

# Isolated Bidirectional Full-Bridge DC–DC Converter with a Flyback Snubber

Chitanya, K.Sowjanya, P.Raghavendran

**Abstract**—An isolated bidirectional full-bridge dc–dc converter with high conversion ratio, high output power, and soft start-up capability is proposed in this paper. The use of a capacitor, a diode, and a flyback converter can clamp the voltage spike caused by the current difference between the current-fed inductor and leakage inductance of the isolation transformer, and can reduce the current flowing through the active switches at the current-fed side. Operational principle of the proposed converter is first described, and then, the design equation is derived. A 1.5-kW prototype with low-side voltage of 48 V and high-side voltage of 360 V has been implemented, from which experimental results have verified its feasibility.

**IndexTerms**— Flybackconverter, isolated full- bridge bidirectional converter, soft start-up.

## I. INTRODUCTION

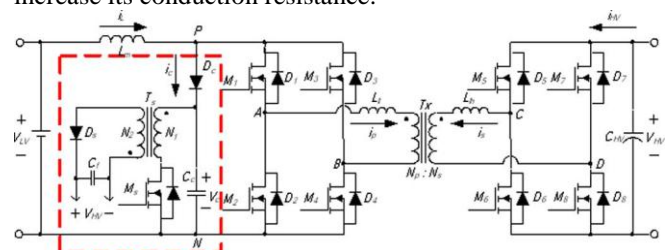
IN RENEWABLE dc-supply systems, batteries are usually required to back-up power for electronic equipment. Their voltage levels are typically much lower than the dc-bus voltage. Bidirectional converters for charging/discharging the batteries are therefore required. For high-power applications, bridge-type bidirectional converters have become an important research topic over the past decade [1]–[7]. For raising power level, a dual full-bridge configuration is usually adopted [8]–[16], and its low side and high side are typically configured with boost-type and buck-type topologies, respectively. The major concerns of these studies include reducing switching loss, reducing voltage and current stresses, and reducing conduction loss due to circulation current. A more severe issue is due to leakage inductance of the isolation transformer, which will result in high voltage spike during switching transition. Additionally, the current freewheeling due to the leakage inductance will increase conduction loss and reduce effective duty cycle. An alternative approach [9] is to precharge the leakage inductance to raise its current level up to that of the current-fed inductor, which can reduce their current difference and, in turn, reduce voltage spike. However, dissipated on the resistor, thus resulting in lower efficiency. A buck converter was employed to replace an RCD passive snubber, but it still needs complex clamping circuits [17], [18]. A simple active clamping circuit was proposed [12], [19], which suits for bidirectional converters. However, its resonant current increases the current stress on switches significantly. In [20], Wang *et al.* proposed a topology to achieve soft-starting capability, but it is not suitable for step-down operation.

This paper introduces a flyback snubber to recycle the absorbed energy in the clamping capacitor. The flyback snubber can be operated independently to regulate the voltage of the clamping capacitor; therefore, it can clamp the voltage to a desired level just slightly higher than the voltage across the low-side transformer winding. Since the current does not circulate through the full-bridge switches, their current stresses can be reduced dramatically under heavy-load condition, thus improving system reliability significantly. Additionally, during start-up, the flyback snubber can be controlled to precharge the high-side capacitor, improving feasibility significantly. A bidirectional converter with low-side voltage of 48 V, high-side voltage of 360 V, and power rating of 1.5 kW has been designed and implemented, from which experimental results have verified the discussed performance.

## II. CONFIGURATION AND OPERATION

The proposed isolated bidirectional full-bridge dc–dc converter with a flyback snubber is shown in Fig. 1. The converter is operated with two modes: buck mode and boost mode. Fig. 1 consists of a current-fed switch bridge, a flyback snubber at the low-voltage side, and a voltage-fed bridge at the high-voltage side. Inductor  $L_m$  performs output filtering when power flows from the high-voltage side to the batteries, which is denoted as a buck mode. On the other hand, it works in boost mode when power is transferred from the batteries to the high-voltage side. Furthermore, clamp branch capacitor  $CC$  and diode  $DC$  are used to absorb the current difference between current-fed inductor  $L_m$  and leakage inductance  $L_{ll}$  and  $L_{lh}$  of isolation transformer  $T_x$  during switching commutation

The flyback snubber can be independently controlled to regulate  $V_C$  to the desired value, which is just slightly higher than  $V_{AB}$ . Thus, the voltage stress of switches  $M_1$ – $M_4$  can be limited to a low level. The major merits of the proposed converter configuration include no spike current circulating through the power switches and clamping the voltage across switches  $M_1$ – $M_4$ , improving system reliability significantly. Note that high spike current can result in charge migration, over current density, and extra magnetic force, which will deteriorate in MOSFET carrier density, channel width, and wire bonding and, in turn, increase its conduction resistance.



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Fig. 1. Isolated bidirectional full-bridge dc–dc converter with a flyback snubber

A bidirectional dc–dc converter has two types of conversions: step-up conversion (boost mode) and step-down conversion (buck mode). In boost mode, switches  $M1–M4$  are controlled, and the body diodes of switches  $M5–M8$  are used as a rectifier. In buck mode, switches  $M5–M8$  are controlled, and the body diodes of switches  $M1–M4$  operate as a rectifier. To simplify the steady state analysis, several assumptions are made, which are as follows.

- 1) All components are ideal. The transformer is treated as an ideal transformer associated with leakage inductance.
- 2) Inductor  $L_m$  is large enough to keep current  $i_L$  constant over a switching period.
- 3) Clamping capacitor  $CC$  is much larger than parasitic capacitance of switches  $M1–M8$ .

**A. Step-Up Conversion**

In boost mode, switches  $M1–M4$  are operated like a boost converter, where switch pairs  $(M1, M2)$  and  $(M3, M4)$  are turned ON to store energy in  $L_m$ . At the high-voltage side, the body diodes of switches  $M5–M8$  will conduct to transfer power to  $VHV$ . When switch pair  $(M1, M2)$  or  $(M3, M4)$  is switched to  $(M1, M4)$  or  $(M2, M3)$ , the current difference  $i_C (= i_L - i_p)$  will charge capacitor  $CC$ , and then, raise  $i_p$  up to  $i_L$ . The clamp branch is mainly used to limit the transient voltage imposed on the current-fed side switches. Moreover, the flyback converter can be controlled to charge the high-voltage-side capacitor to avoid over current. The clamp branch and the flyback snubber are activated during both start-up and regular boost operation modes. A nonphase-shift PWM is used to control the circuit to achieve smooth transition from start-up to regular boost operation mode

Referring to Fig. 1, the average power  $PC$  transferred to  $CC$  can be determined as follows:

$$P_C = \frac{1}{2} C_C [(i_L Z_o)^2 + 2i_L Z_o V_{C(R)}] f_s \tag{1}$$

were

$$Z_o = \sqrt{\frac{L_{eq}}{C_C}}$$

$$L_{eq} = L_{ll} + L_{lh} \frac{N_p^2}{N_s^2}$$

$V_C(R)$  stands for a regulated  $V_C$  voltage, which is close to  $(VHV (N_p / N_s))$ ,  $f_s$  is the switching frequency, and  $L_m$   $L_{eq}$ . Power  $PC$  will be transferred to the high-side voltage source through the flyback snubber, and the snubber will regulate clamping capacitor voltage  $V_C$  to  $V_C(R)$  within one switching cycle  $T_s (=1/f_s)$ . Note that the flyback snubber does not operate over the interval of inductance current  $i_p$  increasing toward  $i_L$ . The processed power  $PC$  by the flyback snubber is typically around 5% of the full-load power for low-voltage applications. With the flyback snubber, the energy absorbed in  $CC$  will not flow through switches  $M1–M4$ , which can reduce their current stress dramatically when  $L_{eq}$  is significant. Theoretically, it can reduce the current stress from  $2i_L$  to  $i_L$ .

The peak voltage  $V_C(P)$  of  $V_C$  will impose on  $M1–M4$  and it can be determined as follows:

$$V_{C(P)} = i_{L(M)} Z_o + V_{HV} \frac{N_p}{N_s} \tag{2}$$

where  $i_L(M)$  is the maximum inductor current of  $i_L$ , which is related to the maximum load condition. Additionally, for reducing conduction loss, the high-side switches  $M5–M8$  are operated with synchronous switching. Reliable operation and high efficiency of the proposed converter are verified on a prototype designed for alternative energy applications. The operation waveforms of step-up conversion are shown in Fig. 2. A detailed description of a half-switching cycle operation is shown as follows.

**Mode 1 [ $t_0 \leq t < t_1$ ]:** In this mode, all of the four switches  $M1–M4$  are turned ON. Inductor  $L_m$  is charged by  $V_{LV}$ , inductor current  $i_L$  increases linearly at a slope of  $V_{LV} / L_m$ , and the primary winding of the transformer is short-circuited. The equivalent circuit is shown in Fig. 3(a).

**Mode 2 [ $t_1 \leq t < t_2$ ]:** At  $t_1$ ,  $M1$  and  $M4$  remain conducting, while  $M2$  and  $M3$  are turned OFF. Clamping diode  $D_c$  conducts until the current difference  $(i_L(t_2) - i_p(t_2))$  drops to zero at  $t = t_2$ . Moreover, the body diodes of switch pair  $(M5, M8)$  are conducting to transfer power. During this interval, the current difference  $(i_L(t) - i_p(t))$  flows into clamping capacitor  $CC$ . The equivalent circuit is shown in Fig. 3(b).

**Mode 3 [ $t_2 \leq t < t_3$ ]:** At  $t_2$ , clamping diode  $D_c$  stops conducting, and the flyback snubber starts to operate. At this time, clamping capacitor  $C_c$  is discharging, and flyback inductor is storing energy. Switches  $M1$  and  $M4$  still stay in the ON state, while  $M2$  and  $M3$  remain OFF. The body diodes of switch pair  $(M5, M8)$  remain ON to transfer power. The equivalent circuit is shown in Fig. 3(c).

**Mode 4 [ $t_3 \leq t < t_4$ ]:** At  $t_3$ , the energy stored in flyback inductor is transferred to the high-voltage side. Over this interval, the flyback snubber will operate independently to regulate  $V_C$  to  $V_C(R)$ . On the other hand, switches  $M1$  and  $M4$  and diodes  $D_5$  and  $D_8$  are still conducting to transfer power from  $V_{LV}$  to  $V_{HV}$ . The equivalent circuit is shown in Fig. 3(d).



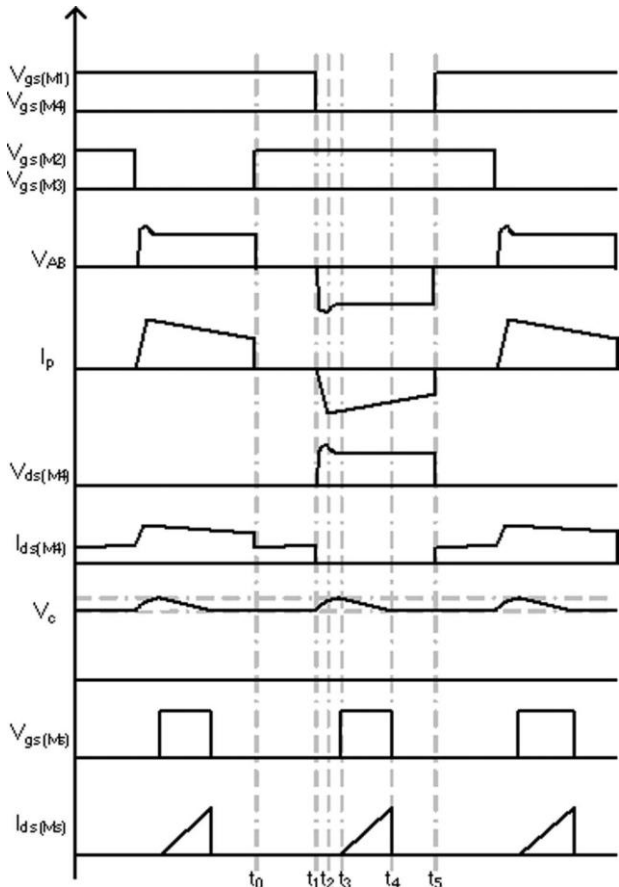


Fig. 2. Operation waveforms of step-up conversion Mode 5 [ $t_4 \leq t < t_5$ ]: At  $t_4$ , capacitor voltage  $V_C$  has been regulated to  $V_C(R)$ , and the snubber is idle. Over this interval, the main power stage is still transferring power from  $V_{LV}$  to  $V_{HV}$ . It stops at  $t_5$  and completes a half-switching cycle operation. The equivalent circuit is shown in Fig. 3(e)

**B. Step-Down Conversion**

In the analysis, leakage inductance of the transformer at the low-voltage side is reflected to the high-voltage side, as shown in Fig. 4, in which equivalent inductance  $L_{leq}$  equals

$$(L_{lh} + L_{ll}(N_1^2/N_2^2))$$

This circuit is known as a phase-shift full-bridge converter. In the step-down conversion, switches  $M_5$ – $M_8$  are operated like a buck converter, in which switch pairs ( $M_5, M_8$ ) and ( $M_6, M_7$ ) are alternately turned ON to transfer power from  $V_{HV}$  to  $V_{LV}$ . Switches  $M_1$ – $M_4$  are operated with synchronous switching to reduce conduction loss. For alleviating leakage inductance effect on voltage spike, switches  $M_5$ – $M_8$  are operated with phase-shift manner. Although, there is no need to absorb the current difference between  $i_L$  and  $i_p$ , capacitor.

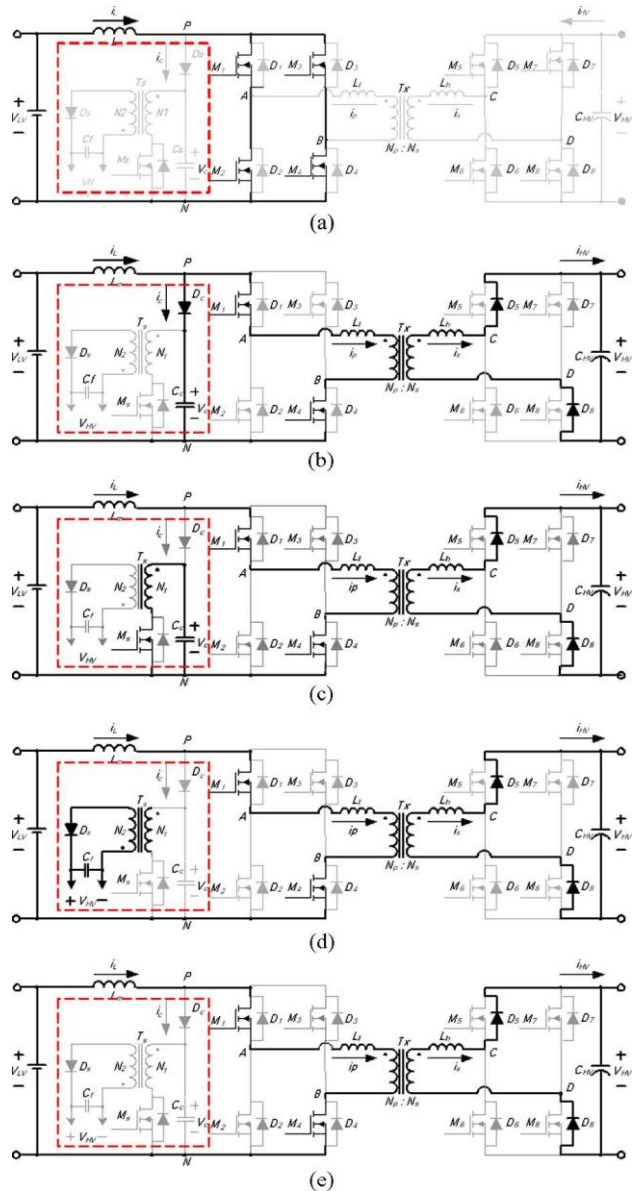


Fig. 3. Operation modes of step-up conversion. (a) Mode 1. (b) Mode 2. (c) Mode 3. (d) Mode 4. (e) Mode 5.

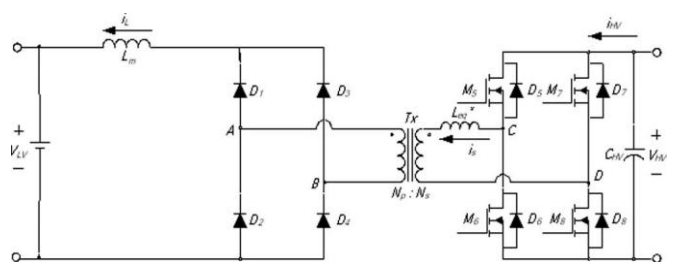


Fig. 4. Phase-shift full-bridge converter topology.

The operation waveforms of step-down conversion are shown in Fig. 5. A detailed description of a half-switching cycle operation is shown as follows.

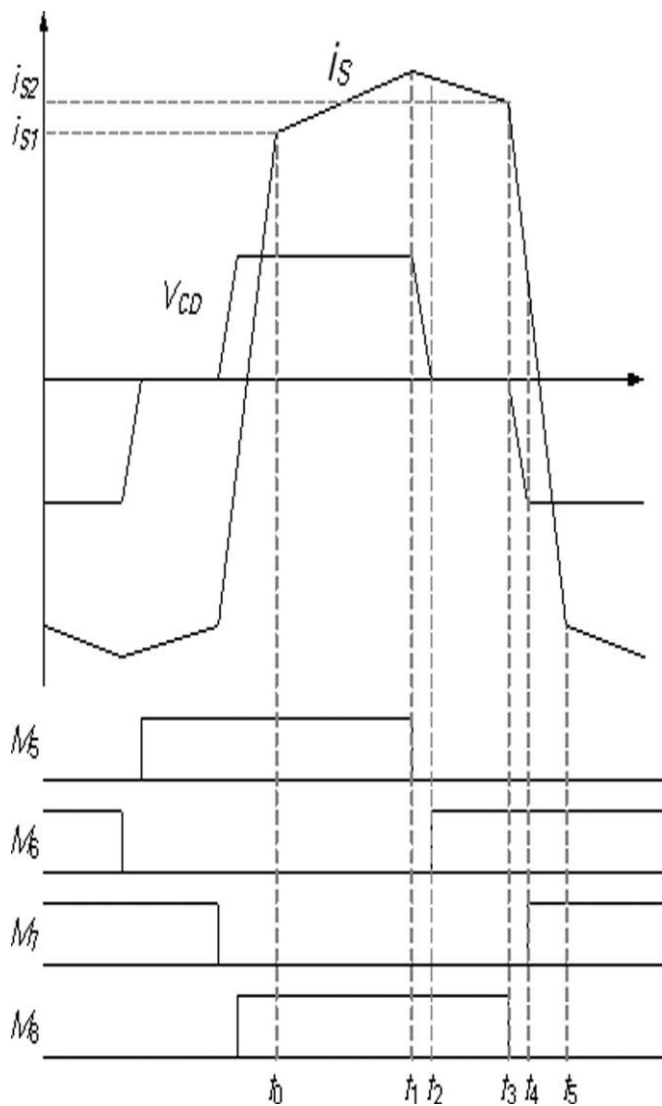


Fig. 5. Operation waveforms of step-down conversion

**Mode 1** [ $t_0 \leq t < t_1$ ]: In this mode,  $M_5$  and  $M_8$  are turned ON, while  $M_6$  and  $M_7$  are in the OFF state. The high-side voltage  $V_{HV}$  is immediately exerted on the transformer, and the whole voltage, in fact, is exerted on the equivalent inductance  $L_{eq}$  and causes the current to rise with the slope of  $V_{HV} / L_{eq}$ . With the transformer current increasing linearly toward the load current level at  $t_1$ , the switch pair ( $M_1, M_4$ ) are conducting to transfer power, and the voltage across the transformer terminals on the current-fed side changes immediately to reflect the voltage from the voltage-fed side, i.e., ( $V_{HV} (N_p / N_s)$ ). The equivalent circuit is shown in Fig. 6(a).

**Mode 2** [ $t_1 \leq t < t_2$ ]: At  $t_1$ ,  $M_8$  remains conducting, while  $M_5$  is turned OFF. The body diode of  $M_6$  then starts to conduct the freewheeling leakage current. The transformer current reaches the load-current level at  $t_1$ , and  $V_{AB}$  rise to the reflected voltage ( $V_{HV} (N_p / N_s)$ ). Clamping diode  $D_c$  starts to conduct the resonant current of  $L_{eq}$  and the clamp capacitor  $C_C$ . This process ends at  $t_2$  when the resonance goes through a half resonant cycle and is blocked by the clamping diode  $D_c$ . The equivalent circuit is shown in Fig. 6(b).

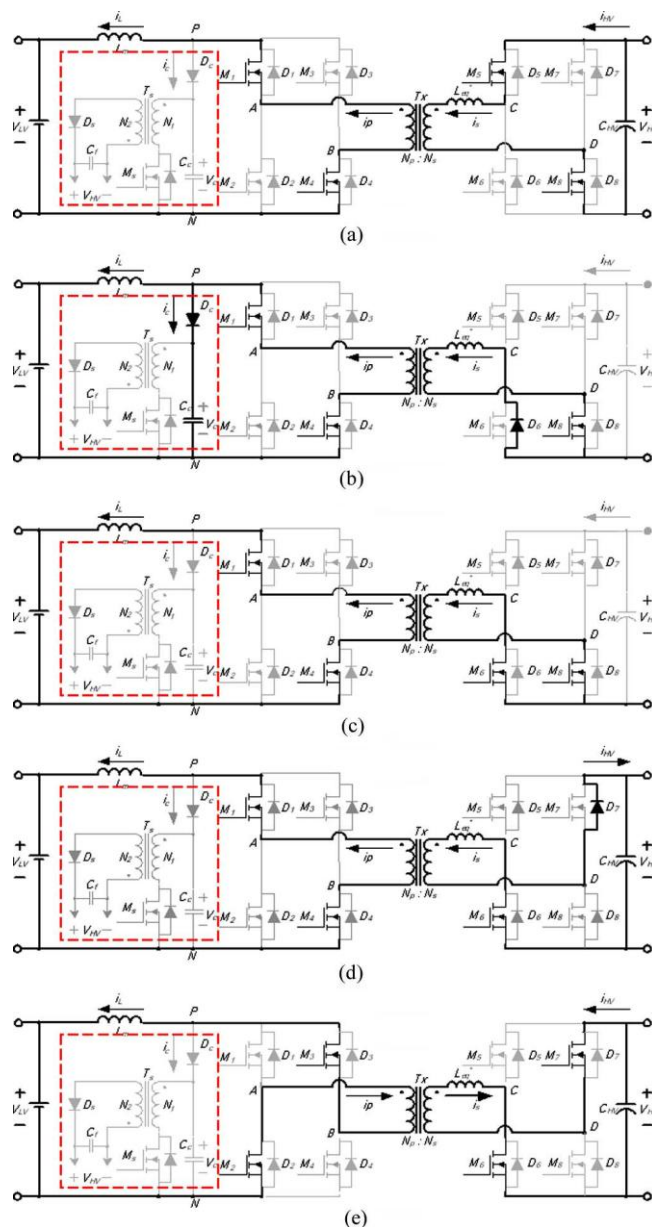


Fig. 6. Operation modes of step-down conversion. (a) Mode 1. (b) Mode 2. (c) Mode 3. (d) Mode 4. (e) Mode 5.

**Mode 3** [ $t_2 \leq t < t_3$ ]: At  $t_2$ , with the body diode of switch  $M_6$  conducting,  $M_6$  can be turned ON with zero-voltage switching (ZVS). The equivalent circuit is shown in Fig. 6(c).

**Mode 4** [ $t_3 \leq t < t_4$ ]: At  $t_3$ ,  $M_6$  remains conducting, while  $M_8$  is turned OFF. The body diode of  $M_7$  then starts to conduct the freewheeling leakage current. The equivalent circuit is shown in Fig. 6(d).

**Mode 5** [ $t_4 \leq t < t_5$ ]: At  $t_4$ , with the body diode of switch  $M_7$  conducting,  $M_7$  can be turned ON with ZVS. Over this interval, the active switches change to the other pair of diagonal switches, and the voltage on the transformer reverses its polarity to balance flux. It stops at  $t_5$  and completes a half-switching cycle operation. The equivalent circuit is shown in Fig. 6(e).

### III. PRACTICAL CONSIDERATION

#### A. Low-Voltage Side

Switch pairs ( $M1, M4$ ) and ( $M2, M3$ ) are turned ON alternately under any load condition. Its minimum conduction time is

$$T_{C(\min)} = \frac{L_{eq} i_L}{V_{AB}} \quad (3)$$

#### B. Clamping Capacitor

For absorbing the energy stored in the leakage inductance and to limit the capacitor voltage to a specified minimal value  $V_{c,l}$ , capacitance  $C_c$  has to satisfy the following inequality:

$$C_c \geq \frac{L_{eq}(i_L - i_P)^2}{V_{c,l}^2} \quad (4)$$

#### C. Flyback Converter

In the interval of  $t1 \leq t \leq t2$ , the high transient voltage occurs inevitably in boost mode, which could be suppressed by the clamp branch ( $D_c, C_c$ ). The energy stored in capacitor  $C_c$  is transferred to the high-voltage side via a flyback converter. The regulated voltage level of the flyback converter is set between 110%–120% of the steady-state voltage at the low-voltage side. Power rating of the flyback converter can be expressed as follows;

$$P_{FB} = 0.5C_c(V_{c,h}^2 - V_{c,l}^2)f_s \quad (5)$$

where  $V_{c,h}$  is the maximum voltage of  $V_c$ ,  $V_{c,l}$  is the minimum voltage of  $V_c$ , and  $f_s$  is the switching frequency.

#### D. Start-Up Operation

High inrush current with the isolated boost converter is the start-up problem before the high-side voltage is established. The initial high-side voltage  $V_{HV}$  should not be lower than  $V_{LV} (N_s / N_p)$  to avoid inrush current. The proposed flyback snubber can be controlled to precharge the high-side capacitor. The operation principle is very similar to the active clamp flyback converter. Before the boost mode, the flyback converter starts to operate. Since the power rating of the flyback snubber is much lower than that of the main power stage, inductor  $L_m$  is operated in discontinuous condition mode. The start-up process usually lasts for a short period.

Low-side Voltage	$V_{LV} = 48 \text{ V}$
High-side Voltage	$V_{HV} = 360 \text{ V}$
Output Power	$P_{o(max)} = 1.5 \text{ kW}$
Switching Frequency	$f_s = 25 \text{ kHz}$
Turns Ratio	$N = N_p / N_s = 4.26$
Leakage Inductance	$L_{ll} = 0.5 \mu\text{H}, L_{lh} = 9 \mu\text{H}$
Current-fed Inductor	$L_m = 500 \mu\text{H}$
Clamping Capacitor	$C_c = 1 \mu\text{F}$
Low-side Switches	$M_1 \sim M_4 : \text{IRFB4321PbF}$ (150V/83A) $\times 2$
Low-side Capacitor	$C_{LV} : 100 \mu\text{F}$
Low-side Inductor	$L_m : 500 \mu\text{H}$
High-side Switches	$M_5 \sim M_8 : \text{IRFP26N60LPBF}$ (600V/26A)
High-side Capacitor	$C_{HV} : 470 \mu\text{F} \times 2$

### IV. CONCLUSION

This paper has presented an isolated bidirectional full-bridge dc–dc converter with a flyback snubber for high-power applications. The flyback snubber can alleviate the voltage spike caused by the current difference between the current-fed inductor and leakage inductance of the isolation transformer, and can reduce the current flowing through the active switches at the currentfed side by 50%. Since the current does not circulate through the full-bridge switches, their current stresses can be reduced dramatically under heavy-load condition, thus improving system reliability significantly. The flyback snubber can be also controlled to achieve a soft start-up feature. It has been successful in suppressing inrush current which is usually found in a boost-mode start-up transition. A 1.5-kW isolated full-bridge bidirectional dc–dc converter with a flyback snubber has been implemented to verify its feasibility.

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