dual-input mode. There are three switching states in a switching period. The equivalent circuit in each state and the key waveforms are shown in figure 16 (a) - (d) respectively. When \( S \) is turned on and \( S_{b1} \) is turned off, \( L \) is magnetized by \( V_{inv} \) as shown in figure 16 (a). When \( S \) is turned off and \( S_{b1} \) is turned on, \( L \) is magnetized by \( V_o \), as shown in figure 16 (b). When \( S \) and \( S_{b1} \) are both turned off, \( L \) releases energy to the load and is demagnetized by \( -V_o \), as shown in figure 16 (c). In the steady state, applying the volt-second balance principle to \( L \), we obtain:

\[
V_o = -\frac{V_o d + V_b d_{b1}}{1 - d - d_{b1}}
\]

(2)

where \( d_{b1} \) is the duty cycle of \( S_{b1} \).

Load-only mode: \( S \) is off and \( S_{b2} \) is on when the TPC is in the load-only mode. The output voltage \( V_o \) is regulated with \( d_{b1} \), the duty cycle of \( S_{b1} \). The equivalent circuit is the figure 16 (b) and figure 16 (c), which is equivalent to a conventional buck/boost converter.

4.2. Control and modulation

The control scheme is shown in figure 17. PV voltage regulator (IVR) for MPPT, battery voltage regulator (BVR) for maximum voltage charging control, battery current regulator (BCR) for maximum current charging control and output voltage regulator (OVR) for output voltage control are employed. \( u_{cS} \), \( u_{cSb1} \) and \( u_{cSb2} \) are the references for generating the gate signals of \( S \), \( S_{b1} \) and \( S_{b2} \). Only two of the three ports can be regulated simultaneously while the third port is left unregulated providing the power balance for the system. As the output target should usually be achieved, minimum competition logic proposed in [19] can be adopted to ensure the smooth transition of the other three regulation targets.

![Figure 17. The equivalent circuits and the key waveforms.](image1)

![Figure 19. Efficiency curve vs battery power at full load.](image2)
4.3. Experimental Results
A 100-W prototype is built to verify analysis results as mentioned above. The key parameters are chosen as follows: $V_{in} = 30V$, $V_b = 12V$, $V_o = 24V$, inductance $L = 45\mu H$, switching frequency $f = 50kHz$. The experimental waveforms of the converter with different operational mode are shown as figure 18, where $u_{L}$ and $i_{L}$ are the voltage and current of the inductor and $u_{S}$, $u_{S1}$ and $u_{S2}$ are the control signals of $S$, $S_{b1}$ and $S_{b2}$. Figure 18(a), (b) shows the waveforms when the TPC operates in the DO and DI mode, which is consistent with the operational mode analysis in figure 15 and 16. The battery is charged at the power about 20W and discharged at the power about 30W. Figure 19 (c) shows the waveforms when the TPC operates in the load-only mode. In this mode, $S$ is off and $S_{b2}$ is on. The battery supplies the load alone at the power of 100W.

The efficiency curve of LP-3-buck/boost under full load power (100W) with different battery power $P_b$ is given in figure 19. Positive value indicates the battery works in charging state while negative value indicates the battery works in discharging state. It can be seen that the more power that the battery involves in DI or DO mode, the lower the overall efficiency will be obtained.

5. Conclusions
In this paper, a family of non-isolated three-port converter (TPC) by embedding a ESE-centric H-bridge cell into the classic buck, boost and buck/boost converters are proposed. The constructed TPCs feature single inductor and single-stage power conversion among the three ports.

Depending on whether to connect H-bridge with the component of the classic converter or not, the TPCs are divided into two categories. The operating mode and port voltage restriction of the TPCs are analyzed and summarized. Principles of connection between H-bridge and the component of classic converter are investigated. These embedding methods of the H-bridge bring the difference in operating modes and efficiency for the constructed TPCs. Finally, operating mode analysis, control methods and experimental results verify the rationality and feasibility of the proposed converters.

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