Minimization of Passive Components in Multi-level Flying Capacitor DC-DC Converter

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In this paper, we propose a minimization design method of the inductance and the capacitance of the flying capacitors for a multi-level flying capacitor DC-DC boost converter (FCBC). The effectiveness of the small capacitances of the flying capacitors in three-level and five-level FCBCs is investigated. We experimentally confirmed that the distortion of the voltage across the input source and the input inductor is drastically reduced by increasing the number of levels. Thus, a small inductance value and a small capacitance value can be used for the input inductor and the flying capacitors, respectively, in an n-level FCBC. Therefore, the minimization of passive components in multi-level FCBCs is achieved. Moreover, the achieved maximum efficiencies of the designed three-level and five-level FCBCs are 98.5% and 97.8%, respectively, at an output power of 1 kW.

Keywords: flying capacitor boost converter, inductor, inductor current ripple, flying capacitor, flying capacitor voltage ripple

1. Introduction
Typical conventional 2-level DC-DC boost converters require a large input inductor, which is bulky and heavy. On the other hand, the flying capacitor boost converter (FCBC) requires only a small inductance of the input inductor because the boost-up energy is transferred from the flying capacitor to the output side. Therefore, reductions of the inductance and the core volume are achieved (1).

Besides, in a conventional 3-level FCBC, the capacitance of the flying capacitor should be large in order to keep the flying capacitor voltage half of the output voltage (1). As a result, the low-voltage-rating switching devices can be used. However, nowadays low-power-loss and high-voltage-rating switching devices, such as SiC-MOSFETs have been developed (2). Thus, small capacitances such as ceramics and films types can be applied due to the availability of high-voltage-rating switching devices with low-power-loss feature. As a result, the capacitance reduction of the flying capacitor can be achieved compared to a conventional 2-level FCBC. The 3-level FCBC with a small capacitance of the flying capacitor has been discussed in Ref. (1). However, the minimum capacitance design method and its influence in the n-level FCBC have not been discussed by other researchers (2)(3).

This paper establishes the minimization design method of the passive components which are the inductance of the input inductor and the capacitance of the flying capacitors in the n-level FCBC in order to reduce the size and weight of the power converter. On the other hand, two prototypes of 3-level and 5-level FCBCs were constructed in order to confirm the validity of the minimization design method for the inductance and the capacitance.
Minimization of passive components in multi-level FCBC (Asmarashid Bin Ponniran et al.)

\[ \Delta V_{f(xn-level)} = \frac{P_{in}D}{V_{in}C_{f(xn-level)}f_{sw}} \]  \\
\[ \Delta V_{f(xn-level)} = (n-1)P_{in}D \]  \\
\[ = 2(n-1)V_{f(xn-level)}_{\text{max}} - 2xV_{out} V_{in}f_{sw} \]  \\
\[ = \Delta V_{f(xn-level)_{\text{min}}} \]

where \( V_{f(xn-level)_{\text{max}}} \) is the maximum flying capacitor voltage which is ideally equal to the withstand voltage of switching devices.

4. Experimental Results

The specifications of the experiment condition are as follows: the duty ratio is 0.25, the input voltage is 350 V, the switching frequency is 100 kHz and the output power is 1 kW. In this paper, the operations of 3-level and 5-level FCBCs prototypes with small capacitances of the flying capacitors are experimentally confirmed. The maximum efficiencies of the 3-level and 5-level FCBCs prototypes with a small capacitance of the flying capacitors are 98.5% and 97.8%, respectively at the output power of 1 kW.

Figure 2 shows the flying capacitor voltage ripples in the 5-level FCBC. The voltage ripples are 10 V and 29 V when the capacitances of the flying capacitors are 1.1 \( \mu F \) and 0.35 \( \mu F \), respectively. It is confirmed that the flying capacitor voltage ripples are same when the same capacitances of the flying capacitors are used as shown by (3).

Figure 3(a) shows the experimental results of the \( k_v\text{conv} \), which is the ratio between the effective values of distorted components \( V_{nfsw} \) against DC component \( V_{DC} \). It is confirmed that the ratio \( k_v\text{conv} \) converges into a constant value when the capacitance of the flying capacitor is increased. Meanwhile, Fig. 3(b) shows the experimental results of the \( k_i\text{conv} \), which is the ratio between the effective values of distorted components \( I_{nfsw} \) against DC component \( I_{DC} \). The ratio of \( k_i\text{conv} \) is not affected on the variation of capacitances of the flying capacitors although small capacitance is used. Thus, the validity of the small capacitance of the flying capacitors in the 3-level and 5-level FCBCs are experimentally confirmed.

Figure 4 shows the harmonics spectrum of \( v_{conv} \) in the 3-level and 5-level FCBCs. The voltage \( v_{conv} \) in the 5-level FCBC obviously has lower harmonic components compared to the 3-level FCBC when the capacitance of the flying capacitor of 1.1 \( \mu F \) is used. From these results, it is clarified that not only the small capacitance for the flying capacitor in fact the small inductance of the input inductor can be considered in the n-level FCBC.

5. Conclusion

This paper established the minimization design method of the passive components in n-level FCBCs which are the inductance of the input inductor and the capacitance of the flying capacitors. The effectiveness of the small capacitance of the flying capacitors is evaluated by analyzing the distorted voltage across the input voltage source and the input inductor and the distorted current to the output side which includes the output capacitor and the load.

In a future work, converter volume estimation of a multi-level FCBC with minimized input inductor and small capacitances of the flying capacitors will be conducted for weight and size reduction.

References

