Minimum Flying Capacitor for N-level Capacitor DC/DC Boost Converter

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***Abstract*-- This paper proposes a Flying Capacitor DC/DC Boost Converter (FCBC) with a small capacitance of the flying capacitor. As a result the size and weight of the proposed converter can be reduced. The capacitance of the flying capacitor is designed based on switching device voltage rating and regardless of the output voltage ripple influences. Moreover, the achieved maximum efficiency of the designed 3-level FCBC is 98.5% at the output power of 1 kW. Finally, the effectiveness of small capacitances of the flying capacitor in the 3-level and 5-level FCBCs are investigated. The characteristics of the distorted voltage across an input voltage source and an input inductor and the distorted current to the output side which is an output capacitor and a load are investigated with several capacitances of the flying capacitors for 3-level and 5-level FCBCs. As a result, it is experimentally confirmed that the distortion of the voltage across the input voltage source and the input inductor is drastically reduced by increasing the number of level. On the other hand, the distortion of the current to the output side which is the output capacitor and the load is almost same even the number of level is increased. Therefore, the experimental results show that small capacitance of the flying capacitor can be used in the n-level FCBC.**

***Index Terms*—flying capacitor, output voltage ripple, multi-level flying capacitor boost converter.**

I. INTRODUCTION

In general, a DC/DC boost converter in high-power-capacity applications typically demands high conversion efficiency with low weight, volume, and cost of the converter. Nevertheless, if a typical conventional DC/DC boost converter is considered, the bulkiness of the input inductor must be taken into consideration because the typical conventional DC/DC boost converter requires large inductors for energy storage.

The FCBC requires only a small input inductor in order to suppress the inrush current from a power supply to a flying capacitor [1-4,7]. In addition, one important feature of the FCBC is that the boost-up energy is transferred from the flying capacitor to the output side, which means that the input inductor can be designed with a small inductance and a reduced core volume of the inductor[2,4]. Consequently, the overall size and weight of the input inductor can be greatly reduced as compared to a conventional two-level DC/DC boost converter [1,2,5,7].

Generally, in conventional 3-level FCBCs, the capacitance of the flying capacitor should be large in order to keep the flying capacitor voltage of half of the output voltage [1,2,4,7]. As a result, the low-voltage-rating switching devices can be used. Low-voltage-rating switching devices usually have fast switching performance and low on-resistance features compared to high-voltage-rating devices. However, nowadays low-power-loss and high-voltage-rating switching devices, such as SiC-MOSFETs have been developed [6]. Thus, small capacitances such as from ceramics and films types with high voltage capability can be considered together with high-voltage-rating switching devices. As a result, the volume of the flying capacitor can be reduced compared to conventional FCBCs. The 3-level FCBC with a small flying capacitor is discussed in Ref [7]. However, the minimum capacitance selection and its influence in the *n*-level FCBC have not been discussed [1-3,8,9].

In this paper, the FCBC considering a small capacitance of the flying capacitor is proposed in order to reduce the size and weight of the power converter. First, the principle of the FCBC is described. Next, a design method for minimum capacitance of the flying capacitor is clarified. Then, the minimum capacitance design method for the flying capacitor is experimentally verified. Finally, the distortion of the voltage across a input voltage source and a input inductor and the current to the output side which the output capacitor and the load are investigated for the 3-level and the 5-level of the FCBCs in terms of small capacitance of the flying capacitor.

II. PRINCIPLE OF THE FCBC

First, a principle of a 3-level FCBC is described. Next, parameters of passive components in a n-level FCBC is described.

A. 3-level FCBC

Basically, the 3-level FCBC consists of two diodes, two switches, an input inductor L, a flying capacitor C_{fc}, and an output capacitor C_{out}. The input inductor is used in order to control independently the output voltage by controlling the duty ratio D. The relationship between the input voltage V_{in} and the output voltage V_{out} is expressed by (1) using the boost ratio β

$$V_{out} = \beta V_{in} \quad (1)$$

β is expressed by (2).

$$\beta = \frac{1}{1-D} \quad (2)$$

Fig. 1 shows the circuit configuration and the operation mode of the 3-level FCBC. During one switching period, the operation mode is repeated. Only the boost ratio in the range of $1 < \beta \leq 2$ is considered in this study. The inductance of the input inductor $L_{(3\text{-}level)}$ and inductor core volume $Vol_{(3\text{-}level)}$ in the 3-level FCBC is expressed by (3) and (4) [4,7].

$$L_{(3-level)} = 0.25 \times L_{conventional} \quad (3)$$

$$Vol_{(3-level)} = 0.35 \times Vol_{conventional} \quad (4)$$

where $L_{conventional}$ is the inductance of the input inductor and $Vol_{conventional}$ is the volume of the input inductor in the conventional 2-level DC/DC boost converter.

From (3) and (4) the inductance of the input inductor and the inductor core volume are greatly reduced compared to the conventional 2-level DC/DC boost converter.

B. n-level FCBC

Fig. 2 shows the n-level FCBC circuit configuration. In the n-level FCBC, the balancing of each flying capacitor voltages need to considered. The unbalanced condition is due to improper charging and discharging of the flying capacitor [10-12]. This condition will lead an increasing the voltage stress of switches. In the section III (C), the important expressions for the n-level FCBC are discussed.

The inductance of the input inductor $L_{(n\text{-}level)}$ and inductor core volume $Vol_{(n\text{-}level)}$ in the n-level FCBC are expressed by (5) and (6), respectively.

$$L_{(n-level)} = \frac{L_{conventional}}{(n-1)^2} \quad (5)$$

$$Vol_{(n-level)} = \left(\frac{1}{(n-1)^2}\right)^{0.75} \times Vol_{conventional} \quad (6)$$

From both of (5) and (6), it is confirmed that the inductance of the input inductor and inductor core volume are inversely proportional to the number on level n. Thus the inductance of the input inductor and inductor core volume are reduced when the higher level of a FCBC is considered.

III. Minimum Capacitance Estimation of the Flying Capacitor

A. 3-level FCBC

Table 1 shows the specification of the simulation and experiment conditions. First, the detailed analysis of minimum capacitance of the flying capacitor is based on 3-level FCBC. In this chapter, the relationship between the flying capacitor $C_{fc(3\text{-level})}$ and the output voltage ripple ΔV_{out}. is considered.

Principally, the time constant $R_{out}C_{out}$, which consists of the output resistance R_{out} and output capacitance C_{out}, is considered in order to estimate the relationship between the capacitance of the flying capacitor and the output voltage ripple. If the output voltage ripple is

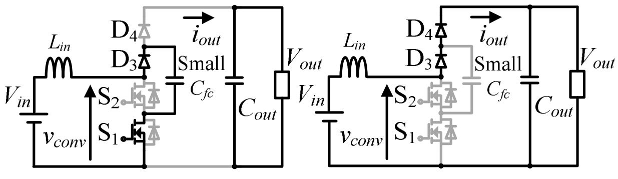


Fig. 1. Operation modes f 3-level FCBC

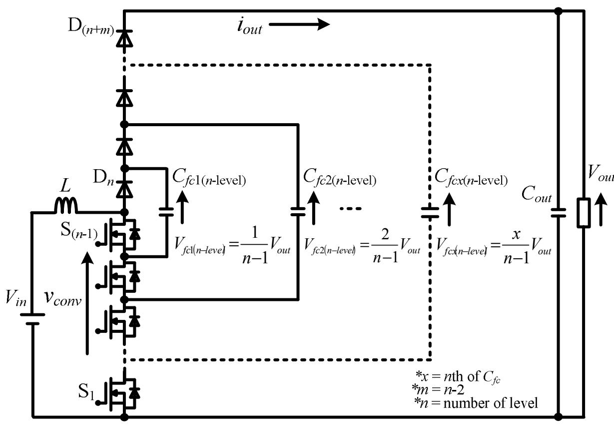


Fig. 2. n-level FCBC

TABLE 1
SPECIFICATIONS OF THE SIMULATION AND EXPERIMENT FOR 3-LEVEL AND 5-LEVEL FCBCS

Specification	Value
Input Voltage V_{in}	262.5 V
Output Voltage V_{out}	350 V
Output power P_{out}	1 kW
Input current I_{in}	4.24 A
Switching frequency f_{sw}	100 kHz
Duty ratio D	0.25
Input inductance L	200 μH
Capacitance of the flying capacitor C_{fc}	1.1 μF
Output capacitance C_{out}	1.5 μF
Maximum inductor current ripple ΔI_{L-max}	1.1 A
MOSFET	IRFB4229PBF
SiC Schottky Diode	IDW30G65C5

TABLE 2
TIME CONSTANT AND SWITCHING PERIOD

Output Capacitance C_{out}	Output Resistance R_{out}	Time Constant $R_{out}C_{out}$	Switching Period $1/f_{sw} = T$
1.5 μF	110 Ω	165 μs	10 μs
6 μF		660 μs	
9 μF		990 μs	

always constant even the capacitance of the flying capacitor varies, the time constant $R_{out}C_{out}$ should be greater than the switching period $1/f_{sw}$, as expressed by (7)

$$R_{out}C_{out} = \frac{V_{out}^2}{P_{out}}C_{out} > \frac{1}{f_{sw}} \quad (7)$$

where P_{out} is the output power.

In the simulation and the experiment, three capacitances of the output capacitor and an output resistor are selected. The switching frequency f_{sw} is 100 kHz and equal to the switching period of 10 μs. Table 2 shows the calculation results which are all of the time constants $R_{out}C_{out}$ for the numerous output capacitances are greater than the switching period. In the condition of the Table 2, the capacitance of the flying capacitor and the output voltage ripple is always independent of each other. The output voltage ripple ΔV_{out} can be expressed as (8).

$$\Delta V_{out} = \frac{P_{out}(\beta - 1)}{\beta V_{out} C_{out} f_{sw}} \quad (8)$$

From (8), it is obvious that the relationship between the flying capacitor and the output voltage ripple is independent. Consequently, the capacitance of the flying capacitor is designed without the consideration of the output capacitor and output voltage ripple.

Next, the design of the small capacitance of the flying capacitor $C_{fc(3\text{-level})}$ based on the maximum switching device voltage rating $V_{DS(3\text{-level})\text{-}max}$ is described. If Mode I in Fig. 1 is referred, the maximum voltages across the flying capacitor $V_{fc(3\text{-level})\text{-}max}$ and the switch S_2 $V_{S2(3\text{-level})\text{-}max}$ are same due to the parallel connection of the flying capacitor and the switch S_2. In addition, In Mode I, both voltages are reached up to maximum. Therefore, the maximum voltage rating of the switch $S_{2(3\text{-level})}$ is according to the maximum flying capacitor voltage. The maximum voltage rating of other switches also can be based on it.

Theoretically, in the 3-level FCBC, the average voltage of the flying capacitor is half of the output voltage as expressed by (9). Meanwhile, from the operation mode of the 3-level FCBC, the flying capacitor and drain-source terminal of MOSFETs of $S_{1(3\text{-level})}$ and $S_{2(3\text{-level})}$ are connected in parallel. Thus, the maximum voltage stresses for both devices can be expressed by (10).

$$V_{fc(3-level)} = \frac{V_{out(average)}}{2} \quad (9)$$

$$V_{S1(3-level)-\max} = V_{S2(3-level)-\max} = V_{fc(3-level)-\max} \quad (10)$$

Fig. 3 shows the simulation results of the waveforms of the inductor current $I_{L(3\text{-level})}$, the flying capacitor voltage $I_{fc(3\text{-level})}$, the flying capacitor voltage $V_{fc(3\text{-level})}$ and the output voltage V_{out}, respectively. The total charge Q_{total} from charging and discharging processes for the flying capacitor current is equal to zero. Therefore, the charge for both of the charge Q_{charge} and the discharge $Q_{discharge}$ are expressed by (11) as in Fig. 3, [13-15].

$$Q_{charge} = Q_{discharge} \quad (11)$$

The peak-to-peak flying capacitor voltage ripple $\Delta V_{fc(3\text{-level})}$ is determined by the flying capacitor current as

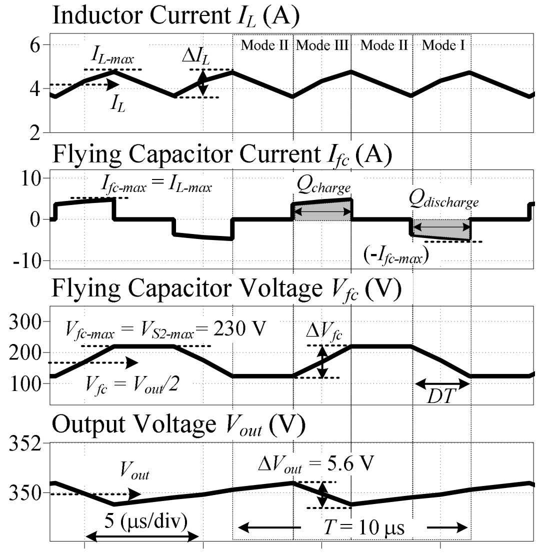


Fig. 3. Simulation waveforms of the inductor current, the flying capacitor current, the flying capacitor voltage and the output voltage

shown in Fig. 3. The flying capacitor voltage ripple in the 3-level FCBC $\Delta V_{fc(3\text{-}level)}$ is expressed by (12).

$$\Delta V_{fc(3-level)} = \frac{I_{in-\max} D}{C_{fc(3-level)} f_{sw}} = \frac{P_{in} D}{V_{in} C_{fc(3-level)} f_{sw}} \quad (12)$$

where P_{in} is the input power.

The average flying capacitor voltage is $V_{out}/2$. Therefore, the maximum flying capacitor voltage $V_{fc(3\text{-level})\text{-}max}$ is expressed by (13). The maximum voltage across the switch S_2 $V_{S2(3\text{-level})\text{-}max}$ is also determined by the maximum of the flying capacitor voltage $V_{fc(3\text{-level})\text{-}max}$ as shown by (13). Therefore, referring to (13), the minimum capacitance of the flying capacitor $C_{fc(3\text{-level})\text{-}min}$ in the 3-level FCBC is expressed by (14) from (13).

$$V_{fc(3-level)-\max} = V_{S2(3-level)-\max} = \frac{V_{out}}{2} + \frac{1}{2}\Delta V_{fc(3-level)} = \frac{V_{out}}{2} + \frac{1}{2}\frac{P_{in} D}{C_{fc(3-level)-\min} V_{in} f_{sw}} \quad (13)$$

$$C_{fc(3-level)-\min} = \frac{P_{in} D}{\left(2V_{fc(3-level)-\max} - V_{out}\right) V_{in} f_{sw}} \quad (14)$$

B. 5-level FCBC

In the 5-level FCBC, three flying capacitors are required which are $C_{fc1(5\text{-level})\text{-}min}$ and $C_{fc2(5\text{-level})\text{-}min}$, $C_{fc3(5\text{-level})\text{-}min}$. The maximum flying capacitor voltages which are $V_{fc1(5\text{-level})\text{-}max}$, $V_{fc2(5\text{-level})\text{-}max}$ and $V_{fc3(5\text{-level})\text{-}max}$ in the 5-level FCBC are expressed by (15), (16) and (17), respectively.

$$V_{fc1(5-level)-\max} = \frac{1}{4}V_{out} + \frac{1}{2}\frac{P_{in} D}{C_{fc1(5-level)-\min} V_{in} f_{sw}} \quad (15)$$

$$V_{fc2(5-level)-\max} = \frac{1}{2}V_{out} + \frac{1}{2}\frac{P_{in} D}{C_{fc2(5-level)-\min} V_{in} f_{sw}} \quad (16)$$

$$V_{fc3(5-level)-\max} = \frac{3}{4}V_{out} + \frac{1}{2}\frac{P_{in}D}{C_{fc3(5-level)-\min}V_{in}f_{sw}} \quad (17)$$

Furthermore, capacitance of each flying capacitors in 5-level FCBC are expressed by (18), (19) and (20), respectively.

$$C_{fc1(5-level)-\min} = \frac{2P_{in}D}{\left(4V_{fc1(5-level)-\max} - V_{out}\right)V_{in}f_{sw}} \quad (18)$$

$$C_{fc2(5-level)-\min} = \frac{2P_{in}D}{\left(4V_{fc2(5-level)-\max} - 2V_{out}\right)V_{in}f_{sw}} \quad (19)$$

$$C_{fc3(5-level)-\min} = \frac{2P_{in}D}{\left(4V_{fc3(5-level)-\max} - 3V_{out}\right)V_{in}f_{sw}} \quad (20)$$

The maximum voltage stress on switching devices for the 5-level FCBC is expressed by (21).

$$V_{sw(5-level)-\max} = \frac{1}{4}V_{out} + \frac{1}{2}\frac{P_{in}D}{V_{in}C_{fc1(n-level)-\min}f_{sw}} \quad (21)$$

C. n-level FCBC

In this section, the capacitance of the flying capacitor and the maximum voltage stress on switching devices in the *n*-level FCBC are explained.

The flying capacitor voltage in the *n*-level FCBC $V_{fcx(n-level)}$ and the required number of flying capacitor *m* are expressed by (22) and (23), respectively.

$$V_{fcx(n-level)} = \frac{x}{(n-1)}V_{out} \quad (22)$$

$$m = n - 2 \quad (23)$$

where *x* is the nth of flying capacitor in *n*-level FCBC.

The minimum capacitance of the flying capacitor in *n*-level FCBC is expressed by (24).

$$C_{fcx(n-level)-\min} = \frac{(n-1)P_{in}D}{\left(2(n-1)V_{fcx(n-level)-\max} - 2xV_{out}\right)V_{in}f_{sw}} \quad (24)$$

On the other hand, the ripple voltage of the flying capacitor for *n*-level FCBC is expressed by (25).

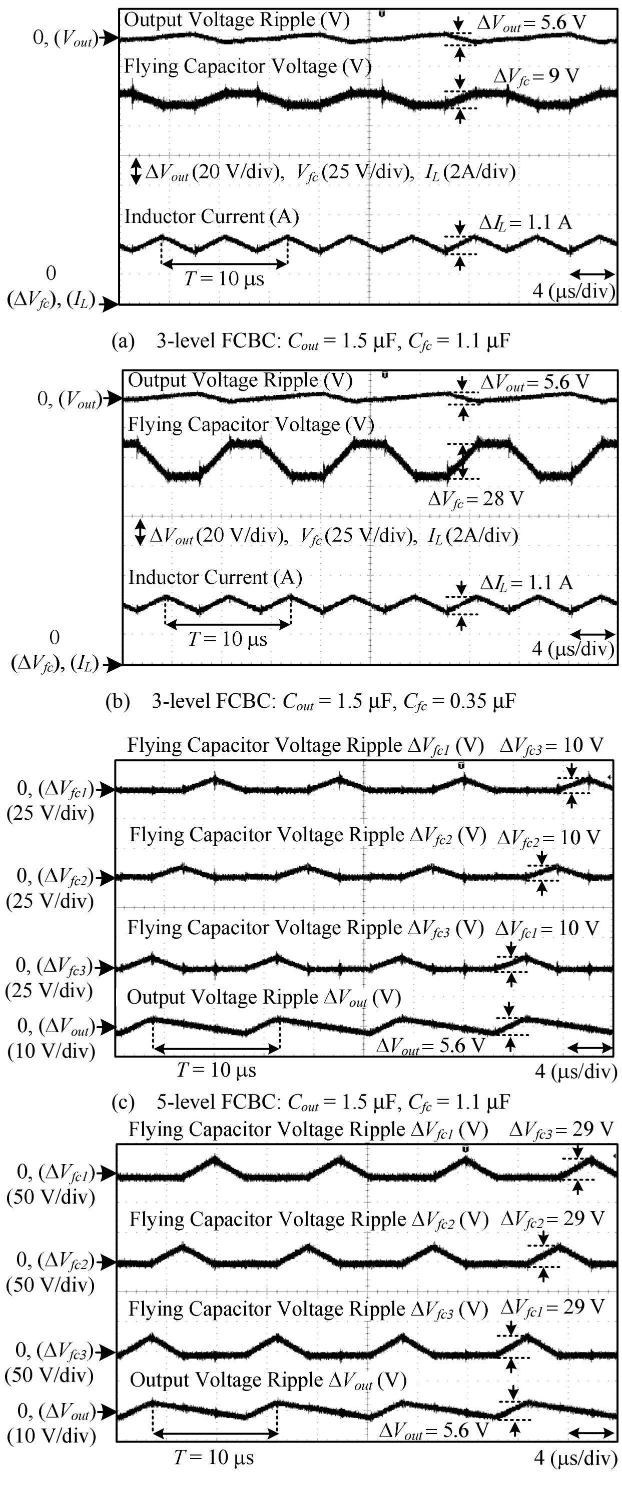
$$\Delta V_{fcx(n-level)} = \frac{P_{in}D}{V_{in}C_{fcx(n-level)}f_{sw}} \quad (25)$$

Therefore the maximum voltage stress on switching devices for the *n*-level FCBC is expressed by (26).

$$V_{sw(n-level)-\max} = \frac{1}{(n-1)}V_{out} + \frac{1}{2}\frac{P_{in}D}{V_{in}C_{fc1(n-level)-\min}f_{sw}} \quad (26)$$

IV. Experimental Results

In order to confirm the operation of the FCBC under the minimum capacitance of the flying capacitor and the maximum voltage stress on switching devices in the *n*-level FCBC, 3-level and 5-level FCBCs prototypes are constructed. The specifications of the experiment and simulation conditions are shown in Table 1.



(a) 3-level FCBC: C_{out} = 1.5 μF, C_{fc} = 1.1 μF

(b) 3-level FCBC: C_{out} = 1.5 μF, C_{fc} = 0.35 μF

(c) 5-level FCBC: C_{out} = 1.5 μF, C_{fc} = 1.1 μF

(d) 5-level FCBC: C_{out} = 1.5 μF, C_{fc} = 0.35 μF

Fig. 4. (a), (b): Experimental waveforms of the output voltage, the flying capacitor voltage and the inductor current in 3-level FCBC; (c), (d): Experimental waveforms of the flying capacitor voltage ripples and the output voltage ripple in 5-level FCBC.

Fig. 4 shows the experimental waveforms of the flying capacitor voltage ripples and the output voltage ripple when the output capacitance is 1.5 μF and the capacitances of the flying capacitors are 1.1 μF and 0.35

μF in the 3-level and 5-level FCBCs. From Fig. 4(a) and (b), it is confirmed that the peak-to-peak output voltage ripple is always 5.6 V at the 3-level FCBC although various capacitance of the flying capacitor are used. In addition, the output voltage ripple is always 5.6 V at both of the 3-level FCBC and the 5-level FCBC although various capacitances of the flying capacitor are used. These experimental results are agreed with the theoretical analysis in the section III whereby the relationship between capacitances of the flying capacitor and the output voltage ripple are independent.

Besides, Fig. 4 shows the flying capacitor voltage ripples in the 3-level and 5-level FCBCs when the capacitance of the flying capacitor of 1.1 μF and 0.35 μF are used. From these results, the flying capacitor voltage ripples are same when same capacitance of the flying capacitors is used. The flying capacitor voltage ripples are approximately 10 V and 29 V, respectively as shown in Fig. 4. Therefore, it is confirmed that the experimental result agrees with the theoretical analysis shown in the section III.

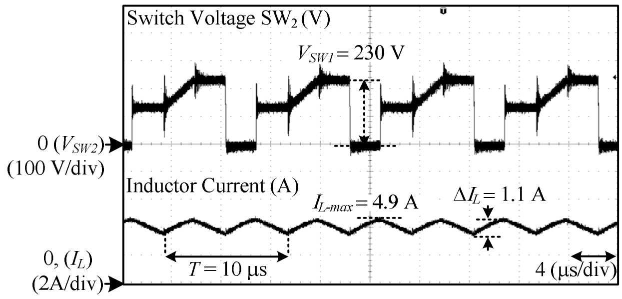
Fig. 5(a) shows the experimental waveforms of the voltage of the switch S_2 is 230 V when the capacitance of the flying capacitor which of 0.11 μF is used in the 3-level FCBC. Experimental value of the maximum voltage of the switch S_2 agrees with the calculated value which is 230 V by (13).

Besides, Fig. 5(b) shows the experimental waveform of the switch voltages S_1 and S_4 when the capacitance of the flying capacitor of 0.35 μF is used in the 5-level FCBC. The experimental maximum switch voltage of S_4 is 110 V. It is confirmed that the experimental value agrees with the calculated value based on (21).

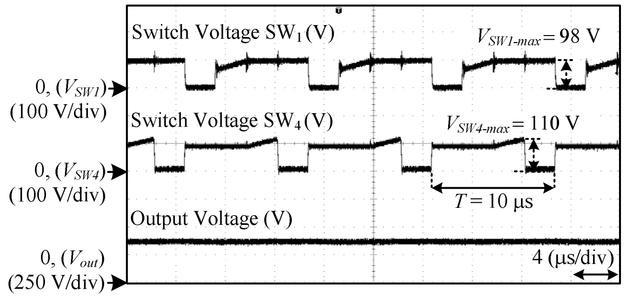
Furthermore, the voltage across a switching device is determined based on the flying capacitor voltage ripple and capacitance of the flying capacitor. Thus, the design method to determine the minimum capacitance for the flying capacitor was experimentally verified.

Fig. 6 shows the converter efficiency characteristics. The output voltage is fixed at 350 V. Several capacitances of the flying capacitor are considered for the efficiency measurement of the constructed prototype circuit. The achieved maximum efficiency is 98.5 % at the output power of 1 kW. In the heavy load region, the efficiency is almost same among the three conditions of the flying capacitor. On the other hand, the efficiency with the largest capacitance of the flying capacitor is higher than that of other conditions of the flying capacitor. This is because the switching loss under the largest capacitance of the flying capacitor is lower than that of other conditions due to low voltage stress of the switches.

Fig. 7 shows the power loss distribution of the 3-level FCBC for several output power when a capacitance of the flying capacitor is 1.1 μF and an output capacitance is 1.5 μF. The total power loss of 100 % (16.58 W) is based on the total power loss when the output power is 1 kW. The total power loss at the output power of 1 kW is a reference in Fig. 7. The major power loss is the diode conduction loss when the output power is 1 kW. Moreover, the ESR losses in the flying capacitor and



(a) 3-level FCBC



(b) 5-level FCBC

Fig. 5. (a) Experimental waveforms of the switch S_2 voltage and the inductor current in the 3-level FCBC; (b) Experimental waveforms of the switch voltages (S_1 and S_4) and the output voltage in the 5-level FCBC.

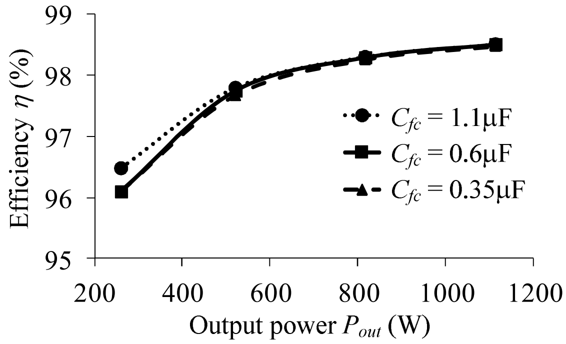


Fig. 6. Converter efficiency characteristic in 3-level FCBC

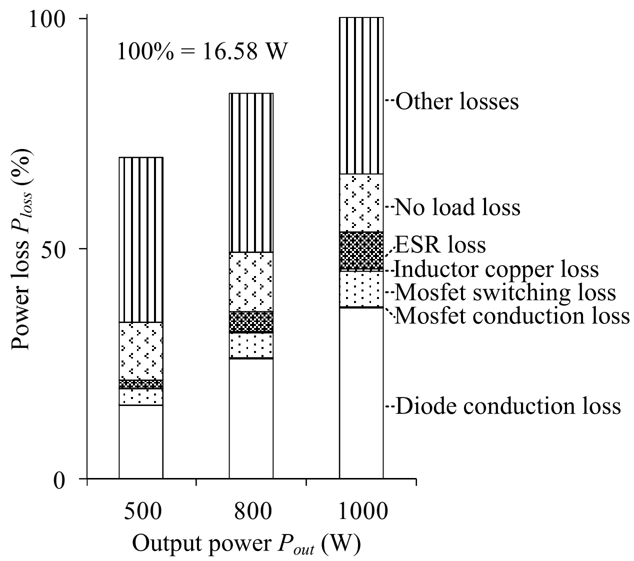


Fig. 7. Loss distribution in 3-level FCBC with various output powers

output capacitor can be further decreased by considering low ESR capacitors. In order to reduce the power loss in the MOSFETs when a high boost ratio is considered, low-on-resistance MOSFETs must be selected. As an option, the on-resistance can be further reduced by connecting the MOSFETs in parallel connection.

V. The Effectiveness of Small Capacitance of Flying Capacitor

A. Ripple voltage of the flying capacitor characteristic

Fig. 8 shows the relationship between flying capacitor voltage ripples and several capacitances of the flying capacitors in the 3-level and 5-level FCBCs. It is confirmed that each voltage ripple of the flying capacitors are same when same capacitance of the flying capacitor is selected in the 3-level and 5-level FCBCs although 5-level FCBC has different switching patterns and three different flying capacitor voltages. As a result, it is experimentally confirmed that the ripple voltage of the flying capacitor voltage does not depend on the number of level as shown in (25). Besides, it is confirmed that the flying capacitor voltage ripples is reduced with regard to the increasing capacitances of the flying capacitor as shown in (25).

The increasing of the flying capacitor voltage ripples will contribute into switching loss of the semiconductor switches. However the performance of high voltage semiconductor switches is improving recently. Therefore, high flying capacitor voltage ripple is acceptable although small capacitance of the flying capacitor is used.

The flying capacitor voltage ripples are same in the 3-level and 5-level FCBCs when same capacitance of the flying capacitor is considered even the number of the level is different. Therefore, the capacitance of the flying capacitor can be reduced by considering the constant ratio of the flying capacitor voltage ripples against capacitances of the flying capacitor. In order to design the minimum capacitance of the flying capacitors in the 5-level FCBC, (18)-(20) are referred.

B. Harmonics analysis of the voltage across the input voltage source and the input inductor, and the current to the output side in the 3-level and 5-level FCBCs

Fig. 9 (a) shows the experimental results of the k_{iout} which is the ratio between the effective values of distorted components I_{nfsw} against DC component I_{DC}, which is introduced in order to evaluate the distorted current to the output side which is the output capacitor and the load. The results show ratio of k_{iout} converges into a constant value with various capacitances of the flying capacitors. Therefore, the ratio of k_{iout} is not affected on the variation of capacitances of the flying capacitors although small capacitance is used. Thus, the small capacitances can be used for the flying capacitor in the 3-level and 5-level FCBCs.

Fig. 9 (b) shows the experimental results of the k_{vconv} which is the ratio between the effective values of distorted components V_{nfsw} against DC component V_{DC}, which is introduced in order to evaluate the distorted voltage across the input voltage source and the input inductor. It is confirmed that the ratio k_{vconv} is converges into a constant value when the capacitance of the flying capacitor is increased.

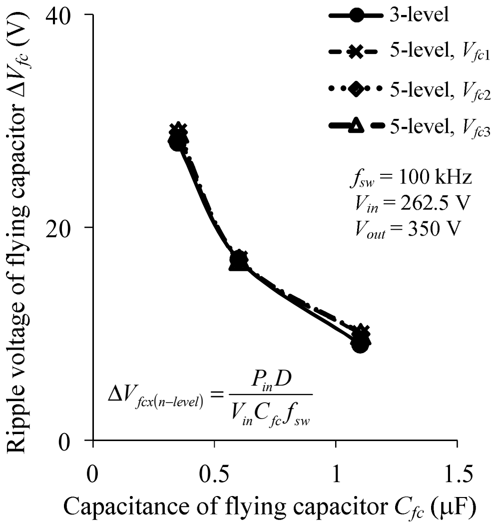
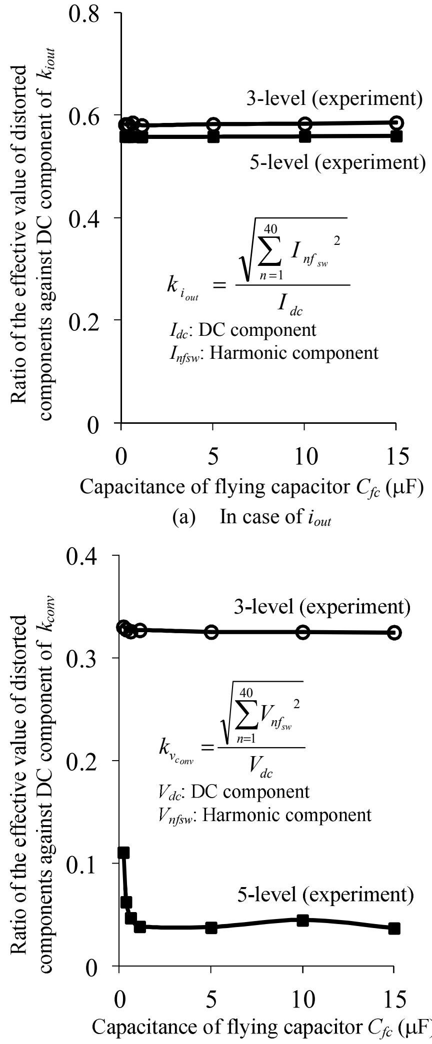
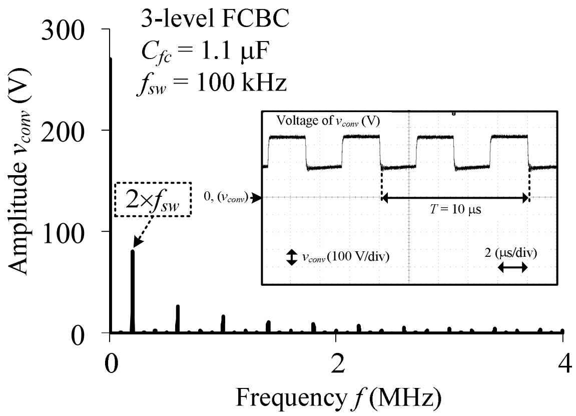


Fig. 8. Experimental results of the ripple voltage of flying capacitor with various of capacitances of the flying capacitors

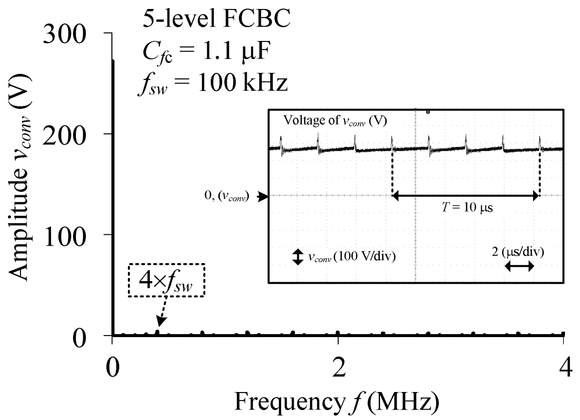


(b) In case of v_{conv}.

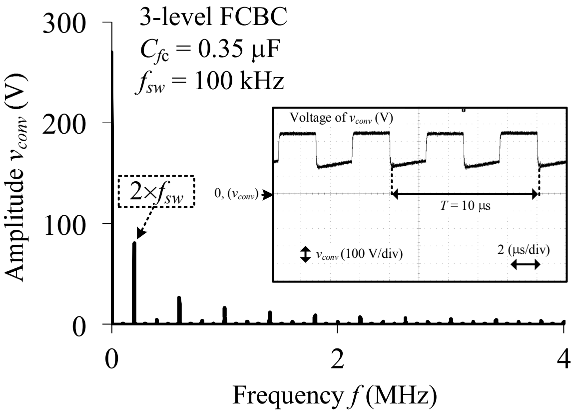
Fig. 9. Ratio of the effective value of distorted components against DC component



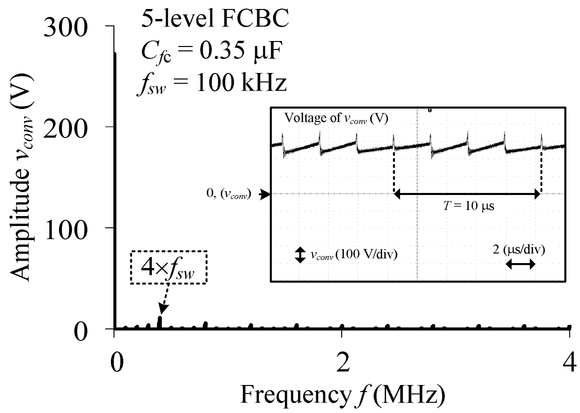
(a) 3-level FCBC: v_{conv} components, C_{fc} = 1.1 μF



(b) 5-level FCBC: v_{conv} components, C_{fc} = 1.1 μF

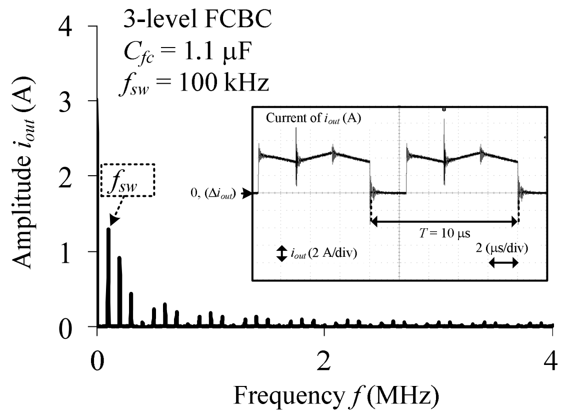


(c) 3-level FCBC: v_{conv} components, C_{fc} = 0.35 μF

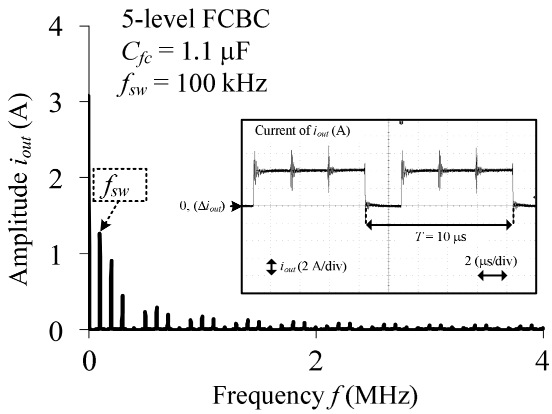


(d) 5-level FCBC: v_{conv} components, C_{fc} = 0.35 μF

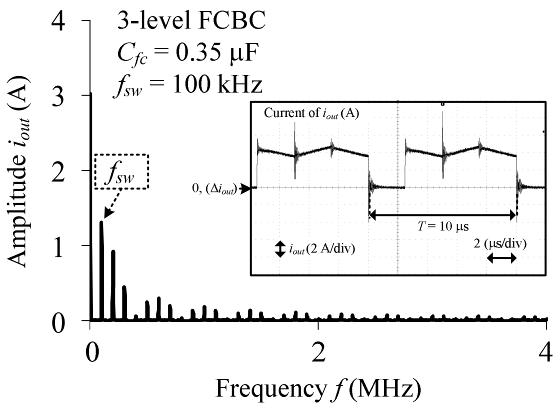
Fig .10. Harmonics components of v_{conv}



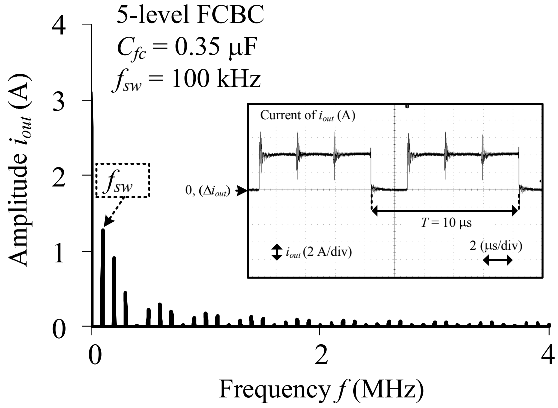
(a) 3-level FCBC: i_{out} components, C_{fc} = 1.1 μF



(b) 5-level FCBC: i_{out} components, C_{fc} = 1.1 μF



(c) 3-level FCBC: i_{out} components, C_{fc} = 0.35 μF



(d) 5-level FCBC: i_{out} components, C_{fc} = 0.35 μF

Fig .11. Harmonics components of i_{out}

From Fig. 9, the small capacitance can be used for the flying capacitor in both 3-level and 5-level FCBCs. From these experimental results, 5-level FCBC has obviously lower k_{vout} compared to the 3-level FCBC. Thus the k_{vout} has significant difference when the level is increased. Meanwhile, 5-level FCBC also has lower k_{Ix} compared to the 3-level FCBC. However the different is small.

C. Harmonics components of v_{conv} and i_{out} in the 3-level and 5-level FCBCs

Fig. 10 shows the harmonics spectrum of v_{conv} and i_{out} with various capacitances of the flying capacitors in the 3-level and 5-level FCBCs. For these experimental results, only two capacitances of the flying capacitors are selected which are 1.1 µF and 0.35 µF.

Fig. 10 (a), (b), (c) and (d) show the harmonics spectrum of v_{conv} in the 3-level and 5-level FCBCs. From these experimental results, 5-level FCBC has obviously lower harmonic components compared to the 3-level FCBC when capacitances of 1.1 µF and 0.35 µF for the flying capacitor are used.

Meanwhile, Fig. 11 (a), (b), (c) and (d) show the harmonic components of i_{out} in the 3-level and 5-level FCBCs. From these results harmonics spectrum, the patterns between 3-level and 5-level FCBCs are almost same. The difference of harmonic components is not obvious because the ripple current of i_{out} is not different from between two FCBCs due to their operation modes.

VI. CONCLUSIONS

In this paper, the authors revealed the minimum capacitance of the flying capacitor consideration in multi-level FCBC based on the switching device voltage rating. Moreover, the relationship between the capacitance of the flying capacitor and the output voltage ripple is independent of each other and it was confirmed by simulation and experimental results. Meanwhile, the minimum capacitance based on the maximum voltage rating of switching devices was confirmed by the experimental results in the 3-level and 5-level FCBCs. Besides the expression clarification in order to design minimum capacitance of the flying capacitor in the *n*-level FCBC is also shown. The maximum efficiency of the 3-level FCBC prototypes with a small capacitance of the flying capacitor is 98.5 % at the output power of 1 kW. Then, the distortion of the voltage across the input voltage source and the input inductor is measured. In addition, the distortion of the current to the output side which is the output capacitor and the load is also measured. As a result, it is experimentally confirmed that a small capacitance of the flying capacitors can be used in the 3-level, 5-level and *n*-level FCBCs.

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