A Review of Bidirectional Dual Active Bridge Converter

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Abstract—To have a systematic synthesis and galvanic isolation, it is common to use a full-bridge bidirectional DC-DC converter which is sometimes called dual active bridge. A comparative evaluation of full-bridge based bidirectional DC-DC converter is presented in this paper. Basic operation, control algorithm, advantages and disadvantages of several types of bidirectional converters are explained.

Keywords—bidirectional converter; full bridge; soft switching; resonant converter; phase shift

I. INTRODUCTION

Nowadays with the growth of electricity demand, concern about environmental issues and possible energy crisis, hybrid systems based on renewable energy resources have been received more attentions [1]-[27]. All renewable energy resources have an inherent feature that varies randomly [1], resulting in an energy storage system is needed to provide clean and safe power for loads [2]. Bidirectional DC/DC converters as a key component in hybrid systems, interface between renewable energy resources such as a fuel cells or a photovoltaic (PV) arrays and energy storage elements such as a batteries and supercapacitors. They are used in many applications such as hybrid electric vehicles [3]-[7], distribution systems [8]-[10], electric aircrafts [11] and uninterruptable power supplies (UPS) [12].

Presented methods provided many different configurations for bidirectional DC-DC converters which can be classified into two major groups. One is nonisolated type that is commonly based on switched-capacitor converters [13], interleaving techniques [14], or using coupled-indicators [15]-[16]. If high-voltage ratio and isolation are not required, this type is always employed due to its simple structure and control scheme. In the isolated type a high frequency transformer is employed as a key component to provide voltage gain ratio and galvanic isolation. When high power density is required, it is common to use a dual active bridge (DAB) topology to control the power flow and generate an output voltage that is higher or lower than the transformer input voltage [1]-[12],[17]-[27].

There are plenty of control algorithms and configurations to achieve soft-switching conditions in DAB bidirectional DC-DC converter (BDC). The soft-switching conditions reduce the switching losses and electromagnetic interferences (EMI). Also the switching frequency can be increased to enhance the converter power density. Phase-shift control, model based phase-shift control and phase-shift plus pulse-width-modulation (PWM) control, are the commonly used control methods.

A traditional DAB BDC is shown in Fig. 1 that was presented in [24]. With advancements in power devices technology such as developing trench-gate IGBT, and employing new enhanced control algorithms for expanding soft-switching range [1],[5], BDCs are introduced efficiencies over 97% [18]. Also increasing the efficiency up to 99% would be attainable by using SiC-MOSFETs [18].

II. CONVERTER OPERATION

The conventional full-bridge (FB) based isolated BDC (Fig. 1), includes a high-frequency transformer which is primarily used to maintain galvanic isolation between input and output terminals. For this converter $V_a$ is the input voltage, $V_b$ is the output voltage, $n$ is the transformer turns ratio of, $\phi$ is phase shift between two ac voltage, $(V_{ac,A}$ and $V_{ac,B})$, and $L_k$ represents the sum of primary-referred transformer leakage inductance and an optional external inductor. The key waveforms of this converter are shown in Fig. 2. In this converter, each bridge generates a square-wave voltage. The two voltages $V_{ac,A}$ and $V_{ac,B}$ are phase-shifted with respect to each other with the angle of $\phi$ to control the amount of power flow through the inductor $L_k$. The average of transferred power can be expressed as

$$P = \frac{V_a V_b}{2 n L_k} \left( 1 - \frac{\phi}{\pi} \right)$$

Leading or lagging phase shift (to transfer power from A to B or B to A respectively) is implemented by proper timing control of the converter switches.

Figure 1. The conventional full bridge based isolated bidirectional DC-DC converters
This method suffers from high circulating-current, therefore is not proper for wide range of operation. The soft-switching range depends on the dc voltage conversion ratio which defines as \( d = V_d/(nV_{dc}) \). If the input voltage changes in a wide range, soft-switching may be lost [7]. For the side-A, hard-switching can be occurred when \( d > 1 \). Under idealized conditions the soft-switching operation range is as

\[
|\phi| > \frac{\pi}{2} \left(1 - \frac{1}{d}\right)
\]

(2)

For the side-B, hard-switching can be occurred when \( d < 1 \) and the soft-switching operation range is as

\[
|\phi| > \frac{\pi}{2} (1 - d)
\]

(3)

Full control range under soft-switching is achievable for \( d = 1 \). [19]

II. BIDIRECTIONAL of DC-DC CONVERTERS BASED ON DAB

Fig. 3 depicts several methods to achieve soft-switching conditions for the switches. As shown in Fig. 3a, a simple method to achieve ZVS operation is placing an external capacitor in parallel with the switches which along with the parasitic capacitance holds the switch voltage constants during transition intervals. According to [17], the switches losses are proportional to the capacitance exists in parallel with switch. This converter operates in ZVS only in specific conditions. This method suffers from high circulating-current, therefore is not proper for wide range of operation.

The other methods for achieving special features such as high current and high voltage conversion ratio are presented in Fig 3b to 3d which are respectively active-clamp, passive-clamp and flyback [20]-[21]. In active- or passive-clamp, the DC-link inductor is placed at low voltage side to minimize the current ripple and improve the battery charging efficiency. However in converter with active clamp due to the difference of current between the DC-link and the transformer leakage inductance, the converter needs a large clamping snubber capacitor [20]. The soft switching method presented in [2] reduces the power that flows into the passive snubber, nevertheless it cannot achieve ZVS for all switches. In the converter with a flyback snubber (Fig. 3d), \( C_C \) and \( D_C \) absorb the current difference between the magnetizing inductor \( L_m \) and the transformer leakage inductance. Spike current circulating through the power switch is omitted, so system reliability is significantly improved [21]. These advantages are thanks to using several auxiliary devices which increase the converter size and cost.

The voltage-fed FB with voltage doubler bidirectional DC-DC converter is shown in Fig 3e [12]. All the switches are turn-on under ZVS in an expanded range by using phase-shift modulation and phase-shift with duty cycle control algorithms. The average of transferred power in the two operating modes that are designated as stable operation and dynamic operation, is calculated to be as [19]

\[
P = \frac{V_A V_B}{2 L_{m0} \omega_k} \left[ 1 - \frac{\phi}{\pi} \right]
\]

(4)

\[
P = \frac{V_A V_B}{4 L_{m0} \omega_k} \left[ \frac{1}{\pi} - \phi + D - \phi \left(1 + \frac{\phi - D}{\pi}\right) \right]
\]

(5)

According to (4), in the dynamic operation at a given phase shift more power is transferred, comparing with the condition in which only phase shift has been employed. Using hybrid modulation method makes the converter controller more complicated for analysis and design, and needs digital signal processors.

Hybrid converters, are new structures for high current isolated BDCs [3],[22]. Two transformers are employed to associate with a half-bridge circuit and a FB circuit as shown in Fig. 3f. For this porpuse, it is common to use magnetic integration with planner core for reducing the converter size and increasing the converter efficiency and power density. In [22] one boost inductor and two transformers are integrated into one E-I-E core which introduces higher magnetizing inductance which comparing to the separated transformers reduces current stresses. When input voltage varies over a wide range, \( S_1 \) and \( S_2 \) are controlled by the duty cycle to reduce the current stresses. \( C_2 \) is added in series with primary winding of \( T_2 \) to block DC-voltage over the transformer.

A ZVZCS full-bridge BDC with small ripple of input current and small ripple of output voltage is proposed in [8] as shown in Fig 3g. The transformer leakage inductance and one capacitor are utilized to create a resonant network. This converter has a symmetric switching pattern. For achieving ZVS turn-on, before turning the main switch on, the switches voltage is discharged to zero. At the same time, the circuit current starts a resonant via the LC network. Hence, before the switch is turned off and the current falls to zero, both of main switches can be commutated under the ZCS.

Fig. 3h presents a topology based on series resonant converters. All switches may work in ZVS or ZCS for wide variations in load or the supply voltage. For this topology two ac equivalent circuits with acceptable accuracy that simplify the design procedure are presented in [1]. To ensure a comparable level of power transfer for both directions, [4] presents a topology composed of two resonant converters showing in Fig. 3i. This circuit has different resonant capacitors for each power flow direction. The switch \( k \) which can be a mechanical switch or a bidirectional semiconductor switch is used for adding the \( C_{odd} \). In the boost mode, the...
switch \( k \) is close and in the buck mode is open. The multi-resonant tank is another choice for providing soft-switching condition in BDCs. A fully soft-switched one is described in [23] (fig 3j) where by merging two LLC resonant tanks a new CLLC resonant tank is developed. ZVS for the inverting switches and ZCS for the rectifying switches are attained. A drawback of series resonant converters is that the series capacitor has to handle the full-load current, resulting in the increase of volume and cost [20].

A BDC based on DAB is presented in Fig. 4a [25]. In this converter the output voltage of the power source on HV side and DC current passing through power source on the LV side can be shared. Therefore the rated capacity to be processed by the transformer, transformer size and losses are decreased but the proposed converter has no function to isolate the input and output power terminals.

Multi-port DC–DC converters are used in applications utilizing multiple sustainable energy resources which could accommodate different sources and combine their advantages. Reference [9] introduces a family of multiport BDCs, with a simple topology and minimum number of power devices by using a combination of DC-link and magnetic coupling that is shown in Fig 4c. The basic switching cells (Fig. 4b) comprise of the canonical switching cell, boost-half-bridge cell and half-bridge cell. The full bridge is a basic cell, although it is not shown in Fig 4c. For the case where there is only one source coupled to the winding and the operation mode is square wave, the full bridge and the half bridge are interchangeable. Within the DC bus and between the DC buses, the power flow can be controlled respectively by duty cycle and phase shifts of the voltages applied to the transformer windings. A three-port bidirectional series-resonant converter with high voltage gain is proposed in [10]. This converter has two phase-shift control variables \( \phi_{13} \) and \( \phi_{12} \) as shown in Fig. 4d.

Phase shift control [21], PI controller [19], model based phase shift control [26], phase shift plus duty cycle control [3],12,23 and model based for the digital control [28] are the most widely used algorithms. Advantages of a digital implementation are a considerably higher flexibility compared to analog electronics, a high EMI immunity and the enhanced possibility of process and fault monitoring using an external interface or a network connection. Table 1 summarizes the purposes of different control algorithms. Dual-phase-shift control method depicted in [27] which introduces another phase shift between \( Q_i \) and \( Q_{i+2} \) (in Fig. 1 \( i = 1, 2, 5, 6 \)). Therefore, the primary and secondary voltages will have variable pulse-width, not fixed at one half period. However it is rather complicated to modulate two phase-shift controllers simultaneously.

<table>
<thead>
<tr>
<th>Control Algorithm</th>
<th>Purpose</th>
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<tbody>
<tr>
<td>Phase shift</td>
<td>control the power direction</td>
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<tr>
<td>Model base</td>
<td>Improve the dynamic performance</td>
</tr>
<tr>
<td>Phase shift plus PWM</td>
<td>More flexible control and expanding soft switching range</td>
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<tr>
<td>Dual phase shift</td>
<td>Eliminating reactive power</td>
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III. Conclusion

Several full-bridge-based isolated bi-directional DC-DC converters have been reviewed and compared. Snubber minimizes the ripple current and reduces current circulating through the power switches. Hybrid converters are new structures for high current isolated DC-DCs. By using topologies based on series resonant converters, all switches may work in ZVS or ZCS for wide variation of load or supply voltage. The full bridge can be employed in multi-port converters. Proper control algorithms such as phase-shift modulation and phase-shift with duty cycle control algorithms, expand the operating voltage range.

REFERENCES


