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Digital Control of the Buck Converter Using the Law of Conservation of Energy

Streszczenie. *Rosnące wymagania stawiane układom zasilającym sprawiają, że coraz trudniej je spełnić wykorzystując klasyczne metody sterowania przetwornicami. Obecnie intensywnie poszukuje się metod udoskonalenia sterowania lub opracowywane są nowe. Takim rozwiązaniem jest wykorzystanie zasady zachowania energii do stabilizacji napięcia wyjściowego przetwornicy (projekt Bumblebee). W trakcie prac nad cyfrową wersją układu sterującego pracą przetwornicy zaobserwowano charakterystyczne oscylacje w stanie ustalonym. W artykule pokazano przyczyny tego niepożądanego zjawiska i sposób jego eliminacji.* ***(Cyfrowe sterowanie przetwornicą Buck wykorzystując zasadę zachowania energii).***

Abstract. *Increasing requirements for power supplies make it increasingly difficult to meet these requirements by using classical converter control methods. Already developed control methods are constantly being improved, while at the same time new solutions are tested. Such a solution is to use the law of conservation of energy to stabilize the output voltage of the converter (Bumblebee project). During the research on the digital version of the converter control circuit operating according to the new method, the characteristic oscillations in the steady state were observed. The article shows the causes of this undesirable phenomenon and how to eliminate it.*

Słowa kluczowe: Prawo zachowania energii, przetwornice DC/DC, projekt Bumblebee.
Keywords: Law of conservation of energy, DC/DC converters, project Bumblebee.

Introduction

Buck converters are widely used in various types of electrical equipment supply systems because of their high power efficiency, small size and low weight. The disadvantage of such converters is the sensitivity of the output voltage of the power stage to the change of circuit's operating point. The biggest undesirable changes in the output voltage of the converter are caused by changes in the supply voltage and changes in the converter load [1–5], whether they use an analogue or digital control systems. It is particularly important for systems that supply modern processors with high and sudden changes in current consumption. The results of the research on solving this problem are examples of the use of advanced control methods [6–18] for both Voltage Control Mode (VCM) and Current Control Mode (CCM).

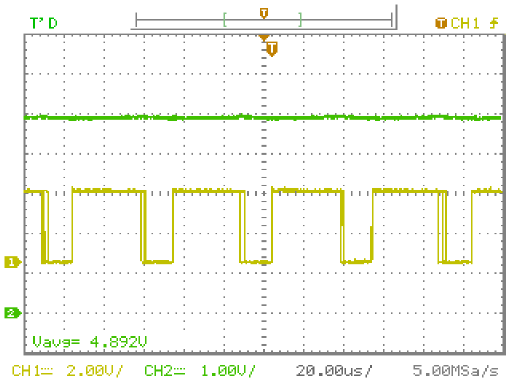

Fig.1. Output voltage and PWM signal waveforms of tested prototype

Another way to achieve very good output voltage stabilization parameters, regardless of even very large load changes, is the control system of the converter using the principle of conservation of energy [19, 20]. Analysis of the stability of the converter controlled by such system is shown in [21]. The small signal model, issues related to the digital implementation of this idea, and the tests of the digitally controlled Buck converter with such regulator is shown in [22-24]. Based on the work [21-23] the proposed solution was patented in the EU and US states [25, 26]. During further work on the development of the prototype device presented in [24], sub-harmonic oscillation of the output voltage of the converter has been observed in steady state. The oscillation of the PWM control signal of the prototype is shown in the Fig. 1.

Method using law of conservation of energy

Circuit of power stage of Buck converter is presented in Fig. 2a.

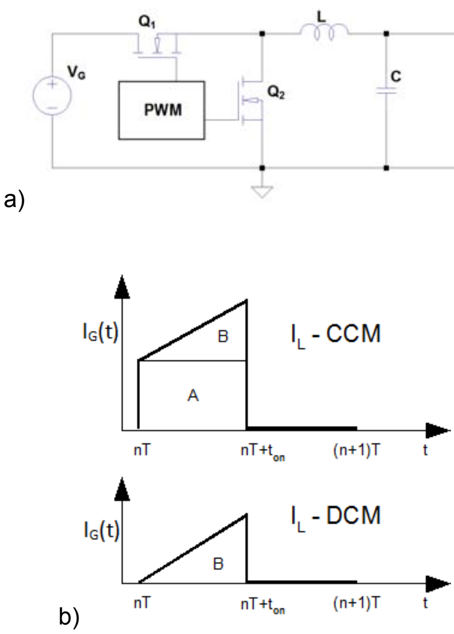

Fig.2. a) Power stage of Buck converter; b) $I_G(t)$ waveforms during one cycle in steady state

Voltage Control Mode (VCM) or Current Control Mode (CCM) converters use the V_{ref} reference voltage to stabilize the V_c output voltage [27, 28]. In the proposed method of stabilizing the output voltage of the converter using the law of conservation of energy, the reference energy is equivalent to the reference voltage (3). Mathematical description uses voltages and currents averaged over a single duty cycle of the converter - similarly as for the averaged, small signal models describing the operation of the converter power stage [27, 28]. The exact mathematical description is given in [19, 22-24, 29]. The reference energy is determined for steady state when the output voltage of the converter is V_{ref}. The reference energy consists of three components: the energy stored in L and C of the power stage and the energy used on the R_O load in a single duty cycle. Taking into account that averaged equations (1) and (2) are satisfied for the power stage in the steady state [27]:

$$\overline{V_C}(n) = V_{ref} \tag{1}$$

Where: n – the number of converter switching cycle, $\overline{V_C}(n)$ – the average output voltage for a single switching period n, V_{ref} – set output voltage of the converter

$$\overline{I_L(n)} = \frac{V_{ref}}{R_0(n)} \tag{2}$$

Where: $\overline{I_L(n)}$ – the RMS value of inductor current L for a single switching period n, $R_o(n)$ – output load resistance for a single switching period n

The reference energy in a single cycle of the converter power stage is described in equation (3):

$$E_{ref}(n) = \frac{1}{2} \cdot C \cdot V_{ref}^{\ 2} + \frac{1}{2} \cdot L \cdot \left(\frac{V_{ref}}{R_0(n)} \right)^2 + \frac{V_{ref}^{\ 2}}{R_0(n)} \cdot T \tag{3}$$

Where: T – period of a single duty cycle of the converter.

In order to maintain the output voltage V_C of the power stage at the specified level, the control system must supply sufficient energy from the source V_G in each switching cycle. This requires taking into account the amount of energy E_{P0} already accumulated in the power stage. At the beginning of each converter cycle, energy already stored in the converter power stage is determined:

$$E_{P0}(n) = \frac{1}{2} \cdot \overline{V_C(n-1)}^2 + \frac{1}{2} \cdot \overline{I_L(n-1)}^2 \tag{4}$$

The amount of energy that the control system should deliver in a single duty cycle is defined by:

$$E_X(n) = E_{ref}(n) - E_{P0}(n) \tag{5}$$

Taking into account that only in the ON phase the converter charges energy from the V_G source and the entire current from V_G source flows through the inverter inductor (Fig. 2a), the amount of energy describes the following equation:

$$E_Z(n) = \int_{n \cdot T+0}^{n \cdot T+t_{on}} V_G(t) \cdot I_G(t) dt \tag{6}$$

Where: t_{on} – duration of phase ON in cycle n, $E_z(n)$ – energy charged from source in cycle n, $V_G(t)$ – supply voltage for the converter, $I_G(t)$ – current drawn from V_G source

During phase ON (Q_1 switched on, Q_2 does not conduct) $I_G(t)$ current is equal to inductor current $I_L(t)$, during phase OFF (Q_1 - switched off) $I_G(t) = 0$. Depending on the CCM or DCM mode for the converter power stage $I_G(t)$ current waveform is shown in Fig. 2b.

Assuming simplified that during the phase ON in cycle n do not change the value of $R_O(n)$, voltage $V_G(n)$ based on equations (5) and (6), and $L \cdot dI_L(dt) = V_G - V_C$ (Fig. 2b), an equation describing the duration of the ON phase to charge the appropriate amount of energy is given below:

$$A' \cdot t_{on}^{\ 2} + B' \cdot t_{on} + C' = 0 \tag{7}$$

Equation (7) coefficients are given in [19, 22–24]. If the determinant of the equation (7) is negative, there is no phase ON during the converter's duty cycle and the converter has too much energy stored in the L and C elements. This is the case, for example, step reduction of the converter load from high power consumption to a smaller one. If the determinant of the square equation is positive, the duration of the phase ON is greater than zero. Always only one element of equation (7) has a positive value - this is the value of the phase ON. Possible compensation of energy loss in the power stage and explanation of why the influence of the inductor resistance on the increase of the inductor current in the ON phase can be omitted is given in [19].

Proposed method implementation

The method of compensation of delays caused by the measurement, numerical complexity of the algorithm and regulation of the control system dynamics are given in [23, 24]. To reduce the amount of calculations needed to implement the method, for example in DSP processor, simplification discussed in the papers [19, 23, 24] has been introduced. Among other things, the RMS values of the inductor current and voltage on the capacitor are replaced by instantaneous values at the start of cycle n. The development of converter constructions caused, among other things, the reduction of the value of inductor used in the power stage. In such converters, the change in inductor current becomes too large to, what can be observed for small inductor currents in Continuous Current Mode (CCM) or Discontinuous Current Mode (DCM). For this reason, it is not always possible to replace the RMS inductor current (for a single cycle period n-1) by the instantaneous value of the inductor current $i_L(nT)$ at the start of the new cycle. If the inductor currents changes are too high, specific oscillations will occur in steady state. These oscillations are produced in a similar way to the Current Control Mode (CCM) method without slope compensation of inductor current [27, 28]. Their cause is completely different, the control system based on the minimum current value of the inductor determines the too large amount of Ex(n) energy to be delivered to the converter power stage. Consequently, in the next cycles, it turns out that it is too much the energy stored in L and C of the converter power stage and the time of phase ON decreases. This phenomenon is periodical in steady state. The effect of this phenomenon on the output voltage of the power stage V_C, the inductor current I_L and the value of the PWM duty cycle of the control signal are shown in the Fig. 3a, 3b and 4.

Simulation-based research studies

Simulation of the proposed circuit was performed in MATLAB/SIMULINK (library Simscape), without the use of equivalent small signal models of the converter power stage. In simulation power stage of Buck converter was the same as power stage in Texas Instruments TMDSC2KWRKSHPKIT Development Board. The operating conditions of the converter power stage were selected so that the approximation of the inductor current RMS value was as accurate as possible.

Zoom in Fig. 3a shows the changes in the converter output voltage in the time interval 1.5 [ms] – 2.6 [ms]. Suppression of the output voltage oscillation for the converter using the approximation $\overline{I_L(n-1)} \approx i_L(n \cdot T)$ is only if the converter inductor current has increased due to the converter output load change, Fig. 3b.

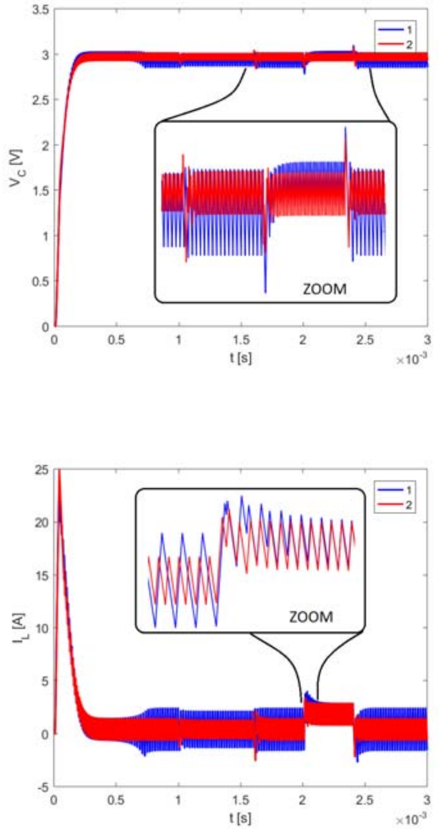

Fig.3. a) Voltage V_O waveform; 1 – operating with $\overline{I_L(n-1)} \approx i_L(n \cdot T)$; 2 – operating with determination of the RMS value of the inductor current; b) The inductor current I_L waveform; 1 – operating with $\overline{I_L(n-1)} \approx i_L(n \cdot T)$; 2 – operating with determination of the RMS value of the inductor current

According to the documentation of the Development Board, it was assumed that equivalent circuit parameters are:

L = 10 μH, R_L = 42.4 mΩ (inductor series resistance), C = 726 mF, R_C = 40 mΩ (capacitor equivalent series resistance), R_O = 7.5Ω, R_{Q1ON} = 5 mΩ, R_{Q2ON} = 1.1 mΩ (drain to source resistance in ON state), f_{PWM} = 300 kHz, V_G = 9, V_{ref} = 3 V.

Test signals:

$V_G(t)$ =V_G + 0.35*V_G Heaviside(t-1 [mS]) - V_G Heaviside(t-1.6 [mS])

$R_O(t)$ =R_O - 2[Ω]*Heaviside(t-2 [mS]) + 2[Ω]*Heaviside(t-2.4 [mS])

Heaviside (t-t_0) – step function

Zoom in Fig. 3b shows the changes in the converter inductor current during the converter output load change from 7.5 [Ω] to 1.59 [Ω] in the time interval 1.93 [ms] – 2.15 [ms]. Changing the output load increases the RMS value of the inductor current and causes the oscillation to disappear for the system with the approximation $\overline{I_L(n-1)} \approx i_L(n \cdot T)$ applied.

Fig. 4 shows the changes in the PWM duty cycle. A step change in load at time t = 2 [ms] causes the oscillation to disappear for a control circuit utilizing an approximation of the effective value of the inductor current. This is due to the increase of the RMS value of the inductor current – Fig. 3b.

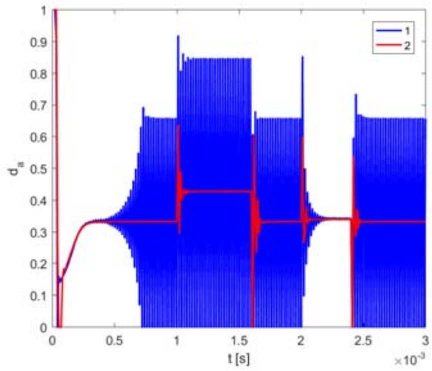

Fig.4. PWM duty cycle waveform; 1 – operating with $\overline{I_L(n-1)} \approx i_L(n \cdot T)$; 2 – operating with determination of the RMS value of the inductor current

Concluding remarks

Using the law of conservation of energy to control DC-DC converters allows the control system to respond very quickly to changes in the operating point, for example converter output load. In order to reduce the calculation effort, the RMS current of the inductor current has been used to approximate the current in the single duty cycle. The authors have presented in the paper, that not always such simplification is acceptable. Replacing the inductor current value at the beginning of each i_L(nT) duty cycle with the RMS value $\overline{I_L(n-1)}$ requires a change only in the equation (4) describing the amount of energy EP0 stored in the converter. This does not cause significant changes in the implementation of the algorithm in the control system. Determination of the RMS value of the inductor current can be realized by a measurement or numerical calculation. If converter is operating in CCM and the inductor current DC component is greater than the AC component, then approximating the RMS inductor current value does not cause sub-harmonic oscillations and can be successfully applied.

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