Renewable Energy Integrated High Step-Up Interleaved Boost Converter for DC Microgrid Applications

P. Yogananthini, A. Kalaimurugan

Abstract—This project report presents the development of design, modeling and simulation of high step-up interleaved boost converter to achieve high step-up ratio and high efficiency for DC microgrid applications. In this project, a modular interleaved boost converter is given by integrating a forward energy-delivering circuit with voltage doublers to achieve high step-up ratio and high efficiency for dc microgrid applications. The operation principle and characteristics of the system are presented. Then, steady-state analyses are made to show the merits of the proposed converter module. For higher power applications, more modules can be paralleled to increase the power rating and the dynamic performance.

Index Terms—Renewable energy, DC microgrid, high step-up converter, high efficiency.

I. INTRODUCTION

RENEWABLE energy is becoming increasingly important and prevalent in distribution systems, which provide different choices to electricity consumers whether they receive power from the main electricity source or in forming a microsource not only to fulfill their own demand but alternatively to be a power producer supplying a microgrid [1], [2]. In recent years, due to the public concern about global warming and climate change, much effort has been focused on the development of environmentally friendly distributed generation (DG) technologies [3]. It is well known that when many DGs are connected to utility grids, they can cause problems such as voltage rise and protection problem in the utility grid [4],[5]. To solve these problems, new concepts of electric power systems are proposed, and dc microgrid is one of the solutions [6]–[7]. DC microgrid is suitable to use where most of the loads are sensitive dc electronic equipment. The advantage of a dc microgrid is that loads, sources, and energy storage can be connected through simpler and more efficient power electronic interfaces. Moreover, it is not necessary to process ac power quality issues. So far, dc microgrids have been used in telecom power systems, data centers system, generating stations, traction power systems, and residential houses [8]–[9].

Briefly speaking, the output voltages of most distributed energy resources such as fuel cells and photovoltaic (PV) are usually relatively low, requiring a high step-up converter for practical applications [10]. Recently, an interleaved boost converter extended by magnetically coupling a Cuk-type auxiliary step-up circuit that charges a voltage-doubler in the output was proposed to achieve the required voltage gain [11]. As a similar solution, a sepic integrated boost converter which provides an additional step-up gain with the help of an isolated sepic-type auxiliary step-up circuit was also proposed [12]. Nevertheless, the circuit structures of the Cuk/sepic integrated high step-up converters are relatively complex and expensive; thus, they might be difficult to mass manufacture.

The main objective of this paper is to develop a modular high-efficiency high step-up boost converter with a forward energy-delivering circuit integrated voltage-doubler as an interface for dc microgrid system applications. In the proposed topology, the inherent energy self-resetting capability of auxiliary transformer can be achieved. Analysis and control of the overall system are also made. In high-power applications, interleaving of two boost converters is very often employed to improve performance and reduce size of the PFC front end. Namely, because interleaving effectively doubles the switching frequency and also partially cancels the input and output ripples, the size of the energy storage inductors and differential-mode electromagnetic interference (EMI) filter in interleaved implementations can be reduced[13]–[15].

II. CIRCUIT OPERATION

A. Circuit Description

The proposed interleaved converter topology with high voltage transfer ratio is proposed as shown in Fig. 1. It can be seen from Fig. 1, the proposed converter consists of two phase circuits with interleaved operation.

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The first phase is a boost integrating the forward-type circuit structure, which includes inductor $L_1$ and switch $S_1$ for the boost and an isolated forward energy-delivering circuit with turn ratio $N$. The second phase of the proposed converter is a boost circuit which contains inductor $L_2$, switch $S_2$, blocking capacitor $C_2$, and diode $D_2$ followed by the common output capacitor $C_o$. From Fig. 1, one can see that the proposed converter is basically based on the conventional voltage-doubler [13] for the second phase circuit. However, for the first phase, in order to reduce the voltage stress of switch $S_1$ and diode $D_1$, an additional blocking capacitor $C_1$, is added to function as that of $C_2$ for the second phase.

As the main objective is to obtain high voltage gain and such characteristic is achieved when the duty cycle is greater than 0.5, hence, the steady-state analysis is made only for this case. It is important to point out that the proposed high step-up converter can also function for duty cycle lower than 0.5. However, with duty cycle lower than 0.5, the secondary induction voltage of the transformer is lower, and consequently, it is not possible to get the high voltage gain as that for duty ratio greater than 0.5. In addition, with duty cycle larger than 0.5, due to the charge balance of the blocking capacitor, the converter features automatic current sharing of the currents through the two interleaved phases that obviates any current-sharing control circuit. In comparison, when duty cycle is smaller than 0.5, the converter does not possess the automatic current sharing capability any more, current sharing control between each phases should be taken.

From Fig. 2, we can see that when the duty ratio is greater than 50%, there are four operation modes according to the ON/OFF status of the active switches. Referring to the key waveforms shown in Fig. 2, the operating principle of the proposed converter can be explained briefly as follows.

![Fig 2 Key waveforms of proposed converter](image-url)
B. Principle of Circuit Operation

Mode 1 \([t_0 < t \leq t_1]\): For mode 1, switches \(S_1, S_2\) are turned on. Diode \(D_0\) is forward biased, while diodes \(D_1, D_2, D_E\) are reverse biased. During this operation mode, both \(i_{L1}\) and \(i_{L2}\) are increasing to store energy in \(L_1\) and \(L_2\), respectively. Meanwhile, the input power is delivered to the secondary side through the isolation transformer and inductor \(L_f\) to charge capacitor \(C_1\). Also, the output power is supplied from capacitor \(C_o\). The voltage across inductances \(L_1\) and \(L_2\) can be represented as follows:

\[
L_1 \frac{di_{L1}}{dt} = V_{in} - V_{c1} - V_{c2}
\]

(1)

Mode 2 \([t_1 < t \leq t_2]\): For this operation mode, switch \(S_1\) remains conducting, and \(S_2\) is turned off. Also, diodes \(D_1\) and \(D_E\) remain reverse biased, \(D_2\) and \(D_0\) are forward biased. The energy stored in inductor \(L_2\) is now released through \(C_2\) and \(D_2\) to the output. However, the first phase circuit including the forward-type converter remains the same. The voltage across inductances \(L_1\) and \(L_2\) can be represented as the following:

\[
L_1 \frac{di_{L1}}{dt} = V_{in}
\]

(2)

\[
L_2 \frac{di_{L2}}{dt} = V_{in} + V_{c2} - V_{bus}
\]

(3)

Mode 3 \([t_2 < t \leq t_3]\): For this operation mode, both \(S_1\) and \(S_2\) are turned on. The corresponding operating principle turns out to be the same as Mode 1.

Mode 4 \([t_3 < t \leq t_4]\): During this operation mode, \(S_1\) is turned off, and \(S_2\) is turned on. Diode \(D_2\) and \(D_0\) are reverse biased, and diode \(D_1\) is forward biased. Since diode \(D_0\) is reverse biased, diode \(D_0\) must turn on to conduct the inductor current \(i_{L1}\). The energy stored in \(L_1\) is now released through \(C_1\) and \(D_0\) to charge capacitor \(C_2\) for compensating the lost charges in previous modes. The energy stored in transformer is now treated to perform the self-resetting operation without additional resetting winding. Also, the output power is supplied from capacitor \(C_o\). The voltage across inductances \(L_1\) and \(L_2\) can be represented as follows:

\[
L_1 \frac{di_{L1}}{dt} = V_{in} + V_{c1} - V_{c2}
\]

(4)

\[
L_2 \frac{di_{L2}}{dt} = V_{in} + V_{c2} - V_{bus}
\]

(5)

III. Steady State Analysis

The capacitor average voltage \(V_{c1}\) can be derived as follows, which is equal to the average voltage across diode \(D_0\):

\[
V_{c1} = V_{f2,\text{avg}} = DN V_{jn}
\]

(6)

The average voltage across diode \(D_1\) can be described as,

\[
V_{d1,\text{avg}} = V_{c2} - V_{c1}
\]

As to the voltage conversion ratio of the proposed converter, it can be calculated according to the volt-second balance principle of the boost inductors. From (1), (2) and (4), the volt-second balance equation for boost inductor \(L_1\) becomes

\[
\frac{V_{jn}}{L_1} DT_S + \frac{V_{in} - V_{c1} - V_{c2}}{L_1} = (1 - D)T_S
\]

(9)

Thus, from (6), (8) and (9), the voltage conversion ratio \(M\) of the proposed converter can be obtained as follows:

\[
M = \frac{V_{bus}}{V_{in}} = \frac{2}{1 - D} + ND
\]

(10)

The open circuit voltage stress of switches \(S_1\) and \(S_2\) can be obtained directly as follows:

\[
V_{s1,\text{max}} = V_{c1} - V_{c2}
\]

(11)

\[
V_{s2,\text{max}} = V_{bus} - V_{c1}
\]

(12)

It follows from (6), (8) and (10) that the same voltage stress is obtained for both active switches as follows:

\[
V_{s1,\text{max}} = V_{s2,\text{max}} = V_{c2} - V_{c1}
\]

(13)

For convenient comparison, the normalized voltage stress of the active switches, namely \(M_S\), can be expressed as

\[
M_S = \frac{V_{s1,\text{max}}}{V_{bus}} = \frac{K - ND}{2M}
\]

(14)

In fact, one can see from (13) that the resulting voltage stress is obviously smaller than \(V_{bus}/2\). Naturally, both conduction and switching losses can be reduced as well. Similarly, the open circuit voltage stress of the corresponding diodes can be expressed as follows

\[
V_{d1,\text{max}} = V_{bus} - V_{c1} = V_{bus} - DN
\]

(15)

\[
V_{d2,\text{max}} = 2V_{c1} - V_{bus} = \frac{V_{bus}}{2} - \frac{DN V_{jn}}{2}
\]

(16)

It follows from (15) and (16) that the corresponding normalized voltage stress becomes

\[
M_{dL} = \frac{V_{d1,\text{max}}}{V_{bus}} = 1 - \frac{DN}{K}
\]

(17)
IV. EXPERIMENTAL RESULTS

The proposed method is realized on a solar photovoltaic (PV) system that is directly connected to the dc link. The switching frequency is 50 KHZ and the power system parameters are $L=100\mu H$, $C=440\mu F$, $L_1=L_2=200\mu H$, $C_1=C_2=3.3\mu F$. The whole system is simulated in MATLAB SIMULINK.

The high step-up interleaved boost converter is designed using the following specifications given below:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage ($V_1$)</td>
<td>20-40VDC</td>
</tr>
<tr>
<td>Output Voltage ($V_o$)</td>
<td>230VDC</td>
</tr>
<tr>
<td>Switching Frequency $f_s$</td>
<td>50kHz</td>
</tr>
<tr>
<td>Output Capacitor $C_o$</td>
<td>440µF</td>
</tr>
<tr>
<td>Leakage inductor $L_f$</td>
<td>600µH</td>
</tr>
<tr>
<td>Capacitance $C_1$ &amp; $C_2$</td>
<td>3.3µF</td>
</tr>
<tr>
<td>Resistance $R_0$</td>
<td>20Ω</td>
</tr>
<tr>
<td>Inductance $L_1$ &amp; $L_2$</td>
<td>200µH</td>
</tr>
</tbody>
</table>

The complete schematic of proposed circuit of high step-up converter for closed loop circuit is shown in Fig. 1. The main advantages of the proposed circuit are low switcher voltage stress, lower duty ratio and higher voltage transfer ratio. The Current and Voltage waveforms of the proposed converter are depicted in Fig.3 and then, input voltage $V_{IN} = 38V$, at selected values of output power. The value of the total leakage inductance referred to the secondary side of the transformer was measured to be $L_f = 600\mu H$.

Fig 3 shows the simulated output current and voltage waveform. There is an increase in the output current and voltage compared to that of conventional converter.

Fig 4 Peak to peak current and voltage waveform

Fig 5 shows the generated output current and voltage waveform of closed loop system from the renewable energy source. This voltage and current going to synchronized with the grid. This output waveform obtained with the utilization of controller, the output of the controller controls the both voltage and current flowing towards to the grid.

Fig 5 output current and output voltage waveform

Fig 5 shows the simulated output current and voltage waveform of closed loop system. Here the input voltage given is 38v and the output voltage is 230v.

Fig 6 Peak to peak current and voltage waveform
V. Conclusion

This paper presents a new modular interleaved boost converter by integrating a forward energy-delivering circuit and voltage-doubler is proposed for achieving high step-up and high-efficiency objective. The simulation of the module layout was successfully carried out using MATLAB simulink software and the obtained waveforms were observed. This project has presented the high step-up interleaved boost converter for achieving high step-up ratio and high efficiency. Thus, steady state analyses are made to show the merits of the proposed converter topology. For higher power applications, the modules of high step-up converters are paralleled to reduce input and output ripples. The operation principle, converter design methodology, simulation and experimental results have been presented and analyzed. The proposed interleaved high step-up boost converter is a simple topology and can be of high practical value for various industrial applications and hence achieve the highest efficiency.

References


