Analysis of a Single-Switch Transformer less Buck-Boost Converter with High Voltage Gain

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Abstract: The analysis of a transformerless buck boost dc to dc converter is proposed in this paper. The proposed converter has three times voltage gain compared to traditional buck boost converter. By assigning appropriate duty cycle higher voltages can be achieved. This converter possess only one power switch and it has low voltage stress across it. The operation, small-signal analysis, calculation of currents voltage gain and voltage stress across the switch is explained by operating it in continuous conduction mode (CCM). Further we execute a feedback control using PI and hysteresis controllers separately. A PI controller improves system stability, and it can reduce steady state error and forced oscillations. However, implementing the integral action in the system will leads to slower response. The Hysteresis controller has faster response and it will eliminate the ripple content presented in the output voltage. The model and results of the proposed converter is shown and verified by using MATLAB/SIMULINK.

Keywords: Power switch, Transformerless buck-boost dc to dc converter, Voltage stress across switch, Voltage gain

1. Introduction:

At present renewable energy sources dominating power sector around the globe with their clean form of nature. The Conventional energy source creates environmental problems like global warming and climate change by elevated emissions of CO2. In order to reduce these problems we depend on renewable energy sources. In any of the inexhaustible power sources like fuel cells, wind, sunlight, they generate zero harmful emissions or pollutants in the environment [1]. To put back fuels which are using in Hybrid vehicles and reserve power systems using fuel cells are efficient choice, but its output voltage is low, not stable and it is not permit to connect directly to load. Such system demands a stable output DC voltage and it can be achieved by a buck–boost dc to dc converter [2].

The conventional buck boost converter with a modest design has the limitations such as poor efficiency, negative output voltage, limited voltage gain and number of power switches and diodes, at the same time discontinuous input and output currents. Several voltage boost dc to dc converters are suggested to get high voltage gain with the reduced duty ratio by a novel technique is a smart alternative proposed in and. For sample, the flyback converter can achieve high voltage gain with reduced duty ratio [3]. The flyback converter’s voltage gain can be added on by increasing transformer turns ratio. But it experience voltage spike over the power switches and less efficiency since it has the recovery issues and leakage inductor is proposed. A boost converter with a coupled inductor is executed in which increase the voltage gain. The inductance of the coupled inductor is very significant and it increases the voltage stress and induces the high voltage spikes. To get high voltage gain a switched capacitor model is executed. To reduce the stress across the switch a bidirectional converter is intended [4]. A bidirectional converter with transformation ratio is offered, but it has more conduction losses at switches which decrease efficiency and increases expenditure since it consists of five switches. A new KY converter and CUK converter are used to get doubled voltage gain with two primary switches are implemented. Different output voltages can be obtained by using proposed structure, but it requires more power switches. By using two parallel traditional buck boost converter we can implement a two level inverting as proposed, but to correct power factor in this converter another method is implements which doesn’t need extra switch [4].
Achieves reduced voltage stress and three times voltage gain, but output voltage contains more ripples. To improve the stability of a system and to reduce ripple content we introduce PI and Hysteresis controllers in the proposed converter.

A new structure of single switch nonisolated transformerless buck boost DC to DC converter is proposed in this paper. This converter

Fig-1. (a) Analogous circuit of a proposed converter, (b) First Mode operation, (c) Second Mode operation

2. Operation of the Proposed Converter

The equivalent of a converter is demonstrated in Fig. 1(a). The proposed converter contains diodes D1, D2, and D3, inductors L1, L2, and L3, only one switch S, capacitors C1, C2, C3, C4, and Co and load R.

a) Mode I [0 ≤ t ≤ DT]: Throughout this time period, the operation as demonstrated in Fig. 1(b). When the power switch S is in ON position, the diodes cannot conducts since they are in reverse bias condition. The three inductors store the energy linearly and the capacitors C1 and C4 charges C1 and C4 respectively. Therefore, the suitable equations can be stated as:

\[ V_{L1} = V_i \]  
\[ V_{L2} = -V_{C1} + V_{C2} + V_i \]  
\[ V_{L3} = V_{C3} - V_{C4} + V_i \]

b) Mode II [DT ≤ t ≤ T]: Throughout this time period, the operation as demonstrated in Fig. 1(c). When the power switch S is in OFF position, the diodes conducts since they are in forward bias condition. The three inductors discharge the energy linearly and the Li charges Ci and the capacitors C1 and C4 discharged. Therefore, the suitable equations can be stated as:

\[ V_{L1} = -V_{C2} \]  
\[ V_{L2} = V_{C1} = V_{C2} - V_{C3} \]  
\[ V_{L3} = V_{C1} - V_{C4} = V_{C3} - V_0 \]

3. Steady State Analysis

3.1. Voltage Gain of the converter

From volt-sec balance fundamental on the L1, L2, and L3 and (1)–(6) equations, we get
\[
\frac{1}{T_s} \left( \int_{0}^{T_s} V_i \, dt + \int_{D T_s}^{T_s} (V_{c2}) \, dt \right) = 0 \quad (7)
\]

\[
\frac{1}{T_s} \left( \int_{0}^{D T_s} (V_{c2} - V_{c1} + V_i) \, dt \right. \\
+ \left. \int_{D T_s}^{T_s} (V_{c2}) \, dt \right) = 0 \quad (8)
\]

\[
\frac{1}{T_s} \left( \int_{0}^{D T_s} (V_{c3} - V_{c4} + V_i) \, dt \right. \\
+ \left. \int_{D T_s}^{T_s} (V_{c1} - V_{c4}) \, dt \right) = 0 \quad (9)
\]

By using (5) and (7)–(9), the voltage across \( C_1, C_2, C_3, \) and \( C_4 \) \( (V_{c1}, V_{c2}, V_{c3} \) and \( V_{c4} ) \) is as

\[
V_{c1} = V_{c4} = \frac{2 D V_i}{1 - D} \quad (10)
\]

\[
V_{c2} = V_{c3} = \frac{D V_i}{1 - D} \quad (11)
\]

By using equations (10) & (11), the voltage gain in CCM \( (M_{CCM}) \) is determined as:

\[
M_{CCM} = \frac{V_o}{V_i} = \frac{V_{c3} + V_{c4}}{V_i} = \frac{3 D}{1 - D} \quad (12)
\]

From (12), it is showing that the proposed converter has three times voltage gain compared to traditional converter. Fig. (2) Represents the model waveforms of proposed converter.

Fig. (3) Represents the voltage gain comparison between proposed and remaining converters.

**Current calculations**

The average current of the capacitor \( C_0 \) in switch ON period \( (I_{C0, on}) \) can be obtained as:

\[
I_{C0, on} = -I_0 \quad (13)
\]

The average currents of \( C_1, C_2 \) and \( L_2 \) \( (I_{C1, on}, I_{C2, on}, \) and \( I_{L2} ) \) in switch ON interval is achieved as:

\[
I_{L2} = I_{C1, on} = -I_{C2, on} \quad (14)
\]

The average current of the \( C_3, C_4 \) and \( L_3 \) in switch ON interval \( (I_{C3, on}, I_{C4, on}, \) and \( I_{L3} ) \) can be obtained as:

\[
I_{L3} = I_{C4, on} = -I_{C3, on} \quad (15)
\]

The average current of the \( C_1 \) in switch OFF interval \( (I_{C1, off}) \):

\[
I_{C1, off} = I_{L2} - I_{C3, off} - I_{L3} \quad (16)
\]

The average current of the \( C_4 \) in switch OFF interval \( (I_{C4, off}) \):

\[
I_{C4, off} = I_{L3} - I_{C0, off} - I_0 \quad (17)
\]

From current-sec balance fundamental on \( C_1, C_2, C_3, C_4 \) and \( C_0 \), we get

\[
\frac{1}{T_s} \left( \int_{0}^{D T_s} (I_{C1,2,3,4,0, on}) \, dt \right. \\
+ \left. \int_{D T_s}^{T_s} (I_{C1,2,3,4,0, off}) \, dt \right) = 0 \quad (18)
\]

where, \( I_{C0, off}, I_{C1, off}, I_{C2, off}, I_{C3, off}, I_{C4, off} \) are the \( C_1, C_2, C_3, C_4 \) and \( C_0 \) average currents in switch OFF period.

By substituting equations (13) to (17) into equation (18), we get

\[
I_{L2} = I_{L3} = -I_{C0, on} = I_{C1, on} = -I_{C2, on} = -I_{C3, on} = I_{C4, on} = I_0 \quad (19)
\]

From Fig. 1(c), the average of inductor current \( (I_L) \) can be get as:

\[
I_L = (I_{L2} + I_{L2} - I_{C1} - I_{C4})_{off} = \frac{1 + 2D}{1 - D} I_0 \quad (20)
\]

From Fig. 1(b), the average of power switch current \( (I_s) \) can be get as:
\[ I_s = I_{L1} + I_{C1,on} + I_{C4,on} = \frac{3}{1-D} I_0 \]  

(21)

The average of input current \( (I_i) \) is acquired as follows:

\[ I_i = \frac{1}{T_s} \int_0^{T_s} (I_{L1} + I_{C1} + I_{C4})_{\text{on}} dt + \]  

\[ = \frac{3D}{1-D} I_0 \]  

(22)

The diode currents can be achieved as

\[ I_{D1} = I_{L1} - I_{C1,\text{off}} - I_{C4,\text{off}} = \frac{I_0}{1-D} \]  

(23)

\[ I_{D2} = I_{L2} + I_{C1,\text{off}} = \frac{I_0}{1-D} \]  

(24)

\[ I_{D3} = I_{L3} + I_{C4,\text{off}} = \frac{I_0}{1-D} \]  

(25)

Where, \( I_0 \) is the current flowing through load.

**Table-1.** Comparison of contents between proposed converter and other converters

<table>
<thead>
<tr>
<th>Content</th>
<th>Proposed converter</th>
<th>Converter in [19]</th>
<th>Traditional converter</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of switches</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Number of diodes</td>
<td>3</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>Number of inductors</td>
<td>3</td>
<td>3</td>
<td>1</td>
</tr>
<tr>
<td>Number of capacitors</td>
<td>5</td>
<td>4</td>
<td>1</td>
</tr>
<tr>
<td>Voltage stress across switch</td>
<td>( V_o - \frac{3}{3} )</td>
<td>( V_o + \frac{2}{2} )</td>
<td>( V_o + 1 )</td>
</tr>
<tr>
<td>Voltage gain</td>
<td>( \frac{3D}{1-D} )</td>
<td>( \frac{2D}{1-D} )</td>
<td>( \frac{D}{1-D} )</td>
</tr>
</tbody>
</table>

**Table-2.** Proposed converter details

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Boost mode</th>
<th>Buck mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input Voltage (V0)</td>
<td>11 V</td>
<td>11 V</td>
</tr>
<tr>
<td>Frequency</td>
<td>33 KHz</td>
<td>37 KHz</td>
</tr>
<tr>
<td>Duty Ratio (D)</td>
<td>0.6</td>
<td>0.23</td>
</tr>
<tr>
<td>L1</td>
<td>100 µH</td>
<td>1 mH</td>
</tr>
<tr>
<td>L2 and L3</td>
<td>260 µH</td>
<td>580 µH</td>
</tr>
</tbody>
</table>

The table-1 represents comparison of contents like components, voltage stress and voltage gain of the implemented converter in and traditional buck boost converter. Even though the component requirement is more but it has lesser voltage stress and higher voltage gain. Table-2 represents the specifications and component requirement for proposed converter.

### 3.2. Voltage Stress on Power Switch

The diode voltage and switch voltage are smaller than \( V_o \) for this converter. Therefore voltage stress appeared on switch \( (V_s) \) is given as:

\[ V_s = \frac{V_o}{1-D} \]  

(26)

Fig. (4) Represents the comparison of voltage stress between proposed converter and other

### 4. Results and Discussions

#### 4.1. Open Loop Control System (without feedback):

**Fig- 5(a).** Boost mode operation of proposed converter.

Open Loop Control System (OLCS) is a system in which the control operation is not depends on system output. Manual control system is an example of open loop control system. Fig.5(a) and fig.5(b) shows the waveforms of \( V_o, I_o, I_{L1}, I_{L2}, I_{L3}, V_{D1} \) and \( V_s \) of proposed converter without controller operating in boost mode and buck mode respectively.
Fig- 5(b). Boost mode operation of proposed converter.

4.2. Closed Loop Control System (CLCS):

CLCS is a system in which output has an influence on the input corresponding that the input will regulate itself according to output generated. OLCS can be transformed in to CLCS by subjected to a feedback. The feedback necessarily forms the required changes in the output. Like this CLCS is called automatic control system. Fig.6 represents the implemented converter with closed loop PI controller whereas fig.7 represents the implemented converter with Hysteresis controller.

4.2.1. PI (Proportional and Integral) Controller:

It is an alliance of an integral and proportional controllers, the generated signal is equivalent to the summation of integral and proportional of the error signal. So PI controller output is directly proportional to the summation of integration of error and proportional of the error signal. Therefore,

\[ A(t) = K_i \int_0^t e(t) dt + K_p e(t) \]  \hspace{1cm} (27)

Where, \( K_i \) is integral constant and \( K_p \) is proportional constant.

Using of PI controller in the feedback improves converter stability and it keeps the constant output voltage without regard to the load conditions. The values of \( K_p \) and \( K_i \) of PI controller are 1.85 and 0.016 respectively. Fig. 6(a) and fig. 6(b) shows the waveforms of \( V_0 \), \( I_0 \), \( I_{L1} \), \( I_{L2} \), \( I_{L3} \), \( V_{D1} \) and \( V_S \) of proposed converter with PI controller operating in boost mode and buck mode are shown in respectively.

Fig- 6. Proposed converter with PI controller

Fig-6(a). Proposed converter with PI controller operated in Boost mode

Fig- 6(b). Proposed converter with PI controller operated in Boost mode

4.3. Hysteresis Controller:

A buck-boost converter with hysteresis control is one of the closed loop control technique. This scheme contains a buck-boost converter and the hysteresis current control circuit in its feedback loop. The hysteresis band and switching frequency depend on
changes of load current. Consequently, it speed up the regulation and decreases overshoot. The ripple signal sensed from output current is used to control the power switches with logic gates. Hysteresis controller is stabilises itself, so further frequency compensation capacitor is not required. Therefore, it contributes to a very fast response. Fig. 7(a) and fig. 7(b) shows the waveforms of $V_0$, $I_0$, $I_{L1}$, $I_{L2}$, $I_{L3}$, $V_{D1}$ and $V_S$ of proposed converter with Hysteresis controller operating in boost mode and buck mode respectively.

![Fig-7. Proposed converter with Hysteresis controller](image)

*With Hysteresis Controller:*

- In boost operation $V_0=40V$ and in buck operation $V_0=10V$ at a same frequency.
- Response is fast compared to, converter without controller and with PI controller.
- The steady state error is 0.2% in boost mode and 0.1% in buck mode.
- We can obtain up to 75V in boost mode and up to 3V in buck mode without waveform distortion by changing the carrier current signal.

![Fig-7(a). Proposed converter with Hysteresis controller operated in Boost mode](image)

![Fig-7(b). Proposed converter with Hysteresis controller operated in Boost mode](image)

5. Conclusion

A new control schemes for DC-DC converters to get high voltage gain, fast transient response and better regulation are developing frequently. The operation, small signal analysis and performance of converter with feedback controllers are determined in this paper. By using proposed buck-boost converter, without using the excessive duty ratio, low or high output voltage is achieved. A PI controller and Hysteresis controllers are used separately in the feedback of the proposed system. A PI controller improved the system stability. And the Hysteresis controller posses the fast response and decrease the overshoot.

The comparison of proposed converter, converter with PI controller and converter with Hysteresis controller is distinguished by working on MATLAB/SIMULINK. Proposed converter shows benefits like less voltage stress, high voltage gain, lower rise time, quick settling time, stable output and absolute control strategy and it can be used for universal input voltage and broad output power range. The buck boost dc to dc converter is used in many applications like mobile phones, gadgets, notebooks, LED drivers, fuel-cell systems and car electronic devices.

References:

