Family of Dual-Input Dual-Buck Inverters Based on Dual-Input Switching Cells

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Abstract

A family of dual-DC-input (DI) dual-buck inverters (DBIs) is proposed by employing a DI switching cell as the input of traditional DBIs. Three power ports, i.e. a low voltage DC input port, a high voltage DC input port and an AC output port, are provided by the proposed DI-DBIs. A low voltage DC source, whose voltage is lower than the peak amplitude of the AC side voltage, can be directly connected to the DI-DBI. This supplies power to the AC side in single-stage power conversion. When compared with traditional DBI-based two-stage DC/AC power systems, the conversion stages are reduced, and the power rating and power losses of the front-end Boost converter of the DI-DBI are reduced. In addition, five voltage-levels are generated with the help of the two DC input ports, which is a benefit in terms of reducing the voltage stresses and switching losses of switches. The topology derivation method, operation principles, modulation strategy and characteristics of the proposed inverter are analyzed in-depth. Experimental results are provided to verify the effectiveness and feasibility of the proposed DI-DBIs.

Key words: Circuit topology, Dual-Buck, Dual-input, High efficiency, Inverter

I. INTRODUCTION

Inverters are key elements for the interface an AC load or grid and various DC sources. They have been widely used in renewable energy power systems, micro-grids, uninterruptable power supplies, air-plane power systems and so on [1], [2]. Despite their long history, inverter topologies are still evolving. The search for new inverter topologies with a higher efficiency and a high reliability has never stopped in an effort to meet the requirements of various new applications. As a result, new topological variations and innovations have been continuously emerging [3], [4].

Generally speaking, inverter topologies can be classified into three types: Buck-type, Boost-type and Buck-Boost type. Among them, the buck type inverters, e.g. full-bridge inverters, are more popular due to their simplicity and high efficiency.

However, full-bridge inverters, whose switching legs are composed of two active switches in a series connection, have the potential for a dangerous short-through [5]. The reverse recovery problem of the body-diodes of active switches is another threat to the reliability and efficiency of full-bridge inverters [6]. The reverse-recovery problem can be avoided by adopting SiC diodes. However, the forward-voltage of a SiC diode is much higher than that of a Si diode or the body-diode of a Si switch. Therefore, it is very difficult to make the current commutate to a SiC diode by paralleling a SiC diode with a Si switch. In addition, the short-through problem cannot be solved when SiC diodes are used in full-bridge inverters. In order to overcome these drawbacks, dual-buck inverters (DBIs) were proposed by splitting the switching-leg in the full-bridge inverter into two buck-type switching-legs [7]-[11]. Since the switching-leg of a DBI is composed of a series-connected active switch and diode. The problems of short-through and reverse-recovery of the body diodes can be solved perfectly. Therefore, DBIs have attracted a lot of attention for use in high reliability and high efficiency applications, such as airplane power systems and the grid-tied inverters for renewable power systems [12]-[14].

Since the DBI is a buck type converter, another Boost converter has to be used as the front-end DC-DC converter if
the voltage of the DC input is lower than the peak amplitude of the AC output voltage. As a result, all of the input power has to be processed by both the front-end Boost converter and the downstream DBI, which hurts the overall efficiency of the DC-AC power system. Although a lot of efforts have been made to improve the efficiency of DBI topologies [15], [16], the power rating and power losses of the front-end Boost converter cannot be reduced. When the DC input voltage is lower than the peak amplitude of the AC output voltage, a Boost type or buck-boost type inverter is more promising in terms of reducing the conversion stages [17]-[20]. However, even though single-stage power conversion can be achieved with a Boost or Buck-Boost type inverter, the conversion efficiency of the Boost or Buck-Boost type inverter is usually lower than that of a buck-type inverter due to the high voltage/current stresses of the devices as well as their complicated topologies and controls.

It is noted that the AC side voltage of an inverter periodically varies between zero and its peak value, which means that the instantaneous value of the AC voltage is not always higher than the voltage of the low voltage DC energy source. This suggests that a low voltage DC input source can directly supply power to an inverter in single-stage power conversion if a low voltage DC input port can be introduced to the inverter. The major contribution of this paper is to propose a new family of dual-DC-input dual-buck inverters (DI-DBIs) to improve the overall conversion efficiency of DC-AC power systems. The structures of the proposed DI-DBI-based and traditional DBI-based DC-AC power conversion systems are shown in Fig. 1. It is important to note that the proposed inverter is referred to as a dual-input dual-buck inverter because both \( V_L \) and \( V_H \) are DC inputs for the inverter stage. However, in terms of the entire DC-AC power system, the \( V_H \) port is an intermediate DC-bus, not a real DC source, and that only the \( V_L \) port is a DC source. In practice, like the intermediate DC-bus in a conventional two-stage DC-AC power system, the \( V_H \) port for the DI-DBI is provided by a front-end Boost converter. The \( V_L \) and \( V_H \) ports are the input and output of the Boost converter, respectively. With the proposed DI-DBIs, the power conversion stage is reduced and the efficiency of the DC-AC power system is improved. In addition, the power stress of the front-end Boost is significantly reduced. Therefore, the power losses, power rating and cost of the Boost converter are all reduced as well. Moreover, the multi-level characteristic is realized with the proposed DI-DBIs, which is beneficial for the reduction of switching loss.

II. DERIVATION OF DI-DBI TOPOLOGIES

The proposed DI-DBI is derived by cascading a dual-input switching cell and a traditional DBI topology. The general structure of the proposed DI-DBI is shown in Fig. 2, where it can be seen that the dual-input switching cell is used as the input of the DBI. Therefore, the dual-input switching cell is the key for the generation of DI-DBI topologies.

Four types of dual-input switching cells are illustrated in Fig. 3. It can be seen that the dual-input switching cell is composed of a high voltage DC source \( V_H \), a low voltage DC source \( V_L \), an active switch \( S_H \) and a diode \( D_L \) or active switch \( S_L \). The two voltage sources can share a common ground, as shown in Fig. 3(a) and Fig. 3(b), or can be connected in series, as shown in Fig. 3(c) and Fig. 3(d). For the switching cells in Fig. 3(a) and Fig. 3(b), the voltage of \( V_H \) must be greater than \( V_L \). Meanwhile, there are no limitations on the voltages of \( V_H \) and \( V_L \) for the switching cells in Fig. 3(c) and Fig. 3(d). In Fig. 3(a) and Fig. 3(c), the diode \( D_L \) is in-series with \( V_H \), which means that \( V_L \) can only output power to the downstream DBI. In Fig. 3(b) and Fig. 3(d), an active switch \( S_L \) is used to connect \( V_L \). Therefore, the power flows of both \( V_L \) and \( V_H \) can be bidirectional.

The operation principles of the four dual-input switching cells are all similar. Take the dual-input switching cell in Fig. 3(a) as an example. Since the voltage \( V_H > V_L \), the diode \( D_L \) is reverse-biased when \( S_H \) is ON. Therefore, once \( S_H \) is ON, the high voltage DC source \( V_H \) supplies power to the downstream DBI. When \( S_H \) is OFF, \( D_L \) conducts so that \( V_L \) supplies power to the inverter. Obviously, by regulating the ON/OFF states of \( S_H \) and \( D_L \), the two DC inputs can alternatively supply power to the inverter.

The topologies of the proposed DI-DBI can be derived by cascading the dual-input switching cell in Fig. 3 and a traditional single-input DBI. Following this principle, a family of DI-DBI topologies, which can simultaneously interface a low voltage DC source and a high voltage DC source, can be derived. Three examples of the proposed DI-DBIs are shown in Fig. 4. These topologies are obtained based on the dual-input switching cell shown in Fig. 3(a). The three single-input DBIs used in Fig. 4(a), Fig. 4(b) and Fig. 4(c) can be found in [7], [8] and [9], respectively. It should be noted that the DI-DBIs are not limited to the ones shown in Fig. 4. The topology derivation method is also effective for
the three dual-input cells shown in Fig. 3(b)-(d). In addition, the single-input DBI used to construct a DI-DBI can be another.

In practical applications, the low voltage DC source $V_L$ can be made up of photovoltaic arrays, fuel cells, batteries, low-voltage DC buses or other low-voltage DC sources. The high voltage DC source $V_H$ can be the output of a Boost converter, whose input is a low voltage DC source $V_L$. When the low voltage source $V_L$ fully meets the needs of the output voltage $v_o$, all of the output power can be provided by $V_L$. When the low voltage source $V_L$ cannot meet the requirements of the output voltage $v_o$, the output power is provided by $V_L$ and $V_H$ alternatively. Since part of the input power is directly fed to the inverter from $V_L$, the power losses and power rating of the Boost converter are significantly reduced, which is helpful for the improvement of the overall efficiency.

III. OPERATION PRINCIPLE, MODULATION STRATEGY AND CHARACTERISTICS

The operation principles and characteristics of the proposed DI-DBIs are similar to each other. The DI-DBI shown in Fig. 4(a) is taken as an example for analysis to explain the operation principles and characteristics.

A. Operation Principle

As mentioned above, the dual-input switching cell in a DI-DBI is used as the input stage of a traditional dual-buck inverter. However, the DI-DBI is not a simple combination of two circuits. After the dual-input switching cell and a dual-buck inverter are connected as an integrated inverter topology, both the switches in the dual-input switching cell and the switches in the original dual-buck inverter can be used to regulate the output voltage/current/power of the AC side. Since the dual-input switching cell is the input stage of the converter, the switch $S_H$ and the diode $D_L$ work regardless of whether the converter operates in the positive half-cycle or negative half-cycle of the AC output voltage. On the other hand, the two buck converters in the original dual-buck inverter operate alternatively in the positive and negative half-cycles of the AC output voltage. More specifically, for the DI-DBI shown in Fig. 4(a), the switch $S_1$ is kept ON, $S_3$ and $D_1$ are operated at a high frequency, while $S_2$, $D_2$ and $S_3$ are kept in the OFF state if the DI-DBI operates in the positive half-cycle of the output voltage $v_o$. On the other hand, $S_1$, $D_1$ and $S_2$ are always OFF and $S_2$, $D_2$ and $S_4$ are modulated in the negative half-cycle of the output voltage $v_o$.

Depending on the switching states of these switches, there are a total of six switching states for the DI-DBI shown in Fig. 4(a). The equivalent circuits of these switching states are shown in Fig. 5.

State I [Fig. 5(a)]: The switches $S_{hi}$, $S_1$ and $S_3$ conduct, the other switches and diodes are off. The voltage stress of the diode $D_L$ is clamped by the voltage difference $(V_{hi} - V_L)$. The high voltage source $V_{hi}$ supplies energy to the AC side. The voltage $v_{ab}$ between the mid-points of the two switching legs is clamped by the high side voltage $V_{hi}$, i.e. $v_{ab} = V_{hi}$. The output voltage $v_o$ is in its positive half cycle with $v_o > 0$.

State II [Fig. 5(b)]: The switches $S_1$ and $S_3$ and the diode $D_L$ are ON, while the other switches and diodes are OFF. The
voltage stress of the switch $v_{AB}$ is clamped by voltage difference ($V_H - V_L$). The low voltage source $V_L$ supplies energy to the load. $v_{AB} = 0$ and $v_o > 0$.

State III [Fig. 5(c)]: The switch $S_1$ and the diode $D_1$ are ON, and the other switches and diodes are OFF. The current of the inductor $L_1$ freewheels through the switch $S_3$ and the diode $D_1$. The voltage stress of the switch $S_1$ is $V_L$. Neither the high voltage source $V_H$ nor the low voltage source $V_L$ supply energy to the load. $v_{AB} = 0$ and $v_o > 0$.

State IV [Fig. 5(d)]: The switches $S_2$ and $S_4$ are ON, while the other switches and diodes are OFF. The voltage stress of the diode $D_2$ is clamped by the voltage difference ($V_H - V_L$). The high voltage source $V_H$ supplies energy to the load. $v_{AB} = -V_H$ and $v_o < 0$.

State V [Fig. 5(e)]: The switches $S_2$ and $S_4$ are ON, and the other switches and diodes are OFF. The current of the inductor $L_2$ freewheels through the switch $S_4$ and the diode $D_2$. The voltage stress of the switch $S_1$ is $V_L$. Neither the high voltage source $V_H$ nor the low voltage source $V_L$ supply energy to the load. $v_{AB} = 0$ and $v_o < 0$.

According to the six switching states, the relationship of the switching state, the energy source and the mid-points voltage $v_{AB}$ can be summarized and listed in Table I, where 1 and 0 show when the corresponding switch is in the ON and OFF state, respectively.

From Table I, it can be seen that five voltage levels, i.e. $+V_H$, $+V_L$, $-V_H$, $-V_L$, and $0$, are derived from the mid-points of the switching bridge. When the mid-points voltage $v_{AB}$ is $+V_H$ or $-V_H$, the high voltage source $V_H$ supplies energy to the load. When the mid-points voltage $v_{AB}$ is $+V_L$ or $-V_L$, the low voltage source $V_L$ supplies energy to the load. Neither $V_H$ nor $V_L$ supply energy to the load when $v_{AB}$ is 0. The switches $S_1$ and $S_4$ conduct in the positive and negative half-cycles of the output voltage $v_o$, respectively. As a result, the two switches work at a low frequency. With the proper control method, the mid-points voltage $v_{AB}$ is able to switch between two adjacent voltage levels, so that there is only one switch working at a high-frequency at any given time.

**Table I**

<table>
<thead>
<tr>
<th>Output voltage</th>
<th>Voltage Source</th>
<th>$v_{AB}$</th>
<th>$S_1$</th>
<th>$S_2$</th>
<th>$S_3$</th>
<th>$S_4$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$v_o &gt; 0$</td>
<td>$V_H$</td>
<td>$+$</td>
<td>1</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>$V_L$</td>
<td>$+$</td>
<td>0</td>
<td>1</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>$-$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td>$v_o &lt; 0$</td>
<td>$V_H$</td>
<td>$-$</td>
<td>1</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$V_L$</td>
<td>$-$</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>$-$</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>1</td>
</tr>
</tbody>
</table>
B. Modulation Strategy

The above analysis indicates that the low voltage source $V_L$ can directly supply energy to the load. It also shows that five voltage levels can be obtained from the mid-points of the switching bridge. The multi-level characteristic is helpful to reduce the voltage stress of the switches and the volume/loss of the output filter. It should be noted that unlike traditional multi-level inverters, which generate balanced multiple voltage-levels, the five voltage-levels generated by the DI-DBI are asymmetrical. The low voltage level is not fixed and is determined directly by the low-voltage DC source $V_L.$

In practical applications, the low voltage source $V_L$ of a DI-DBI can be the output of a renewable energy source, a low voltage battery, a DC voltage bus and so on. In other words, the voltage of $V_L$ is directly determined by the DC energy source and can be lower than the peak amplitude of the AC output voltage. However, the high voltage source $V_H$ has to be designed to satisfy the modulation index and the peak voltage of the AC output voltage $v_o.$ The voltage $V_H$ can be generated by the $V_L$ through the front-end Boost converter. In order to reduce the power conversion stages and the power losses of the Boost converter, it is necessary to design a modulation strategy to maximize the input power from the $V_L$ port of the DI-DBI.

Due to the symmetrical configuration of the circuit, the operation of the negative half-cycle is similar to that of the positive half-cycle. Therefore, the positive half-cycle of $v_o$ is taken as an example to explain the modulation strategy and characteristics of the converter. According to the relationship between $V_L$ and the instantaneous value of the output voltage $v_o,$ the inverter has two operation modes in the positive half cycle of $v_o.$ As shown in Fig. 6, the inverter works in mode I when the low voltage source $V_L$ is greater than the instantaneous value of the output voltage $v_o.$ In addition, it can be seen that the DI-DBI works in mode II when the low voltage source $V_L$ is lower than the instantaneous value of the output voltage $v_o.$

Mode I: $V_L \geq v_o$

In this mode, the low voltage source $V_L$ can fully meet the needs of the output voltage $v_o.$ Therefore, the output power of the inverter can be provided directly from the low voltage source $V_L.$ In this mode, the mid-point voltage $v_{AB}$ only needs to be switched between the low voltage level $V_L$ and zero. In other words, the inverter only needs to switch between state II and state III.

Mode II: $V_L \leq v_o$

In this mode, the low voltage source $V_L$ cannot meet the needs of the output voltage $v_o.$ There are two possible modulation strategies. In the first strategy, all of the output power is provided by the high voltage source $V_H.$ The mid-point voltage $v_{AB}$ is switched between the high voltage level $V_H$ and zero. In other words, the inverter only needs to switch between state I and state III. In the second strategy, the output power is provided by both the high voltage source $V_H$ and the low voltage source $V_L.$ The mid-points voltage $v_{AB}$ is switched between the high voltage level $V_H$ and the low voltage level $V_L.$

Fig. 7. Modulation strategies: (a) Control block diagram; (b) Key waveforms.
carrier $v_c$, $v_{PH}$ and $v_{SH}$ are obtained by subtracting $\Delta V_C$ from $v_{NL}$ and $v_{PL}$, respectively. $v_{SH}$ and $v_{SH}=v_{SL}$ are the driving signals of the switches $S_H$ and $S_L$, respectively, and $v_{SL}$ is the voltage between the mid-points of the two switching bridges.

The driving signals $v_{SH}$ and $v_{SL}$ are obtained by comparing $v_{PL}$ and $v_{NL}$ with the carrier $v_c$. Since the switch $S_H$ is shared by positive and negative Buck converters, the drive signal $v_{SH}$ is generated by comparing $v_{PH}$ and $v_{SH}$ together with the carrier $v_c$. In the positive half cycle, when $v_{PL}$ is smaller than $\Delta V_C$, $v_{PH}$ is a negative value and the DI-DBI works in Mode I. In this mode, $S_H$ switches at a high frequency, while $S_L$ is kept off. When $v_{PL}$ is greater than $\Delta V_C$, $v_{PH}$ is a positive value and the DI-DBI works in Mode II. In this mode, $S_H$ switches at a high frequency, while $S_L$ is kept on. Like conventional PWM, the peak value of the modulation wave $v_{PH}$ should satisfy the modulation index and be lower than the peak value of the carrier $v_c$:

$$V_{PH\_peak}\leq \Delta V_C$$  \hspace{1cm} (1)

where $V_{PH\_peak}$ is the peak value of $v_{PH}$. Therefore, the relationship between the peak value of $v_{PL}$ and $\Delta V_C$ should satisfy:

$$V_{PL\_peak}\leq 2 \times \Delta V_C$$  \hspace{1cm} (2)

where $V_{PL\_peak}$ is the peak value of $v_{PL}$.

C. Characteristics and Analysis

The energy directly transferred from $V_L$ to the load is called direct transmitted energy. The energy transferred to the load through the $V_H$ port is called indirect energy. The more direct energy, the higher the system efficiency. The relationship between the direct energy and a low voltage $V_L$ will be analyzed. In order to simplify the analysis, it is assumed that the output voltage $v_o$ is in phase with the output current $i_o$. Due to the symmetrical configuration of the circuit, the following only analyzes the relationship in the positive half cycle.

According the above analysis, when $V_L\geq v_o$, all of the energy of the load is provided by the low voltage source $V_L$. Therefore, the power supplied by the low voltage source $V_L$ is expressed as:

$$p_L = v_o i_o = 2 P_o \sin^2(\omega t)$$  \hspace{1cm} (3)

where $p_L$ is the instantaneous power supplied by the low voltage source $V_L$, and $p_o$ and $P_o$ are the instantaneous and average values of the output power, respectively.

When $V_L\leq v_o$, the energy of the load is provided by both the high voltage source $V_H$ and the low voltage source $V_L$. Therefore:

$$p_H + p_L = p_o$$  \hspace{1cm} (4)

where $p_H$ and $p_L$ are the average power provided by the high voltage source $V_H$ and the low voltage source $V_L$ in every switching period. Therefore, $p_H$ and $p_L$ can be expressed as:

$$p_H = V_H i_o (1 - d_{SH})$$  \hspace{1cm} \hspace{1cm} (5)

where $d_{SH}$ is the duty cycle of the switch $S_H$. In addition, according to the volt-second balance of the filter inductor $L_1$, the duty cycle $d_{SH}$ can be obtained as:

$$d_{SH} = \frac{v_o - V_L}{V_H - V_L}$$  \hspace{1cm} (6)

Substituting equation (6) into (4) and (5) yields:

$$p_L = \frac{V_L (V_H - v_o)}{v_o}$$

For better understanding, the direct power ratio $k_P$ of the average power provided by the low voltage source $V_L$ relative to the total output power in every period of the output voltage is calculated as follows:

$$k_P = \frac{\int_0^\pi p_L d(\omega t)}{\pi P_o}$$  \hspace{1cm} (8)

The curves of the direct power ratio $k_P$ are illustrated in Fig. 8 with the conditions of $v_o = 115\sqrt{2} \sin \omega t$ V and $V_H = 180$V.

IV. EXPERIMENTAL RESULTS

Based on aeronautical applications, a 1kW prototype was built and tested based for the DI-DBI topology shown in Fig. 4 (a). As mentioned above, the advantage of the DI-DBI is its ability to improve the efficiency of a system by reducing the indirect power and increasing the direct power. To evaluate the
Fig. 9. DC-AC system: (a) DI-DBI-based DC-AC system; (b) DBI-based DC-AC system ($v_{AB} = +V_L$, $v_o > 0$).

![Fig. 9](image)

**TABLE II**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_H$</td>
<td>180V</td>
</tr>
<tr>
<td>$V_L$</td>
<td>(60-150)V</td>
</tr>
<tr>
<td>$v_o$</td>
<td>115V/400Hz</td>
</tr>
<tr>
<td>$S_H$</td>
<td>IPB320N20N3G</td>
</tr>
<tr>
<td>$S_1$-$S_4$</td>
<td>IRFB4137PBF</td>
</tr>
<tr>
<td>$D_c$</td>
<td>SBR10A300CTB</td>
</tr>
<tr>
<td>$L_1$+$L_2$</td>
<td>0.3mH</td>
</tr>
<tr>
<td>$C_o$</td>
<td>1μF</td>
</tr>
<tr>
<td>Switching frequency</td>
<td>50kHz</td>
</tr>
</tbody>
</table>

**DI-DBI/DBI**

- $S_a$ = IXF69N30P
- $D_a$ = DPG30C300HB
- $L_a$ = 320uH
- Switching frequency = 100kHz

**Boost**

- Switching frequency = 50kHz

![Fig. 10](image)

![Fig. 11](image)

Effectiveness of this method, a traditional prototype of the DBI has also been built. A Boost converter is used as the front-end DC-DC converter for both the DI-DBI and the DBI. Schematics of the DI-DBI and DBI-based DC-AC systems are shown in Fig. 9. For the DI-DBI-based DC-AC system, the low voltage source $V_L$ and high voltage source $V_H$ are connected to the input and output port of Boost, respectively. By regulating the Boost, $V_H$ is maintained at about 180V. For the DBI-based DC-AC system, the DBI is cascaded with the Boost directly. It should be noted that the parameters, devices and PCB boards of the two DC-AC systems are exactly the same except for the DI cell. The parameters and devices are listed in Table II.

### A. Experimental Waveforms and Analysis

Fig. 10 shows experimental waveforms of $v_{gsH}$, $v_{gs1}$, $v_{gs3}$ and $v_o$ of the DI-DBI with $V_L = 60V$. The positive and negative voltages of the driving signals are +15V and -9V, respectively. In the positive half cycle of $v_o$, the switch $S_3$ remains conductive, while the switches $s_H$ and $s_1$ are alternately operated at a high frequency. When the switch $s_H$ is operated at a high frequency, the switch $s_1$ remains on. When the switch $s_1$ is operated at a high frequency, the switch $s_H$ remains off. In the negative half cycle of $v_o$, the switches $s_1$ and $s_3$ are kept off while the switch $s_H$ is still operated at a high frequency. In the positive half cycle of $v_o$, the switch $s_H$ in high frequency operation, $V_L \leq v_o$. Meanwhile, when the switch $s_1$ is in high frequency operation, $V_L \geq 2v_o$. Obviously, when $V_L = 60V$, because the voltage of $V_L$ is relatively low, the high frequency working time of the switch $s_1$ is relatively short and the high frequency working time of the switch $s_H$ is relatively long. The experimental waveforms are consistent with the theoretical analysis. Fig. 11(a) and Fig. 11(b) show the waveforms of $i_{L1}$, $i_{L2}$, $v_{AB}$ and $v_o$ with $V_L = 90V$ and $V_L = 150V$, respectively, where $i_{L1}$ and $i_{L2}$ represent the current through the inductors $L_1$ and $L_2$, respectively. It can be seen that the inductors $L_1$ and $L_2$ operate in the positive and negative half cycles of $v_o$, respectively. Five voltage levels are obtained from the mid-points of the switching bridge. Unlike the usual five-level characters, the low voltage level $V_L$ is variable. When $V_L = 90V$, the five levels are symmetrical while
they are asymmetrical when $V_L = 150V$. In addition, it can be seen form Fig. 11(b) that the high frequency working time of the switch $s_1$ is relatively long since the voltage of $V_L$ is relatively high.

Fig. 12(a) shows dynamic waveforms of the DI-DBI with a load step-up when the output voltage of $v_o$ is regulated. It can be seen that the output voltage can be well controlled. Fig. 12(b) shows dynamic waveforms of the DI-DBI with $V_L$ increases when the output voltage of $v_o$ is regulated. It can also be seen that the output voltage can be well controlled.

B. Comparative Analysis

To help the design tradeoff and topology selection, a comparison between DC-AC systems based on the proposed DI-DBI and the traditional DBI-based is necessary.

The efficiency and THD are tested by a power analyzer WT1806 of YOKOGAWA. Fig. 13 shows a wiring diagram for the efficiency and THD tests, where $I_B$ and $U_B$ are the input current and voltage of the Boost converter, $I_L$ and $V_L$ are the input current and voltage of the $V_L$ port of the DI-DBI, $I_H$ and $V_H$ are output current and voltage of the Boost converter, and $I_o$ and $V_o$ are output current and voltage of the DI-DBI, respectively. In the tests, the efficiencies of the Boost, the DI-DBI and the entire DC-AC system are defined as follows:

$$\eta_{\text{BOOST}} = \frac{V_B I_H}{V_B I_B} \times 100\%$$

$$\eta_{\text{DIDBI}} = \frac{V_o I_o}{V_L I_L + V_H I_H} \times 100\%$$

$$\eta_{\text{DC-AC}} = \frac{V_o I_o}{V_B I_B + V_L I_L} \times 100\%$$

Efficiency comparison results between the proposed DI-DBI and the traditional DBI are shown in Fig. 14, where Fig. 14(a) shows the tested efficiency and Fig. 14(b) shows the calculated power loss distribution of the DI-DBI. It can be seen in Fig. 14(a) that the efficiency of the DI-DBI is higher than that of the DBI. In addition, the value of $V_L$ has little impact on efficiency. It can be seen in Fig. 14(b) that although more conductive losses are caused by the addition of $S_H$ and $D_L$, the switching loss of the proposed DI-DBI is reduced significantly thanks to its multilevel characteristics. The total losses of the proposed DI-DBI are lower than those of the traditional DBI, which shows good agreement with the tested results.

Fig. 15 shows an efficiency comparison between DI-DBI-based and traditional DBI-based DC-AC systems, where Fig. 15(a) and Fig. 15(b) show the DC-AC system’s tested efficiency results, and Fig. 15(c) shows the calculated power loss distribution between the front-end Boost and the down-stream inverter. It can be seen from Fig. 15(a) and Fig. 15(b) that the efficiency improvement of the proposed DI-DBI-based DC-AC system increases with an increase of
Fig. 15. Efficiency comparison between DI-DBI-based and traditional DBI-based DC-AC systems: (a) Tested results with \( V_L = 60\,\text{V} \) and \( V_L = 120\,\text{V} \); (b) Tested results with \( V_L = 90\,\text{V} \) and \( V_L = 150\,\text{V} \); (c) Power loss distribution.

\( V_I \), and that the efficiency is improved by 1.2% to 1.8%. It can be seen from Fig. 15(c) that the power loss of the frond-end Boost in the DI-DBI-based DC-AC system is smaller than that of the traditional DBI-based DC-AC system and that this advantage becomes more obvious when \( V_L \) increases. This is because the power and loss of the frond-end Boost in the proposed system are greatly reduced. Together with the efficiency improvement of the inverter, the efficiency improvement of the proposed DI-DBI-based DC-AC system is more obvious, which coincides with the tested results. The efficiency results verify the effectiveness of the DI-DBI in improving the efficiency of the system.

Thanks to the multi-level characteristics, the harmonics of \( v_{AB} \) and can be improved when compared with the traditional DBI. Fig. 16 shows comparison results of the THD of \( v_{AB} \). It can be seen that the THD of \( v_{AB} \) in the DI-DBI is much better than that of the DBI in the whole range of \( V_L \). In addition, the calculated and simulated results coincides with the tested results very well.

The tested results are a little lower than the calculated and simulated results. This is caused by the bandwidth limitation of the power analyzer. Fig. 17 shows the harmonic spectrum analysis of \( v_{AB} \) with \( V_L = 100\,\text{V} \) and \( V_L = 150\,\text{V} \). It can be seen that the harmonic spectrum is distributed around the switching frequency and the integer times of the switching frequency. In addition, the harmonic component when \( V_L = 150\,\text{V} \) is higher than that when \( V_L = 100\,\text{V} \). Fig. 18 shows the THD of the output current \( i_o \) in the DI-DBI. After filtering, the value of the THD is about 2% in the whole range of \( V_L \), which indicates the effectiveness of the DI-DBI in improving THD.
TABLE III
VOLUME COMPARISON OF THE INDUCTORS FOR THE TWO
DC-AC SYSTEMS

<table>
<thead>
<tr>
<th>Inverter</th>
<th>DI-DBI-based</th>
<th>Full-bridge-based</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductor value</td>
<td>0.3mH</td>
<td>0.46mH</td>
</tr>
<tr>
<td>Current through inductor</td>
<td>RMS:6.149A</td>
<td>RMS:8.696A</td>
</tr>
<tr>
<td>Type</td>
<td>Peak:12.3</td>
<td>Peak:12.3</td>
</tr>
<tr>
<td>Core</td>
<td>NPF157026</td>
<td>NPF200026</td>
</tr>
<tr>
<td>Outer Diameter</td>
<td>3.988cm</td>
<td>5.08cm</td>
</tr>
<tr>
<td>Height</td>
<td>1.448cm</td>
<td>1.346cm</td>
</tr>
<tr>
<td>Number of winding</td>
<td>90</td>
<td>119</td>
</tr>
<tr>
<td>Inductor value</td>
<td>0.32mH</td>
<td>0.32mH</td>
</tr>
<tr>
<td>Current through inductor</td>
<td>RMS:13.55</td>
<td>RMS:16.67</td>
</tr>
<tr>
<td>Type</td>
<td>RMS:16.3</td>
<td>RMS:19.5</td>
</tr>
<tr>
<td>Boost</td>
<td>POCO</td>
<td>POCO</td>
</tr>
<tr>
<td>Core</td>
<td>NPF200026</td>
<td>NPF225026</td>
</tr>
<tr>
<td>Outer Diameter</td>
<td>5.08cm</td>
<td>5.715cm</td>
</tr>
<tr>
<td>Height</td>
<td>1.346cm</td>
<td>1.397cm</td>
</tr>
<tr>
<td>Number of winding</td>
<td>100</td>
<td>97</td>
</tr>
<tr>
<td>Inductor volume</td>
<td>2*28.87cm³</td>
<td>42.49cm³</td>
</tr>
<tr>
<td>Total</td>
<td>103.51 cm³</td>
<td>104.45cm³</td>
</tr>
</tbody>
</table>

Fig. 19. Picture of the inductors in DI-DBI-based and full-bridge-based DC-AC systems.

It is well known that the DBI has one more inductor when compared with the traditional full-bridge inverter which seems to be bad for the power density and cost. A volume comparison of the inductor between DI-DBI-based and traditional full-bridge-based DC-AC systems are listed in Table III. Fig. 19 shows a picture of the inductors in the two system, where $L_1$ and $L_2$ are the inductors of the DI-DBI, $L_B$ is the inductor of the full-bridge and $L_B$ is the inductor of the Boost. The values of inductors of the two systems are calculated according to the current ripple requirements. Thanks to the multi-level effects, the single inductor value of the DI-DBI is smaller than that of the full-bridge. Secondly, the RMS value of the current though the inductor of the DI-DBI is smaller than that of the full-bridge since the inductor only works in half a cycle. Thirdly, the power of front-end Boost is largely reduced in the DI-DBI-based DC-AC system. As a result, the current through the inductor of the front-end Boost in the proposed DC-AC system is smaller than that in the traditional full-bridge-based DC-AC system. Therefore, although one more inductor is used in the proposed DC-AC system, the total volume of the two systems is about the same.

The power density of an inverter is determined by the inductors. In addition, it is also affected a lot by the thermal stress, heat sink, mechanical stress, etc. Since higher efficiency is achieved, the thermal stress is reduced. In addition, a lot of work has been done to reduce the volume and weight of the output filtering inductor [21]-[23] which can be used to further optimize the inductor of the DI-DBI.

V. CONCLUSIONS

A family of dual-DC-input dual-buck inverters (DI-DBIs) has been proposed for efficiency improvements. A low DC-input port is introduced to a traditional DBI by employing a dual-input switching cell as the input of the DBI. As a result, a low voltage source, whose voltage is lower than the peak amplitude of the AC output voltage, can be directly connected to the DBI to supply power to the AC side in single-stage power conversion. The advantages of high efficiency and high reliability of a traditional DBI can be achieved with the proposed DI-DBIs. In addition, theoretical analysis and experimental verifications indicate that the proposed DI-DBIs have a number of advantages. 1) The conversion stages of a DI-DBI-based DC-AC power system are reduced, since part of the DC input power can be directly fed to the AC side within a single power conversion stage. 2) The power rating and power losses of the front-end Boost converter are reduced. 3) Multi-level characteristics are achieved with the DI-DBIs, which can help to reduce the switching losses and the volume of the output filter. All these features make the proposed DI-DBIs good candidates for high-efficiency and high-reliability DC-AC power systems.

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REFERENCES


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