AUDIO SUSCEPTIBILITY OF THE BUCK CONVERTER IN CURRENT-MODE POWER STAGE

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Abstract: For the Buck Converter operating in Current-Mode Power Stage, the subharmonic oscillations can be eliminated by adding an external ramp. This ramp leads to reaching the null value of the audio susceptibility. When the null value of the audio susceptibility is reached, the error signal phase is shifted with -180^0 . The external ramp value chosen for the null value of the audio susceptibility does not always coincide with the value for eliminating the subharmonic oscillations. Our paper deals with the compromise in order to obtain a power supply with an audio susceptibility as close to the null value as possible, a fast transient response as well as a good stability.

Key words: *Buck Converter, Audio susceptibility, subharmonic oscillations, external ramp.*

I. INTRODUCTION

Certain Switch Mode Power Supplies require a lower noise in output voltage. Thus, every input voltage perturbation must modify the output as little as possible. Notice that the audio susceptibility is considerably reduced at current mode control compared to the voltage mode control. This is an important advantage of the current mode control [1].

In current mode control of the buck converter, for a duty cycle D greater than 50% (in practical applications even for a duty cycle lower than 50%), the same problem of subharmonic oscillations occurs. If they are not eliminated, the system becomes unstable and may fail. These subharmonic oscillations can be eliminated by adding an external ramp. In order to reach the null value of the audio susceptibility, this ramp must be equal to half the magnitude of off-time slope of current-sense signal. In practical applications, in some cases, the subharmonic oscillations are not cancelled for this ramp value and we need to add ramp until they are eliminated. At the same time, the addition of external ramp leads to the decrease of the transient response and of the audio susceptibility.

This paper aims to monitor the influence of adding an external ramp on the audio susceptibility and the transient response of the dc-dc converter, as well as presenting possible measures for optimizing the dynamic response of the buck converter in order to obtain an audio susceptibility as low as possible.

II. BUCK CONVERTER OPERATING IN CURRENT-MODE CONTROL

Fig. 1 shows the PWM Converter with Current-Mode Control. In this case the instantaneous value of the inductor current is summed with an external ramp and used to control the duty cycle. The peak current setpoint is set according to the error voltage and varies with the output power demand. A resistor measures the current that flows into the switch. This resistor (Ri) fixes the current loop gain. In Fig. 1, $S_n = \frac{V_{on}}{L} R_i$ represents the magnitude of the on-time slope of the current-sense signal; S_e is the added external ramp slope , and V_c is the control voltage [1].

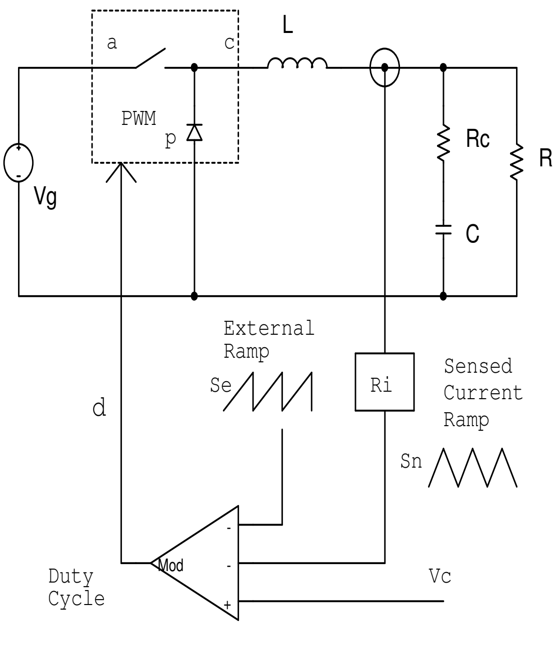

Fig.1 PWM Converter with Current-Mode Control

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III. EQUATIONS

Table 1 shows the equations for the PWM Converter with Current-Mode Control, operating in CCM [3].

	CCM
1st order pole	$\frac{1}{2*\pi*R_{load}*C_{out}}$
2nd order pole	None because of CCM
Left Half-Plane Zero	$\frac{1}{2*\pi*R_{ESR}*C_{out}}$
Right Half-Plane Zero	-
V_{output}/V_{input} DC Gain	D
V_{output}/V_{error} DC Gain	$K*R_{load}$

Table 1. Buck Current-Mode Equations

F_{sw} = switching frequency
D = duty-cycle
R_{load} = output load
R_{ESR} = output capacitor's Equivalent Series Resistor
C_{out} = output capacitor
V_{in} = input voltage
V_{out} = output voltage
K = max.Ipeak/max.V_c
V_c = control voltage
I_{peak} = K*V_c

IV. AVERAGED

In order to analyze the converter audio susceptibility, we use the small-signal model proposed by Raymond Ridley [2] and shown in Fig.2.

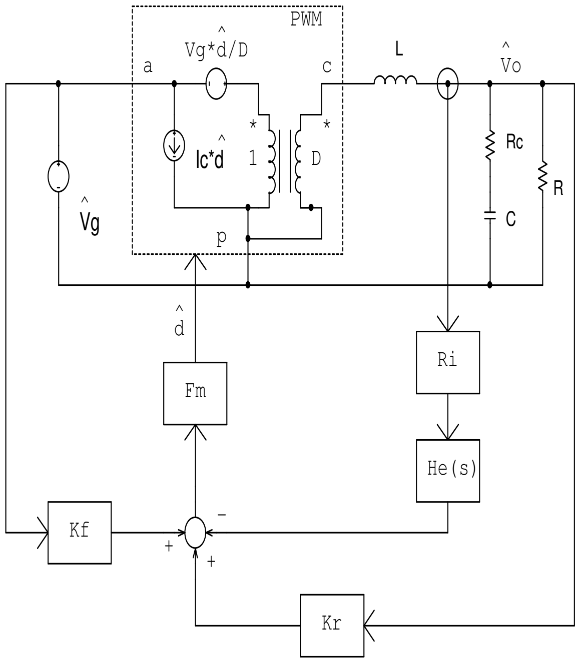


Fig.2 Converter System with Current-Loop Closed and Input Perturbation

The circuit in Fig.2 allows obtaining the expression of the audio susceptibility. The transfer function can be approximated [2]:

$$\frac{\hat{V}_o}{\hat{V}_g} = \frac{D[m_c D' - (1 - D/2)]}{\frac{L}{RT_S} + (m_c D' - 0.5)} F_p(s) F_h(s) \quad (1)$$

where: $$F_p(s) = \frac{1 + sCR_c}{1 + \frac{s}{\omega_p}} \quad (2)$$

$$\omega_p = \frac{1}{CR} + \frac{T_S}{LC}(m_c D' - 0.5) \quad (3)$$

$$F_h(s) = \frac{1}{1 + \frac{s}{\omega_n Q_p} + \frac{s^2}{\omega_n^2}} \quad (4)$$

$$Q_p = \frac{1}{\pi(m_c D' - 0.5)} \quad (5)$$

$$D' = 1 - D \quad (6)$$

$$m_c = 1 + \frac{S_e}{S_n} \quad (7)$$

The numerator of the dc gain of the expression (1) is the difference of two terms. Consequently, we may obtain the nulling of the audio susceptibility of the buck converter by a suitable design of the power stage parameters.

V. SIMULATION

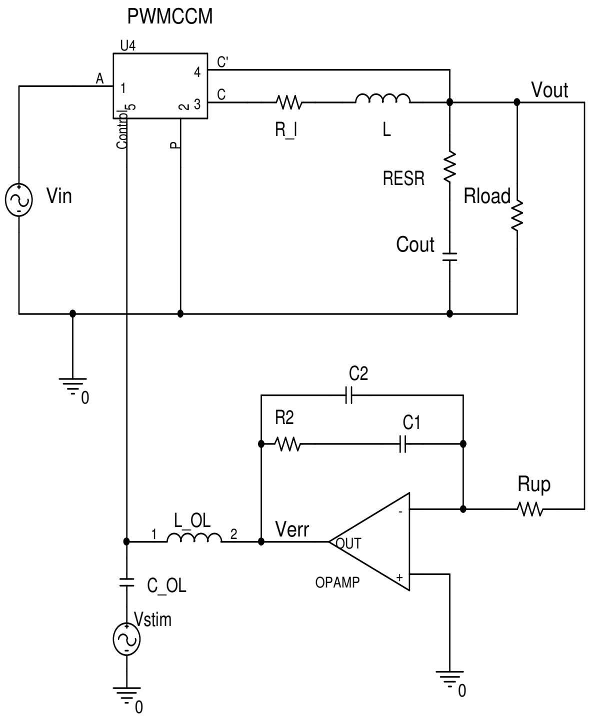


Fig. 3 Spice model of buck converter for ac analysis

Using a small-signal controller proposed by Raymond Ridley placed in a buck converter, we intend to calculate its audio susceptibility (Fig.3). For instance, we use a buck converter operating in CCM with the following parameters: V_{in} = 15 ÷30V; V_{out} = 12V; F_{sw} = 50Khz ; L = 180uH; Ri= 50mΩ; R_{ESR}=150mΩ; Cout = 220µF; R_{load} = 6Ω; R_l=0.1Ω.

The L_OL and C_OL elements are a fast way to temporarily open the loop in order to isolate the error amplifier in ac and adjust the compensation network. The introduction of the 1KH value for the L_OL inductor will stop any ac error signal, but it will allow the passage of the dc signal. The 1KF value for the C_OL capacitor allows the ac signal but stops the dc signal.

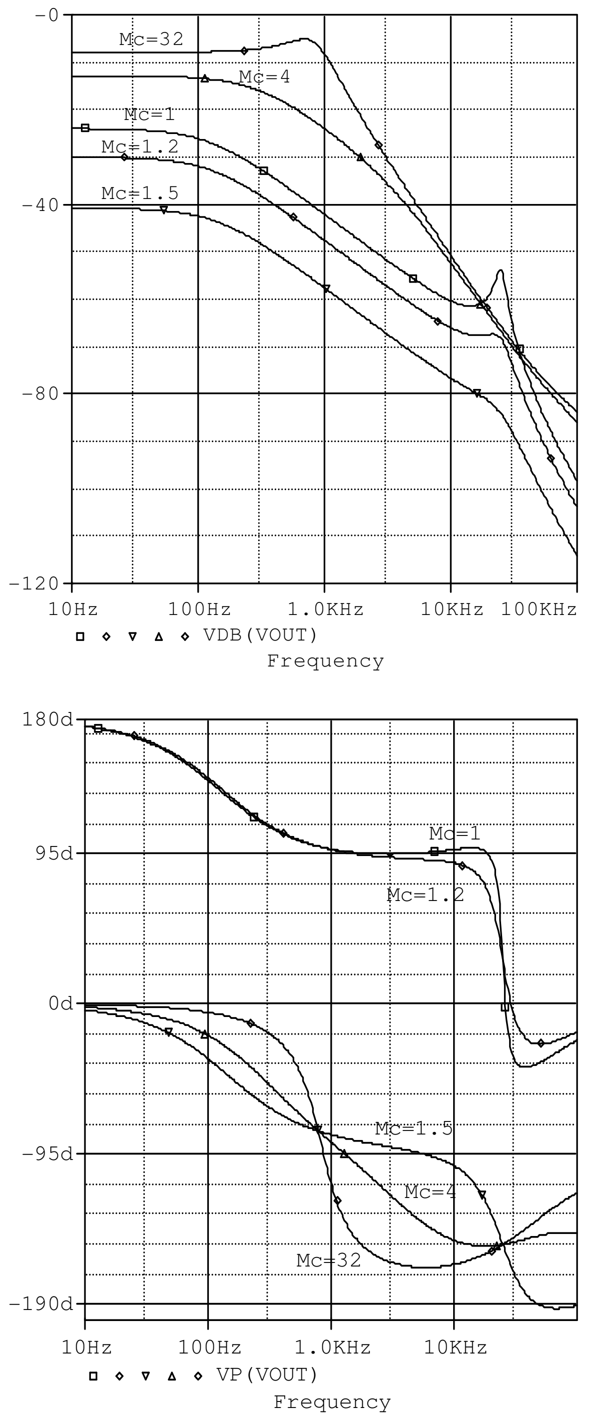


Fig. 4 a and b shows the phase and gain of V_{out}/V_{in} in open loop

In order to calculate the audio susceptibility, the V_{in} source is replaced with an ac source V_{ac}. Fig. 4a and b show the audio susceptibility diagram in open loop for different values of the external ramp. Mc=1 means there is no external ramp added while Mc=32 corresponds to an extremely high ramp, reproducing the characteristics of voltage-mode control. Notice that the audio susceptibility of the buck converter operating in voltage-mode control is significantly susceptibility decreases. This ramp damps the peaking of poles at half the switching frequency.

The null value of audio susceptibility is reached with a ramp $S_e=S_f/2$, where S_e is the external ramp slope, S_f is the magnitude of the off-time slope of current-sense signal [2]. This external ramp is important in practical applications where the noise output must be as low as possible. In Fig. 4a, we can see that the small changes of external ramp lead to important changes of the audio susceptibility near the null value.

As we can see from Fig. 4b, for Mc<1.5, the transfer function phase of audio susceptibility starts from 180^o. When the null value is reached (Mc=1.5), the phase will start from 0^o. That means we are in the null area of the audio susceptibility.

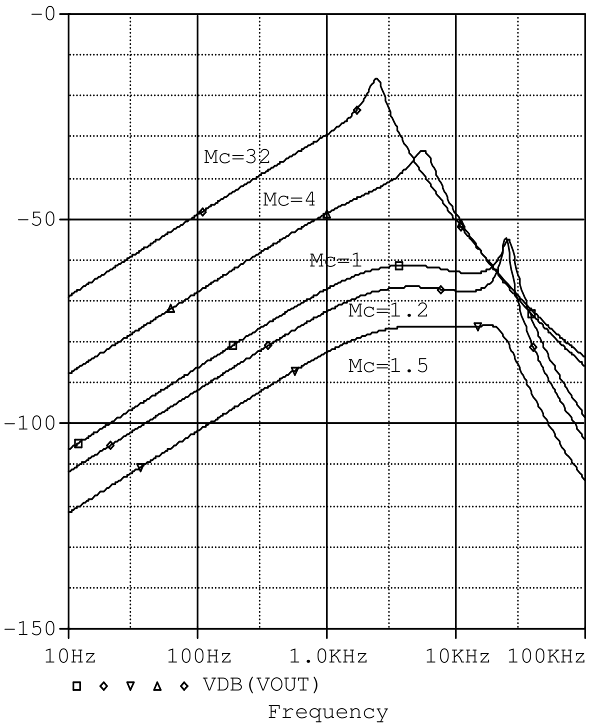


Fig. 5 Audio susceptibility diagram in closed loop for different values of the external ramp

Fig. 5 shows the buck converter audio susceptibility in closed loop for different values of the external ramp. We can see the influence of the closed loop on the elimination of output noise.

In current-mode control of the buck converter, for a duty-cycle greater than 50% (in practical applications even for a duty cycle lower than 50%), we are confronted to subharmonic oscillations. They may be eliminated by adding the same external ramp. Before calculating the type of compensation network, we must eliminate the subharmonic oscillations. If the subharmonic oscillations are cancelled for Mc<1.5, then in order to obtain a null value for audio susceptibility we add ramp until Mc equals to 1.5. At this moment, we choose the type of compensation network that may ensure a corresponding phase margin and gain margin as well as a good transient response.

In our example, the crossover frequency is 10Khz, as shown in Fig. 7, the phase margin is $57,6^0$ and the gain margin is 8.2 db. To design the network compensation components, we used the K-Factor concept [6] and we obtained R_{up}=4k7, C_2=84p, C_1=2.62n, $R_2=34.3k\Omega$, the first pole is at (R_2-C_2)=54.9Khz, and the first zero is at (R_2-C_1)=1.763Khz, the shifted phase is 70^0 (the maximum value recommended in practical applications), K-Factor K=5.67.

If subharmonic oscillations do not disappear for Mc=1.5, we add ramp as necessary for their elimination. In this case, we cannot reach the null value of audio susceptibility. This is a compromise we need to make in order to obtain a stable system.

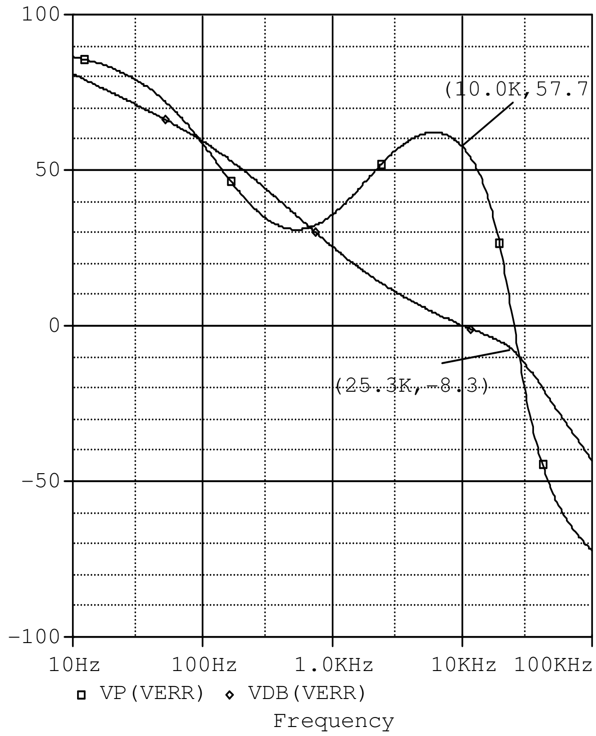
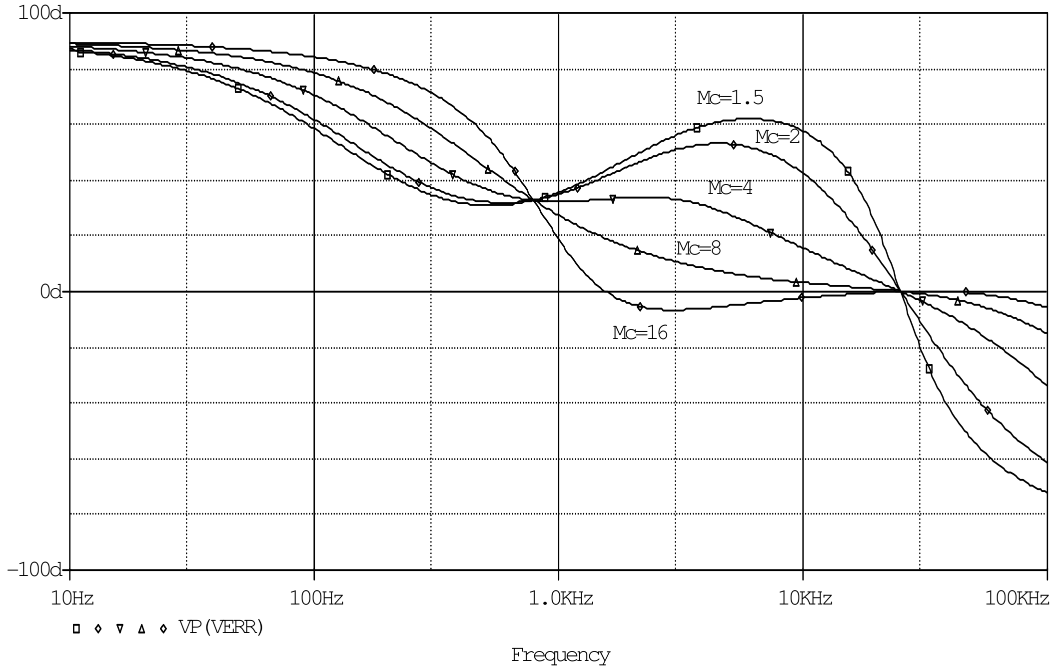


Fig. 6 Phase and gain of voltage error for Mc=1.5

It is shown in Fig.7a and 7b that the phase margin decreases by adding ramp, while the gain margin increases. We can also see that cross-over frequency decreases, leading to a low transient response. Table 2 shows the cross-over frequency, the phase margin and the gain margin variation according to the external ramp.

Mc	Cross-over frequency (Khz)	Phase margin (^{0})	Gain margin (dB)
1.5	10	57.6	-8.2
2	8.2	47.2	-13
4	6.1	24.3	-22.6
8	4.45	7.5	-29
16	2.9	-6.5	-39

Table 2. Cross-over frequency, phase margin and gain margin variation according to the external ramp



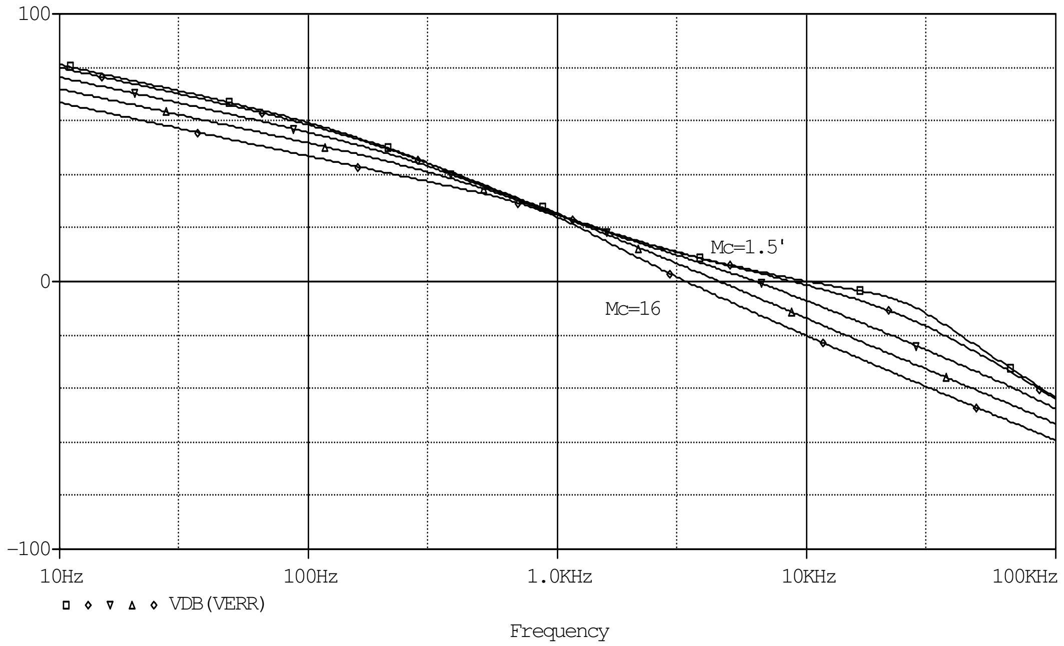


Fig.7a, 7b. Phase and gain of error-signal according to the external ramp

The advantage obtained by eliminating the subharmonic oscillations with external ramp where Mc>1.5 leads to the decrease of the cross-over frequency and implicitly to a lower transient response. By choosing the type of compensation network allowing the desirable gain and phase margin, we may have a stable system.

VI. CONCLUSION

In order to eliminate subharmonic oscillations, we add an external ramp whose value is practically established according to the switching mode power supply input data. For nulling the audio susceptibility, Mc term must be equal to 1.5, that means the value of the external ramp is equal to the magnitude of off-time slope of current-sense signal. If this is not possible, we increase the external ramp until subharmonic oscillations are eliminated. Now we can choose the type of compensation network in order to obtain the best transient response.

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