High Voltage Gain Three Coupled Winding DC-DC Interleaved Boost Converter with Arduino Microcontroller for the PV Panel Control

Karrar S. Faraj¹ and Jasim F. Hussein²

¹,² Department of Electrical Engineering, University of Technology, Baghdad, Iraq.

Abstract. In many applications, high-step converters are widely used, including powered vehicles, Photovoltaic (PV) systems, continuous power supplies, Gas lighting and fuel cell systems. The most important requirements in the energy conversion process are reliability, quality, maintenance and size reduction. This paper presents an Interleaved Boost Converter (IBC) to raise voltage gain with three coupled winding. This converter consists of three pairs of coupled inductors to collect energy in parallel and release energy to the series load, which provides a much higher output load voltage than the traditional DC-DC boost converter. To validate the performance, an investigation was introduced by means of steady state analysis and operation. The operation modes and mathematical analysis are presented. Arduino UNO microcontroller was used to implement Pulse Width Modulation (PWM) gate drive based on Maximum Power Point Tracking (MPPT). The DC-DC IBC with High Voltage Gain (HVG) produces low voltage stress across switches, low input and output current ripple, and also improves the efficiency. These features made this converter suitable for applications where a high voltage gain is demanded. This converter was tested using Matlab/Simulink to validate the performance in terms of input and output ripples. The results supported the mathematical analysis. The cancelation of the ripple in input and output voltages has significantly detected. The ripple amplitude is reducing in DC-DC HVG IBC comparing with traditional DC-DC boost converter, and the ripple frequency is doubled. This tends to reduce the output filter losses, and size. Also improves the efficiency of the converter.

Keyword. High voltage gain, Ferrite core, Interleaved Boost Converter, Low input and output ripples, Arduino UNO Microcontroller, Maximum Power Point Tracking, Current and Voltage sensors.

1. Introduction

The PV systems are comprised from the solar array and the power conversion units. The PV module is the first part in these systems. It is solid-state devices that convert the sun light energy directly to electricity, without intervening any rotating equipment or heat engines. Lately solar energy among renewable energies has become a rapidly growing source of electricity. Reducing fossil energy resources, increasing emissions, environmental pollution, and high fossil fuel costs have driven researchers and engineers into renewable energy. The PV generation uses energy that is clean with low-cost. The PV power generation system is now a favourable source of power, particularly in remote areas where power network access is not available. There has been a great deal of research
displaying that PV power generation that is an appropriate substitute for traditional power plants. The converter efficiency plays a very important role in creating PV power. High gain converter, recently as circuit that can boost a power supply’s low voltage to a much higher voltage, has gained considerable attention in many applications because of their potential [1-2]. Figure 1 shows the DC-DC converter of the PV diagram of this work.

This converter has found a few industrial applications in Uninterruptible Power Systems (UPS) and some developing communication systems. Furthermore, with the introduction of renewable energy sources and their use in grid-connected systems, high-level converters were required to boost the low voltage of feasible structures based on PV or fuel cells [3]. These high-voltage converters are a solution to traditional single-phase boost topologies that due to high losses in the power devices generated by the parasitic components and the high duty cycles necessary to achieve the required output voltage. The HVG IBC consists of two parallel-connected boost power trains operated with a phase difference of $\frac{\pi}{2}$.

Advantages of HVG IBC over traditional single stage boost converters include [2,4]:

- Substantial reduction in input and output current ripple.
- Higher power density.
- Higher current handling capacity.
- Improved efficiency.
- Faster response.

![Figure 1](image)

Figure 1. The DC-DC converter of the PV diagram in this work.

The MPPT is a strategy followed to harvest the most generated power from certain sources like PV systems and wind turbine [5]. In this research, the mission was entrusted by a microcontroller-based DC-DC converter that optimizes the match between the solar array (PV panels), and the load. Simply, it is an algorithm fed by the values of the voltage and current of the panel at each instant. It has an ability to utilize these values in changing the input resistance of the load to match the internal resistance of the panel at each instant by changing the pulse width of the DC-DC converter [6].

There are many kinds of MPPT algorithms, the common algorithms are [7]:

- Constant Voltage Method.
- Short-Current Pulse Method.
- Open Voltage Method.
- Perturbation and observation (P&O) Method.
- Incremental Conductance (I-C) Method.
Because of many requirements and conditions, each type has several advantages and disadvantages that make the user prefer one of them. The P&O method has been widely used because of its simple implementation structure. The P&O operating essentially on the perturbation of the system by increasing or decreasing the “ON” time of the PWM at each cycle of MPPT and observation of the terminal array voltage and the array current to detect the maximum point of the PV curve, but when it reaches the maximum point still perturbation existed that make the oscillation around the maximum power point (MPP) causes decreasing on the harvesting power from the panel array. There are some types of P&O algorithms that have been implemented later, but the classical one will be relied on here. At each algorithm cycle, there is a difference between the array terminal voltage and power as compared with the previous one, these are $\Delta V$ and $\Delta P$ respectively as shown in Figure 2.

![Figure 2. The P&O MPPT algorithm.](image)

Figure 3 shows that HVG IBC circuit produces low input and output current ripple and small voltage stress across the switches are the main benefits of the DC-DC converter topology, but the duty cycle is limited, as it must be higher than 0.5.

![Figure 3. The High Voltage Gain Interleaved Boost Converter circuit.](image)

**2. Operation of high voltage gain DC-DC IBC**

The HVG IBC that proposed in this paper is a combination of two-phase IBC. The two switching devices (here is Power IGBT IRGP4063D) are controlled in $\frac{T}{2}$ phase delay to each other simultaneously (interleave technique method), in order to smooth the output ripple current, raising
power rating and efficiency [8-9]. This technique has benefits such as reducing the size of the inductor [10-11] and decreasing the ripple of input and output current and also the voltage for input and output side. The DC-DC IBC inductor current can be decreased by using the interleaving technique [12]. The two-phase HVG IBC presents four different operating modes corresponding to all the combinations of the ON and OFF-state of the switches. Figure 4 shows the operating waveforms of the proposed converter when it is under an ideal operation when the duty cycle $\delta$ is higher than 50%.

![Figure 4. Operating waveforms.](image)

**Mode 1:** As shown in Figure 5 $S_1$ turned ON and $S_2$ turned OFF, where $I_{L1}$ only flows through the $L_1$, $I_{L2}$ flows through $L_2, D_2, D_3, L_C$ and $C_{out}$.

![Figure 5. Operating of Mode 1.](image)

By using Kirchhoff’s voltage law (KVL) to calculate the voltage across $R_{Load}$, the following equations can be derived such that:

$$V_{in} = N_e \frac{\Delta \phi_1}{T_1}$$  \hspace{1cm} (1)

$$V_{in} = N_e \frac{\Delta \phi_2}{T_1} - N_e \frac{\Delta \phi_c}{T_1} + V_o$$  \hspace{1cm} (2)

Where:

- $N_e, N_C$: The number of turns for external and central winding (turn).
- $V_{in}$: The input voltage (V).
- $V_o$: The output voltage (V).
- $D$: Diode for ($D_2$-$D_4$).
- $\Delta \phi_1, \Delta \phi_2$ and $\Delta \phi_c$: The variations of magnetic flux in the inductors $L_1, L_2$ and $L_C$, respectively (Wb).
$T_1$: The time duration of Mode 1.

**Mode 2:** As shown in Figure 6 $S_1$ is turned OFF and $S_2$ is turned ON, $I_{L1}$ flows through $L_1$, $D_1$, $D_4$, $L_c$ and $C_{out}$. $I_{L2}$ flows only through the winding $L_2$.

**Figure 6.** Operating of Mode 2.

By using KVL to calculate the voltage across $R_{load}$, the following equations can be derived such that:

$$V_{in} = N_e \frac{\Delta \phi_1}{T_2} + N_c \frac{\Delta \phi_c}{T_2} + V_0$$

$$V_{in} = N_e \frac{\Delta \phi_2}{T_2}$$

Where:

$T_2$: The time in Mode 2.

**Mode 3:** As shown in Figure 7, $S_1$ and $S_2$ are turned OFF and $I_{L1}$ flows through $L_1$, $D_1$, $D_3$ and $C_{out}$; while $I_{L2}$ flows through $L_2$, $D_2$, $D_4$ and $C_{out}$.

**Figure 7.** Operating of Mode 3.

By using KVL to calculate the voltage across $R_{load}$, the following equations can be derived such that:

$$V_{in} = N_e \frac{\Delta \phi_1}{T_3}$$

$$V_{in} = N_e \frac{\Delta \phi_2}{T_3} + V_0$$

Where:

$T_3$: The time duration of Mode 3.
**Mode 4**: As shown in Figure 8, $S_1$ and $S_2$ are turned ON, where $I_{L1}$ flows only through $L_1$, and $I_{L2}$ through $L_2$. The diodes stay OFF and there do not current flowing through the central winding of the coupled inductor.

![Figure 8. Operating of Mode 4.](image)

By using KVL to calculate the voltage across $R_{\text{Load}}$, the following equations can be derived such that:

$$V_{\text{in}} = N_e \frac{\Delta \Phi_1}{T_4}$$  \hspace{1cm} (7)

$$V_{\text{in}} = N_e \frac{\Delta \Phi_2}{T_4}$$  \hspace{1cm} (8)

Where:

- $T_4$: The duration of Mode 4.

As a result, this converter has a voltage gain presented at different duty cycle values. The voltage gain when the duty cycle $\delta$ is increased from 0.5 can be derived from this, where only modes (1, 2 and 4) are used in Figure 4 [2].

$$V_{L1 \text{ mode4}} + V_{L1 \text{ mode1}} + V_{L1 \text{ mode4}} + V_{L1 \text{ mode2}} = 0$$  \hspace{1cm} (9)

$$M_{\delta>0.5} = \frac{V_o}{V_{\text{in}}} = \frac{(1 + N)}{(1 - \delta)}$$  \hspace{1cm} (10)

$$N = \frac{N_c}{N_e}$$  \hspace{1cm} (11)

$$V_{Lc} = NV_{L1} - V_{L2}$$  \hspace{1cm} (12)

$$L = \frac{V_{\text{in}} \delta}{2 \Delta t_{L} f}$$  \hspace{1cm} (13)

Assume $L = L_1 = L_2$ and $V_L = V_{L1} = V_{L2}$

$$L_c = \frac{V_{Lc} \delta}{\Delta t_{Lc} f}$$  \hspace{1cm} (14)

The capacitor $C$ is given by:

$$C_{\text{min}} = \frac{\delta}{R \left( \frac{\Delta V_{\text{in}}}{V_o} \right) f}$$  \hspace{1cm} (15)
Figure 9 shows the conventional DC-DC boost converter, the DC-DC boost converter increases the voltage input to the required magnitude of the output voltage. The main components used in the DC-DC boost converter are; inductor (L), diode (D), switching device (S) and capacitor (C).

To calculate the output voltage of the DC-DC boost converter in equation (16)

\[ V_o = \frac{V_{in}}{1 - \delta} \]  

Equation (17) and (18) to calculate the inductor and capacitor of DC-DC boost converter.

\[ L = \frac{V_{in}\delta}{\Delta i_L f} \]  
\[ C = \frac{\delta}{R \left( \frac{\Delta V_o}{V_o} \right) f} \]

3. Simulation Results

By using Matlab/Simulink platform, the simulation design is developed. Figure 10 shows the high voltage gain IBC simulink, which consists of two IGBT transistors, four diodes, three winding coupling inductors, resistance, capacitor and MPPT to control the PV. Table 1 and Table 2 show the PV module specification and design of the parameter for the HVG IBC.
Table 1. PV module specification at 25°C & 1000 W/m²

| Parameter                        | Value  |
|----------------------------------|--------|
| Maximum Power ($P_{max}$)        | 80.73W |
| Open Circuit Voltage ($V_{OC}$)  | 21.84V |
| Short Circuit Current ($I_{ShC}$)| 4.97A  |
| Voltage at Max. Power ($V_{mp}$) | 17.42V |
| Current at Max. Power ($I_{mp}$) | 4.63A  |

Table 2. Parameters of the High Voltage Gain Interleaved Boost Converter.

| Parameter             | Value  |
|-----------------------|--------|
| Inductor $L_1$        | 2 mH   |
| Inductor $L_2$        | 2 mH   |
| Inductor $L_c$        | 2 mH   |
| Capacitor $C_{in}$    | 2.2µF  |
| Capacitor $C_{out}$   | 68 µF  |
| Output voltage $V_o$  | 110 V  |
| Load resistance $R_L$ | 160 Ω  |
| Switching frequency $f_s$ | 31.3 KHz |
| Duty Cycle $\delta$   | 0.8    |
| $N$                   | 1      |

Figure 10. The High Voltage Gain Interleaved Boost Converter Simulink.

The P&O method has been widely used because of its simple implementation structure. The P&O operates essentially on the perturbation of the system by increasing or decreasing the “ON” time of the PWM at each cycle. It is observed the terminal module voltage and current to detect the maximum point of the PV curve. Figure 11 shows the P&O algorithm based on Matlab/Simulink.
Figure 11. The P&O of the generated PWM using block Simulink.

Figure 12 shows the PWM for DC-DC converter, using P&O way to generation of PWM gives MPPT from PV panel. The phase shift between PWM 1 and PWM 2 are $\frac{T}{2}$. The PWM has shoot-through state, where the two switches device are turned ON (short–circuit) on the input source. Also there overlap between two PWM, due the duty cycle is 0.8.

Figure 13 and Figure 14 show the input and the output voltage of the converter, the input voltage is 17.47V and the output voltage is 109.9V. Where the voltage gain is the ratio of output to input is 6.29. The input voltage ripple is 0.023V and the output voltage ripple is 0.1247V.

Figure 13. Input voltage.
Figure 14. Output voltage.

Figure 15 and Figure 16 show input and output current of the converter, the input current is 4.595A and the output current is 0.6855A. The input current ripple is 0.2003A and the output current ripple is 0.000687A. We noticed the ripple of the input and the output current has reduced due to the sum of the frequencies for switches $S_1$ and $S_2$ that is reflected at the input (supply) and the output. As a result, the total input and output current ripples has reduced.

Figure 15. Input current.

Figure 16. Output current.

Figure 17 shows the inductor of each $L_1$ and $L_2$, central inductor $L_c$ and input of currents, where the input current of the IBC converter is sum of the currents of each inductors for $L_1$ and $L_2$.

Figure 17. The $I_{L1}$, $I_{L2}$, $I_{Lc}$ and $I_{In}$ currents of the HVG IBC.
Figure 18 and Figure 19 show the inductor currents flowing through the inductors $I_{L_1}$, $I_{L_2}$ and $I_{LC}$. Where the ripple frequencies for $L_1$ and $L_2$ are 62.6KHz.

![Figure 18. The inductors current of $I_{L_1}$ and $I_{L_2}$.
](image1)

![Figure 19. The central inductor current of $I_{LC}$.
](image2)

Figure 20 shows the inductor voltages of each $V_{L_1}$, $V_{L_2}$, and $V_{LC}$, where the input is 17.47V and the output voltage is 109.9V.

![Figure 20. The voltage of each inductors $V_{L_1}$, $V_{L_2}$, and $V_{LC}$ of the HVG IBC.
](image3)
Figure 21 presents the voltage stress across the switching $V_{s1}$ and $V_{s2}$ reduced compared to the output voltage. The output voltage is 109.9 V while the voltage stress is 107 V. This one important feature of the HVG IBC decreases the voltage stress across the switches.

Figure 21. The voltages stress on switching $V_{s1}$ and $V_{s2}$.

4. Experimental Results
A prototype was designed to demonstrate the efficiency of the converter to check the validity of the HVG IBC. The specifications and component model of the component used are shown in Table 3.

| Component | Value or model |
|-----------|----------------|
| Inductor $L_1$, $L_2$, $L_c$ | 2 mH, Power transformer ferrite core model (T63×38×25G) |
| IGBT $S_1$, $S_2$ | IRGP4062D |
| Diode $D_1$, $D_2$, $D_3$, $D_4$ | RURP3060 |
| Output Capacitor $C_{out}$ | 68 μF/450 V |
| Number of turns ratio $N$ | 1 |

Figure 22 shows the MPPT kit that is composed by the Arduino UNO microcontroller, current sensor and voltage sensor. The MPPT kit measures the current and the voltage, and then calculates the power supplied from PV module. It uses certain algorithm to calculate the MPP, in each instance. This kit is used to generate the PWM based on MPP that has been extracted of PV systems by changing certain algorithm conditions and setup.

Figure 22. The MPPT kit.
Figure 23 exhibits the complement practical implementation setup of experimental board.

![Figure 23. The Practical Prototype of the High Voltage Gain Interleaved Boost Converter.](image)

Figure 24 shows the two channels PWM of gates drive pulses. Each channel is operating at 0.8 duty ratio, within 31.37 KHz frequency. It is clear that the two channels PWM are identical pulses with relative phase-shift complementary $\frac{T}{2}$ with respect to the frequency.

The PWM of the gate pulses are used to drive the switching transistors (ON/OFF) complementary at two channels.

![Figure 24. The PWM of the converter.](image)

Figure 25 and Figure 26 show the output voltage and current for the HVG IBC, the output voltage is 108 V and output current is 0.678 A.
Figure 25. The output voltage.

Figure 26. The output current.

Figure 27 and Figure 28 show the voltage across the inductors $V_{L1}$, $V_{L2}$ and $V_{LC}$. The ripple frequency for $L_1$ and $L_2$ are 62.74KHz.

Figure 27. The inductor voltages $V_{L1}$ & $V_{L2}$.

Figure 28. The central inductor voltage $V_{LC}$. 
Figure 29 shows the voltage stress across the switches $V_{S1}$ and $V_{S2}$. The switching voltage stress value is approximately appearing as reflected from the inductor voltage together with the voltage of the source.

![Figure 29. The voltage stress on switching $V_{S1}$ and $V_{S2}$.](image)

Figure 30 and Figure 31 present the inductors current flow through the $I_{L1}$, $I_{L2}$ and $I_{Lc}$ respectively. The ripple frequency for inductors $L_1$ and $L_2$ are 62.74KHz.

![Figure 30. The inductors current of $I_{L1}$ and $I_{L2}$.](image)

![Figure 31. The central inductor current of $I_{Lc}$.](image)
Table 4 shows a comparison between the simulation and practical results for the HVG IBC.

**Table 4.** The comparison between simulation and practical results, also the percentage difference between the simulation and practical for HVG IBC.

| Parameter                  | Simulation | Practical | Percentage (%) |
|----------------------------|------------|-----------|----------------|
| Switching frequency $f_s$ (KHz) | 31.3       | 31.3      | 1              |
| Output voltage $V_o$ (V)     | 109.9      | 108       | 0.982          |
| Output voltage ripple $\Delta V_o$ (V) | 0.1247     | 0.138     | 0.9            |
| Voltage gain ($M$)           | 6.29       | 6.199     | 0.98           |
| Output current $I_o$ (A)     | 0.6855     | 0.678     | 0.989          |
| Output current ripple $\Delta I_o$ (A) | 0.000687  | 0.00083   | 0.82           |
| $f_{ripple}$ for $L_1$ and $L_2$ (KHz) | 62.6       | 62.74     | 0.99           |
| Voltage stress (V)           | 107        | 106.4     | 0.99           |
| Output power $P_o$ (W)       | 75.33      | 73.224    | 0.97           |
| Input power $P_{in}$ (W)     | 80.27      | 80.6      | 0.995          |
| Efficiency $\eta$ ($P_o/P_{in}$) (%) | 93.845    | 90.848    | 0.968          |

Through the table, we noted the converter increases the voltage gain, also the ripple output voltage and current reduced. The voltage stress across the switching devices are decreased.

Figure 3.2 presents the prototype power circuit for the HVG IBC. The power circuit of the converter consists of two IGBT transistor, four diode, three winding coupling inductors, variable load and capacitor.

![Power Circuit](image)

**Figure 3.2.** Power Circuit.

Figure 3.3 shows the Power transformer ferrite core model (T63×38×25G) used in the power circuit, each core consists of $L_1$, $L_2$, and $L_c$ inductors.
Figure 33. The ferrite core model (T63×38×25G).

Figure 34 shows the relation between the voltage gain with duty cycle for the HVG IBC. The converter depended on the number of turns ratio \( N \), when \( N \) increases, the voltage gain for the converter also increases.

![Graph showing voltage gain vs duty cycle for different \( N \) values.](image)

**Figure 34.** The duty cycle vs voltage gain when \( N = 1,2,4,8 \).

The 3-D graph for the relation between the duty cycle (\( \delta \)), voltage gain, and the number of turns ratio (\( N \)) is plotted in Figure 35. It can be observed that the converter voltage-gain increases when the number of turns ratio is more than 2 and also voltage gain increases when the duty cycle (\( \delta \)) increase.

![3-D graph showing voltage gain vs duty cycle and number of turns ratio.](image)

**Figure 35.** 3-D graph for voltage gain versus duty cycle (\( \delta \)) and number of turns ratio \( N \) of the HVG IBC.
Table 5 shows the comparison between the HVG IBC and conventional DC-DC boost converter.

**Table 5. The comparison between the HVG IBC and conventional boost converter.**

| Parameter                        | HVG IBC   | Conventional Boost Converter |
|----------------------------------|-----------|------------------------------|
| Switching frequency $f_s$ (KHz) | 31.3      | 31.3                         |
| Output voltage $V_o$ (V)         | 109.9     | 84.42                        |
| Output voltage ripple $\Delta V_o$ (V) | 0.1247 | 0.15                         |
| Voltage gain ($M$)               | 6.29      | 4.729                        |
| Output current $I_o$ (A)         | 0.6855    | 0.6505                       |
| Output current ripple $\Delta I_o$ (A) | 0.000687 | 0.004                        |
| Voltage stress (V)               | 107       | 85.28                        |
| Output power $P_o$ (W)           | 75.33     | 54.91                        |
| Input power $P_{in}$ (W)         | 80.27     | 80.11                        |
| Efficiency $\eta$ ($P_o$/$P_{in}$) (%) | 93.845 | 68.54                        |

Through the table, the output voltage for the HVG IBC is greater than the conventional boost converter and the voltage gain increases. The output voltage and current ripples reduced compared to the conventional boost converter. Figure 36 shows the relation between the voltage gain with duty cycle ($\delta$) for the HVG IBC and conventional boost converter.

**Figure 36. The duty cycle vs voltage gain.**

5. Conclusion

This paper presented HVG IBC by incorporating additional inductor coupled winding used to reset the magnetic flux core during the converter operation. Detailed analysis has been done through mathematical within various modes of operation and simulation to investigate the benefits of HVG IBC. The simulations have been done using Matlab/Simulink. The PWM was adjusted based on MPPT utilized P&O algorithm. The output voltage of this converter is 109.9V and the voltage gain is 6.29 while the output voltage is 84.42V and the voltage gain is 4.729 in conventional boost converter. The analysis and simulation results show that the converter is superior in terms of voltage gain, ripples in the input and output current and voltage, decrease the voltage stress across the switching devices and improve the efficiency compared to the conventional boost converter. Where the voltage-gain is increased when the turns ratio $N$ is increased.

Finally, the device prototype had been implemented practically and evaluated to validate the concepts experimentally. The correlation between the simulation and the practical results are perfect and this gives confidence that the converter will allow the goal to be achieved.
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