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Highly Efficient Non-Isolated Bidirectional DC-DC Converter for a Full Range of Load

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ABSTRACT

Highly Efficient Non-isolated Bidirectional Dc-Dc converter throughout a full range of load is proposed. In order to get high efficiency for all loads, an auxiliary circuit consisting of only two switches, four diodes, and an inductor has been introduced . The minimization of conduction losses is achieved with the help of ZVS of main switches resulting from the energy storage in auxiliary inductor. However, for light loads, the action of auxiliary inductor is not needed to attain ZVS, thereby simplify the circuit and reducing conduction loss. Thus, ZVS of main switches can be achieved in all load ranges. Due to ZVS switching, the switching losses are also reduced resulting in higher efficiency as compared with the conventional hard switching bi-directional converter. The proposed converter was simulated using PSIM, and the simulation result has been presented here.

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INTRODUCTION

Bidirectional dc-dc converters (BDC) have recently received much attention due to the increasing need for systems with the capability of bidirectional energy transfer between two dc buses. Apart from traditional application in dc motor drives, new applications of BDC include energy storage in renewables systems, fuel cell energy systems, and uninterruptible power supplies (UPS). The fluctuation nature of most renewable energy resources, like wind and solar, makes them unsuitable for standalone operation as the sole source of power. A common solution to overcome this problem is to use an energy storage device besides the renewable energy resource to compensate for these fluctuations and maintain a smooth and continuous power flow to the load. As the most common and economical energy storage devices are Batteries and Supercapacitors. A dc-dc converter is always required to allow energy exchange between storage device and the rest of the system. Such a converter must have bidirectional power flow capability with flexible control in all operating modes. To charge and discharge the storage element, the bidirectional DCDC converter is used.

Depending on the purpose of use, the bidirectional dc–dc converter is divided into two types, isolated type, and not- isolated type (Kim, 2013; Rodriguez, 2013). The significant advantage of an isolated bidirectional dc–dc converter is galvanic isolation which is an effective method for breaking a ground loop. However, this converter requires an isolated transformer and more than four switches for galvanic isolation so that its efficiency is lower than that of a non-isolated-type converter. On the other hand, the advantages of a non-isolated bidirectional dc–dc converter are simple structure, fundamentally including an inductor and two switches, and higher efficiency than an isolated type converter. Furthermore, by applying soft switching techniques to the non-isolated bidirectional dc–dc converter, soft switching of power switches is realized in a wide range of loads, and switching noise is also reduced. These soft-switching techniques are particularly necessary for downsizing converters and high efficiency by minimizing switching losses on power switches.

The zero-voltage switching (ZVS) operation of this converter is always achieved regardless of loads because of the large circulating current flowing through the auxiliary LC resonant circuit. However, large circulating current, which flows regardless of loads, increases conduction losses significantly. The overall efficiency is degraded due to significant conduction loss particularly at light load. In a soft-switching, bi-directional converter with a coupled inductor was proposed. It can provide soft-switching characteristic and a ripple-free inductor current. However, its conduction loss is substantial due to large circulating current.

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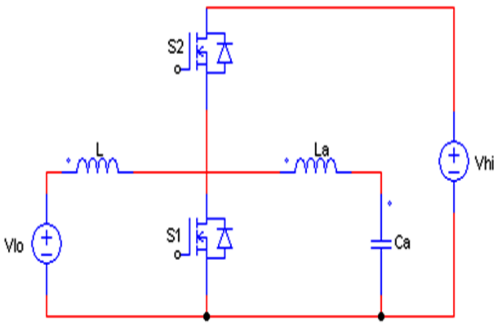

Fig.1: Conventional soft-switching bidirectional dc-dc converter.

Analysis of proposed converter:

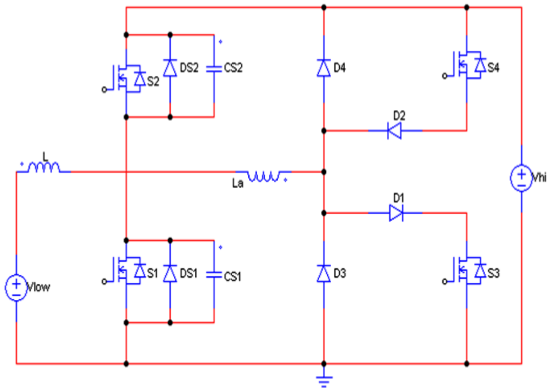

Fig. 2: Proposed bidirectional dc-dc converter.

In order to overcome these problems, a high-efficiency bidirectional dc–dc converter with low circulating current and ZVS characteristic throughout a full range of loads is proposed, as shown in Figure.4.2. In the proposed converter, current injection to the auxiliary inductor is accomplished through one of the two auxiliary switches: S3 for boost mode and S4 for buck mode. The energy stored in the auxiliary inductor can be controlled according to loads by varying the on-time of the auxiliary switches. At light load, ZVS of main switches can be achieved without the help of the auxiliary circuit. Therefore, the auxiliary circuit is inactive to minimize the conduction loss. Therefore, the proposed converter provides high efficiency throughout a full range of loads.

Figure.2 shows the circuit diagram of the proposed bidirectional dc–dc converter. The low-side voltage V_{lo} is substituted for a battery, and the high-side voltage V_{hi} signifies a dc bus for subsequent utilization. When the proposed converter operates in boost mode, the switch S1 acts as a main switch and the switch S2 acts as a synchronous switch. When operating in buck mode, S1 acts as a synchronous switch and S2 acts as a main switch. The auxiliary circuit is composed of the auxiliary inductor La, additional switches S3 and S4, reverse-blocking diodes D1 and D2, and freewheeling diodes D3 and D4. The switch S3 and the diodes D1 and D4 are active for boost mode. In buck mode, the switch S4 and the diodes D2 and D3 are active. Since, at light load, the ZVS of the main switches S1 and S2 is naturally achieved, the auxiliary circuit stays inactive, and the proposed converter acts as a conventional bidirectional dc–dc converter without any auxiliary circuit. The diodes DS1 and DS2 are the intrinsic body diodes of S1 and S2, respectively. The capacitors CS1 and CS2 represent the parasitic output capacitances of S1 and S2, respectively.

Boost mode:

The proposed bi-directional converter operates in two modes (buck and boost) of operation. In this mode, the proposed converter acts as a boost converter. The corresponding mode transitions of boost mode with the equivalent circuits for the proposed circuit is shown in Fig. 3.

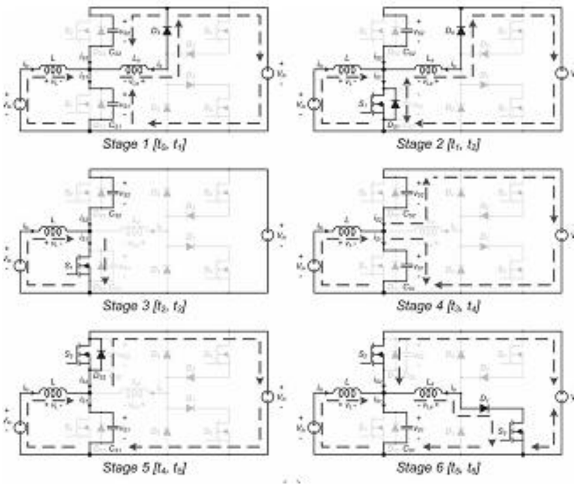

Fig. 3: Modes of operation- Boost Mode.

MODE 1:

When S2 and S3 are turned off at the same time, this stage begins. The capacitor CS1 starts to discharge, and CS2 starts to charge. Since S3 is turned off, the current ia flows through the freewheeling diode D4.

MODE 2:

CS1 is fully discharged and V_{S1} reaches zero by means of iS1, the value of which is negative as (Ia − In), flowing through DS1. Then, the gate pulse VGS1 is applied to S1 before VS1 is changed. Since S1 has zero voltage at the moment of the turn-on, the ZVS operation of S1 is achieved.

MODE 3:

The auxiliary inductor current ia becomes zero, and D4 is turned off at zero current. Thus, zero current switching (ZCS) of D4 is achieved.

MODE 4:

The capacitor CS1 starts to charge, and CS2 begins to discharge. With an assumption that the capacitances of CS1 and CS2 are very small and the time interval in this stage is very short, ilo can be regarded as constant, and the voltages VS1 and VS2 vary linearly.

MODE 5:

CS2 is fully discharged, and VS2 reaches zero by means of ilo flowing through DS2. Then, VGS2 is applied to S2 before VS2 is changed. Since S2 has zero voltage at the moment of the turn-on, the ZVS operation of S2 is achieved.

MODE 6:

This mode begins when the switch S3 is turned on. Since VLa is −Vhi, ia decreases.

B. BUCK MODE:

In this mode, the auxiliary switch S4 is active for satisfying the ZVS operation of S2.The current ilo decreases linearly and reaches the minimum value –Im.

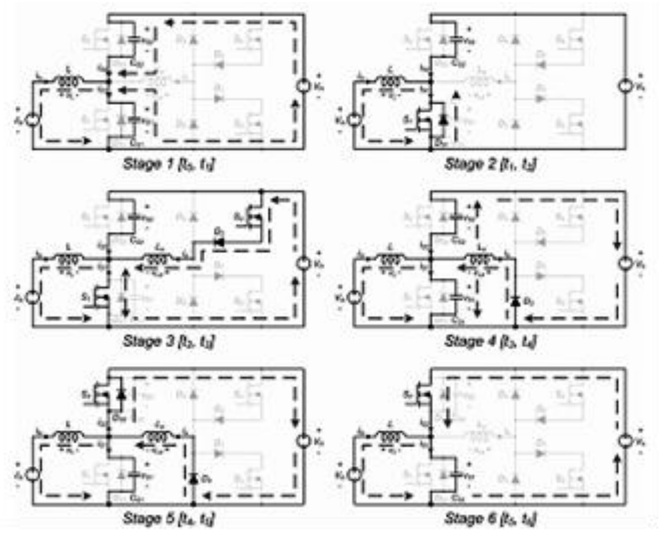

Fig. 4: Modes of operation- Buck Mode.

MODE 1:

The capacitor CS1 starts to discharge, and CS2 begins to charge. With an assumption that the capacitances of CS1 and CS2 are very small and the time interval in this stage is very short, the current ilo can be regarded as constant, and the voltages VS1 and VS2 vary linearly.

MODE 2:

CS1 is fully discharged, and VS1 reaches zero by means of ilo flowing through DS1. Then, the gate pulse VGS1 is applied to S1 before VS1 is changed. Since S1 has zero voltage at the moment of the turn-on, the ZVS operation of S1 is achieved.

MODE 3:

This stage begins when S4 is turned on. Since VLa is Vhi, ia increases linearly.

MODE 4:

When S1 and S4 are turned off at the same time, this mode begins. The capacitor CS1 starts to charge, and CS2 begins to discharge. With an assumption that the capacitances of CS1 and CS2 are very small and the time interval in this stage is very short, the currents ilo and ia can be regarded as constant, and the voltages VS1 and VS2 vary linearly.

MODE 5:

CS2 is fully discharged, and VS2 reaches zero by means of iS2, the value of which is negative as −(Ia − In), flowing through DS2. Then, VGS2 is applied to S2 before VS2 is changed. Since S2 has zero voltage at the moment of the turn-on, the ZVS operation of S2 is achieved.

MODE 6:

D3 is turned off at zero current. Thus, ZCS of D3 is achieved.

I. Characteristics And Zvs Operation:

A. Relationship between vlo and vhi:

The volt–second balance law gives,

$$V_{lo}DT_S = (V_{hi}-V_{lo})(1-D)\ T_S \qquad (1)$$

From (1), the voltage gain of the proposed converter is obtained as follows,

$$(V_{lo}/\ V_{hi}) = 1/(1-D) \qquad (2)$$

B. Zvs operation in boost mode:

When a conventional bidirectional dc–dc converter operates in boost mode, ZVS turn-on of S2 is always satisfied. However, ZVS turn-on operation of S1 is only achieved at light load by means of the reverse current flowing through the primary inductor. For this reason, in the proposed converter, the auxiliary circuit operates at medium- and heavy-load conditions in order to satisfy ZVS of S1. At light load, the auxiliary circuit is inactive, and the conduction loss is minimized.

The following ZVS condition should commonly be satisfied,

$$T_{DT} < T_{ZVS} \qquad (3)$$

Where TDT is the dead time of S1 and S2 for a proper ZVS operation of the main switches and TZVS is the time when the switch S1 is reverse biased and the reverse current is flowing through the intrinsic body diode DS1. Because the gate pulse should be applied to the main switches after the voltage across the main switches has decreased to zero and before the current flowing through the intrinsic body diode changes its direction, the dead time should be considered.

In this case, the minimum current of iS1 is obtained by,

$$I_n = -\frac{V_{lo}}{L}T_{ZVS} \qquad (4)$$

The maximum output power for ZVS operation in boost mode is expressed as follows,

$$P_{out} < \left(\frac{D}{2} - \frac{1}{100}\right)\frac{\eta V_{lo}^2}{L}T_S \qquad (5)$$

C. Zvs Operation In Boost Mode:

In buck mode, the auxiliary circuit operates at medium- and heavy-load conditions in order to satisfy ZVS of S2.The following ZVS condition should commonly be satisfied.

$$T_{DT} < T_{ZVS} \qquad (6)$$

The minimum current of iS2 is obtained by,

$$I_n = \frac{V_{hi}-V_{lo}}{L}T_{ZVS} \qquad (7)$$

The maximum output power for ZVS operation in buck mode is expressed as follows,

$$P_{out} < \left(\frac{1}{2} - \frac{1}{100(1-D)}\right)\frac{V_{lo}^2}{L}DT_S \qquad (8)$$

Simulation Results And its Discussion:

Simulation' in general terms can be defined as the representation of a system in its realistic form. Before implementing a new project, by simulation, one can see the effect of various parameters or components on the output accordingly change them to get a desired output. PSIM denotes Power Simulation. PSIM is simulation software specifically designed for the analysis and design of power electronics and control circuits. It provides a powerful environment to display and analyze simulation results. The proposed bidirectional non-isolated DC-DC converter is verified with PSIM (a commercially available software package dedicated for power electronic converter simulations) and proposed converter was simulated under both buck and boost mode based on the following specifications: boost output voltage V_o= 200 volts, d = 0.5 (boost mode), buck mode output voltage V_o= 80 volts, d = 0.8 (buck mode) ,output power P_o= 100 W, Input voltage V_{in}= 100volts, and switching frequency fs=40KHz.

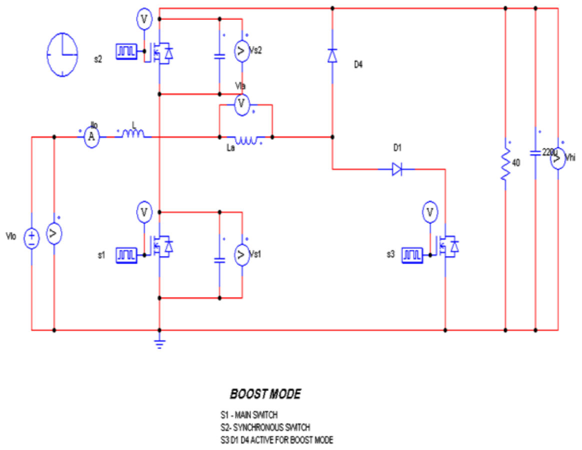

Fig. 5: Simulation circuit of proposed converter operates as boost converter.

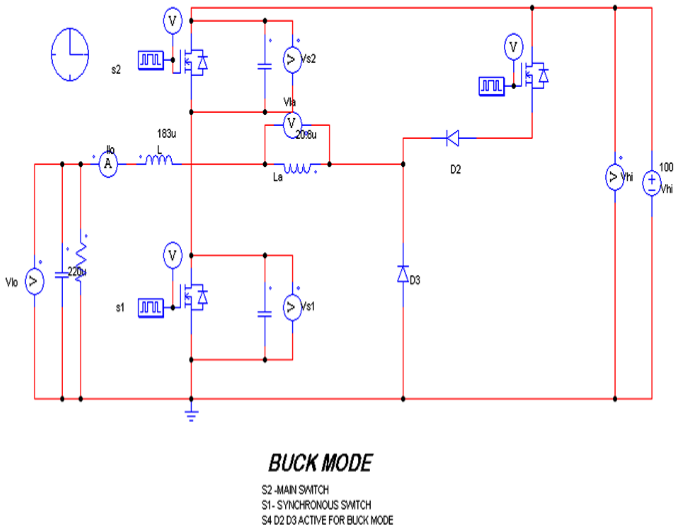

Fig. 6: Simulation circuit of proposed converter operates as buck converter.

Fig. 5 and Fig. 6 shows the simulation circuits of proposed converter of boost and buck mode of operation respectively. The simulation results that was obtained using PSIM software has been displayed in the following section along with their explanations about bi-directional converter waveforms and its output waveforms.

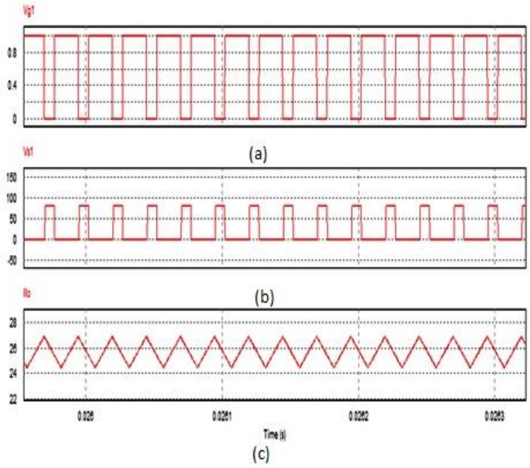

Fig. 7: Simulated switching waveforms of proposed converter.

The circuit has been simulated at 100Vdc input by using PSIM Software. Figure 7 demonstrates the Simulated switching waveforms of proposed converter. In these waveforms gate pulse signals of the MOSFET, switch S1 is shown in Fig. 7(a). The ZVS operation of the switch during turn-on and turn-off are shown in Fig. 7(b). This proposed method combines the benefits of hard switching and soft switching.

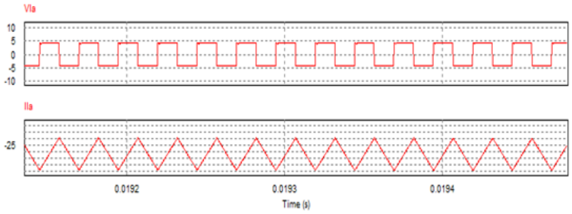

Fig. 8: Simulated auxiliary inductor voltage and current waveforms of proposed converter.

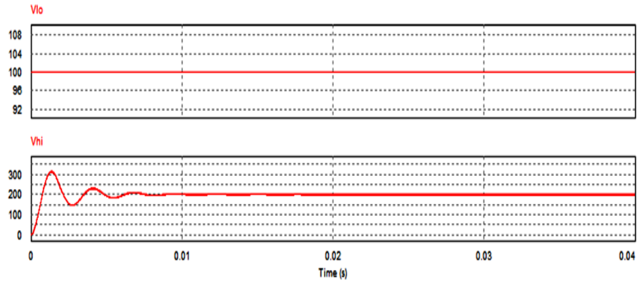

Fig. 9: Input and Output Voltage waveforms of proposed converter- Boost mode.

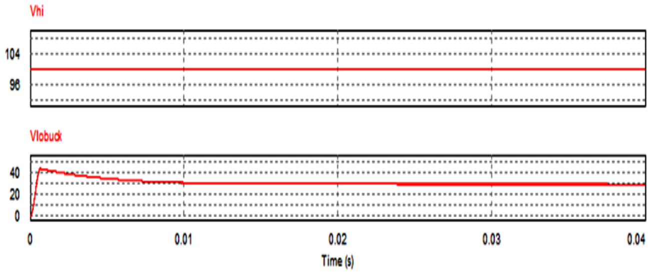

Fig. 10: Input and Output Voltage waveforms of proposed converter- Buck mode.

The inductor current I_{la} and inductor voltage V_{la} of the proposed boost dc-dc converter operation is illustrated in Fig. 8. In Fig. 8 the inductor current I_{la} gets down to be zero level is indicated and time taken to reach zero level depends upon the load power.

The proposed converter in boost mode with load resistance R=40Ω, d = 0.1-0.5 is simulated and corresponding output voltage waveform is shown in Fig. 9. It is also simulated for various duty cycle d=0.1, d=0.3, d=0.5 and its voltage conversion ratio M is calculated using the relation M= Vout / Vin . At d = 0.1, Vin = 100, Vout = 200 the Voltage conversion ratio is M = 2. At d=0.3, M= 2.5 and at d=0.5, M=3.7.Here for 200W output power, 95% efficiency is achieved for voltage conversion ratio M= 2.

Moreover, also the proposed circuit is simulated in buck mode and step down output voltage is obtained as shown in Fig. 10 with R =40 Ω, d = 0.5 and other duty cycle values. Also step down conversion ratio similar to boost mode of operation is obtained.

Conclusion:

The new proposed bidirectional non-isolated DC-DC converter can work in either boost and buck mode. The zero voltage and zero current switching operations have been verified in the simulation results to ensure lower switching and circulating current losses. The inherent properties of the dc-dc converter have been clarified from the simulation results as follows:

- When the proposed converter operates at light load, the auxiliary circuit is turned off, and it acts as a conventional bidirectional dc–dc converter so that high efficiency and ZVS operation are easily obtained.
- Significantly reduced switching loss by means of the ZVS operation of the main switches and the minimized conduction loss by conducting the auxiliary circuit for a short time interval.
- Eventually, low circulating current for high efficiency and ZVS characteristic throughout a full range of loads are achieved.

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