Abstract

Background/Objective: A novel soft switching technique is implemented in a Bidirectional DC-DC converter by using an Active clamped Auxiliary switch and in turn it achieves continuous current of inductor and operates at constant frequency is used to turn ON and turn OFF the switches. Methods/Statistical Analysis: The Power electronics converter systems have DC bus voltages they are connected to batteries or supercapacitors. Bidirectional converters which are connected to battery, supercapacitor allows them to charge or discharge. A new soft switching Bi-directional direct current to direct current converter is presented in this paper. This converter is operated in zero voltage and zero current switching, continuous inductor current and constant frequency that frequency is used to turn ON and turn OFF the switches. The switching stresses are reduced in this proposed method by auxiliary switches compared to traditional methods. The simulation results are obtained by using MATLAB software in this paper. Findings: The proposed converter is implemented by using an Auxiliary switch with soft switching technique. The output is ripple free DC voltage of 63.5V. Improvements: The Bidirectional Converter will operate at continuous inductor current also with less ripples in output voltage.

Keywords: Auxiliary Circuit, Continuous Inductor Current, DC-DC Converter, Power Electronics, Pulse Width Modulation, Soft-Switching

1. Introduction

In Space and automotive, the power electronics systems are widely used. These power electronic systems are integrated to DC bus through Bidirectional converters. Batteries and super capacitors which are used in power electronic system are allowed to charge or discharge. This converter may be isolated\(^1\) or non-isolated\(^2\) and it depends up on application. In\(^1\) achieving bidirectional power flow provides a simple, efficient and galvanically isolated topology that is especially attractive for use in battery charging. In\(^2\) non–isolated system uses an auxiliary circuit to obtain soft switching of converter this leads to improve efficiency of converter.

In this proposed converter we are representing a non-isolated Bi-directional converter which is heritage of Buck/Boost converter. In Figure 1 \(S_1\) switch is going to operate as a boosting switch and \(S_2\) acts as boosting diode in which power transfer takes place from the lower voltage side \(V_{lo}\) to the higher voltage side \(V_{hi}\), and \(S_1\) acts as a bucking diode and \(S_2\) operates as a boosting diode where power transfer takes place from \(V_{hi}\) to \(V_{lo}\).

Generally it’s very easy to use soft-switching technique in Isolated Bidirectional direct current to direct current Converter when compared to Non-Isolated Bidirectional converter. As they are inheritance of half bridge and full bridge converters which uses inductive energy that is stored in transformer to discharge the capacitor which is present across the switches of converter. It’s a little bit tough task to carry out for non-isolated converters due to the absence of transformer. There are several soft-switching techniques that are used previously and they can be differentiated as follows:
The Converters proposed in\(^3\) and\(^4\) are referred on circuitry in Figure 1 which are operated with the flow of current in both directions through inductor during every cycle. Two switches will on at different time periods, some times in each half-cycle, the stored energy of inductor is used to turn on other device with Zero Voltage Switching (ZVS), due to the impact of turning off switch. Demerits of this method are current in inductor contains ripple with a very high value which results in turn-off losses which in turn causes decrease in efficiency of converter.

Another method of approach is quasi-resonant, multi-resonant circuitries. By these techniques, the results of the converter are going to have high power stresses and this causes Bidirectional converter to operate at different switching frequencies which in turn causes complicate design in hardware. It becomes complicated while designing the filter components and magnetics when the converter operated at different switching frequencies. In case of the converter proposed in\(^5\) can be operated at constant frequency of switching but stress of the device remains same. A Bi-directional converter of fixed switching frequency resonant type is proposed in\(^6\), but this requires half bridge converters more than one in series which is costly.

The other method is to use auxiliary circuitry to guide the switching devices to operate in soft-switching mode as in ZVT converters which are proposed in\(^7\)-\(^11\). Even though this is an improvement, compared to existing techniques, but it lags at complexity and cost. This complexity is due to use of four switches in which two auxiliary switches are used for two main switches. Conventional control switches replaced by two stage buck boost converter for improving the system quality\(^12\) and efficiency. Multi Port Converters implemented to produce a bidirectional power flow with high efficiency and reduced losses\(^13\). An architecture of On Chip switched capacitor\(^14\) produced reduced ripple voltage with high switching frequency. In quasi Z-source impedance networks implemented to produce an output voltage and current with reduced ripple\(^15\). Advanced vehicles\(^16\), i.e. parameters and characteristics of vehicles estimated by DC-DC converter.

Because of the myths of the existing methods such as maximum current stress, variable switching frequencies, those methods are not preferred. In the proposed converter, operation will be discussed and Simulation results are obtained by using matlab Simulink. Now, in the next section we are going to discuss about Modeling of the proposed converter, operation of converter and simulation results.

### 2. Proposed Bi-Directional Active Clamped Converter

#### 2.1 Proposed Converter

A new ZVS based soft switching technique is proposed for Bi-directional direct current to direct current converter. In this converter we will use a single auxiliary Active circuit. The proposed one (Figure 3) and the conventional one (Figure 1) is almost similar only difference is one

| Parameters       | Values          |
|------------------|-----------------|
| PV Input Voltage | 70 V            |
| Battery Input Voltage | 36 V      |
| Inductor        | Lr1=Lr2=12.5 µH, Lin = 500 µH |
| Capacitor       | Cr = 470 µF Co =1000 µF |
| Switching Frequency | 10 kHz     |

Figure 1. Conventional soft-switched Non-isolated DC-DC converter.

Figure 2. Earlier proposed bidirectional converters (a) converter proposed in\(^9\) (b) converter proposed in\(^10\).

Figure 4. Conventional soft-switched Non-isolated DC-DC converter.
auxiliary switch, one capacitor and two inductors. These elements make the circuit simple, which is well accepted Active clamp technique and these are used to operate in Boost/Buck mode with main switches \( S_1 \) and \( S_2 \). This converter is made to operate with continuous flow of inductor current, constant frequency is used to turn ON and turn OFF the switches.

Modes of operation of converter goes through two modes, one is Boosting mode, and another is Bucking mode. The Figure 4, Figure 5 represents equivalent circuit diagrams for both operations. The waveforms for both modes of operation are shown in Figure 6. From Figure 3

![Proposed soft-switched Non-isolated DC-DC converter.](image-url)

**Figure 3.** Proposed soft-switched Non-isolated DC-DC converter.

![Equivalent circuit diagrams from Mode 0 to Mode 7 of boost operation.](image-url)

**Figure 4.** Equivalent circuit diagrams from Mode 0 to Mode 7 of boost operation.

![Equivalent circuit diagrams from Mode 0 to Mode 7 of buck operation.](image-url)

**Figure 5.** Equivalent circuit diagrams from Mode 0 to Mode 7 of buck operation.
it is seen that the current entering through inductor \((I_{L1})\) is positive if it enters through positive terminal. The capacitor current is positive at positive terminal of capacitor \(Cr\).

### 2.2 Modes of Operation of Bidirectional Converter in Boost Region

**Mode 0\((t<t_0)\):** Earlier than \(t=t_0\) when switch \(S_1\) is on, when current flowing through the inductor \(L_{in}\) current in the inductor starts increasing, the converter is going to operate as a Boost converter.

**Mode 1\((t_0<t<t_1)\):** During time \(t=t_0\) switch \(S_1\) is going to turn off, voltage at Switch1 is slanted by capacitor \((C_{s1})\) connected across it. Current starts flowing in \(Cr\) when current \((L_{s1})\) charges \((C_{s1})\). Also in this mode current is delivered to \((L_{s2})\) and the capacitance at switch2, \(C_{s2}\), starts discharging.

**Mode 2\((t_1<t<t_2)\):** This is continuation of mode 1 but the current at \(t=t_1\) through \((C_{s2})\) is not completely discharged and the current flows through antiparallel diode across switch 2.

**Mode 3\((t_2<t<t_3)\):** At \(t=t_2\) the it acts as boost converter and current through the active clamping circuit stops flowing. As negative voltage is appeared across \(L_{in}\), the current through this inductor reduces.

**Mode 4\((t_3<t<t_4)\):** At \(t=t_3\) before the switch \(S_1\) is on, Auxiliary switch \((S_a)\) is on with Zero-Current Switching (ZCS). The current through \(C_{a}\) starts discharging through \((L_{s1} + L_{r_1})\) since \(I_{L_{in}}\) tends to reduce.

**Mode 5\((t_4<t<t_\infty)\):** During this, Current in inductor \((L_{s1})\) begins to flow through the output capacitor of switch \(S_1\) when the Auxiliary switch \((S_a)\) is made to be opened. Voltage drop across the switch1 is Zero because the capacitor \(C_{s1}\) discharges through switch 1.

**Mode 6\((t_5<t<t_\infty)\):** During \(t=t_5\) the capacitor \((C_{s2})\) is drained and the anti-parallel diode will ON and turn on the switch at this particular time.

**Mode 7\((t_6<t<t_\infty)\):** switch 1 is ON at \(t=t_6\) later the current \((L_{s1})\) reverses its path of flow so current path takes place from inductor \(L_{s2}\) to switch 1.

### 2.3 Modes of Operation of Bidirectional Converter in Buck Region

**Mode 0\((t<t_0)\):** Before \(t=t_0\) when the switch \(S_2\) is on, the converter is going to operate as a Buck converter and the current through \(L_{in}, I_{l_{in}}\) starts raising.

**Mode 1\((t_0<t<t_2)\):** At time \(t=t_0\), \(S_2\) is going to turn off and voltage across Switch \(S_2\) is limited by capacitor \((C_{s2})\) connected across it. The current starts flowing through \(Cr\) when current through \(L_{s1}\) charges up \(C_{s1}\). Also in this mode input current is delivered to \(L_{s1}\) and the capacitance across \(S_1, C_{s1}\) starts discharging.

**Mode 2\((t_2<t<t_3)\):** This mode is continuation of mode 1 but the current through \(C_{s2}\) is completely discharged at \(t=t_3\) and \(C_{s2}\) may or may not be completely discharged and current stops flowing through \(C_{s2}\).

**Mode 3\((t_3<t<t_\infty)\):** At time \(t=t_3\) the converter operates as boost converter and the current through the active clamping circuit stops flowing. As negative voltage is appeared across \(L_{in}\), the current through this inductor reduces and converter operates in freewheeling mode.

**Mode 4\((t_\infty<t<t_4)\):** At time \(t=t_4\) before the \(S_1\) is to be turned on, Auxiliary switch \((S_a)\) is turned on with Zero-Current Switching (ZCS). The current through \(C_{a}\) starts discharging through \(L_{s1}\) and \(L_{r_1}\) since \(I_{L_{in}}\) tends to reduce.

**Mode 5\((t_4<t<t_\infty)\):** Auxiliary switch \((S_a)\) is turned off at time \(t=t_4\) the current passing through inductor \((L_{r_1})\) is used to discharge capacitor \((C_{s2})\).

**Mode 6\((t_\infty<t<t_6)\):** At time \(t=t_6\) the capacitor \(C_{s1}\) is completely discharged and the anti-parallel diode is going.

### Table 2. Output results of the proposed converter

| Parameters     | Magnitude |
|----------------|-----------|
| Output voltage | 63.5V     |
| Output power   | 270W      |
to conduct which is across switch $S_2$, we can turn on the switch at this instant.

Mode 7($t_6 < t < t_7$): After switch 2 is turned on at $t=t_6$, the direction of the current is reversed and the current is transfer from its inductor $L_{r1}$ to switch 2.

Now, we are going to discuss about the Matlab simulation results in the next section.

### 3. Results and Discussions

The simulation of the proposed converter is done through Matlab Simulink environment. This circuitry was designed to work at lower side voltage of $V_{lo}=36$ V and high voltage of $V_{hi}=70$ V as shown in Figure 7. Highest rating of power is 270 W, and the frequency is used turn ON and turn OFF the switches are of 10 kHz. In this Bidirectional DC-DC converter we use PV as High voltage and Battery as Low Voltage sources. The Bidirectional converter can perform both buck and boost mode of operations.

Figure 8 depicts you a Matlab circuit of Bidirectional circuitry. This consists two switches (MOSFETS), Inductors ($L_{in}, L_{r1}, L_{r2}$) and capacitor ($C_r$). Pulse generation circuit is also shown in the Figure 8. The switching frequency is 10 kHz.

In Figure 9 Input voltage and current waveforms from PV panel are shown i.e $V_{in}=64.5$ V, $I_{in}=5.2$ A. In Figure 10 output voltage and current delivered to load are shown i.e, $V_{out}=63.5$ V, $I_{out}=4.2$ A. and you can observe that there is drop in voltage and current. The output is ripple free in both voltage and current. In Figure 11 Buck voltage is shown which is used to charge the battery and the voltage to battery is 35.3 V and the output is pure DC with less ripple content. This Buck Operation is done by Bidirectional converter. In Figure 12 Boost voltage is shown which is given by battery source and it is delivered to load and the voltage is constant after certain time period. In Figure 13 the battery SOC (State of Charge) which is 50% means the battery is in charging condition which is linear in nature and voltage of 35.75 V, current of 4.7A is shown.
4. Conclusion

A new DC-DC Bidirectional converter is implemented and the features of this circuit are flow of current through inductor is continuous, constant frequency of switching, switch stress are less due to the usage of Auxiliary circuit. The simulation results are shown by using Matlab Simulink. The typical voltage, current waveforms are unveiled.

5. References

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