ELECTRONICS AND ELECTRICAL ENGINEERING
ISSN 1392 – 1215 2012. No. 3(119)
ELEKTRONIKA IR ELEKTROTECHNIKA

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Reduction of Output Voltage Ripples in Frequency Modulated Power Converter

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crossref http://dx.doi.org/10.5755/j01.eee.119.3.1361

Introduction

Nowadays switch-mode power converters (SMPC) are essential to electric power conversion with high efficiency (linear regulators used widely in the past had very low efficiency and therefore nowadays they are in rather limited use) [1–3]. SMPC are widely used in power supplies of various electronic devices, active power factor correctors, etc. Despite their advantages (mainly high efficiency and specific power) [3, 4], they have also their drawbacks: high electromagnetic interference (EMI) both conducted and radiated [2, 5]. Filters, shielding, grounding etc are classical ways to mitigate EMI. Another successful method to reduce EMI is spread spectrum which is usually based on the use of switching frequency modulation (FM) [1, 2, 6].

Despite the fact that FM has its benefits in reducing EMI, it can increase output voltage ripples significantly [7-13]. In addition to natural high-frequency (HF) output voltage ripples, FM causes also low-frequency (LF) output voltage ripples which are more problematic than HF ones [8, 9]. Detailed examination of the effect of FM on the output voltage ripples in SMPC operating in continuous and discontinuous conduction modes (CCM and DCM respectively) was performed mainly in [7, 9–13]. Although the main causes of the increase in the output voltage ripples in CCM are found out in [7, 9, 10] and expressions to calculate the peak-to-peak output voltage ripples V_{ofmp-p} in closed-loop FM SMPC are derived in [9], closed-form expression for V_{ofmp-p}, which can appreciably simplify analysis of the effect of SMPC and modulating signal parameters on V_{ofmp-p}, is not derived. Recommendations to reduce the ripples proposed in [9] consider mainly the LF ripples not V_{ofmp-p}. So the main aim of the paper is quantitative analysis of the ripples followed by worked-out recommendations to reduce them.

Output voltage ripples of FM SMPC

For the examination closed-loop FM buck converter (Fig. 1) will be used. It is assumed that the converter operates in CCM. As it is concluded in [7–13] FM increases output voltage ripples. In general the ripples consist of HF switching ripples with switching frequency f_{sw} and LF ripples with modulation frequency f_m, as it can also be seen in Fig. 2 (b-d), where simulated in SIMULINK output ripples for the open-loop and closed-loop buck converter (using simulation circuit shown in Fig. 2 (a)) are shown.

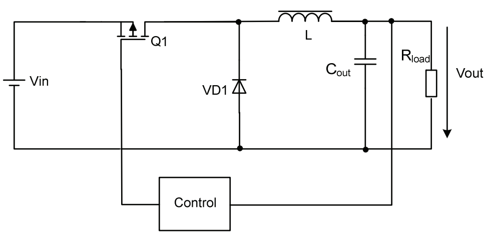

Fig. 1. Schematic of closed-loop buck converter

A general expression to calculate the peak-to-peak output voltage ripples in FM SMPC is derived in [9] as follows

$$V_{ofmp-p} = \max\{\tilde{v}_{LF}(t) + A_{HF}(t)\} - \min\{\tilde{v}_{LF}(t) - A_{HF}(t)\}, \quad (1)$$

where $\tilde{v}_{LF}(t)$ is the LF ripples; $A_{HF}(t)$ is the envelope of the HF ripples, which can be derived by substituting instantaneous switching frequency $f_{sw}(t)$ into the expression for the unmodulated SMPC output voltage ripples V_{p-p}. As it is derived in [9], for instance, for FM buck SMPC with typical output filter capacitor in CCM

$$A_{HF}(t) = \frac{r_{cout} V_{out}(1-D)}{2Lf_{sw}(t)}, \quad (2)$$

where L is the power inductor inductance; r_{cout} is the equivalent series resistance (ESR) of the output capacitor; D is the average duty ratio; V_{out} is DC output voltage.

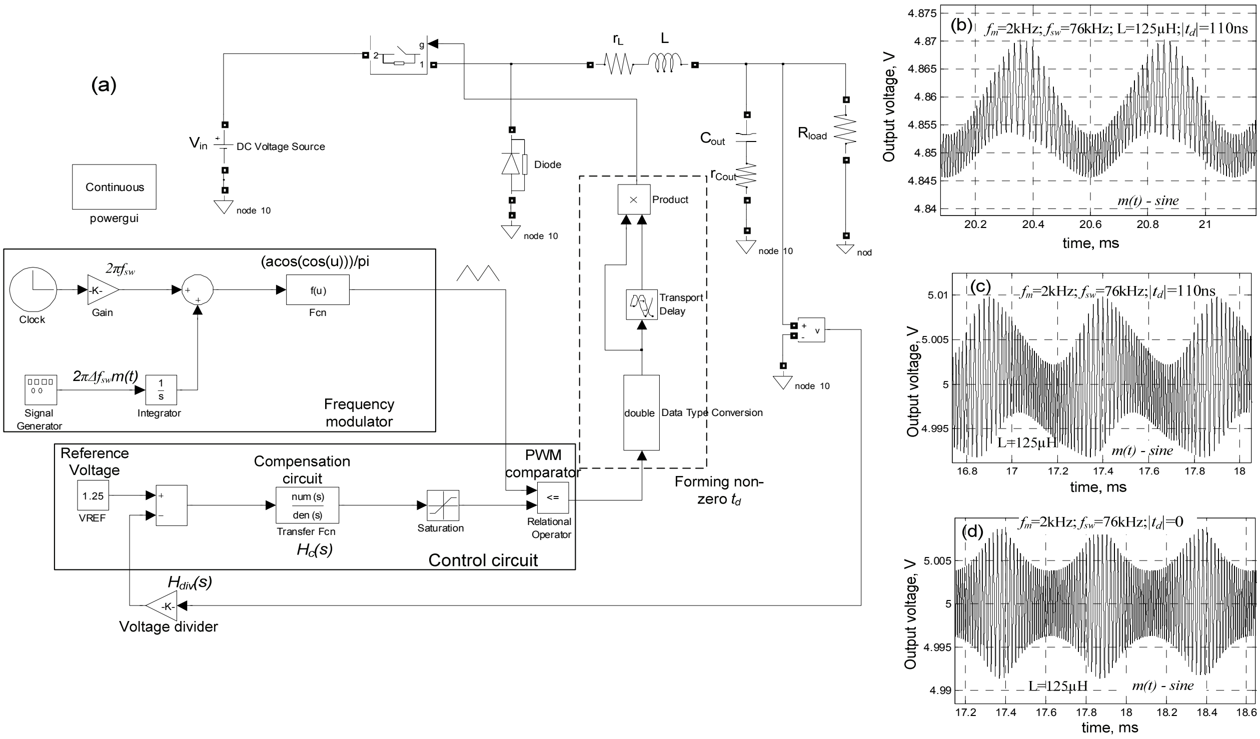

Fig. 2. Closed-loop buck FM converter simulation circuit (a) and simulated output voltage waveforms: (b) open-loop; (c), (d) closed-loop. (D=0.5*;* Δf_{sw}=30kHz; open loop gain cut-off frequency f_{cut}=5kHz; R_{load}=10Ω)

The instantaneous switching frequency is

$$f_{sw}(t) = f_{sw} + \Delta f_{sw} m(t)\,, \qquad (3)$$

where Δf_{sw} is the switching frequency deviation; $m(t)$ is the modulating signal (e.g. sine, triangular, sawtooth, etc); f_{sw} is the nominal switching frequency.

The main cause of the LF ripples for FM SMPC in CCM is nonzero difference $|t_d|$ between the switching delays [7,9,10,12], which are mainly due to power transistor switches, their drivers and logic circuits (e.g. flip-flops) of pulse width modulated (PWM) integrated circuits. A general expression to calculate the LF ripples of closed-loop FM SMPC in CCM considering nonzero $|t_d|$ is derived in [9] in operator form as follows

$$\tilde{v}_{LF}(s) = \tilde{d}(s) H_{co}(s)/(1+T(s)) = |t_d|\,\Delta f_{sw} m(s) H_{co}(s)/(1+T(s))\,, \qquad (4)$$

where $H_{co}(s)$ is the control-to-output transfer function; the open loop gain $T(s)=H_{div}(s)H_c(s)H_{co}(s)H_{PWM}(s)$ [15] (where $H_{PWM}(s)$is PWM gain; $H_{div}(s)$ and $H_c(s)$ are voltage divider and compensation circuit transfer functions). As an example the transfer functions for the closed-loop buck SMPC are shown in Fig. 3. The buck converter $H_{co}(s)$ in CCM is [14]

$$H_{co}(s) = \frac{V_{in}(1 + s r_{cout} C_{out})}{s^2 L C_{out} + s(L/R_{load} + C_{out} r_{cout}) + 1}\,, \qquad (5)$$

To derive the steady-state LF ripples $\tilde{v}_{LF}(t)$ in time domain, the inverse Laplace transform of the (4) should be applied. The LF ripples in the time domain for sinusoidal FM can be easily obtained from (4) as follows

$$\tilde{v}_{LF}(t) = |t_d|\,\Delta f_{sw} \cos\left[2\pi f_m t + \arg\left(H_{full}(j2\pi f_m)\right)\right] \left|H_{full}(j2\pi f_m)\right|\,, \qquad (6)$$

where $H_{full}(j2\pi f_m)=H_{co}(j2\pi f_m)/(1+T(j2\pi f_m))$. The LF peak-to-peak ripples of FM SMPC in CCM are

$$V_{LFp-p} = 2\,|t_d|\,\Delta f_{sw} \left|H_{full}(j2\pi f_m)\right|. \qquad (7)$$

As it can be seen from (4) and (7) V_{LFp-p} are proportional to $|t_d|$ and Δf_{sw}.

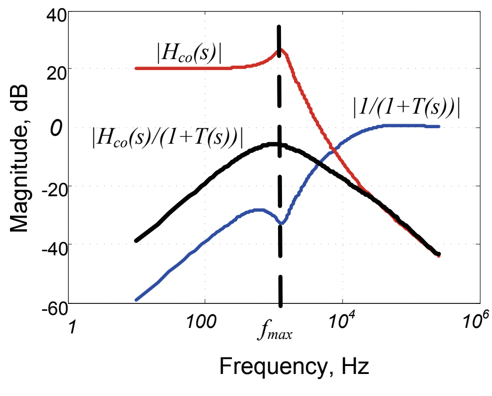

Fig. 3. Closed-loop buck FM SMPC transfer functions in CCM. (Parameters: C_{out}=330uF; L=125μH; r_{cout}=0.04Ω; R_{load}=10Ω; f_{cut}=5kHz; V_{in}=10V)

Derivation of closed-form expression for V_{ofmp-p}

Expression (1) derived in [9] does not clearly show the effect of FM and SMPC parameters on V_{ofmp-p}, because it can be evaluated only numerically**.** Therefore closed-form expression for V_{ofmp-p} needs to be derived. In order to get the expression, (1) can be used, as it can also be deduced from Fig. 4. Since Δf_{sw} is usually lower than $0.25f_{sw}$ [2], then (2) can be approximated using the firstorder-Taylor-series-approximation as follows

$$A_{HF}(t)=V_{p-p}(1-\delta\cdot m(t))/2\,, \tag{8}$$

where $\delta=\Delta f_{sw}/f_{sw}$; unmodulated buck SMPC output voltage peak-to-peak ripples V_{p-p} are as follows:

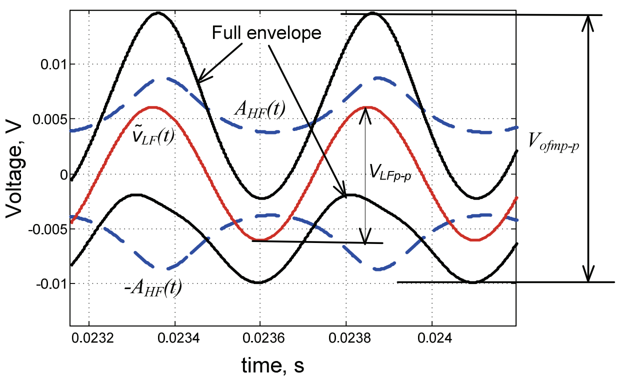

Fig. 4. Calculated envelopes of the output voltage ripples for open-loop buck FM SPC in CCM taking in account $|t_d|$=110ns. (Parameters: C_{out}=330uF; L=125μH; V_{in}=10V; f_m=2kHz; Δf_{sw}=30kHz; f_{sw}=76kHz; r_{cout}=0.04Ω; D=0.5; R_{load}=10Ω; *m(t)* is sine)

$$V_{p-p}=r_{cout}V_{out}(1-D)/(Lf_{sw})\,. \tag{9}$$

Since for sinusoidal FM $m(t)=sin(2\pi f_m t)$, then closed-form expression for V_{ofmp-p} can be simply derived

$$V_{ofmp-p}=V_{p-p}+\Delta f_{sw}\sum_{l=1}^{2}\sqrt{t_d^2\left|H_{full}(j2\pi f_m)\right|^2+\left(\frac{V_{p-p}}{2f_{sw}}\right)^2-(-1)^l\frac{V_{p-p}}{2f_{sw}}\left|t_d\right|\left|H_{full}(j2\pi f_m)\right|\cos\left[\arg(H_{full}(j2\pi f_m))\right]}\,. \tag{10}$$

It can be seen that difference between unmodulated and FM buck SMPC output peak-to-peak ripples V_{ofmp-p}-V_{p-p} is proportional to Δf_{sw} and V_{in}. Similarly closed-form expressions for V_{ofmp-p} can also be derived for other *m(t)*.

In order to prove that derived expression is useful experimental verification and SIMULINK simulations were performed for closed-loop buck SMPC with sinusoidal FM.

Table 1. Comparison of the theoretical, simulated and experimental results for closed-loop buck FM SPC with Δf_{sw}=30kHz; f_{sw}=150kHz; f_{cut}=5kHz; t_d=110ns; *m(t)* is sine; R_{load}=10Ω

f_m, kHz	Calculated		Simu-lated	Experi-mental
	Using (1),(2),(6)	Using (10)		
	V_{ofmp-p}, mV	V_{ofmp-p}, mV	V_{ofmp-p}, mV	V_{ofmp-p}, mV
Unmo-dulated	5.3	5.3	5.3	6
0,2	10	9.9	10	10.5
1	11.8	11.7	11.9	11.5
2	9.8	9.7	10	10.5
10	6.7	6.5	6.7	7

The comparison results for different f_m are shown in Table 1. As it can be seen the results are in a good agreement proving that (10) is precise enough to calculate the peak-to-peak output voltage ripples in buck FM SMPC.

Effect of *D* and R_{load} on V_{ofmp-p}

Since D and R_{load} (or output power P_{out}) in real SMPC are continuously changing parameters, it is of importance to investigate how they affect V_{ofmp-p} of FM buck SMPC. By analyzing (10) it is concluded that V_{ofmp-p} is almost independent on P_{out} (as it can also be seen in Fig. 5).

In fact unmodulated buck SMPC output ripples are also independent on R_{load} in CCM (as it can be deduced from (9)). After analyzing the (10), it is concluded that V_{ofmp-p} depends on *D,* as it can also be seen in Fig. 6. Moreover D_{max} at which V_{ofmp-p} is maximum is equal to 0.5, as it is also for unmodulated buck SMPC V_{p-p}.

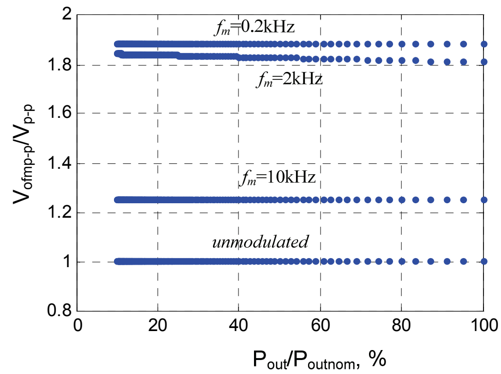

Fig. 5. V_{ofmp-p}/V_{p-p} versus P_{out}/P_{outnom} (where P_{outnom} is nominal output power). (Parameters: P_{outnom}=12.5W; f_{cut}=5kHz; f_{sw}=150kHz; D=0.5; Δf_{sw}=30kHz; *m(t)* is sine)

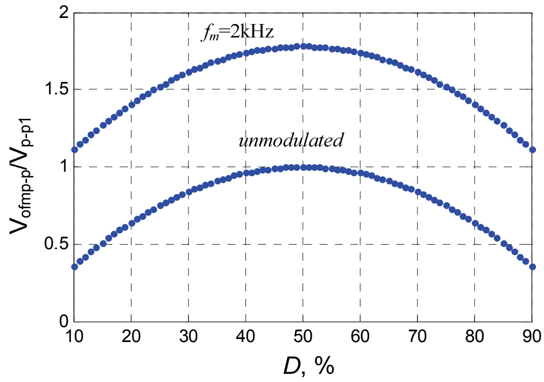

Fig. 6. V_{ofmp-p}/V_{p-p1} versus D (where V_{p-p1} is V_{p-p} at D=0.5). (Parameters are the same as in Fig. 5)

Recommendations to reduce V_{ofmp-p}

The analysis provided allows us to propose some recommendations to reduce the ripples:

- t_d should be as small as possible; for this purpose the techniques proposed in [9] can be used;
- Choice of f_m and Δf_{sw}: (a) from V_{ofmp-p} point of view: the lower Δf_{sw} is the lower V_{ofmp-p} is; f_m should not be chosen in the vicinity of the resonance frequency f_{max} of the buck converter output filter (see Fig. 3); (b) from

EMI attenuation point of view: the higher $\Delta f_{sw}/f_m$ is the better EMI attenuation can be achieved [1]; so when selecting the modulation parameters, trade-off between EMI attenuation and V_{ofmp-p} should be considered.

Conclusions

Increase in peak-to-peak output voltage ripples due to FM in buck SMPC in CCM can be simply analyzed using the closed-form expression derived. The expression that takes into account also non-zero t_d, can give us a possibility also examine the effect of D and the output power on the ripples. It is concluded that V_{ofmp-p} is almost independent on the output power, but depends on D. Moreover the worst-case-scenario D=0.5 at which the peak-to-peak ripples are maximum, is the same as for unmodulated buck converter.

The expressions derived as well as SIMULINK simulations and experiments for closed-loop buck SMPC show that V_{ofmp-p} can be effectively neutralized when t_d is small as possible. When selecting the modulating signal parameters, the trade-off between EMI attenuation and V_{ofmp-p} should be considered. The results obtained in the analysis and the recommendations proposed can be used when designing high-quality FM SMPC.

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Received 2011 07 05
Accepted after revision 2011 09 15

D. Stepins, J. Jankovskis. Reduction of Output Voltage Ripples in Frequency Modulated Power Converter // Electronics and Electrical Engineering. – Kaunas: Technologija, 2012. – No. 3(119). – P. 45–48.

In the paper the closed-loop frequency modulated (FM) buck converter output voltage ripples are examined theoretically, using SIMULINK simulations and experimentally. A closed-form expression to calculate and analyze the peak-to-peak output voltage ripples in continuous conduction mode is derived and confirmed experimentally. The expression can appreciably simplify the analysis of the effect of FM on peak-to-peak output voltage ripples of FM buck converter. The effect of duty ratio and the output power on the output voltage ripples of the FM buck converter is also analyzed. Some useful recommendations to mitigate the ripples effectively are proposed. Ill. 6, bibl. 15, tabl. 1 (in English; abstracts in English and Lithuanian).

D. Stepins, J. Jankovskis. Įtampos pulsacijų sumažinimas dažninės moduliacijos keitiklyje // Elektronika ir elektrotechnika. – Kaunas: Technologija, 2012. – Nr. 3(119). – P. 45–48.

Uždarojo ciklo dažninės moduliacijos (DM) žeminančiojo keitiklio įtampos pulsacijos tyrinėtos teoriškai, taikant SIMULINK modeliavimą, ir eksperimentiškai. Gauta išraiška pastebimai supaprastina žeminančiojo keitiklio įtampos pulsacijų efekto analizę. Ištirtas impulsų skvarbos ir išėjimo galios įtakos įtampos pulsacijoms efektas DM žeminančiajame keitiklyje. Pateikta pasiūlymų, kaip efektyviai sumažinti įtampos pulsacijas. Il. 6, bibl. 15, lent. 1 (anglų kalba; santraukos anglų ir lietuvių k.).