Design and Implementation of a Bidirectional DC-DC Forward/Flyback Converter with Leakage Energy Recycled

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***Abstract*—A bidirectional interleaved forward-flyback DC-DC converter with leakage energy recycled is proposed in this paper. The proposed converter uses two transformers to reduce the current stress on the power components to reduce the conduction loss and improve the efficiency. When the proposed converter is operated in the step-up mode, the voltage across switches is clamped at the input voltage, and the leakage energy is recycled to the voltage source. When the proposed converter is operated in the step-down mode, the voltage of switches is clamped at the input voltage, and the leakage energy is recycled to the clamping capacitor or the voltage source. As the proposed converter is based on flyback converter, it is characterized with simple structure. Since the leakage inductance energy is recycled, the conversion efficiency is improved compared to conventional flyback converter. Finally, a laboratory prototype circuit with 200 V/24 V and output power 500 W is implemented to verify the feasibility of the proposed converter. The highest efficiency in the step-up and step-down stage is 92.3% and 95.5% respectively.**

***Keywords*—forward/flyback converter, leakage energy recycled, bidirectional converter**

I. INTRODUCTION

The renewable energies, such as photovoltaic power, wind power, and ocean current, are not stable compared to the conventional power generation system. To overcome the unstable drawbacks of renewable energies, battery is treated as an importance energy storage component in the renewable power system. The bidirectional DC-DC converter is required to regulated the power between the battery and dc-bus in the battery integrated renewable energy system. When the green energy generates higher energy than the need for load, surplus energy is transferred from the DC bus to the battery through the bidirectional DC-DC converter. When the green energy can't provide sufficient energy to the load, the battery releases the stored energy to the DC bus. Therefore, the load can receive stable and sufficient energy and is not affected by the unstable green energy.

The bidirectional DC-DC converter can be divided into non-isolated topology and isolated topology. The non-isolated topology is low cost and easy to design [1]-[3]. However, for the sake of the safety consideration, an isolated topology is required. The forward-type isolated bidirectional converter has been proposed [4]-[6]. However, the forward type converter need additional inductor to store energy, the volume of circuit is increase. The bidirectional flyback DC-DC converter stores energy in the transformer, the circuit volume can be reduced. But, this topology will impact by leakage inductance due to the air gap. In order to solve these problems. The interleaved bidirectional DC-DC forward/flyback converter with leakage energy recycled is proposed in this paper. The proposed converter use interleaved topology to reduce the current stress and recycle the leakage energy to increase efficiency.

II. OPERATING PRINCIPLE ANALYSIS

Fig. 1 shows the proposed bidirectional forward-flyback converter with leakage energy recycled. The interleaved topology can reduce the current stress as well as the current ripple of the main switches and the transformers. Compared with the single transformer flyback converter, the proposed converter is suitable for higher power applications. Besides, the diodes are used to clamp the voltage and recycle the leakage energy. The operating principle of the proposed bidirectional forward-flyback converter in step-down and step-up modes are derived as follow.

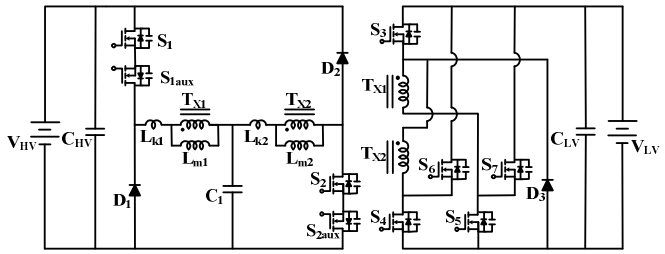

Fig. 1. The topology of the proposed converter

- *Step-up mode:*

Fig. 2 shows the equivalent circuit in step-up mode. When the proposed converter operated in step-up mode, S_3, S_4, and S_5 are the main switches. The diode D_1 and D_2 are used for rectifiers, the anti-parallel diode of S_6 and S_7 and the diode D_3 are used to recycle leakage energy. In order to prevent current flow through the anti-parallel diode of S_1 and S_2, S_{1aux} and S_{2aux} are always turned off in this stage. By adjusting the duty ratio of S_3, S_4, and S_5, the voltage gain can be changed and the energy can be transfer from V_{LV} to V_{HV}. Fig. 3 shows the key waveforms of step-up mode.

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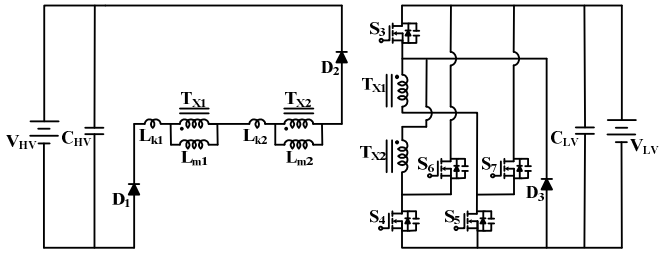


Fig. 2. The equivalent circuit of the proposed converter in step-up mode

Mode 1:[t_0~t_1]

During this interval, the switches S_3, S_4, and S_5 are turned on. The equivalent circuit of mode 1 is shown in Fig. 4 (a). The magnetizing inductances L_{m1} and L_{m2} are charged by V_{LV}, since the current of the magnetizing inductances i_{Lm1} and i_{Lm2} increase linearly. The leakage inductances L_{k1} and L_{k2} release energy through the diodes D_1 and D_2, since the leakage inductance currents i_{Lk1} and i_{Lk2} decrease quickly. This mode ends when currents i_{Lk} and i_{Lk2} decreases to zero.

Mode 2:[t_1~t_2]

During this interval, the switches S_3, S_4, and S_5 are turned on. The equivalent circuit of mode 2 is shown in Fig. 4 (b). The magnetizing inductances L_{m1} and L_{m2} are charged by V_{LV}, so the current i_{Lm1} and i_{Lm2} increase linearly. This mode ends when the switch S_3, S_4, and S_5 are turned off.

Mode 3:[t_2~t_3]

During this interval, the switches S_3, S_4, and S_5 are turned off. The equivalent circuit of mode 3 is shown in Fig. 4 (c). The magnetizing inductances L_{m1} and L_{m2} release energy to V_{HV} through the diode D_1 and D_2, since the magnetizing inductance currents i_{Lm1} and i_{Lm2} decrease linearly. The leakage inductance currents i_{Lk1} and i_{Lk2} cannot increase to the same values of the magnetizing inductance currents i_{Lm1} and i_{Lm2} immediately. The difference between these two currents will go through the winding of transformer and the anti-parallel diode of S_6 and S_7, and the diode D_3. The leakage inductance L_{k1} and L_{k2} are charged by the magnetizing inductances L_{m1} and L_{m2}, since leakage inductance currents i_{Lk1} and i_{Lk2} increase quickly. This mode ends when the currents i_{Lk1} and i_{Lk2} increase to the currents i_{Lm1} and i_{Lm2}.

Mode 4:[t_3~t_4]

During this interval, the switches S_3, S_4, and S_5 are turned off. The equivalent circuit of mode 4 is shown in Fig. 4 (d). The magnetizing inductance currents i_{Lm1} and i_{Lm2} and the leakage inductance currents the i_{Lk1} and i_{Lk2} are the same. Both the magnetizing inductance and the leakage inductance release energy to V_{HV} through the diodes D_1 and D_2, since the magnetizing inductance current and the leakage inductance current decrease linearly. This mode ends when the switches S_3, S_4, and S_5 are turned on.

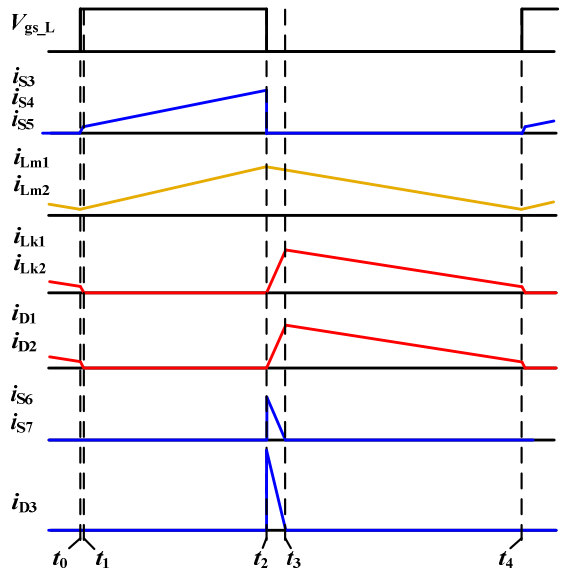


Fig. 3. Key waveforms in step-up mode

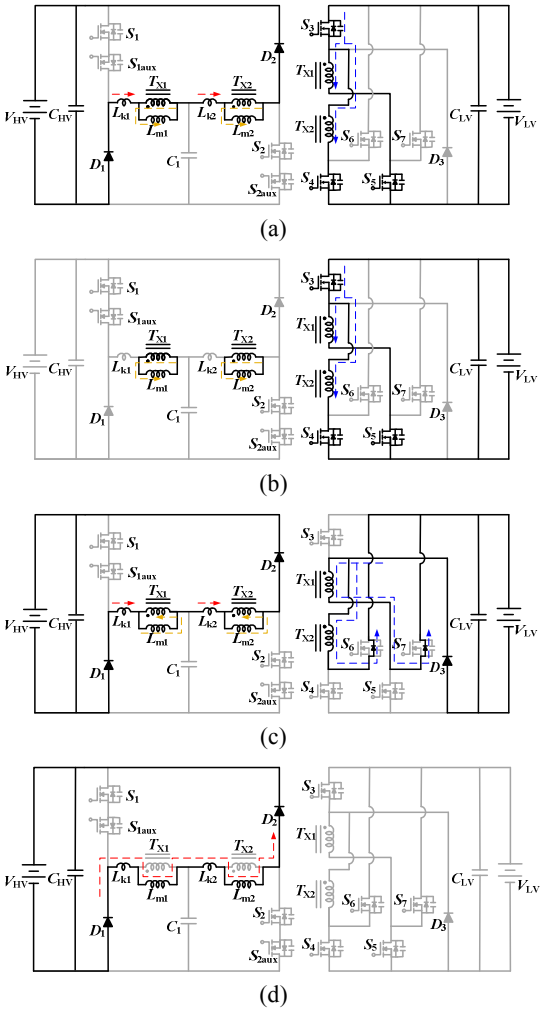


Fig. 4. Equivalent circuits of step-up mode operation (a) mode 1(b) mode 2 (c) mode 3(d) mode 4

- *Step-down mode:*

In step-down stage, the main switches are S_1 and S_2. The switches S_4, S_5, S_6, and S_7 and the diode D_3 are used for rectifier. The diodes D_1 and D_2 are used to recycle leakage energy. The switches S_{1aux} and S_{2aux} are always turned on, and the switch S_3 is always turned off. The equivalent circuit in step-down stage is shown in Fig. 5 and the key waveforms of step-down stage are shown in Fig. 6. Since the operating modes from t_0 to t_5 is symmetrical with t_6 to t_{10}.

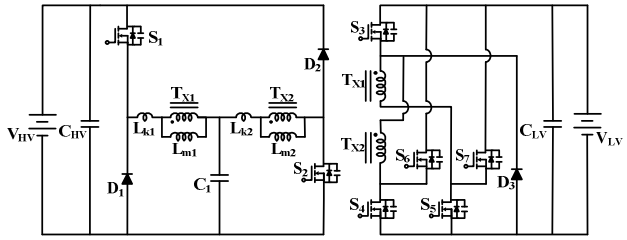


Fig. 5. The equivalent circuit of the proposed converter in step-down mode

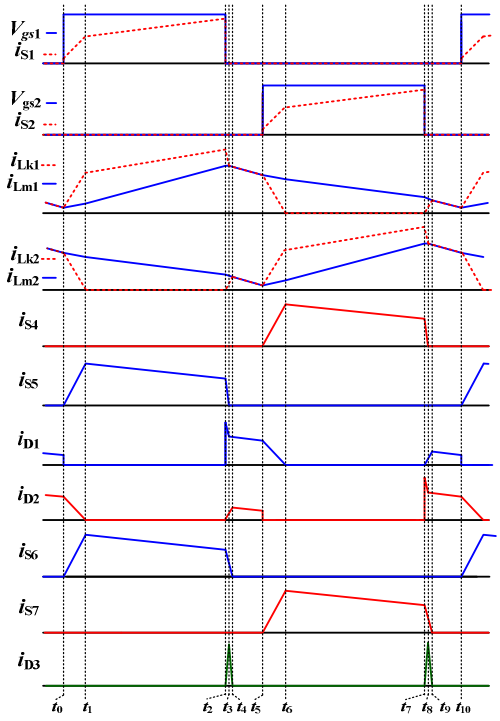


Fig. 6. Key waveforms in step-down stage

Mode 1: [t_0~t_1]

During this interval, the switch S_1, S_5, and S_6 are turned on and the switch S_2, S_4, and S_7 are turned off. The equivalent circuit of mode 1 is shown in Fig. 7 (a). V_{HV} provides energy to the capacitor C_1 and provides energy to V_{LV} through the transformer T_{X1} and the switch S_5 and S_6. The magnetizing inductance L_{m1} and the leakage inductance L_{k1} are charged by V_{HV}, so the current i_{Lm1} and i_{Lk1} increase linearly. The magnetizing inductance L_{m2} releases energy to V_{LV} through the transformer T_{X2} and the switch S_5 and S_6. The leakage inductance L_{k2} releases energy to V_{HV} through the diode D_2. Therefore, the current i_{Lm2} and i_{Lk2} decrease linearly. This mode ends when the current i_{Lk2} decrease to zero.

Mode 2: [t_1~t_2]

During this interval, the switch S_1, S_5, and S_6 are turned on, switch S_2, S_4, and S_7 are turned off. The equivalent circuit of mode 2 is shown in Fig. 7 (b). V_{HV} provides energy to the capacitor C_1 and provides energy to V_{LV} through the transformer T_{X1} and the switch S_5 and S_6. The magnetizing inductance L_{m1} and leakage inductance L_{k1} are charged by V_{HV}, so the current i_{Lm1} and i_{Lk1} increase linearly. The magnetizing inductance L_{m2} releases energy to V_{LV} through the transformer T_{X2} and the switch S_5 and S_6. This mode ends when switch S_1 is turned off.

Mode 3: [t_2~t_3]

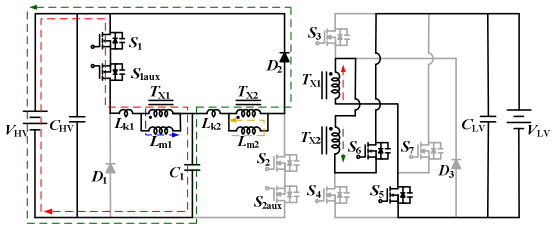
During this interval, the switch S_5 and S_6 are turned on, the switches S_1, S_2, S_4, and S_7 are turned off. The magnetizing inductance L_{m2} releases energy to V_{LV} through the transformer T_{X2}. The equivalent circuit of mode 3 is shown in Fig. 7 (c). In the beginning, the values of i_{S5} and i_{S6} are the same. The difference between i_{S5} and i_{S6} goes through the diode D_3 since the current i_{Lk1} decreases faster than i_{Lk2} and the low voltage side current i_{S5} decreases faster than i_{S6}. When the diode D_3 conduction, the voltage of T_{X1} is clamped at zero, the magnetizing inductance current i_{Lm1} keeps a constant. The leakage inductance L_{k1} releases energy to capacitor C_1 through the diode D_1. The current i_{Lk1} decrease linearly. The leakage inductance L_{k2} is charged by L_{m2}. The current i_{Lk2} increase linearly. This mode ends when the value of current i_{Lk1} is equal to current i_{Lm1}.

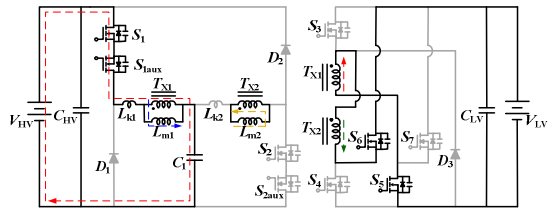
Mode 4: [t_3~t_4]

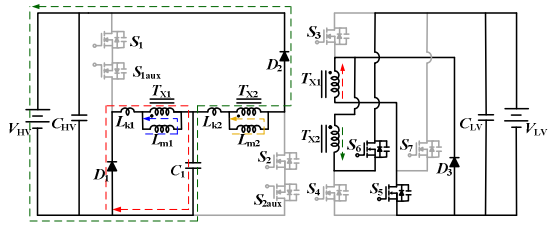
During this interval, the switch S_6 is turned on and the switches S_1, S_2, S_4, S_5, and S_7 are turned off. The equivalent circuit of mode 4 is shown in Fig. 7 (d). The magnetizing inductance L_{m1} and leakage inductance L_{k1} release energy to the capacitor C_1 through the diode D_1, so the current i_{Lm1} and i_{Lk1} decreases linearly. Because the current i_{Lm1} is equal to current i_{Lk1}, the transformer T_{X1} is decoupled. The V_{LV} side voltage of transformer T_{X2} is equal to V_{LV}. The magnetizing inductance L_{m2} releases energy to V_{LV} through the transformer T_{X2}, the switch S_6, and the diode D_3, so the current i_{Lm2} decrease linearly. The leakage inductance L_{k1} is charged by L_{m2}, so the current i_{Lk2} increases linearly. This mode ends when the value of current i_{Lk2} equal to current i_{Lm2}.

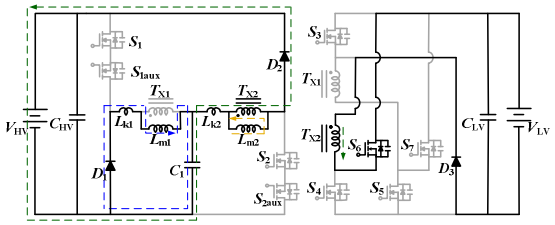
Mode 5: [t_4~t_5]

During this interval, the switches S_1, S_2, S_4, S_5, S_6, and S_7 are turned off. The equivalent circuit of mode 5 is shown in Fig. 7 (e). The magnetizing inductance L_{m1} and the leakage inductance L_{k1} release energy to the capacitor C_1 through the diode D_1, so the currents i_{Lm1} and i_{Lk1} decreases linearly. The magnetizing inductance L_{m2} and the leakage inductance L_{k2} releases energy to V_{HV} through the diode D_2, so the current i_{Lm2} and i_{Lk2} decreases linearly. This mode ends when the switch S_2, S_4 and S_7 are turned on.









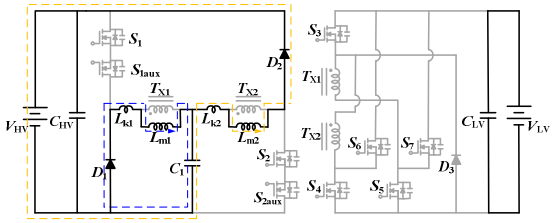


Fig. 7. Equivalent circuits of step-down mode operation (a) mode 1 (b) mode 2 (c) mode 3(d) mode 4 (e) mode 5

III. Steady State Analysis

To simplify the calculation, the leakage inductance and the transient time are ignored. Assume that the characteristic of transformers T_{X1} and T_{X2} are the same. In the step down mode, the voltage gain can be derived by the voltage-second balance of L_{m1}. It can be expressed as Eq. (1). Eq. (1) can be simplified as Eq. (2)

$$(V_{HV}-V_{C1})DT_s+(-V_{C1})(\frac{1-2D}{2})T_s+\left[(V_{C1})\frac{n_2}{n_1}-V_{LV}\right]\frac{n_1}{n_2}DT_s+(-V_{C1})(\frac{1-2D}{2})T_s=0 \quad (1)$$

$$\frac{V_{LV}}{V_{HV}}=\frac{4D-1}{2ND} \text{ where } N=\frac{n_1}{n_2} \quad (2)$$

The magnetizing inductance L_{BCM} can be derived by calculating the magnetizing inductance current in BCM. The key waveforms of the magnetizing inductance current i_{Lm1} and the diode current i_{S7} are shown in Fig. 8. The average current of S_7 is half of the output current. It can be derived as following:

$$i_{Lm1}(t_2)=i_{S7}(t_2)=\left[NDV_{LV}+V_{HV}(\frac{1}{4}-D)\right]\frac{T_sN}{L_{m1}} \quad (3)$$

$$i_{Lm1}(t_3)=i_{S7}(t_3)=\frac{V_{HV}}{2L_{m1}}(\frac{1-2D}{2})T_sN \quad (4)$$

$$i_{S7,ave}=\frac{I_{o,BCM}}{2}=\left[\frac{V_{HV}(1-3D)+2NDV_{LV}}{2}\right]N\frac{DT_s}{2L} \quad (5)$$

The boundary conduction inductance $L_{m1,BCM}$ can be derived from Eq. (5) as shown in Eq. (6)

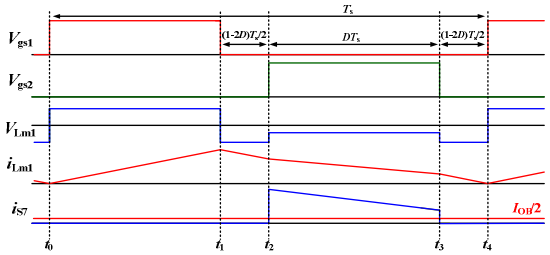


Fig. 8. Key waveforms of BCM in neglecting the effect of leakage inductance in step-down stage

$$L_{m1,BCM}=V_{HV}(\frac{V_{HV}}{2V_{HV}-NV_{LV}})^2\frac{NT_s}{8I_{o,BCM}} \quad (6)$$

When the proposed converter operates in step-up mode, the voltage gain can be derived as following:

$$V_{LV}\frac{n_1}{n_2}DT_s+(-\frac{1}{2}V_{HV})(1-D)T_s=0 \quad (7)$$

The Eq. (1) can be simplified as Eq. (2)

$$\frac{V_{HV}}{V_{LV}}=\frac{2ND}{1-D}\ (N=\frac{n_1}{n_2}) \quad (8)$$

The key waveforms of the magnetizing inductance currents i_{Lm1}, i_{Lm2}, and the diode currents i_{D1}, i_{D2} are shown in Fig. 9. The average output diode currents $i_{D1,ave}$ and $i_{D2,ave}$ are equal to output current $I_{o,BCM}$. It can be expressed as Eq. (9).

$$i_{D1,pk}=i_{D2,pk}=i_{Lm1,pk}=i_{Lm2,pk}=\frac{2I_{o,BCM}}{1-D} \quad (9)$$

Because the converter operates in BCM, the total energy stored in magnetizing inductance will release to load.

$$\frac{P_{o,BCM}}{2}=\frac{V_oI_{o,BCM}}{2}=\frac{1}{2}L_{m1}i_{Lm1,pk}^2f_s=\frac{1}{2}L_{m2}i_{Lm2,pk}^2f_s \quad (10)$$

By substituting Eq. (9) to Eq. (10), the equation of boundary inductances $L_{m1,BCM}$ and $L_{m2,BCM}$ can be expressed as Eq. (11)

$$L_{m1,BCM} = L_{m2,BCM} = \frac{V_{HV}(1-D)^2}{4I_{o,BCM}f_s} \quad (11)$$

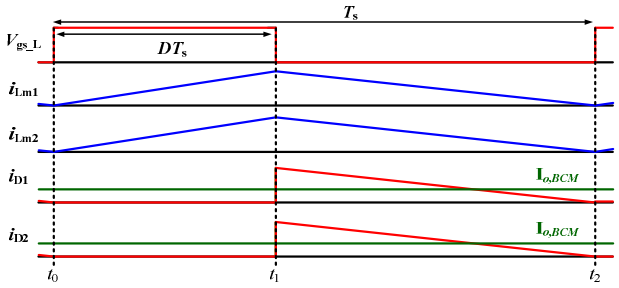


Fig. 9 Key waveforms of BCM in neglecting the effect of leakage inductance in step-up stage

The two values of $L_{m,BCM}$ can be solved in step-down mode and step-up mode. The larger one is chosen. It can ensure that the converter meets the specifications. Because the smaller one leads the converter which operates in BCM at the power larger than specifications.

IV. Experimental Results

A bidirectional DC-DC forward/flyback converter with leakage energy recycled is proposed and implementation in this paper. The specifications of the proposed converter are shown in Table 1. When the switch is turned off, the leakage energy can be recycled and the conversion efficiency is improved. The voltage across the switch can be clamped. As shown in Fig. 10 to Fig. 13, the voltage and current waveforms of key components are illustrated. The synchronous rectifier is added into the circuit to increase efficiency. Therefore, the highest efficiency in step-up and step-down stage is 92.7% and 95.5% respectively, as shown in Fig. 14 and Fig. 15.

Table 1. System Specifications

(a)

Step-up Mode	
Input Voltage V_{LV}	24 V
Output Voltage V_{HV}	200 V
Rated Output Power	500 W
Switching Frequency	50 kHz

(b)

Step-down Mode	
Input Voltage V_{HV}	200 V
Output Voltage V_{LV}	24 V
Rated Output Power	500 W
Switching Frequency	50 kHz

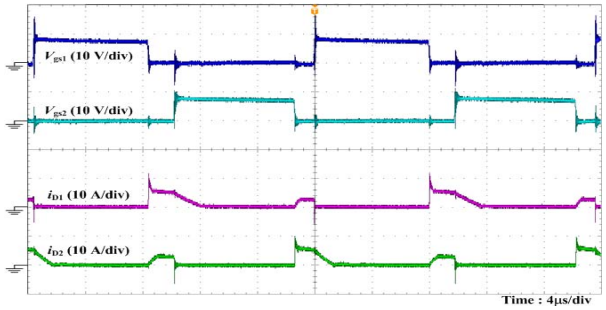


Fig. 10 The waveforms of V_{GS1}, V_{GS2}, i_{D1}, and i_{D2} (Step-down mode 500 W)

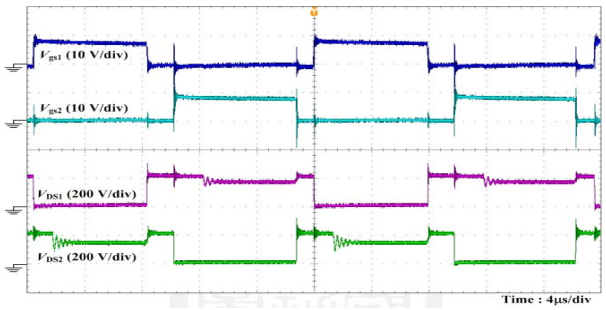


Fig. 11 The waveforms of V_{GS1}, V_{GS2}, V_{DS1}, and V_{DS2} (Step-down mode 500 W)

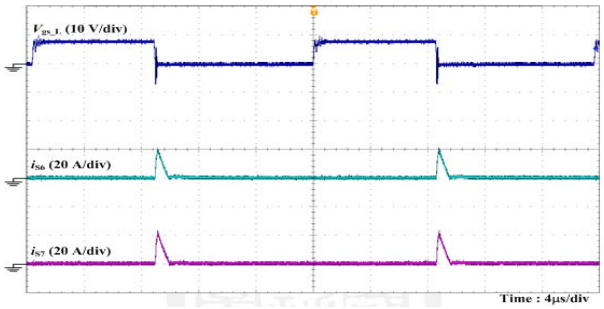


Fig. 12 The waveforms of V_{GS}, i_{S6}, and i_{S7} (Step-up mode 500 W)

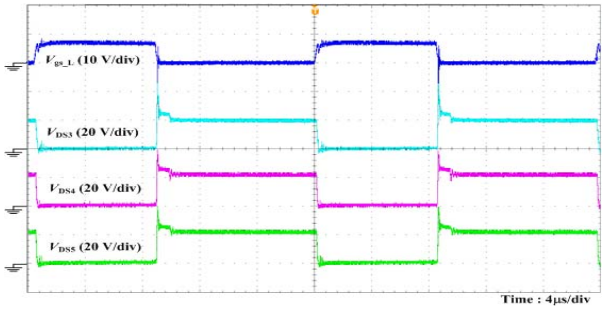


Fig.13 The waveforms of V_{GS1}, V_{DS3}, V_{DS4}, and V_{DS5} (Step-up mode 500 W)

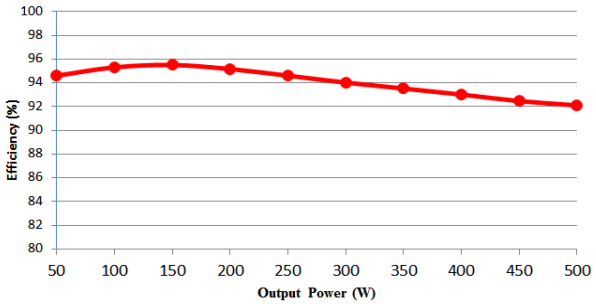


Fig. 14 The efficiency curve in step-down mode

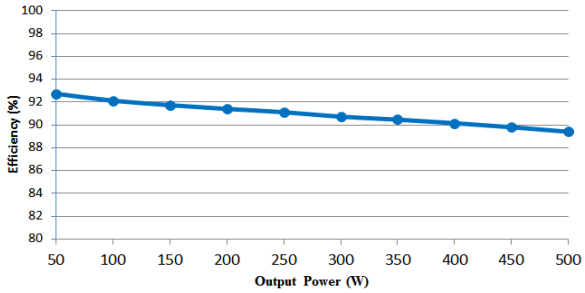


Fig.15 The efficiency curve in step-up mode

V. Conclusions

The proposed bidirectional forward-flyback converter is composed of two transformers. The current stress and ripple can be reduced by using interleaved topology. The proposed converter uses the leakage energy recycled and the voltage clamping technologies to increase the efficiency. Besides, the current in low voltage is up to 20.83 A, the synchronous rectifier technology is added to reduce the conduction loss in heavy load. Finally, a laboratory prototype circuit with 200 V/24 V and output power 500 W is implemented to verify the feasibility of the proposed converter. The measured waveforms of prototype circuit correspond to the theory waveforms. When the converter is operated in step down stage, the highest efficiency is 95.5% and the full load efficiency is 92.1%. When the converter is operated in step-up stage, the highest efficiency is 92.3% and the full load efficiency is 90.3%.

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