

Modelling the PWM SEPIC Converter in Discontinuous Conduction Mode

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Abstract: - A full-order dynamic model of the pulse-width modulation (PWM) DC-to-DC SEPIC converter in discontinuous conduction mode (DCM) is presented in this paper. The derivation procedure is based on the small-signal PWM switch model in DCM used in conjunction with a PWM derived SEPIC topology. The small-signal characteristics of the PWM SEPIC converter in DCM obtained in a similar way as the small-signal properties of a linear amplifier are presented in a symbolic form. Such a model can be directly used in conjunction with a computational environment as Matlab, MathCAD and Mathematica to analyze the small-signal low-frequency dynamics of the PWM SEPIC converter in DCM.

Key-Words: - Full-order small-signal model, PWM switch model, PWM SEPIC converter in DCM

1 Introduction

The fourth-order PWM converters are networks with four storage elements: two inductors and two capacitors. Cuk, SEPIC and Zeta converters are examples of basic fourth-order PWM converters with many applications [1] – [8].

In this paper, the ac model of the pulse-width modulation (PWM) switch in discontinuous conduction mode (DCM) is used in the modeling process of the PWM SEPIC (Single-Ended Primary Inductor Converter) converter operating in DCM. As has been presented in [9], the ac model of the PWM switch in DCM represents the small-signal characteristics of the nonlinear part of the converter, which consists of the active and passive switch pair. This averaged technique is easily applied to all three second-order PWM converter, i.e. buck, boost and buck-boost converter and Cuk converter where the PWM switch is clearly highlighted. Using the model of the PWM switch in DCM, the PWM Cuk converter in DCM is analyzed for dc and small-signal low-frequency characteristics in [9]. Its small-signal transfer functions confirm the fact that the Cuk converter operating in DCM is a fourth-order system. The other fourth-order converters namely SEPIC and Zeta converters in CCM were completely analyzed in [10] as converters belonging to boost and buck family, respectively. The ac (small-signal low-frequency) characteristics of an isolated SEPIC converter with synchronous rectifier in CCM are derived in [11]. There, the original circuit is transformed into an equivalent circuit in order to point out the PWM switch.

A full-order dynamic model and ac characteristics of the same converter operating in DCM as a fourth-order

system, to the best of the author's knowledge, have not been reported until now. This lack in the SEPIC converter modeling is essentially due to the dedicated applications of SEPIC converter in the power factor correction area. Our work aims to carry out the small-signal dynamic model of the PWM SEPIC converter in DCM in the terms of line-to-output voltage, control-to-output voltage, load-to-input current and control-to-input current transfer functions, and output impedance and input admittance. Such a model in symbolic form is appropriate for a computer-aided analysis of this converter. Certainly, the dynamic model of which derivation is based on an averaging method is subject to the usual limitation of linear models [12]-[19].

The paper is organized as follows. The basic and derived SEPIC converter topologies and the model of PWM switch in DCM are presented in Section II. The dc characteristics, small-signal equivalent circuit of derived SEPIC converter in DCM and its full-order dynamic model in a symbolic form are given in Section III. The modeling procedure is presented for an ideal no-coupled inductor converter, but it can be applied to an isolated converter and coupled-inductor converter including the parasitic elements. The Section IV concludes the paper.

Generally, the usual notations and conventions are employed in this paper. For instance, the constant switching frequency is denoted f_s and the distinct time intervals are denoted d_1T_s , d_2T_s and d_3T_s , with $d_1 + d_2 = 1$ for CCM and $d_1 + d_2 + d_3 = 1$ for DCM respectively. For a voltage-mode control, the duty cycle d_1 is the control variable. The time interval d_1T_s is the time during which the transistor is on and the diode is off. The time interval d_2T_s is the time during which the transistor is off and the diode is on, and the third interval d_3T_s is the time

during which both the transistor and diode are off. The capital letters represent the large-signal dc values, while the lower-case letters represent the time-varying variables. The lower-case letters with “^” above them denote the small-signal *s*-domain expressions of the corresponding time-varying variables.

2 SEPIC Converters

A PWM SEPIC converter consists of an active and passive switch pair, and two inductors and two capacitors likewise the Cuk and Zeta converters. The advantages and disadvantages of this converter type as low input and/or output current ripples and need an extra capacitor with large ripple-current-carrying capability are widely presented in literature.

2.1 Basic and derived SEPIC converter topologies

The schematic diagram of the basic SEPIC converter topology is given in Fig. 1 and the derived SEPIC converter topology in Fig. 2. The second converter topology is obtained by changing only the place of the energy storage capacitor *C*₁ by moving it into the return line.

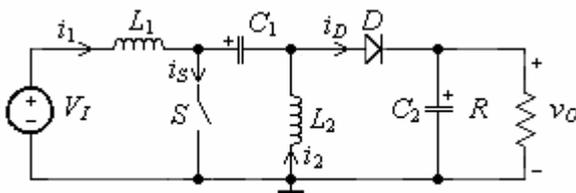


Fig. 1. Schematic diagram of the PWM basic SEPIC converter

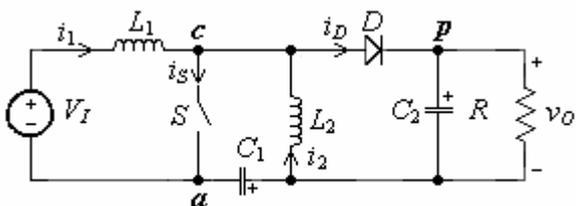


Fig. 2. Schematic diagram of the PWM derived SEPIC converter

A detailed simulation shows an identical operation of the two PWM SEPIC circuits. The dc analysis of the two topologies in CCM and DCM shows an identical behaviour of these two converters. Also, the same state equations describe the two converters operating either in

CCM or DCM as it can be seen at first glance from the switched circuits of the two topologies over a switching period. So, studying only one of these converters, we obtain the characterization of both basic and derived SEPIC converters. Among these two SEPIC converters, only the schematic diagram of the derived converter highlights the PWM switch with its three terminals denoted *a* (active), *p* (passive) and *c* (common) as it is shown in Fig. 1b. However, in the derived SEPIC converter topology, if a common reference potential of the input and output is required, the control of the power transistor has to be realized potential free with respect to the potential reference. We must mention that the PWM derived SEPIC converter in Fig. 1b serves here exclusively for a clear evidence of the PWM switch in the SEPIC structure.

The dc characteristics of the PWM SEPIC converter in DCM are analyzed in [20]. For its dc analysis, a lot of simplified and detailed analysis methods could be applied to converter inclusively those based on the PWM switch model in DCM. Also, the well-known method of the state-space averaging yields the same results as previously mentioned method. For the sake of brevity, this shall not be treated in more detail here and we will give some dc results of a simplified analysis of separated-inductor converter in which the effect of the parasitic elements of circuit was neglected. Only the quantities of interest for the modelling process together with their significations and/or definitions are given below as follows:

- DC voltage conversion ratio, $M=V_o/V_I=D_1/D_2$;
- Parameter of conduction through an equivalent inductor with inductance $L_e=L_1//L_2$, $K_e=2L_e f_s / R$;
- $D_2=\sqrt{K_e}$; $V_{C1}=V_I$; $I_S=M^2 V_I / R$; $I_D=MV_I / R$.

The effect of inductor coupling can be included in the equivalent inductance of converter and the above formulae remain unchanged.

2.2 AC model of the three terminal PWM switch in DCM

The following two equations describe the ac (small-signal low-frequency) model of the three terminal PWM switch in DCM as it is demonstrated in [9]:

$$\hat{i}_a = g_i \hat{v}_{ac} + k_i \hat{d}_1 \tag{1}$$

$$\hat{i}_p = g_f \hat{v}_{ac} + k_o \hat{d}_1 - g_o \hat{v}_{cp} \tag{2}$$

where

$$g_i = I_a / V_{ac} \tag{3}$$

$$k_i = 2I_a / D_1 \tag{4}$$

$$g_f = 2I_p / V_{ac} \tag{5}$$

$$k_o = 2I_p / D_1 \tag{6}$$

$$g_o = I_p / V_{pc}. \quad (7)$$

Equations (1) and (2) correspond to the equivalent circuit model shown in Fig. 3.

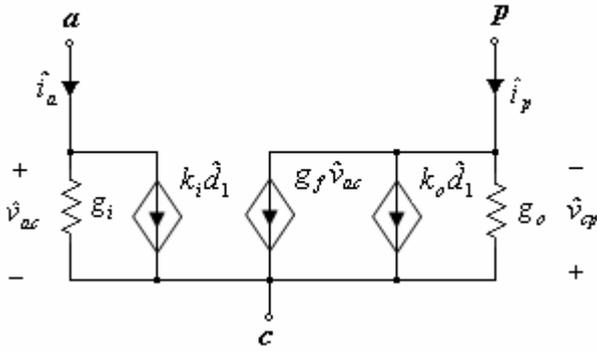


Fig. 3. Small-signal model of the PWM switch in DCM

For a given dc operating point of SEPIC converter, the currents I_a and I_p , and the voltages V_{ac} and V_{cp} have the following expressions: $I_a = I_s = M^2 V_I / R$; $I_p = I_D = M V_I / R$; $V_{ac} = V_I$; $V_{cp} = V_O = M V_I$. The equations (3) – (7) yield the model parameters corresponding to respective operating point: $g_i = M^2 / R$; $g_f = 2M / R$; $g_o = 1 / R$; $k_i = 2M^2 V_I / R D_1$; $k_o = 2M V_I / R D_1$.

3 Small-Signal Model of the PWM SEPIC Converter in DCM

In this section, the ac equivalent circuit model of the PWM switch in DCM is used to carry out the small-signal model of the PWM SEPIC converter. In the modeling process of the power processor that is open-loop converter, we consider the small-signal disturbances of the line voltage, load current and duty cycle, i.e. \hat{v}_i , \hat{i}_d and \hat{d}_1 , as input variables, and their results in the disturbances of the output voltage and input current, i.e. \hat{v}_o and \hat{i}_i , as output variables, as it is schematic shown in Fig. 4.

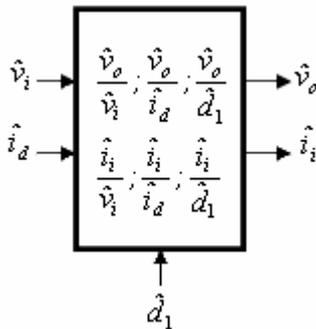


Fig. 4. Variables considered in modelling of the power processor

The small-signal low-frequency dynamic model of the PWM SEPIC converter in DCM will be described by the following equation:

$$\begin{bmatrix} \hat{v}_o(s) \\ \hat{i}_i(s) \end{bmatrix} = \begin{bmatrix} G_{u11}(s) & G_{u12}(s) \\ G_{u21}(s) & G_{u22}(s) \end{bmatrix} \begin{bmatrix} \hat{v}_i(s) \\ \hat{i}_d(s) \end{bmatrix} + \begin{bmatrix} G_{d1}(s) \\ G_{d2}(s) \end{bmatrix} \hat{d}_1(s). \quad (8)$$

The above equation contains all ac characteristics of an open-loop PWM converter, namely:

- The line-to-output voltage transfer function (audio susceptibility)

$$G_{u11}(s) = \left. \frac{\hat{v}_o(s)}{\hat{v}_i(s)} \right|_{\substack{\hat{i}_d=0 \\ \hat{d}_1=0}}; \quad (9)$$

- The output impedance

$$G_{u12}(s) = Z_o(s) = \left. \frac{\hat{v}_o(s)}{\hat{i}_d(s)} \right|_{\substack{\hat{v}_i=0 \\ \hat{d}_1=0}}; \quad (10)$$

- The control-to-output voltage transfer function

$$G_{d1}(s) = \left. \frac{\hat{v}_o(s)}{\hat{d}_1(s)} \right|_{\substack{\hat{v}_i=0 \\ \hat{i}_d=0}}; \quad (11)$$

- The input admittance

$$G_{u21}(s) = Y_{in}(s) = \left. \frac{\hat{i}_i(s)}{\hat{v}_i(s)} \right|_{\substack{\hat{i}_d=0 \\ \hat{d}_1=0}}; \quad (12)$$

- The load-to-input current transfer function (the load current disturbance is $\hat{i}_o = -\hat{i}_d$)

$$G_{u22}(s) = \left. \frac{\hat{i}_i(s)}{\hat{i}_d(s)} \right|_{\substack{\hat{v}_i=0 \\ \hat{d}_1=0}} = - \left. \frac{\hat{i}_i(s)}{\hat{i}_o(s)} \right|_{\substack{\hat{v}_i=0 \\ \hat{d}_1=0}}; \quad (13)$$

- The control-to-input current transfer function

$$G_{d2}(s) = \left. \frac{\hat{i}_i(s)}{\hat{d}_1(s)} \right|_{\substack{\hat{v}_i=0 \\ \hat{i}_d=0}}; \quad (14)$$

Under small-signal disturbances in average variables of converter at a given dc operating point (I_p , V_{ac} , D_1), the substitution of the small-signal equivalent circuit model of the PWM switch of Fig. 3 into the PWM derived SEPIC converter results in the circuit in Fig. 5 from which we get the following equations in s domain:

$$\hat{v}_i + \hat{v}_{ac} - sL_1 \hat{i}_i = 0, \quad (15)$$

$$\hat{v}_{c1} + \hat{v}_{ac} - sL_2 \hat{i}_2 = 0, \quad (16)$$

$$sL_2 \hat{i}_2 + \hat{v}_{cp} + \hat{v}_o = 0, \quad (17)$$

$$\hat{i}_i + (g_i + g_f) \hat{v}_{ac} + (k_i + k_o) \hat{d}_1 + \hat{i}_2 - g_o \hat{v}_{cp} = 0, \quad (18)$$

$$sC_1 \hat{v}_{c1} = \hat{i}_i + g_i \hat{v}_{ac} + k_i \hat{d}_1, \quad (19)$$

$$g_f \hat{v}_{ac} + k_o \hat{d}_1 - g_o \hat{v}_{cp} + (sC_2 + g_o) \hat{v}_o - \hat{i}_d = 0. \quad (20)$$

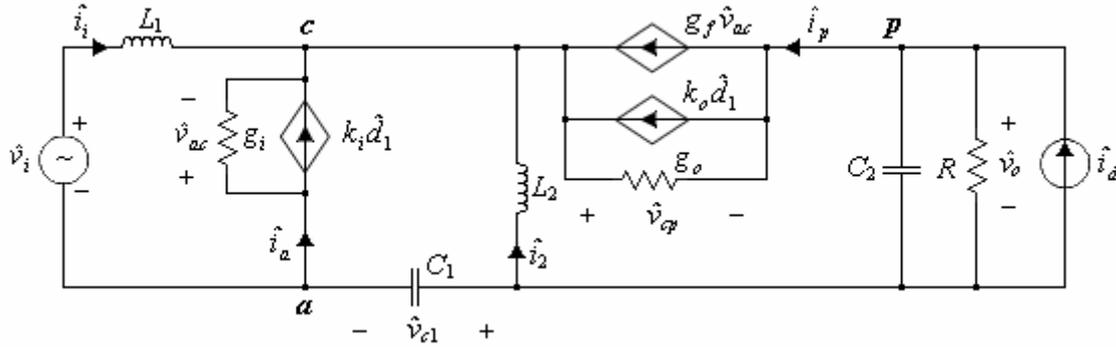


Fig. 5. Small-signal equivalent circuit of PWM derived SEPIC converter in DCM

After some algebra, we get the expressions of the above mentioned open-loop transfer functions and input and output impedance as follows:

$$G_{u11}(s) = \frac{M(1 + b_2 s^2)}{1 + a_1 s + a_2 s^2 + a_3 s^3 + a_4 s^4} = \frac{M(1 + b_2 s^2)}{D(s)}, \quad (20)$$

$$G_{u12}(s) = Z_o(s) = Z_o(0) \frac{1 + c_1 s + c_2 s^2 + c_3 s^3}{D(s)}, \quad (21)$$

$$G_{u21}(s) = Y_{in}(s) = Y_{in}(0) \frac{1 + e_1 s + e_2 s^2 + e_3 s^3}{D(s)}, \quad (22)$$

$$G_{u22}(s) = -\frac{f_2 s^2}{D(s)}, \quad (23)$$

$$G_{d1}(s) = -G_{d1}(0) \frac{1 + m_1 s + m_2 s^2 + m_3 s^3}{D(s)}, \quad (24)$$

$$G_{d2}(s) = -G_{d2}(0) \frac{1 + n_1 s + n_2 s^2 + n_3 s^3}{D(s)}. \quad (25)$$

The dc voltage conversion ratio, output resistance and input conductance, and polynomial coefficients appearing in equations (20) – (25) have the following expressions:

$$M = g_f / 2g_o; Z_o(0) = R_o = 1 / 2g_o;$$

$$Y_{in}(0) = G_{in} = g_i; G_{d1}(0) = k_o / 2g_o; G_{d2}(0) = k_i;$$

$$a_1 = g_i L_1 + g_o L_2 / 2 + C_2 / 2g_o;$$

$$a_2 = C_1(L_1 + L_2) + g_i g_o L_1 L_2 / 2 + C_2(g_i L_1 + g_o L_2) / 2g_o;$$

$$a_3 = C_1 L_1 L_2 (2g_i + g_f + g_o) / 2 + C_2 [C_1(L_1 + L_2) 2g_o + g_i L_1 L_2 / 2];$$

$$a_4 = C_1 C_2 L_1 L_2 (g_i + g_f + g_o) / 2g_o;$$

$$b_2 = C_1 L_2 (1 + g_o / g_f);$$

$$c_1 = g_i L_1 + g_o L_2;$$

$$c_2 = C_1(L_1 + L_2) + g_i g_o L_1 L_2;$$

$$c_3 = C_1 L_1 L_2 (g_i + g_f + g_o);$$

$$e_1 = C_1 / g_i + C_2 / 2g_o + g_o L_2 / 2;$$

$$e_2 = C_1 C_2 / 2g_i g_o + L_2 (C_1 + C_2) / 2 + C_1 L_2 (g_i + g_f + g_o) / 2g_i;$$

$$e_3 = C_1 C_2 L_2 (g_i + g_f + g_o) / 2g_i g_o;$$

$$f_2 = C_1 L_2 / 2;$$

$$m_1 = L_1 (k_o g_i - k_i g_f) / k_o;$$

$$m_2 = C_1 (L_1 + L_2);$$

$$m_3 = C_1 L_1 L_2 [k_o g_i - k_i (g_f + g_o)] / k_o;$$

$$n_1 = C_2 / 2g_o + L_2 g_o / 2;$$

$$n_2 = C_1 L_2 + C_1 L_2 k_o / 2k_i + C_2 L_2 / 2;$$

$$n_3 = C_1 C_2 L_2 (k_i + k_o) / 2g_o k_i.$$

The denominator $D(s)$ of the open-loop transfer functions shows that the PWM SEPIC converter in DCM is of fourth order:

$$D(s) = 1 + a_1 s + a_2 s^2 + a_3 s^3 + a_4 s^4. \quad (26)$$

For a properly designed fourth-order converter, the denominator consists of two quadratic factors whose resonances are well separated and almost entirely damped by the load. The parasitic resistances have almost no effect on the two resonant frequencies of $D(s)$ and contribute very little to the damping of the resonances under normal loading conditions. Therefore, we can write [11]:

$$D(s) = \left(1 + \frac{s}{\omega_{01} Q_1} + \frac{s^2}{\omega_{01}^2} \right) \left(1 + \frac{s}{\omega_{02} Q_2} + \frac{s^2}{\omega_{02}^2} \right). \quad (27)$$

Comparing the equation (26) to (27) under the assumption of moderate to high quality factors and well-separated resonances, we find out the relationships between the coefficients a_i and the resonance pulsations and quality factors, respectively, as follows:

$$a_1 \cong \frac{1}{\omega_{01} Q_1}; a_2 \cong \frac{1}{\omega_{01}^2};$$

$$a_3 \cong \frac{1}{\omega_{01} Q_1 \omega_{02}^2} + \frac{1}{\omega_{02} Q_2 \omega_{01}^2}; a_4 \cong \frac{1}{\omega_{01}^2 \omega_{02}^2}. \quad (28)$$

After some algebra, we get:

$$\omega_{01} = \frac{1}{\sqrt{a_2}}; Q_1 = \frac{\sqrt{a_2}}{a_1}; \omega_{02} = \sqrt{\frac{a_2}{a_4}};$$

$$Q_2 = \frac{a_2 \sqrt{a_2 a_4}}{a_3 a_2 - a_1 a_4}. \quad (29)$$

Comparing the ac model of PWM SEPIC converter in DCM and that of PWM SEPIC converter in CCM as it is given in [10] and [11], one observes the same forms and polynomial degrees of the homonym transfer functions and input and output impedances. This similarity confirms again the fact that the PWM SEPIC converter operating in DCM has fourth-order system behaviour.

The modeling procedure proposed here can be easily applied to the PWM SEPIC converter with coupled inductors. In the derived ac model, only the inductance L_1 and L_2 must be replaced with their equivalent inductances:

$$L_{1e} = \frac{(1 - k_c^2) L_1}{1 - k_c / n}, \quad (30)$$

$$L_{2e} = \frac{(1 - k_c^2) L_2}{1 - k_c n}. \quad (31)$$

In above equations, k_c is the coupling coefficient and n the turn ratio.

This open-loop model allows us to predict the small-signal low-frequency dynamic behaviour of SEPIC converter in DCM and to embed it within a feedback control loop.

4 Conclusion

A full-order dynamic model of the PWM SEPIC converter in discontinuous conduction mode is presented in this paper. The derivation procedure is based on the small-signal PWM switch model in DCM used in conjunction with a PWM derived SEPIC topology. This derived SEPIC converter topology is identical with the basic SEPIC converter topology concerning its operational behaviour and serves exclusively for modeling process here. Substitution of the ac model of the PWM switch in DCM into the equivalent circuit of the derived SEPIC converter allows us to develop the ac characteristics of the open-loop PWM SEPIC converter in DCM in a symbolic form in terms of audio susceptibility, control-to-output voltage transfer function, load-to-input current transfer function, control-to-input current transfer function, input admittance and

output impedance. Such a dynamic model that characterizes the PWM SEPIC converter in DCM as a fourth-order system can be directly used in conjunction with a computational environment as Matlab, MathCAD and Mathematica to analyze the small-signal low-frequency dynamics of the PWM SEPIC converter in DCM.

The full-order ac model of the PWM SEPIC converter operating in DCM developed in this paper comes to complete the characterization of the small-signal low-frequency dynamic behaviour of the PWM SEPIC converter.

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