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 realised. Low-voltage rated devices ultimately reduce the conduction losses. The principle of operation and 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 DES 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 losses, 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, 10]. 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, minimise the current ripple, improve the transient response, and realise 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.

Here, an alternative structure based on half-bridge-double 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 this advantage, stacking the secondary-side half-bridge-double 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 (L1 and L2) with the same number of turns in the primary and secondary sides. The primary winding of the coupled inductors n1p and n2p are connected in parallel to share the large input current on the low-voltage side and are coupled to their corresponding secondary windings n1s and n2s. The primary and secondary windings are denoted by coupling references “s” and “p”. 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 realised by stacking the primary-side bridgeless boost rectifier voltages formed by capacitors C1, C2 and diodes D1, D2 and that of the coupled inductors secondary windings bridgeless boost rectifier formed by the C3, C4 and diodes D3, D4 respectively.

The equivalent circuit of the proposed converter is shown in Fig. 2. The coupled inductor can be modelled as an ideal

Fig. 1 Circuit configuration of the proposed converter
transformer with defined turns’ ratio \([2, 10]\). The primary winding of the ideal transformer is connected in parallel with the magnetising inductor \(L_{m1}, L_{m2}\) and then in series with leakage inductance \(L_1, L_2, S_1, S_2\) are the main power switches of the converter. The power diodes \(D_1, D_2\) serve as clamp diodes and \(C_1, C_2\) are the clamp capacitors. \(C_o\) 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 \(C_1, C_2, C_3, \) and \(C_4\) are large enough and assumed to be constant.
3. The turns ratio of the coupled inductor \(N\) is equal to \(n_2/n_1\) and coupling coefficient \(k\) is expressed as \(L_0/L_{k+L_m}\)

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. Fig. 3 shows the typical steady state waveform of the converter in one switching cycle. 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 \([t_0 - t_1]\): before \(t_0\), the main switch \(S_1\) is off and \(S_2\) is on, the diodes \(D_2\) and \(D_3\) are reverse biased, while \(D_1, D_4\) are forward biased. Magnetising inductor \(L_{m1}\) as well as the leakage inductor \(L_{s1}\) are charged linearly by the input voltage. Consequently, capacitor \(C_4\) is charged by the induced voltage of \(n_{2s}\). The leakage inductor energy \(L_{s1}\) is released into the capacitor \(C_2\).

Stage 2 \([t_1 - t_2]\): \(S_1\) and \(S_2\) are both on at time \(t_1\). All the diodes are reversed biased, the load is supplied by the capacitors \(C_1, C_2, C_3, \) and \(C_4\) respectively. The coupled inductors are linearly charged by the input voltage \(V_{in}\).

Stage 3 \([t_2 - t_3]\): At time \(t_2\), the main switch \(S_2\) turns off. The drain-source voltage of main switch \(S_2\) rise to the capacitor voltage \(V_{C1}\), which makes the diode \(D_1\) to conduct. The leakage inductor energy of \(L_{s1}\) is released to the capacitor \(C_1\). 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 \(n_{2s}\). The voltage of the main switch \(S_2\) is clamped to the voltage of the capacitor \(C_1\).

Stage 4 \([t_3 - t_4]\): 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 \(D_1\) has reached its peak and begins to fall; the current falling rate of the diodes is controlled by leakage inductors \(L_2, L_3\) and \(L_4\).

Stage 5 \([t_4 - t_5]\): The 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 6 \([t_5 - t_6]\): At time \(t_5\), switch \(S_1\) turn-offs 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

\[
V_{ds1} = V_{ds2} = V_{C1} = V_{C2} = \frac{V_{in}}{(1 - D)}
\]

(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

\[
V_{C3} = V_{C4} = \frac{N V_{in}}{(1 - D)}
\]

(2)
The output voltage of the converter is the summation of the capacitor voltages given by

\[ V_O = V_{C1} + V_{C2} + V_{C3} + V_{C4} = \frac{2V_{in}}{1-D} + \frac{2NV_{in}}{1-D} \] (3)

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

\[ M_{\text{ideal}} = \frac{V_O}{V_{in}} = \frac{2(N+1)}{(1-D)} \] (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.

\[ V_{ds1} = V_{ds2} = \frac{V_O}{2(N+1)} \] (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

\[ V_{D3} = V_{D4} = \frac{2NV_{in}}{1-D} = \frac{NV_O}{N+1} \] (7)

The relationship between the power devices voltage stress and turns ratio is plotted in Fig. 4. The voltage stress on the power switches \( S_1, S_2 \) and that of power diodes \( D_1, D_2 \) decrease as the coupled inductor turns ratio increase. Conversely, the voltage stress on the diodes \( D_3, D_4 \) increases as the turns ratio increases (Fig. 6).

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 is 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. It can be seen that the voltage stress of the switches is 30 V, which is one-quarter of the output voltage. This allows low-rated devices with low \( R_{ds-on} \) 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 $D_3$, $D_4$ are shown in Fig. 10. The voltage stress of the diodes is 65V 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 magnetising 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.

5 Conclusion

Table 1 Converter prototype specifications

| Parameter                      | Value        |
|--------------------------------|--------------|
| Output Power ($P_o$)            | 140 W        |
| Input Voltage ($V_{in}$)        | 12 V         |
| Output Voltage ($V_o$)          | 120 V        |
| Switching Frequency ($f_s$)     | 50 KHz       |
| Main Switches (S)               | FDP047AN     |
| Diodes ($D_1$, $D_2$, $D_3$ and $D_4$) | MBUR42050G   |
| Capacitors ($C_1$, $C_2$)       | 4.7 μF       |
| Capacitors ($C_3$, $C_4$)       | 10 μF        |
| Turns Ratio ($n_2/n_1$)         | 1:1          |
| Magnetising Inductance ($L_m$)  | 35 μH        |
| Leakage Inductance ($L_{lk}$)   | 1.3 μH       |

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 high step-up power converter.
6 References

[1] Barreto, L.H.S.C., Praca, P.P., Oliveira, D.S., et al.: ‘High-voltage gain boost converter based on 3-state commutation cell for battery charging using PV panels in a single conversion stage’, IEEE Trans. Power Electron., 2014, 29, (1), pp. 150–158

[2] Qun, Z., Lee, F.C.: ‘High-efficiency, high step-up DC-DC converters’, IEEE Trans. Power Electron., 2003, 18, (1), pp. 65–73

[3] Axelrod, B., Berkovich, Y., Ioinovici, A.: ‘Switched-capacitor/switched-inductor structures for getting transformerless hybrid DC-DC PWM converters’, IEEE Trans. Circuits Sys., 2006, 55, (2), pp. 687–696

[4] Yi, Z., Li, W., Yan, D., et al.: ‘High step-up boost converter with coupled inductor and switched capacitor’, 5th IET Int. Conf. on Power Electronics, Machines and Drives (PEMD), Brighton, UK, 2010

[5] Muhammad, M., Armstrong, M., Elgendy, M.A.: ‘Analysis and implementation of high-gain non-isolated DC-DC boost converter’, IET Power Electron., 2017, 10, (11), pp. 1241–1249

[6] Luo, F.L., Ye, H.: ‘Super-lift boost converters’, IET Power Electron., 2014, 7, (7), pp. 1655–1664

[7] Kuo-Ching, T., Chi-Chih, H., Chun-An, C.: ‘A high step-up converter with voltage-multiplier modules for sustainable energy applications’, IEEE J. Emerging Sel. Topics Power Electron., 2015, 3, pp. 1100–1108

[8] Muhammad, M., Armstrong, M., Elgendy, M.A.: ‘A non-isolated interleaved boost converter for high voltage gain applications’, IEEE J. Emerging Sel. Topics Power Electron., 2015, 9, (1), pp. 1–10

[9] Zhou, L.-W, Zhu, B.-X, Luo, Q.-M, et al.: ‘Interleaved non-isolated high step-up DC/DC converter based on the diode–capacitor multiplier’, IET Power Electron., 2014, 7, (2), pp. 390–397

[10] Muhammad, M., Armstrong, M., Elgendy, M.A.: ‘Non-isolated, high-gain boost converter for power electronic application’. 8th IET PEMD Conf. Proc., Glasgow, UK, April 2016, p. pp. 6–6

Fig. 12 Measured converter efficiency