Self-compensation of DC–DC converters under peak current mode control

A. El Aroudi✉, K. Mandal, D. Giaouris and S. Banerjee

A new self-compensation technique is proposed for eliminating subharmonic oscillation and chaotic regimes in dc–dc switching converters under peak current mode control. The proposed method extracts a control signal from the error between the inductor current and a suitable reference and does not require an external signal generator as in the conventional ramp compensation scheme. The analytical expressions of the control domain using Filippov method are obtained. Simulation results show that the proposed technique can be implemented using standard analogue devices and can effectively eliminate subharmonic and chaotic oscillations and can ensure a stable operation for a wide range of the duty ratio.

Introduction: Subharmonic and chaotic oscillations are phenomena that commonly occur in dc–dc switching converters and their control is of great importance for power electronic designers. Although many control techniques exist in the literature for suppressing these undesired behaviours, slope compensation using an external periodic ramp signal with a constant slope is the conventional strategy preferred by engineers for stabilising switching converters under peak current mode control [1, ch. 11]. The use of constant slope compensation can increase the stability range of the desired periodic behaviour, but as a penalty, it reduces some of the benefits of current mode control. For example, a drawback with this strategy is that the inductor current peak value deviates from its desired reference which can cause severe problems in applications where an accurate tracking of the reference signal is needed such as in power factor correction [2] and in grid-connected photovoltaic systems [3].

In order to accurately track the reference current while eliminating subharmonic oscillation in a dc–dc buck converter, a dynamic slope compensation scheme was proposed in [4]. The technique was also adapted for a boost ac-dc converter in [2]. In both these approaches an external signal generator is still needed. Another technique proposed in [5] consists of extracting the control signal from the output voltage after differentiation, integration and resetting to zero. The resulting compensation signal is practically sinusoidal with a time varying slope with an optimum value at the switching instant. However, the technique, using the output voltage for extracting the compensating signal, can only be applied to the buck converter for which the derivative of the output voltage is continuous. For other switching converters, the derivative of the output voltage is discontinuous and the previous technique will result in noise problems.

In this Letter a novel self-compensation technique is proposed for eliminating subharmonic and chaotic oscillations in all dc-dc switching converters under peak current mode control. The technique is based on extracting a control signal from the error between the inductor current and a constant reference being applicable to the converter. The novel control strategy achieves the same control effect of the existing compensation schemes with the possibility of an accurate reference tracking.

We begin our study with a brief description of the technique followed by a stability analysis and a possible realisation using standard analogue devices. Some design-oriented expressions are also provided for ensuring the stability of the system. PSIM© simulations are used to validate its operation and performances.

Proposed self-compensation strategy: The inductor current in DC–DC converters includes a dc component and ac switching ripple. This Letter proposes a method to eliminate subharmonic and chaotic instabilities by utilising the ac inductor current ripple. We propose a novel ripple-dependent self-compensating signal governed by the following expression:

$$v_{\mathrm{mod}}(t) = \frac{r_a}{T}\int_0^{t \bmod T} (i_r - i_L(\zeta))\,\mathrm{d}\zeta \tag{1}$$

where i_r is a current reference and r_a is suitable gain both to be specified later. The value of the integral variable is reset to zero at the beginning of each switching cycle of time period T.

Unified dynamical model and stability analysis: Fig. 1 shows the unified three-terminal circuit diagram of elementary switching converters buck, boost and buck-boost under peak current mode control. All these converters have a three-terminal switching cell including an active switch S and a passive switch $\overline{S}$. The common node between the switches S and $\overline{S}$ connects to the inductor whose inductance is L. The switching element $\overline{S}$ is a diode in unidirectional converters while it is a transistor in bidirectional and synchronous converters. The switch S is closed ($u = 1$) at the beginning of each switching cycle and it opens ($u = 0$) when the inductor current (scaled by a gain R_s) reaches the signal $R_s i_{\mathrm{ref}} - v_{\mathrm{mod}}$. The state of the switch $\overline{S}$ is complementary to that of S.

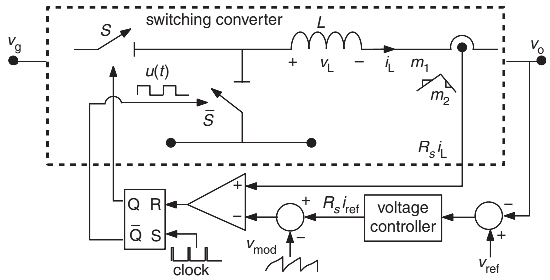

Fig. 1 *Unified circuit diagram of an elementary switching converter such as buck, boost and buck-boost under CMC. The block in dashed border can be changed depending on the converter topology chosen*

For simplicity, the output voltage v_o and the reference provided by the voltage loop are considered constant. The equation governing the behaviour of the inductor current is

$$\frac{\mathrm{d}i_L}{\mathrm{d}t} = m(t) = \begin{cases} m_1 & \text{for } u = 1 \\ m_2 & \text{for } u = 0 \end{cases} \tag{2}$$

where $m(t) = v_L/L$ and v_L is the inductor voltage. The parameters m_1 and m_2 are the rising and the falling slopes of the inductor current respectively. The switching condition can be expressed as follows:

$$\sigma(t) := R_s(i_{\mathrm{ref}} - i_L(t)) - \frac{r_a}{T}\int_0^t (i_r - i_L(\zeta))\,\mathrm{d}\zeta = 0 \tag{3}$$

where i_{ref} is the peak current reference if no compensation is used. To perform an accurate stability analysis of the system we use Floquet theory combined with Filippov method [6, 7].

Because of the reset at each clock cycle, one of the eigenvalues is zero. The expression of the non-zero eigenvalue λ of the system is as follows:

$$\lambda = 1 + \frac{(m_2 - m_1)(R_s - r_a D)}{R_s m_1 + (r_a/T)(i_r - i_L(DT))} \tag{4}$$

The value of the effective peak current $i_L(DT)$ can be derived by solving (3) which results in:

$$i_L(DT) = \frac{R_s(i_{\mathrm{ref}} - m_1 DT) - r_a(Di_r - (D^2 m_1 T/2))}{R_s - r_a D} + m_1 DT \tag{5}$$

Two different choices for the parameter i_r are proposed resulting in the following versions of the new proposed self-compensation scheme.

First version ($i_r = i_{ref}$): Similar to the conventional linear ramp compensation scheme, the value of the peak current is smaller than the desired value i_{ref}. Imposing $\lambda = -1$ and $\lambda = +1$ in (4) we can obtain respectively, the lower and the upper stability limits ℓ_{m1} and ℓ_M of the system in the parameter space. In terms of the control parameter r_a, the stability range is obtained as:

$$\ell_{m1} := \frac{R_s}{D}\left(1 - \sqrt{\frac{1-D}{D}}\right) < r_a < \frac{R_s}{D} := \ell_M \tag{6}$$

Second version ($i_r = i_{ref} - m_1 DT/2$): From (3) it can be demonstrated that $i_L(DT)$ will be equal to the current reference i_{ref} if $i_r = i_{\mathrm{ref}} - m_1 DT/2$. In this case, the stability limits become:

$$\ell_{m2} := \frac{R_s}{D^2}(2D - 1) < r_a < \frac{R_s}{D} := \ell_M \tag{7}$$

In both versions, a value of $r_a = R_s$ guarantees stability for all values of the duty ratio. The control domain for both cases is shown in Fig. 2 in terms of the operating duty ratio and the parameter r_a for $R_s = 1\ \Omega$.

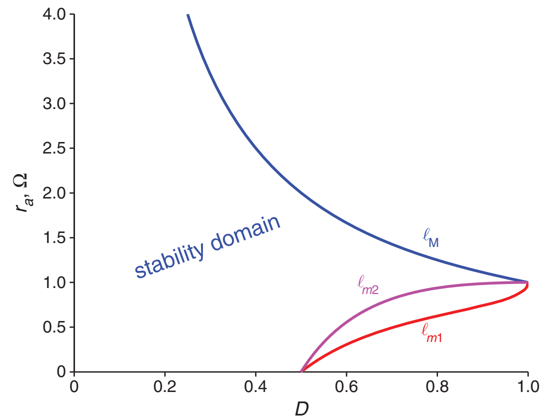

Fig. 2 *Control domain in the parameter space (D, r_a)*

Time-domain simulation and validation of the self-compensation scheme: Numerical simulations are performed using PSIM© software to validate the theoretical results related to the novel self-compensation scheme which can be implemented by the analogue circuit diagram depicted in Fig. 3 where a resettable integrator has been used. Without loss of generality, the resistance R_T and the capacitance C_T are selected in such a way that $R_T C_T = T$, where T is the switching period. A boost converter under peak current mode control is used to validate the proposed scheme and the related theoretical results with the following parameter values: $v_g = 5$ V, $v_o = 20$ V ($D = 0.75$), $L = 1$ mH, $T = 40$ μs, $i_{ref} = 1$ A and $R_s = 1$ Ω.

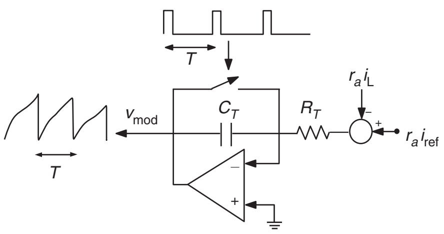

Fig. 3 *Circuit diagram of the novel modulating signal generator*

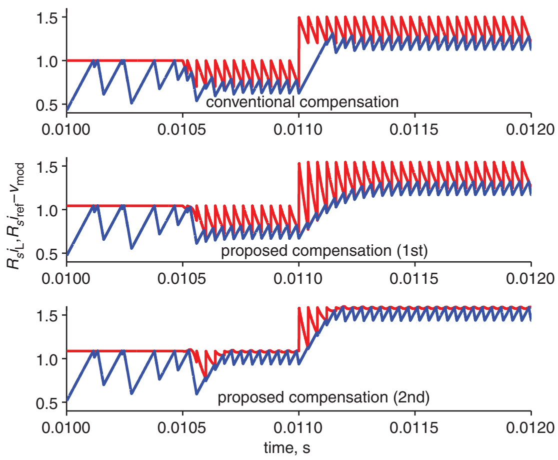

Fig. 4 *System response under the activation of compensation at t = 0.0105 s and to a step change in the reference current at time t = 0.011 s for the conventional linear ramp compensation scheme (top), the first version of the proposed self-compensation strategy (middle) and its second version (bottom)*

Fig. 4 shows the time domain response of a boost converter under peak current mode control. The system is operated with a duty cycle $D = 0.75$ which implies subharmonic oscillation without compensation. At $t = 0.0105$ s, the self-compensation strategy is applied with $r_a = 1$ Ω and the system is stabilised within a few switching cycles. At $t = 0.011$ s, a step change from 1 to 1.5 A is applied to the reference current. For a fair comparison, the amplitude of the conventional compensation ramp is selected to be equal to the one corresponding to the first version of the proposed self-compensation scheme in steady-state. This amplitude is 0.3 V. While a similar stabilising effect can be observed in the conventional ramp compensation strategy and in the first version of the proposed self-compensation scheme, it can be noted that the second version of the proposed control technique outperforms both of them in terms of accurate current reference tracking.

Conclusions: We have presented a self-compensation technique for eliminating subharmonic and chaotic oscillations in current-mode controlled switching converters. Simulation results show that the technique can easily be implemented with a simple analogue circuit. Compared with the conventional slope compensation, the strategy does not require an external signal generation and extracts a modulating signal directly from the error between the inductor current and a suitable reference. The proposed strategy has the same stabilising effect as the conventional slope compensation technique, but also has the advantage of accurate current reference tracking.

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One or more of the Figures in this Letter are available in colour online.

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