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

Zain Bhinder[1], Gurdeep Singh[2]
Dept. of Electrical and Computer Engineering,
Concodia University,
Montreal, Canada
z_bhinde@encs.concordia.ca[1], s_urdeep@encs.concordia.ca[2]

***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 quadrans 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.

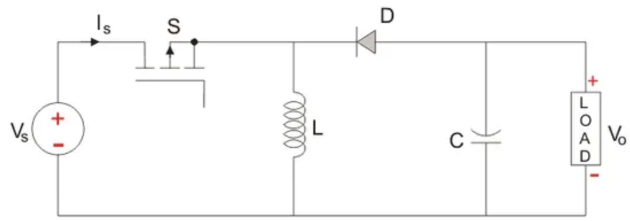


Figure 1:Equivalent Circuit of Conventional Buck-Boost Converter

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.

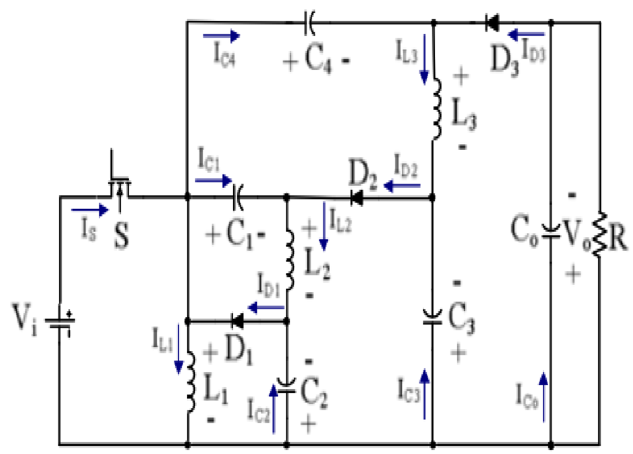


Figure 2: Equivalent Circuit of the proposed Converter

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 Ro. 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 [$0 \le t \le DT_s$]:** 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:

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

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

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

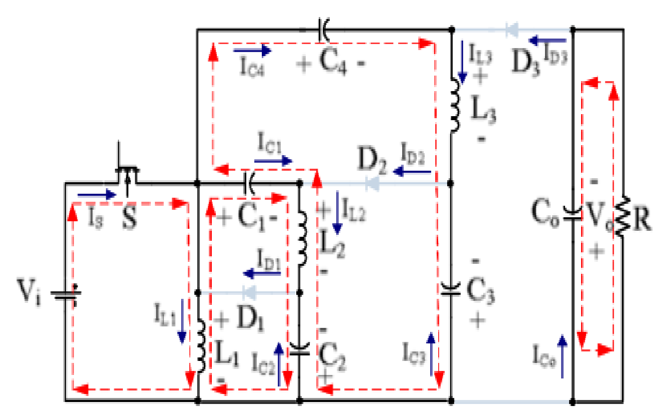


Figure 3:Equivalent circuit during Mode 1

2) **Second Mode [$DT_s \le t \le T_s$]:** 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_1 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:

$$V_{L1} = -V_{c2} \quad (4)$$

$$V_{L2} = -V_{c1} = V_{c2} - V_{c3} \quad (5)$$

$$V_{L3} = V_{c1} - V_{c4} = V_{c3} - V_o \quad (6)$$

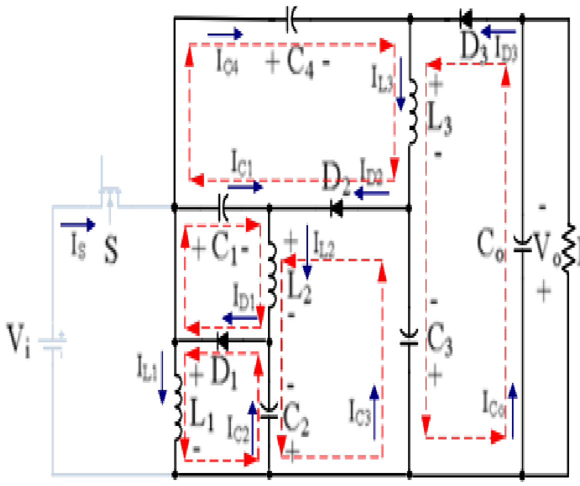


Figure 4: equivalent Circuit during Mode 2

IV. Steady Analysis of Proposed Convertr

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):

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

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

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

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:

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

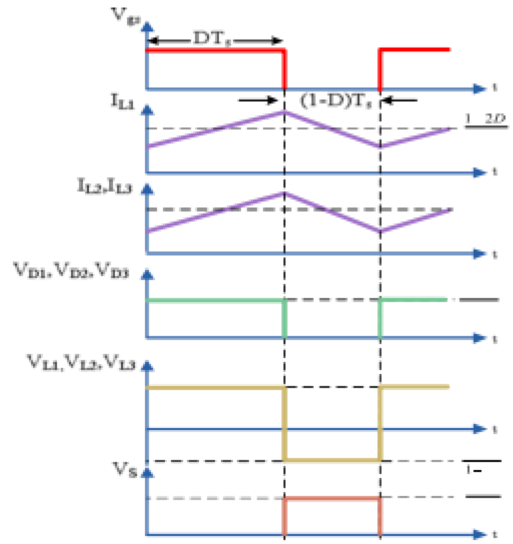


Figure 5:Waveforms of the Proposed Converter

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

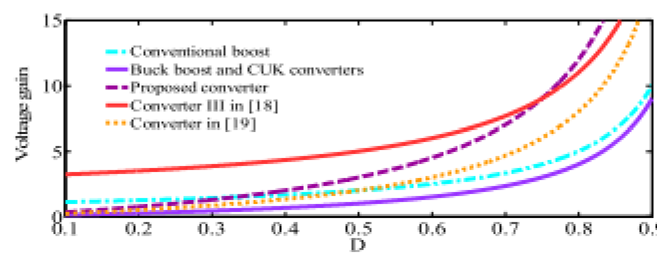


Figure 6: Comparison of Voltage Gain of different Converters[10]

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:

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

$$I_{\mathrm{C1},Ton} = -I_{c2,Ton} = I_{L2} \quad (14)$$

$$I_{\mathrm{C3},Ton} = -I_{c4,Ton} = I_{L3} \quad (15)$$

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

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

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

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:

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

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 ΔI 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. τ_b is the boundary normalized inductor time constant. If τ_b is larger than the τ_L then the converter is said to be operating in DCM where τ_L *and* τ_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 ΔV_{c1} *and* $\Delta V_{c2,3,4,o}$ across capacitor C_1 *and* $C_{2,3,4,o}$ can be derived with the help of Fig. 7:

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

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

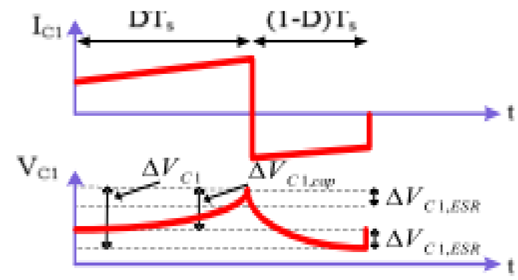
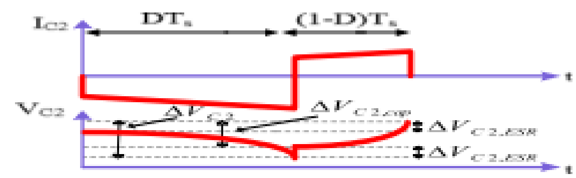
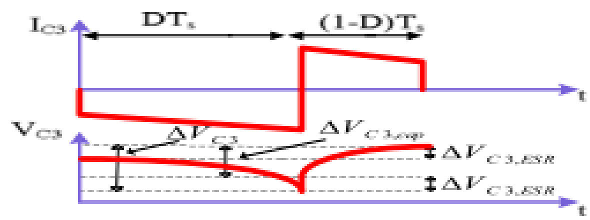


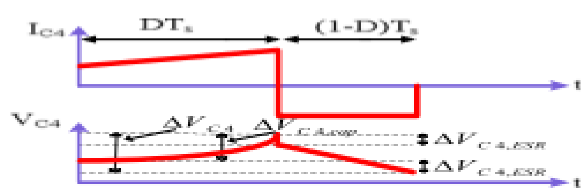
Figure 7:(a) Current and voltage across capacitor C_1



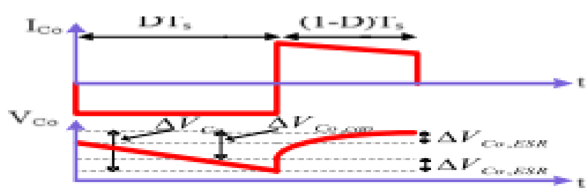
Current and voltage of the capacitor C_2.



Current and voltage of the capacitor C_3



Current and voltage of the capacitor C_4.



Current and voltage of the capacitor C_o.

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

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. $\boldsymbol{Duty, D} = \frac{V_O}{V_O+V_{IN}} = \frac{42}{42+11} = 0.56$

B. $\boldsymbol{Output\ Current, I_o} = \frac{P_O}{V_O} = \frac{135}{42} = 3.214A$

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

D. $\boldsymbol{Inductor, L_1}$

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

$$I_{L1} = 15.487A$$

Inductor Ripple, ΔIL_1= 0.01* IL_1= 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. $\boldsymbol{Inductor, L_2}$

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

Inductor Ripple, ΔIL_1= 0.01* IL_2= 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. $\boldsymbol{Inductor, L_3}$

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

ΔIL_3= 0.01* IL_3= 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. $\boldsymbol{Capacitor, C_1}$

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

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

$$C_2 = \frac{D*V_o}{f_s*\Delta*R_o} = 194.8\text{uF}$$

H. $\boldsymbol{Capacitor, C_2}$

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

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

$$C_2 = \frac{D*V_o}{f_s*\Delta*R_o} = 389.6\text{ uF}$$

I. $\boldsymbol{Capacitor, C_3}$

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

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

$$C_3 = \frac{D*V_o}{f_s*\Delta*R_o} = 389.6\text{ uF}$$

J. $\boldsymbol{Capacitor, C_4}$

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

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

$$C_4 = \frac{D*V_o}{f_s*\Delta*R_o} = 194.8\text{uF}$$

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, τ_L is larger than τ_b meaning that the converter is operating in continuous conduction mode.

VI. Simulation Results

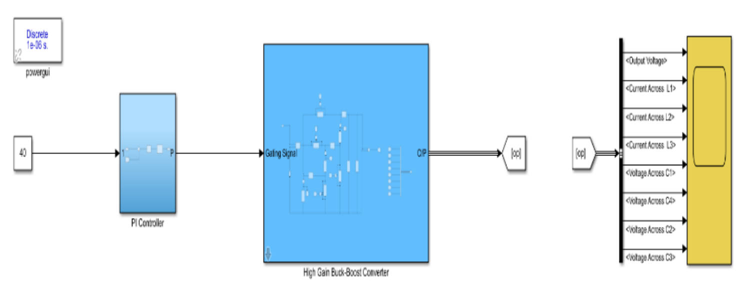


Figure 9: MATLAB/Simulink Model

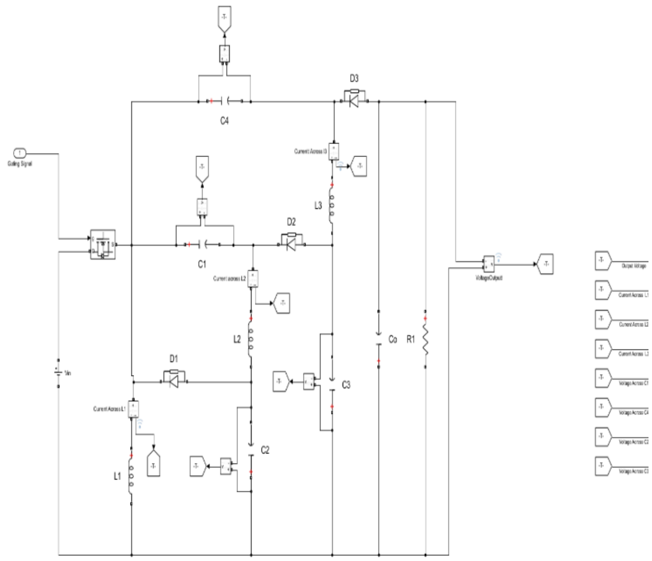


Figure 10: Proposed converter Simulink Model

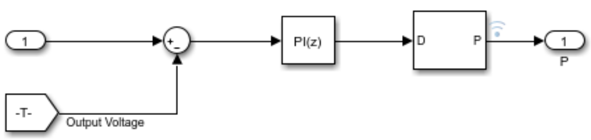


Figure 11: PI Controller

A. *Simulation Results without PI Controller*

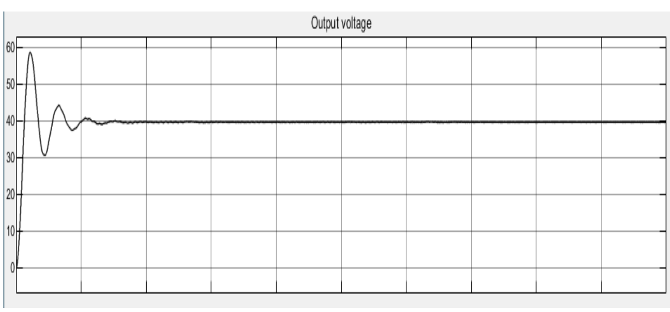


Figure 12: Output Voltage without PI Controller

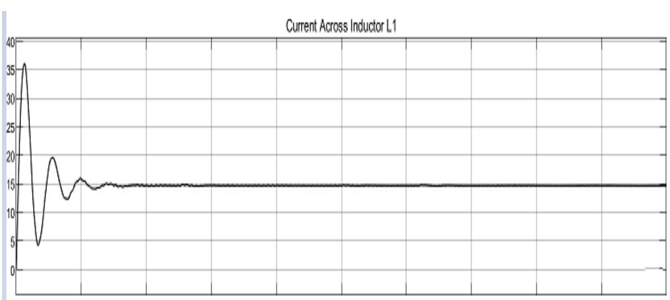


Figure 13: Current Across Inductor L_1

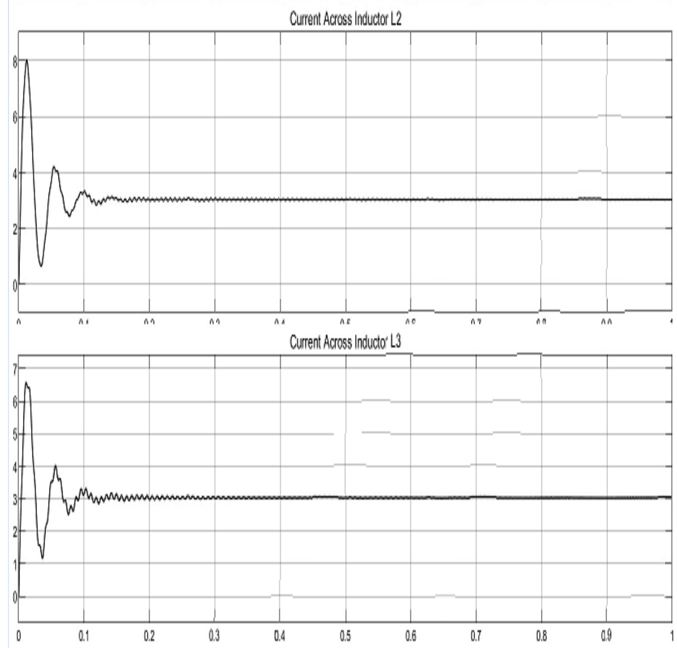


Figure 14: Currents Across Inductor L_2 and L_3 Without PI Controller

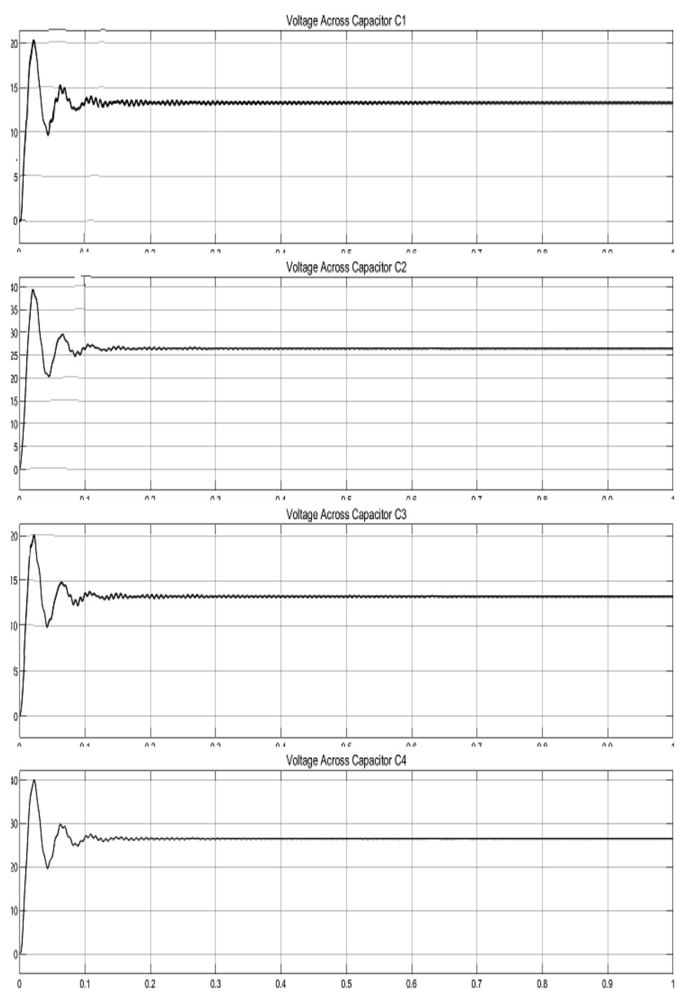


Figure 15: Voltage Across Capacitors without PI Controller

B. ***Simulation Results With PI Controller***

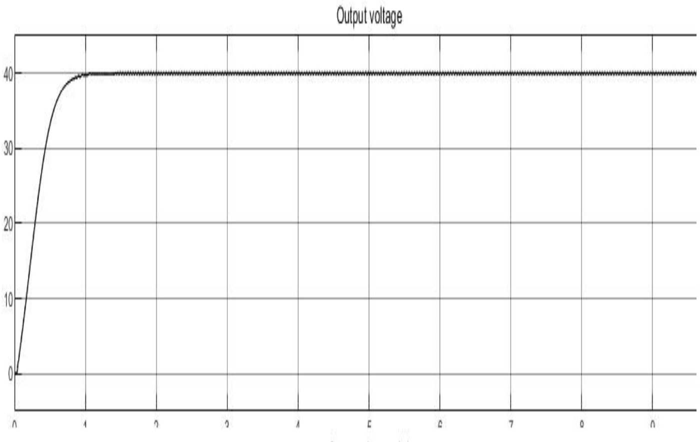


Figure 16: Output Voltage with PI Controller

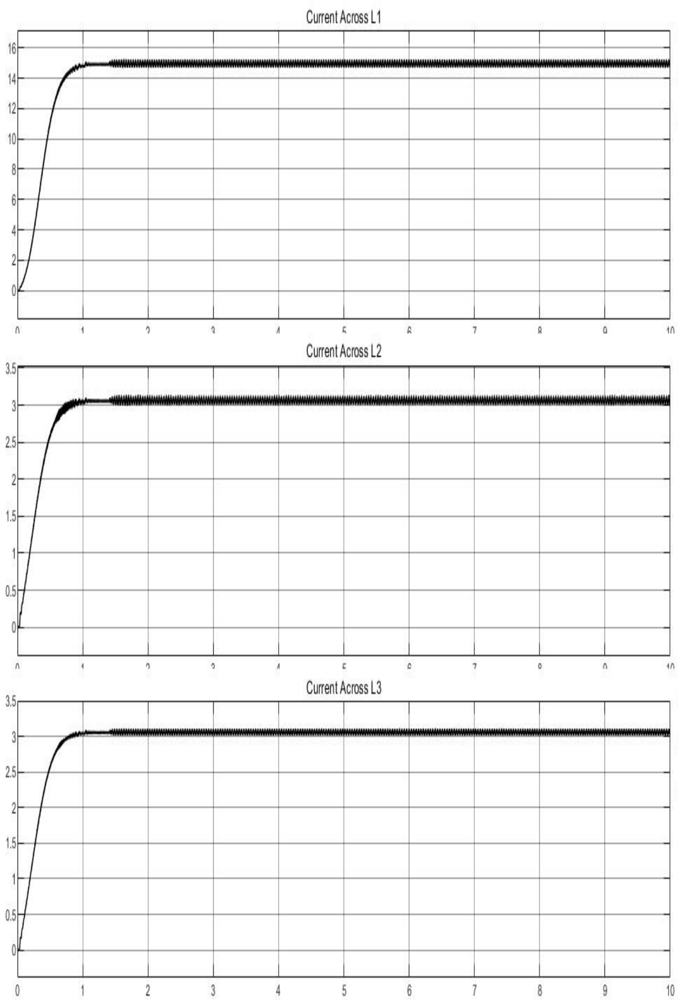


Figure 17: Current Across Inductors with PI Controller

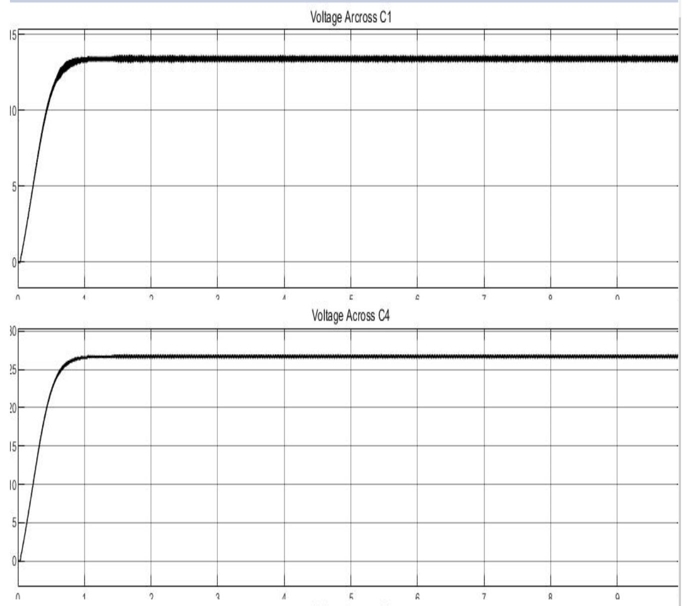


Figure 18: Voltage Across Capacitor C_1 and C_4

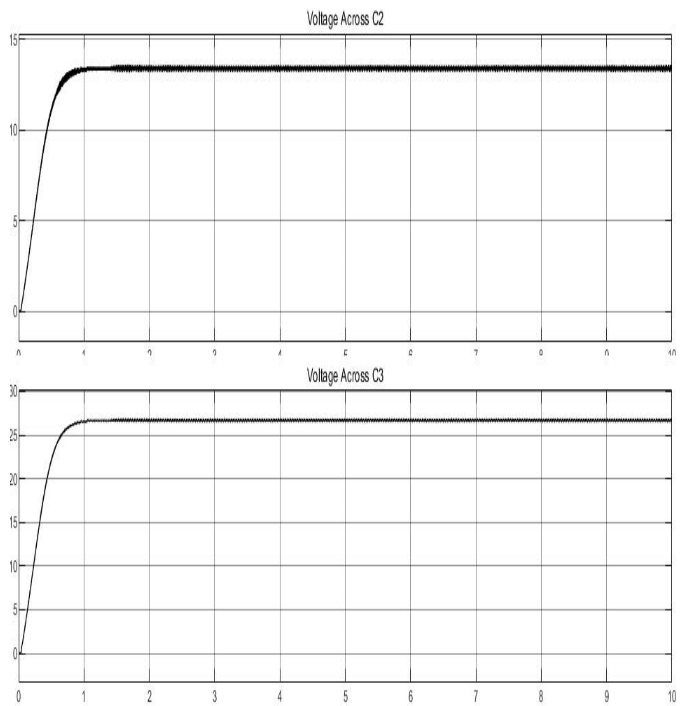


Figure 19: Voltage Across Capacitor C_2 and C_3

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 the 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.

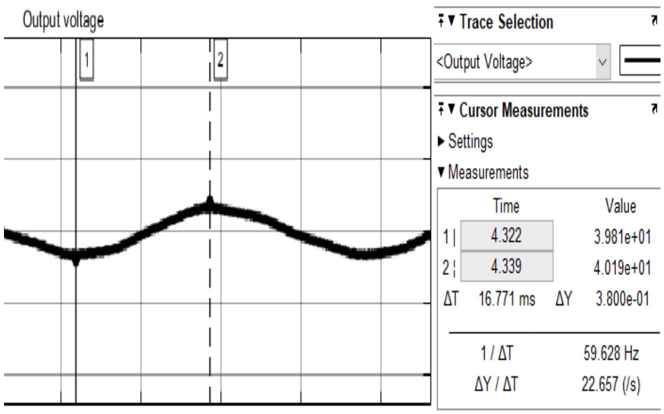


Figure 20: Output Voltage Ripple Calculation

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

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.

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