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High Step-up Interleaved Boost Converter Utilising Stacked Half-bridge Rectifier Configuration

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Abstract

This paper proposes a solution to complement the insufficient voltage gain and voltage stress distribution of classical interleaved boost converter in high step up application. An interleaved converter integrating coupled inductor and voltage multiplier cell, which provides an additional voltage gain is proposed. By stacking the secondary side of the interleaved coupled inductor to its primary side, a high step-up voltage gain and distributed voltage stress are realized. Low voltage rated devices, ultimately reduce the conduction losses. The principle of operation, the performance characteristic of the converter are presented and verified by an experimental prototype of 140 W, 12 V input, and 120 V output.

1 Introduction

There is an increasing demand of distributed energy sources (DES) such as solar PV, batteries and fuel cells in applications ranging from smart grids, energy storage system (ESS), distributed generation and electric vehicle (EV). However, the typical output of DES used in such applications has relatively low voltage level compared to the required voltage level of emerging applications, which ranges from 200 to 400 V [1]. High efficiency high step-up dc-dc converters are required to facilitate the connection of DER to the grid. To date, various topologies have been proposed to achieve this voltage step-up and they are either transformer [2] based or transformer-less [3] and their variations [4-9].

The classical boost converter is the simplest converter for voltage step-up. However, it suffers extreme duty cycle operation, the power devices sustain high voltage stress and reverse recovery loses which inhibits the efficiency. To overcome the problem of extreme duty cycle operation, many single switch converters have been proposed. These include switched capacitor/switched inductor techniques [5], voltage lift [6], and voltage multiplier [7]. These methods require multiple cells to achieve high voltage conversion ratio, which typically results in complex structures.

A common alternative technique is to use a coupled inductor to enlarge the voltage gain in non-isolated dc-dc converters [2]. Coupled inductor boost converters can provide high voltage gain without extreme duty cycle operation, with a relatively simple topology. Consequently, they can reduce the switch voltage stress and allow the use of low voltage rated, high performance, semiconductor devices. However, the main drawbacks of coupled inductor converters typically include severe voltage spikes across the switch due to the leakage energy of the coupled inductor and the large input current ripple. To mitigate the current ripple, interleaving is usually adopted as an effective solution in high power applications to reduce the passive component size, increase the power level, minimize the current ripple, improve the transient response, and realize thermal distribution. However, the voltage gain of the conventional interleaved boost converter is also limited.

To address this issue, one can find many promising interleaved hybrid topologies integrating magnetic and capacitive means mainly for voltage gain [8-9]. To limit the switch voltage excursion due to the leakage energy of the coupled inductor, energy recycling schemes are usually adopted.

In this paper, an alternative structure based on half bridge-doubler rectifier configuration in both the primary and secondary side is investigated to obtain a high efficiency and high step-up dc-dc conversion. To further exploit their advantages, stacking the secondary side half bridge-doubler rectifier on top of its primary side counterpart is considered, the stack structure would ultimately enlarge the voltage gain and distribute the voltage stress of the devices as well. Importantly, lower turns ratio can be employed to achieve high conversion ratios which reduce the copper losses and leakage inductance of the coupled inductor. Interleaving is adopted on the primary side to share the input current and cancel the current ripple of the coupled inductors.

2 Converter Operational Analysis

2.1 Topology Description

Fig. 1 shows the circuit configuration of the proposed topology integrating coupled inductor and stacked half bridge-doubler rectifier. The converter employs two coupled inductors \((L_1\text{ and }L_2)\) with the same number of turns in the primary and secondary sides. The primary winding of the coupled inductors \(n_{1p}\text{ and }n_{2p}\) are connected in parallel to share the large input current on the low voltage side and are coupled to their corresponding secondary windings \(n_{1s}\text{ and }n_{2s}\). The primary and secondary windings are denoted by coupling references ‘‘*’’ and ‘‘o’’. The secondary windings are in series on the high voltage side to achieve windings coupled configuration and extend the voltage conversion ratio. The output voltage of the converter is a stacking the
primary side bridgeless boost rectifier voltages formed by

capacitors $C_3, C_4$ and diodes $D_1, D_2$ and that of the coupled

inductors secondary windings bridgeless boost rectifier

form"},  

The equivalent circuit of the proposed converter is shown in

Fig. 2. The coupled inductor can be modelled as an ideal

transformer with defined turns ratio. The primary winding of

the ideal transformer is connected in parallel with the

magnetizing inductor $L_{m1}$, $L_{m2}$ and then in series with

leakage inductance $L_{k1}$, $L_{k2}$. $S_1$, $S_2$ are the main power

switches of the converter. The power inductors $D_1$, $D_2$ serve as

clamp diodes and $C_1$, $C_2$ are the clamp capacitors. $C_3$ is the

output capacitor and $V_{in}$. $V_O$ represent the input and output

voltages respectively.

To simplify the analysis the following assumptions are made:

1) The power switch is ideal, but the parasitic capacitor

is considered in the analysis.

2) The voltages across capacitors $C_3, C_2, C_1$ and $C_4$ are

large enough and assumed to be constant.

3) The turns ratio of the coupled inductor $N$ is equal to

$\frac{n_2}{n_1}$ and coupling coefficient $k$ is expressed as

$\frac{L_m}{L_{k1} + L_m}$.

2.2 Operational Modes

The following analysis is confined to continuous current

mode (CCM) operation, and the operation is guaranteed

throughout the full range of the duty cycle variation with

resistive loads. During steady-state operation, the duty cycle

$D$ is higher than 0.5. Typical steady state waveform of the

operation in one switching cycle; the equivalent circuits and

current flow path corresponding to each operational stage are

shown in Fig. 4. The converter operation is analysed as follows:

Stage 1 ($t_0$ to $t_1$) (Fig. 4a): before $t_0$, the main switch $S_1$ is

on and $S_2$ is off, the diodes $D_2$ and $D_3$ are reversed biased

while $D_1$ and $D_4$ are forward biased. Magnetizing inductor $L_{m2}$

as well as the leakage inductor $L_{k2}$ are charged linearly by the

input voltage. Consequently, Capacitor $C_4$ is charged by the

induced voltage of $n_{s2}$. The leakage inductor energy $L_{k2}$

is released into the capacitor $C_2$. $L_{d2}$

Stage 2 ($t_1$ to $t_2$) (Fig. 4b): $S_1$ and $S_2$ are both on at time $t_1$. 

All the diodes are reversed biased, the load is supplied by the

capacitors $C_3$, $C_2$, $C_1$ and $C_4$ respectively. The coupled

inductors are linearly charged by the input voltage $V_{in}$. 

Stage 3 ($t_2$ to $t_3$) (Fig. 4c): At time $t_2$, the power switch $S_2$

turns off. The drain-source voltage of main switch $S_2$ rise to

the capacitor voltage $V_{C_1}$, which makes the diode $D_3$ to

conduct. The leakage inductor energy $L_{k1}$ is released to

the capacitor $C_2$. During this time, the coupled inductor $L_1$

acts as a filter inductor and $L_2$ acts as a transformer. 

Consequently, Capacitor $C_3$ is charged by the induced voltage

of $n_{s1}$. The voltage of the main switch $S_2$ is clamped to the

voltage of the capacitor $C_2$. 

![Fig. 1: Circuit configuration of the proposed converter](image1)

![Fig. 2: Equivalent circuit](image2)

![Fig. 3: Key waveforms of proposed converter](image3)
Stage 4 \( [t_3 - t_4] \) (Fig. 4d): The gating signal of the power switch \( S_2 \) is applied at time \( t_3 \) and the diode \( D_2 \) equally becomes reversed biased. The current through the diode \( D_2 \) has reach its peak and begins to fall, the rate of change of magnetizing inductors \( L_{m1} \) and \( L_{m2} \) linearly. At the end of

Stage \( n \) (b) Stage \( n \) (Fig. 4f): At time \( t_2 \), the gating signal of the power switch \( S_2 \) (Fig. 4d): The gating signal of the power switch \( S_2 \) is applied at time \( t_2 \) and the diode \( D_2 \) equally becomes reversed biased. The current through the diode \( D_2 \) has reach its peak and begins to fall, the rate of change of magnetizing inductors \( L_{m1} \) and \( L_{m2} \) linearly.

Stage \( n \) (c) Stage \( n \) (Fig. 4e): This operating stage is similar to stage 2, all the power switches are on and all the power diodes are reversed biased. The load is supplied by the capacitors \( C_1, C_2, C_3 \) and \( C_4 \) respectively. The coupled inductors are charged linearly by the input voltage source.

Stage \( n \) (d) Stage \( n \) (Fig. 4f): At time \( t_5 \), switch \( S_1 \) turns-off and the diode \( D_1 \) becomes forward biased. A new switching cycle ensue in similar fashion.

3 Circuit Analysis

3.1 Voltage Conversion Ratio

Here, the coupled inductors are assumed to be ideal with no leakage inductance, the power switches are also considered lossless with zero conduction voltage drops, and no parasitic capacitances. Therefore, the voltage stress of the power switches and that of capacitors \( C_1, C_2 \) when either of the main switches turns off is given by

\[
V_{d1} = V_{d2} = V_{C1} = V_{C2} = \frac{V_n}{1 - D} \tag{1}
\]

The output capacitors \( C_3 \) and \( C_4 \) are charged by energy transformation from the coupled inductor primary side when either of the primary switches is on or off. For example, each capacitor is charged by the sum of the induced voltages from the respective primary windings. Therefore, \( V_{C3} \) and \( V_{C4} \) are derived as

\[
V_{C3} = V_{C4} = \frac{NV_n}{1 - D} \tag{2}
\]

The output voltage of the converter is the summation of the capacitor voltages given by

\[
V_o = V_{C1} + V_{C3} + V_{C2} + V_{C4} = \frac{2V_n}{1 - D} + \frac{2NV_n}{1 - D} \tag{3}
\]

From (1), (2), and (3) the ideal voltage gain is given by

\[
M_{idc} = \frac{V_o}{V_n} = \frac{2(N + 1)}{1 - D} \tag{4}
\]

The coupled inductor turns ratio \( N \) can be adjusted to achieve the desired voltage conversion ratio without resorting to extreme duty cycle operation. The curve relating the voltage gain as a function of duty cycle and turns ratio is shown in Fig. 5.
3.2 Power Devices Voltage Stress

By neglecting the voltage ripple on the capacitors, the voltage stress of the switches are the same given by

\[ V_{d11} = V_{d12} = \frac{2(N+1)}{V_o} \]  

(5)

The voltage stress on the diodes \( D_1, D_2 \) is the sum of the voltage stresses of capacitor \( C_1 \) and \( C_2 \) respectively given by

\[ V_{d1} = V_{d2} = \frac{2V_{in}}{(1-D)} = \frac{V_o}{(N+1)} \]  

(6)

The voltage stress of the power diode \( D_3, D_4 \) is the summation of the voltage across capacitors \( C_3 \) and \( C_4 \) respectively expressed as

\[ V_{d3} = V_{d4} = \frac{2N V_{in}}{(1-D)} = \frac{N V_o}{(N+1)} \]  

(7)

The relationship of the between the power devices voltage stress and turns ratio is plotted in Fig. 4. The voltage stress on the power switches \( S_2, S_3 \) and that of power diodes \( D_2, D_3 \) decrease as the turns ratio increase. Conversely, the voltage stress on the diodes \( D_3, D_4 \) increases as the turns ratio increases.

4 Experimental Validation

In order to verify the operation and evaluate the performance of the converter a 12 V input, 120 V output 140 W prototype circuit is built and tested in the laboratory. The specification of the converter along with the components rating are listed in Table 1. The following experimental results are measured under full load conditions with 12 V input voltage. The 180 degrees out of phase gating signals along with power switches drain-source voltages of the power switch are shown in Fig. 7.

![Fig. 5: Voltage gain as a function of duty ratio and turns ratio](image)

![Table 1: Converter prototype specifications](table)

It can be seen that voltage stress of the switches is 30 V, which is one-quarter of the output voltage. This allows low rated devices with low \( R_{dss} \) to be employed and reduce the conduction loss. Fig. 8 shows the current and voltage stress of the power switches. The voltage and current waveforms of the diodes \( D_1, D_2 \) are illustrated in Fig. 9. When either of the main switches turns-off the diodes \( D_1, D_2 \) conducts and the leakage inductor energy is released to the capacitors \( C_1, C_2 \). The diodes act as a passive clamp circuit for limiting the switch voltage excursion due to leakage inductor energy. Both diodes turn-off naturally with no reverse recovery problem. It is worth noting that the diodes voltage stress is far less than the output voltage. The voltage and current waveforms of the diodes \( D_3, D_4 \) is shown in Fig. 10. The voltage stress of the diodes is 65 V which is also less than the output voltage of 120 V, this further confirms the voltage stress distribution of the converter. As illustrated in Fig. 10, the diodes turn off naturally, leading to the reverse recovery alleviation.

Fig. 11 shows the leakage inductor currents (coupled inductor primary current) and the input current. Typical coupled inductor primary current is large due to the magnetizing inductor and reflected secondary winding currents. However, the ripple magnitude of the input current is small due to interleaving. The input current is continuous over the entire switching cycle. Fig. 12 shows the measured efficiency of the converter. The maximum efficiency is 96% at an output power of 60 W, the conversion efficiency is 95% at a full load of 140 W.

![Fig. 7: Switches gating signals and drain source voltages](image)
5 Conclusion

This paper presents a new high step-up interleaved dc-dc boost converter based on half bridge-doubler rectifier configuration in both the primary and secondary side. The turns ratio of the coupled inductor can be adjusted to enlarge the voltage gain. The interleaved structure allows currents sharing and reduce the current stress of the components. The stack arrangement distributes the power devices voltage stress, hence lower voltage rated devices can be utilised to reduce the conduction losses. The leakage energy of the coupled inductor is recycled to the output. Theoretical analysis of the circuit’s principle of operation and experimental results presented from a 140 W prototype confirm the effectiveness of the proposed topology as a non-isolated, high step-up power converter.

References