

# A Novel Topology for Single-Switch Transformerless High Gain Buck-Boost Converter

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**Abstract**—In this project, a novel Transformerless DC-DC converter with high gain is implemented. The voltage Gain of the converter implemented in this project is higher than traditional buck-boost, boost, SEPIC, CUK and ZETA converters. Another advantage of this proposed topology is that there is only one switch to control the converter thus resulting in reduced conduction losses which results in improved efficiency of the converter. Modes of operation and steady state analysis of the converter will be performed and results will be verified through simulation using MATLAB/Simulink. Furthermore, a PI-controller will be implemented to reduce the over-shoot of the converter.

**Keywords**—Transformerless, DC-DC converter, Buck-Boost converter, High Gain, PI Controller.

## I. INTRODUCTION

Environmental problems such as climate change, pollution and deforestation has resulted in increased carbon emissions all around the world. Due to these concerns, there has been an increased stress on the importance of renewable energy resources. Part of this effort is electrification of vehicles. Fuels cell vehicles is one of the clean alternatives to internal combustion engine vehicles. Taking fuel cell vehicles into account, they can be implemented on electric vehicles. The output of fuel cell is variable but it suffers from one drawback of low output voltage. This problem can be overcome with the help of DC-DC converters.

Applications which require constant dc voltage, buck-boost is required. The traditional buck-boost converters are low in efficiency and due to smaller voltage gain, it is not suitable for fuel cells which require converter with a higher gain [1-5]. Another drawback of traditional converter is that their efficiency is low due to ESR of capacitors and inductors and due to the losses across diodes and switch [6]. Another technique to accomplish high is through flyback converter. It is usually done so through increasing the turns ratio but it suffers from the drawback lower efficiency caused by the leakage inductance and problems regarding reverse recovery []. Another option to obtain high gain is the use of dc converter with a coupled inductor. Here, the main drawback is the added voltage stress across the switch and high voltage spikes. [5, 6].

Another alternative is to use a bi-directional dc-dc converter with a high gain. In such converter, 8 switches are used which become the cause of conduction losses resulting in decreased

efficiency of the system [7]. Another technique is to use an interleaved buck-boost converter where two switches are used to control the circuit. Here, gain of the converter is more than twice the traditional converter [8]. The proposed converter that is going to be implemented in this project has a voltage gain higher than the other converters like the traditional boost, buck-boost, SEPIC, CUK and ZETA converters [10]. Since this converter has a higher voltage gain so it can be implanted for applications where high dc voltage is required. This project will be implemented in MATLAB/Simulink.

## II. DC-DC CONVERTERS

There are two major techniques through DV power can be transformed from one potential to another. These two major techniques are Isolated DC-DC converters and Non-isolated DC-DC converters. In Isolated DC-DC converters, DC input is isolated from output with the help of galvanic isolation. This isolation is provided through the use of transformers. They are usually used where very high voltage step-up or step-down ratio is required. Bi-direction DC-DC converter is an example of the isolated converter. Second one is the non-isolated converters DC input and DC output are connected to the same potential. Due to the absence of transformer, converter becomes lighter and smaller. This converter improves efficiency as there are no transformer losses. In this project, a nonisolated DC-DC converter is implemented.

### A. Buck-Boost Converter

This converter is a combination of diode rectifier with a buck-boost converter, and it only needs one switch to regulate the output with high ripple, high PF and low harmonics, when it is used as uni-directional converter. used for bidirectional purposes, this converter can work as a voltage source rectifier and inverter with reduced energy storage elements for fast response [9]. It operates in four quadrants and is capable to work only as boost or as a buck, if necessary, and in order to reduce the size of the filters, it has to increase the switching frequency. It has a high EMI value in the input current. The single-switch topologies increase the component stresses and sizes, that is why it is so important to use an interleaving technique. The

equivalent circuit of conventional buck-Boost converter is given in Fig. 1.

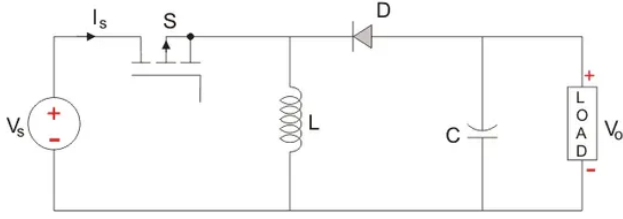


Figure 1: Equivalent Circuit of Conventional Buck-Boost Converter

The input voltage is directly connected to the switch and the second switch can be replaced with a diode if it is working as a uni-directional converter. The switch is controlled by Pulse Width Modulation.

### III. PROPOSED CONVERTER TOPOLOGY

The structure of the proposed converter is simple. As the converter is a single switch converter, so its control is not that complex. Across diodes and switch, voltage stress is lower than the output voltage which ultimately reduces the conduction losses resulting in increased efficiency of the converter. This converter can be used to power different devices such as consumer electronics and electronics in an electric vehicle. Moreover, it can also be used to step-up voltage in a Fuel cell electric vehicle since it has high voltage gain. The equivalent circuit of the proposed converter is given in Fig.2.

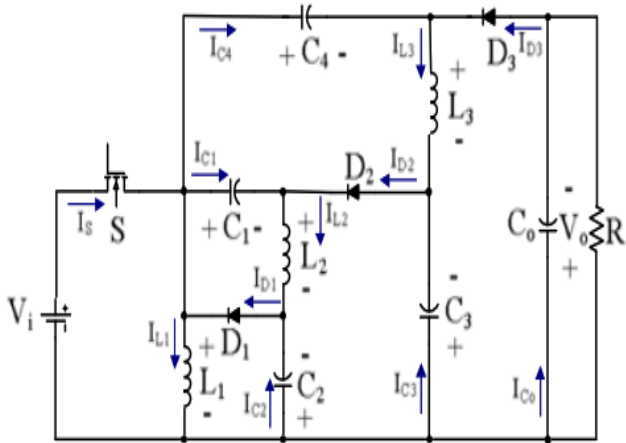


Figure 2: Equivalent Circuit of the proposed Converter

The proposed converter consists of three diodes namely  $D_1, D_2, D_3$ , five capacitors namely  $C_1, C_2, C_3, C_4$ , and  $C_o$ , three inductors  $L_1, L_2, L_3$ , switch S and lastly load resistance  $R_o$ . To

make the steady state analysis simpler, few assumptions has been considered which are:

- 1) It is assumed that the capacitance of the capacitors used in the converter is large enough that the output voltage is constant.
- 2) Parasitic capacitor of the switch is ignored and the switch is considered as ideal.

#### A. Modes of Operation

This converter can be operated in two modes of operation. Also, this converter can work in both Continuous conduction mode and discontinuous conduction mode. If the converter is operating under CCM condition then two modes are explained as follows:

- 1) **First Mode [  $0 \leq t \leq DT_s$  ]:** For this interval switch S is turned On and diodes  $D_1, D_2, D_3$  are reversed biased. Inductors  $L_1, L_2, L_3$  are being charged in this interval and capacitors  $C_1$  and  $C_4$  are being charged by the capacitors  $C_2$  and  $C_3$  respectively. The equivalent circuit of the converter in this stage is given in Fig. 3. The corresponding equations across this stage can be written as follows:

$$V_{L1} = V_i \quad (1)$$

$$V_{L2} = V_{c2} - V_{c1} + V_i \quad (2)$$

$$V_{L3} = V_{c3} - V_{c4} + V_i \quad (3)$$

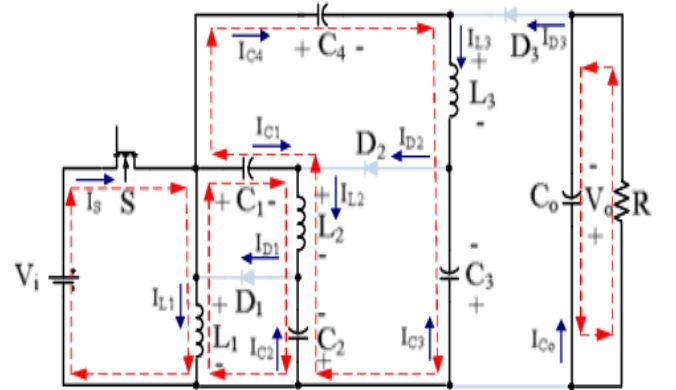


Figure 3: Equivalent circuit during Mode 1

- 2) **Second Mode [  $DT_s \leq t \leq T_s$  ]:** In this mode, the switch is turned off and Diodes  $D_1, D_2, D_3$  start conducting. All of the inducts are discharged in this mode. Inductor  $L_1$  charges capacitor  $C_2$  and inductor  $L_2$  charges capacitor  $C_3$ . Capacitors  $C_1$  and  $C_4$  are being discharged respectively. The equivalent circuit in this stage is given in the figure 4. The

corresponding equations in this mode are as follows:

$$V_{L1} = -V_{C2} \quad (4)$$

$$V_{L2} = -V_{C1} = V_{C2} - V_{C3} \quad (5)$$

$$V_{L3} = V_{C1} - V_{C4} = V_{C3} - V_o \quad (6)$$

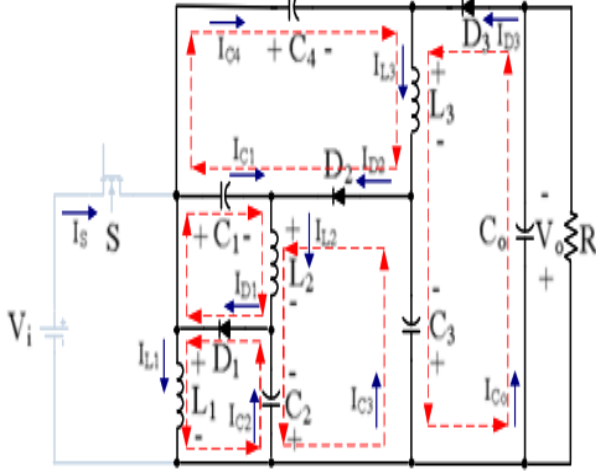


Figure 4: equivalent Circuit during Mode 2

#### IV. STEADY ANALYSIS OF PROPOSED CONVERTER

##### A. Gain of the Converter

The voltage gain of the converter can be derived using a volt-sec balance principle and applying it across inductors  $L_1$ ,  $L_2$ ,  $L_3$  with the help of equations (1)-(6):

$$\frac{1}{T_s} \left( \int_0^{DT_s} V_i dt + \int_{DT_s}^{T_s} (-V_{C2}) dt \right) = 0 \quad (7)$$

$$\frac{1}{T_s} \left( \int_0^{DT_s} (V_{C2} - V_{C1} + V_i) dt + \int_{DT_s}^{T_s} (-V_{C1}) dt \right) = 0 \quad (8)$$

$$\frac{1}{T_s} \left( \int_0^{DT_s} (V_{C3} - V_{C4} + V_i) dt + \int_{DT_s}^{T_s} (V_{C1} - V_{C4}) dt \right) = 0 \quad (9)$$

Now, the voltage across the capacitors  $C_1, C_2, C_3, C_4$ , and  $C_o$ , can be determined the help of above equations as follows:

$$V_{C1} = V_{C4} = \frac{2DV_i}{1-D} \quad (10)$$

$$V_{C2} = V_{C3} = \frac{DV_i}{1-D} \quad (11)$$

With the help of equations (10) and (11), the gain of the converter can be derived as follows:

$$M_{CCM} = \frac{V_o}{V_i} = \frac{V_{C3} + V_{C4}}{V_i} = \frac{3D}{1-D} \quad (12)$$

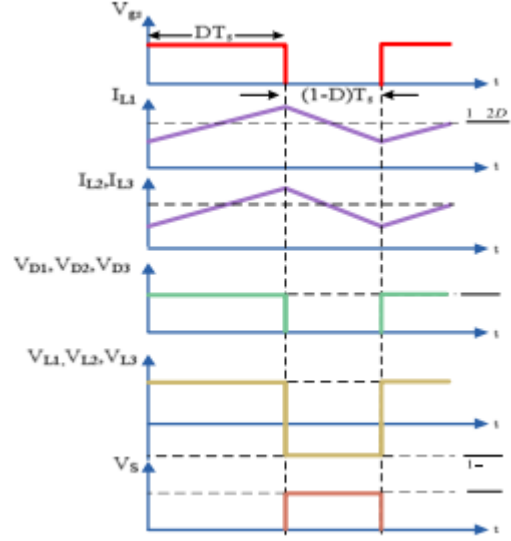


Figure 5: Waveforms of the Proposed Converter

The above figure represents the waveforms of the proposed converter under Continuous Conduction Mode.

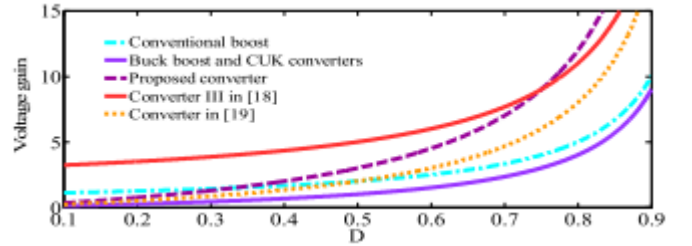


Figure 6: Comparison of Voltage Gain of different Converters[10]

As is visible from the graph curve in the Fig. 6, the voltage gain of the proposed converter is higher than as compared to other converters link traditional boost, buck-boost, SEPIC, CUK and ZETA converters.

##### B. Calculations for Currents

When the converter is operating under Mode 1, during the switch S is turned on then the current across the output, inductors and capacitors is given by:

$$I_{Co, Ton} = -I_o \quad (13)$$

$$I_{C1, Ton} = -I_{C2, Ton} = I_{L2} \quad (14)$$

$$I_{C3, Ton} = -I_{C4, Ton} = I_{L3} \quad (15)$$

During the Mode 2, currents can be given by following equations:

$$I_{C1, Toft} = I_{L2} - I_{C3, Toft} - I_{L3} \quad (16)$$

$$I_{C4, Toft} = I_{L3} - I_{Co, Toft} - I_o \quad (17)$$

By using the current equations which has been derived for both Mode 1 and Mode 2, average current across inductors and capacitors can be written as follows:

$$\begin{aligned} I_{L2} = I_{L3} = I_{C1, \text{on}} = -I_{C2, \text{on}} = -I_{C3, \text{on}} = I_{C4, \text{on}} \\ = -I_{C0, \text{on}} = I_o. \end{aligned} \quad (18)$$

Meanwhile, the average current across  $L_1, D_1, D_2, D_3$ , is given by:

$$I_{L1} = \frac{1+2D}{1-D} I_o \quad (19)$$

$$I_{D1} = I_{D2} = I_{D3} = \frac{I_o}{1-D} \quad (20)$$

The average input current and current across switch is given by:

$$I_s = \frac{3}{1-D} I_o \quad (21)$$

$$I_{in} = \frac{3D}{1-D} I_o \quad (22)$$

In the inductors, ripple current  $\Delta I$  can be calculated as follows:

$$\Delta I_{L1,2,3} = \frac{DV_i}{L_{1,2,3}f_s} = \frac{(1-D)V_o}{3L_{1,2,3}f_s} \quad (23)$$

### C. Boundary Condition

In the boundary condition, the gain of the converter in CCM is equal to DCM.  $\tau_b$  is the boundary normalized inductor time constant. If  $\tau_b$  is larger than the  $\tau_L$  then the converter is said to be operating in DCM where  $\tau_L$  and  $\tau_b$  is given by:

$$\tau_b = \frac{(1-D)^2}{9} \quad (24)$$

$$\tau_L = \frac{2L_e}{RT_s} \quad (25)$$

Here  $L_e$  is equivalent inductance of the circuit.

$$\frac{1}{L_e} = \frac{1}{L_1} + \frac{1}{L_2} + \frac{1}{L_3} \quad (26)$$

### D. Calculations for voltage Ripple in the Capacitors

The voltage ripple  $\Delta V_{C1}$  and  $\Delta V_{C2,3,4,0}$  across capacitor  $C_1$  and  $C_{2,3,4,0}$  can be derived with the help of Fig. 7:

$$\Delta V_{C1} = \frac{DT_s V_o}{RC_1} \quad (27)$$

$$\Delta V_{C2,3,4,0} = \frac{DT_s V_o}{RC_{2,3,4,0}} \quad (28)$$

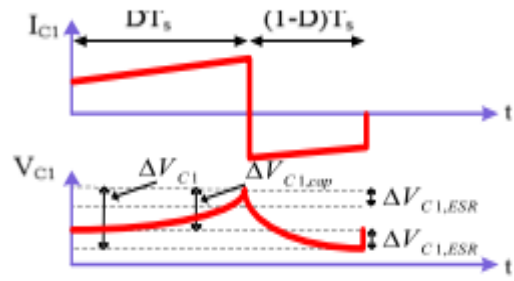
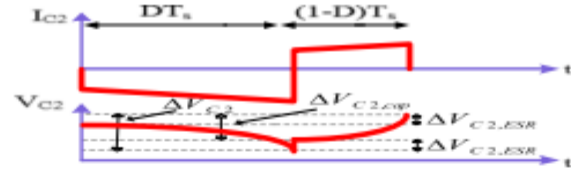
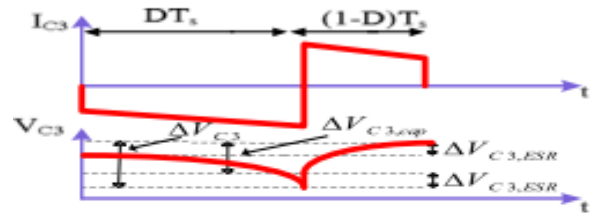


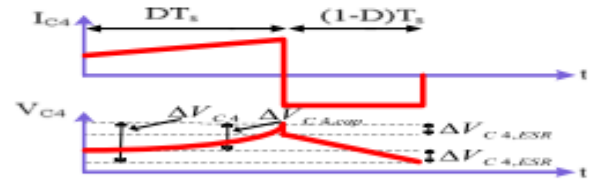
Figure 7:(a) Current and voltage across capacitor  $C_1$



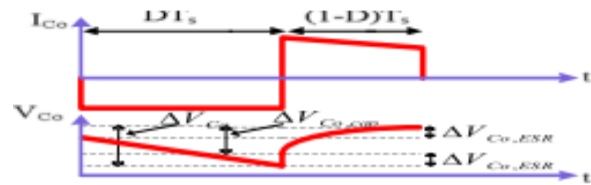
Current and voltage of the capacitor  $C_2$ .



Current and voltage of the capacitor  $C_3$



Current and voltage of the capacitor  $C_4$ .



Current and voltage of the capacitor  $C_0$ .

Figure 8: Voltage and Currents across Capacitors  $C_{2,3,4,0}$

## V. CONVERTER PARAMETERS CALCULATIONS

### Specifications:

Input Voltage,  $V_{in} = 11V$

Output Voltage,  $V_o = 42V$

Switching frequency,  $f_s = 33KHz$

Output Power,  $V_{in} = 1135W$

Input Voltage,  $V_{in} = 11V$

A. **Duty,  $D$**   $= \frac{V_o}{V_o + V_{IN}} = \frac{42}{42+11} = 0.56$

B. **Output Current,  $I_o$**   $= \frac{P_o}{V_o} = \frac{135}{42} = 3.214A$

C. **Output Resistance,  $R_o$**   $= \frac{V_o^2}{P_o} = \frac{42^2}{135} = 13.667\Omega$

D. **Inductor,  $L_1$**

$$\text{Inductor Current, } I_{L1} = \frac{1+2D}{1-D} I_o = \frac{1+2*0.56}{1-0.56} * 3.214$$

$$I_{L1} = 15.487A$$

$$\text{Inductor Ripple, } \Delta I_{L1} = 0.01 * I_{L1} = 154.87 * 10^{-3} A$$

$$L_1 = \frac{D * V_{in}}{f_s * \Delta I_{L1}} = \frac{0.56 * 11}{(154.87 * 10^{-3})} = 1.205mH$$

E. **Inductor,  $L_2$**

$$\text{Inductor Current, } I_{L2} = I_o = 3.214 A$$

$$\text{Inductor Ripple, } \Delta I_{L1} = 0.01 * I_{L2} = 32.142857 * 10^{-3} A$$

$$L_2 = \frac{D * V_{in}}{f_s * \Delta I_{L1}} = \frac{0.56 * 11}{(32.142 * 10^{-3})} = 5.8mH$$

F. **Inductor,  $L_3$**

$$\text{Inductor Current, } I_{L3} = I_o = 3.214 A$$

$$\Delta I_{L3} = 0.01 * I_{L3} = 32.142857 * 10^{-3} A$$

$$L_3 = \frac{D * V_{in}}{f_s * \Delta I_{L1}} = \frac{0.56 * 11}{(32.142 * 10^{-3})} = 5.8mH$$

G. **Capacitor,  $C_1$**

$$V_{C1} = \frac{2 * D * V_{in}}{1 - D} = 28V$$

$$\Delta V_{C1} = 0.01 * V_{C1} = 280mV$$

$$C_2 = \frac{D * V_o}{f_s * \Delta * R_o} = 194.8\mu F$$

H. **Capacitor,  $C_2$**

$$V_{C2} = \frac{2 * D * V_{in}}{1 - D} = 14V$$

$$\Delta V_{C2} = 0.01 * V_{C2} = 140mV$$

$$C_2 = \frac{D * V_o}{f_s * \Delta * R_o} = 389.6 \mu F$$

I. **Capacitor,  $C_3$**

$$V_{C3} = \frac{D * V_{in}}{1 - D} = 14V$$

$$\Delta V_{C3} = 0.01 * V_{C3} = 140mV$$

$$C_3 = \frac{D * V_o}{f_s * \Delta * R_o} = 389.6 \mu F$$

J. **Capacitor,  $C_4$**

$$V_{C4} = \frac{D * V_{in}}{1 - D} = 28V$$

$$\Delta V_{C4} = 0.01 * V_{C4} = 280mV$$

$$C_4 = \frac{D * V_o}{f_s * \Delta * R_o} = 194.8\mu F$$

K. **To check whether it is working in CCM or DCM**

$$\tau_L = \frac{2 * L_e}{R_o * T_s} = 4.302222$$

$$\tau_b = \frac{(1-D)^2}{9} = 21.511111 * 10^{-3}$$

In this case,  $\tau_L$  is larger than  $\tau_b$  meaning that the converter is operating in continuous conduction mode.

## VI. SIMULATION RESULTS

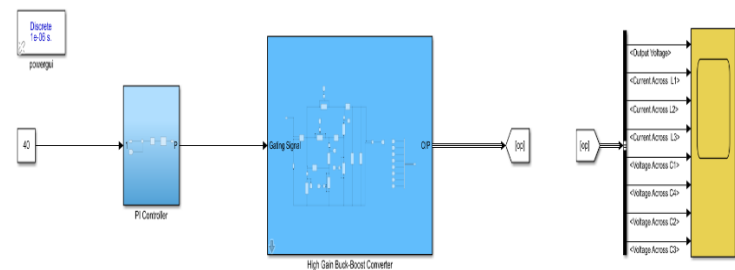


Figure 9: MATLAB/Simulink Model

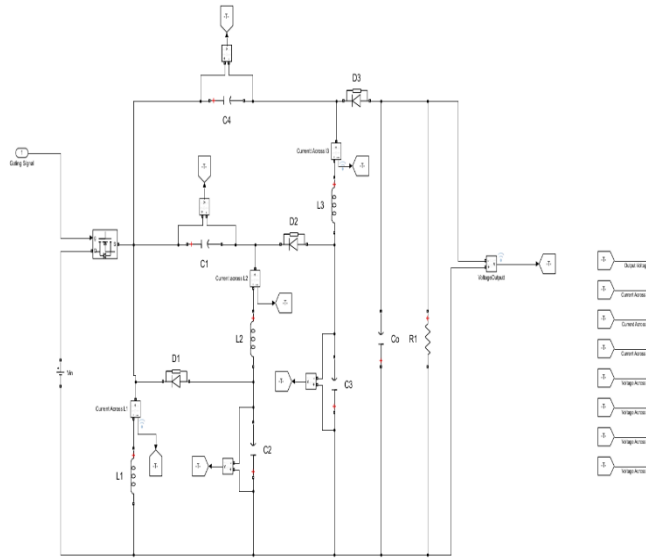


Figure 10: Proposed converter Simulink Model

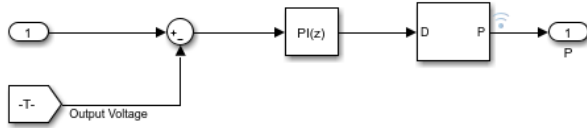


Figure 11: PI Controller

### A. Simulation Results without PI Controller

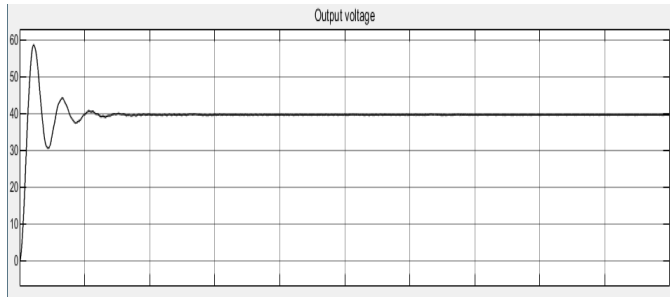


Figure 12: Output Voltage without PI Controller

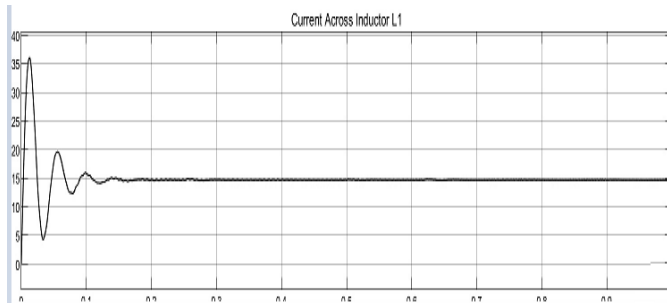


Figure 13: Current Across Inductor  $L_1$

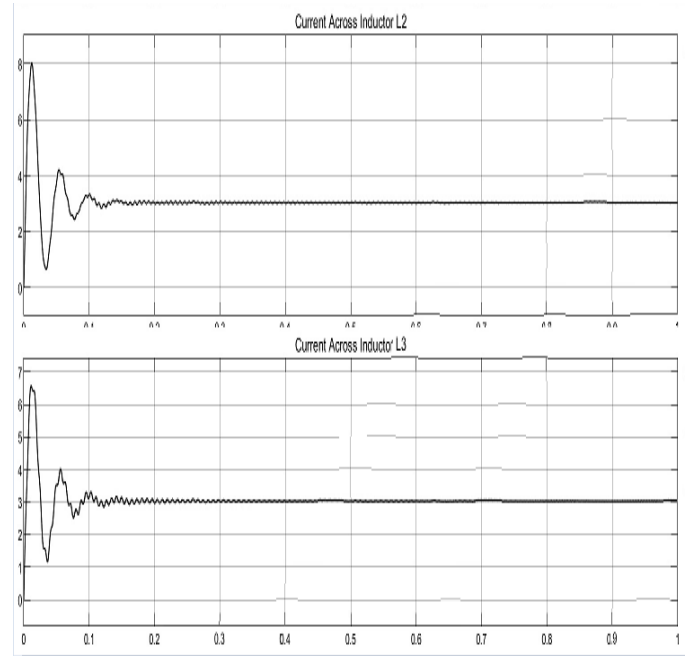


Figure 14: Currents Across Inductor  $L_2$  and  $L_3$  Without PI Controller

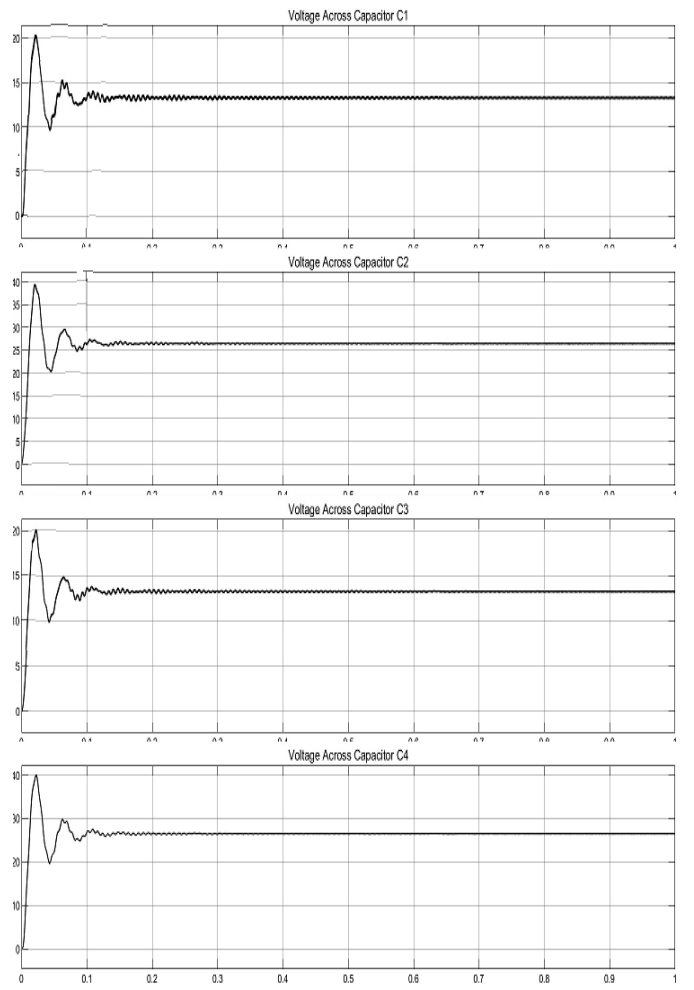


Figure 15: Voltage Across Capacitors without PI Controller

## B. Simulation Results With PI Controller

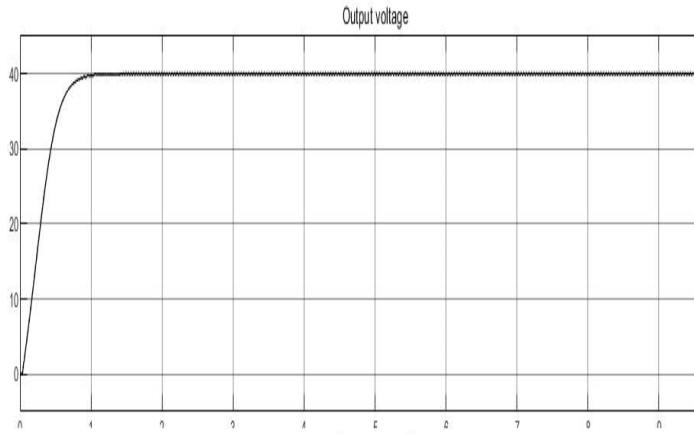


Figure 16: Output Voltage with PI Controller

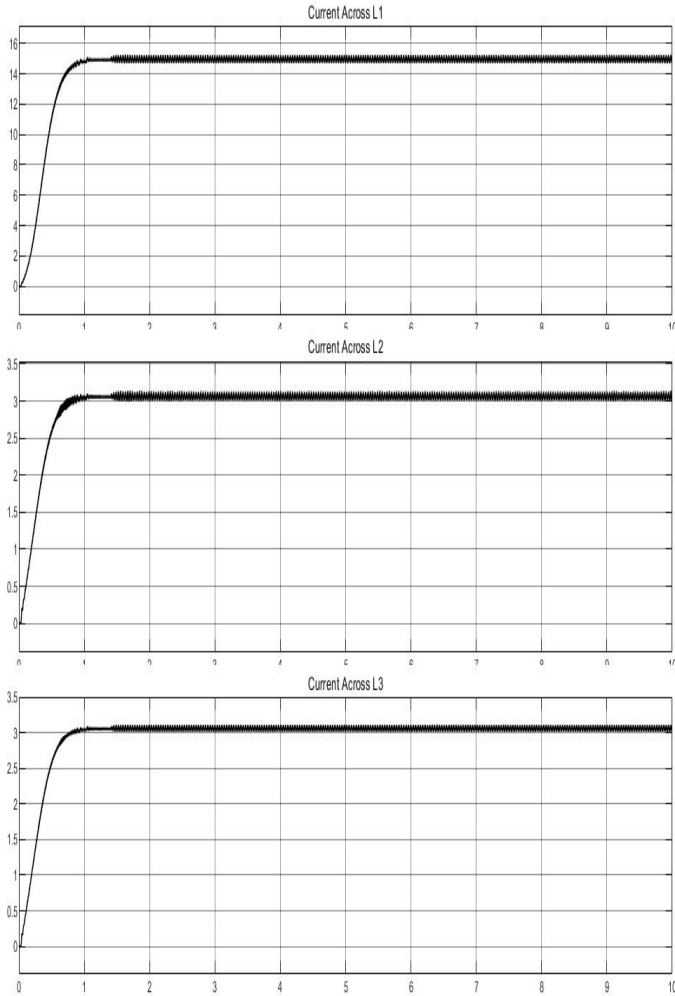


Figure 17: Current Across Inductors with PI Controller

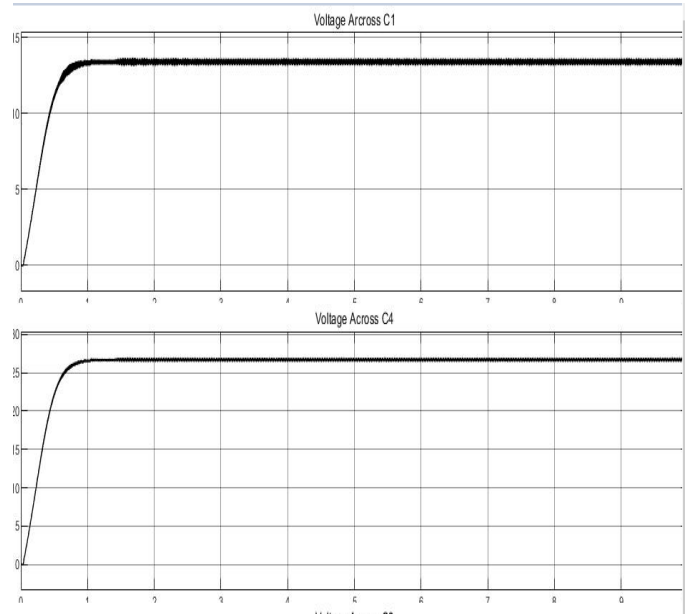


Figure 18: Voltage Across Capacitor  $C_1$  and  $C_4$

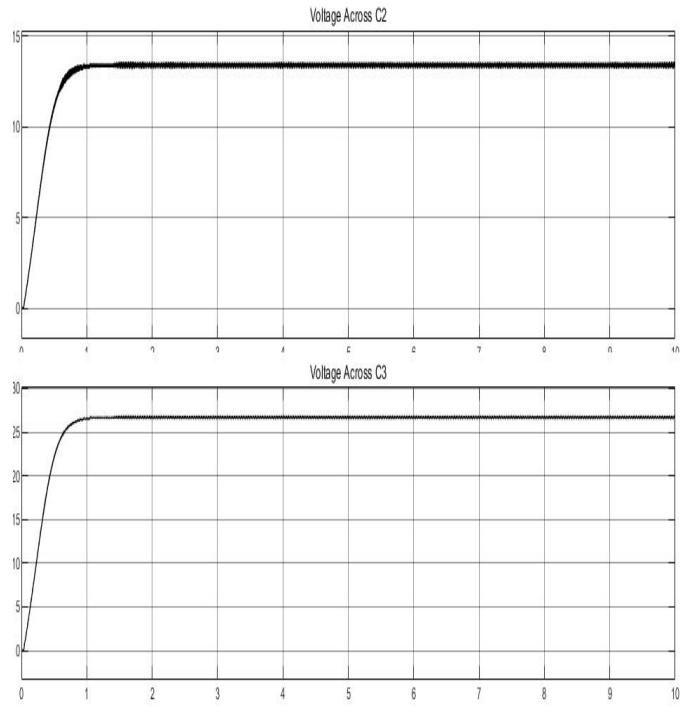


Figure 19: Voltage Across Capacitor  $C_2$  and  $C_3$

As is visible from the system response that when this converter is simulated without PI controller, there is large overshoot but when the PI controller is implemented then there is no overshoot in the system. The system response is much faster as compared to earlier.

### C. Percentage ripple in the output Voltage

The parameters of the converter were calculated using 1% ripple in the current across inductors and voltage across capacitors. When the ripple across output voltage is calculated then it comes about to be 1% which verifies that calculated parameters were in fact correct. The ripple calculation is given in the Fig. 19.

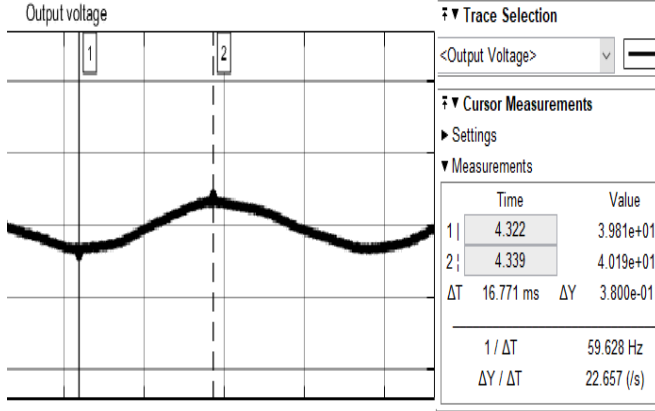


Figure 20: Output Voltage Ripple Calculation

$$\%V_{o \text{ ripple}} = \frac{3.8 \times 10^{-1}}{40} \times 100 = 0.95\%$$

### VII. CONCLUSION

A novel technique for a transformerless high gain buck-boost converter is implemented in this project whose structure is simple and does not require complex control algorithm. The voltage gain of this converter is higher than conventional Boost, Buck-Boost, CUK, SEPIC and ZETA converters. First its response is observed without PI controller in which case there is large overshoot. Then it is simulated with PI controller in which case there is no overshoot and system settle down to the reference value. In the future work, loss analysis of this converter will be performed. Furthermore, a CLC filter could be implemented to further reduce the ripple in output voltage so that this converter could be used in applications where precise voltage is required.

### REFERENCES

- [1] K. Jin, X. Ruan, M. Yang, and M. Xu, "A hybrid fuel cell power system," *IEEE Trans. Ind. Electron.*, vol. 56, no. 4, pp. 1212–1222, Apr. 2009.
- [2] J. W. S. Liu, J. F. Chen, T. J. Liang, R. L. Lin, and C. H. Liu, "Analysis, design, and control of bidirectional cascaded configuration for a fuel cell hybrid power system," *IEEE Trans. Power Electron.*, vol. 25, no. 6, pp. 1565–1575, Jun. 2010.
- [3] S.-K. Changchien, T.-J. Liang, J.-F. Chen, and L.-S. Yang, "Novel high step-up DC-DC converter for fuel cell energy conversion system," *IEEE Trans. Ind. Electron.*, vol. 57, no. 6, pp. 2007–2017, Jun. 2010.
- [4] W. Jiang and B. Fahimi, "Active current sharing and source management in fuel cell-battery hybrid power system", *IEEE Trans. Ind. Electron.*, vol. 57, no. 2, pp. 752–761, Feb. 2010.
- [5] A. A. Ahmad and A. Abrishamifar, "A simple current mode controller for two switches buck-boost converter for fuel cells, in *Proc. IEEE Elect. Power Conf.*, 2007, pp. 363–366.
- [6] R. J. Wai, C. Y. Lin, R. Y. Duan, and Y. R. Chang, "High-efficiency DC–DC converter with high voltage gain and reduced switch stress," *IEEE Trans. Ind. Electron.*, vol. 54, no. 1, pp. 354–364, Feb. 2007.
- [7] T. J. Liang, J. H. Lee, S. M. Chen, J. F. Chen, and L. S. Yang, "Novel isolated high-step-up dc–dc converter with voltage lift," *IEEE Trans. Ind. Electron.*, vol. 60, no. 4, pp. 1483–1491, Apr. 2013.
- [8] G. Spiazzi, P. Mattavelli, and A. Costabeber, "Effect of parasitic components in the integrated boost-flyback high step-up converter," in *Proc. 35th Annu. Conf. IEEE Ind. Electron. Soc.*, Nov. 2009, pp. 420–425.
- [9] B. Singh, B. N. Singh, A. Chandra, K. Al-Haddad, A. Pandey, D. P. Kothari, "A Review of Single-Phase Improved Power Quality AC–DC Converters"; *IEEE Transactions On Industrial Electronics*, Vol. 50, No. 5, October 2003.
- [10] M. R. Banaei and H. A. F. Bonab, "A Novel Structure for Single-Switch Nonisolated Transformerless Buck–Boost DC–DC Converter," in *IEEE Transactions on Industrial Electronics*, vol. 64, no. 1, pp. 198–205, Jan. 2017, doi: 10.1109/TIE.2016.2608321.