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Closed-Loop Input Impedance of PWM Buck-Derived DC-DC Converters

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Abstract—The small-signal closed-loop input impedance is derived for the PWM buck dc-dc converter operated in continuous conduction mode (CCM), taking into account all parasitic resistances. The plots of the closed-loop input impedance are shown versus frequency for four values of the equivalent series resistance of the capacitor.¹

I. INTRODUCTION

A small-signal linear circuit model of the PWM buck converter has been developed, taking into account all parasitic resistances [1]–[3]. This derivation used an energy conservation method. The current ripple in the inductor is neglected in [1], [2] and is taken into account in [3]. Open-loop small-signal characteristics were illustrated using this model. The purpose of this paper is to present the derivation of the closed-loop input impedance of the voltage-mode-controlled PWM buck dc-dc power converter with a proportional controller for CCM.

II. SMALL-SIGNAL CIRCUIT MODEL OF THE PWM BUCK CONVERTER

A circuit of the PWM buck converter is shown in Fig. 1(a). It consists of a power MOSFET as a switch S , a diode $D1$, an inductor L , and a filter capacitor C . The converter is fed by a dc input voltage source V_I and is loaded by a dc load resistance R . The switch is turned on and off at the switching frequency $f_s = 1/T$ and the on-duty ratio is $D = t_{on}/T$, where t_{on} is the time interval during which the switch is on. Parasitic components associated with each circuit component, where r_{DS} is the MOSFET's on-resistance, R_F is the diode forward resistance, V_F is the diode threshold voltage, r_L is the equivalent series resistance of inductor L , and r_C is the ESR of the filter capacitor C .

Fig. 1(b) depicts a small-signal model of this converter [1], where d is the ac component of the switch duty ratio, v_i is the ac component of the input voltage, v_o is the ac component of the output voltage, I_L is the dc component of the inductor current, and i_l is the ac component of the inductor current. Resistance r is an equivalent averaged resistance (EAR) and is given by [1]

$$r = Dr_{DS} + (1 - D)R_F + r_L. \quad (1)$$

Fig. 1(c) shows a block diagram of a closed-loop buck converter. T_p represents a small-signal model of the buck

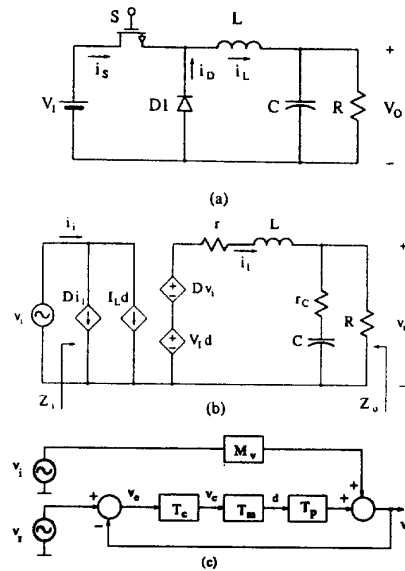


Fig. 1: PWM buck converter. (a) Circuit. (b) Small-signal model (c) Block diagram of the closed-loop voltage-mode-controlled converter.

converter, T_m represents a PWM modulator, T_c represents a controller, M_v represents an input-to-output voltage transfer function, T_{ol} is the open-loop control-to-output transfer function, v_c is the output voltage of the controller, v_e is the error signal applied to the input of the controller, and v_r is the ac component of the reference voltage. This is a two-input and a single-output system. It is driven by two independent sources, v_r and v_i . The ac component of the output voltage is

$$v_o(s) = \frac{T_{ol}}{1 + T_{ol}} v_r(s) + \frac{M_v(s)}{1 + T_{ol}} v_i(s). \quad (2)$$

The PWM buck-derived converters such as the forward, push-pull, half-bridge, and full-bridge converters (which contain transformers) have the same small-signal model and characteristics as the PWM buck converter [2]. Therefore, the transformer turns ratio n is included in the subsequent equations. The equivalent averaged resistance r is the only difference between these converters [2].

III. OPEN-LOOP TRANSFER FUNCTIONS

The small-signal model of Fig. 1(b) can be used to describe the converter performance for frequencies f up to

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about one-half the switching frequency f_s . Using this model, one can derive the *control-to-output* (or *duty ratio-to-output*) transfer function in the s -domain

$$\begin{aligned} T_p(s) &\equiv \frac{v_o(s)}{d(s)} \Big|_{v_i(s)=0} \\ &= \frac{V_I R r_C}{nL(R+r_C)} \frac{s + \frac{1}{Cr_C}}{s^2 + s \frac{C(Rr_C + Rr + r_C r) + L}{LC(R+r_C)} + \frac{R+r}{LC(R+r_C)}} \\ &= \frac{V_I R \omega_r^2}{n\omega_z(R+r)} \frac{s + \omega_z}{s^2 + 2\xi_r \omega_r s + \omega_r^2} \end{aligned} \quad (3)$$

where the frequency of the zero is

$$\omega_z = \frac{1}{Cr_C} \quad (4)$$

the corner frequency is

$$\omega_r = \sqrt{\frac{R+r}{LC(R+r_C)}} \quad (5)$$

and the damping ratio is

$$\xi_r = \frac{C(Rr_C + Rr + r_C r) + L}{2\sqrt{LC(R+r_C)(R+r)}} \quad (6)$$

Fig. 2(a) and (b) shows plots of the magnitude and the phase of T_p . The characteristics of T_p are plotted for four values of r_C because they strongly depend on r_C .

The voltage transfer function of the PWM modulator is

$$T_m \equiv \frac{d(s)}{v_c(s)} = \frac{1}{V_{Tm}} \quad (7)$$

where V_{Tm} is the peak value of the ramp voltage of the PWM modulator. It is assumed that $V_{Tm} = 5$ V, resulting in $T_m = 0.2 = -14$ dB.

The control-to-output transfer function of the converter and the modulator is given by

$$\begin{aligned} T_1(s) &\equiv \frac{v_o(s)}{v_c(s)} = T_m T_p(s) \\ &= \frac{V_I R \omega_r^2}{n\omega_z V_{Tm}(R+r)} \frac{s + \omega_z}{s^2 + 2\xi_r \omega_r s + \omega_r^2} \end{aligned} \quad (8)$$

Fig. 2(c) depicts a Bode plot of $|T_1|$. The phase shift ϕ_{T_1} of T_1 is the same as the phase shift ϕ_{T_p} and is depicted in Fig. 2(b).

To obtain a wide bandwidth of the open-loop transfer function, a proportional controller is used. The controller which employs an inverting op-amp is shown in Fig. 3. Since the operation at high frequencies is of interest, the frequency response of the op-amp should be taken into account. For this reason, a pure proportional controller is difficult to realize. The voltage transfer function of the controller for the ac component is

$$T_c(s) \equiv \frac{v_c(s)}{v_e(s)} = \frac{A_{vo}}{1 + \frac{s}{\omega_{Hf}}} = \frac{A_{vo}}{1 + \frac{sA_{vo}}{\omega_1}} \quad (9)$$

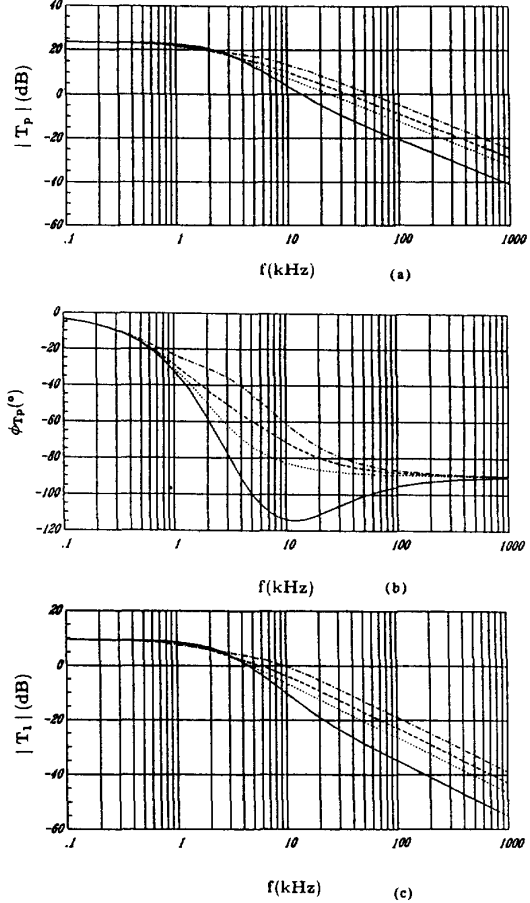


Fig. 2: Control-to-output transfer function $T_p = |T_p| e^{j\phi_{T_p}}$ and $|T_1|$ for $V_I = 30$ V, $n = 1$, $L = 5$ μ H, $C = 1$ mF, $R = 0.25$ Ω , $r = 0.15$ Ω , $D = 0.3$, and various values of $r_C = 0.01$ (solid line), 0.03, 0.05, and 0.1 Ω . (a) $|T_p|$ against f . (b) $\phi_{T_p} = \phi_{T_1}$ against f . (c) $|T_1|$ against f .

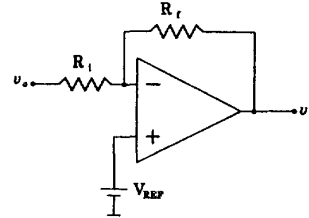


Fig. 3: Circuit diagram of the proportional controller.

where the low frequency gain is

$$A_{vo} = \frac{R_f}{R_i} \quad (10)$$

The open-loop control-to-output transfer function is

$$T_{ol}(s) = T_c(s)T_1(s) = T_c(s)T_m T_p(s). \quad (11)$$

Plots of T_{ol} are shown in Fig. 4. The crossover frequency f_c of the open-loop transfer function $|T_{ol}|$ is 27 to 100 kHz

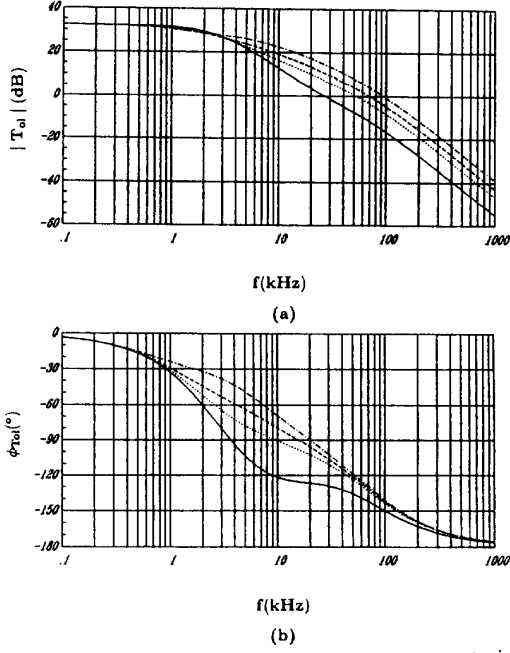


Fig. 4: Open-loop transfer function $T_{ol} = |T_{ol}| e^{j\phi_{T_{ol}}}$ for $L = 5 \mu\text{H}$, $C = 1 \text{ mF}$, $R = 0.25 \Omega$, $r = 0.15 \Omega$, $D = 0.3$, $A_{v_o} = 14$, and various values of $r_C = 0.01$ (solid line), 0.03, 0.05, and 0.1Ω . (a) $|T_{ol}|$ against f . (b) $\phi_{T_{ol}}$ against f .

for r_C ranging from 0.01 to 0.1Ω . The phase margin is greater than 45° . Since the phase $\phi_{T_{ol}}$ never crosses -180° , the gain margin cannot be determined.

The *input-to-output* (or *line-to-output*) *voltage transfer function* (which describes the input-output noise transmission), is

$$\begin{aligned} M_v(s) &\equiv \frac{v_o(s)}{v_i(s)} \Big|_{d(s)=0} \\ &= \frac{DRr_C}{nL(R+r_C)} \frac{s + \frac{1}{Cr_C}}{s^2 + s \frac{C(Rr_C + Rr + r_C r) + L}{LC(R+r_C)} + \frac{R+r}{LC(R+r_C)}} \\ &= \frac{DR\omega_r^2}{n\omega_z(R+r)} \frac{s + \omega_z}{s^2 + 2\xi_r\omega_r s + \omega_r^2}. \end{aligned} \quad (12)$$

It follows from (12) that $|M_v|$ increases with increasing D . Therefore, M_v should be considered for the maximum value of D . Plots of $|M_v|$ are shown in Fig. 5.

The *open-loop input impedance* is

$$\begin{aligned} Z_i(s) &\equiv \frac{v_i(s)}{i_i(s)} \Big|_{d(s)=0} \\ &= \frac{n^2 L}{D^2} \frac{s^2 + s \frac{C(Rr_C + Rr + r_C r) + L}{LC(R+r_C)} + \frac{R+r}{LC(R+r_C)}}{s + \frac{1}{C(R+r_C)}} \\ &= \frac{n^2 L}{D^2} \frac{s^2 + 2\xi_r\omega_r s + \omega_r^2}{s + \omega_{cr}} \end{aligned} \quad (13)$$

where

$$\omega_{cr} = \frac{1}{C(R+r_C)}. \quad (14)$$

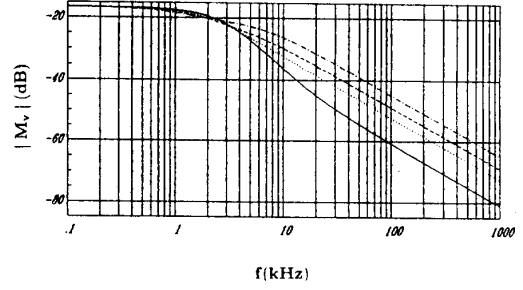


Fig. 5: Magnitude of the open-loop input-to-output transfer function $|M_v|$ against f for $V_I = 30 \text{ V}$, $n = 1$, $L = 5 \mu\text{H}$, $C = 1 \text{ mF}$, $R = 0.25 \Omega$, $r = 0.15 \Omega$, $D = 0.3$, and various values of $r_C = 0.01$ (solid line), 0.03, 0.05, and 0.1Ω .

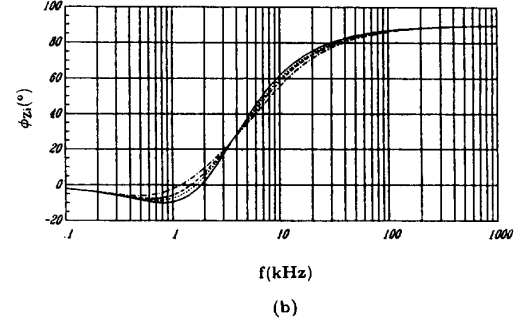
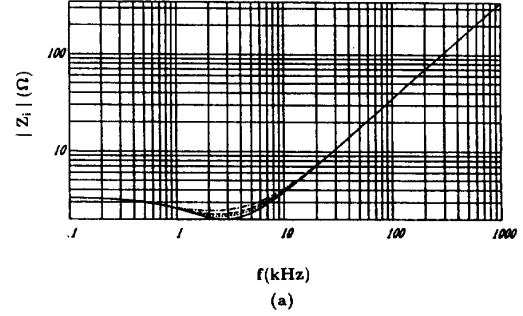


Fig. 6: Open-loop input impedance $Z_i = |Z_i| e^{j\phi_{Z_i}}$ for $D = 0.3$, $n = 1$, $L = 5 \mu\text{H}$, $C = 1 \text{ mF}$, $R = 0.25 \Omega$, $r = 0.15 \Omega$, $D = 0.3$, and various values of $r_C = 0.01$ (solid line), 0.03, 0.05, and 0.1Ω . (a) $|Z_i|$ against f . (b) ϕ_{Z_i} against f .

For $s = 0$,

$$Z_i(0) = \frac{n^2(R+r)}{D^2}. \quad (15)$$

Fig. 6 shows plots of Z_i as a function of frequency.

IV. CLOSED-LOOP INPUT IMPEDANCE

The closed-loop input impedance can be derived as follows. Referring to the block diagram shown in Fig. 1(c) and assuming $v_r = 0$,

$$v_o = T_p d + M_v v_i \quad (16)$$

$$d = -v_o T_c T_m = -(T_p d + M_v v_i) T_c T_m. \quad (17)$$

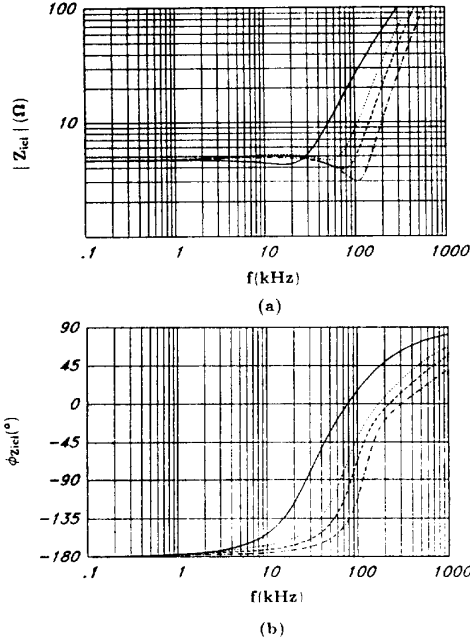


Fig. 7: Closed-loop input impedance $Z_{icl} = |Z_{icl}| e^{j\phi_{Z_{icl}}}$ for $A_{vo} = 14$, $f_1 = 1$ MHz, $V_{Tm} = 5$ V, $D = 0.3$, $n = 1$, $L = 5$ μ H, $C = 1$ mF, $R = 0.25$ Ω , $r = 0.15$ Ω , $D = 0.3$, and various values of $r_C = 0.01$ (solid line), 0.03, 0.05, and 0.1 Ω . (a) $|Z_{icl}|$ against f . (b) $\phi_{Z_{icl}}$ against f .

Dividing (12) by (3) gives

$$M_v = \frac{D}{V_I} T_p. \quad (18)$$

Substitution of (11) and (18) into (17) yields

$$\begin{aligned} d &= -\frac{T_c T_m M_v}{1 + T_c T_m T_p} v_i = -v_i \left(\frac{M_v}{T_p} \right) \left(\frac{T_{ol}}{1 + T_{ol}} \right) \\ &= -\frac{D T_{ol}}{V_I (1 + T_{ol})} v_i. \end{aligned} \quad (19)$$

Neglecting V_F in a dc model of the buck converter [1],

$$I_L = \frac{D V_I}{n(R + r)}. \quad (20)$$

Finally, the closed-loop input admittance is given by

$$\begin{aligned} Y_{icl} &= \frac{1}{Z_{icl}} \equiv \frac{i_i}{v_i} = \frac{D i_L + I_L d}{n v_i} \\ &= \frac{1}{Z_i} \frac{1}{1 + T_{ol}} - \frac{D I_L}{V_I} \frac{T_{ol}}{1 + T_{ol}} \\ &= \frac{1}{Z_i} \frac{1}{1 + T_{ol}} - \frac{D^2}{n^2 (R + r)} \frac{T_{ol}}{1 + T_{ol}} \end{aligned} \quad (21)$$

where $i_i = n(Dv_i + V_I d)/(D^2 Z_i)$. If $s = 0$ and $|T_{ol}| \gg 1$ then

$$Z_{icl}(0) \approx -\frac{n^2 (R + r)}{D^2} = -Z_i(0). \quad (22)$$

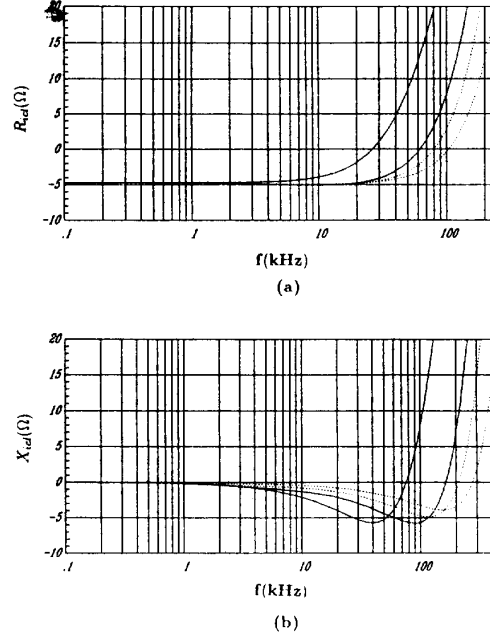


Fig. 8: Closed-loop input impedance $Z_{icl} = R_{icl} + jX_{icl}$ for $A_{vo} = 14$, $f_1 = 1$ MHz, $V_{Tm} = 5$ V, $D = 0.3$, $n = 1$, $L = 5$ μ H, $C = 1$ mF, $R = 0.25$ Ω , $r = 0.15$ Ω , $D = 0.3$, and various values of $r_C = 0.01$ (solid line), 0.03, 0.05, and 0.1 Ω . (a) R_{icl} against f . (b) X_{icl} against f .

For $f \gg f_c$ and $|T_{ol}| \ll 1$, $Z_{icl} \approx Z_i(1 + T_{ol}) \approx Z_i$. Figs. 7 and 8 show plots of the closed-loop input impedance. It can be seen from Fig. 8(a) that the closed-loop input resistance R_{icl} is negative at low frequencies.

V. CONCLUSIONS

The small-signal closed-loop input impedance of the PWM buck-derived dc-dc power converters has been derived and illustrated for four values of the ESR of the filter capacitor. A proportional controller was used. Plots of the closed-loop input-impedance have been shown. The closed-loop input resistance is negative at low frequencies. The results agree with those obtained from the state-space averaging method [4].

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