Small-Signal Model for Current Mode Control Full-bridge Phase-shifted ZVS Converter

Xu Xiaofeng
Department of Electrical Engineering, Northern Jiaotong University, Beijing 100044, P.R.China
Phone: 010-62257771-3498
E-mail:xfxu@center.njtu.edu.cn

Abstract In this paper, the small-signal model of current mode control full-bridge phase-shifted ZVS PWM converter is derived based on the small-signal model of the converter. Through the transformation of the current mode small-signal model into the respective transfer function model, a simplified close loop current mode small-signal transfer function of the converter is obtained. By using the derived small-signal model, it is possible to design the compensation network of the converter in frequency domain.

Key words Full-bridge Converter; Phase-shifted Control; Small-signal Model; Current Mode Control

1. Introduction

In recent years, FBPS(Full-bridge Phase-shifted) zero-voltage-switched PWM converter has been found widely use in many applications such as telecommunication power supplies, battery chargers and welding machines. This topology permits all switching device to operate under zero voltage switching by incorporating all circuit parasitic such as leakage inductance and junction capacitance of devices into resonant process[1]. The ZVS operation of the converter enables high switching frequency of the devices while maintaining some distinct characteristics such as high conversion efficiency, lower stress of power devices and lower EMI.

It is well known that for push-pull and full-bridge topology, the magnetic biasing of the transformer is most important problem to affect proper operation of the converter. Although there are some methods to solve this problem, but they all have some drawbacks. Compare with other methods to prevent magnetic basing, current mode control provide an effective way to solve this problem which is very easy to implement[2][3]. Perhaps one of the most important merits of the full-bridge converter using current mode control is that mono-direction magnetic biasing problem can be prevented without using dc component isolation capacitor in primary side, which is very appreciable for high power converter operating under high frequency. Besides, by using current mode control, converter can also obtain some other good characteristics.

Small-signal model play an important role in the transient analysis of the converter. V.Vlatkovic et al. gives a complement small-signal model of the phase-shifted PWM converter[4][5]. But it is a open loop small-signal model, so one can only obtain open loop small-signal characteristics of the converter. In reference [6], an averaged switch model for the phase-shifted PWM converter is derived. The model can be easily implemented using PSPICE circuit analysis program, and an analysis example of close loop voltage mode control phase-shifted PWM converter is presented. In this paper, a current mode control phase-shifted PWM converter is derived. Based on the derived small-signal model, some characteristic function such as output -Impedance , audio-susceptibility and control to output transfer function can be obtained.

2. Small-signal Model of PSFB-ZVS Converter

The circuit diagram of the full-bridge phase-shifted PWM converter is shown in Fig.1. In Fig 1.(a),the primary voltage and current of the transformer are

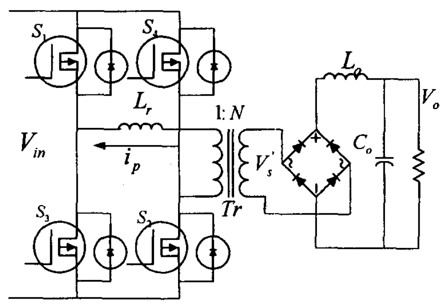


Fig.1 The Circuit diagram of the FB-ZVS converter

represented by V_p and i_p respectively, and secondary voltage of the transformer can be represented by $V_s^{'}$. The turns ratio of the transformer is defined as $N_p/N_s = 1/n$. L_r is the leakage inductance of the transformer.

In Fig.2, the main analytical waveforms of the primary and secondary voltage and primary current waveforms of the converter are shown in one cycle. When power is delivered from primary to secondary, secondary voltages are $V_s^{'} = nV_s$. Because of the leakage inductance of the transformer, the wavefoms of primary current increases or

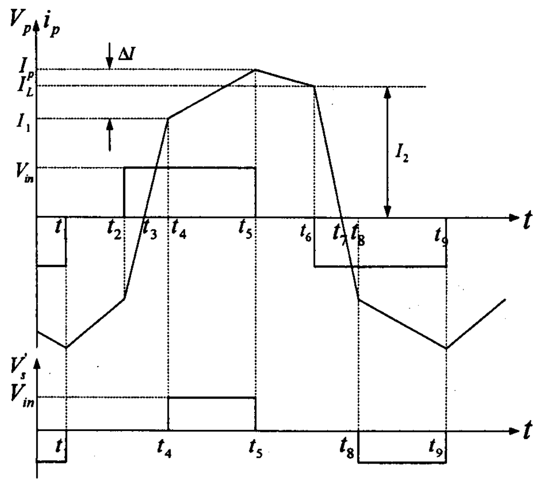


Fig.2 the main analytical waveforms of the converter

decreases according to the slope defined by leakage inductance or output filter inductance, for example, the slope of the primary current waveform is V_s/L_r during $t_2 - t_4$ stage, while during $t_4 - t_5$ stage, the slope is determined by $\left(V_s - V_o^{'}\right)/L_o^{'}$, $L_o^{'}$ and $V_o^{'}$ is the respective converted values from secondary to primary side.

The duty cycle of the primary and secondary side can derived based on Fig .1(b) as follows:

primary duty cycle: $D = \left(t_5 - t_2\right)/T_s/2$

secondary duty cycle or effective duty cycle:

$$D_{eff} = \left(t_5 - t_4\right)/T_s/2$$

It is obviously that effective duty cycle is smaller than primary duty cycle due to the existence of leakage inductance of the transformer.

The voltage plus of the FB ZVS-PWM converter can be represented by $V_o/V_{in} = D_{eff}\, N_s/N_p = nD_{eff}$. Assuming that ΔD represents the duty cycle loss, then we obtain

$$D = D_{eff} + \Delta D \tag{1}$$

The primary current at time instant $t = t_4$ in Fig .1(b) can be derived as:

$$I_1 = n\left(I_L - \Delta I/2\right) \tag{2}$$

whereas at time instant $t = t_6$

$$I_2 = n\left[I_L + \Delta I/2 - (1-D)V_o\, T_s/2L_o\right] \tag{3}$$

Based on Fig.2, ΔD can be derived as :

$$\Delta D = \left(I_1 + I_2\right)\Big/\left(\frac{V_{in}}{L_r}\frac{T_s}{2}\right) \tag{4}$$

By combining (2) and (3) into (4) obtain

$$\Delta D = \frac{n}{\dfrac{V_{in}}{L_r}\dfrac{T_s}{2}}\left[2I_L - \frac{V_o}{L_o}(1-D)\frac{T_s}{2}\right] \tag{5}$$

Considering (1), D_{eff} can be obtained:

$$D_{eff} = D - \frac{2nL_r}{V_{in}T_s}\left[2I_L - \frac{V_o}{L_o}(1-D)\frac{T_s}{2}\right] \tag{6}$$

Form (6) one see that effective duty cycle can be affected by many quantities such as load, input voltage and primary duty cycle. So other then the small-signal model of buck converter where only one controlled current source is used to represent the disturbance, the small-signal model of PSFB-ZVS PWM converter uses two additional controlled sources which represent the disturbance quantity of load to effective duty cycle and the disturbance quantity of input to effective duty cycle.

The small-signal model of full-bridge phase-shifted PWM converter [5]is shown in Fig.3.

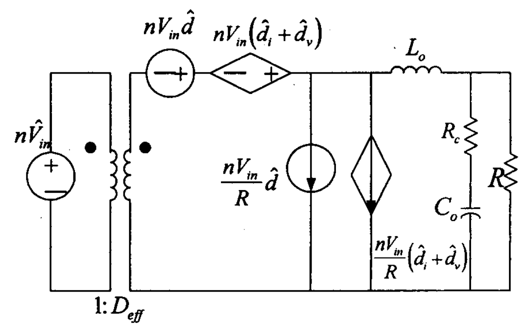


Fig.3 small-signal of PSFB ZVS PWM converter

The variables in Fig.3 is define as follows:

V_{in}: input voltage of the converter in steady state;

$\hat{d}_i$:output filter inductor current disturbance to effective duty cycle ;

$\hat{V}_{in}$: input voltage disturbance;

$\hat{V}_o$: output voltage disturbance;

$\hat{d}_v$:input voltage disturbance to effective duty cycle ;

$\hat{i}_L$: output filter inductor current disturbance;

$\hat{d}$: disturbance of the duty cycle in the primary of the transformer;

$\hat{d}_d$: disturbance of primary duty cycle to effective duty cycle

T_s : switching period of the device;

f_s : pulsating frequency of the current in output filter frequency;

The variables in the small-signal model can be defined as:

$$\hat{d}_v = \frac{2nL_r f_r I_L}{V_{in}^2}\hat{V}_{in} \tag{7}$$

$$\hat{d}_i = \frac{2nL_r f_r}{V_{in}}\hat{i}_L \tag{8}$$

$$\hat{d}_d = \left(1 - \frac{L_r}{L_o}n^2 D_{eff}\right)\hat{d} \tag{9}$$

Considering $\hat{d}_d \cong \hat{d}$, below equation can be obtained according to above relations:

$$\hat{d}_{eff} = \hat{d} + \hat{d}_i + \hat{d}_v \tag{10}$$

3. Small-signal Model of Current Mode PSFB-ZVS Converter

Based on the small-signal model of full-bridge phase-shifted ZVS PWM converter, the respective current mode control converter small-signal model can be derived as shown in Fig4.

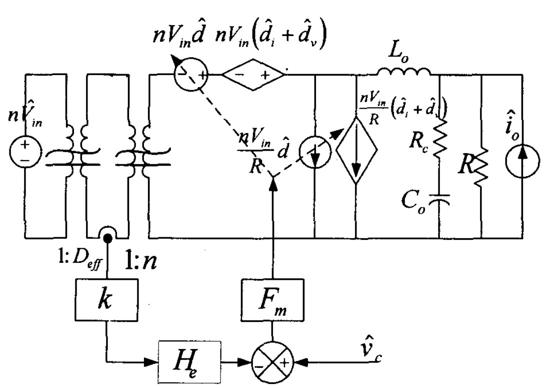


Fig 4 small-signal model of current mode control PSFB-ZVS converter

From the small-signal model shown in Fig4, its respective transfer function model in frequency domain can be obtained as shown in Fig5. The transfer function in Fig5 can be derived as represented by following equations.

$$F_1 = \frac{\left(\frac{R_1}{V_{in}}I_L + nD_{eff}\right)Z_c}{Z_f - R_1} \qquad F_2 = \frac{nV_{in}Z_c}{Z_f - R_1}$$

$$F_3 = \frac{\frac{R_1}{V_{in}}I_L + nD_{eff}}{Z_f - R_1} \qquad F_4 = \frac{nV_{in}}{Z_f - R_1}$$

$$F_5 = -\frac{Z_c}{Z_f - R_1} \quad F_6 = \left(1 - \frac{Z_c}{Z_f - R_1}\right)Z_c$$

$$F_7 = 1 + \frac{R_1}{R} \qquad F_8 = \frac{R_1 I_L}{RV_{in}}$$

$$F_9 = \frac{nV_{in}}{R} \qquad F_i = nkH_e(s)$$

$$F_m = \frac{1}{(S_n + S_e)T_s/2} = \frac{1}{m_c S_n T_s/2}$$

$$m_c = 1 + \frac{S_e}{S_n} \qquad S_n = \frac{n^2 k(1 - D_{eff})}{L}V_{in}$$

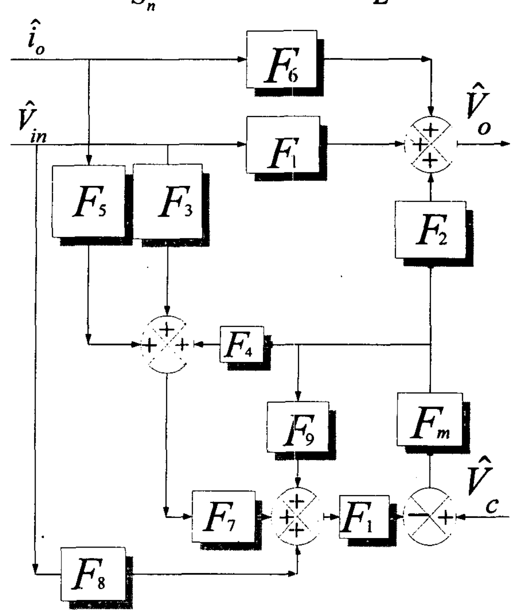


Fig 5. Small-signal transfer function model of Current mode PSFB-ZVS converter

In the above equations, S_n represents the on-time slope of sensed current waveform in primary side , while as

S_e is defined as the slope of external ramp current. Some variables in the above equations can be presented as follow:

$$Z_f = \frac{LC_o(R+R_c)s^2 + \left(L + RR_cC_o\right)s + R}{1+\left(R+R_c\right)C_o s}$$

$$Z_c = \frac{R\left(1+R_cC_o s\right)}{1+\left(R+R_c\right)C_o s} \qquad R_1 = 2n^2 L_r f_r$$

The sampling action transfer function of the current mode control can be represented as[7]:

$$H_e(s) = \frac{sT_s}{e^{sT_s}-1} \approx 1 - \frac{T_s}{2}s + \left(\frac{T_s}{\pi}\right)^2 s^2$$

The small-signal transfer function model of Current mode PSFB-ZVS converter of Fig.5 can be further simplified into Fig.6, in which voltage error amplifier transfer function G_c is included.

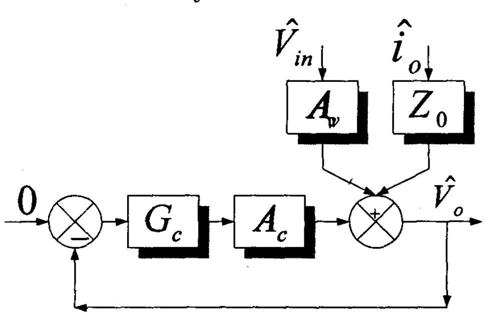


Fig.6

Simplified close loop current mode PSFB-ZVS converter small-signal model

In Fig.6 characteristic transfer function of the current mode control PSFB-ZVS PWM converter can be derived as follows:

the transfer function of control to the output voltage:

$$A_c = \left.\frac{\hat{V}_o}{\hat{V}_c}\right|_{\left(\hat{V}_{in}=\hat{I}_o=0\right)} = \frac{F_m F_2}{1 + F_m F_i F_9 + F_4 F_7 F_m F_i}$$

the Audio-Susceptibility transfer function:

$$A_v = \left.\frac{\hat{V}_o}{\hat{V}_{in}}\right|_{\left(V_c=I_o=0\right)} = F_1 - \frac{F_2F_3F_7F_mF_i + F_2F_8F_mF_i}{1 + F_mF_iF_9 + F_4F_7F_mF_i}$$

the Output-Impedance transfer function:

$$Z_o = \left.\frac{\hat{V}_o}{\hat{i}_o}\right|_{\left(\hat{V}_{in}=\hat{V}_c=0\right)} = F_6 - \frac{F_2F_5F_7F_mF_i}{1 + F_9F_mF_i + F_4F_7F_mF_i}$$

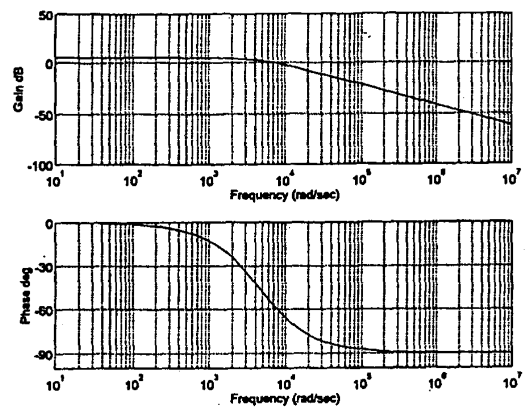
It is obviously that by giving circuit parameters of the converter and its specific operating cases with respect to output load, input voltage and duty cycle, the Bode plots of both open loop and close loop of characteristic transfer function of the converter can be obtained by using the Matlab simulation program. This is desirable for the designers.

4. Design Example and Simulation Results

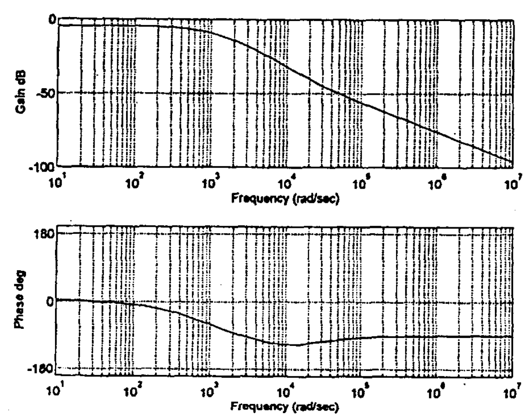
By using the derived results, we can obtain the Bode plots of the A_c A_v and Z_o transfer function of an 5KW current mode control PSFB-ZVS PWM converter power unit in normal load condition. The parameters of the converter in normal load condition are listed as follows:

$$V_{in} = 600V \quad L_r = 36\mu H \quad R_c = 40m\Omega$$
$$V_o = 280V \quad L_o = 209\mu H \quad n = 0.714$$
$$R = 28\Omega \quad C_o = 600\mu F \quad T_s = 50\mu s$$
$$k = 0.125A/V \quad D = 0.632 \quad f_r = 40KHZ$$

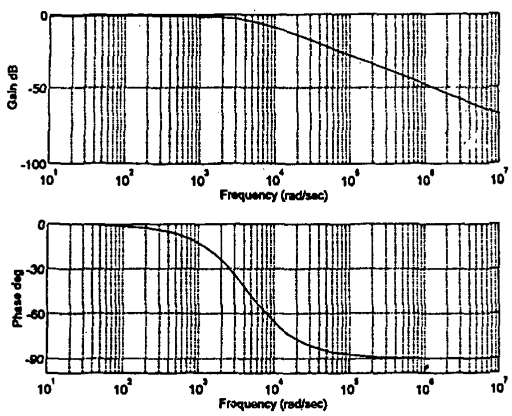
To avoid subharmonic instability, we choose $S_n/S_e = 0.5$. The simulation results are shown in



(a).transfer function of control to output voltage A_c



(b).Audio-Susceptibility transfer function A_v



(c).Output Impedance transfer function Z_o

Fig.7 Bode plots of A_c A_v Z_o of current mode control of PSFB-ZVS PWM converter

Fig.7.The results show that the transfer function of control to output voltage almost exhibits the first-order characteristics at different ramp compensation. So we can conclude that using current mode control eliminate the pole and second-order characteristics caused by out put filter unit. The fact that the reduction of A_c and Z_o from second-order to first order greatly simplifies the designed of compensation network of error amplifier which additional zeros is not needed. It is apparently that by using the derived model one can get the characteristic of current mode control PSFB-ZVS converter in different load conditions and different external compensation ramps if they are needed.

5. Conclusions

In this paper the small signal model of PSFB-ZVS converter[4] is extended to the current mode control. The small -signal transfer function model of PSFB-ZVS converter is derived based on the current sampling model of current mode control. The Bode plots of the current mode control PSFB-ZVS converter reveal that the control to output transfer function exhibits first-order characteristic, thus the need for additional zero in the compensation network of the error amplifier is eliminated.

References

[1]. Sabate J A, Vlatkovic V, Ridley, *et al* "Design considerations for high-voltage high-power full-bridge zero-voltage-switched PWM converter" APEC,1990:275~284

[2]. Robtert Mammano, "Switching Power Supply Topology Voltage Mode vs. Current Mode.", Unitrode Application Design Note,1993, 587~589.

[3]. Current Mode Control of Switching Power Supplies. Unitrode Applications, 1993,C3-1~C3-9

[4].V.Vlatkovic, J.A.Sabate, *et al* "Small-signal Analysis of the Zero-voltage-switched, Full-bridge PWM Converter.", HFPC 1990, pp.262-272.

[5]. V.Vlatkovic, J.A.Sabate, *et al* " Small-signal Analysis of the Phase-shifted PWM Converter", IEEE Trans on Power Electronics, Vol.17, No.1, 1992, pp128-135.

[6]. Fu-Shen Tsai, " Small-signal and Transient Analysis of a Zero-Voltage-Switched, Phase-Control PWM Converter using Averaged Switch Model", IEEE Industrial Applications Society Annual Meeting, 1991,pp.1010-1016.

[7]. Ray B.Ridley, "A New Continuous-time Model for Current-Mode Control," IEEE Trans on Power Electron.,Vol.6, No.2,pp271-280,1991