

Dynamics and control of a novel buck-boost converter with low stresses on switches and diodes



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ABSTRACT

This paper studies dynamics and control of a converter with advantages like: High step down gain, common ground between input and output terminal, positive output voltage and low voltage stress on switches and diodes. However, gate drive circuitry is more complex due to floatation of MOSFET sources. Converter's small signal model is extracted using State Space Averaging (SSA). A controller is designed for the obtained model using MATLAB® control system toolbox. This paper shows that control of converter can be done using a simple I- type controller. This is another advantage for studied topology.

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1. Introduction

Voltage bucking/boosting is required in many applications such as car electronics (Luo and Ye, 2004; Zhu and Luo, 2007a, 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 & Yau, 2008, 2009; Hwu et al., 2009a, 2009b). In Liao et al. (2012) a non-inverting buck-boost converter for fuel cell systems was proposed. Ismail et al. (2008) puts two switched capacitor cell into the basic converter and obtained a series of DC-DC converters but input and output are not common grounded. Designing appropriate controller is an important aspect of power electronics converters. Without appropriate controller, output changes due to disturbances like: Output load's changes and input source's changes. Dynamic and control of a recently published buck-boost converter Miao et al. (2016) studied in this paper. Converter in Miao et al. (2016) has the benefits such as voltage stresses on switches and diodes are low, high step down gain, input and output terminal share the same ground, and output voltage is positive.

Floatation of MOSFET's (i.e. MOSFET sources are not connected to ground) is the main disadvantage of this converter. It needs a more complex gate drive circuitry.

This paper is organized as follows: Operating principle and steady state analysis are presented in section 2. Converter's small signal model, Controller design and Simulink® simulations are discussed in section 3. Finally, the appropriate conclusion is drawn.

2. Operating principles and steady state analysis

Fig. 1 shows the converter proposed in Miao et al. (2016).

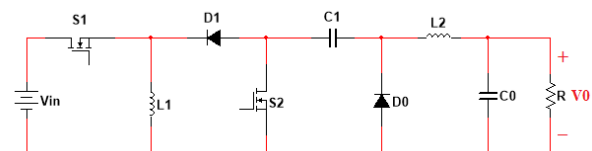


Fig. 1: Converter's structure

There are two possible operation modes when converter operates in CCM.

$$\text{Mode 1) } NT_s < t < (N + D)T_s$$

During this time interval, the power switches S_1 and S_2 are conducted while the diodes D_1 and D_0 are reverse biased. Fig. 2 shows the equivalent circuit of this time interval:

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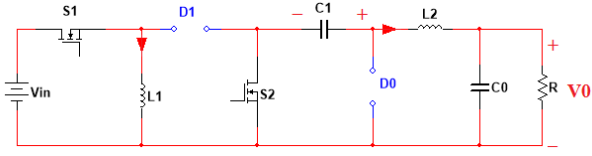


Fig. 2: Equivalent circuit of mode 1

Mode 2) $(N + D)T_s < t < (N + 1)T_s$

During this time interval, diodes D_0 and D_1 are forward biased while switches S_1 and S_2 are turned off. Fig. 3 shows the equivalent circuit of this time interval:

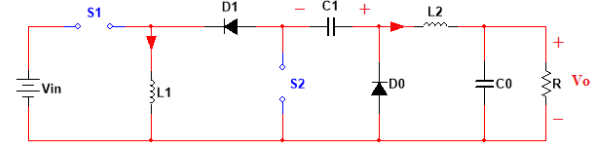


Fig. 3: Equivalent circuit of mode 2

Applying volt second balance (Mohan and Undeland, 2007) principle on the inductors L_1 and L_2 leads to (Eqs. 1 and 2):

$$V_{c1} = \frac{D}{1-D} V_{in} \tag{1}$$

$$M = \frac{V_o}{V_{in}} = \frac{D^2}{1-D} \tag{2}$$

Converter step down the input voltage when $D < 0.618$. Otherwise it steps up the input voltage. Voltage stresses on the power switches (S_1 and S_2) and diodes (D_0 and D_1) can be obtained as follows (Eqs. 3-6). A comparison is done in Table 1.

$$V_{s1} = \frac{1}{1-D} V_{in} \tag{3}$$

$$V_{s2} = \frac{1}{1-D} V_{in} \tag{4}$$

$$V_{D0} = \frac{1}{1-D} V_{in} \tag{5}$$

$$V_{D1} = V_{in} \tag{6}$$

Table 1: Comparison among converters

Topology	Traditional buck-boost converter (Wu and Chen, 1998)	Buck-boost in Maksimovic and Cuk (1991)	Miao et al. (2016) topology
Voltage Gain(V_o/V_{in})	$-\frac{D}{1-D}$	$-\frac{D^2}{1-D}$	$\frac{D^2}{1-D}$
Voltage stress of switches(V_s/V_{in})	$\frac{1}{1-D}$	$\frac{1}{1-D}$	$S_1 \frac{1}{1-D}$
			$S_2 \frac{1}{1-D}$
Voltage Stress of diodes(V_d/V_{in})	$\frac{1}{1-D}$	$D_1 \frac{1}{1-D}$	$D_1 \frac{1}{1-D}$
		$D_2 \frac{1}{1-D}$	$D_0 \frac{D}{1-D}$
		$D_3 \frac{1}{1-D}$	

3. Small signal modeling and controller design

Modeling is the process of formulating a mathematical description of the system. Obtaining the mathematical model of system is the first step toward designing a controller in model base controller design techniques. Switching power converters are nonlinear variable structure systems. Various techniques can be found in literature to obtain a linear continuous Time Invariant (LTI) model of a DC-DC converter. The most well-known methods are: Current injected approach, circuit averaging and state space averaging (Middlebrook and Cuk, 1977; Kislovski et al., 1991; Mohan and

Undeland, 2007). Averaging and small signal linearization is key steps of these methods.

State Space Averaging (SSA) described in Middlebrook and Cuk (1977) is appropriate to describe converters that work in CCM while is less suitable for converters work in DCM. The current injected method (Kislovski et al., 1991; Mohan and Undeland, 2003) can do the job of modeling in either CCM or DCM. Circuit averaging gained a lot of attention recently due to its generality (Hren and Slibar, 2005). This paper uses, SSA to obtain the converter's model. Fig. 4 shows the equivalent circuit for mode 1 ($NT_s < t < (N + D)T_s$).

Corresponding differential equations are established as (Eq. 7):

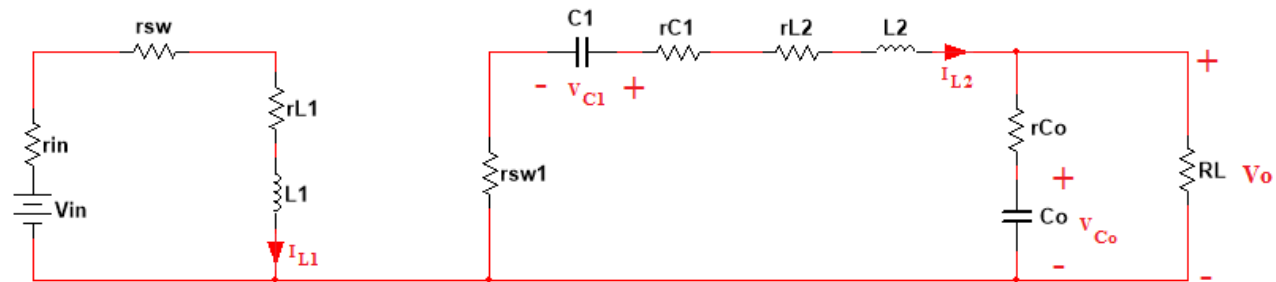


Fig. 4: Equivalent circuit of mode 1 in presence of circuit's non idealities

$$\begin{cases} \frac{d(i_{L1})}{dt} = -\frac{(r_{in}+r_{sw1}+r_{L1})}{L_1}i_{L1} + \frac{1}{L_1}V_{in} \\ \frac{d(i_{L2})}{dt} = -\frac{1}{L_2}(r_{sw2} + r_{C1} + r_{L2} + \frac{r_{Co}}{\alpha})i_{L2} + \frac{1}{L_2}v_{C1} - \frac{1}{L_2}(1 - \frac{r_{Co}}{R \times \alpha})v_{Co} \\ \frac{d(v_{C1})}{dt} = -\frac{1}{C_1}i_{L2} \\ \frac{d(v_{C2})}{dt} = \frac{1}{\alpha \times C_o}i_{L2} - \frac{1}{R \times \alpha \times C_o}v_{Co} \end{cases} \quad (7)$$

where $\alpha = 1 + \frac{r_{Co}}{R}$. Fig. 5 shows the equivalent circuit for mode 2 $((N + D)T_s < t < (N + 1)T_s)$. The

equations for describing this mode can be derived as (Eq. 8):

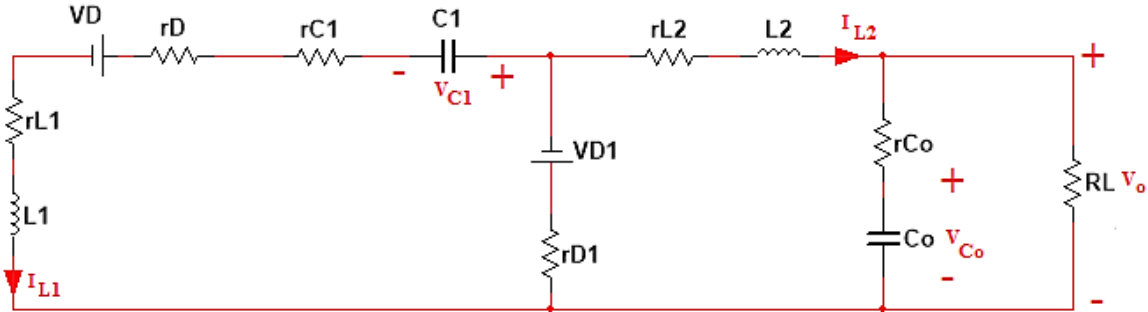


Fig. 5: Equivalent circuit of mode 1 in presence of circuit's non idealities

$$\begin{cases} \frac{d(i_{L1})}{dt} = -\frac{(r_{D0}+r_{D1}+r_{C1}+r_{L1})}{L_1}i_{L1} - \frac{r_{D0}}{L_1}i_{L2} - \frac{v_{C1}}{L_1} - \frac{2}{L_1}v_D \\ \frac{d(i_{L2})}{dt} = -\frac{r_{D0}}{L_2}i_{L1} - \frac{1}{L_2}(r_{D0} + r_{L2} + \frac{r_{Co}}{\alpha})i_{L2} - \frac{1}{L_2}(1 - \frac{r_{Co}}{R \times \alpha})v_{Co} - \frac{1}{L_2}v_D \\ \frac{d(v_{C1})}{dt} = \frac{1}{C_1}i_{L1} \\ \frac{d(v_{C2})}{dt} = \frac{1}{\alpha \times C_o}i_{L2} - \frac{1}{R \times \alpha \times C_o}v_{Co} \end{cases} \quad (8)$$

Using pencil-and-paper analysis to extract converter's small signal transfer function is tedious, time consuming and error prone. MATLAB can be quite helpful for this purpose. Assume a converter with the following parameters:

$V_{in} = 15\text{ V}$, $r_{internal} = 0.01\ \Omega$, $f = 25\text{ Khz}$, $D = 0.75$, $L_1 = 3\text{ mH}$, $r_{L1} = 30\text{ m}\Omega$, $L_2 = 1\text{ mH}$, $r_{L2} = 10\text{ m}\Omega$, $C_1 = 20\ \mu\text{F}$, $r_{C1} = 5\text{ m}\Omega$, $C_o = 20\ \mu\text{F}$, $r_{Co} = 15\text{ m}\Omega$, $V_D = 0.7$, $r_D = 0.05\ \Omega$, $r_{MOSFET} = 40\text{ m}\Omega$, $R_L = 15\ \Omega$.

With this values output voltage must be about 30. Assume output load changes from $15\ \Omega$ to $12\ \Omega$ at $t = 25\text{ ms}$. Output of this scenario is shown in Fig. 6.

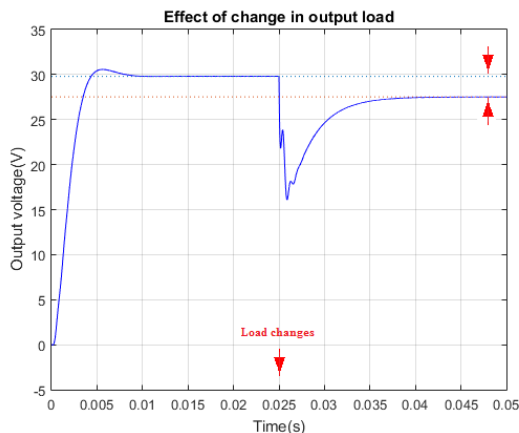


Fig. 6: Effect of output load change on output voltage

As shown in Fig. 6 output voltage is affected so a controller is required to keep output voltage constant despite of such disturbances. Applying SSA to Eqs. 7 and 8 leads to following transfer functions

(Eqs. 9, 10, and 11). Pole-zero diagram of these transfer functions are shown in Fig. 7, 8, and 9:

$$\frac{\tilde{v}_o(s)}{d(s)} = \frac{2.11 \times 10^9 s^2 - 1.521 \times 10^{13} s + 1.077 \times 10^{16}}{s^4 + 3425 s^3 + 7.944 \times 10^7 s^2 + 9.978 \times 10^{10} s + 5.545 \times 10^{13}} \quad (9)$$

$$\frac{\tilde{i}_{L1}(s)}{d(s)} = \frac{1.935 \times 10^4 s^3 + 9.942 \times 10^7 s^2 - 1.763 \times 10^{12} s + 3.96 \times 10^{15}}{s^4 + 3425 s^3 + 7.944 \times 10^7 s^2 + 9.978 \times 10^{10} s + 5.545 \times 10^{13}} \quad (10)$$

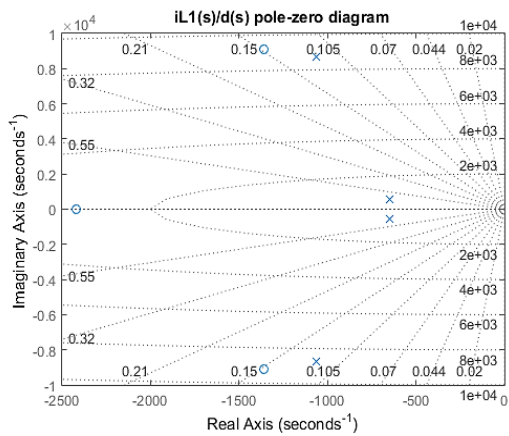
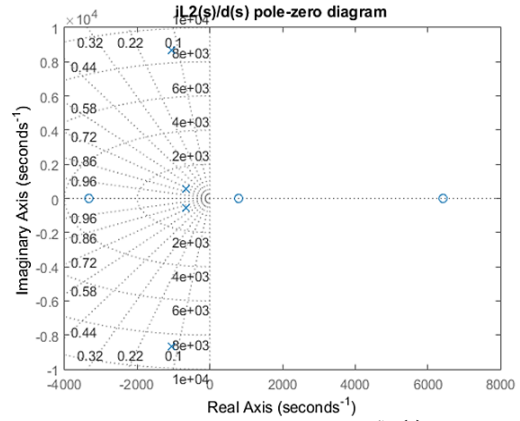
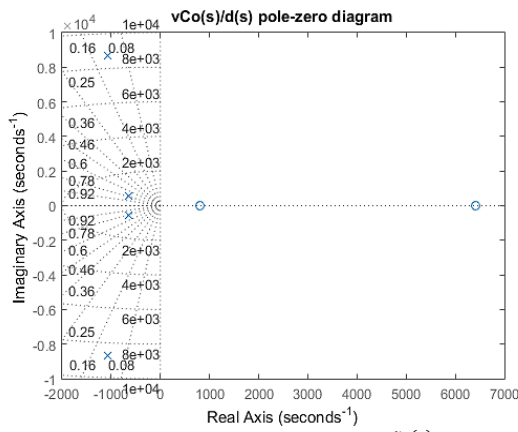
$$\frac{\tilde{i}_{L2}(s)}{d(s)} = \frac{4.222 \times 10^4 s^3 - 1.636 \times 10^8 s^2 - 7.987 \times 10^{11} s + 7.178 \times 10^{14}}{s^4 + 3425 s^3 + 7.944 \times 10^7 s^2 + 9.978 \times 10^{10} s + 5.545 \times 10^{13}} \quad (11)$$

As shown in the above figures, $\frac{\tilde{v}_o(s)}{d(s)}$ and $\frac{\tilde{i}_{L2}(s)}{d(s)}$ are non-minimum phase, i.e. have zeros in Right Half Plane (RHP). Although control engineering has considerable progress over recent decades, most applications use PID controllers, because of their low price and simplicity. Generally speaking, using derivative term is not so common in power electronics converters control. Usually a P or PI controller is all that is required.

Assume zero steady state error is required. So, open loop transfer function must contain an integrator. Assume a simple I-type controller (Eq. 12):

$$H_{controller}(s) = \frac{K_i}{s} \quad (12)$$

Using Routh-Hurwitz table $0 < K_i < 2.36$ stabilize the close loop system. $K_i = 0.40$ is selected to have no overshoot. Fig. 10 shows the Simulink diagram of the system.



Testing the performance of close loop system is done with the aid of following scenario: Input voltage source changes from 15 V to 12 V at $t=200\text{ms}$, output load changes from $15\ \Omega$ to $7.5\ \Omega$ at $t=300\ \text{ms}$ and finally, control system reference signal changes from 20 V to 25 V at $t=350\ \text{ms}$. Table 2 summarize the aforementioned scenario. Simulation result is shown in Fig. 11. As shown in Fig. 11, controller keeps output voltage constant despite of disturbances.

Table 2: Test scenario

Parameter	Time	From	To	Initial – Final
				Initial
Input voltage	200 ms	15 V	12 V	-20%
Output load	300 ms	$15\ \Omega$	$7.5\ \Omega$	-50%
Reference voltage	350 ms	20 V	25 V	+25%

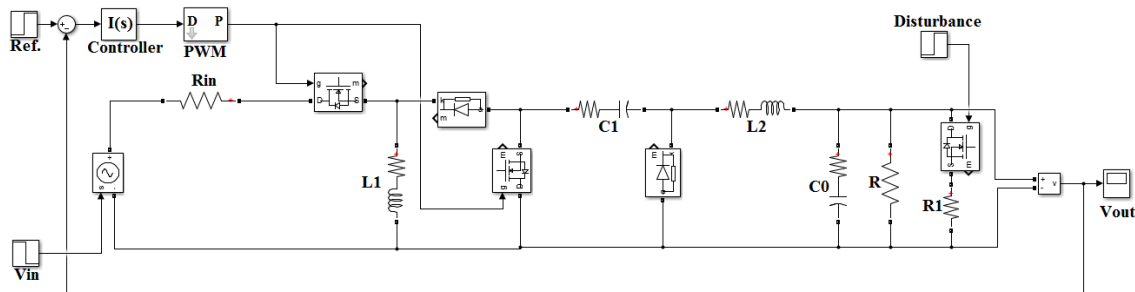
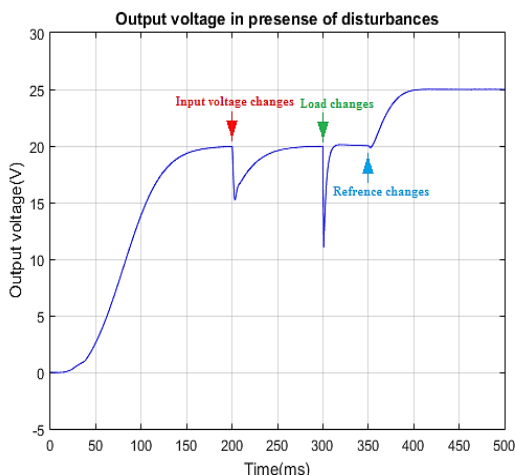


Fig. 10: Simulink diagram of system



4. Conclusion

Dynamics and control of a recently published buck-boost converter is studied in this paper. Studied converter has advantages like: Low voltage stresses on switches and diodes, high step down gain, positive output voltage and common ground between input and output. This paper shows studied converter has even one more advantage: its control can be done with a simple I-type controller. Proposed system can be used to drive DC motors.

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