Bidirectional Double-Boost DC-DC Converter

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Abstract This paper presents a novel bidirectional DC-DC converter with high conversion ratio for the renewable energy systems. The proposed converter uses the coupled-inductor technique to achieve high conversion ratio. Besides, this converter has simple circuit topology and simple control technique. In the discharging mode, the proposed converter likes two stage boost converters and only needs to control one active switch that can achieve high voltage step-up ratio conversion. When the charging mode, it likes two buck converters in cascaded, and the active switches are operated in the same duty cycle that can achieve high voltage step-down ratio conversion. This paper has analysed the proposed converter operating principles, steady-state circuit characteristics. Eventually, a prototype circuit with conversion voltage 12 V/100 V. The maximum efficiency is obtained at both discharging and charging mode respectively.

Keywords — Bidirectional converter, high conversion ratio, coupled-inductor.

I. INTRODUCTION

The bidirectional DC-DC converter is currently widely used in many renewable energy applications. The conventional boost/buck bidirectional converter with very high or very low duty ratio can achieve the high step-up/down voltage conversion ratio. However, the extreme duty ratio will significantly reduce the conversion efficiency because of the effects of parasitic elements [5]. In previous studies, the bidirectional converter has been classified into two types, namely, isolated and non-isolated types. Moreover, the high voltage conversion ratio of bidirectional DC-DC converters is achieved by adjusting the turns ratio of the isolated transformer. For example, the bidirectional forward flyback/flyback DC-DC converter is a simple and low cost configuration. However, it is only suitable in low power applications because of its high voltage stress and leakage inductance energy. Moreover, the higher-power applications, namely, bidirectional full-bridge/half-bridge/push-pull DC-DC converters, and bidirectional DC-DC converters can be used. [6]–[8]. The proposed converter was used for the bidirectional transfer of the energy between the low voltage side VL, which was connected to a 12 V battery, and the high voltage side VH, which was connected to 100 V DC bus. Fig. 1 shows the proposed converter circuit with leakage.

II. PROPOSED BIDIRECTIONAL CONVERTER

A. Discharging mode

The power switch S1 is the main power switch. The switches S2 and S3 are turned off during entire period but its body diodes DS2 and DS3 are concerned. The typical waveforms of the proposed converter in the discharging mode are shown in Fig. 2. The operating principles during one switching cycle are described as follows:

Mode I: [t0 ~ t1]

In this mode, switch S1 and diode DS3 are turned on. The equivalent circuit is shown in Fig. 3(a). The energy stored in the leakage inductor LK2 is released to the capacitor C2. The leakage inductor current iLk2, namely iS3, is decreased gradually. The battery voltage VL releases its energy to the leakage inductor LK1. So the leakage inductor current iLk1 is increased rapidly. Meanwhile, the magnetizing inductance current iLm is equal to iLk1 + nLk2, where n = NS/NP. This mode ends when the current iS3 is reduced to zero and diode DS3 is turned off.

\[
v_s = v_L - v_{Lk1}\]  

\[
v_{C2} = v_{LK2} + v_n + v_s\]  

Mode II: [t1 ~ t2]

In this mode, switch S1 and diode D4 are turned on. The equivalent circuit is shown in Fig. 3(b). The magnetizing inductor Lm and the leakage inductor LK1 is charged by the battery voltage VL. The magnetizing- inductor current iLm and the leakage-inductor current iLk1 are increased linearly. In addition, the battery voltage VL transfers its energy to the capacitor C2 by the secondary winding NS and diode D4. So the voltage across the capacitor C2 is charged to nVL. This mode ends when switch S1 is turned off.

\[
v_p = v_L - v_{Lk1}\]
\[ V_z = V_{C2} - V_{LK2} \]  

(4)

**Mode III**: \([ t_2 - t_3 ]\)

In this mode, switch S1 is turned off, the diodes DS2 is turned on and DS3 are turned off. The equivalent circuit is shown in Fig. 3(c). The energies of the leakage inductor LK1 and LK2 are released to the capacitor C2 through DS2 and D4 respectively. This mode ends when the current iLK2, namely iD4, is equal to zero and diode D4 is turned off.

\[ V_p = V_L - V_{LK1} - V_{C2} \]  

(5)

\[ V_z = V_{C2} - V_{LK2} \]  

(6)

**Mode IV**: \([ t_3 - t_4 ]\)

In this mode, switch S1 is turned off, diodes DS2 and DS3 are turned on. The equivalent circuit is shown in Fig. 3(d). The energies of the battery voltage VL, the magnetizing inductor Lm, and the leakage inductor LK1 are released to the capacitor C2 through DS2. Moreover, the part energy of the magnetizing inductor Lm is transferred to the capacitor CH and the load RH by the secondary side of the coupled inductor. This mode ends when the voltage across C2 is equal to nVin.

\[ V_{C2} = V_z - V_p - V_{LK1} \]  

(7)

\[ V_z = V_L - V_p - V_{LK1} - V_{LK2} - V_H \]  

(8)

\[ V_z = nV_p \]  

(9)

\[ V_{LK2} = nV_{RH2} \]  

(10)

Substituting (9) and (10) into (8), yielding

\[ V_p = \frac{V_L - V_H - V_{LK1}}{1 + \frac{1}{n}} \]  

(11)

\[ V_z = \frac{V_L - V_H - V_{LK2}}{1 + \frac{1}{n}} \]  

(12)

**Mode V**: \([ t_4 - t_5 ]\)

In this mode, switch S1 is turned off, diodes DS2 and DS3 are turned on. The equivalent circuit is shown in Fig. 3(e). The energy of magnetizing inductor Lm is released to the capacitor CH via the coupled-inductor and diode DS3. The magnetizing-inductor current iLm is decreased linearly. The energy stored in capacitor C2 is transferred to CH and the load RH. This mode ends when switch S1 is turned on.

\[ V_p = \frac{V_L - V_H - V_{LK1}}{l + n} \]  

(13)

\[ V_p = \frac{\alpha V_L - V_H - V_{LK2}}{l + n} \]  

(14)

\[ V_{C2} = V_H + V_{LK2} + V_H \]  

(15)

**Mode VI**: \([ t_5 - t_6 ]\)

In this mode, switch S1, diodes DS2 are turned off and DS3 is turned on. The equivalent circuit is shown in Fig. 3(f). The energy of the magnetizing inductor Lm is released to the capacitor CH and the load RH via the secondary side of the coupled-inductor and diode DS3. The energy stored in capacitor C2 is also transferred to CH and the load RH. This mode ends when switch S1 is turned on.

\[ V_z = V_{C2} - V_{LK2} - V_H \]  

(16)

\[ V_p = \frac{V_{C2} - V_{LK2} - V_H}{n} \]  

(17)

Fig. 2. Typical waveforms in discharge mode
The average magnetizing-inductor voltage $V_{Lm}$ over one switching cycle is zero during steady-state. Since the leakage inductors $L_{K1}$ and $L_{K2}$ are much smaller than the magnetizing inductor $L_{m}$, the time intervals $t_0$-$t_1$ and $t_2$-$t_3$ can be omitted. The storing energy time interval for $L_{m}$ is Mode II, thus the voltage across $L_{m}$ equals $V_{L}$. Other time intervals of energy releasing for $L_{m}$ are Mode IV and Mode VI, and the voltage across $L_{m}$ is $(nV_{L}-V_{H})/n$. According to the voltage-second balance principle in the magnetizing inductor $L_{m}$, the following equation is given by

$$V_{Lm} = \frac{\tau}{1-D}$$

(19)

**B. Charging mode**

The power switches $S_2$ and $S_3$ are controlled by the same gate deriver single. Another power switch $S_1$ has served as diode $D_{S1}$. The typical waveforms of the proposed converter in the charging mode are shown in Fig. 4. The operating principles during one switching cycle are described as follows:

![Fig.4. Typical waveforms in charging mode](image)

**Mode I** : $(t_0 \sim t_1)$

In this mode, diode $D_{S1}$ is turned on. The equivalent circuit is shown in Fig. 5(a). The magnetizing inductor $L_{m}$ releases its energy to the capacitor $C_{1}$ and the load $R_{L}$. The magnetizing current $i_{Lm}$ is decreased linearly. The DC bus voltage $V_{H}$ is released its energy to capacitors $C_{2}$, $C_{L}$ and load $R_{L}$. This mode ends when the energy stored in $C_{2}$ is released to load $R_{L}$.

**Mode II** : $(t_1 \sim t_2)$

In this mode, switches $S_2$ and $S_3$ are turned on and diode $D_{S1}$ is turned off. The equivalent circuit is shown in Fig. 5(b). The magnetizing inductor $L_{m}$ is charged by the voltage source $V_{H}$. The voltage across the primary winding equals $V_{p}$. The magnetizing-inductor current $i_{Lm}$ is increased linearly. The energy stored in the leakage inductor $L_{k2}$ is recycled to the capacitor $C_{2}$. This mode ends when the current $i_{Lm}$ is reduced to zero.
Mode III: \([t_2 \rightarrow t_3]\)

In this mode, switches S2 and S3 are turned on and the diodes DS1 and D4 are turned off. The equivalent circuit is shown in Fig. 5(c). The voltage source VH and capacitor C2 release their energies to the magnetizing inductor \(L_m\), capacitor CL and load \(R_L\). The magnetizing-inductor current \(i_{Lm}\) is increased linearly. This mode ends when the switches S2 and S3 are turned off.

\[
\begin{align*}
V_S &= V_H - V_{LK2} - V_{C2} \\
V_F &= V_H - V_L - V_{DO} - V_D - V_L \\
V_{C2} &= V_H - V_{LK2} - \nu_1
\end{align*}
\]

Substituting (25) and (26) into (23)

\[
\begin{align*}
\nu_S &= \frac{V_H - V_L}{1 + n} - V_{LK1} \\
\nu_F &= \frac{n(V_H - V_L)}{1 + n} - V_{LK2}
\end{align*}
\]

Mode IV: \([t_3 \rightarrow t_4]\)

In this mode, switches S2 and S3 are turned off and diode DS1 is turned on. The equivalent circuit is shown in Fig. 5(d). The energies of leakage inductors \(L_{K1}\) and \(L_{K2}\) are released to the capacitors CL and C2 by DS1 and D4 respectively. This mode ends when the energy stored in leakage inductor \(L_{K2}\) is released to zero.

\[
\begin{align*}
\nu_S &= V_{C2} - V_{LK1} \\
\nu_F &= \nu_L - V_{LK1}
\end{align*}
\]

Mode V: \([t_4 \rightarrow t_5]\)

In this mode, switches S2 and S3 are turned off and diode DS1 is turned on. The equivalent circuit is shown in Fig. 5(e). The magnetizing inductor \(L_m\) not only releases its energy to the capacitor CL and the load \(R_L\) but also transfers energy to capacitor C2 by the secondary winding NS and diode D4. The magnetizing-inductor current \(i_{Lm}\) is decreased linearly.

\[
\begin{align*}
V_S &= V_{C2} - V_{LK1} \\
V_F &= \nu_L - V_{LK1}
\end{align*}
\]

The main interval of storing energy for \(L_m\) is Mode III, and the voltage across \(L_m\) equals \((V_H - V_L)/(1 + n)\). The main intervals of releasing energy for \(L_m\) are Mode V, and the voltage across \(L_m\) is \((-V_L)\). The following equation can be derived by using the voltage-second balance principle in \(L_m\).

\[
\frac{V_H - V_L}{1 + n} + T_{DS} \cdot \frac{(-V_L)}{1 - n} + D_{DS} = 0
\]

Thus, the voltage gain can be derived as follows:

\[
\frac{V_L}{V_H} = \frac{D}{1 + n - nD}
\]
III. EXPERIMENTAL RESULTS

A prototype circuit of the proposed converter is built to verify the feasibility. The specifications and component parameters are selected as:

\[ V_L = 12 \text{ V}, \quad V_H = 100 \text{ V}, \quad f_s = 50 \text{ kHz}, \quad n = 3, \quad L_m = 37 \mu\text{H}, \quad C_L = C_H = 1000 \mu\text{F}, \quad \text{and} \quad C_2 = 330 \mu\text{F}. \]

The power switch \( S_1, S_2 \) and \( S_3 \) are IRFP250N; and the diode \( D_4 \) is U1560. The discharging mode is \( D = 70 \% \) and charging mode is \( D = 30 \% \).

Fig. 6 shows the experimental waveforms in the discharging mode at full load condition. Fig.6(a) shows switch voltage \( V_{DS} \) across \( S_1 \) and diode \( D_4 \). Fig.6(b) shows switch voltage \( V_{DS} \) across \( S_2 \) and \( S_3 \). Fig. 7 shows the experimental waveforms in the charging mode at full load. Fig.7(a) shows switch voltage \( V_{DS} \) across \( S_2 \) and \( S_3 \). Fig.7(b) shows switch voltage \( V_{DS} \) across \( S_1 \) and diode \( D_4 \).

Fig. 8 shows the experimental setup of the proposed converter.

IV. CONCLUSION

This paper presents a novel bidirectional DC-DC converter for the renewable energy systems. This converter can achieve steep voltage conversion ratio by using the coupled-inductor technique. The voltage stress on the power devices is reduced by a clamping circuit, and the leakage-inductor energy can be recycled. From the experimental results, it is seen that the experimental waveforms agreed with the operating principle and steady-state analysis. Eventually, the efficiency in full load condition either in discharging mode or charging mode are over 90 \%.
REFERENCES


