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Abstract: The non-inverting buck boost (NIBB) converter has attracted significant attention in recent years, as it shares ground between input and output, and the voltage stress of switches is lower. In order to investigate the differences between NIBB and conventional buck boost converters, a comprehensive comparison and analysis of these two converters were conducted in terms of their operation principles, which includes multi-mode control strategy and dual-edge modulation here, and also the characteristics of switches and passive components in the two converters were analysed. The results show that NIBB is better than conventional buck boost circuit in these aspects of electrical stress, power loss, cost, passive component volume, and so on. Two prototypes for the two converters with 10 kW/20 kHz were designed and simulated, respectively, for verifying the results. Analytical and simulated results confirmed the conclusions.

1 Introduction

There are many kinds of non-isolated DC–DC converters that can achieve both step-up and step-down power conversions, such as the conventional buck boost, Ćuk, Zeta, and Sepic. The conventional buck boost and Ćuk output a negative voltage, resulting in complicated auxiliary power supply and drive circuit [1]. Zeta and Sepic have too many passive components, leading to a lower power density [2]. Furthermore, the voltage stress of switches in these four topologies is the sum of input and output voltages.

Fig. 1 shows the conventional buck boost converter and the non-inverting buck boost (NIBB) converter. The NIBB converter, sometimes also called four switch buck boost converter [2], is first proposed in 1998 [3]. It can be seen as a cascaded connection of buck and boost converters. The output voltage has the same polarity of the input, and the voltage stress of the buck switches and boost switches is the input and output voltage, respectively, which is lower than that of the aforementioned four converters [2].

As the NIBB converter has many advantages mentioned above, it is used in many applications such as PFC [4, 5], electric vehicle [6, 7], fuel-cell system [8], telecommunication, and photovoltaic systems. Many variations of this topology are proposed, such as zero voltage switching NIBB [9] and interleaved NIBB [7, 8]. Many papers analysed the operation principle, modulation strategy, and operation mode transition of NIBB [2, 10]. However, the comparison of NIBB and conventional buck boost is rare. The following sections will focus on the analysis and comparison of NIBB and the conventional buck boost circuit.

2 Operating principle analysis of non-inverting buck boost converter

If the switching periods of $S_1$ and $S_4$ are both $T$, a switching period of NIBB converter can be divided into four stages, as shown in Fig. 2. In stage I, $S_1$ and $S_4$ are both on, the current of the inductor $i_L$ increases rapidly. In stage II, $S_1$ is on and $S_4$ is off, $i_L$ decreases when the converter operates in boost mode, $i_L$ increases when the converter operates in buck mode. In stage III, $S_1$ and $S_4$ are both off, $i_L$ decreases rapidly. In stage IV, $S_1$ is off and $S_4$ is on, $i_L$ remains unchanged (if the resistance in the current loop is ignored).

In fact, if the switching frequency of $S_1$ and $S_4$ are different, the converter can also operate normally, because the switch status of the converter can still be seen as a combination of these four stages.

\[
\begin{align*}
\text{stage I: } & \frac{di_L}{dt} = u_1 \\
\text{stage II: } & \frac{di_L}{dt} = u_1 - u_o \\
\text{stage III: } & \frac{di_L}{dt} = -u_o \\
\text{stage IV: } & \frac{di_L}{dt} = 0
\end{align*}
\]
degenerates to a buck circuit when NIBB circuit degenerates to a boost circuit when ... the falling edge of \( S_1 \), in other words, the time ratio \( S_1 \) and \( S_4 \) are fully synchronised and the circuit degenerates to buck boost circuit, the inductor current ripple is the largest. It can be derived as

\[
\Delta i_L = \left\{ \begin{array}{ll}
\frac{u_i d_1 u_o}{u_i + u_o} \times \frac{T}{L} & \text{if } u_o > u_i \\
\frac{u_i d_{11} u_o}{u_i + u_o} \times \frac{T}{L} & \text{if } u_o < u_i
\end{array} \right.
\]

Equation (5) is also the current ripple calculation formula of conventional buck boost circuit. Therefore, the inductor current ripple of NIBB is smaller than the conventional buck boost circuit obviously. Furthermore, if \( d_1 \) and \( d_2 \) do not change but \( d_\phi = 0 \), which means \( S_1 \) turns on at the same time \( S_2 \) turns off, the on-ratio of \( S_1 \) and the off-ratio of \( S_2 \) overlap most, and the inductor current ripple will further decrease [2]. Using this modulation method, (4) can be rewritten as (6).

\[
\Delta i_L = \left\{ \begin{array}{ll}
\frac{u_i d_1 u_o}{u_o} \times \frac{T}{L} & \text{if } u_o > u_i \\
\frac{u_i d_1 u_o}{u_i} \times \frac{T}{L} & \text{if } u_o < u_i
\end{array} \right.
\]

When the NIBB operates in its degenerate mode, it can be derived as (7).

\[
\Delta i_L = \left\{ \begin{array}{ll}
\frac{u_i(u_o - u_i)}{u_o} \times \frac{T}{L} & \text{if } u_o > u_i \\
\frac{u_i(u_i - u_o)}{u_i} \times \frac{T}{L} & \text{if } u_o < u_i
\end{array} \right.
\]

Fig. 3 shows the analytical value and simulation result of inductor current ripple in NIBB and the conventional buck boost using the same capacitance, inductance, and resistive load. The solid curve in this figure refers to analytical value by (5) and (7), and the mark \( \times \) refers to the simulation result. It can be seen that the current ripple of NIBB is obviously less than conventional buck boost, and the simulation results are in good agreement with the theoretical calculations.

Without loss of generality, the following is an example of the inductance calculation and design when power transfers from left to right, assuming the rated power of the converter is \( P \). An energy balance relation of the converter can be derived as (8). If the inductor works in continuous current mode (CCM), the minimum required inductance can be derived according to the energy balance relation.

\[
k = \frac{d_1}{1 - d_2}
\]
In practice, when the converter degenerates to boost mode \( (d_1 = 1) \) or buck mode \( (d_2 = 0) \), the inductor current ripple is the largest. The minimum required inductance is derived as (9).

\[
L_{\text{min}} = \begin{cases} \frac{u_i(u_o - u_i)}{u_i} \times \frac{T}{2P} & u_o > u_i \text{ degenerate to boost} \\ \frac{u_o(u_i - u_o)}{u_o} \times \frac{T}{2P} & u_o < u_i \text{ degenerate to buck} \end{cases}
\]

However, the minimum required inductance when the conventional buck boost circuit operates in CCM is

\[
L_{\text{min}} = \frac{u_i^2TP}{2P(u_i + u_o)}
\]

In most cases, the minimum inductance requirement of NIBB is smaller than the conventional buck boost circuit.

Similarly, using (2) and (6), the maximum inductor current of NIBB can be derived as below

\[
i_{\text{max}} = \frac{P + u_i(u_o - u_i)}{u_i} \times \frac{T}{2L} \quad u_o > u_i
\]

\[
i_{\text{max}} = \frac{P + u_i(u_i - u_o)}{u_i} \times \frac{T}{2L} \quad u_o < u_i
\]

and for conventional buck boost, the maximum inductor current is shown below. In many cases, (11) is less than (12), especially when the output voltage is not too far from the input voltage.

\[
i_{\text{max}} = \frac{P}{u_i} + \frac{u_i(u_i - u_o)}{u_i} \times \frac{T}{2L}
\]

Take a 10 kW/20 kHz converter as an example, if the inductor operates in CCM when \( P > 2 \text{ kW} \), the curve of minimum required inductance and converter voltage ratio is shown in Fig. 4, and the maximum inductance is shown in Fig. 5.

Compared with conventional buck boost circuit, it can be seen that the NIBB circuit has the following characteristics: NIBB requires smaller inductance than conventional buck boost circuit at the same voltage ratio. The closer to 1 \( k \) is, the smaller the inductance needed, and the required inductance is even zero when \( k = 1 \). This is a very good feature for DC–DC converter, which means the closer to 1 \( k \) is, the smaller the current ripple is, so that the smaller the noise, EMI, and power loss is.

### 4 Capacitor voltage ripple analysis and capacitance design

Because the input side and output side of NIBB circuit are symmetrical, without loss of generality, only the output capacitor is analysed below. The minimum required capacitance can be derived by the capacitor energy balance relation in (13), when \( u_o > u_i \) and (14) when \( u_o < u_i \).

\[
\frac{1}{2}C(u_o + \frac{1}{2}\Delta u_i)^2 - \frac{1}{2}C(u_o - \frac{1}{2}\Delta u_o)^2 = d_iTP
\]

\[
\frac{1}{2}C(u_o + \frac{1}{2}\Delta u_i)^2 - \frac{1}{2}C(u_o - \frac{1}{2}\Delta u_o)^2 = \frac{1}{2} \frac{\Delta u_i}{2} + \frac{T}{2} \times u_i
\]

Substituting (2) into them, the capacitor voltage ripple can be derived in (15).

\[
\Delta u_o = \frac{(u_o - u_i)TP}{Cu_o} \quad u_o > u_i \text{ degenerate to boost}
\]

\[
\Delta u_o = \frac{(u_o - u_i)TP}{8u_iCL} \quad u_o < u_i \text{ degenerate to buck}
\]

Fig. 6 shows the output voltage ripple of NIBB and the conventional buck boost using the same capacitance, inductance, and resistive load. The solid curve in the figure refers to analytical value, and the mark \( x \) refers to the simulation result. It can be seen that the voltage ripple of NIBB is obviously less than conventional buck boost, and the simulation results are in good agreement with the theoretical calculations.

In another form, the minimum required capacitance can be derived as shown in (16).

\[
C_{\text{min}} = \frac{(u_o - u_i)TP}{\Delta u_o \times u_i} \quad u_o > u_i \text{ degenerate to boost}
\]

\[
C_{\text{min}} = \frac{(u_o - u_i)TP}{8u_i\Delta u_iL} \quad u_o < u_i \text{ degenerate to buck}
\]

Still take the 10 kW/20 kHz converter as an example. If \( L \) is designed according to Section 3, and the output voltage ripple is required to be less than 1%, the curve of minimum capacitance \( C_{\text{min}} \) and converter voltage ratio \( k \) is shown in Fig. 7. Similarly, the NIBB circuit has the following characteristics compared with conventional buck boost circuit: the NIBB circuit requires smaller capacitance than conventional buck boost circuit at the same voltage ratio. The closer to 1 \( k \) is, the smaller the capacitance required, and no filter capacitor is even needed when \( k = 1 \). Similar to the previous analysis of inductance, this is a very good feature.
for DC–DC converter, which means the closer to 1 \( k \) is, the smaller the output voltage ripple is.

5 Discussion and conclusion

5.1 Passive element volume

From the analyses in Sections 3 and 4, a significant feature of NIBB is that it requires smaller capacitance and inductance than the conventional buck boost circuit. From the passive element volume point of view, the volume of capacitor can be quantitatively compared by the maximum energy storage capacity, which is calculated by (17), where \( U_{\text{max}} \) refers to the maximum capacitor voltage.

\[
E_{\text{Cmax}} = \frac{1}{2}CU_{\text{max}}^2
\]

(17)

As \( C \) and \( U_{\text{max}} \) in NIBB are both smaller than those in conventional buck boost circuit, it can be considered that the capacitor volume of NIBB is smaller than conventional buck boost.

Similarly, the volume of inductor can be quantitatively compared by the area product (AP), where \( I_{\text{max}} \) refers to the maximum inductor current, and \( B_s, J, K_0 \) are constants related to the shape and material of inductor [11].

\[
\text{AP} = \frac{LI_{\text{max}}}{B_sJK_0}
\]

(18)

As \( L \) and \( I_{\text{max}} \) in NIBB are both smaller than those in conventional buck boost circuit, it can be considered that the inductor volume of NIBB is smaller than conventional buck boost, also.

5.2 Switch power loss

On the surface, the power loss of NIBB will be considered more than conventional buck boost circuit, because it has more switches. In fact, this conclusion may not be true. The switch power loss can be roughly estimated by (19) below, where \( V_{\text{exp}} \) refers to the withstand voltage of the switch, \( I_{\text{exp}} \) refers to the switching current, \( C_{\text{on}} \) and \( C_{\text{off}} \) are constants related to the characteristic of the switch itself [12].

\[
\begin{align*}
E_{\text{on}} &= C_{\text{on}}V_{\text{exp}}I_{\text{exp}} \\
E_{\text{off}} &= C_{\text{off}}V_{\text{exp}}I_{\text{exp}}
\end{align*}
\]

(19)

As mentioned in Section 1, the withstand voltage of each switch in buck boost converter is \( u_i^+ + u_o^+ \), but the withstand voltage of buck switches \( S_1 \) and \( S_2 \) is \( u_o^+ \) for boost switches \( S_3 \) and \( S_4 \), the withstand voltage is \( u_o^+ \). Both of them are less than \( u_i^+ + u_o^+ \). Obviously, the maximum inductor current is also the maximum switch current, and the maximum inductor current of NIBB and conventional buck boost circuit is derived in (11) and (12), separately.

It can be seen from (19), the on-state loss is roughly proportional to the switching current and the transient loss is roughly proportional to the product of switching current and switching voltage. As of the smaller requirement of rated switch voltage and rated switch current, although the number of switches in NIBB circuit is double that in buck boost circuit, the total power loss of NIBB is even less than that of buck boost circuit in many cases.

5.3 Switch cost

As analysed above, the rated current and rated voltage of switches in buck boost circuit are smaller than that in NIBB circuit, although it needs twice the number of switches. When the output voltage is not too far from the input voltage, the withstand voltage of switches in conventional buck boost circuit is double that in NIBB circuit. Therefore, take the unidirectional DC–DC converter as an example, two low voltage switches are needed in NIBB circuit, and one high voltage switches are needed in buck boost circuit. Actually, high voltage switch is more difficult to manufacture, and the cost of two switches is often inexpensive than only one switch whose rated voltage is the double, particularly when the converter is used for high voltage applications. Moreover, smaller capacitors and inductors are used in NIBB circuit, which means the cost of passive components is more inexpensive for NIBB circuit.

6 Conclusion

The NIBB converter is analysed in detail compared with buck boost circuit. The inductor current ripple and capacitor voltage ripple of NIBB are lower than the conventional buck boost circuit. From the design point of view, NIBB circuit can achieve the same performance with smaller passive devices. Because the rated voltage and rated current of switches are lower, the power loss, cost of switching devices, and passive devices will be less than conventional buck boost circuit, although there are more switches used.

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