NOVEL D^2T CONTROL FOR SINGLE-SWITCH DUAL-OUTPUT SWITCHING POWER CONVERTERS

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ABSTRACT

A method for programming current in dc/dc converters operating in discontinuous conduction mode is described in this paper. The control variable is the product of the square of the duty cyle and the switching period (D^2T), which is directly proportional to input and output currents of a discontinuous-mode converter. A method of controlling D^2T is applied to converters that utilize one switch (or one set of synchronous switches) for achieving two control functions. In particular a single-switch two-output boost converter is studied. In this system, current-mode control is used to regulate the output voltage of the continuous-mode converter and the proposed D^2T control is used to regulate the other discontinuous-mode converter. The result is a generic current-mode controlled dual-output converter.

1. INTRODUCTION

This paper describes a single-switch two-output regulator which comprises two boost converters, one operating in continuous conduction mode (CCM) and the other in discontinuous conduction mode (DCM) [1]. Previously reported control methods take advantage of the insensitivity of the CCM converter to switching frequency, and apply duty-cycle control to regulate the CCM converter while regulating the DCM converter by frequency modulation [1, 2]. In this paper, we consider application of generic current-mode control to both converters in order to achieve faster transient responses [3]. Specifically, we use a standard current programming for the CCM converter and a novel D^2T control for regulating the DCM converter. We will also discuss the local stability of the combined current-mode and D^2T control scheme, and present a practical circuit implementation of the controller.

2. OUTLINE OF THE PROPOSED CONTROL

Inspired by its averaged behaviour model, the DCM converter can be controlled by varying the control quantity D^2T which is proportional to the output current [4]. In principle, if the quantity D^2T is adjusted via a feedback mechanism, the output load voltage can be regulated. A special but practically important case is when either the on-time or off-time duration is already determined by another control law. We shall make reference to a single-switch two-output boost converter later in the paper.

Suppose the duty cycle is D, and the period begins with the switch turned off. Thus, after a duration of $(1-D)T$, the switch is turned on; and after another duration of DT, the switch is turned off again, completing one cycle.

Our objective is to derive a scheme, whereby the off-time duration $(1-D)T$ is pre-determined and the period T is adjusted to give the desired value of D^2T. The proposed controller consists of a periodic parabola generator $p(t)$ and a ramp generator $r(t)$:

$$p(t) = a(t-t_0)^2 \quad (1)$$

$$r(t) = b(t-t_0') \quad (2)$$

where t_0 and t_0' are arbitrary start instants for the two generators, and a and b can be considered as constant for the time being. Fig. 1 (a) shows these generator waveforms.

At the start of the switching cycle, say $t=0$, the ramp generator is triggered to start. At $t=(1-D)T$ (which is determined externally), the switch is turned on. At the same time, the parabola generator is triggered to start from zero. As soon as the outputs of the generators are equal, the switch is turned off whereby spawning a new cycle. Clearly, this condition forces

$$p(DT) = r(T) \;\Rightarrow\; a(DT)^2 = bT \;\Rightarrow\; D^2T = b/a. \quad (3)$$

Hence, the quantity D^2T can be made controllable by varying b/a. A conceptual implementation of this control scheme is shown in Fig. 1 (b). In this scheme, the off-time duration is externally determined, and the control circuit in turn produces a pulse to set the period. Thus, the proposed control can be viewed as a frequency modulator which, for each cycle, maintains a constant D^2T. If the current sources (i.e., a and b) are controllable, the quantity D^2T can be modulated via feedback.

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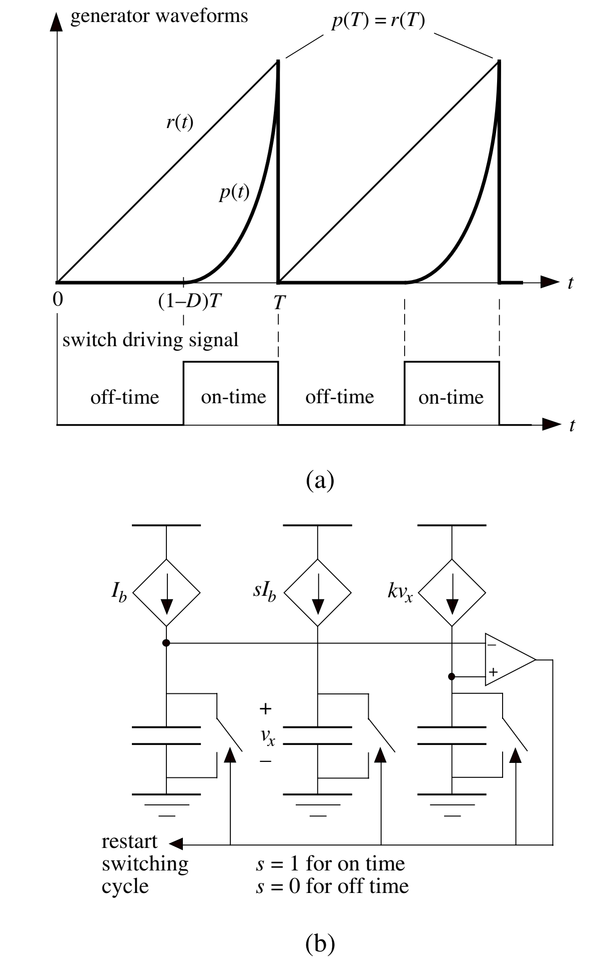


Fig. 1: (a) Waveforms of the parabolic and ramp generators in the conceptual D^2T control scheme; (b) conceptual implementation.

3. LOCAL STABILITY OF COMBINED CURRENT-MODE AND D^2T CONTROL

Our interest in this section is to study the local stability of the proposed control scheme when the off-time duration is pre-determined by a current-mode control scheme. Essentially, in a typical continuous-mode dc/dc converter under current-mode control, the turn-off instant is determined by comparing the inductor current with a reference level. Thus, effectively, this conventional scheme is controlling the on-time duration. In our scheme, however, we control the off-time duration instead. As we will see, this has an important implication on the stability. In brief, the switch is turned on at the instant the inductor current descends to a reference level. The turn-off instant, moreover, is determined by our proposed D^2T control. In other words, the repetition period is controlled by the D^2T controller. The stability issue therefore involves the consideration of the stability of the current-mode control with off-time duration being

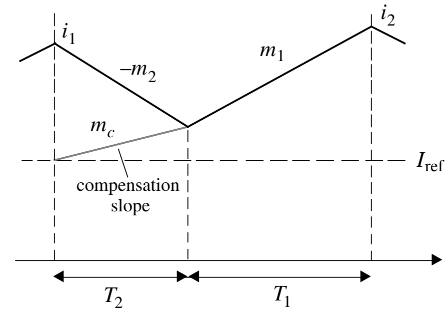


Fig. 2: Inductor current waveform for stability analysis.

pre-determined and the period being controlled by the D^2T scheme.

First, referring to Fig. 2, we can write the inductor current values at the start and end of a period as

$$\begin{aligned} i_1 &= I_{\rm ref} + (m_c + m_2)T_2 \\ i_2 &= I_{\rm ref} + m_c T_2 + m_1 T_1 \end{aligned} \tag{4}$$

where T_1 is the on-time duration, T_2 is the off-time duration, m_1 is the on-time inductor current slope, m_2 is the off-time inductor current slope, and m_c is the compensation slope. Note that we consider here the general case where a compensation slope is included in the current-mode control. Upon differentiating (4), we get

$$\frac{\delta i_2}{\delta i_1} = \frac{m_1 \delta T_1 + m_c \delta T_2}{(m_c + m_2)\delta T_2} = \frac{m_c + m_1 \frac{\delta T_1}{\delta T_2}}{m_c + m_2}. \tag{5}$$

Let us now introduce the D^2T control to the abovementioned current-mode controlled converter. In the steady state, the aim is to fix the value of D^2T, i.e.,

$$\frac{T_1^2}{T_1 + T_2} = \text{constant}, \tag{6}$$

where the constant in the RHS is equal to the steady-state value of D^2T. Thus, differentiating (6), we get

$$\frac{\delta T_1}{\delta T_2} = \frac{D}{2 - D}. \tag{7}$$

Hence, from (5), and using $m_1 D = m_2(1 - D)$, we have

$$\frac{\delta i_2}{\delta i_1} = \frac{m_c + m_1 \frac{D}{2-D}}{m_c + m_2} = \frac{m_c + m_2 \frac{1-D}{2-D}}{m_c + m_2} \tag{8}$$

Local stability requires that the magnitude of the above expression be less than 1. Thus, we can see that stability is guaranteed for all D since

$$0 < \frac{1 - D}{2 - D} < \frac{1}{2} \quad \text{for all } D \in (0, 1), \tag{9}$$

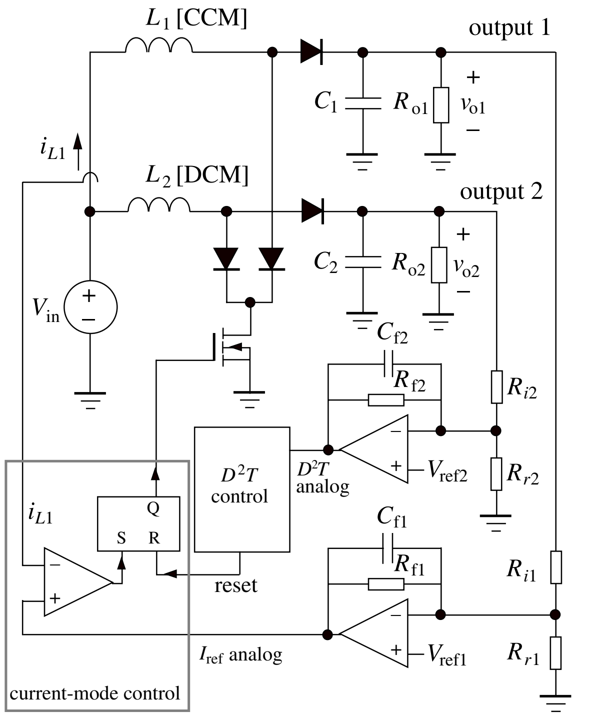


Fig. 3: Schematic of dual-output boost regulator under combined current-mode D^2T control.

which implies $|\delta i_2/\delta i_1| < 1$ for all $0 < D < 1$.

It is interesting to note that the stability of the system is unaffected even when the compensation ramp is zero. In other words, the D^2T control inherently stabilizes the current-mode control, eliminating the need for the use of ramp compensation.

4. APPLICATION TO DUAL-OUTPUT BOOST REGULATOR

In this section we present a single-switch two-output boost regulator, as outlined previously in the Introduction. Fig. 3 shows the schematic of the system. In brief, this regulator consists of a CCM boost converter and a DCM boost converter, sharing one common switch. The circuit design aspect has been studied extensively by Sebastián and Uceda [1] and Charanasomboon *et al.* [2]. Here, we focus on the application of the proposed combined current-mode and D^2T control for simultaneous regulation of the two outputs, and verify the control function by SPICE simulation. In the simulation, real devices are used for the boost converters, while the D^2T control block is constructed based on the conceptual circuit shown in Fig. 1 (b). Component and parameter values for simulation are summarized in Table 1.

It is worth noting that the inductor current of the CCM converter is referenced at the turn-on instant, and hence its peak is generally unlimited (actually determined by the D^2T control). It is thus necessary to impose a peak limiter to limit the maximum switching period. This arrangement has been incorporated in our simulation study.

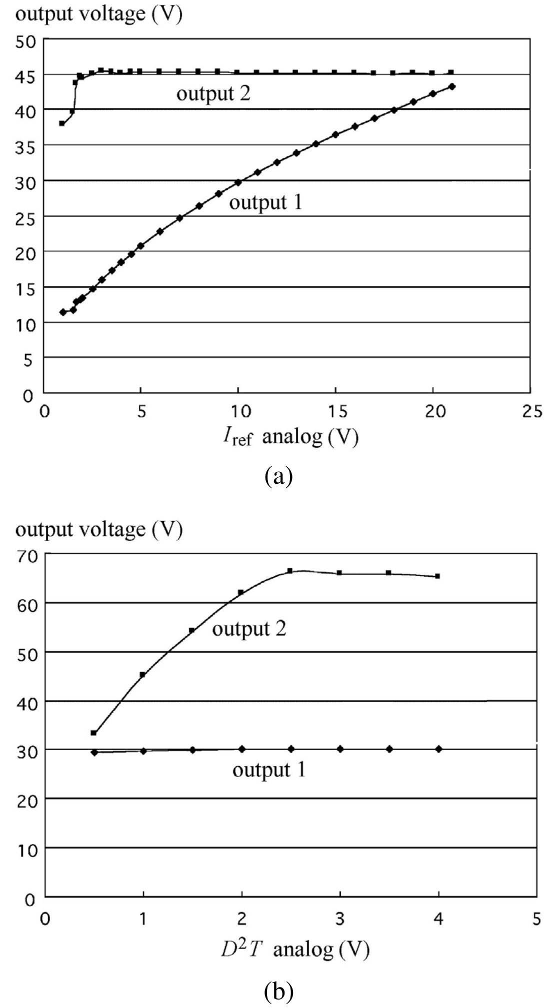


Fig. 4: Steady-state control-to-output characteristics. (a) Output voltages versus $I_{\rm ref}$ analog (control voltage of the CCM converter) with D^2T analog (control voltage of the DCM converter) kept at 1 V; (b) output voltages versus D^2T analog (control voltage of the DCM converter) with $I_{\rm ref}$ analog (control voltage of the CCM converter) kept at 10 V. Note that the abrupt drop or saturation of output 2 at either end of the control range is a result of the use of a maximum period limiter.

Several tests have been performed to verify the operation of the proposed control. First of all, the steady-state control-to-output transfer characteristics have been obtained by plotting the output voltages against the control voltage analogs. Results are shown in Fig. 4. Then, the transient performance has been evaluated, including input regulation, load regulation and cross regulation. Results are shown in Figs. 5 and 6. In Fig. 5, the transient responses are recorded when the input voltage is stepped, whereas in Fig. 6, the

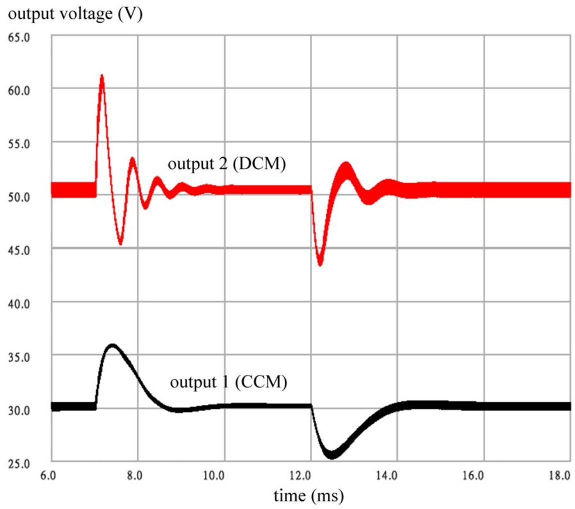


Fig. 5: Output transient responses for step changing input voltage. At $t = 7$ ms, $V_{\rm in}$ steps up from 8 V to 12 V, and at $t = 12$ ms, it steps down back to 8 V.

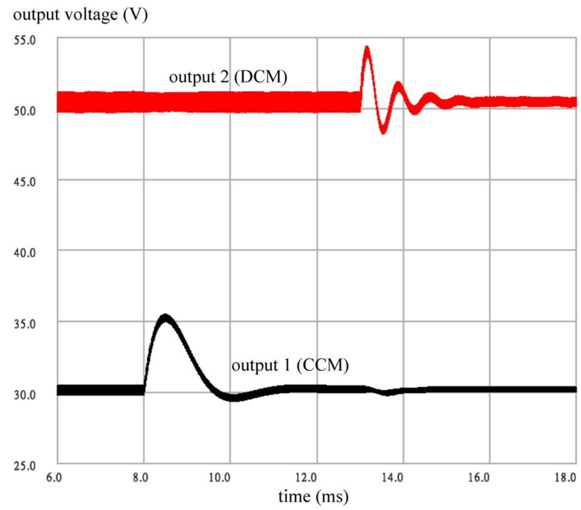
Table 1: Component and parameter values for simulation

Component/parameter	Value
Inductance 1 (CCM), L_1	100 μH
Inductance 2 (DCM), L_2	10 μH
Output capacitance 1, C_1	50 μF
Output capacitance 2, C_2	5 μF
Input voltage, $V_{\rm in}$	10 V
Load resistance 1, R_{o1}	8–12 Ω
Load resistance 2, R_{o2}	80–120 Ω
On-resistance of MOSFET	0.005 Ω
Frequency	20–170 kHz

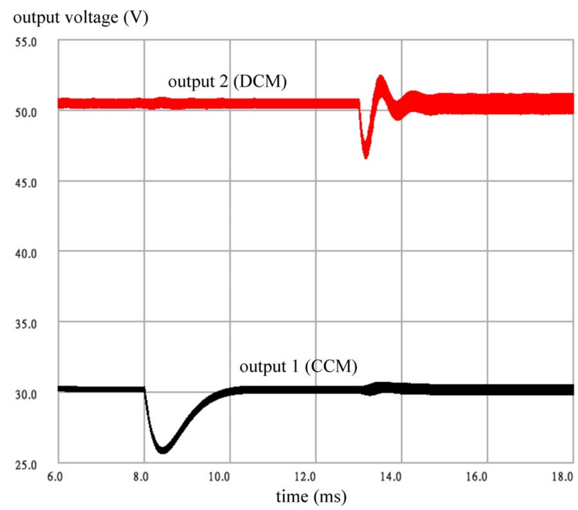
transient responses are recorded when the load resistances are stepped. Note that Fig. 6 reflects very satisfactory self load regulation performance as well as cross regulation performance, i.e., transient of v_{o1} (or v_{o2}) when R_{o2} (or R_{o1}) is stepped.

5. CONCLUSION

In a dual-output voltage regulator, where two dc/dc converters (one operating in CCM and the other in DCM) are sharing one switch, generic current-mode control can be achieved by applying conventional current-mode control to the CCM converter and a D^2T programming control to the DCM converter. In this paper we propose a strategy for controlling the D^2T quantity, whereby both outputs can be tightly regulated. Satisfactory cross regulation is possible by virtue of the CCM converter being insensitive to frequency changes and the DCM converter being directly current-programmed.



(a)



(b)

Fig. 6: Output transient responses for step changing loads. (a) At $t = 8$ ms, R_{o1} changes from 8 Ω to 12 Ω, and at $t = 13$ ms, R_{o2} changes from 80 Ω to 120 Ω. (b) At $t = 8$ ms, R_{o1} changes from 12 Ω to 8 Ω, and at $t = 13$ ms, R_{o2} changes from 120 Ω to 80 Ω.

6. REFERENCES

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