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Impact of inductor current ringing in DCM on output voltage of DC-DC buck power converters

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Abstract: Ringing of an inductor current occurs in a DC-DC BUCK converter working in DCM when current falls to zero. The oscillations are the source of interferences and can have a significant influence on output voltage. This paper discusses the influence of the inductor current ringing on output voltage. It is proved through examples that the oscillations can change actual value of duty a cycle in a way that makes the output voltage difficult to predict.

Key words: Inductor current ringing, DCM, BUCK converter, parasitic capacitance, electromagnetic compatibility in DC-DC converters

1. Introduction

Basic BUCK and BOOST converters working in discontinuous conduction mode (DCM) are widely used in electronics, especially for power factor correction (PFC). Inertia of the converters working in this mode can be described with a simpler model than in CCM [1]. The small-signal transmittances are presented as second order functions [2-5]. But since the second pole frequency in DCM is usually comparable to the switching frequency (or even higher), in some applications its influence on the frequency characteristics is negligible and a first order function can be used instead [4 chapter 11], [6, 7]. The first order transfer function simplifies the process of control circuit designing compared to a second order description, typical for CCM. One of disadvantages of DCM is the ringing of the inductor current when it reaches zero value [8, 9]. It is known that the ringing can be a source of additional losses, and electromagnetic interferences. In this paper the other consequences of the ringing are observed, namely unwanted changes of the output voltage.

The next section of this paper describes the origin of the inductor current ringing, which appears when a converter works in DCM. Subsequently an impact of the oscillations on the output voltage control is explained and the results of measurements are presented. At the end some of known methods used to eliminate the oscillations are mentioned and used to improve the response of the output voltage to a duty cycle change.

2. Origin of ringing in DCM

The BUCK and BOOST converters contain a resonant circuit consisted of inductance *L* and parasitic capacitances of high-side and low-side switches [4, 9-11]. The circuit does not have a noticeable effect on an inductor current when a converter works in CCM. But in DCM a resonance appears in the form of inductor current ringing, when it reaches zero value. The ringing occurs in the inductor current and switch node voltage, which in the BUCK converter is the equivalent to the diode voltage. Waveforms of the BUCK converter in which the ringing occurred have been presented in Figs. 2-4. The waveforms apply to a converter with following parameters: $V_G = 12$ V, $T_S = 5$ µs, $L = 15$ µH, $C = 330$ µF, $G = 0.01$ S, $D = 0.3$, an IDD03SG60C Schottky diode, IRFZ44V transistor. Sometimes additional spikes in the inductor current can be observed. Those spikes are the result of parasitic inductances and often they can be minimized with a proper measurement method [12]. But such current spikes won't be discussed further, as they are not a subject of this paper.

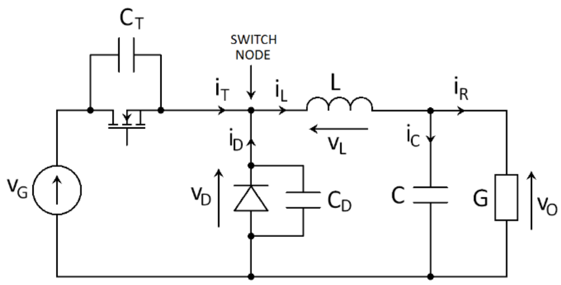


Fig. 1. BUCK converter with parasitic capacitances of switches

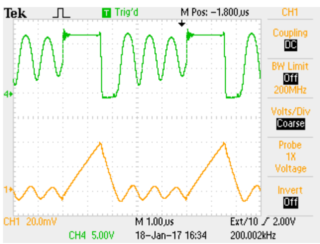


Fig. 2. Diode voltage (top) and inductor current (bottom) of BUCK converter working in DCM

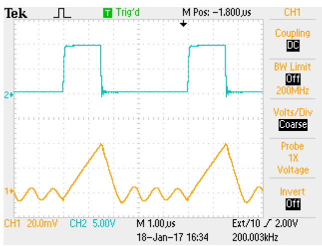


Fig. 3. Gate-source voltage (top) and inductor current (bottom) of BUCK converter working in DCM

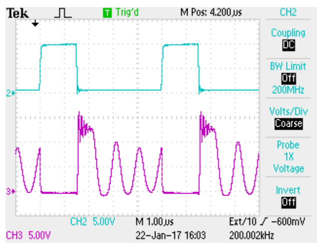


Fig. 4. Gate-source voltage (top) and drain-source voltage (bottom) of BUCK converter working in DCM

The waveform of the ringing can be described as [8]:

$$v_{LX}(t) = v_G + (v_O - v_G)\cos\omega_0(t - t_2), \qquad t_2 \le t \le t_3, \tag{1}$$

$$i_L(t) = \frac{v_G - v_O}{\omega_0 L}\sin\omega_0(t - t_2), \qquad t_2 \le t \le t_3, \tag{2}$$

where: v_{LX} is the voltage drop between a switch node and ground, t_2 is the point of time where an inductor current reaches zero value, t_3 is the point of time where an inductor current starts to rise from zero value.

Value ω_0 can be calculated as the resonant pulsation of inductance L and capacitance C_{PAR}, where C_{PAR} should be calculated as a parallel connection of switches' parasitic capacitance:

$$\omega_0 = \frac{1}{\sqrt{LC_{\mathrm{PAR}}}}. \tag{3}$$

3. Impact of ringing on output voltage

Side effects of the inductor current ringing, mentioned in literature, usually involve increased emission of electromagnetic interferences [13] and higher losses which lead to the lower efficiency of a converter [8]. Another drawback of oscillations which isn't usually mentioned is related to a switching signal and output voltage. When the ringing occurs, the current oscillates between the inductor and parasitic capacitances of high-side and low-side switches. If a new switching cycle begins when an inductor current is equal to zero as shown in Fig. 5 (subinterval 1) then values $t_{\mathrm{ON1}} = t_{\mathrm{ON1}}'$ and the output voltage react to a switching signal accordingly to a known mathematical model (4) [4-7].

$$V_{O(\mathrm{BUCK\,DCM})} = V_G \frac{G_Z D}{2G}\left(\sqrt{D^2 + 4\frac{G}{G_Z}} - D\right), \tag{4}$$

$$G_Z = \frac{T_S}{2L}, \tag{5}$$

where: T_S is the period of a switching signal, D is the duty cycle of a switching signal, G is the output conductance.

Let's consider a situation from Fig 5 (subinterval 2). A new switching cycle starts when an oscillating inductor current is above zero. The duty cycle of control signal v_{GS} can be determined based on t_{ON2}. But if one tries to measure the duty cycle as a time interval when the inductor current is larger than zero, then it would appear that the actual duty cycle, determined by t_{ON2}' is larger than the duty cycle of the control signal (since $t_{\mathrm{ON2}}' > t_{\mathrm{ON2}}$). Therefore the output voltage would be higher than expected. Similar situation appears, when the new switching cycle starts while the inductor current is below zero (Fig. 5 subinterval 3).

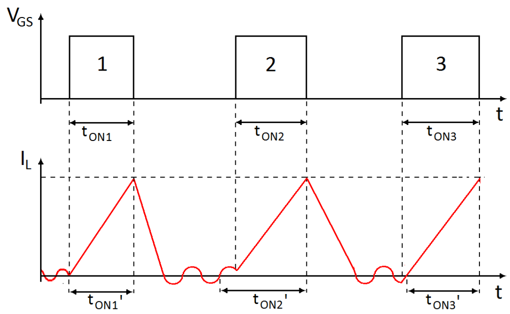


Fig. 5. Intervals of control signal V_{GS} and inductor current I_L in DCM

In that case the measured duty cycle would be smaller than the duty cycle of the control signal (since $t_{ON3}' < t_{ON3}$). This situation would influence the output voltage, making it smaller than expected. The variation of the output voltage would repeat in the wide range of the duty cycle, making the output voltage oscillate around the expected value, determined by (4). This effect can be observed when the peak value of the inductor current is relatively small i.e. when amplitude of oscillations is higher than ~ 5% of the inductor current amplitude. The inductor current amplitude depends on value of the inductor, switching frequency, and load resistance, therefore to prevent noticeable influence of the oscillations proper values of the parameters need to be considered.

An experimental BUCK converter has been designed to verify the presented theory. An APP9962 transistor (high-side) and MBRS340 Schottky diode (low-side) were used as switches. An IRS2186PBF device was used as a transistor driver. Other parameters of the converter during the measurement were as follows: $V_G = 12$ V, $T_S = 10$ µs, $L = 30$ µH, $C = 330$ µF, $G = 0.01$ S. During the experiment output voltage was measured while the duty cycle D of the control signal was changing between 0.1 and 0.6 with a step of 0.01. The result of the experiment is presented in Fig. 6a. Another measurement was made when the transistor was changed to IRFZ44, which has got higher value of output capacitance. The result of the measurement is presented in Fig. 6b.

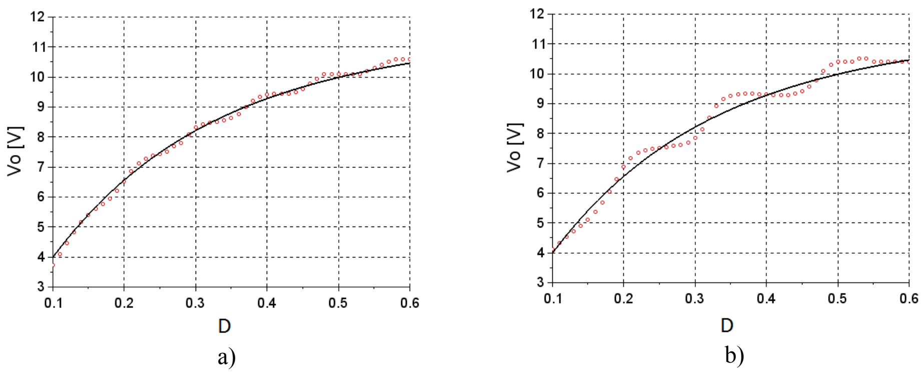


Fig. 6. Output voltage of a BUCK converter in DCM: a) an AP9962 transistor as a high-side switch; b) an IRFZ44 transistor as a high-side switch; solid – calculated from Eq. (4); dots – measured value

As shown in Fig. 6a the measured output voltage not only does not follow the simulation but oscillates around it. Another measurement presented in Fig. 6b indicates that using a switching element with higher parasitic capacitance can increase the difference between theoretical and measured value of the output voltage. If a transistor, diode and the inductor are chosen and parameters of the oscillations are fixed, then influence of the oscillations on the characteristic $V_O(D)$ depends on switching frequency. Such dependency is presented in Fig. 7, where a different BUCK converter was used: $V_G = 12$ V, $L = 15$ μH, $C = 470$ μF, $G = 0.01$ S, an APP9962 transistor, IDD03SG60C Schottky diode. The waveforms of gate-source voltage and inductor current, related to each frequency, are presented in Fig. 8.

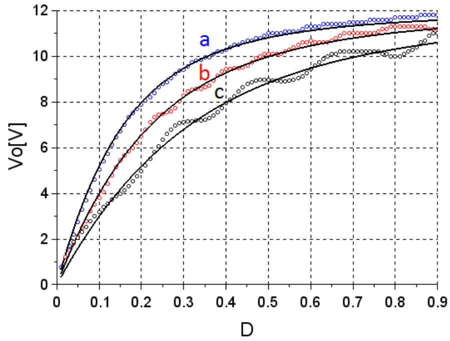
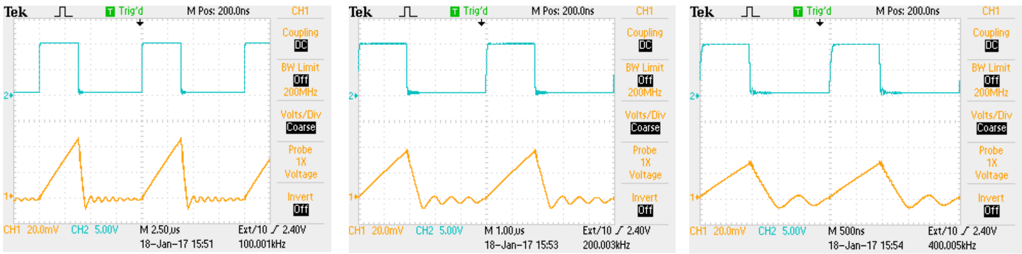


Fig. 7. Output voltage of a BUCK converter (APP9962 transistor, IDD03SG60C diode) in DCM for different frequencies: a – f_S = 100 kHz; b – f_S = 200 kHz; c – f_S = 400 kHz; solid line – calculated from Eq. (4); dotted line – measured value



a) b) c)

Fig. 8 Gate-source voltage (top) and inductor current (bottom) of BUCK converter(transistor APP9962, diode IDD03SG60C) in DCM for different frequencies: a – f_S=100kHz, b – f_S=200kHz; c – f_S=400kHz

As shown in Fig. 7 the value of the switching frequency can increase or decrease the impact of the oscillations on converter characteristics. If the switching frequency increases the peak value of inductor current decreases, which makes the characteristics more susceptible to the oscillations.

It can be noticed in Fig. 6 and Fig. 7 that at some points a change in the duty cycle does not influence the output voltage. This can be shown with another experiment, where a step change $\Delta d = 0.02$ was introduced to value D_0 of the duty cycle according to Eq. (6).

$$D = D_0 + \Delta d. \quad (6)$$

The value of step change Δd was constant but D_0 was increased in each step by a constant value. This experiment simulates a situation where a control circuit tries to change the duty cycle in order to regulate the output voltage. Parameters of the converter are the same as for measurement from Fig. 6a. The result of the measurement is presented in Fig. 9.

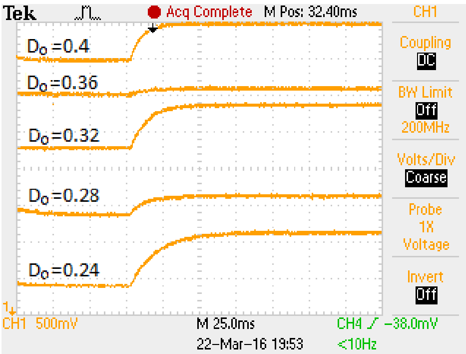


Fig. 9. Response of output voltage to step change of duty cycle

Measurements presented in Fig. 9 show that change in output voltage does not have the same transient character for all D_0 values due to presence of inductor current oscillations. Such differences can lead to incorrect control of the output voltage. In the next section some of methods used to suppress or eliminate ringing are described.

4. Elimination of ringing influence on output voltage

4.1. Proper selection of switches

There are a few methods which can be used to decrease or eliminate the ringing of inductor current [8, 11-16]. One of them includes appropriate selection of switching elements with lower capacitance. This approach increases frequency of the oscillations, which in turn increases the EMI, but it also decreases amplitude of the oscillations which can be further suppressed with a damping resistor or a snubber. An example of using transistor with lower value of C_T is presented in Figs. 10-11. Parameters of the converter are as follows: $V_G = 12$ V, $L = 15$ µH, $C = 470$ µF, $G = 0.01$ S, $D = 0.3$, $T_S = 10$ µs. Using PN diodes instead of Schottky diodes is not recommended because of the reverse recovery charge, which increases the power loss. An example of an inductor current waveform, in the case when a PN diode was used, is presented in Fig. 12. All parasitic capacitances have been evaluated based on characteristics from a datasheet and input voltage $V_G = 12$ V, which corresponds to the transistor and diode voltage when they are turned off.

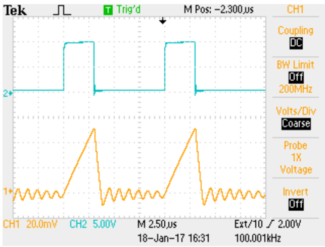


Fig. 10. Gate-source voltage (top) and inductor current (bottom) of a BUCK converter which uses transistor IRFZ44 (C_T = 650 pF) and diode IDD03SG60C (CD = 30 pF)

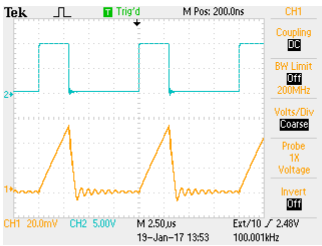


Fig. 11. Gate-source voltage (top) and inductor current (bottom) of a BUCK converter which uses transistor AP9962 (C_T = 250 pF) and diode IDD03SG60C (C_D = 30 pF)

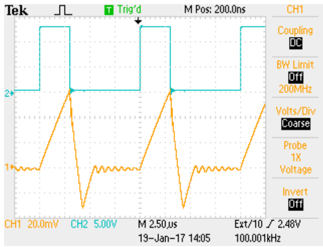
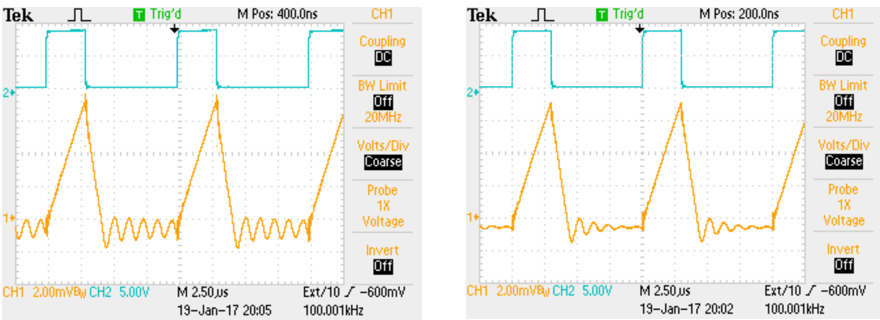


Fig. 12. Gate-source voltage (top) and inductor current (bottom) of a BUCK converter which uses transistor AP9962 (C_T = 250 pF) and diode 1N4007 (C_D = 4.5 pF, *trr* = 1 µs)

4.2. Damping resistor

Apart from proper selection of switches one can use an additional damping resistor, connected in parallel with the inductor [14]. To minimize the influence of the resistor on converter characteristics, its value should be much higher than inductor reactance calculated for specific switching frequency. In the example presented in Fig. 13b a resistor with a value of 1 kΩ has been connected in parallel to a 30 µH inductor. A switching frequency of 100 kHz was used. Other parameters are the same as for measurement from Fig. 6a.



a) b)

Fig. 13. Gate-source voltage (top) and inductor current (bottom) of a BUCK converter working in DCM, a) without damping resistor; b) with damping resistor connected in parallel to inductor

Fig. 13a shows an inductor current waveform during measurement of the characteristic presented in Fig. 6a. An additional damping resistor not only reduced amplitude of the ringing but it also improved response of the output voltage to a duty cycle as shown in Fig. 14.

A more sophisticated approach is presented in [8] where a transistor, instead of the damping resistor, is connected in parallel to the inductor. The transistor is turned on when the inductor current reaches zero value. Because of small resistance R_{DSON} of the transistor, such solution can eliminate the oscillations more efficiently than the damping resistor. The main drawback of using a transistor instead of a damping resistor is that it requires additional circuits such as a transistor driver and a circuit that detects the point when the inductor current reaches zero value.

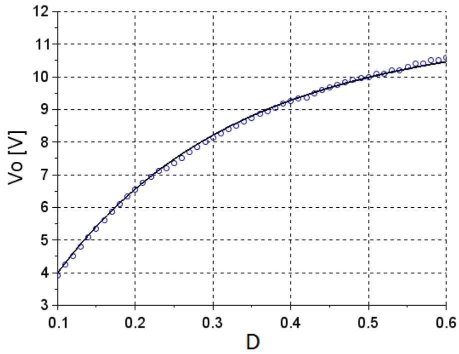


Fig. 14. Output voltage of a BUCK converter in DCM: solid – calculated from Eq. (4); dots – measured value

4.3. Snubber

A method which is frequently used to suppress any kind of oscillations is a *RC* circuit called a snubber. The snubber is usually connected in parallel with a low-side switch (Fig. 15). This solution can be easily found in literature along with methods of calculation R_S and C_S values [11-13, 15-16].

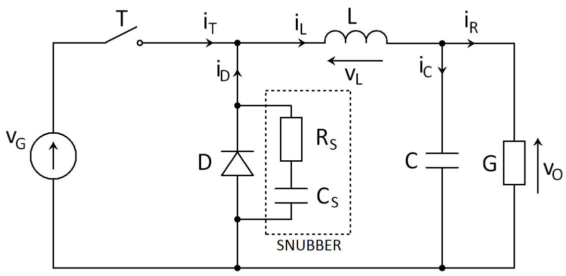


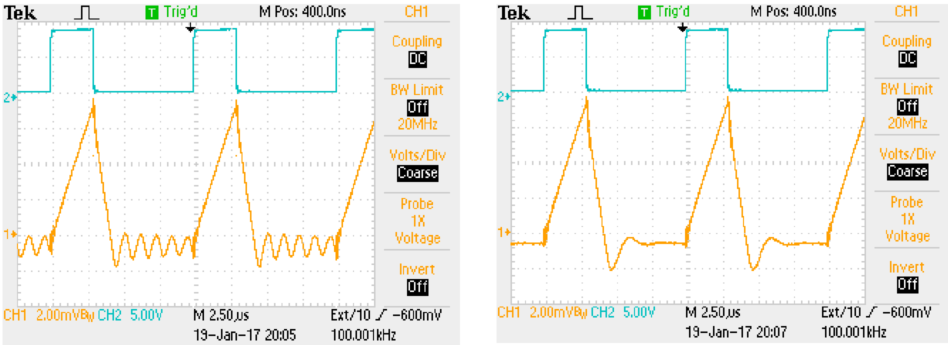
Fig. 15. Snubber circuit in BUCK converter

Values of a snubber capacitor and resistor can be changed to get the highest damping rate of the oscillations. However it is important to point out, that the snubber also dissipates power. In applications where high efficiency is required the snubber capacitance needs to be chosen carefully since it is involved in power dissipation according to the following formula [12]:

$$P_{\mathrm{SNUB}} = \frac{1}{2} C_S V_{\mathrm{SNUB}}^2 f_S \,, \tag{7}$$

where: V_{SNUB} is the voltage across the snubber, f_S is the switching frequency.

As a result of using a snubber in the converter related to Fig. 6a the inductor current oscillations are being suppressed, as shown in Fig. 16.



a) b)

Fig. 16. Gate-source voltage and inductor current of a BUCK converter: a) without snubber; b) with snubber connected in parallel with diode

Additional experiments have been performed to evaluate if the snubber circuit improves the voltage response to a change in a duty cycle. The experiments were performed in a similar way to those presented in the previous section (Fig. 6a and Fig. 9). The only difference was that a snubber circuit was used to suppress inductor current oscillations. The results of measurements are presented in Fig. 17-18.

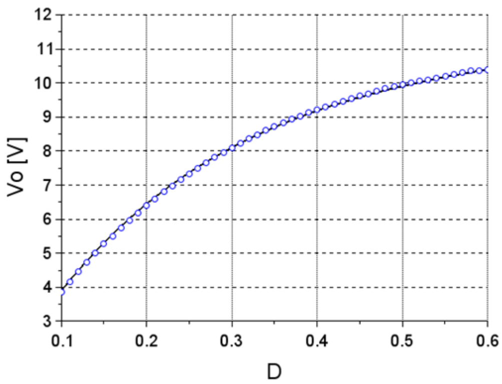


Fig. 17. Output voltage of a BUCK converter in DCM with snubber connected to diode: solid – calculated from Eq. (4); dots – measured value

The results of measurements presented in Figs. 17-18 show improvement in output voltage response to a change in a duty cycle. The value of the output voltage does not oscillate around theoretical value and it is consistent with a mathematical model (4). If the duty cycle is higher than 0.6 the output voltage of the measured converter differs from the theoretical value due to presence of the reverse current (Fig. 16b).

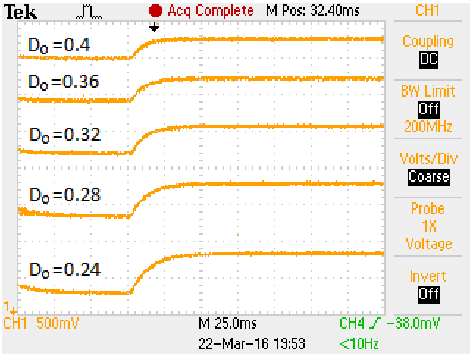


Fig. 18. Response of output voltage to step change of duty cycle in BUCK converter working in DCM with snubber connected to diode

One can notice that the negative current in Fig. 16b has higher amplitude and duration than the first negative oscillation in Fig. 16a. The duration and amplitude can be changed by using different parameters of the snubber [12]. In spite of reverse current presence an improvement has been achieved making the presented converter controllable in the range between $0 < D < 0.6$.

5. Conclusions

A control circuit should be designed based on a proper mathematical model of a converter. As a result of its operation, a PWM signal with a specific duty cycle is applied to the transistor driver. Any disturbance, not included in the assumed model, can substantially affect output voltage. This paper presents an influence of inductor current oscillations (present in DCM) on the response of the output voltage to duty cycle change. It has been shown, that the duty cycle, evaluated based on an inductor current waveform, can be different than the value of the duty cycle introduced to the transistor gate. The difference is a source of inconsistency in the output voltage and it depends on various parameters of a converter. In order to eliminate the oscillations some of known solutions have been presented. Two common methods using a dumping resistor and a snubber circuit were implemented in a real converter and measurements were made. As a result a good consistency between the theoretical and measured values of the output voltage was observed, confirming that the oscillations were the source of differences in the output voltage and proving usefulness of the damping resistor and snubber circuit.

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