A novel buck-boost converter

Farzin Asadi 1,*, Nurettin Abut 2, Ismet Kandilli 3

1Mechatronics Engineering Department, Kocaeli University, Kocaeli, Turkey
2Electrical Engineering Department, Kocaeli University, Kocaeli, Turkey
3Electronics and Automation Department, Kocaeli University, Kocaeli, Turkey

A R T I C L E  I N F O
Article history:
Received 19 January 2017
Received in revised form 28 April 2017
Accepted 28 April 2017

Keywords:
Buck-boost converter
Low stress
Non-minimum phase system
State space averaging

A B S T R A C T
In this paper, a novel buck-boost converter with the voltage gain of \( \frac{2D-1}{1-D} \) is proposed. Output voltage is positive and the voltage stresses on the power switches and the diodes are low. Suggested topology is based on conventional boost converter. Proposed converter can provide a large step down voltage conversion ratio. Control of converter can be done with a simple I-type (Integrator) controller.

© 2017 The Authors. Published by IASE. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/)

1. Introduction

Voltage bucking/boosting is required in many applications such as car electronics (Luo and Ye, 2004; Zhu and Luo, 2007a; Zhu and Luo, 2007b), fuel cell systems (Sahu and Rincón-Mora, 2004; Ren et al., 2008; Changchien et al., 2010; Liu et al., 2010) and digital devices like notebooks and cell phones. Some topologies are suggested for buck-boost converter using KY converter (Hwu and Yau, 2008; Hwu et al., 2009a; Hwu et al., 2009b). In Liao et al. (2012) a non-inverting buck-boost converter for fuel cell systems was proposed.

Ismail et al. (2008) put two switched capacitor cell into the basic converter and obtained a series of DC-DC converters but input and output are not common grounded. Miao et al. (2016) proposed a buck-boost topology with high step-down gain, common ground between input and output and low voltage stresses on switches and diodes. This paper introduces a new buck-boost converter. Suggested converter can provide a wide range of output voltages. Its control can be done with a simple I-type controller. However, its uses more switches so switching and conduction losses increase. Also, output terminal and input terminal have no common ground.

Converter’s operating principles; steady-state analysis, small-signal model and controller design problem are studied in this paper. Finally, the Simulink® simulation is done.

2. Suggested topology

Suggested topology is shown in Fig. 1.

![Fig. 1: Suggested topology](image)

Switches \( S_1 \), \( S_2 \) and \( S_3 \) are turned on and off simultaneously. To derive the relationship between input and output voltages, these assumptions are made:

a) Inductor (capacitor) is very large so the current in (voltage across) it is constant.
b) Circuit is operating in steady state (i.e. voltages and currents are periodic).
c) For duty ratio of \( D \), switches \( S_1 \), \( S_2 \) and \( S_3 \) are close for time \( DT \) and open for \((1-D)T\).
d) Switches and diodes are ideal.

When switches \( S_1 \), \( S_2 \) and \( S_3 \) are closed, the diodes are off and circuit is as shown in Fig. 2.
Output voltage \( V_o \) must be positive otherwise diode \( D_3 \) can’t be reverse biased. Inductor voltage \( V_L \) for \( 0 < t < DT \) can be calculated as (Eq. 1):

\[
v_L = V_s
\]  \( (1) \)

When switches \( S_1, S_2 \) and \( S_3 \) are opened, the diodes are closed and circuit is as shown in Fig. 3.

\[
\text{Inductor voltage } (V_L) \text{ for } DT < t < T \text{ can be calculated as (Eq. 2):}
\]

\[
v_L = -V_s - V_o
\]  \( (2) \)

Average voltage across inductor must be zero for periodic operation. Eq. 1 and 2 are combined to get (Eq. 3):

\[
V_s \times D \times T + (-V_s - V_o) \times (1 - D) \times T = 0
\]  \( (3) \)

result is (Eq. 4):

\[
M = \frac{V_o}{V_s} = \frac{2D-1}{1-D}
\]  \( (4) \)

Voltage conversion ratio \( (M) \) vs. duty ratio \( (D) \) is shown in Fig. 4.

For Continuous Current Mode (CCM) operation, the inductor current \( (I_L) \) must remain positive for all times. Maximum and minimum inductor current can be calculated as (Eqs. 5 and 6):

\[
I_{L_{\text{max}}} = \frac{2D-1}{(1-D)^2} \times \frac{V_s}{R_L} + \frac{D}{2L} V_s
\]  \( (5) \)

\[
I_{L_{\text{min}}} = \frac{2D-1}{(1-D)^2} \times \frac{V_s}{R_L} + \frac{D}{2L} V_s
\]  \( (6) \)

To determine the boundary between continuous and discontinuous current, minimum inductor current \( (I_{L_{\text{min}}}) \) is set to zero. This leads to (Eq. 7):

\[
L_{\text{max}} = \frac{D}{2} \times \frac{(1-D)^2}{2D-1} \times R_L
\]  \( (7) \)

so, converter works in CCM if (Eq. 8):

\[
L > L_{\text{max}}
\]  \( (8) \)

3. Voltage stresses

Voltage stress on different components of the circuit is the most important criteria to choose the appropriate devices. When switches \( S_1, S_2 \) and \( S_3 \) are closed diodes \( D_1 \) and \( D_2 \) are reverse biased with voltage equal to \(-V_s\) volts and \( D_3 \) is reverse biased with \(-V_o\) volts. When diodes \( D_1, D_2 \) and \( D_3 \) are forward biased switches \( S_1, S_2 \) and \( S_3 \) must tolerate \( V_s, V_s \) and \( V_o \) volts, respectively.

4. Dynamic of converter

When switches \( S_1, S_2 \) and \( S_3 \) are closed \( (0 < t < DT) \) circuit’s Eq. can be written as (Eq. 9):

\[
\begin{cases}
\frac{dI_s}{dt} = V_s \\
\frac{dV_c}{dt} = -\frac{V_c}{R_c}
\end{cases}
\]  \( (9) \)

When Diodes \( D_1, D_2 \) and \( D_3 \) are forward biased \( (DT < t < T) \) circuit’s Eq. can be written as (Eq. 10):

\[
\begin{cases}
\frac{dI_s}{dt} = -V_s - V_c \\
\frac{dV_c}{dt} = i_L - \frac{V_c}{R_c}
\end{cases}
\]  \( (10) \)

Applying State Space Averaging (SSA) to these Eq. 11 leads to:

\[
\begin{cases}
\frac{d\phi_s}{dt} = (D-1)\phi_s + \frac{(2D-1)}{L} V_s + \left(\frac{V_o}{(1-D)L}\right) dt \\
\frac{d\phi_c}{dt} = \frac{1-D}{C} i_L - \frac{V_c}{R_c} + \frac{1-2D}{R_c L C (1-D)} V_o dt
\end{cases}
\]  \( (11) \)

DC Operating point can be obtained as (Eq. 12):

\[
\begin{cases}
I_L = \frac{2D-1}{R_L (1-D)^2} \times V_s \\
V_c = \frac{2D-1}{1-D} V_s
\end{cases}
\]  \( (12) \)

Applying Laplace transform to Eq. (11) leads to (Eq. 13):
\[ \begin{bmatrix} I_L(s) \\ V_C(s) \end{bmatrix} = \begin{bmatrix} \frac{s}{D-1} + \frac{1-D}{L} & 1 \\ s + \frac{1}{R_LC} & \frac{1}{1-2D} \end{bmatrix}^{-1} \begin{bmatrix} \frac{1}{(1-D)L}V_s \\ \frac{1}{1-2D} \end{bmatrix} \times \hat{d}(s) \] (13)

So, small signal transfer functions can be calculated as (Eq. 12):

\[ \begin{bmatrix} I_L(s) \\ V_C(s) \end{bmatrix} = \frac{V_s}{s^2 + \frac{1}{R_LC} + \frac{1}{L}} \times \left( s + \frac{1}{R_LC} \right) + \frac{2D-1}{1-2D} \frac{R_LC}{(1-D)} \] (14)

5. Simulation

Simulation is done for a converter with the following values:

\[ V_s = 100 \text{ V}, f = 50 \text{ KHz}, D = 0.75, L = 480 \mu \text{H}, C = 48 \mu \text{F}, V_{\text{Diode}} = 0.7 \text{ V}, r_{\text{Diode}} = 0.05 \Omega, r_{\text{MOSFET}} = 40 \text{ m}\Omega, R_L = 50. \]

Simulink diagram is shown in Fig. 5. Output voltage is shown in Fig. 6.

Output voltage of ideal converter, i.e. converter with ideal components, must be:

\[ \frac{2D-1}{1-2D} \times V_s = \frac{2 \times 0.75-1}{1-0.75} \times 100 = 200 \text{ V}. \]

Output voltage of non-ideal converter is 190 V, a little less than ideal case. Assume output load changes from 50 Ω to 18.75 Ω at \( t= 20 \text{ ms}. \) As shown in Fig. 7, output voltage changes.

To avoid such changes, a close loop control system must be designed. For the aforementioned values control to output transfer function is calculated as (Eq. 15):

\[ \frac{\mathcal{P}(s)}{d(s)} = -\frac{3.33 \times 10^5 s^2 + 4.34 \times 10^9}{s^4 + 4416.7s + 2713 \times 10^5} \] (15)

Pole-zero and Bode diagram of Eq. 15 is shown in Fig. 8 and 9, respectively.
MATLAB provides a rich set of functions for control system analysis and design. Assume an I-type controller (Eq. 16):

$$H(s) = \frac{K_I}{s}$$  \hspace{1cm} (16)

Using Routh-Hurwitz table $0 < K_I < 0.249$ stabilize the system. Using MATLAB’s control system toolbox $K_I = 0.11$ is selected to have no overshoot. Testing the performance of close loop system is done with the aid of following scenario: Input voltage source changes from 100 V to 75 V at t=100ms, output load changes from 50 Ω to 18.75 Ω at t=200 ms and finally, control system reference signal changes from 200 V to 250 V at t= 300 ms. Table 1, summarize the aforementioned scenario.

| Parameter       | Time  | From   | To      | Initial - Final |
|-----------------|-------|--------|---------|-----------------|
| Input voltage   | 100 ms| 100 V  | 75 V    | -25%            |
| Output load     | 200 ms| 50 Ω   | 18.75 Ω | -62.5%          |
| Reference voltage| 300 ms| 200 V  | 250 V   | +25%            |

Response of close loop system to the test scenario is shown in Fig. 10.

6. Conclusion

Voltage bucking/boosting has many applications. A novel buck-boost topology has been proposed in this paper. Steady state, dynamical behavior and control of proposed converter has been studied. Control of suggested topology can be done with a simple I type controller. Proposed topology can provide a high step down gain and can be used for applications which load’s voltage must change in a large range.

References

Changchien SK, Liang TJ, Chen JF, and Yang LS (2010). Novel high step-up DC–DC converter for fuel cell energy conversion system. IEEE Transactions on Industrial Electronics, 57(6): 2007–2017.

Hwu KI and Yau YT (2008). A novel voltage-bucking/boosting converter: KY buck-boost converter. In the IEEE International Conference on Industrial Technology (ICIT08), IEEE, Chengdu, China: 1-4. https://doi.org/10.1109/ICIT.2008.4608692

Hwu KI, Chen YH, and Lin ZF (2009a). Negative-output KY buck-boost converter. In the 4th IEEE Conference on Industrial Electronics and Applications (ICIEA’09), IEEE, Xi’an, China: 3347-3350. https://doi.org/10.1109/ICIEA.2009.5138823

Hwu KI, Lin ZF, and Chen YH (2009b). A novel negative-output KY buck-boost converter. In the International Conference on Power Electronics and Drive Systems (PEDS’09), IEEE: 1158-1162. https://doi.org/10.1109/PEDS.2009.5385717

Ismail EH, Al-Saffar MA, Sabzali AJ, and Fardoun AA (2008). A family of single-switch PWM converters with high step-up conversion ratio. IEEE Transactions on Circuits and Systems I: Regular Papers, 55(4): 1159-1171.

Liao HK, Liang TJ, Yang LS, and Chen JF (2012). Non-inverting buck-boost converter with interleaved technique for fuel-cell system. IET Power Electron, 5(8): 1379–1388.

Liu WS, Chen JF, Liang TJ, and Lin RL (2010). Analysis, design, and control of bidirectional cascaded configuration for a fuel cell hybrid power system. IEEE Transactions on Power Electronics, 25(6): 1565-1575.

Fig. 9: Bode diagram of $\frac{P_o(s)}{R(s)}$

Fig. 10: Response of close loop system to load change scenario

Fig. 11: Close loop response for a large change in $V_{ref}$
Luo FL and Ye H (2004). Positive output multiple-lift push-pull switched-capacitor Luo-converters. IEEE Transactions on Industrial Electronics, 51(3): 594-602.

Miao S, Wang F, and Ma X (2016). A novel buck-boost converter with low stresses on switches and diodes. In the 8th IEEE International Conference on Power Electronics and Motion Control (IPEMC-ECCE Asia), IEEE, Hefei, China: 3344-3347. https://doi.org/10.1109/IPEMC.2016.7512831

Ren X, Tang Z, Xian R, Wei J, and Hua G (2008). Four switch buck-boost converter for telecom DC–DC power supply applications. In the 23rd Annual IEEE Conference on Applied Power Electronics and Exposition (APEC’08), IEEE, Austin, USA: 1527–1530. https://doi.org/10.1109/APEC.2008.4522927

Sahu B and Rincón-Mora GA (2004). A low voltage, dynamic, noninverting, synchronous buck-boost converter for portable applications. IEEE Transactions on Power Electronics, 19(2): 443-452.

Zhu M and Luo L (2007a). Implementing of developed voltage lift technique on SEPIC, Cuk and double-output DC-DC converters. In the 2nd IEEE Conference on Industrial Electronics and Applications (ICIEA’07), IEEE: 674–681. https://doi.org/10.1109/ICIEA.2007.4318492

Zhu M and Luo L (2007b). Development of voltage lifts technique on double output transformer less DC-DC converter. In the 33rd Annual Conference of the IEEE Industrial Electronics Society (IECON’07), IEEE, Taipei, Taiwan: 1983–1988. https://doi.org/10.1109/IECON.2007.4460172