High gain multiphase boost converter based-on capacitor clamping structure

Oday Saad Fares, Jasim Farhood Hussein
Department of Electrical Engineering, University of Technology, Baghdad, Iraq

Article Info

Article history:
Received Jun 14, 2021
Revised Aug 31, 2021
Accepted Sep 4, 2021

Keywords:
Capacitor clamping structure
DC-DC converter
High voltage gain
Multiphase boost converter

ABSTRACT
In the last few years, the non-isolated dc converters involving high voltage gain with adequate performance are becoming quite popular in industrial applications. This is resulting in high voltage and current stress on the power device (switches and diodes), as well as a limited output voltage with a high duty cycle. This paper proposes a multi-phase non-isolated boost converter that uses capacitor clamping to increase output voltage while reducing stress across the power device. There are two stages in the proposed converter (first stage is three inductors and three switches and the second stage is clamper circuit of three capacitors and three diodes). The proposed converter is high voltage gain, with low voltage stress through switches transistors. To justify the theoretical analysis, the concept was validated through mathematical analysis and by simulation using MATLAB/SIMULINK. The results carried out the results permit the converter behavior and performance to be accurately.

This is an open access article under the CC BY-SA license.

Corresponding Author:
Oday Saad Fares
Department of Electrical Engineering
University of Technology, Baghdad, Iraq
Email: eee.19.20@grad.uotechnology.edu.iq

1. INTRODUCTION
Due to its sustainable and endless source supply nature, renewable energy sources (photovoltaic, fuel cells, and uninterruptible power supply (UPS)) are developed continuously and swiftly replenished, and it is employed in remote places. The output voltage of these energy sources is still much lower than a direct current (DC) system requirement [1]-[3]. On the other side The large input current ripple, on the other hand, shortens the lifetime of photovoltaic (PV) and fuel cells [3]-[5]. High current ripple and unregulated low voltage are two major drawbacks of adopting renewable energy sources. As a result, in recent years, numerous approaches have been presented to achieve high voltage gain, reduced current ripple, component size reduction, and increased efficiency [1]-[25].

The traditional boost converter concept can be thought of as a basic key to suggesting a DC voltage boosting device. The typical boost converter, on the other hand, has some shortcomings, such as high input current ripple, voltage gain limitation, high current stress, and low efficiency. Another disadvantage of standard DC converters is that they have the biggest conduction losses due to the switching system, which is a major issue that affects the converter output power [6]-[8]. The used of high frequency pulsewidth modulation (PWM) topology is very important to increase voltage gain, reduce losses, ripple and component siz [9]-[11].

The multiphase switching inductors technique used as first stage is essentially a mix of three ordinary DC converters connected in a parallel layout. Because of the benefit of current redistribution among the phases, this configuration can reduce output voltage and input current ripple but the voltage conversion
ratio still the same of conventional converter. Because the input current is shared according to multiphase in parallel, the multiphase switching approach has a faster transient response due to low switching losses. This benefit reduces their switching losses, increasing efficiency, and it also reduces current stress. In addition, due to the input distributed current, the size and component rating are lowered [12]-[15].

Using a clamber capacitor circuit in the second stage provides the following advantages:

a) A huge voltage spike was limited across switches by the passive clamp function [16].

b) Low voltage stress, high voltage gain and low input current ripple [17]-[20].

c) There is extra gain adding to main dc boost converter [21]-[25].

This paper offers a three-channel boost converter DC converter based on a capacitor clamping circuit. The capacitor clamping side achieves the high voltage gain. This design will provide low ripple at the input (current and voltage) and output (current and voltage) sides, as well as minimize switch element stress to the (Vout/3) lower than the output voltage.

2. THREE PHASE BOOST CONVERTER BASED-ON CAPACITOR CLAMPING OPERATION IN (CCM) MODE

Figure 1 is present the proposed converter. It is constituted by three channels inductors and capacitor clamping structure. The proposed converter consists of three shared inductors and switches that controlled by three PWM operation signals with 120-degree phase shift between them. The suggested converter has six modes of operation. The following is a discussion of the converter operating in continuous conduction mode during the steady state for one period.

![Diagram](image)

**a)** Operational mode I: is shown in Figure 2. The three switches (S1, S2, and S3) are turned ON. Thus, the diodes D1, D2, and D3 tended to turn OFF (reverse bias state). This action causes storage energy in L1, L2, L3. While Cout are discharged its energy towards to the load side.

\[
V_{in} = L_1 \frac{di_{L1}}{dt} = L_2 \frac{di_{L2}}{dt} = L_3 \frac{di_{L3}}{dt} \tag{1}
\]

\[
v_{c_{out}} = v_o = R_L i_o \tag{2}
\]

**b)** Operational mode II: is shown in Figure 3. Where S1, S2 keep ON while S3 is turned OFF. So, the diodes D1 and D2 are reverse bias state. Whereas D3 is in ON state (forward biased). In second mode the inductors L1 and L3 are stored energy with positive slope of \( \frac{V_{in}}{L} \) where \( L = L_1 = L_2 = L_3 \), in the same time the supply energy \( V_{in} \) and the stored energy in L2 are transfer energy in series to \( C_1 \). Furthermore, \( C_{out} \) discharged its energy to \( R_L \) in series.

\[
V_{in} = L_1 \frac{di_{L1}}{dt} = L_2 \frac{di_{L2}}{dt} = L_3 \frac{di_{L3}}{dt} \tag{3}
\]

\[
V_{in} - L_2 \frac{di_{L2}}{dt} - V_{c1} = 0 \tag{4}
\]

\[
V_{Cout} = R_L i_o = V_o \tag{5}
\]
High gain multiphase boost converter based on capacitor clamping structure (Oday Saad Fares)

Figure 2. Mode 1, mode 3, and mode 5

Figure 3. Mode 2

c) Operational mode III: (S1, S2 and S3) are ON state. So, is equivalent to mode I.

d) Operational mode IV: is shown in Figure 4. S3 Is turned off while S1 and S2 keep turning-on. So, the diodes D1 and D2 are reverse bias state. Whereas D3 is in ON state (forward biased). In fourth mode the inductors L1 and L2 are stored energy with positive slope of \( \frac{V_{\text{in}}}{L} \) where \( L = L_1 = L_2 = L_3 \). In the same time the supply energy \( V_{\text{in}} \) and the stored energy in \( L_3 \) are transfer energy in series to \( C_2 \). Furthermore, \( C_{\text{out}} \) discharged its energy to \( R_L \) in series.

\[
\begin{align*}
V_{\text{in}} &= L_1 \frac{di_{L2}}{dt} = L_2 \frac{di_{L3}}{dt} \\
V_{\text{in}} - L_3 \frac{di_{L4}}{dt} - V_{C2} &= 0 \\
V_{\text{Cout}} &= R_L i_o = V_o
\end{align*}
\]

Mathematical equations (6) through (8)

e) Operational mode V: S1, S2 and S3 all are on. The operating principle is same as mode I.

f) Operational mode VI: As shown in Figure 5. The modes of operation waveforms shown in Figure 6. Where S1 is turned off while S2 and S3 keep turning-on. So, the diodes D2 and D3 are reverse bias state. Whereas D1 is ON state (forward biased) in sixth mode the inductors L4 and L3 are stored energy with positive slope of \( \frac{V_{\text{in}}}{L} \) where \( L = L_1 = L_2 = L_3 \). In the same time the supply energy \( V_{\text{in}} \) and the stored energy in \( L_1 \) are transfer energy in series with \( V_{C1} \) and \( V_{C2} \) transfer energy to \( C_{\text{out}} \) and in the same time to \( R_L \).

\[
\begin{align*}
V_{\text{in}} &= L_2 \frac{di_{L3}}{dt} = L_3 \frac{di_{L4}}{dt} \\
V_{\text{in}} - L_1 \frac{di_{L1}}{dt} - V_{C1} - V_{C2} + V_{\text{Cout}} &= 0 \\
V_{\text{Cout}} &= R_L i_o = V_o
\end{align*}
\]

Mathematical equations (9) through (11)

Figure 4. Mode 4

Figure 5. Mode 6
3. PROPOSED CONVERTER STEADY-STATE ANALYSIS

3.1. Voltage gain

According to volt-second balance principle on $L_1$, can be obtained:

$$V_{Lavg} = V_{in} \cdot t_{on} + (V_{in} - V_{c1}) \cdot t_{off} = 0 \quad \text{where} \quad t_{on} = D, \quad t_{off} = (1 - D)$$

$$V_{Lavg} = DV_{in} + (1 - D)(V_{in} - V_{c1}) = 0 \quad \text{Where:} \quad D: \text{on period}, \quad (1-D): \text{off period}.$$  

$$V_{in} - V_{c1}(1 - D) = 0 \quad \text{so} \quad V_{c1} = \frac{V_{in}}{1-D} \quad (12)$$

Also, according to volt-second balance principle on inductor $L_3$ the capacitor 2 voltage as shown (13):

$$V_{Lavg} = DV_{in} + (1 - D)(V_{in} - V_{c2}) = 0 \quad (13)$$

At last, according to volt-second balance principle on inductor $L_2$ the output capacitor voltage as shown (14):

$$V_{Lavg} = V_{in} \cdot t_{on} + (V_{in} - V_{Cout} + V_{c1} + V_{c2}) \cdot t_{off} = 0 \quad t_{on} = D, \quad t_{off} = (1 - D)$$

$$V_{Lavg} = DV_{in} + (1 - D)(V_{in} - V_{Cout} + V_{c1} + V_{c2}) = 0$$

$$V_{Cout} = V_{in}/(1 - D) + (V_{c1} + V_{c2}) \quad (14)$$

By sub 12 & 13 in 14 we get:

$$V_{O} = V_{Cout} = \frac{V_{in}}{1-D} + (V_{c1} + V_{c2}) = \frac{V_{in}}{1-D} + \frac{V_{in}}{1-D} + \frac{V_{in}}{1-D}$$

$$V_{O} = 3 \frac{V_{in}}{1-D} \quad (15)$$

3.2. Input current ripple

The input current for the proposed converter will distributed among three inductors $L_1, L_2, L_3$ with phase shift of 120 degree in switches operation between switches. Therefore, the operation frequency of the input current will be three times than operation frequency of switching Figure 6.

$$\Delta I_{in} = \frac{3 V_{in} D}{F_{sw}} \quad (16)$$

3.3. Output voltage ripple

The output voltage ripple can be reduced by the proposed converter because of the output frequency three times than the input frequency as shown in Figure 6:

$$V_{\text{ripple}} = \frac{\Delta V_{o}}{V_{o}} = \frac{D}{3F_{sw}CRL} \quad (17)$$

3.4. Semiconductor voltage stress

3.4.1. Voltage stress across the switches

From mode 2, mode 4 and mode 6 the voltage stress across switches $S_3, S_2, and S_1$ as shown in Figure 6.

$$V_{S2 \text{ stress}} = V_{S1 \text{ stress}} = V_{S3 \text{ stress}} = \frac{V_{in}}{1-D} = \frac{V_{o}}{3} \quad (18)$$

3.4.2. Voltage stress across the diodes

The voltage stress across diode when diode be in reverse biasing, and it explained below:

- Voltage stress across $D_1$ pass in two stages: Stage 1 in mode 2 and Stage 2 in the mode 4.

$$V_{D1 \text{ stress}} = V_{Cout} - (V_{C1} + V_{C2}) = \frac{V_{in}}{1-D} = \frac{V_{out}}{3} \quad (19)$$

$$V_{D1 \text{ stress}} = V_{Cout} - V_{C1} = V_{D1 \text{ stress}} = \frac{2V_{in}}{1-D} = \frac{2V_{out}}{3} \quad (20)$$

- Voltage stress across $D_2$ pass in two stages: Stage 1 in the mode 4 and Stage 2 in the mode 6.
High gain multiphase boost converter based-on capacitor clamping structure (Oday Saad Fares)

\[
V_{D2 \text{ stress}} = V_{C1} = \frac{V_{\text{in}}}{1-D} = \frac{V_{\text{out}}}{3} \quad (21)
\]

\[
V_{D2 \text{ stress}} = V_{Cout} - V_{C2} = \frac{2V_{\text{in}}}{1-D} = \frac{2V_{\text{out}}}{3} \quad (22)
\]

- Voltage stress across D3 pass in two stages: Stage 1 in the mode 2 and Stage 2 in the mode 6.

\[
V_{D3 \text{ stress}} = V_{C2} + V_{C1} = \frac{2V_{\text{in}}}{1-D} = \frac{2V_{\text{out}}}{3} \quad (23)
\]

\[
V_{D3 \text{ stress}} = V_{C2} = \frac{V_{\text{in}}}{1-D} = \frac{V_{\text{out}}}{3} \quad (24)
\]

The voltage stress across diodes with respect to modes of operation are shown in Figure 6.
4. SIMULATION AND RESULTS

The use of MATLAB R2018B to simulate the proposed converter and converter parameter listed in Table 1. The three control signals with phase shift 120 degree shown in Figure 7. Output voltage is 480V as shown in Figure 8. The three inductors voltages waveform are shown in Figure 9 voltage stress across diodes is 160V as shown in Figure 10. The maximum voltage stress across switches is 320V as shown in Figure 11.

![Power switches voltage control waveform](image7)

**Figure 7. Power switches voltage control waveform**

![Output voltage waveform](image8)

**Figure 8. Output voltage waveform**

![Inductors voltage waveform](image9)

**Figure 9. Inductors voltage waveform**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L_1, L_2, L_3$</td>
<td>700 µH</td>
</tr>
<tr>
<td>$C_1, C_2, C_3$</td>
<td>20 µF</td>
</tr>
<tr>
<td>Load Resistance $R_L$</td>
<td>230 Ω</td>
</tr>
<tr>
<td>Switching Frequency $f_{sw}$</td>
<td>25 kHz</td>
</tr>
<tr>
<td>Input Voltage</td>
<td>32 V</td>
</tr>
<tr>
<td>Output Voltage</td>
<td>480 V</td>
</tr>
<tr>
<td>Duty Cycle</td>
<td>80%</td>
</tr>
</tbody>
</table>

Table 1. Parameter of the proposed converter
5. CONCLUSION

This paper presented a non-isolated DC-DC converter consist of two construction (three shared inductor and clamper capacitor circuit). This converter fed by single input source. The converter provides a high transformation ratio, lower voltage stress across power device (switches and diodes). The proposed converter suitable for power application where using renewable energy (P. V, Fuel cell and UPS) source. Because the input current of this source will be continuous and has lowest ripple. In this paper illustrated the analysis of the proposed converter and its design and checked it with MATLAB Simulation. The efficiency of proposed converter is 93%. Because of lower voltage stress across power device the total cost of converter will reduced.

REFERENCES


BIographies of authors

Oday Saad Fares was born in Baghdad, Iraq in 1978. He received the BSc in Electrical Engineering from university of technology Iraq in 2000 in 2019. He is currently working toward the M. Sc degree in Electrical Engineering at university of technology, Iraq. His research interest are the area of DC/DC converters, controller design and renewable energy.

Dr. Jasim Farhood Hussein lecturer in the University of Technology Department of Electrical Engineering Iraq-Baghdad. He received the BSc. and M. Sc in Electrical Engineering from university of technology Iraq-Baghdad in 1989 and 2003 respectively. And he received the PhD in Electrical Engineering in 2013 from De Montfort University UK. His area interest includes of power electronics field and renewable energy.