High Gain Transformer-less Inverter Based-on Capacitor Clamping Multi-phase Boost Converter

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ABSTRACT

The boosting converters integrated with inverters are widespread use in many applications under transformer fewer inverter titles, including powered vehicles, PV systems, fuel cells systems, etc. Reliability, quality, maintainability, and reduction in size are important requirements in the energy conversion process. The multi-phase boost converter can be a good solution for high-power applications. The multi-phase boost enhanced by clamping capacitor structure provides low ripple, high gain, and evident improvement in the efficiency compared to the conventional converters. This paper investigates the transformer less inverter based on a capacitor clamping multi-phase boost converter. High gain proposed architectures are being designed to step-up voltage. The converter features a high voltage gain and offers additional solutions based on the capacitor clamping structure. The proposed architectures are being designed to optimize the gaining in popularity as they are increasing the voltage gain and the efficiency and mitigating the switching frequency effect. The investigation of validation performance was introduced through the steady-state analysis and operation. The operation modes and mathematical analysis are presented. To validate the performance in terms of input and output ripple and values, the converters were tested using MATLAB / SIMULINK. The results supported the mathematical analysis. The voltage gains increase reduces ripple in input current, and the output voltage is significantly detected. The switches stresses at the converter side are One-third of the output voltage.

1. Introduction

As the need for electricity grows, renewable energy sources are becoming more important (photovoltaic cells, fuel cells, UPS, and others). It has become important because of its carbon-reducing properties. They help minimize greenhouse gas emissions. To reduce reliance on fossil fuels, renewable energy has become very important as an environmentally friendly source. When sunlight strikes PV, DC electricity is generated, but it is of low unregulated voltage and high current [1,2]. As a result, a device to increase and regulate the voltage of renewable energy sources plays an essential role. Therefore, using a dc boost converter is more important to raise the value of output DC voltage to be suitable for the DC-grid or AC distribution system [3]. There are two types of DC converters, isolated and non-Isolated DC-DC converters.

In an isolated DC-DC boost converter, the main idea is to use a transformer to increase the transformation ratio by controlling the transformer turns ratio. However, using a transformer has the disadvantage of increasing converter size and cost and copper losses due to increased leakage inductance on the high voltage side. In addition, there are increases in switching losses. Therefore, the main disadvantage of the isolated converter is the transformer that increases the converter’s losses, size, and cost. Therefore, the use of a non-isolated converter will solve this problem. The fundamental advantage of a non-isolated converter is that it is an excellent choice for low-power applications that need the use of renewable energy sources. Besides the small size, low cost, lower conduction losses, and higher efficiency [3,4].

HIGHLIGHTS

- High gain Non-isolated DC/DC converter based on clamper circuit is presented.
- Interleave inductor technique for current and voltage ripple reduction, two clamper circuits for voltage gain enhancing.
- Mathematical and simulation gain is 15 at 93.4% efficiency, and switch stress is 33% of \( V_{bus} \).

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Theoretically, the output voltage in the conventional non-isolated boost converter depends on the switching time state (ON-OFF) conditions \( V_{O} = \frac{V_{in} D}{1-D} \). Where \( D = \frac{\tau_{on}}{(\tau_{on} + \tau_{off})} \). Because of component resistance, the increase of the duty cycle is limited (0.8). Therefore the voltage gain is limited in the conventional converter. Another conventional converter disadvantage of high input current ripple caused a lifetime reduction for renewable energy sources, High conduction losses, and high voltage stress across switch and power diode. \( V_{stress} = V_{O} \) [5-7]. At the same time, increasing the current stress passing the power device \( I_{stress} = I_{in} \). Therefore, a large filter component needs to reduce the ripple in output voltage and input current [6-8].

To overcome the conventional boost converter drawback, the proposed converter suggested combining two structures to improve the conventional boost converter features. The first structure is used of \( N \) number of parallel inductors. This structure decreases the ripple in the input current due to multi-phase inductors where current is distributed across them, simultaneously decreasing the conduction losses. Therefore there are improvements in efficiency and faster transient response. Besides that, the voltage ripple in the output voltage is reduced, but the voltage gains and voltage and current stress are the same as in a conventional boost converter [8-12].

The second structure is used two parallel clamper capacitors that produce an extra gain in output voltage, decreasing voltage stress on the power device and reducing the conduction losses. Therefore, the efficiency has improved [12-17].

This paper introduces the proposed converter with the following advantages:

- Increase voltage gain
- Reduce output voltage ripple
- Reduce input current ripple
- Reduce the voltage and current stress
- Reduce the conduction losses
- Improve the converter efficiency

The proposed converter can be utilized with a transformer-less inverter application since the converter voltage is suitable for converting to AC voltage without needing to use a transformer. Besides that, the transformer disadvantage of the increasing system size, cost, and copper losses lead to system efficiency reduction [17].

2. Transformer-Less Inverter Based-on Capacitor Clamping Multi-Phase Boost Converter Analysis

The proposed converter is shown in Figure 1. It is constituted of a two-structure dc converter and transformer-less inverter. The dc converter is made up of two structures. The first structure comprises three channels containing an inductor and switch connected in a parallel arrangement. The second structure of the dc converter is a capacitor clamping structure made of four diodes and three capacitors. The transformer-less inverter comprises switches and filter circuits of inductor and capacitor.

2.1 Capacitor Clamping Multi-Phase Boost Converter Analysis

The proposed converter is shown in Figure 1, and it consists of three shared inductors and switches controlled by three operation signals with a 120-degree phase shift between the first and second signal and between the second and third signal. The proposed converter operation signal waveform is shown in Figure 2.

There are six modes of operation for a proposed converter. The converter at continuous conduction mode operation during the steady-state through one period is discussed respectively as follows:

2.1.1 Mode I

As shown in Figure 3, the three switches \( (S_1, S_2 \text{and } S_3) \) are turned ON. Thus, the diodes \( D_1, D_2, D_3 \text{and } D_4 \) tended to turn OFF (reverse bias state). This action is led to causes storage energy in \( L_1, L_2, L_3 \). \( C_{out} \) are discharged its energy towards the inverter side, while \( C_{out} \) discharged its energy to \( R_L \).

\[
\begin{align*}
V_{in} &= L_3 \frac{di_{L3}}{dt} = L_2 \frac{di_{L2}}{dt} = L_1 \frac{di_{L1}}{dt} \quad (1) \\
V_{c3} &= V_{IN \text{ inverter}} \\
V_{c_{out}} &= V_{out} = I_{out}R_L 
\end{align*}
\]

2.1.2 Mode II

As shown in Figure 4, \( S_1, S_3 \) keep ON while \( S_2 \) is turned OFF. So, the diodes \( D_1, D_3 \text{and } D_4 \) are reverse bias states. Whereas \( D_2 \) is in ON state (forward-biased).In the second mode, the inductors \( L_1 \text{and } L_3 \) are stored energy with a positive slope of \( \frac{V_{IN}}{L} \) where \( L = L_1 = L_2 = L_3 \). At the same time, the supply of energy \( V_{in} \) and the stored energy in \( L_2 \) are transfer energy in series to \( C_1 \). Furthermore, \( C_3 \) discharged its energy as inverter input voltage while \( C_{out} \) discharged its energy to \( R_L \).

\[
\begin{align*}
V_{in} &= L_3 \frac{di_{L3}}{dt} = L_1 \frac{di_{L1}}{dt} \quad (4) \\
V_{in} - L_2 \frac{di_{L2}}{dt} - V_{c3} &= 0 
\end{align*}
\]
\[ V_{c3} = V_{IN \text{ inverter}} \]
\[ V_{c \text{ out}} = V_{out} = I_{out}R_L \]

2.1.3. Mode III

\((S_1, S_2\text{ and } S_3)\) are ON state. So is equivalent to mode I.

![Figure 1: Proposed converter circuit diagram](image1)

![Figure 2: Modes of operation for the proposed converter](image2)

![Figure 3: Mode 1, Mode 3, and Mode 5 of the proposed converter operation](image3)

2.1.4. Mode IV:

As shown in Figure 5, \(S_3\) is turned off while \(S_1\) and \(S_2\) kept tured on. So, the diodes \(D_1\), \(D_2\) and \(D_4\) are reverse bias states. Whereas \(D_3\) is in ON state (forward-biased). In the fourth mode, the inductors \(L_1\) and \(L_2\) are stored energy with a positive slope.
of \( \frac{V_{in}}{L} \), where \( L = L_1 = L_2 = L_3 \). At the same time, the supply of energy \( V_{in} \) and the stored energy in \( L_3 \) are transfer energy in series to \( C_2 \). Furthermore, \( C_3 \) discharged its energy as inverter input voltage and \( C_{out} \) discharged its energy to \( R_L \).

\[
V_{in} = L_2 \frac{di_{L_2}}{dt} = L_1 \frac{di_{L_1}}{dt}
\]

(8)

\[
V_{in} - L_3 \frac{di_{L_3}}{dt} - V_{C_2} = 0
\]

(9)

\[
V_{c_3} = V_{IN \text{ inverter}}
\]

(10)

\[
V_{c_{out}} = V_{out} = I_{out}R_L
\]

(11)

2.1.5. Mode V:

S1, S2, and S3 all are on. The operating principle is the same as mode I.

2.1.6. Mode VI:

As shown in Figure 6, \( S_1 \) is turned off while \( S_2 \) and \( S_3 \) keep turning-on. So, the diodes\( D_2 \) and \( D_3 \) are reverse bias states. Whereas \( D_1 \) and \( D_4 \) is in ON state (forward-biased). In the sixth mode, the inductors \( L_2 \) and \( L_3 \) are stored energy with a positive slope of \( \frac{V_{in}}{L} \), where \( L = L_1 = L_2 = L_3 \). At the same time, the supply of energy \( V_{in} \) and the stored energy in \( L_1 \) are transfer energy in series with \( V_{C_1} \) and \( V_{C_2} \) transfer energy to \( C_3 \). At the same time \( C_3 \) discharged its energy as inverter input voltage while \( C_{out} \) discharged its energy to \( R_L \).

\[
V_{in} = L_2 \frac{di_{L_2}}{dt} = L_3 \frac{di_{L_3}}{dt}
\]

(12)

\[
V_{in} - L_1 \frac{di_{L_1}}{dt} - V_{C_1} - V_{C_2} + V_{C_{out}} = 0
\]

(13)

\[
V_{c_3} = V_{IN \text{ inverter}}
\]

(14)

\[
V_{c_{out}} = V_{out} = I_{out}
\]

(15)

2.2 Inverter Analysis

The analysis of an inverter uses the sinusoidal bipolar pulse width modulation technique to control the operation of switches, as shown in Figure 7. There are two modes of operation.

2.2.1. Mode 1:

In this mode, \( S_4 \) and \( S_5 \) are ON while \( S_6 \) and \( S_7 \) are OFF, as shown in Figure 8-a. This mode is done when the voltage value of the reference signal is larger than the voltage of the carrier signal.

\[
V_{\text{in, ref}} > V_{\text{tri}} \rightarrow V_{\text{out}} = +V_{\text{in}}
\]

(16)

2.2.2. Mode 2:

In this mode \( S_4 \) and \( S_6 \) are ON \( S_5 \) and \( S_7 \) are OFF, as shown in Figure 8-b. This mode is done when the voltage value of the reference signal is larger than the voltage of the carrier signal.

\[
V_{\text{in, ref}} < V_{\text{tri}} \rightarrow V_{\text{out}} = -V_{\text{in}}
\]

(17)

2.3 Proposed Converter Steady-State Analysis.

2.3.1. Voltage gain:

According to the volt-second balance principle on \( L_1 \), \( L_2 \), \( L_3 \), can be obtained: According to the volt-second balance principle on inductor \( L_2 \) the output capacitor voltage is shown in Figure 9.

\[
\begin{align*}
V_{L_{avg}} &= V_{in} \cdot t_{on} + (V_{in} - V_{c_3} + V_{c_1} + V_{c_2}) \cdot t_{off} = 0 \\
&\text{where } t_{on} = D, \quad t_{off} = (1 - D)
\end{align*}
\]

\[
V_{L_{avg}} = DV_{in} + (1 - D)(V_{in} - V_{c_3} + V_{c_1} + V_{c_2}) = 0
\]

(18)

\[
V_{c_3} = (V_{in}/(1 - D)) + (V_{c_1} + V_{c_2})
\]

Also, according to the volt-second balance principle on the inductor \( L_2 \) the capacitor 1 voltage is shown in Figure 9.

\[
V_{in} - V_{c_1}(1 - D) = 0 \quad \text{so} \quad V_{c_1} = \frac{V_{in}}{1 - D}
\]

(19)
At last, according to the volt-second balance principle on the inductor $L_3$ the capacitor 2 voltage is shown in Figure 9.

$$V_{in} - V_{c2}(1 - D) = 0 \quad \text{so} \quad V_{c2} = \frac{V_{in}}{1-D} \quad (20)$$

By substituting equations 19 and 20 in 18, we get:

$$V_{c3} = \frac{V_{in}}{1-D} + (V_{c1} + V_{c2}) = \frac{V_{in}}{1-D} + \frac{V_{in}}{1-D} + \frac{V_{in}}{1-D} = 3 \frac{V_{in}}{1-D} \quad (21)$$

$$M = \frac{V_{c3}}{V_{in}} = \frac{3}{1-D} \quad \text{where } M = \text{dc converter voltage gain} \quad (22)$$

The average output voltage from the inverter is dependent on $m_a$, where $m_a$ (modulation index) and its change sinusoidally with variable duty cycle.

$$m_a = \left(\frac{V_{ref}}{V_{tri}}\right) \quad (23)$$

$$V_{o,avg} = m_a V_{dc} \quad (24)$$

$$V_{o,avg} = V_{dc} \times \left(\frac{V_{ref}(t)}{V_{tri}}\right) \quad (25)$$

$$V_{o,avg} = V_{dc} \times (V_{p,ref} \sin \omega t / V_{tri}) \quad (26)$$

$$V_{o,avg} = V_{dc} \times m_a \sin \omega t \quad (27)$$

$$V_{o,avg} = V_{c3} \times m_a \sin \omega t \quad (28)$$

2.3.2. The proposed dc converter Output voltage ripple

In the proposed dc converter, the ripple of the output voltage can be reduced because the output voltage frequency is three times more than the switching frequency, as shown in Figure 9.

$$V_{ripple} = \frac{\Delta V_o}{V_o} = \frac{D}{3F_{sw}C_{RL}} \quad (29)$$

2.3.3. Semiconductor voltage stress

2.3.1.1 Voltage stress across the switches:

From mode 2, the voltage stress across the switch $S_2$ when the switch is in an off state, hence.

$$V_{S2 \text{ stress}} = \frac{V_{in}}{1-D} = \frac{V_o}{3} \quad (30)$$

And from mode 4, the voltage stress across the switch $S_3$ when the switch is in an off state, hence.

$$V_{S3 \text{ stress}} = \frac{V_{in}}{1-D} = \frac{V_o}{3} \quad (31)$$

In the same way and from mode 6, the voltage stress across the switch $S_1$ when the switch is in an off state:

$$V_{S1 \text{ stress}} = \frac{V_{in}}{1-D} = \frac{V_o}{3} \quad (32)$$

The voltage stress across switches concerning modes of operation is shown in Figure

2.3.1.2 Voltage stress across the diodes:

When a diode is reverse biased, the voltage stress across it is as follows:

Voltage stress across $D_1$ pass in two stages:

stage 1 (mode 2) and Stage 2 (mode 4) when diode in reverse biasing. Therefore, the diode is an open circuit.

$$V_{D1 \text{ stress}} = V_{Cout} - (V_{C1} + V_{C2}) = \frac{V_{in}}{1-D} = \frac{V_{out}}{3} \quad (33)$$

$$V_{D1 \text{ stress}} = V_{Cout} - V_{C1} = V_{D1 \text{ stress}} = \frac{2V_{in}}{1-D} = \frac{2V_{out}}{3} \quad (34)$$
Voltage stress across $D_2$ pass in two stages: stage 1 (mode 4) and Stage 2 (mode 6) when the diode is in reverse biasing. Therefore, the diode is an open circuit.

$$V_{D2\text{stress}} = V_{C1} = \frac{v_{in}}{1-D} = \frac{v_{out}}{3}$$  \hspace{1cm} (35)

$$V_{D2\text{stress}} = V_{C2} - V_{C1} = \frac{2v_{in}}{1-D} = \frac{2v_{out}}{3}$$  \hspace{1cm} (36)

Voltage stress across $D_3$ pass in two stages:
Stage 1 (mode 2) and Stage 2 (mode 6) when diode in reverse biasing. Therefore, the diode as an open circuit.

$$V_{D3\text{stress}} = V_{C2} + V_{C1} = \frac{2v_{in}}{1-D} = \frac{2v_{out}}{3}$$  \hspace{1cm} (37)

$$V_{D3\text{stress}} = V_{C2} = \frac{v_{in}}{1-D} = \frac{v_{out}}{3}$$  \hspace{1cm} (38)

The voltage stress across diodes concerning modes of operation is shown in Figure 10.

3. Simulation

The parameter of the proposed DC-DC converter is listed in Table 1. The MATLAB R2018B is used to simulate the converter. The three DC converter control signals have a difference in phase shift of 120 degrees, as in Figure 11. The switches voltage stress is 125V as in Figure 12, input voltage = 24V, output converter voltage = 360V and output inverter voltage = 310V as in Figure 13, the capacitor voltage of $C_1, C_2, C_3$, and $C_{out}$ are shown in Figure 14. The diodes voltage stress is 250 V, as in Figure 15. The voltage waveform of the three inductors is shown in Figure 16. The MATLAB simulation schematic of transformer-less inverter based-on capacitor clamping multi-phase boost converter is shown in Figure 17.

From the simulation results, it appears that it validates the mathematical calculation where the output voltage is equal to $V_{out} = V_{IN\text{ inverter}} = \frac{3 V_{in}}{1-D} = 360$ Volt, the voltage stress across switches is equal to $\frac{V_{in}}{1-D} = 120$ Volt, and the stress across diodes is equal to $\frac{2V_{in}}{1-D} = 240$ Volt in two diodes and 120 Volt in the other two diodes.

![Figure 4: Mode 2 of the proposed converter operation](image)

| Table 1: Parameter of the proposed converter |
|---------------------------------------------|
| Parameter | value |
| $L_1, L_2, L_3$ | 800 $\mu$H |
| $C_1, C_2, C_3$ | 25 $\mu$F |
| The duty cycle of switches $S_1, S_2$ and $S_3$ (D) | 0.8 |
| Switching Frequency - $f_{sw}$ | 25 kHz |
| Input Voltage | 24 V |
| DC converter Output Voltage | 360 V |
Figure 5: Mode 4 of the proposed converter operation

Figure 6: Mode 6 of the proposed converter operation

Figure 7: Sinusoidal bipolar pulse width modulation technique operation waveform
Figure 8: a. Mode 1  b. Mode 2

Figure 9: Key waveform for the proposed dc converter

Figure 10: Voltage stress across switches waveform
Figure 11: Voltage switch waveform control

Figure 12: Switches voltage stress waveform

Figure 13: Converter and inverter Output voltage

Figure 14: Capacitors voltage waveform

Figure 15: Voltage stress across diodes waveform

Figure 16: Inductors voltage waveform
4. Conclusion

The non-isolated DC-DC boost converter proposed in this study comprises two constructions (three shared inductors and a clamper capacitor circuit). This converter is fed by a single source of input. The converter has a high transformation ratio and lower voltage stress across power devices (switches and diodes), and the second circuit is the transformer-less inverter. The suggested converter is ideal for power applications using renewable energy sources (photovoltaic, fuel cell, and UPS). This is because the source's input current will be continuous and have the least ripple. The analysis of the proposed converter and its design was demonstrated in this work, and it was verified using MATLAB Simulation. The efficiency of the suggested converter is 93.5 percent due to the transformer-less inverter. In addition, the total cost of the converter will be decreased due to lower voltage stress across the power device and the lack of a transformer.

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Author contribution

All authors contributed equally to this work.

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Data availability statement

The data that support the findings of this study are available on request from the corresponding author.

Conflicts of interest

The authors declare that there is no conflict of interest.

References

[1] L. A. Soriano, P. Ponce, A. Molina, Analysis of DC-DC Converters for Photovoltaic Applications based on conventional MPPT Algorithms, in: 2017 14th International Conference on Electrical Engineering, Computing Science and Automatic Control (CCE), Mexico City, Mexico, (2017).

[2] T. Xue, Z. Minxin, Y. Songtao, Maximum Power Point Tracking for Photovoltaic Power Based on the Improved Interleaved Boost Converter, in: IEEE 11th Conference on Industrial Electronics and Applications ICIEA., (2016) 2215-2218. http://dx.doi.org/10.1109/ICIEA.2016.7603957

[3] G. Ganesan, M. Prabhakar, A novel interleaved boost converter with voltage multiplier cell, in: IEEE 2nd International Conference on Electrical Energy Systems., 2014.
[4] A. Mittle, R. K. Singh, S. Chandra J, A New Interleaved High Step-up DC-DC Converter, in: SCES 5th Students’ Conference on Engineering and Systems., 2019.

[5] M. A. Salvador, T. B. Lazzarin, R. F. Coelho, High Step-Up DC-DC Converter with Active Switched-Inductor and Passive Switched-Capacitor Networks, in: IEEE transaction on industrial electronics., 65 (2018).

[6] S. Saravanan, N. R. Babu, A modified high step-up non-isolated DC-DC converter for PV application, J. Appl. Res. Technol., 15 (2017) 242–249. doi.org/10.1016/j.jart.2016.12.008.

[7] A. Farooq, Z. Malik, and D. Qu, A Three-Phase Interleaved Floating Output Boost Converter, Hindawi Publishing Corporation Advances in Materials Science and Engineering., (2015).

[8] Mamdouh L. Alghaythi, Robert M. O’Connell, and Naz E. Islam, A Multiphase-Interleaved High Step-up DC-DC Boost Converter with Voltage Multiplier and Reduced Voltage Stress on Semiconductors for Renewable Energy Systems, in: IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)., (2020).

[9] O. S. Fares, J. F. Hussein, High gain multi-phase boost converter based on capacitor clamping structure, IJECS., 24 (2021) 689-696. doi:10.11591/ijeecs.v24.i2.

[10] S. K. Waghmare, A. S Deshpande, Performance Analysis and Comparison of Conventional and Interleaved DC/DC Boost Converter Using MULTI SIM, IJAREEIE., 4 (2015).

[11] K. S. Faraj, J. F. Hussein, Analysis and Comparison of DC-DC Boost Converter and Interleaved DC-DC Boost Converter, in Eng. Technol. J., 38 (2020) 622-635. doi.org/10.30684/etj.v38i5A.291

[12] M. E. Azizkandi, F. Sedaghati, H. Shayeghi, A New Boost DC-DC Converter Based on a Coupled Inductor and Voltage Multiplier Cells, IECO.,2 (2019) 265-278. doi:10.22111/IECO.2019.28215.1127

[13] A. Alzahrani, P. Shamsi, M. Ferdowsi, A novel interleaved non-isolated high-gain DC-DC boost converter with Greinacher voltage multiplier cells, in: IEEE 6th International Conference on Renewable Energy Research and Applications. ICRERA., (2017). doi: 10.1109/ICRERA.2017.8191270

[14] Hong Li, W. Wang, Y. Zeng, Y. Zhao, A 3L Capacitor Clamping DC-DC Converter with Low Current Ripple and High Voltage Gain, in: IEEE Energy Conversion Congress and Exposition., 29 (2019) 3. doi 10.1109/ECCE.2019.8912843.

[15] B. Sri Revathia, P. Mahalingama, F. G. Longattb, Interleaved high gain DC-DC converter for integrating solar PV source to DC bus, Solar Energy., 188 (2019) 924-934. doi. 10.1016/j.solener.2019.06.072

[16] N. Tewari, V.T. Sreedevi, A novel single switch dc-dc converter with high voltage gain capability for solar PV based power generation systems, Solar Energy., 171 (2018) 466-477. doi.org/10.1016/j.solener.2018.06.081

[17] F. F. Salih, O. A. Ahmed, Improved Y-Source Single-Stage Transformer less Microinverter for PV Residential Applications, Eng. Technol. J., 38 (2020) 1327-1341. doi: https://doi.org/10.30684/etj.v38i9A.1143.