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Modeling and Stability Analysis of a New Transformer less Buck-Boost Converter for Solar Energy Application

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Abstract— A study and configuration of a new transformerless buck-boost converter is proposed in this work. The normal buck-boost converter has simple configuration and high efficiency. The disadvantage of the normal converter is restricted voltage gain, negative output voltage, floating power switch, discontinuous output and input currents. For eliminating the disadvantages of the normal converter, a new transformer less buck-boost converter is proposed. The proposed new transformer less buck-boost converter consists of two switches, two capacitors, two inductors and one resistor load in the circuit. The two power switches of the proposed converter operate simultaneously. The proposed buck-boost converter gives the voltage gain is squared or quadratic times of normal converter which makes it suitable for solar energy applications. In continuous conduction mode, a voltage gain, operating principles, small-signal model and voltage stress are described for the proposed converter. To improve the stability of a system, a PI controller is used in the proposed converter. The structure of the proposed buck-boost converter circuit is simulated in MATLAB/ SIMULINK

Index Terms— High voltage gain, Transformerless buck-boost converter, Small signal model, Voltage stress.

INTRODUCTION

In recent years, extensive use of electrical equipment has increased rapidly. As the insist for power is significantly increasing, naturally replenished energy sources have received a bundle of attention as an alternatives way of generating directly electricity. Using renewable energy sources is able to eliminate harmful emissions from polluting the environment while also offering inexhaustible resources of primary energy. There are various non-conventional energy sources such as wind turbines, solar energy and fuel cells. However, fuel cells & solar cells have small output voltage [1], [2], [3]. So that a high efficiency and step-up DC-DC converter is preferred in the power conversion systems to amplify the voltage supplied to the grid or be compatible in other applications. Basically, the conventional or traditional buck-boost converter is capable of give an extra voltage gain by means of an extremely high duty cycle. A DC-DC converter is a necessary component of alternative and portable devices, renewable energy alteration and many industrial applications. A DC-DC converter is mainly use to transfer the unregulated dc voltage to regulated dc voltage. The solar cell output or rectifier output is the variable dc voltage. The buck-boost converter is the main converter in DC-DC converters. The buck-boost converter mainly depends on duty ratio and it gives the more voltage or low voltage. Switching conversion is better than the linear voltage regulation. The normal buck-boost converter presents inverter topology and simple construction. But it has a few disadvantages such as irregular output and input currents, floating power switch, restricted voltage gain and output voltage is negative. Series connection of normal DC-DC converter is not a feasible to attain high voltage gain. In cascaded high step-up DC-DC converter is used to attain high voltage gain [4]-[5].Cascaded topology requires large number of switches so it has more switch losses. To obtain more voltage gain, isolated converter topologies are used. Transformers and coupled inductors be here in the isolated topology, due to this converter size, price and losses are more increases. Non-isolated converter topologies are used to defeat the drawbacks of isolated converter topologies. The three basic non-isolated converters are Cuk converter, zeta converter and Sepic converter. These three converters exhibit the some disadvantages. The disadvantage of a Sepic converter circuit is a fourth order one and difficult to control. Cuk converter exhibit the negative polarity voltage as similar to the normal buck-boost converter and it has the major disadvantage is it requires the large current carrying capacitors. Mainly basic non-isolated converters have limited voltage gain and disadvantage of this converters are non-ignorable. The Peng and Hwu proposed a new converter [6], which is a arrangement of KY converter and conventional synchronously rectified buck converter. This converter gives the positive output voltage, continuous output current and every instance operates in continuous conduction mode. But its voltage gain is two times of the duty ratio. So it does not give the large vary of output voltage. Based on Cuk

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converter, the proposed buck-boost converter has the small output voltage swell, smallest radio frequency nosiness and one common-ground control switch [7]. However, as a seventh-order circuit, the converter has complex construction, and both input and output terminal don't allocate the same ground. Besides the voltage gain is still restricted. In arrange to achieve the more voltage gain, a voltage-lift technique is employed in Luo converters. But this converter is more difficult, volume, losses and cost increases. Especially in regulate to achieve high voltage step-up or step-down gain, these converters should be operating under extremely high or low duty cycle. So in order to eliminate all the drawbacks, a new transformerless buck-boost converter is proposed. The proposed new transformerless buck-boost converter is obtaining by accumulation the additional network into the conventional buck-boost converter. The main advantage of the proposed converter is that its voltage squared or quadratic times of the traditional buck-boost converter. The proposed buck-boost converter can attain high voltage or low voltage without extreme duty cycle. The proposed converter output voltage is positive and common ground with input voltage.

II. PROPOSED TRANSFORMERLESS BUCK-BOOST CONVERTER

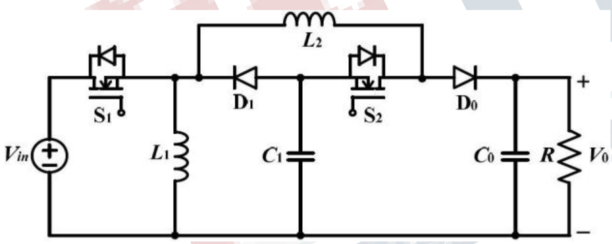

Fig 1 circuit diagram of proposed new transformerless buck-boost converter

The proposed new converter as shown in Fig .1.It consists of two power switches (S_1 and S_2), two capacitors (C_1 and C_0), two inductors (L_1 and L_2), two diodes (D_1 and D_0), and one resistive load R. The Power switches (S_1 and S_2) of the proposed converter operate simultaneously. According to the state of the power switches and diodes, different unique time-domain waveforms for this proposed buck-boost converter working in Continuous conduction mode (CCM) are display in Fig. 2, and the possible function states for the proposed buck-boost converter are shown in Fig. 3.when the power switches S_1 and S_2 are conducted while the diodes D_1 and D_0 are do not conduct. At the time of switches S_1 and S_2 are conducted, the two inductors L_1 and L_2 are magnetized, and both the charge pump capacitor C_1 and the output capacitor C_0 are discharged are shown in fig 3(a). When the power switches S_1 and S_2 are in off state whereas the diodes D_1 and D_0 are conducted for its forward biased voltage. Hence, both the inductor L_1 and L_2 are demagnetized, and both the charge pump capacitor C_1 and the output capacitor C_0 are charged are shown in fig 3(b).Here, in order to consider the circuit we understood that the converter operate in balanced state, all the components of the circuit are standard, and all capacitors are huge enough to keep the voltage transversely them constant.

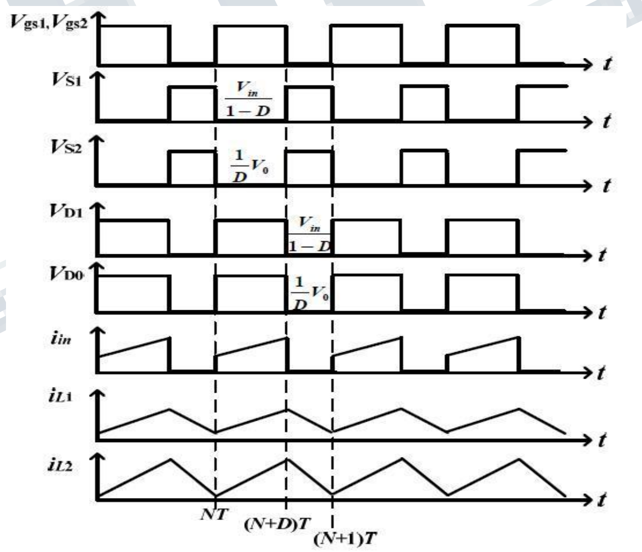

Fig 2 Time-domain waveforms for the proposed buck-boost converter operating in CCM.

A) Operating Principles:

The proposed converter consists of two states of operation. The two states are state 1 and state2 and they are operated in CCM.

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The operating time interval of state1 is (NT<t< (N+D) T). The operating time interval of state2 is ((N+D) T<t< (N+1) T).

State1: (NT<t< (N+D) T)

State1 is operated in the time interval between (NT<t< (N+D) T). During in this interval, the switches S_1 and S_2 are ON, while the diodes D_1 and D_0 are OFF. The inductor L_1 is magnetized from the input voltage V_{in}. While the inductor L_2 is magnetized from the input voltage V_{in} and the charge pump capacitor C_1. Also, the output energy is supplied from the output capacitor C_0 are shown in fig 3(a). The equations of the state1 can be written as,

$V_{L1} = V_{in}$................. (1)

$V_{L2} = V_{in} + V_{C1}$................. (2)

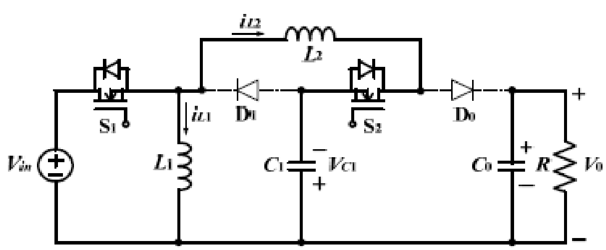

Fig 3(a) equivalent circuit of the state1 of the proposed buck-boost converter

State2: ((N+D) T<t< (N+1) T)

State2 is during the time interval between ((N+D) T<t< (N+1) T). During in this interval, S_1 and S_2 are OFF, while diodes D_1 and D_0 are ON. The energy stored in the inductor L_1 is transfer to the charge pump capacitor C_1 through the diode D_1. At the similar instant, the energy stored in the inductor L_2 is transfer to the charge pump capacitor C_1, output capacitor C_0 and the resistive load R through the diodes D_0 and D_1 are shown in fig3(b). The equations of the state 2 can be written as

$V_{L1} = -V_{C1}$........... (3)

$V_{L2} = -(V_{C1} + V_0)$.............. (4)

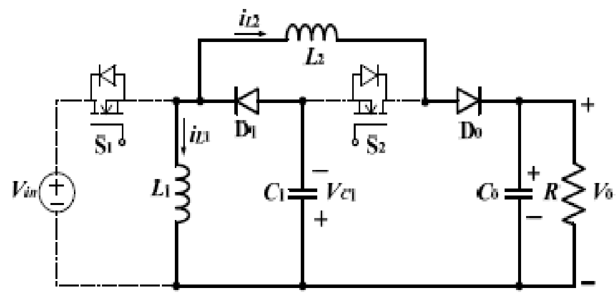

Fig 3(b) equivalent circuit of state2 of the proposed buck-boost converter

Applying the voltage-second balance rule on the inductor L_1,

$$V_{in} \times D = V_{C1} \times (1 - D)$$

Voltage across charge pump capacitor V_{C1} is

$V_{C1} = (\frac{D}{1-D}) \times V_{in}$................ (5)

Where D is the duty ratio.

Duty ratio represents the ratio of turn-on time to the total time.

Correspondingly, by using the voltage-second balance rule on the inductor L_2,

$$(V_{in} + V_{C1}) \times D + \big(-(V_{C1} + V_0) \times (1 - D)\big) = 0$$

$$(V_{in} + V_{C1}) \times D = (V_{C1} + V_0) \times (1 - D) \text{ .... (6)}$$

Put equation (5) in (6)

$$\left(V_{in} + \left(\frac{D}{1-D}\right) V_{in}\right) \times D = \left(\left(\frac{D}{1-D}\right) V_{in} + V_0\right) \times (1 - D)$$

The voltage gain of the proposed new buck-boost converter is

$$\frac{V_0}{V_{in}} = \left(\frac{D}{1-D}\right)^2 \text{ .... (7)}$$

When duty ratio is more than 0.5, the proposed new buck-boost converter can step-up the input voltage. When duty ratio is lower than 0.5, it can step-down the given input voltage.

B) Voltage stress:

Voltage across the charge pump capacitor C_1 voltage can be articulated as

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$V_{C1} = \left(\frac{D}{1-D}\right) \times V_{in} = \left(\frac{1-D}{D}\right) \times V_0 \ldots\ldots(8)$

In step-down mode, the input voltage is greater than V_{C1} and in step-up mode, the output voltage is greater than V_{C1}. Accordingly, the voltage stress on the charge pump capacitor C_1 is small so that we can prefer the minute sized capacitor which have little parasitic resistor to reduce power loss.

The voltage stress across switches S_1 and S_2 are

$V_{S1} = \left(\frac{1}{1-D}\right) \times V_{in} = \left(\frac{1-D}{D^2}\right) \times V_0 \ldots(9)$

$V_{S2} = \frac{D}{(1-D)^2} \times V_{in} = \frac{V_0}{D} \ldots.(10)$

The voltage stress of the two diodes D_1 and D_0 can be derived as

$V_{D1} = \frac{V_{in}}{1-D} = \left(\frac{1-D}{D^2}\right) \times V_0 \ldots(11)$

$V_{D0} = \frac{D}{(1-D)^2} \times V_{in} = \frac{V_0}{D} \ldots(12)$

The voltage on the stress of the power Mosfet S_1 and the diode D_1 are both equal to the voltage stress on the power switch in the traditional buck-boost converter with the same input voltage. Similarly, below the same output voltage condition, it be able to concluded that the voltage stress of the power Mosfet S_2 and the diode D_0 are the same as the voltage stress on the diode in the normal buck-boost converter.

C) Current ripples of inductors:

The ripples of the inductor i_{L1} and i_{L2} can be given as

$$\Delta i_{L1} = \frac{V_{L1}}{L_1} DT_S = \frac{DV_{in}}{L_1 f_S} \ldots(13)$$

$$\Delta i_{L2} = \frac{V_{L2}}{L_2} DT_S = \frac{DV_{in}}{(1-D)L_2 f_S} \ldots.(14)$$

Where f_S is the switching frequency.

If the input voltage V_{in}, the switching frequency f_S , the duty cycle D and the inductor current ripple are known, the inductance of L_1 and L_2 can be intended from the above equations.

D) Voltage ripples of capacitors:

The ripples of the voltage across the capacitors C_1 and C_0 are $\Delta V_{C1}, \Delta V_{C0}$.and it can be described as

$$\Delta V_{C1} = \frac{\Delta Q}{C} = \frac{DV_0}{(1-D)RC_1 f_S}$$

$$\Delta V_{C0} = \frac{\Delta Q}{C} = \frac{DV_0}{RC_0 f_S}$$

If the voltage ripples, the resistive load R ,the output voltage V_0, the switching frequency f_S and the duty ratio D are known, the capacitance of C_1 and C_0 can be calculated based on the above equations.

IV. SMALL SIGNAL MODEL ANALYSIS

Based on small sign model, in state1, the corresponding differential equations are

$$\frac{di_{L1}}{dt} = \frac{V_{in}}{L_1}$$

$$\frac{di_{L2}}{dt} = \frac{V_{in} + V_{C1}}{L2}$$

$$\frac{dV_{C1}}{dt} = -\frac{i_{L2}}{C_1}$$

$$\frac{dV_0}{dt} = -\frac{V_0}{C_0 R}$$

In state 2, the corresponding differential equations are

$$\frac{di_{L1}}{dt} = -\frac{V_{C1}}{L_1}$$

$$\frac{di_{L2}}{dt} = -\frac{V_{C1} + V_0}{L2}$$

$$\frac{dV_{C1}}{dt} = \frac{i_1 + i_{L2}}{C_1}$$

$$\frac{dV_0}{dt} = \frac{i_{L2}}{C_0} - \frac{V_0}{C_0 R}$$

Based on the average method, the average model of the proposed new buck-boost converter operating in CCM can be obtained as follows:

$$\frac{di_{L1}}{dt} = \frac{V_{in}}{L_1} d - \frac{V_{C1}}{L_1}(1-d)$$

$$\frac{di_{L2}}{dt} = \frac{V_{in}}{L2} d + \frac{V_{C1}}{L2}(2d-1) - \frac{V_0}{L2}(1-d)$$

$$\frac{dV_{C1}}{dt} = \frac{i_{L1}}{C_1}(1-d) + \frac{i_{L2}}{C_1}(1-2d)$$

$$\frac{dV_0}{dt} = \frac{i_{L2}}{C_0}(1-d) - \frac{V_0}{C_0 R}$$

Where i_{L1}, i_{L2}, V_{C1}, V_0 and V_{in} are the average values and the duty cycle is d.
Then, the perturbations are added as follows

$i_{L1} = I_{L1} + \hat{i}_{L1}$
$i_{L2} = I_{L2} + \hat{i}_{L2}$
$V_{C1} = V_{C1} + \hat{v}_{C1}$
$V_0 = V_0 + \hat{v}_0$
$V_{in} = V_{in} + \hat{v}_{in}$
$d = D + \hat{d}$

Substituting, separating the perturbations out, neglecting the higher order small signal expressions, and using the Laplace transform the manage to output transfer function can be derived as follows

$$G_{vd} = \frac{b_0 s^3 + b_1 s^2 + b_2 s + b_3}{a_0 s^4 + a_1 s^3 + a_2 s^2 + a_3 s + a_4}$$

Where

$a_0 = L_1 L_2 C_1 C_0 R$
$a_1 = L_1 L_2 C_1$
$a_2 = L_2 C_0 R(1-D)^2 + L_1 C_0 R(1-2D)^2 + L_1 C_1 (1-D)^2$
$a_3 = L_2 (1-D)^2 + L_1 (1-2D)^2$
$a_4 = R(1-D)^4$
$b_0 = -L_1 L_2 C_1 R I_{L2}$
$b_1 = L_1 C_1 R(V_{in} + V_0 + 2V_{C1})(1-D)$
$b_2 = -L_2 R(1-D)^2 I_{L2} - L_1 R(1-2D)^2 I_{L2} + L_1 R(-I_{L1} - 2I_{L2})(1-D)(2D-1)$
$b_3 = R(V_{in} + V_0 + 2V_{C1})(1-D)^3 + R(V_{in} + V_{C1})(1-D)^2(2D-1)$

Based on this transfer function, the small signal dynamic behaviors of the proposed new buck-boost converter are able to analyze.

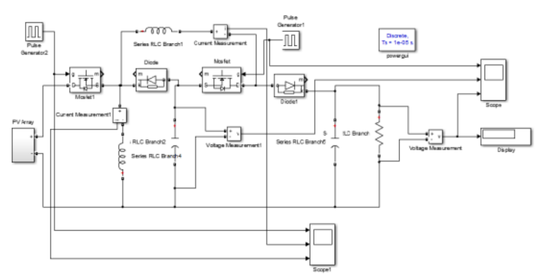
V.SIMULATION DIAGRAM AND RESULTS

The circuit diagram of the new transformerless buck-boost converter is simulated using the MATLAB/SIMULINK software to confirm the above mentioned analyses. Circuit parameters chosen are shown in the below table1.

a) Without feedback

Parameter	Value
V_{in}	18V
f_s	20kHz
D	0.4 - 0.6
L_1	1mH
L_2	3mH
C_1	10µF
C_2	20µF

Table 1 simulation parameter values



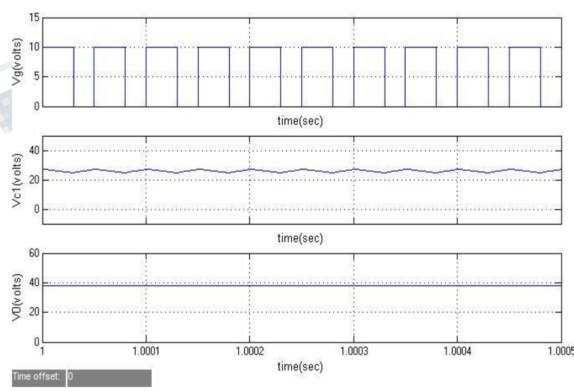


Fig 5 (a) The proposed converter operated in step-up mode.(V_g,V_{c1} and V_0)

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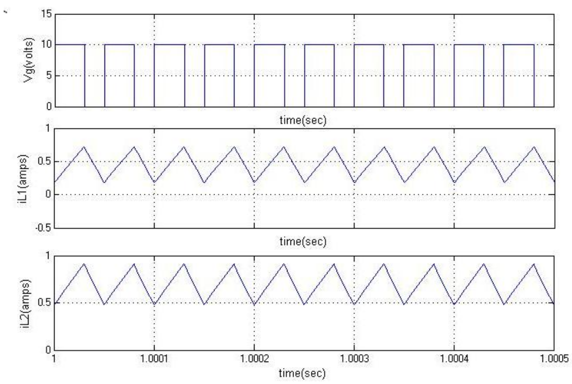


Fig 5(b) The proposed converter operating in step -up mode.(V_g,i_{L1} and i_{L2})

For the proposed converter operating in step-up mode with duty ratio 0.6,the values of V_g, Vc1 and V_0 are shown in fig 5(a).V_g,i_{L1} and i_{L2} are shown in fig 5(b).The theoretical values of the proposed converter are V_g=10V,V_{c1}=27V, V_0=40.5V,i_{L1}=0.3375A and i_{L2}=0.675A.

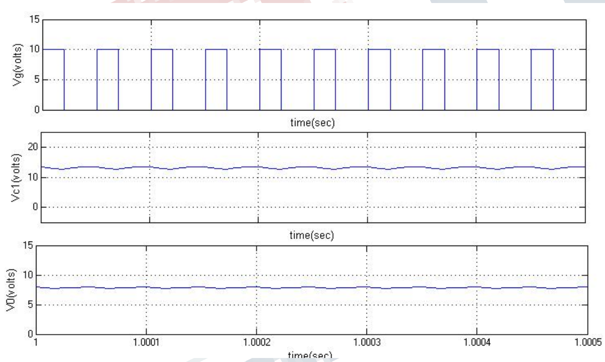


Fig 6(a) The proposed converter operated in step-down mode. (V_g, V_{c1} and V_0)

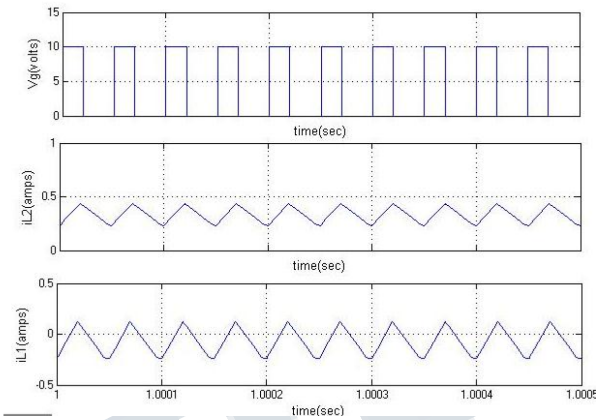
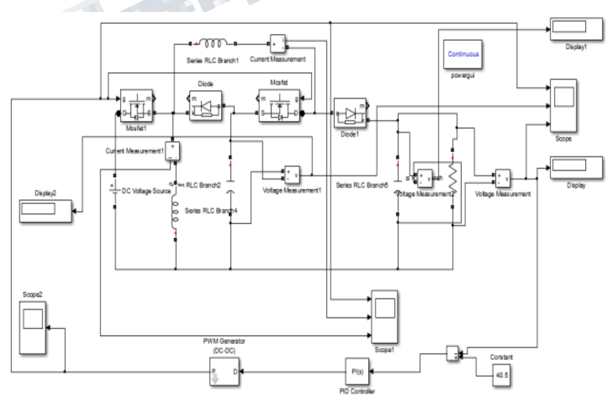


Fig 6(b) The proposed converter operated in step-down mode.(V_g,i_{L1} and i_{L2})

For the proposed converter operating in step-up mode with duty ratio 0.4,the values of V_g, Vc1 and V_0 are shown in fig 6(a).V_g,i_{L1} and i_{L2} are shown in fig 6(b).The theoretical values of the proposed converter are V_g=10V,V_{c1}=12V, V_0=8V,i_{L1}=-0.148A and i_{L2}=0.44A.

b) With feedback:



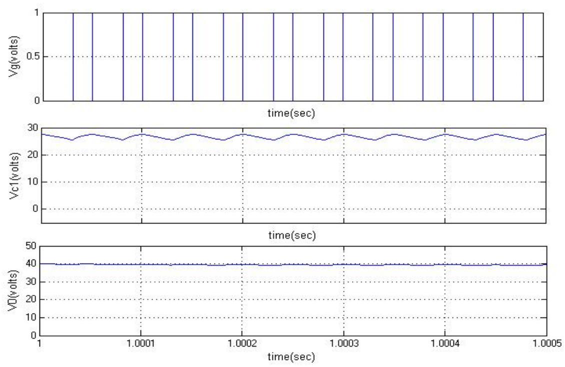


fig 7(a) The proposed converter operated in step-up mode with feedback.(V_g,V_{c1} and V_0)

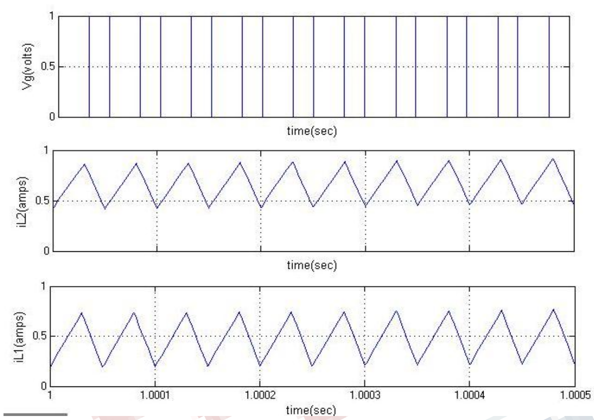


fig 7(a) The proposed converter in step-up mode with feedback.(V_g,i_{L2} and i_{L1})

By using PI controller in the feedback, the stability of the converter is improved and it maintains the constant voltage irrespective of the load conditions. The load value changes from 140Ω to 150Ω, it maintains the constant voltage. The values of $K_{P=}0.0002$, $K_{d=}1.1455$ are used in the PI controller in the step-up mode. The output voltage across the load is V0=40.5v maintains constant in step-up mode irrespective of the load conditions.

The proposed converter operating in step-down mode with feedback as shown in fig 8(a) and fig 8(b).In step-down mode, the load value changes from 30Ω to 40Ω it maintains the constant voltage. The values K_P and K_d are taken based on the trial and error method. The output voltage maintains constant V_0=8volts across the load, irrespective of the load conditions in step-down mode.

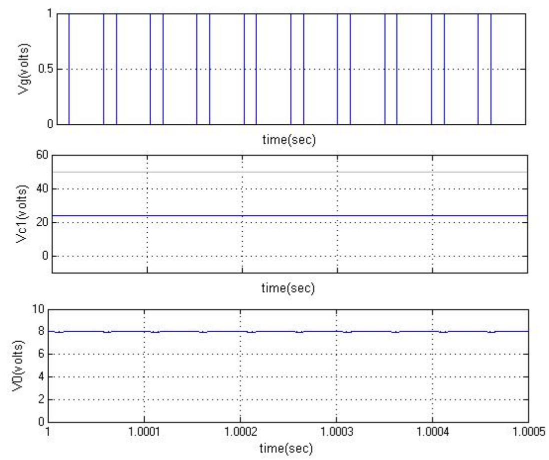


Fig 8(a) the proposed converter operated in step-down mode with feedback. (V_g,V_{c1} and V_0)

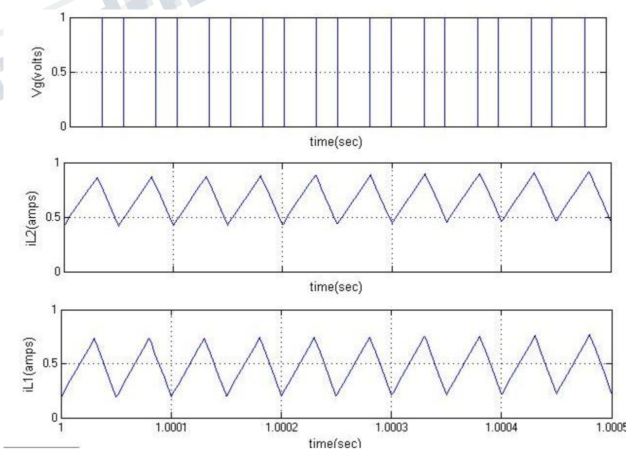


Fig 8(b) the proposed converter operated in step-down mode with feedback.(V_g,i_{L2} and i_{L1})

Comparison between proposed converter without and with feedback

	Transformerless buck-boost converter without feedback	Transformerless buck-boost converter with feedback
No. of switches	2	2
No. of diodes	2	2
No. of inductors	2	2
No. of capacitors	2	2
Output voltage (buck mode)	6.89	8
Output voltage (boost mode)	38.27	40.5

VI.CONCLUSION

The proposed converter is a fourth order circuit .This realizes the optimization between the converter structure and its more voltage gain to overcome the drawback of the normal buck-boost converter. The steady-state analyses, operating principles and small signal modeling are explained in this work. By using this proposed buck-boost converter without using the extreme duty cycle, high or low output voltage gain is obtained .A PI controller is used in the feedback of the proposed system, it improved the stability of the system. By using the PI controller in the feedback, the output voltage maintains constant irrespective of load conditions. The matlab/simulation results are proved that the proposed new transformerless buck-boost converter exhibits the merits such as high step-up/step-down voltage gain, simple construction, output voltage is positive and simple control strategy. The proposed converter is mainly suitable for industrial applications.

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