An Interleaved DC-DC Converter with Quadratic Gain and Bidirectional Capability for Battery Charging

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Abstract- An interleaved DC-DC converter with quadratic gain and bidirectional capability is proposed. This converter is capable of stepping up voltages as low as 24V to 180V. A non-isolated bidirectional DC-DC converter can be used to transfer energy between different sources in both directions and it can be used for application which requires charging and discharging of battery. Four number of power switches are used in the proposed converter along with passive components such as a capacitor and three inductors. The proposed converter voltage gain is high compared to conventional converter in boost mode. The simulation of converter is done using MATLAB/SimulinkR2017 software. A 5W, 10kHz hardware prototype of the base circuit with Vin=5V and Vout=100V is also implemented in the laboratory. PIC16F877A is used for generating the control pulse. mikroC software is used for programming the PIC.

Index Terms—Bidirectional DC-DC Converter, Energy Storage Devices (ESDs), High Gain, Non-Isolated.

I. Introduction

Energy consumption is increasing day by day. The major portion of energy is generated from nonrenewable energy sources. There is depletion in the fossil fuel reserve due to increased consumption and, they will make negative impact on the environment. There is a rapid development in the field of renewable energy system such as photo voltaic systems, wind system, fuel energy system etc. For energy recovery system there is need of charging and discharging of battery which can be done using bidirectional dc-dc converter. This kind of dc-dc converter can be used for energy storage application, which act in boost mode during charging of battery bank and operate in buck mode during discharging mode. Bidirectional converter is used to exchange energy between different sources in both directions [2].

Bidirectional dc-dc converters are the key components of the traction systems in Hybrid Electric Vehicles. Recently many bidirectional dc-dc converter topologies have been reported with soft switching technique to increase the transfer efficiency. Bidirectional converters using coupled inductor were introduced for soft switching technique. For minimizing switching losses and to improve reliability, zero voltage switched technique and zero current switched technique were introduced for bidirectional converter.

Theoretically, the conventional DC-DC converter can provide a very high voltage gain by using an extremely high duty cycle. Large duty cycles result in high current stress in the boost switch. Due to large duty ratio parasitic elements has to be considered and their effects reduce the theoretical voltage gain.

In order to reduce the input current ripple, the Interleaved Bidirectional Converter (IBC) has been proposed [1]. The IBC has the lower input current ripple than the bidirectional chopper by driving two switches with a 180° phase shift. In addition, since the input current is divided into two inductors, the IBC has higher power conversion efficiency. However, the IBC has the same voltage gain in step up conversion as the bidirectional chopper.
There are two different types of bidirectional DC-DC converters in different applications, which include the isolated converters and non-isolated converters. The isolated converters include the Flyback, the Forward-Flyback, the half-bridge and the full-bridge. High voltage-gain is obtained by adjusting the turns ratio of the high frequency transformer. To reduce the voltage stress caused by the leakage inductance, a full bridge bidirectional DC-DC converter with a Flyback snubber circuit [8] and a bidirectional DC-DC converter with an active clamp circuit [9] were proposed.

Conventional quadratic buck or quadratic boost converters are an interesting solution since only uses a single active switch maintaining the voltage ratio as a quadratic function of the duty. But they only provide unidirectional power flow and are only suitable for applications with such requirements [2].

In this paper, a non-isolated interleaved bidirectional Buck-Boost quadratic converter is proposed. This solution is suitable for distributed generation systems where conventional converters are inadequate for high frequency applications and where specified range of input voltages and the specified range of output voltages call for an extremely large range of conversion ratios.

II. INTERLEAVED BIDIRECTIONAL CONVERTER

A modified interleaved converter with considerably reduced voltage stress is proposed. The power topology of the proposed interleaved DC-DC converter is shown in Fig. 2.

![Fig. 2: Proposed interleaved bidirectional converter.]

According with this topology, the power circuit does not require additional passive components (inductors and capacitor) than the required by the classical Boost quadratic converter.

III. OPERATING PRINCIPLE

The interleaved bidirectional converter requires two separate DC voltage sources. This converter is also characterized by a simple control technique since it is only necessary to control one power semiconductor for each operation mode. Here the additional power semiconductors remain always on or always off.
A. Operation in Boost Mode (CCM)

There are mainly two converters buck and boost converter operating both in two modes respectively. There are four semiconductor switches with antiparallel diodes connected across them.

Mode 1: The converter is operating in steady-state, continuous conduction mode (CCM), ideal components and in discharge power mode, transferring the energy from the storage device \(V_1\) to the load. \(V_2\) This mode is achieved when the transistor \(S_2\) is turned-on during the time interval of \(\delta T_S\) \((\delta T_S < t < T_S)\). In this mode, the current through both inductors \(L_1\) and \(L_2\) will linearly increase, transferring energy from storage device and capacitor \(C\) for inductors \(L_1\) and \(L_2\) respectively.

![Fig. 3: Boost Mode 1 operation.](image)

Mode 2: The second mode is obtained when the transistor \(S_2\) is turned-off during the time interval of \((1 - \delta T_S)\), \((\delta T_S < t < T_S)\).

![Fig. 4: Boost Mode 2 operation.](image)

This mode is characterized by the discharge linearly decrease and the energy that was stored in mode 1 is now transferred to the capacitor \(C\) and to the DC bus \(V_2\) of both inductors \(L_1\) and \(L_2\). The theoretical waveform of the converter in both modes is shown in Fig. 5.

![Fig. 5: Theoretical waveforms in Boost Mode](image)
B. Operation in Buck Mode (CCM)

The operation of the converter in buck mode is characterized by the energy transfer from the load to the storage device. Similar to the previous operation mode, only a single transistor controls the output voltage through duty cycle switching. In this case the transistor $S_1$ is responsible for this operation. Thus, the transistors $S_2$ and $S_3$ are now always turned-off and transistor $S_4$ is always turned-on for avoiding additional switching losses.

Mode 1: This stage is achieved when the transistor $S_1$ is turned-on during the time interval of $\delta T_S$, ($0 < t < \delta T_S$).

![Fig. 6: Buck Mode 1 operation.](image)

During this time period the currents in both inductors $L_1$ and $L_2$ will increase in absolute value and the energy will be transferred from the DC bus ($V_2$) and capacitor $C$ to inductors $L_1$ and $L_2$ respectively.

Mode 2: The second mode of this operation mode is obtained when the transistor $S_1$ is turned-off during the time interval of $(1- \delta T_S)$, $(\delta T_S < t < T_S)$.

![Fig. 7: Buck Mode 2 operation.](image)

In this stage the currents in both inductors $L_1$ and $L_2$ will decrease in absolute value. The energy that was stored in both inductors will now be transferred to the capacitor $C$ and to the storage device. Note that in this case $V_2 > V_C > V_1$. The Fig.8 shows the theoretical waveforms in buck mode.

![Fig. 8: Theoretical waveforms in Buck Mode](image)
IV. DESIGN OF COMPONENTS

In this converter an input voltage of 24V (Boost), 180V (Buck) and output voltage 24V (Buck), 180V (Boost) is used and switching frequency is 15 kHz. The rated power output is assumed to be 250W. Duty ratio of 63 % is chosen for boost and 36 % for buck mode. Load resistance 160Ω for boost and 2.4Ω for buck converter. The inductor values in both stages is given by,

\[ L_1, L_2 \geq \frac{V_2^2 + \delta s(1-\delta)^2}{2s f_s L_{1avg}} \]  
\[ L_3 \geq \frac{V_2^2 + \delta s(1-\delta)}{2s f_s L_{3avg}} \]  

The output capacitor is selected based on the amount of charge that is transferred to the output for a desired output voltage ripple. Assuming a voltage ripple of 0.02% of output voltage, the required capacitance is given by,

\[ C_{\text{min}} = \frac{4i_{L1avg}}{27 \Delta V_o f_s} \]  

V. SIMULATION PARAMETERS

The simulation parameters used for multiple input DC-DC converter are shown in Table I.

<table>
<thead>
<tr>
<th>Components</th>
<th>Rating</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage</td>
<td>24V(Boost), 180V (Buck)</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>24V(Buck), 180V (Boost)</td>
</tr>
<tr>
<td>Load Resistance</td>
<td>160Ω(Boost), 2.4Ω(Buck)</td>
</tr>
<tr>
<td>Duty Ratio</td>
<td>63%(Boost), 36% (Buck)</td>
</tr>
<tr>
<td>Inductors</td>
<td>0.25mH, 0.25mH, 0.5mH</td>
</tr>
<tr>
<td>Capacitor</td>
<td>150µF</td>
</tr>
</tbody>
</table>

VI. SIMULATION RESULTS

A 250W model of converter is simulated in MATLAB/ SIMULINK environment. The simulation diagram is shown in Fig. 9 and Fig 10.

Fig. 9: Gate pulse for switch (a) S_1 (b) S_2 (c) S_3 (d) S_4 in Boost mode
The output voltage obtained is about 177.3V and the voltage stresses across the switches are considerably low.

The output voltage obtained is 22.4V in buck mode and the voltage stress across each switch is considerably low.

VII. PERFORMANCE ANALYSIS

For analysis of the converter, it is assumed that all the components are ideal, and the system is under steady state.
Fig. 14: Duty ratio Vs (a) Output Voltage (b) Gain

From Fig 14, it is observed that, as the duty ratio increases the output voltage and gain increases and hence the modified converter is operated at a duty ratio of 0.63 (Boost) and 0.33 (Buck).

![Duty ratio Vs (a) Output Voltage (b) Gain](image)

Fig.15: Efficiency of converter

From Fig 15, the efficiency of the modified converter is high compared to the conventional converter.

VIII. EXPERIMENTAL SETUP AND RESULTS

For the purpose of hardware implementation, a prototype is designed, and the hardware is implemented with an input of 5V, output 100V and frequency of 10 kHz. Table 2 shows the specification.

<table>
<thead>
<tr>
<th>TABLE II: COMPONENTS USED FOR PROTOTYPE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Components</td>
</tr>
<tr>
<td>Inductors</td>
</tr>
<tr>
<td>Capacitor</td>
</tr>
<tr>
<td>Diode</td>
</tr>
<tr>
<td>Controller</td>
</tr>
<tr>
<td>MOSFET</td>
</tr>
<tr>
<td>Driver IC</td>
</tr>
</tbody>
</table>
Fig. 16: Experimental setup

Fig. 16 shows, the experimental setup and fig. 17 shows the switching pulses. The pulses are generated using PIC16F877A. A program is written which uses the four pins of PORTB (pin 33-pin 36) to generate switching pulses for the switches.

Fig. 17: Switching Pulses across the switch (a) S₁ (b) S₂ (c) S₃ (d) S₄ in Boost mode

Fig. 18: Output Voltage

The power supply consists of a step-down transformer, full bridge diode rectifier, filter capacitor and a regulator IC (7812). IRF540 MOSFET is used as the switches. TLP250 driver is used to drive the MOSFET. To generate the switching signal PIC16F8771A was programmed in the laboratory and necessary waveforms were obtained. The switches are working in 10kHz frequency and have a duty ratio of 0.77 in boost mode.
IX. Conclusion

The modified converter is based on an interleaved bidirectional converter topology. The modified interleaved DC-DC converter with bidirectional capability provides an output voltage of 177.3V(Boost) and 22.4V(Buck) and it is observed that the voltage stress across the switches are considerably reduced. The interleaved converter offers uniform current sharing, high gain and low switch voltage stress. The prototype of the interleaved converter in boost mode with input voltage of 5V is built. The output voltage obtained is 86.9V, this verifies the high step up voltage gain of 17.4V is built. The converter exhibits a conversion efficiency of 98.2% and output voltage ripple less than 1% which demonstrate a well-regulated and efficient operation of the converter.

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REFERENCES


