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Developing a MATLAB® Toolbox for MWM Buck-boost Converter Analysis and Design

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Abstract: This paper introduces a MATLAB toolbox for analysis and design of a novel buck-boost topology suggested by Miao, Wang and Ma (MWM). The developed toolbox solves the converter's nonlinear differential equations and draws the circuit's different waveforms. So, component selection can be done by using the obtained waveform's maximum, average, etc. Developed software also calculates the small signal transfer functions. Obtained transfer functions are transferred to MATLAB's workspace so the controller design can be done easily using MATLAB's control system toolbox. Contact the corresponding author to receive the software.

Key words: Buck-boost converter; Converter simulation; State space averaging.

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1 Introduction

Voltage bucking/boosting is required in many applications such as car electronics [1-3], fuel cell systems [4-7] and digital devices like notebooks and cell phones. Some topologies are suggested for buck-boost converter using KY converter [8-11]. In [12] a non inverting buck-boost converter for fuel cell systems is proposed. [13] 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. This paper introduces a toolbox for analysis and design of a recently published buck-boost converter[14]. Converter in [14], has the following benefits:

- Voltage stresses on switches and diodes are low,
- High step down gain,
- Input and output terminal share the same ground,
- Output voltage is positive.

The 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 circuit.

Computers play an important role in modern power electronics. Power electronics converters are nonlinear systems in nature. Nonlinear differential equations must be solved to obtain the converter's exact waveforms. This paper develops a toolbox to analyze the MWM buck-boost converter. The developed software solves the converter's nonlinear differential equations and display voltages and currents. This allows the selection of components to be selected based on the obtained waveform's maximum, average, etc. The developed software can extract converter's small signal model, as well.

This paper is organized as follows: Operating principles of MWM converter is studied in the second section. Developed software is introduced in the third section. Finally, conclusions are drawn in the fourth section.

2 Operating Principles and Steady State Analysis

Figure 1 shows the converter proposed [14:

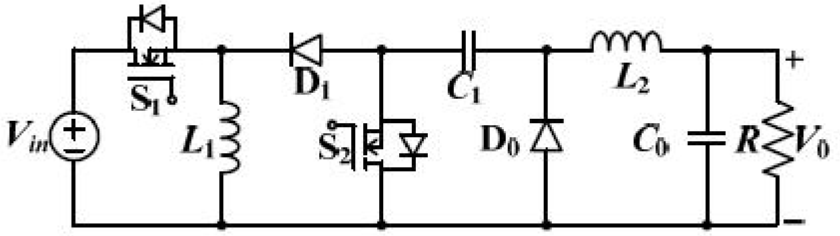


Figure 1 Converter's structure

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

Mode 1) $NT_s < t < (N+D)T_s$:

During this time interval, the power switches S₁ and S₂ are conducted while the diodes D₁ and D₀ are reverse biased. Figure 2 shows the equivalent circuit of this time interval:

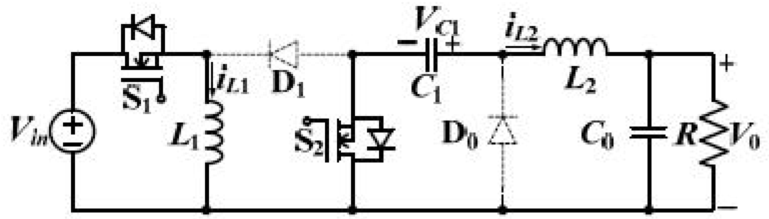


Figure 2 Equivalent circuit of mode 1

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

During this time interval, diodes D₀ and D₁ are forward biased while switches S₁ and S₂ are turned off. Figure 3, shows the equivalent circuit of this time interval:

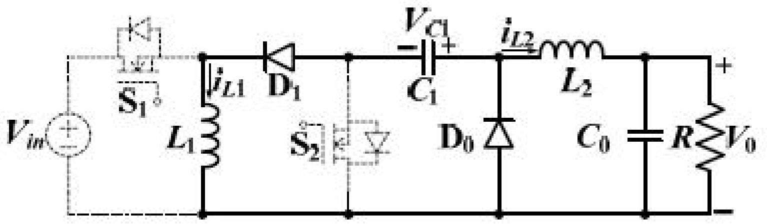


Figure 3 Equivalent circuit of mode 2

Applying volt second balance principle on the inductors L₁ and L₂ leads to:

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

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

The MWM converter, steps downs the input voltage when $1 < 0.618$. Otherwise it steps up the input voltage. Voltage stresses on the power switches (S₁ and S₂) and diodes (D₀ and D₁) can be obtained as follows:

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

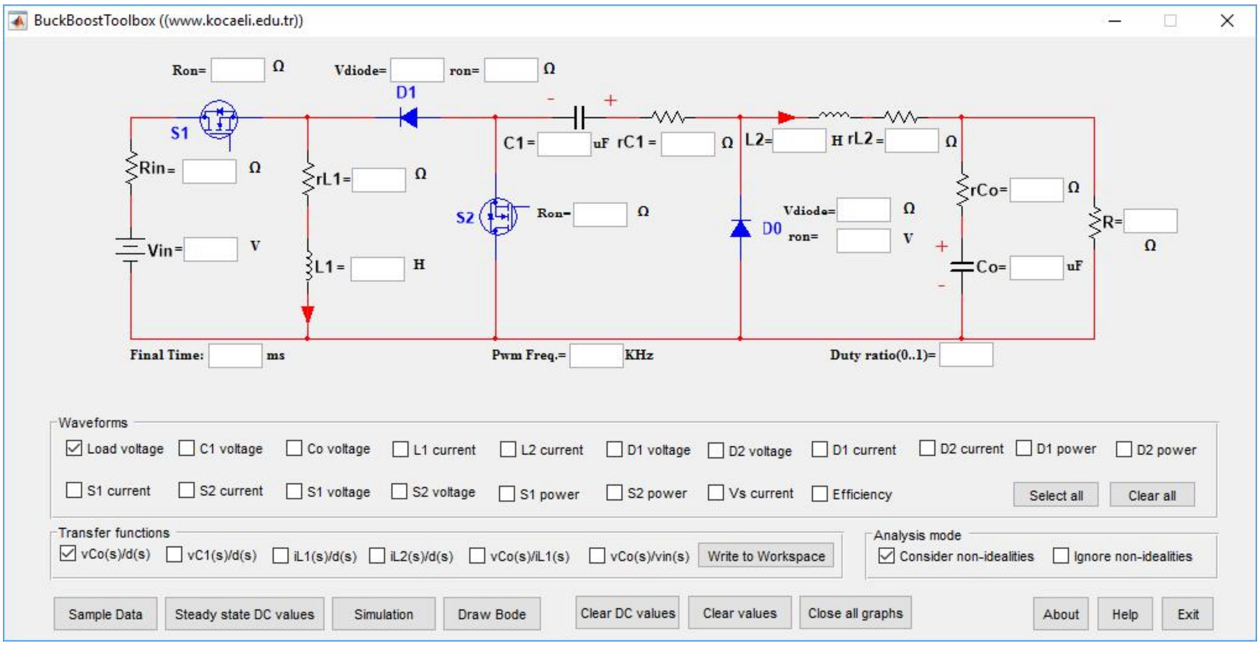
$$V_{s2} = \frac{D}{1-D}V_{in} \tag{4}$$

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

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

3 Developed Software

Figure 4 shows main menu of developed software:



☑ Load voltage ☐ C1 voltage ☐ Co voltage ☐ L1 current ☐ L2 current ☐ D1 voltage ☐ D2 voltage ☐ D1 current ☐ D2 current ☐ D1 power ☐ D2 power

☐ S1 current ☐ S2 current ☐ S1 voltage ☐ S2 voltage ☐ S1 power ☐ S2 power ☐ Vs current ☐ Efficiency

☑ vCo(s)/d(s) ☐ vC1(s)/d(s) ☐ iL1(s)/d(s) ☐ iL2(s)/d(s) ☐ vCo(s)/iL1(s) ☐ vCo(s)/vin(s)

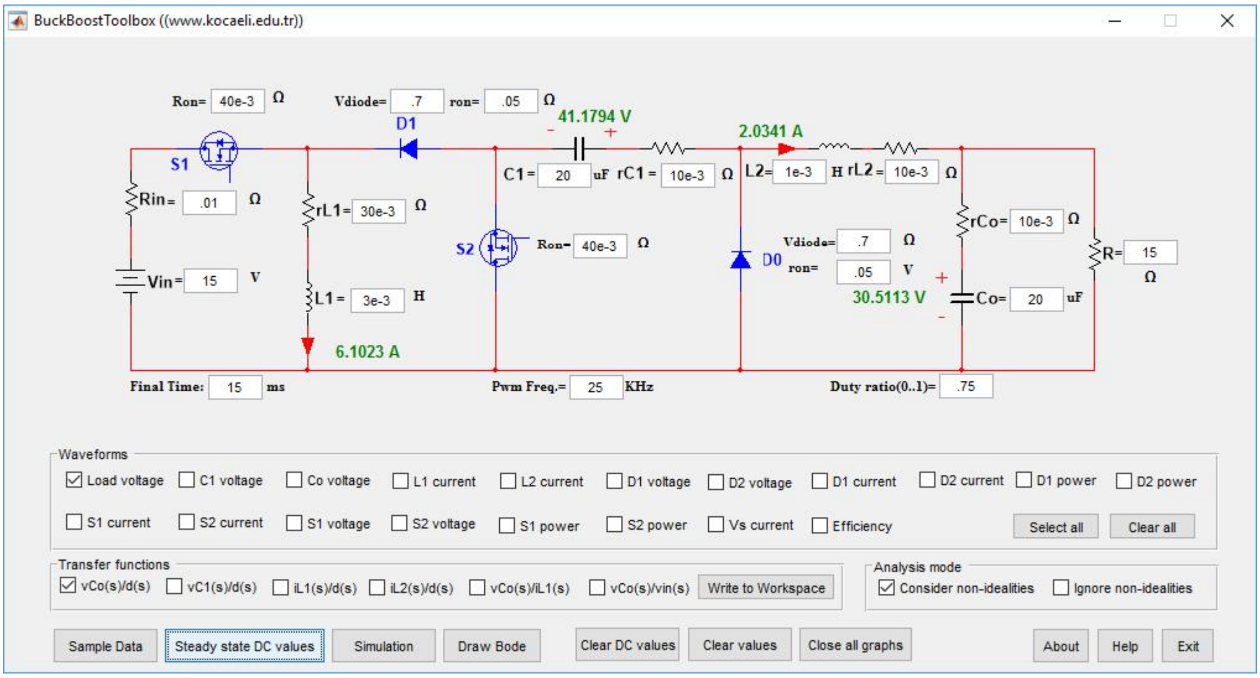
☑ Consider non-idealities ☐ Ignore non-idealities

Figure 4 Main menu of developed software

Entering the circuit's parameter values must be done by user. Assume a circuit with the following values:

V_{in}= 15V, $r_{internal}$= 0.01Ω, f= 25Khz, D= 0.75, L_1= 3mH, rL_1= 30mΩ, L_2= 1mH, rL_2= 10mΩ, C_1= 20µF, r_{C1}= 5mΩ, Co= 20µF, r_{Co}= 10mΩ, V_D= 0.7, r_D= 0.05 Ω, r_{MOSFET}= 40 mΩ, R_L= 10Ω.

Clicking "Steady state DC values" button gives Figure 5:



Ron= 40e-3 Ω
Vdiode= .7
ron= .05 Ω
Rin= .01 Ω
Vin= 15 V
rL1= 30e-3 Ω
L1= 3e-3 H
C1= 20 uF
rC1= 10e-3 Ω
L2= 1e-3 H
rL2= 10e-3 Ω
Ron= 40e-3 Ω
Vdiode= .7 Ω
ron= .05 V
rCo= 10e-3 Ω
Co= 20 uF
R= 15 Ω
Final Time: 15 ms
Pwm Freq.= 25 KHz
Duty ratio(0..1)= .75

☑ Load voltage ☐ C1 voltage ☐ Co voltage ☐ L1 current ☐ L2 current ☐ D1 voltage ☐ D2 voltage ☐ D1 current ☐ D2 current ☐ D1 power ☐ D2 power

☐ S1 current ☐ S2 current ☐ S1 voltage ☐ S2 voltage ☐ S1 power ☐ S2 power ☐ Vs current ☐ Efficiency

☑ vCo(s)/d(s) ☐ vC1(s)/d(s) ☐ iL1(s)/d(s) ☐ iL2(s)/d(s) ☐ vCo(s)/iL1(s) ☐ vCo(s)/vin(s)

☑ Consider non-idealities ☐ Ignore non-idealities

Figure 5 Steady state analysis result

As shown in Figure5, I_{L1}= 6.1023 A, I_{L2}= 2.0341 A, V_{C1}=41.1794 V and V_{Co}= 30.5113 V.

Developed toolbox can draw different waveforms of the converter. It can draw: Diode currents, voltage and dissipated power, MOSFET currents, voltage and dissipated power, capacitors voltage, inductor currents and input source current. Efficiency of converter can be calculated, as well. Some of the waveforms of the converter with aforementioned values are shown in Figure 6-10. Users can save, zoom in and out, trace and print the obtained waveforms.

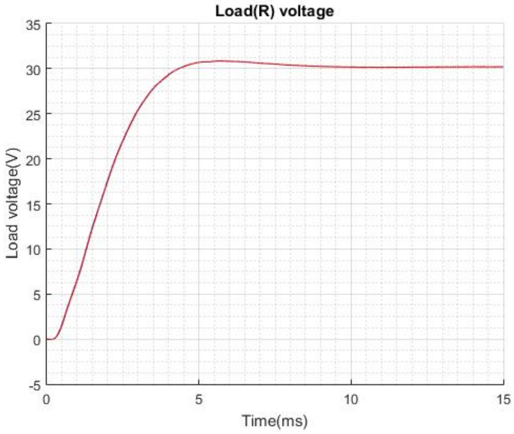


Figure 6 Load votage waveform

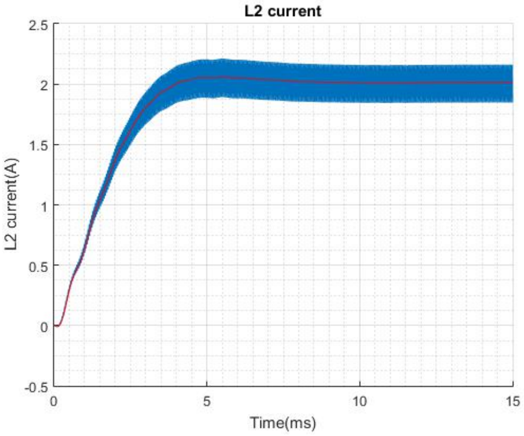


Figure 7 Inductor L_2 current

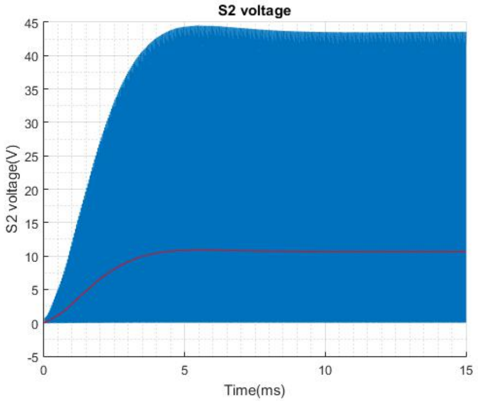


Figure 8 MOSFET S_2 voltage

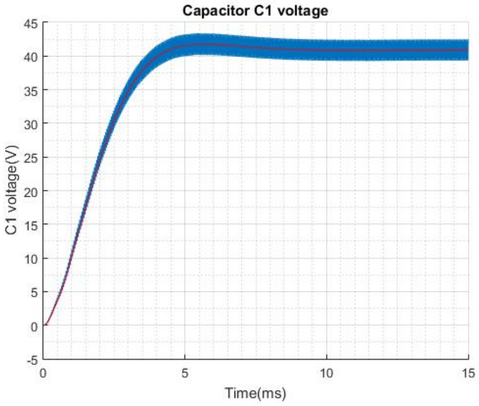


Figure 9 Capacitor C_1 voltage

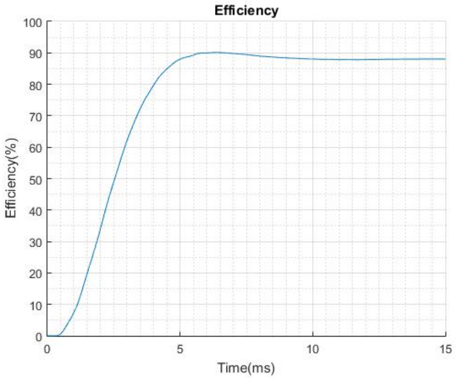


Figure 10 Converter efficiency

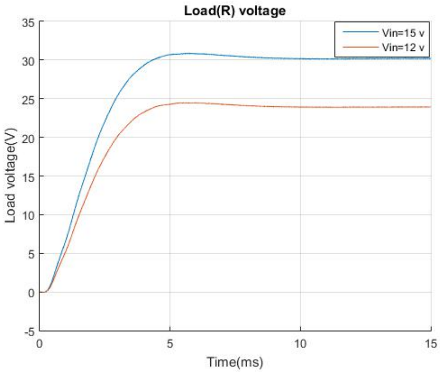


Figure 11 Effect of input source voltage on output voltage

Information like that shown in Figure 6-10 is invaluable for a design problem. Selection of components can be done with the given information. Software can draw different simulation results on the same graph, this makes comparison possible. Fig. 11 compares output voltages for two values of input voltage.

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 [15-18]. Averaging and small signal linearization are key steps of these methods.

State Space Averaging (SSA) described in [15] is appropriate to describe converters that work in CCM while is less suitable for converters work in DCM. The current injected method [16-17] can do the job of modeling in either CCM or DCM. Circuit averaging gained a lot of attention recently due to its generality [19]. This software uses SSA to extract small signal models. Converter's small signal equations can be obtained by selecting the desired transfer function and pressing the "Draw Bode" button. Software gives both graphical Bode diagram and algebraic transfer function. Algebraic transfer functions are transferred to MATLAB's workspace so controller design can be done more easily. Figure 12 and 13 show two of the calculated Bode diagrams. Converter's differential equations can be found in Appendix.

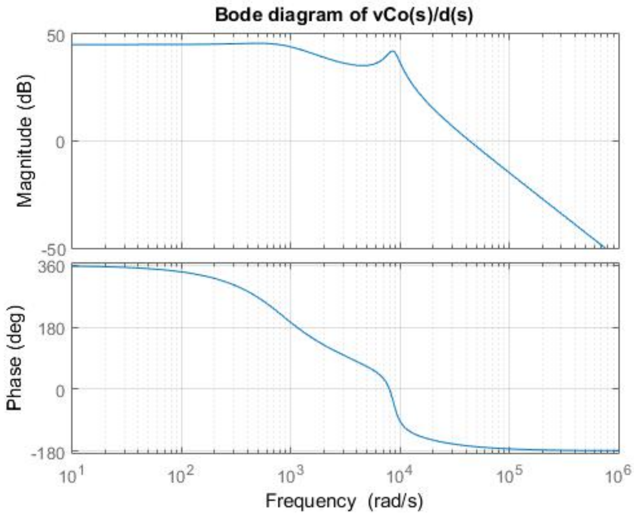


Figure 12 Bode diagram of $\frac{v_{CO}}{\tilde{d}(s)}$

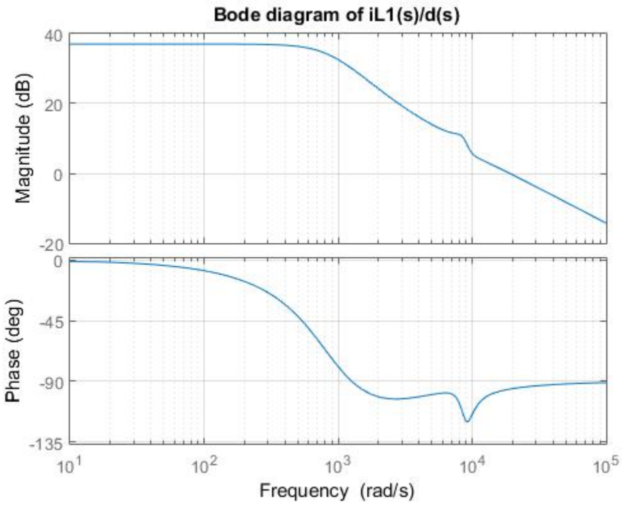


Figure 13 Bode diagram of $\frac{\tilde{i}_{L1}(s)}{\tilde{d}(s)}$

When output load changes, converter's transfer functions changes, too. Software can calculate converter's transfer function for different values of load. Figure 14, shows control to output transfer function for different values of R($15 < R < 50$). This capability can be quite helpful for designing a robust controller.

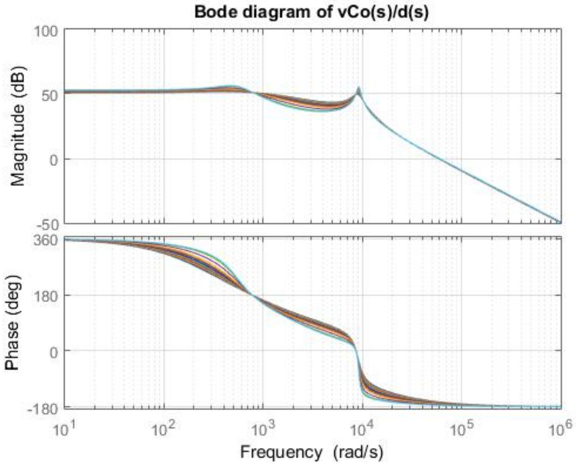


Figure 14 Control to output transfer function for different values of load (15<R<50)

4 Conclusion

Exact analysis of power electronics converters is not an easy task due to non-linearity in switches and other components in the circuit. A digital computer can solve the circuit's nonlinear differential equations and draw the waveforms so designer can choose the component ratings easily. This paper introduces a toolbox for the MWM buck-boost converter analysis and design. Developed software can extract converter's small signal transfer functions so controller designing can be done easily using MATLAB's control system toolbox. Designing a robust controller with the aid of this toolbox is the next research topic.

Appendix

Dynamics of MWM buck-boost converter

Assume a general state space model of following form for a CCM converter:

$$\begin{cases} \dot{x} = A_1 x + B_1 u \\ vo = {C_1}^T x \end{cases} \quad (A-1)$$

$$\begin{cases} \dot{x} = A_2 x + B_2 u \\ vo = {C_2}^T x \end{cases} \quad (A-2)$$

Equation set (A-1) and (A-2), is written under switch close and switch open condition, respectively.

x is state vector, i.e. capacitors' voltage and inductors' current, u is control input and v_o is output voltage of converter. Applying averaging and linearization to equations leads to:

$$\tilde{x}^{\cdot} = [A_1 D + A_2(1-D)]\tilde{x} + [(A_1 - A_2)X + (B_1 - B_2)V]\tilde{d} \qquad (A-3)$$

$$\tilde{v}_o = [C^T{}_1 + C^T{}_2(1-D)]\tilde{x} + [({C_1}^T - {C_2}^T)X]\tilde{d} \qquad (A-4)$$

Where tilde ($\tilde{x}$,$\tilde{d}$,$\tilde{v}_o$) shows small signal variables and D shows stead state duty ratio.

Fig. A-1shows the equivalent circuit for mode 1 ($NT_s < t < (N+D)T_s$).

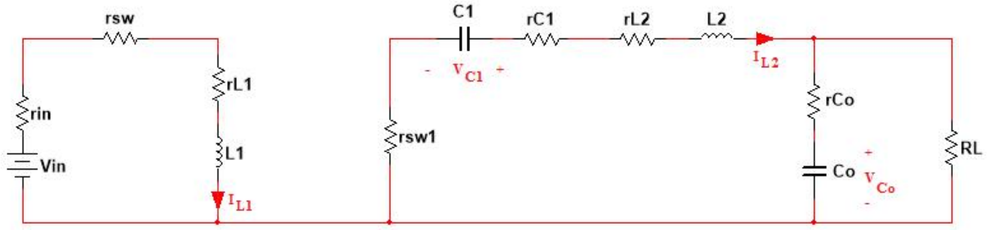


Figure A-1 Equivalent circuit of mode 1 in presence of circuits non idealities

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Corresponding differential equations are established as:

$$\begin{cases} \dfrac{d(i_{L1})}{dt} = -\dfrac{(r_{in}+r_{sw1}+r_{L1})}{L_1} i_{L1} + \dfrac{1}{L_1} V_{in} \\ \dfrac{d(i_{L2})}{dt} =-\dfrac{1}{L_2}\left(r_{sw2}+r_{C1}+r_{L2}+\dfrac{r_{CO}}{\alpha}\right) i_{L2} + \dfrac{1}{L_2} v_{C1} - \dfrac{1}{L_2}(1-\dfrac{r_{Co}}{R\times\alpha}) v_{Co} \\ \dfrac{d(v_{C1})}{dt} =-\dfrac{1}{C_1} i_{L2} \\ \dfrac{d(v_{C2})}{dt} = \dfrac{1}{\alpha\times C_o} i_{L2} - \dfrac{1}{R\times\alpha\times C_o} v_{Co} \end{cases} \qquad (A-5)$$

Where $\alpha = 1 + \frac{r_{Co}}{R}$.

Fig. A-2 shows the equivalent circuit for mode 2 ($(N + D)T_s < t < (N+1)T_s$).

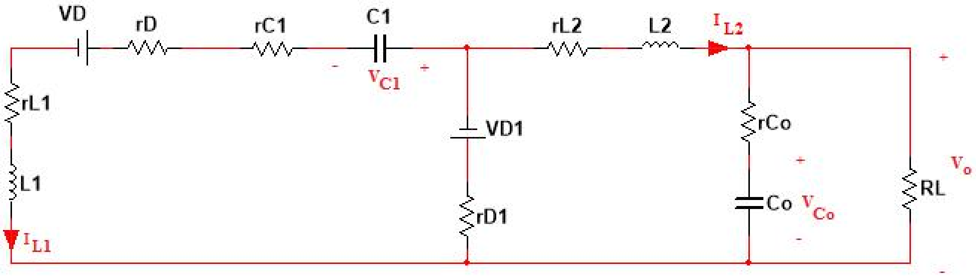

Figure A-2 Equivalent circuit of mode 1 in presence of circuits non idealities

The equations for describing this mode can be derived as:

$$\begin{cases} \dfrac{d(i_{L1})}{dt} = -\dfrac{(r_{D0}+r_{D1}+r_{C1}+r_{L1})}{L_1} i_{L1} - \dfrac{r_{D0}}{L_1} i_{L2} - \dfrac{v_{C1}}{L_1} - \dfrac{2}{L_1} v_{\gamma} \\ \dfrac{d(i_{L2})}{dt} =-\dfrac{r_{D0}}{L_2} i_{L1} - \dfrac{1}{L_2}\left(r_{D0}+r_{L2}+\dfrac{r_{CO}}{\alpha}\right) i_{L2} - \dfrac{1}{L_2}\left(1-\dfrac{r_{Co}}{R\times\alpha}\right) v_{Co} - \dfrac{1}{L_2} v_{\gamma} \\ \dfrac{d(v_{C1})}{dt} = \dfrac{1}{C_1} i_{L1} \\ \dfrac{d(v_{C2})}{dt} = \dfrac{1}{\alpha\times C_o} i_{L2} - \dfrac{1}{R\times\alpha\times C_o} v_{Co} \end{cases} \qquad (A-6)$$

Developed software extract small signal transfer functions using equations A-3, A-4, A-5 and A-6.

References

[1] Luo F L, Ye H (2004). Positive output multiple-lift push-pull switched capacitor Luo-converters, IEEE Trans. Ind. Electron.,vol. 51, no. 3, pp. 594–602.

[2] Zhu M, Luo L (2007). Development of voltage lift technique on double output transformerless DC–DC converter'. Proc. 33rd Annual Conf. Industrial Electronics Society, pp. 1983–1988.

[3] Zhu M, Luo L(2007). Implementing of developed voltage lift technique on SEPIC, Cuk and double-output DC–DC converters. Proc. IEEE Int. Conf. Industrial Electronics, pp. 674–681.

[4] Sahu B, Rincon-Mora G A (2004). A low voltage, dynamic, non-inverting, synchronous buck–boost converter for portable applications', IEEE Trans. Power Electron., vol. 19, pp. 443–451.

[5] Ren X, Tang Z, Xuan R, Wei J and Hua G (2008). Four switch buck–boost converter for telecom DC–DC power supply applications. IEEE APEC, pp. 1527–1530.

[6] Changchien S K, Liang T J, Chen J F and Yang L S (2010). Novel high step up DC–DC converter for fuel cell energy conversion system, IEEE Trans. Ind. Electron.,vol. 57, no. 6, pp. 2007–2017.

[7] Liu W S, Chen J F, Liang T J, Lin R L (2010).

Analysis, design, and control of bidirectional cascaded configuration for a fuel cell hybrid power system , IEEE Trans. Power Electron., 2010, vol. 25, no. 6, pp. 1565–1575.

[8] Hwu K I, Yau Y T (2008). A novel voltage-bucking/boosting converter: KY buck-boost converter. IEEE Int. Conf. Industrial Technology, pp. 1–4.

[9] Hwu K I, Chen Y H, Lin Z F (2009). Negative-output KY buck-boost converter . Fourth IEEE Conf. Industrial Electronics and Applications ICIEA, pp. 3347–3350.

[10] Hwu K I, Lin Z F, Chen Y H (2009). A novel negative-output KY buck-boost converter. Int. Conf. Power Electronics and Drive Systems PEDS, pp. 1158–1162.

[11] Hwu K I, Yau Y T(2009). Two types of KY buck–boost converters, IEEE Trans. Ind. Electron.,vol. 56, no. 8, pp. 2970–2980.

[12] Liao H K, Liang T J, Yang L S, Chen J F(2012). Non-inverting buck–boost converter with interleaved technique for fuel-cell system, IET Power Electron., vol. 5,no 8, pp. 1379–1388.

[13] Ismail E H, Al-Saffar M A, Sabzali A J and Fardoun A A (2008).A family of single-switch PWM converters with high step-up conversion ratio, IEEE Trans. Circuits Syst. I. Reg. Papers, vol. 55, no. 4, pp. 1159-1171.

[14] Miao S, Wang F and Ma X(2016). A novel buck-boost converter with low stresses on switches and diodes, 2016 IEEE 8th International Power Electronics and Motion Control Conference (IPEMC-ECCE Asia), Hefei, 2016, pp. 3344-3347.

[15] Middlebrook RD and Cuk S(1977). A general unified approach to modeling switching-converter power stages. Int. J. Electron., vol. 42, no. 6, pp. 521–550.

[16] Kislovski A S, Ridl R and Socal N(1991). Dynamic analysis of switching mode dc-dc converter, Van Nostrand Reinhold, New York.

[17] Mohan N, Undeland T and Robbins W(2003). Power electronics devices, converters appicat,on and design, John Wiley and Sons, New York, Singapore Toronto, Brisbane.

[18] Cuk S and Middlebrook RD(1977). A general unified approach in modeling switching DC-to-DC converters in discontinuous conduction mode. in Proc. IEEE Power Electronics Special Conf. pp. 36–57.

[19] Hren A, Slibar P(2005), Full order dynamic model of SEPIC converter, Proceedings of the IEEE International Symposium on Industrial Electronics, Dubrovnik, Croatia, vol. 2, pp. 553-558.