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Enhanced voltage conversion and reduced inductor size in a flying capacitor boost converter compared to conventional boost converter for photovoltaic systems

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ABSTRACT

In photovoltaic (PV) systems, conventional boost converters (CBCs) face limitations at high-duty cycles, including low voltage conversion ratio (VCR), high voltage stress, and reduced efficiency. While magnetic coupling components can enhance VCR, they introduce drawbacks such as reduced power rating and leakage current. To overcome these challenges, this paper proposes the flying capacitor boost converter (FCBC) as an alternative for PV systems. We analyze the performance of CBCs, FCBCs, and multilevel boost converters through MATLAB/SIMULINK simulations. The results demonstrate that the FCBC achieves a significantly higher VCR, requiring a smaller inductor size and potentially exhibiting a smoother output voltage compared to the CBC. Furthermore, the paper explores the trade-offs in complexity and cost associated with the FCBC, highlighting its advantages for high-voltage applications. Future research will focus on a comprehensive analysis of efficiency, control complexity, and the scaling of FCBCs to higher levels.

1. Introduction

In recent years the need for renewable energy sources has led to growing interest because it produce minimal air and water pollution, protect ecosystems and public health, do not produce greenhouse gases during operation, mitigate climate change and improve air quality, have lower operating costs than fossil fuels, as they do not require expensive fuel purchases, reduces dependence on foreign energy imports, enhancing national security and energy independence [1]. The renewable energy sector is a rapidly growing industry, creating numerous job opportunities in manufacturing, installation, and maintenance, and others. DC-DC converters are indispensable components in renewable energy systems, facilitating efficient power conversion, voltage matching, regulation, and overall system integration.

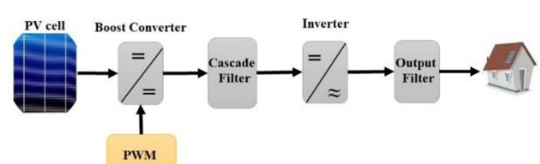

Figure 1. PV solar system

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They play a key role in enabling the reliable and effective use of renewable energy sources, contributing to a sustainable and clean energy future. One remarkable topology which is vital in renewable energy sources is the boost converter where the voltage generated by the source needs to be increased to meet the requirements of the load or the grid see Fig.1, [2-3]. Boost converters are vital for matching voltage levels between the source and the load/grid, maximizing power extraction from renewable energy sources, improving power quality by reducing ripple and noise, and enhancing overall system efficiency and cost-effectiveness. The two-level conventional boost converter, illustrated in Fig. 2, is a cost-effective and efficient solution for voltage step-up applications. It features a relatively simple circuit design, can achieve high efficiency, and its components are readily available and affordable [4-5].

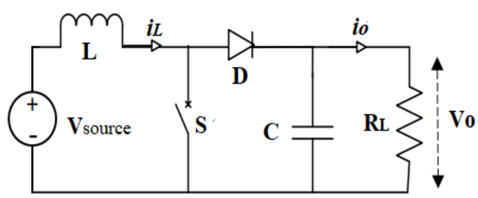


Figure 2. Two-level Conventional Boost converter [7]

The inherent limitations of conventional boost converters, specifically low voltage conversion ratio, and high switch voltage stress, have motivated the development of alternative topologies such as multilevel boost converters and flying capacitor boost converters. The flying capacitor boost converter (FCBC) is an advanced DC-DC converter topology that utilizes additional capacitors to achieve higher voltage gain. The capacitors can offset the output voltage by Vo/2 in both a positive and negative direction, reducing voltage stress on the main switch compared to traditional boost converters. The FCBC is particularly beneficial in applications requiring high voltage conversion ratios and operating with high power levels, such as smart grid systems, electric vehicle charging, and industrial applications, see Fig. 3 [6-8].

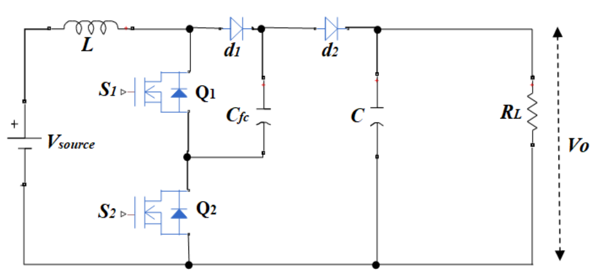


Figure 3. Flying capacitor Boost converter [9]

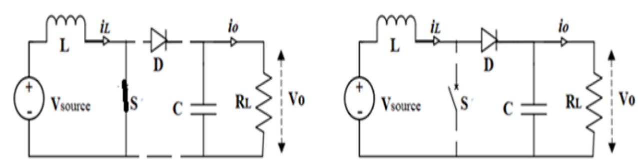
Optimizing the design of a flying capacitor boost converter involves finding ideal values for various parameters to achieve desired performance characteristics such as high voltage gain, compact size, low component count, lower voltage and current ripple, lower switching losses, and low EMI emission [10-11].

The paper is organized into the following sections: Section 2 presents a description of conventional, multilevel, and flying capacitor Boost converter topologies. Section 3 outlines the simulation methodology implemented in the MATLAB environment. Finally, Section 4 concludes with a summary of the results, a discussion of their implications, and overall conclusions.

2. Boost Converter Design

2.1 Conventional boost converter

The conventional boost converter is a type of DC-DC converter that increases the voltage of a DC power supply. It works by storing energy in an inductor during a "switch-on" phase and then releasing that energy into the output during a "switch-off" phase. This process creates an output voltage that is higher than the input voltage. Conventional boost converters are commonly used in various applications, such as powering devices from low-voltage sources, generating higher voltages for LED lighting, and increasing the voltage in solar panels. The principle of a two-level conventional boost converter is illustrated in Fig. 4 [12].



a) Switch ON **b) Switch Off**

Figure 4. The operational modes of conventional Boost converter

From Fig. 4, we can obtain a set of dynamic equations for both states (ON, Off) [7]:

$$L\frac{di}{dt} = -(1-D)V_O + V_{source}; \quad D=1 \rightarrow On; \; D=0 \rightarrow Off$$
$$C\frac{d}{dt}V_O = (1-D)i - \frac{V_O}{R(L)} \tag{1}$$

In a boost converter, the relationship between input and output voltage can be expressed as:

$$D = \frac{(V_O - V_{source})}{V_O}; \quad 0 < D < 1 \tag{2}$$

From this equation, we obtain the voltage conversion ratio (VCR) β, which can be expressed as:

$$\beta = \frac{V_O}{V_{source}} = \frac{1}{1-D} \tag{3}$$

The inductance and capacitance of a conventional boost converter can be calculated by [8]:

$$L(conventional) = V_{source} * \frac{D}{\Delta I(L) * f(sw)} \tag{4}$$

$$C(conventional) \approx I_O * \frac{D}{\Delta V_O * f(sw)} \tag{5}$$

Where L inductance, $V_{(source)}$ input voltage, V_o Output voltage, D duty cycle, $f_{(sw)}$ switching frequency, $\Delta I_{(L)}$ inductance current ripple (3-5 % of output current), C capacitance, ΔV_o voltage ripple (3-5 % of output voltage).

Conventional Boost converter is a valuable term in power electronics, but it suffers from some limitations that can limit its effectiveness, especially voltage gain which is directly proportional to the duty cycle of the switch and switch stress.

2.2 Multilevel boost converter

A multilevel boost converter is a type of DC-DC converter that uses multiple boost stages (two or more) connected in series to achieve a high voltage gain. It offers several advantages over conventional boost converters, particularly in applications requiring high power levels and high voltage boosts. The circuit diagram of the multilevel boost converter can be seen in Fig. 5 [13-14].

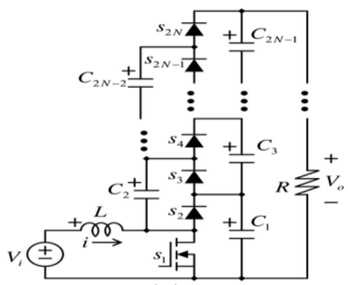


Figure 5. Multilevel boost converter [14]

The multilevel boost converter can be considered an extension of the conventional boost converter, formed by adding switched capacitors at the output, see Fig. 5 which illustrates an N-level boost converter with an added diode-capacitor circuit that multiplies the conventional output voltage by the number of capacitors at the output of the converter [15].

Figure 6 illustrates the multiplication process: when S is ON, C_3 is connected in parallel with C_1; when S is OFF, C_3 is connected in parallel with C_2, fulfilling a high gain without extreme duty cycles [16].

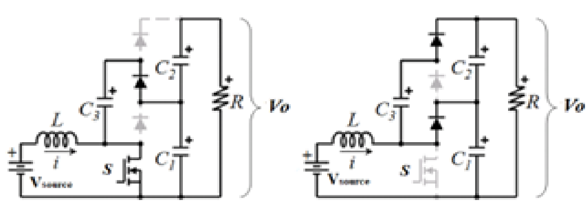


Figure 6. Modes of multilevel Boost converter (2 level)

The dynamic equations for both states (ON, Off) for multilevel Boost converter is:

$$L\frac{di}{dt} = -(1-D)v_1 + V_{source}; \quad D=1 \rightarrow On; \ D=0 \rightarrow Off \tag{6}$$

$$C_1\frac{d}{dt}v_1 = (1-D)i - \frac{(v_1 - v_3)}{R_{C1}}D - \frac{(v_1+v_2)}{R} \tag{7}$$

$$\begin{aligned} C_2\frac{d}{dt}v_2 &= (1-D)\frac{(v_3-v_2)}{R_{C2}} - \frac{(v_1+v_2)}{R}; \\ C_3\frac{d}{dt}v_3 &= (1-D)\frac{(v_3-v_2)}{R_{C2}} + \frac{(v_1-v_3)}{R}D \end{aligned} \tag{8}$$

Where R_{C1} and R_{C2} denote the equivalent resistances observed across the capacitors during the switch-closed and switch-open states, respectively.

2.3 Flying capacitor boost converter

The FCBC is a more advanced topology that can overcome the limitations of conventional boost converters, especially in high-voltage and high-power applications. It can achieve high voltage gain and low switch stress by employing a series of capacitors and switches. The FCBC also has a smaller size and weight. It can also offer other benefits such as low EMI (electromagnetic interference) because of energy transfer through multiple stages, which enables the minimization of EMI generation. This results in cleaner operation and less electromagnetic noise is beneficial for sensitive applications and reduces potential interference with other devices. This converter is presently employed in numerous applications such as AC LED drivers [17], electric vehicles [8], [18-19], and photovoltaic applications [4], [20] and has an efficient performance.

However, this interesting circuit also offers a series of challenges during the design process since each capacitor plays a significant role in the operation of the converter, and choosing the correct values is crucial. The number of voltage levels in an FCBC is theoretically unbounded. However, practical considerations often limit the number of levels to three, four, or five, see Fig. 7.

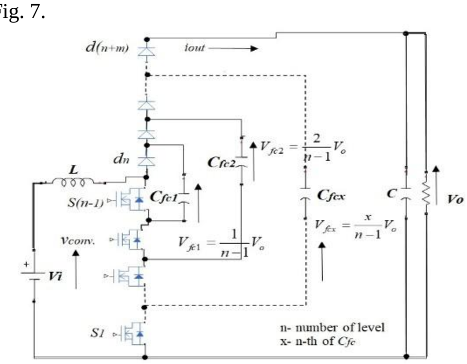


Figure 7 The n-level FCBC

The inductance and the volume of the inductor in n-level FCBC can be calculated by:

In this paper, we will consider the 3-level FCBC. The principle of the FCBC with its switching pattern is illustrated in Fig. 8 and Fig. 9

Two phase-shifted (180°) carrier signals are compared with a duty cycle signal (D) to generate triggering signals (S_1 & S_2), as shown in Fig. 8 and Fig. 9, and Table 1[19-22].

$$L_{(n\ level)} = \frac{L_{(CBC)}}{(n-1)^2}; \tag{9}$$

$$Volume_{(n\ level)} = \left(\frac{1}{(n-1)^2}\right)^{0.75} * Volume_{(conventional)} \tag{10}$$

Table 1. Triggering signals of Q1 and Q2

Duty Cycle	Switching Sequence of S_1& S_2
$D < 0.5$	$\{10, 00, 01, 00, and\ 10\}$
$D > 0.5$	$\{10, 11, 01, 11,\ and 10\}$
$D = 0.5$	$\{10, 01,\ and 10\}$

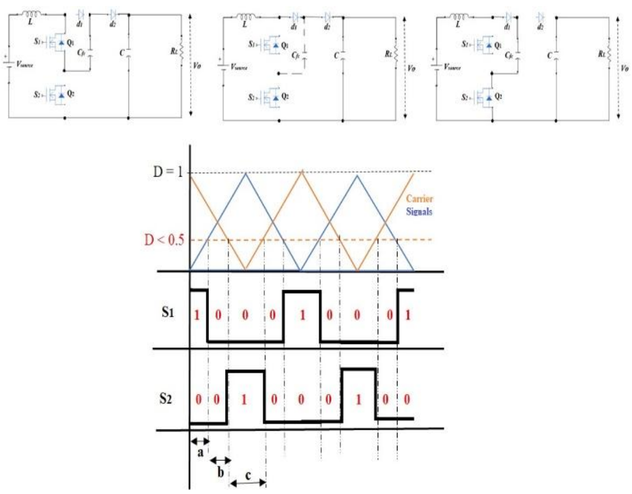


Figure 8. D < 0.5. (a) $S_1, S_2 = 10$. (b) $S_1, S_2 = 00$. (c) $S_1, S_2 = 01$.

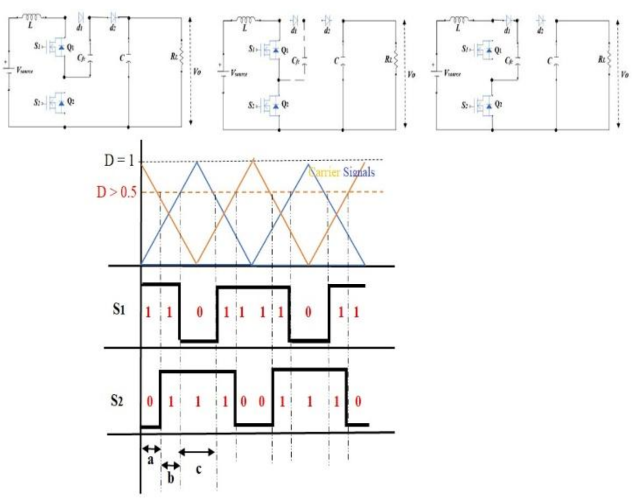


Figure 9. D > 0.5. (a) $S_1, S_2 = 10$. (b) $S_1, S_2 = 11$. (c) $S_1, S_2 = 01$

A 180° phase shift is employed to ensure equal charging and discharging intervals for the boost inductor during each switching cycle. The charging time of the input inductor is a function of the duty ratio and the two carrier signals. The state of the output voltage, according to the mode of the switching process, can be summarized in **Table 2** [7].

Table 2. Relationship between VCR and the output voltage

Duty Cycle	Conversion ratio β	Output Voltage
$D < 0.5$	$0 < \beta < 2$	less than double
$D = 0.5$	$\beta = 2$	Double
$D > 0.5$	$\beta > 2$	More than double

According to Eq. 3 and Table 2, we can compare the VCR in conventional boost converters and flying capacitor boost converters, see Fig. 10.

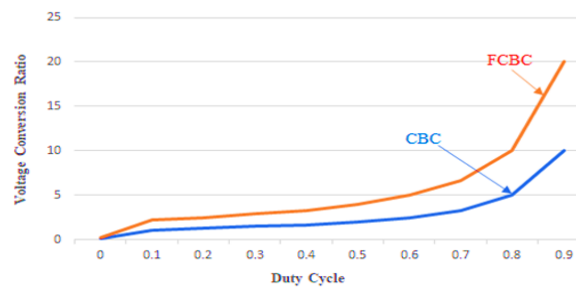


Figure 10. VCR Comparison between CBC and FCBC with respect to duty cycle

The value of the inductor and capacitor of FCBC can be calculated from [7], [9] [21-22] respectively. The inductance of 3-level FCBC is:

$$L(3\ level) = V_O \frac{1}{16 * \Delta I(L) * f(sw)} \tag{11}$$

A comparative analysis of a 3-level FCBC and a 2-level CBC, both with identical component parameters, reveals that:

$$\frac{L(3level-FCBC)}{L(2level-CBC)} = \frac{\dfrac{V_O}{16 * f(sw) * \Delta I_L}}{\dfrac{V_O}{4 * f(sw) * \Delta I_L}} = \frac{1}{4} \tag{12}$$

$$L(FCBC) = 0.25 L(CBC)$$

Using equation (10) we can calculate the volume of inductor of 3-level FCBC:

$$Volume(3\ level) = \left(\frac{1}{(3-1)^2}\right)^{0.75} * Volume(conventional) = 0.35 Volume(conventional) \tag{13}$$

Therefore, when working with 3-level FCBC we reduce the volume of the inductor by 35% with respect to 2-level CBC.

A crucial aspect of flying capacitor boost converter design is the proper selection of the capacitor's size. To minimize voltage fluctuations and ensure stable operation, a sufficiently large capacitor is necessary. This selection involves considering the switching frequency and the maximum tolerable voltage ripple. The formula for calculating capacitance is:

$$C(3\ level) = \frac{V_0}{2 * R * \Delta V_c * f(sw)} \tag{14}$$

The 3-level FCBC architecture results in a substantial reduction in the boost inductor's size compared to a 2-level CBC. This, combined with the presence of the flying capacitor, effectively mitigates input inrush current. The inductance of the boost inductor in a 3-level FCBC is reduced by a factor compared to a 2-level CBC (0.25 of the original value). This reduction in inductance leads to a decreased number of turns in the wind, resulting in reduced copper losses.

$$\Delta i_L = \frac{V_{source}\left(V_O - 2V_{source}\right)}{2 * L * V_O * f(sw)} \quad (15)$$

The voltage of flying capacitor can be calculated according to:

$$V_{fcx(n-level)} = \frac{x * V_O}{(n-1)}; \;\; x - \text{number of flying capacitor} \quad (16)$$

The output voltage ripple for 3-level FCBC is [7]:

$$\Delta V_O = \frac{V_O}{R_L} * \frac{D}{C_2 * f(sw)} \quad (17)$$

Evaluating equation (3) in equation (16) we have:

$$\Delta V_O = \frac{P_O(1-\beta)}{V_O * \beta * C_2 * f(sw)} \quad (18)$$

Equation (17) demonstrates that the output voltage ripple is independent of the flying capacitor. For a stable output voltage, the output time constant (*Rout* * *Cout*) must be less than the switching frequency *f(sw):*

$$R_L * C_2 = \frac{V_O^2}{P} * C_O > \frac{1}{f(sw)} \quad (19)$$

In conclusion, a comparison between CBC and CFBC from one side, and multilevel BC and FCBC from another side is formed as in Table 2, Table 3.

Table 3. Comparison between conventional Boost converter and flying capacitor Boost converter

Type	CBC	FCBC
Structure	Contains an inductor, switch, diode, and output capacitor.	Contains multiple stages, each stage has a capacitor, switch, and diode.
Voltage gain	Depends upon duty cycle *D*.	Has a higher voltage gain, proportional to the number of stages.
Complexity	Simple design	Complex design
Cost	Lower due to fewer components	higher cost
Efficiency	higher due to fewer switching elements and less energy loss	Lower
Control	Simple controller due to one switch in use	More complex controller
Applications	Widely used in applications requiring moderate voltage Boosts	In systems with high voltage gain
Duty cycle	The duty cycle of the switch in a conventional Boost converter directly controls the output voltage.	The duty cycle in a flying capacitor Boost converter plays a less direct role in controlling the output voltage. The output voltage is primarily determined by the number of stages and the voltage across each stage's capacitor.

Table 4. Comparison between multilevel Boost converter and flying capacitor Boost converter

Type	Multi-level Boost converter	FCBC
Structure	Multiple Boost stages in series.	Multiple capacitor stages in series.
Voltage gain	High, achieved by cascading stages.	High, proportional to the number of stages.
Complexity	More complex due to multiple stages and control.	More complex due to multiple stages and complex synchronization.
Cost	Higher due to more components and potentially more complex control	Higher due to more components and complex control
Efficiency	Can be high, depending on the implementation.	Generally lower due to multiple switching stages.
Control	Independent control of each stage.	Complex synchronization of stages.
Applications	High-power applications.	High-voltage applications.
Duty cycle	Each stage has its own independent duty cycle. Each stage is controlled individually to achieve the desired voltage gain and output regulation.	The duty cycle is used primarily for synchronization and efficient energy transfer between stages. The duty cycle of each stage is carefully synchronized to ensure that the capacitors charge and discharge efficiently, without causing voltage spikes or losses.

Finally, quantitative comparisons between CBC and FCBC efficiency can illustrate the remarkable improvements as in Table 4.

3. Simulation process

A comparative analysis of component values for the Conventional Boost Converter (CBC) and the Flying Capacitor Boost Converter (FCBC) is provided in Tables 5 and 6. Performance assessment was achieved through MATLAB/Simulink modeling and simulation, with the results presented in Fig. 11 to Fig.23.

Table 5. Quantitative comparisons between CBC and FCBC efficiency

Term	CBC	FCBC
Switching Losses	Typically have lower switching losses due to a single switching element. The losses are primarily dependent on the switching frequency, on-state resistance of the switch, and the switching current.	Have multiple switching elements, which can increase switching losses. However, the switching frequency can be lower in an FCBC for the same voltage gain, mitigating some of this increase.
Conduction Losses	Conduction losses are primarily due to the current flowing through the switch, diode, and inductor. These losses are proportional to the square of the current and the resistance of the components.	Have additional conduction losses in the flying capacitors, diodes, and switches within each stage. However, the current in each stage is typically lower than in the CBC due to the distributed current flow.
Other Losses	Additional losses include	Have similar additional

	core losses in the inductor, gate drive losses, and parasitic losses in the components.	losses, but the distribution of current and voltage can affect the magnitude of these losses.
Potential Trade-offs	Low voltage conversion ratio(VCR)	Generally, achieve higher VCRs
Inductor size	Big size	Smaller sizes can reduce core losses and potentially improve efficiency.
parasitic losses	Lower due to low component count.	The increased component count in FCBCs can contribute to higher parasitic losses and potentially lower overall efficiency.

Table 5. Parameters value CBC

Parameter	**Value**
Input Voltage V_{Source}	$12V$
Output Voltage Vo	$24V$
Duty cycle D	0.5
Inductor value L	$76.8\ \mu H$
Output Capacitor C	400μ
Switching frequency fsw	$50000Hz$
Load resistance RL	4Ω

Table 6. Parameters value for FCBC

Parameter	Value
Input Voltage V_{Source}	12V
Output Voltage Vo	48V
Duty cycle D	0.67
Inductor value L	$1\ \mu H$
Output Capacitor C	350μ
Flying capacitor value Cfc	$7.5\ \mu F$
Switching frequency fsw	$50000Hz$
Load resistance RL	4000Ω

The circuit of the CBC without a controller, using a fixed duty cycle, is shown in Fig. 11, while the output is shown in Fig. 12.

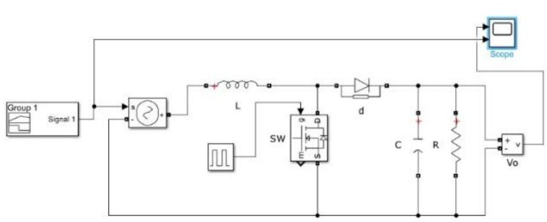


Figure 11. Conventional Boost converter

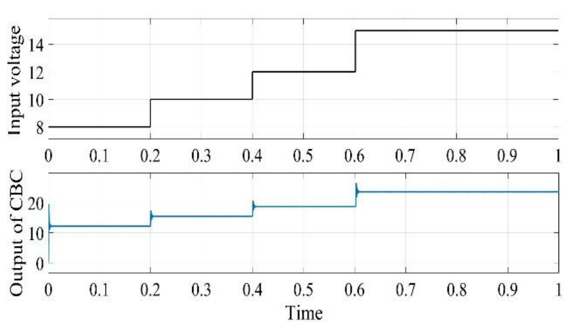


Figure 12. Conventional Boost converter output without controller

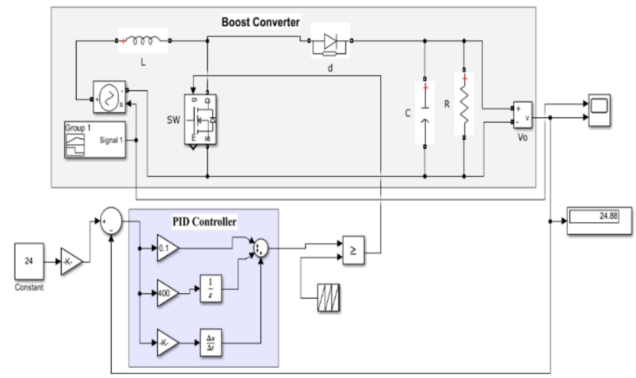


Figure 13. CBC with PID Controller

From Fig. 12, we notice that the output voltage is doubled and unstable. When the input is 10V, the output is 20V; when the input is 12V, the output is 24V; and finally, when the input is 15V, the output is 30V. This behavior is due to the value $0 \le \beta \le 2$, see Table 2. Now if we use PID controller with CBC, see Fig.13 the output now is stable (around 24V) but still double, see Fig. 14. The first scenario to increase the VCR is to use multi-level BC as in Fig. 15. The output of the multi-level BC can be seen in Fig.16. In this type we use a 3- level boost converter.

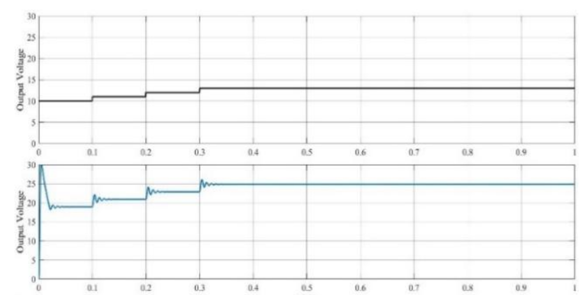


Figure 14. CBC with PID controller

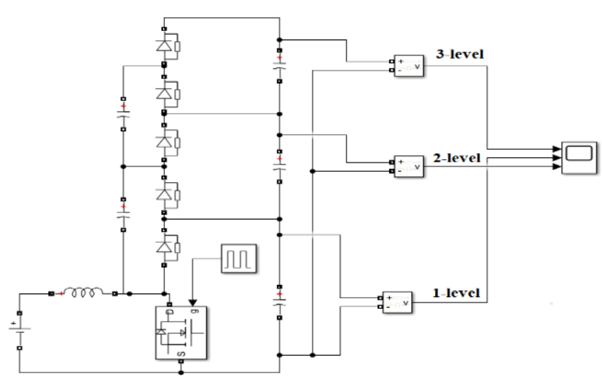


Figure 15. Multilevel Boost converter (3 level)

In this case, the first stage increases the output voltage by a factor of two, the second stage by a factor of three, and the third stage increases the output by a factor of four, see Fig. 16. The first scenario is to use the basic FCBC, see Fig. 17. The first case in this scenario uses a fixed input with fixed switching signals (shifted by 180°) as shown in Fig. 18. In this case, see

Table 2, with a duty cycle of 0.7, the VCR is equal to 0.3, and the output will be as shown in Fig. 19. The second scenario is to use two carrier signals phase-shifted by 180° as previously mentioned in boost converter design, see Fig. 20.

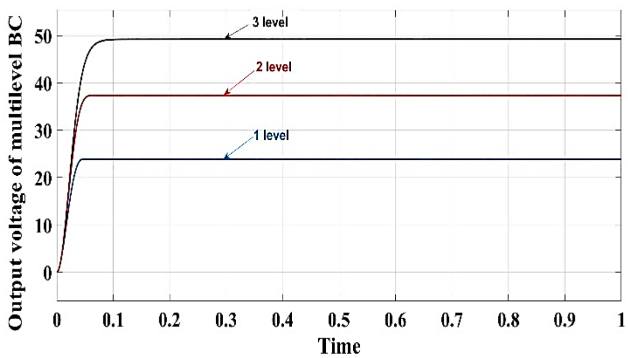


Figure 16. Multilevel boost converter (3 levels) output

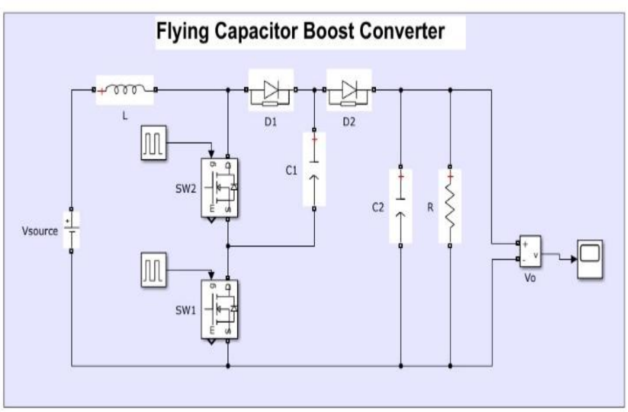


Figure 17. Basic FCBC

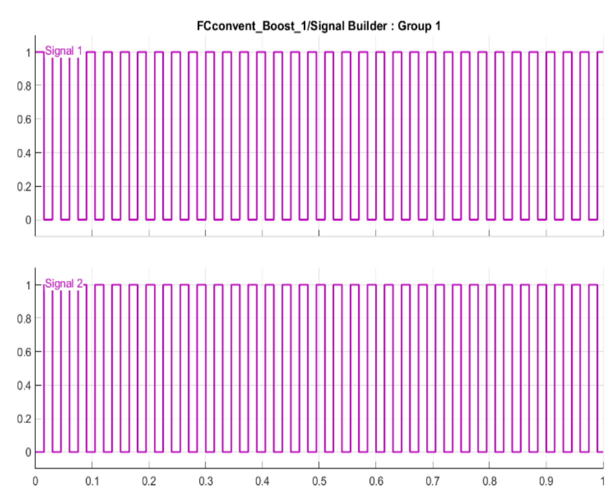


Figure 18. Switching signals of basic FCBC

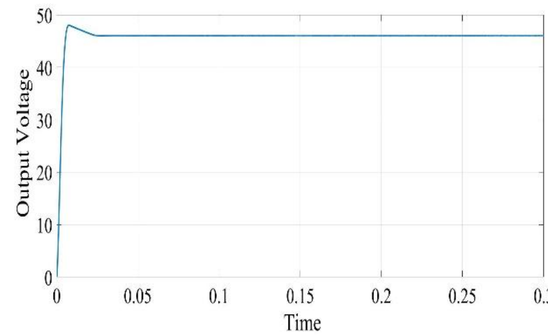


Figure 19. Output of basic FCBC

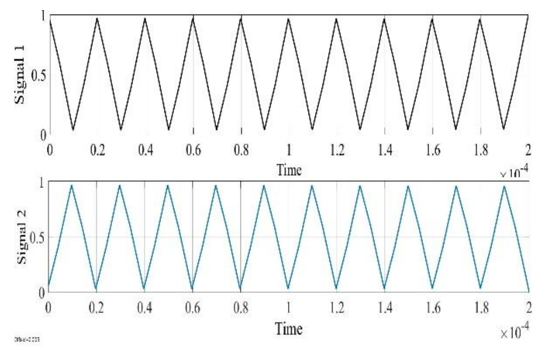


Figure 20. Carrier signals

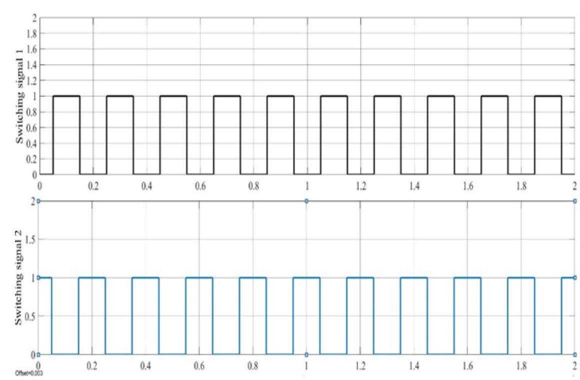


Figure 21. Switching signal of FCBC

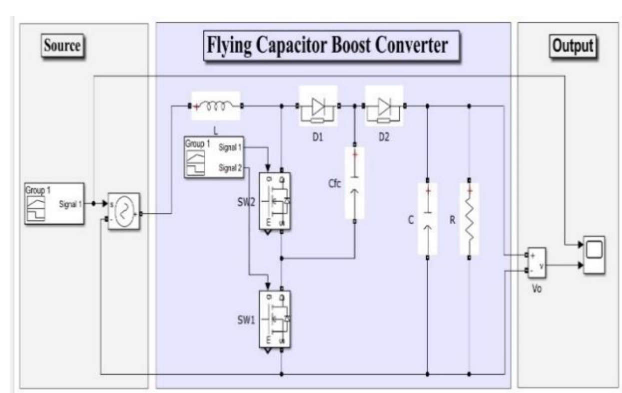


Figure 22. Voltage conversion ratio in FCBC with variable input and duty cycle

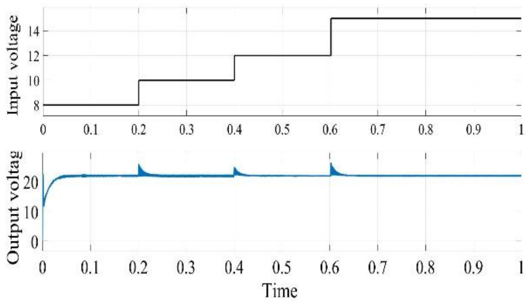


Figure 23. Output of FCBC with variable input

The switching signals to SW_1 and SW_2 are illustrated in Fig.21. The FCBC with variable input voltage 12-15 V, can be seen in Fig. 22, while the waveform is illustrated in Fig. 23. From Fig. 23, we can see that when the input voltage is equal to 12V, the output will stabilize at 48V after 0.0045 seconds. Increasing the input voltage further will not change the output voltage, and the converter will remain stable at 48V.

4. Results and discussion

This paper effectively demonstrates the advantages of using a Flying Capacitor Boost Converter (FCBC) compared to a Conventional Boost Converter (CBC) in photovoltaic (PV) systems. From the simulation process, we conclude the following:

1) Enhanced Voltage Conversion Ratio (VCR):The FCBC achieves a significantly higher VCR than the CBC for the same duty cycle. This is shown in Fig. 11 and further validated in the simulations (Fig. 22). The paper highlights that the VCR in the FCBC is proportional to the number of stages, leading to a greater voltage boost. This allows for higher output voltage from the PV system with less demanding duty cycle requirements, potentially increasing efficiency and reducing switching losses.
2) Reduced Inductor Size and Volume: FCBC advantage: The 3-level FCBC requires a substantially smaller inductance compared to the 2-level CBC (equations 12 and 13). This translates into a smaller inductor core volume (equation 13), which benefits the physical design of the converter. Smaller inductors mean reduced weight, size, cost, and potentially lower copper losses. This makes the FCBC more attractive for compact, lightweight PV systems.
3) Lower Output Voltage Ripple: While the paper doesn't directly compare the output voltage ripples between CBC and FCBC, it highlights that the ripple in the FCBC is independent of the flying capacitor (equation 17). This implies a potentially smoother output voltage, leading to significant performance for sensitive loads.
4) Simulation results: The simulations in MATLAB/Simulink validate the theoretical analysis of both CBC and FCBC (Figures 11-22). This provides a crucial visual representation of the key advantages of the FCBC. The paper shows that a PID controller can be implemented for the CBC (Fig.12), demonstrating the potential for improving performance and stability. However, it would be beneficial to include a similar control implementation for the FCBC to facilitate a direct comparison.

The limitations of this work and future proposal work are listed below:

a. For a more realistic and comprehensive assessment of the converters' performance incorporating real-world factors such as component tolerances, switching losses, and parasitic elements can be considered.
b. While the paper mentions the potential for higher efficiency, it doesn't provide a direct comparison of efficiency between the CBC and FCBC. A detailed analysis of efficiency, taking into account switching losses and conduction losses, would be valuable.
c. The paper discusses the higher cost of the FCBC due to more components, but a more thorough cost analysis would be beneficial.
d. The paper focuses on a 3-level FCBC. It would be valuable to extend the analysis to higher-level FCBCs to investigate the trade-offs in performance, complexity, and cost as the number of stages increases.

5. Conclusion

This paper demonstrates the advantages of using a Flying Capacitor Boost Converter (FCBC) compared to a Conventional Boost Converter (CBC) in photovoltaic (PV) systems. The FCBC achieves a significantly higher voltage conversion ratio (VCR) for the same duty cycle. Simulation results show the FCBC can achieve a VCR of 4, while the CBC only achieves a VCR of 2 with a similar duty cycle. This allows for higher output voltage from the PV system with less demanding duty cycle requirements, potentially increasing efficiency (around 95%) and reducing switching losses. Furthermore, the inductance of the 3-level FCBC significantly was reduced compared to the 2-level CBC, leading to a reduced inductor core volume by approximately 35%. This translates into a smaller inductor, which benefits the physical design of the converter, reducing weight, size, and cost, and potentially lowering copper losses.

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