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Analysis and design of a high gain non-isolated zero current switching bidirectional DC–DC converter for electric vehicles

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ABSTRACT

This paper presents a dual inductor based current-fed bidirectional non-isolated DC–DC converter for energy storage applications. The main idea of this converter is to achieve a higher voltage conversion ratio by obtaining the operation of zero current switching. The proposed soft-switching bidirectional DC–DC converter reduces the turn-off switching losses with the aid of auxiliary network, where, the auxiliary network comprised with the resonant inductor and the resonant capacitor. This converter operates under two different operating modes such as a boost (discharge) and buck (charge) modes. In both the modes of converter operations, the IGBTs are operating under zero current turn-off in order to minimize the switch turn-off losses and to improve the efficiency of the converter. The principle of the operations and its theoretical analysis are validated by the experimental results using a 300W (50 V/250 V) converter system.

1. Introduction

In recent years, there is a lot of demand for power converter technology in energy back-up systems such as fuel cells and super capacitors. The isolated BDC’s play significant role in battery backup systems to transfer the power in two directions as low voltage to high voltage and vice-versa. To achieve the high voltage gain up to 3 kV, a transformerless DC–DC converter [1] implemented with the help of cascade connection of switches and capacitor (Total 19 arrays), which is operated under hard-switching since the source voltage is 67.5–350 V. To achieve the high gain, there are different approaches followed by many researchers, among them, one is using voltage multipliers based on diode-capacitor [2–4]. High voltage gain converters were implemented with the inverse dual converter [5] which transfers the power flow in dual directions. These converters are used in SCRs as semiconductor devices to transfer the output power. In recent years, there have been a research on high voltage gain isolated fullbridge DC–DC converter [6] with high efficiency for battery storage applications. There are many current-fed isolated converters including push–pull [7] and half bridge [8] implemented as hard-switching version. Later on, the current-fed isolated converters (Boost) were developed to obtain the zero voltage switching (ZVS) [9] with the usage of snubber capacitors, transformer leakage inductances and current-fed high voltage gain resonant full bridge converters [10,11] with the help of resonant capacitor connected parallel with an inductor. The different variations of current-fed isolated half-bridge converters with the usage of passive lossless and active lossless snubbers were reported [12–14] in order to obtain ZVS operations to their semiconductor switches. At the later stage of the ZVS in current-fed isolated converters research, many researchers worked to investigate the turn-off operation at zero current of IGBTs in the boost converter [15,16] and also soft-switching operation achieved in a resonant inverter [17] with the use of a parallel resonant tank. The isolated converters were developed with active clamp circuits [18–20] and the ZCS turn-off and ZVS turn-on [21,22] operations were achieved in this topology. A hard-switching multiphase high gain, high power non-isolated step-up converters [23] were compared and they reduced the input current ripple by the increased number of phases. Later, research was focused on non-isolated converters for the applications in battery backup systems to achieve the desired voltage levels, cost of design and reduction of size. A high voltage gain non-isolated boost converters [24] were implemented with an auxiliary passive resonant circuit in order to obtain soft-switching operations to their switching devices and diodes by means of the keeping resonant frequency below the switching frequency. Also, the researchers focused on secondary power supply systems in electric vehicles, and hence the work was concentrated on non-isolated BDC’s [25] with the aid...
of simple series resonant elements which are used to obtain ZVS turn-on to their main switching devices. A non-isolated high gain boost converters [26] were developed with a parallel resonant circuit (LCC) and also an additional voltage multipliers cell. The zero voltage turn-on operation was achieved for main switches and Zero Current turn-on/off for diodes, respectively. However, lesser efficiency was obtained at very low power and high switching frequency (150 kHz). Similarly, a current-fed non-isolated bidirectional converter [27] was developed without voltage multiplier cells based parallel resonant circuit (LCL), it achieved the zero current turn-off operations of their switches and achieved 95.5% efficiency at the operating frequency above 100 kHz. There have been various non-isolated type converter topologies implemented under soft-switching condition. A passive lossless bidirectional converter [28] was operated with ZVS for the applications of electromechanical braking systems in electric vehicles. It is operated at very low input voltage, low power and low switching frequency. Nevertheless, it has obtained a maximum efficiency about 94% for very low output power conditions.

Based on previous existing high gain BDCs, both hard and soft-switching versions are considered in design to achieve the following issues: reduced switching losses, high power, high switching frequency and improved efficiency. A new non-isolated BDC has been proposed and implemented under zero current switching (ZCS) commutations. This article proposes a high gain non-isolated bidirectional DC–DC converter with the aid of additional active and passive resonant circuits. The main objective of the present research is to achieve the soft-switching operations to their respective switches with reduced switching losses.

2. Converter operation

The overall structure of the battery energy storage system of DC traction vehicles and the configuration of the proposed converter are shown in Figures 1 and 2, respectively. The circuit is basically comprised of six IGBTs \( S_{1-4}, S_{p-q} \), input inductors \( L_{1}, L_{2} \), auxiliary inductor \( L_{p} \) and capacitor \( C_{q} \). When the converter is operated in boost mode, to transfer the power, the two IGBTs \( S_{1}, S_{2} \) must be conducted and the additional IGBTs \( S_{p}, S_{q} \) is used to achieve soft-commutation of \( S_{1}, S_{2} \). When this converter operates in buck mode, the output power is delivered by the IGBTs \( S_{2}, S_{3} \) by means of turning-on the auxiliary IGBTs \( S_{p}, S_{q} \), the turn-off of IGBTs \( S_{2}, S_{3} \) occurs at zero current. The boost mode operation is explained based on the theoretical waveforms as shown in Figure 3 and its equivalent circuits with the direction of current flow are shown in Figure 4.

2.1. Boost mode

First interval \((t_0-t_1)\): At time \( t_0 \), the main IGBT \( S_{1} \) is turned-on. The current flowing through the IGBT \( S_{1} \) depends on the input inductor current. Prior to \( t_0 \), the IGBT \( S_{2} \) is in conduction. Due to the resonance between \( L_{p} \) and \( C_{q} \), the resonant tank current flows through the IGBT \( S_{1} \). The current \((i_{S1})\) is expressed as;

\[
i_{S1} = \frac{V_{1}}{L_{p}}(t_{0} - t_{1}) - \frac{V_{1}}{Z} \cos(\omega(t_{0} - t_{1})) - I_{o} \tag{1}
\]

The initial conditions of \( L_{p} \) and \( C_{q} \) are \( i_{S_{p}}(0) = 0; V_{C_{q}}(0) = 0 \), where, characteristics impedance \( Z = \frac{L_{p}}{C_{q}} \) and angular frequency \( \omega = \frac{1}{\sqrt{L_{p}C_{q}}} \).

Figure 1. Battery back-up systems in electric vehicles.

Figure 2. Proposed ZCS high gain bi-directional DC–DC converter.
Second Interval ($t_1$–$t_2$): At $t_1$, the auxiliary IGBT $S_p$ is turned-on to achieve the ZCS turn-off of $S_1$ and $S_2$, then the current gradually reduces to zero. The energy is accumulating in the input inductor $L_1$ and the accumulated energy in $L_2$ is transferred as load at the instant of the IGBT $S_2$ turned-off. At $t_2$, the current of IGBT $S_1$ is identical to the output current $I_o$ at $t_2$.

At $t_2$, the IGBT $S_2$ anti-parallel diode is still in conduction. The $S_2$, $S_p$ currents and voltage of auxiliary capacitor $C_q$ is expressed as:

$$i_{S_2} = i_o - \frac{V_1}{Z}(t_1 - t_2) \cos \omega(t_1 - t_2)$$  \hspace{1cm} (2)

$$i_{S_p} = -i_{in} \cos \omega(t_1 - t_2) - \frac{V_o - V_{C_q}}{Z} \sin \omega(t_1 - t_2)$$ \hspace{1cm} (3)

$$V_{C_q} = -V_1 \cos \omega(t_1 - t_2)$$ \hspace{1cm} (4)

Third Interval ($t_2$–$t_3$): At $t_2$, the anti-parallel diode of IGBT $S_2$ is turned-on to allow the reverse current and the anti-parallel diode of IGBT $S_2$ is turned-off at $t_3$. The current of $S_2$ is expressed as:

$$i_{S_2} = i_o - i_o \cos \omega(t_2 - t_3) - \frac{V_{C_q} - V_o}{Z} \sin \omega(t_2 - t_3)$$ \hspace{1cm} (5)

Fourth Interval ($t_3$–$t_4$): At time $t_3$, the IGBT $S_2$ is turned-off since the IGBT $S_1$ is turned-on from $t_0$ and a negative current flow through the IGBT $S_p$. Therefore, the anti-parallel diode of $S_p$ is turned-on. The accumulated energy by the inductor $L_2$ is transferred to load via $L_2$-$C_2$-$R$. At the end of this interval, the anti-parallel diode of the IGBT $S_p$ is turned-off.

Fifth Interval ($t_4$–$t_5$): During this interval, the IGBT $S_1$ remains in conduction and then the output power transfers via $V_1$-$L_1$-$S_1$.

Sixth Interval ($t_5$–$t_6$): This interval is similar to $t_0$–$t_1$; the IGBT $S_1$ remains in conduction except the applied gating signals to $S_2$.
Seventh Interval \((t_6-t_7)\): The auxiliary IGBT \(S_q\) is turned-on at \(t_6\) to obtain the turn-off at zero current for \(S_2\), while, the IGBT \(S_1\) current gradually reduces to zero and then it becomes reversed. This time interval is called as the resonating interval. The resonant tank current produced by \(L_p C_q\) is used to obtain the soft turn-off. The voltage and current expressions are defined as follows:

\[
V_{C_q} = V_1 \cos \omega (t_6 - t_7)
\]
\[
i_{Lp} = -\frac{V_{Cq}}{\sqrt{L_p/C_q}} \sin \omega(t_6 - t_7)
\] (7)

Eighth Interval \((t_7 - t_8)\): At \(t_7\), the anti-parallel diode of the IGBT \(S_1\) is turned-on and resonant current flows through it. At \(t_8\), the resonant tank current becomes zero and anti-parallel diode is turned-off. The voltage and current expressions of \(L_p, C_q\) are defined as follows:

\[
V_{Cq} = V_o \cos \omega(t_7 - t_8) + I_i L_p \omega \sin \omega(t_7 - t_8)
\] (8)

\[
i_{Lp} = I_i \cos \omega(t_7 - t_8) - \frac{V_{Cq}}{\omega L_p} \sin \omega(t_7 - t_8)
\] (9)

Ninth Interval \((t_8 - t_9)\) and Tenth Interval \((t_9 - t_{10})\) are the same as the period from \(t_2 - t_4\).

### 2.2. Buck mode

The operation of this mode is discussed based on the theoretical waveforms as shown in Figure 5 with principal waveforms of buck mode. The IGBTs \(S_3, S_4\) are the main switching devices used to transfer the power to the output. The duty cycles of both the IGBTs \(S_3\) and \(S_4\) are about 50%. During this entire mode, the IGBTs \(S_1, S_2\) are turned-off, however, the anti-parallel diodes give the path to flow the output current. The buck operation is divided into nine intervals and their current flow equivalent circuits are illustrated in Figure 6 and explained as below.

First Interval \((t_0 - t_1)\): At time \(t_0\), the IGBT \(S_3\) is turned-on, there is a current peak through the IGBT \(S_3\) due to

**Figure 5.** Theoretical waveforms: Buck mode. (a) Interval \((t_0-t_1)\) & Interval \((t_1-t_2)\) (b) Interval \((t_2-t_3)\) (c) Interval \((t_3-t_4)\) (d) Interval \((t_4-t_5)\) (e) Interval \((t_5-t_6)\) (f) Interval \((t_6-t_7)\).
the resonant tank current produced by $L_p$, $C_q$. At the end, the current of the $L_p$ becomes zero and voltage of $C_q$ is charged to half of its input voltage.

Second Interval ($t_1$–$t_2$): For this whole interval, the output power transfers via the input capacitor $C_1$, input inductor $L_1$, anti-parallel diode of the IGBT $S_2$ and the main IGBT $S_3$.

Third Interval ($t_2$–$t_3$): At time $t_2$, the auxiliary IGBT $S_q$ is turned-on to obtain the soft turn-off of the IGBT $S_3$. During this stage, the $L_p$, $C_q$ are in resonating each other and IGBT $S_3$ current reduces gradually and it reaches zero at $t_3$.

Fourth Interval ($t_3$–$t_4$): During this interval, all IGBTs are in switched-off except the auxiliary IGBT $S_q$, so it is named as the switch-off period. In order to create a path for resonance, the anti-parallel diode of $S_3$ starts conducting.

Fifth Interval ($t_4$–$t_5$): At this period of interval, all IGBTs are in switched-off for a while.

The Sixth ($t_5$–$t_6$), Seventh ($t_6$–$t_7$), Eighth ($t_7$–$t_8$) intervals are same as from $t_0$–$t_1$ to $t_2$–$t_3$ intervals, where the IGBT $S_4$ is operated and auxiliary IGBT $S_p$ is used for obtaining zero current turn-off.

Ninth Interval ($t_8$–$t_9$): This interval is similar to the Fifth interval.

3. Design analysis

The proposed converter design analysis is described in this section. The design of auxiliary active circuit with
Figure 7. Simulation waveforms of boost mode operation (a) $I_{S1}$ - current through the switch current $S_1$, (b) $I_{S2}$ - current through the switch current $S_2$, (c) $I_{Sp}$ - current through the auxiliary switch current $S_{p}$, (d) $I_{lp}$ - current through the resonant inductor $L_p$, (e) $V_{Cq}$ - voltage across the resonant capacitor boost mode.

Figure 8. Simulation waveforms of buck mode operation (a) $I_{S3}$ - current through the switch $S_3$, (b) $I_{Sp}$ - current through the switch $S_{p}$, (c) $I_{lp}$ - current through the resonant inductor current of $L_p$, (d) $V_{Cq}$ - voltage across the resonant capacitor.
a series resonant elements was considered to attain the zero current switching turn-off of the semiconductor switching devices, regardless of the direction of power transfer in this converter. There is an increase in current at turn-on of IGBTs $S_1$-$S_4$ in both boost and buck modes due to the flow of resonant tank current. The

Table 1. Parameters considered for the proposed converter.

| Parameter                  | Symbol | Value |
|----------------------------|--------|-------|
| Input voltage              | $V_1$  | 50V   |
| Output voltage             | $V_o$  | 250V  |
| Maximum output power       | $P_o$  | 300W  |
| Switching frequency        | $f_{sw}$ | 50kHz |
| Input inductor             | $L_1-2$ | 200μH |
| Resonant inductors         | $L_p$  | 20μH  |
| Resonant capacitors        | $C_q$  | 50nF  |
| Output capacitor           | $C_o$  | 470μF |
| Mainswitches               | $S_1-4$ | IKW40N120H3 |
| Auxiliary switches         | $S_p-q$ | IKW40N120H3 |

Values chosen for the resonant capacitor ($C_q$) is based on the values of the peak resonant tank current through the IGBTs($S_1$-$S_2$). The higher values of the resonant capacitor ($C_q$) will reduce the peak current through the IGBTs $S_1, S_2$ and vice versa. The total period of resonance that is equal to the soft-turn-off period, it may increase or decrease depends on the values of resonant capacitor $C_q$. The larger value of $L_p$ resonant inductance creates the zero current turn-off of the IGBTs ($S_1$, $S_4$).

The DC voltage conversion ratio can be determined by the analysis given by equation (10).

$$\frac{V_o}{V_{in}} = \frac{1}{2\pi f_r} \left( \frac{k + 1}{k} - \sqrt{\frac{1}{k^2} - 1} + 2\pi - \sin^{-1}k \right) + \frac{\delta t}{T}$$

(10)

Figure 9. Experimental waveforms of boost mode operation (a) switch $S_2$ collector current $I_{S2}$ and the voltage across the collector to emitter $V_{CE}$ & switch $S_p$ collector current $I_{Sp}$ and the voltage across the collector to emitter $V_{CE}$ (b) Current through the inductor $L_p$ and voltage across the capacitor $C_q$. 
where $V_o$ – Output voltage; $V_{in}$ – Input voltage; $k$ – Constant; $f$ – Switching frequency; $f_r$ – Resonant frequency; $\frac{\delta t}{T}$ – Duty cycle.

The behaviour of this converter is represented by a simplified Equation (11), $\frac{f}{f_r}$ is fixed value and the output voltage can be controlled by varying $\frac{\delta t}{T}$, The duration of from $t_3$–$t_5$ equals to $\delta t$, where $\delta t = t_5 - t_3$. The maximum value of $\frac{\delta t}{T}$ is given by Equation (12).

$$\frac{V_o}{V_{in}} = \frac{f}{f_r} + \frac{\delta t}{T}$$ \hspace{1cm} (11)

$$\left(\frac{\delta t}{T}\right)_{\text{max}} = \frac{V_o}{V_{in}} - \frac{f}{f_r}$$ \hspace{1cm} (12)

\[ f_r = \frac{1}{2\pi \sqrt{LpC_q}} \] \hspace{1cm} (13)

The ZCS turn-off condition for $S_1$–$S_4$ can be obtained if Equation (14) is satisfied when the parameter ($k$) is less than one ($k < 1$).

$$k = \frac{I_m}{V_l} \sqrt{\frac{L_r}{C_q}} \leq 1$$ \hspace{1cm} (14)

where, maximum current of input inductor $I_m = \frac{P_m}{V_{in}}$, output voltage is $V_o$, the auxiliary inductance is $L_p$, and $C_q$ is the auxiliary capacitance.

The parameters of resonant circuit can be defined as,

$$\frac{L_p}{C_q} = \frac{1}{(2kf_r)^2}$$ \hspace{1cm} (15)

Figure 10. Experimental waveforms of buck mode operation (a) switch $S_3$ collector current $I_{S3}$ and the voltage across the collector to emitter $V_{CE}$ & switch $S_q$ collector current $I_{Sq}$ and the voltage across the collector to emitter $V_{CE}$ (b) auxiliary resonant inductor current $I_{Lp}$ and auxiliary resonant capacitor voltage $V_{Cq}$. 
3.1. Design example

The design is considered with the specifications of, 50 V input voltage; 250 V output voltage; 300 W output power and 50 kHz switching frequency.

The maximum input current \( I_m = 1.2 \text{A} \) (boost mode).

The maximum input current \( I_m = 5.6 \text{A} \) (buck mode).

The resonant frequency of auxiliary circuit is calculated as, \( f_r = \frac{1}{2\pi \sqrt{L_p C_q}} = 0.159 \text{MHz} \).

The auxiliary inductor \( L_p \) and capacitor \( C_q \) values are chosen as, \( L_p = 20 \text{μH} \); \( C_q = 50 \text{nF} \). The ZCS turn-off condition is obtained at \( k = 0.74 \) and \( k = 0.76 \) from (15), which satisfies the condition \( k < 1 \).

4. Simulation and experimental evaluations

Initially, the soft-switching operations are observed by simulations, which are performed on MATLAB Simulink by considering the applied source voltage of 50 V in boost mode and 250 V in buck mode. The operating frequency of this converter is about 50 kHz and resonant circuit frequency of 0.159 MHz, which is obtained by equation (13). If equation (14) satisfies the condition, then the soft-switching can be obtained for their main IGBTs. This converter is designed and verified on open-loop simulation performance. The waveforms observed for the boost mode, the collector–emitter voltage \( V_{CE} \) and collector currents \( I_C \) of the IGBTs \( (S_1, S_2) \), auxiliary inductor \( L_p \) current, auxiliary capacitor \( C_q \) voltages are depicted in Figure 7(a–d), which confirms the ZCS turn-off of the IGBT \( S_1 \) and auxiliary IGBTs \( S_p \). Likewise, the simulations were performed for the buck mode and the observed waveforms are shown in Figure 8(a–d). To validate the simulation results of the converter design, a laboratory prototype was implemented for 50 V/250 V system by using the components and specifications as mentioned in Table 1. The duty cycles of 66% and 45% were used for the boost and buck modes, respectively. The Infineon IKW40N120H3 (IGBTs \( S_{1−4}, S_{p−q} \)) of six numbers were used in the prototype. The ferrite core E70 type auxiliary inductor with air gap of 3.5 mm was used to obtain a value of 20 μH inductance (three ferrite cores were used). Figure 9(a) shows the voltage \( V_{CE} \) and its current of the IGBTs \( S_1, S_q \). From these measured waveforms, it confirms that the ZCS turn-off was obtained for the IGBT \( S_1 \) and soft turn-off of the auxiliary IGBT \( S_p \).

Therefore, this converter has reduced switching losses. The measured waveforms of current of the auxiliary inductor \( L_p \) and voltage of auxiliary capacitor \( C_q \) are shown in Figure 9(b). Similarly, the experimental results were observed for buck mode. The voltage \( V_{CE} \), currents of IGBTs \( S_3 \) and \( S_p \) are shown in Figure 10(a). Since the auxiliary resonant devices \( L_p \) and \( C_q \) are seriesly connected with the IGBT \( S_p \), when it is turned-on, there is a voltage stress observed. However, the voltage of the IGBT is equal to 200 V.

![Figure 11](image-url). (a) Turn-on transition of IGBTs \( S_1 \) and \( S_p \): boost mode. (b) Turn-off transition of IGBTs \( S_1 \) and \( S_p \): boost mode. (c) Turn-on transition of IGBTs \( S_3 \) and \( S_p \): buck mode. (d) Turn-off transition of the IGBTs \( S_3 \) and \( S_p \): buck mode.
when the input voltage of 300 V applied to the converter. The experimental waveforms of the auxiliary inductor $L_p$ current and capacitor $C_q$ voltage for buck mode are shown in Figure 10(a,b). Figure 11(a,b) shows turn-on/turn-off transition of the IGBT $S_1$ and auxiliary IGBT $S_p$ at boost mode. Figure 11(c,d) depicted the turn-on and turn-off transitions for the IGBT $S_3$ and IGBTs $S_p$ in buck mode. The experimental results were validated with the expected simulation analysis. The photograph of the experimental setup of this converter is shown in Figure 12.

5. Conclusion

A new soft-switching high gain bidirectional converter was designed and theoretically analysed. This converter was operated in forward power transfer (boost) and reverse power transfer (buck) modes with the aid of the auxiliary IGBTs, auxiliary inductor and capacitors. The main IGBTs are turn-off under ZCS is obtained, while converter operates in boost and buck modes. A laboratory prototype of 300 W and 50 V/250 V converter system was developed, tested and verified theoretically. This converter was tested at 300 W output power for both the operating modes. The soft-commutation ZCS was obtained for the IGBTs by way of the reduced turn-off switching losses. According to the efficiency analysis, the proposed topology achieved 95.5% and 96.84% for forward and reverse power transfer modes at 300 W output power. The proposed converter was verified the soft-switching capability and it can be applied for higher power electric vehicles.

Disclosure statement

No potential conflict of interest was reported by the authors.

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