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A New Novel Soft Switching Scheme for an Isolated Bidirectional Single Phase Full-Bridge DC-DC Converter

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Abstract

This paper deals with reducing switching loss, reducing voltage and current stresses, and reducing conduction loss due to circulation current. An isolated bidirectional full-bridge dc–dc converter with high conversion ratio, high output power, and soft start-up capability is proposed. 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. The proposed system using flyback converter is modeled by using MAT LAB/SIMULINK. 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.

Keywords: Metal Oxide semiconductor field-effect transistor (MOSFET), Flyback converter, Soft start-up, MATLAB, SIMULINK, Zero Voltage Switching (ZVS)

1. 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. For raising power level, a dual full-bridge configuration is usually adopted, 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 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, since the current level varies with load condition, it is hard to tune the switching timing diagram to match these two currents. 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.

2. BLOCK DIAGRAM OF THE PROPOSED SYSTEM

The proposed isolated bidirectional full-bridge dc–dc converter with a flyback snubber is shown in Fig.1.1. The converter is operated with two modes: buck mode and boost mode. Fig. 1.1 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 C_C and diode D_C 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 $M1$–$M4$ can be limited to a low level.

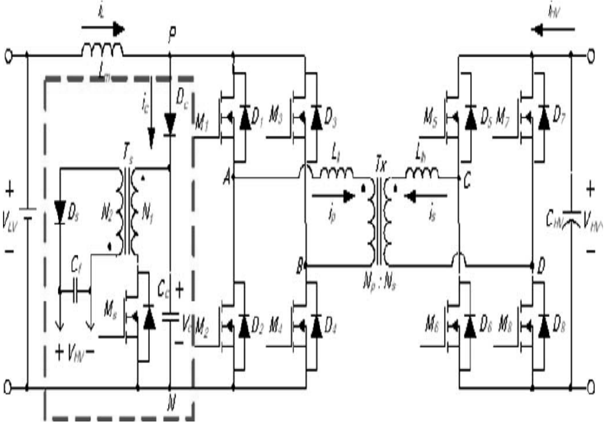

Fig. 1.1 Isolated bidirectional full-bridge dc–dc converter with a flyback snubber.

The major merits of the proposed converter configuration include no spike current circulating through the power switches and clamping the voltage across switches $M1$–$M4$, 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. 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 C_C is much larger than parasitic capacitance of switches $M1$–$M8$.

3. 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

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

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:

$$C_c \geq \frac{L_{\mathrm{eq}}(i_L - i_P)^2}{V_{C,l}^2}.$$

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:

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

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.

4. RESULTS AND DISCUSSION

The simulation model for boost and buck modes of isolated bidirectional full bridge dc-dc converter by using flyback converter and their voltage and current waveform are obtained. A battery module working at the low-voltage side is employed as an energy-storage element, whose voltage rating is 48 V. The high-voltage side is 360 V for boost operation. These simulation results for boost and buck modes of isolated bidirectional full-bridge dc-dc converter with a flyback snubber are obtained by using the simulink in MATLAB and their voltage and current waveform are obtained by using V_{LV}=48V, V_{HV}=360V, f_s=25khz, $L_{ll}=0.5$ µH, $L_{lh}=9$ µH, $L_{m}=500$ µH, $C_{LV}=$100 µf, $C_{HV}=$470 µf×2.

The primary side four MOSFET switches are used and four diodes are used in the secondary side of the transformer.The circuit model of isolated boost D.C to D.C. converter is shown in Fig 4.1.DC input voltage is 48V as shown in fig.4.2.The square Pulse width is applied with constant frequency and driving pulses for MOSFETS M1 – M4 and M_s is shown in the fig 4.4. The inverter output voltage is shown in Fig 4.3. Current waveform i_{ds} of switch M4 is shown in the fig.4.5. Voltage waveform i_{ds} of switch M4 is shown in the fig.4.6.The transformer is stepped up the voltage and then converted A.C into D.C with capacitor is connected across the R-load.The simulation model for D.C to D.C converter operating in buck mode is shown in Fig 4.7.The driving pulses for MOSFETS M1 – M4 are shown in fig.4.10. Simulink model of the proposed dc-dc converter with a motor load is shown in the fig.4.12 and the waveform for speed measured is shown in the fig.4.13.

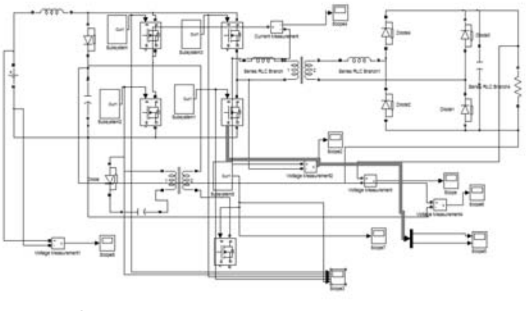

Fig.4.1. Simulink model of the proposed isolated bidirectional full-bridge dc-dc converter with a flyback snubber for boost mode

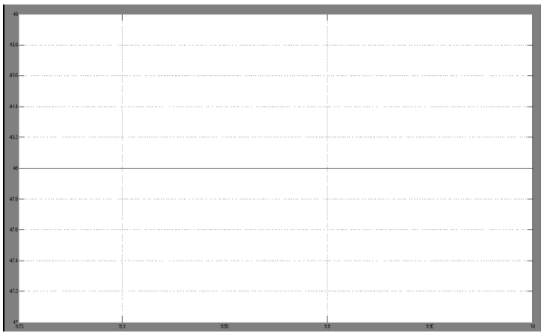

Fig.4.2 Input voltage waveform of boost converter

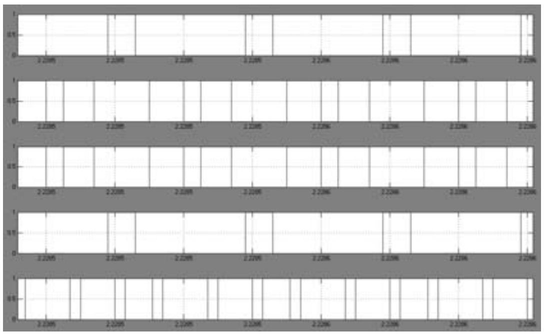

Fig.4.4 Driving pulses for MOSFETS M1-M4 and M_s

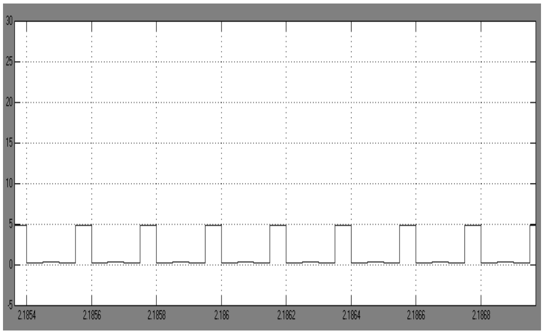

Fig.4.6 voltage v_{ds} of switch M4

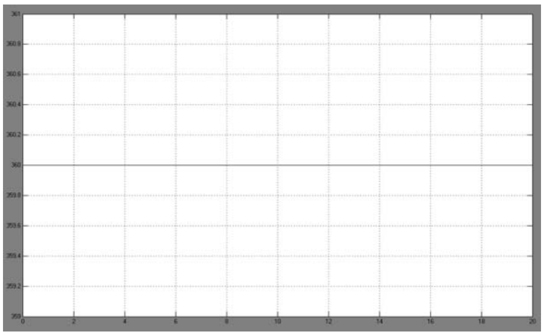

Fig.4.8 Input voltage waveform of buck converter

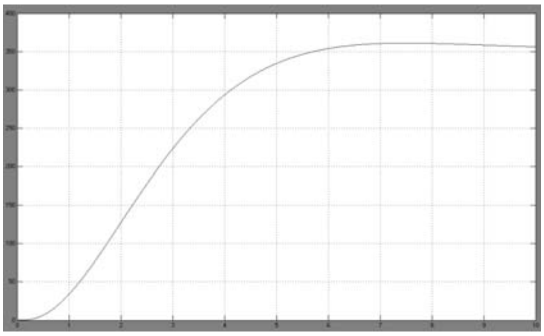

Fig.4.3 Output voltage waveform of boost converter

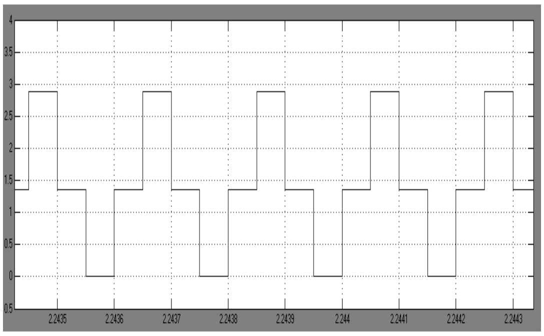

Fig.4.5 Current i_{ds} of switch M4

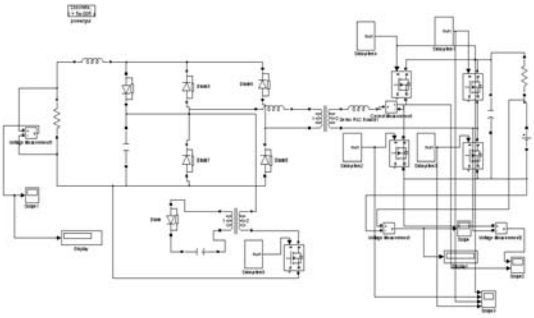

Fig.4.7 Simulink model of the proposed isolated bidirectional full-bridge dc-dc converter with a flyback snubber for buck mode

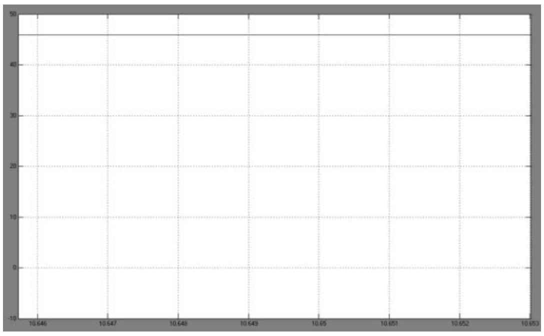

Fig.4.9 Output voltage waveform of buck converter

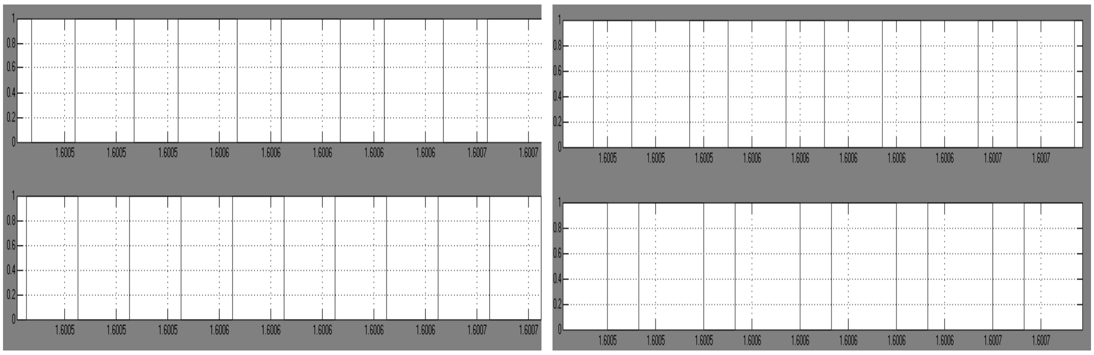

Fig.4.10 Driving pulses for MOSFETS M1-M4

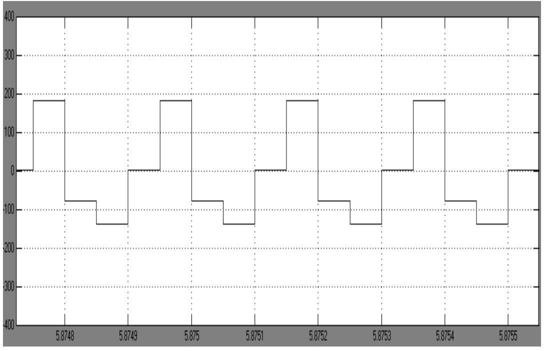

Fig.4.11 Transformer secondary voltage

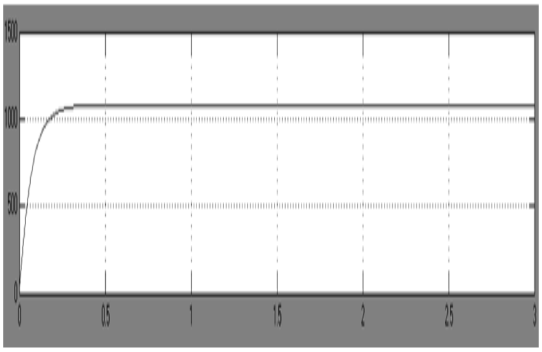

Fig.4.13 Waveform of Speed in rpm

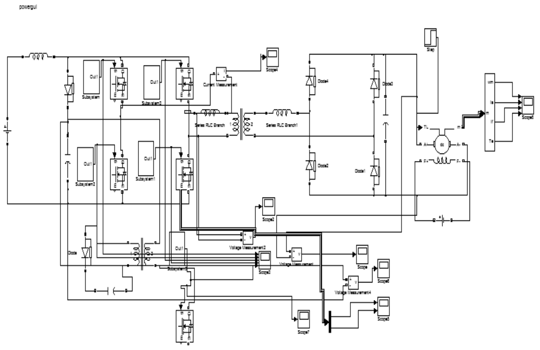

Fig.4.12 Simulink model of the proposed dc-dc converter with a motor load

5. 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 current fed 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. A battery module working at the low-voltage side is employed as an energy-storage element, whose voltage rating is 48 V. The high-voltage side is 360 V. It can be observed that the conversion efficiency of the proposed converter is around

90%–92%.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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