Application of Novel D^2T Control to Single-Switch Two-Output Switching Power Converters

Siu-Chung Wong, *Member, IEEE,* and Chi K. Tse, *Senior Member, IEEE*

***Abstract*—A novel 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, i.e., 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, in which a continuous-mode converter and a discontinuous-mode converter share one active switch, 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 two-output converter.**

***Index Terms*—Current-mode control, dc/dc converters, discontinuous conduction mode, double converters.**

I. Introduction

THE DESIGN of multiple-output dc–dc converters is one of the old problems studied in the 1980s and 1990s [1]–[4]. Recently, due to the advances in integrated circuit customization and the quest for versatile on-chip dc regulators, the control and circuit design of multiple-output dc–dc converters have received renewed interest [5], [6]. Moreover, the emphasis has shifted toward the integrability of the control and power circuits.

This paper revisits the problem of controlling single-switch fully-regulated-two-output dc–dc converters, and in particular 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], [2]. The basic principle of the single-switch two-output converter takes advantage of the insensitivity of the CCM converter to switching frequency and the general dependence of the DCM converter upon the switching frequency. Thus, when only one switch is used to regulate two converters, one of the converters must operate in DCM in order to provide an extra control variable (i.e., switching frequency in this case), in addition to the duty cycle. Clearly, it is theoretically possible to operate both converters in DCM. In general, the control scheme uses duty cycle as the control variable for the CCM converter, and switching frequency as the control variable for the DCM converter, in order to achieve simultaneous regulation of both converters sharing one power switch. Previously reported control methods apply voltage-mode duty-cycle control to regulate the CCM converter while regulating the DCM converter by frequency modulation [1]–[4]. In this paper, we consider application of generic current-mode control to both converters in order

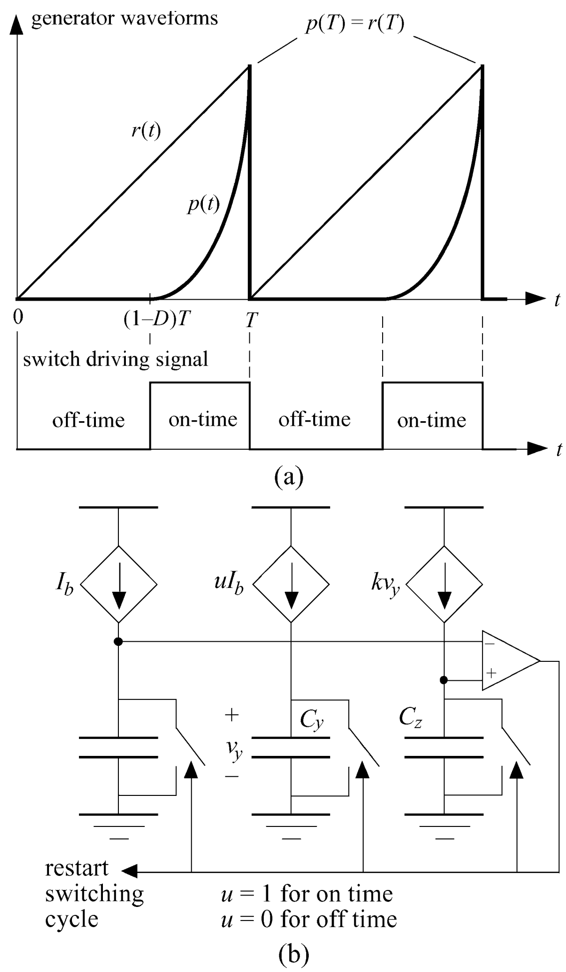

Fig. 1. (a) Waveforms of the parabolic and ramp generators in the conceptual D^2T control scheme and (b) conceptual implementation. The current source on the left charges up a capacitor whose voltage ramps up linearly from the start of the off-time, thus emulating the required ramp generator $r(t)$. The current source in the middle charges up another capacitor (C_y) whose voltage (v_y) ramps up linearly from the start of the on-time. This voltage, v_y, is then used to control the current source on the right, which charges up another capacitor (C_z) whose voltage is the required parabola $p(t)$. When $r(t)$ and $p(t)$ become equal in magnitude, the comparator output goes high momentarily and discharges all capacitors, thereby resetting the cycle.

Manuscript received October 21, 2003; revised October 27, 2004. This work is supported by Hong Kong Polytechnic University under Grant G-T662. Recommended by Associate Editor Y.-F. Liu.

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Digital Object Identifier 10.1109/TPEL.2005.850942

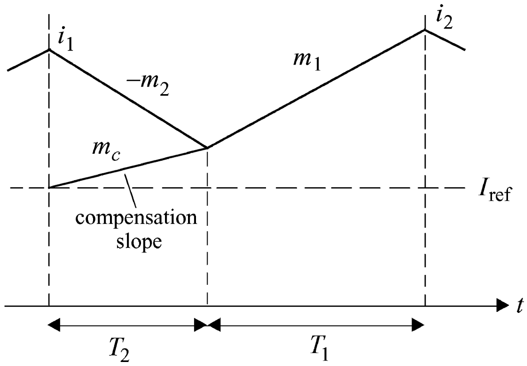


Fig. 2. Inductor current waveform for stability analysis. Compensation ramp is included for completeness of analysis. This compensation ramp is, under the proposed control, unnecessary as the inner current loop has been shown unconditionally stable.

to achieve faster transient responses [7]. Specifically, we use a standard current programming for the CCM converter [7], [8] 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 describe a simple circuit implementation of the controller. Experimental results will be presented for verification.

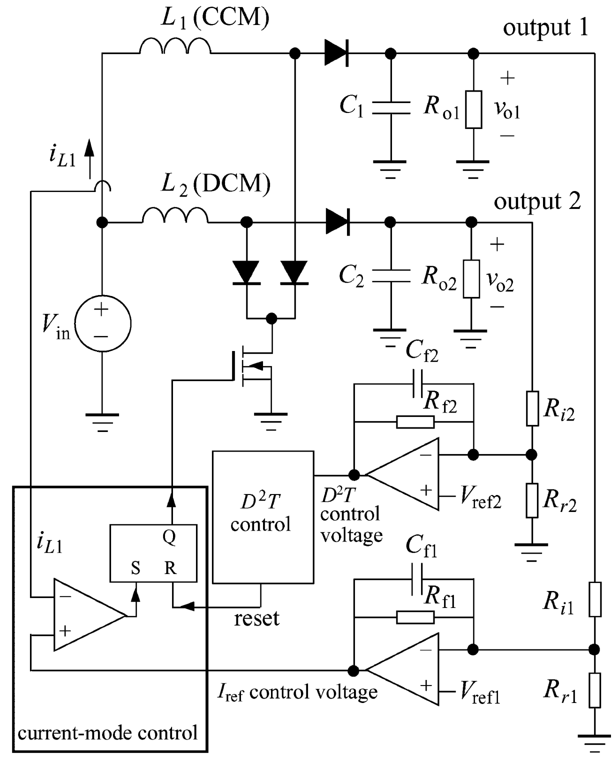


Fig. 3. Schematic of dual-output boost regulator under combined current-mode D^2T control. Details of the D^2T control block is shown in Fig. 4.

TABLE I
COMPONENT AND PARAMETER VALUES OF EXPERIMENTAL PROTOTYPE

Component/parameter	Value
Inductance 1 (CCM), L_1	100 μH
Inductance 2 (DCM), L_2	20 μH
Output capacitance 1, C_1	47 μF
Output capacitance 2, C_2	100 μF
Input voltage, $V_{\rm in}$	12 to 16 V
Load resistance 1, R_{o1}	10 to 40 Ω
Load resistance 2, R_{o2}	40 to 147 Ω
Power MOSFET	IRFP 360
Frequency	20 to 100 kHz

II. Basic Concept of D^2T Control

Inspired by its averaged behavior model, the DCM converter can be controlled by varying the control quantity D^2T which is proportional to the output current [9]. 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 will 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

$$\begin{aligned} p(DT) &= r(T) \\ \Rightarrow a(DT)^2 &= bT \\ \Rightarrow D^2T &= b/a. \end{aligned} \quad (3)$$

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

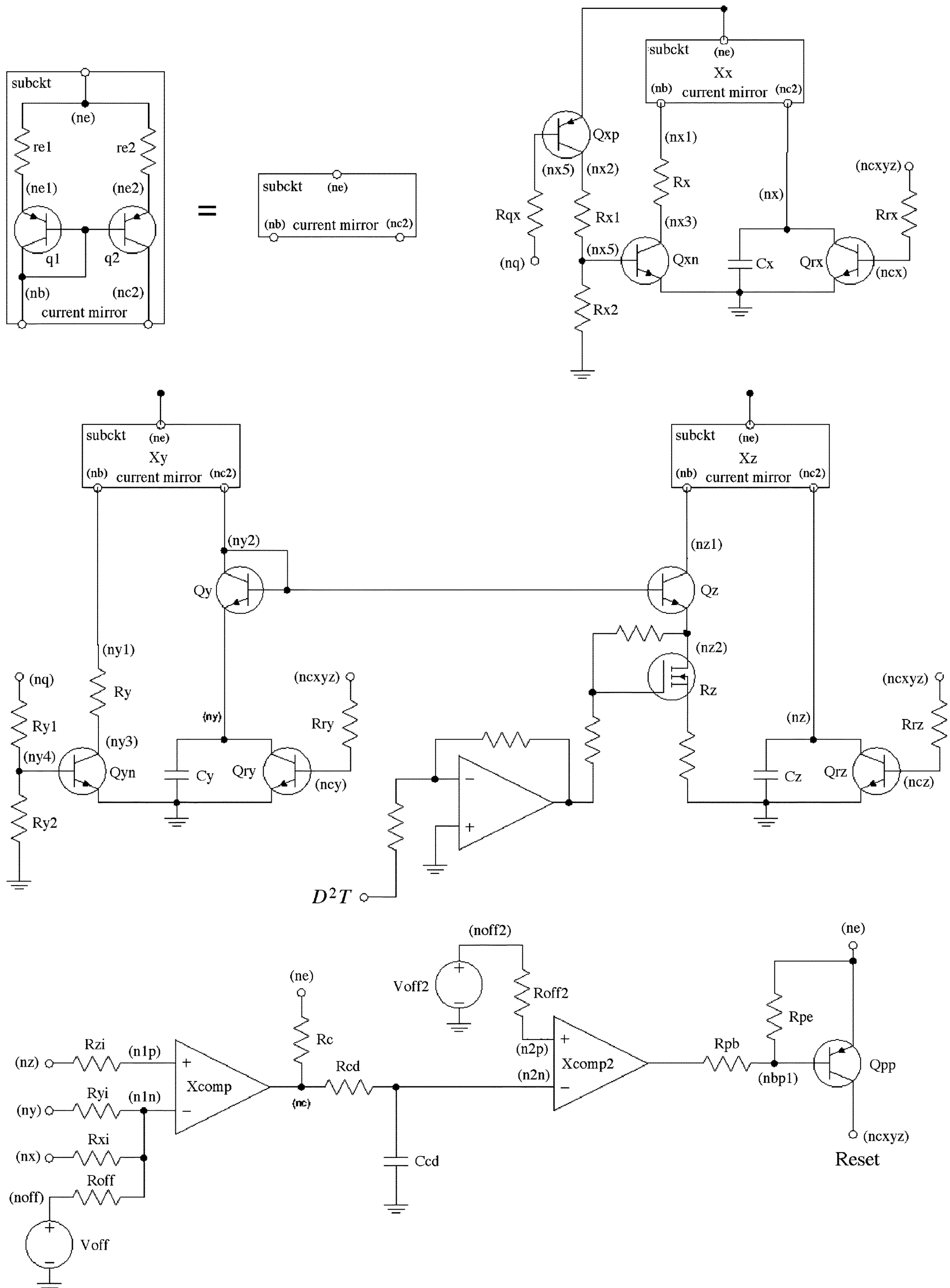


Fig. 4. Detailed circuit schematic of the D^2T control using discrete components. The current sources in Fig. 1(b) are realized by simple voltage-controlled current mirrors, represented by "subckt."

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.

III. 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

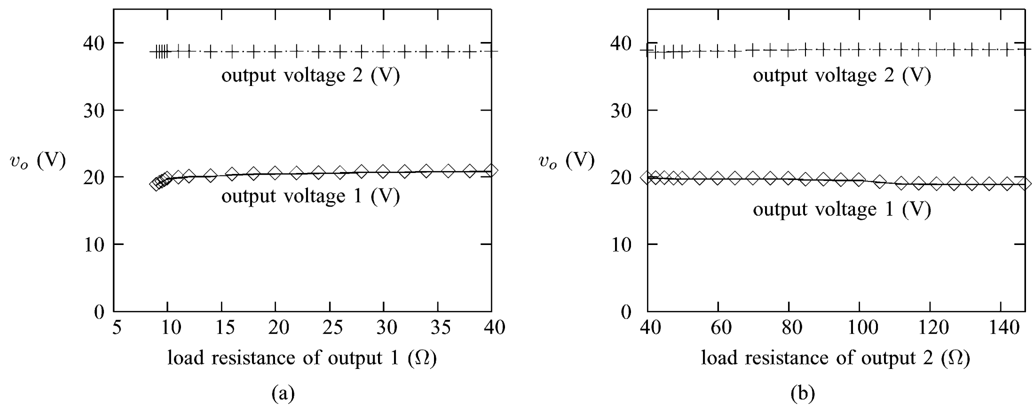


Fig. 5. (a) Experimentally measured steady-state output voltages versus load variation in output 1, with the load at output 2 fixed at 60 Ω and (b) experimentally measured steady-state output voltages versus load variation in output 2, with the load at output 1 fixed at 10 Ω.

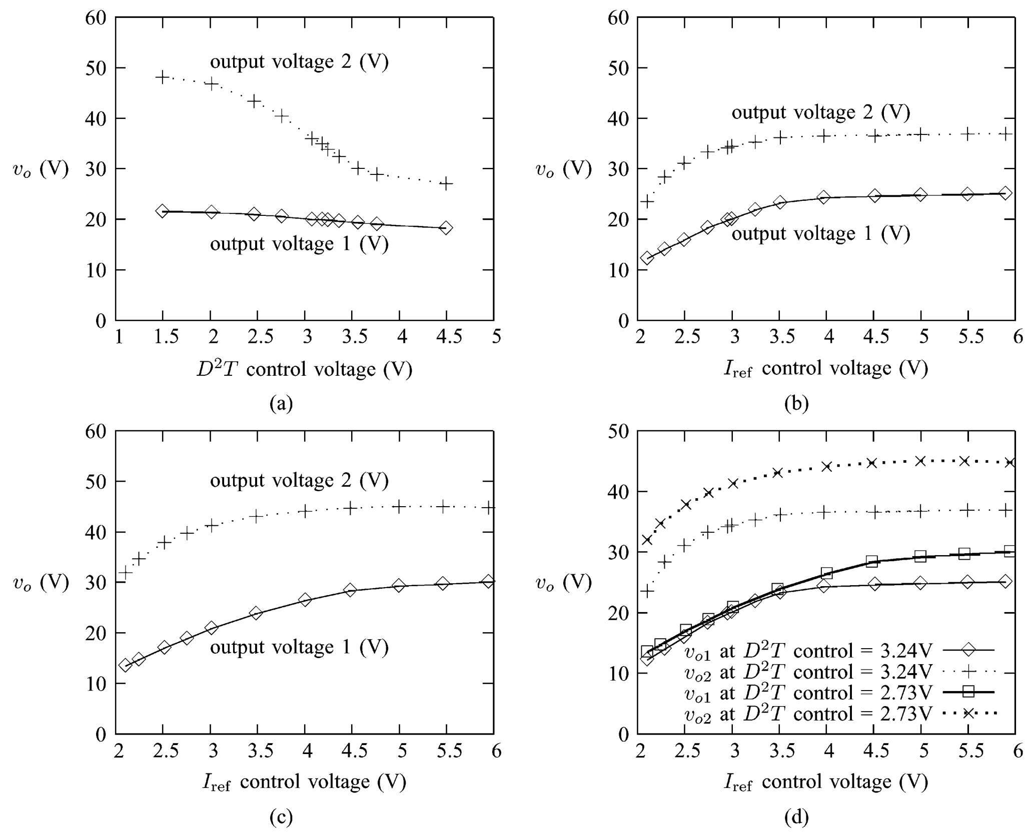


Fig. 6. Experimentally measured control-to-output transfer characteristics. (a) Outputs versus control voltage of D^2T when control signal of $I_{\rm ref}$ =2.96 V, (b) outputs versus control signal of $I_{\rm ref}$ when control signal of D^2T =3.24 V, (c) outputs versus control signal of $I_{\rm ref}$ when control signal of D^2T =2.73 V, and (d) comparison of outputs versus control signal of $I_{\rm ref}$ at two different values of control signal of D^2T.

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 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

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

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.

$$\frac{T_1^2}{T_1 + T_2} = \text{constant} \quad (6)$$

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

$$\frac{\delta T_1}{\delta T_2} = \frac{2 - D}{D}. \quad (7)$$

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

$$\frac{\delta i_2}{\delta i_1} = \frac{m_c + m_1 \frac{D}{2-D}}{m_c + m_2} = \frac{m_c + m_2 \frac{1-D}{2-D}}{m_c + m_2}. \quad (8)$$

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

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

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 [10].

IV. Application to Two-Output Boost Regulator: Experimental Verification

A. Circuit Description

In this section we present a single-switch two-output boost regulator, as outlined previously in the Introduction. Figs. 3 and 4 show the schematic of the system and the detailed circuit of the D^2T controller, respectively. 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 *et al.* [1]–[3]. 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 with an experimental prototype. In the experiment, discrete components are used to construct the the D^2T control block, as shown in Fig. 1(b). Component and parameter values of the prototype are summarized in Table I.

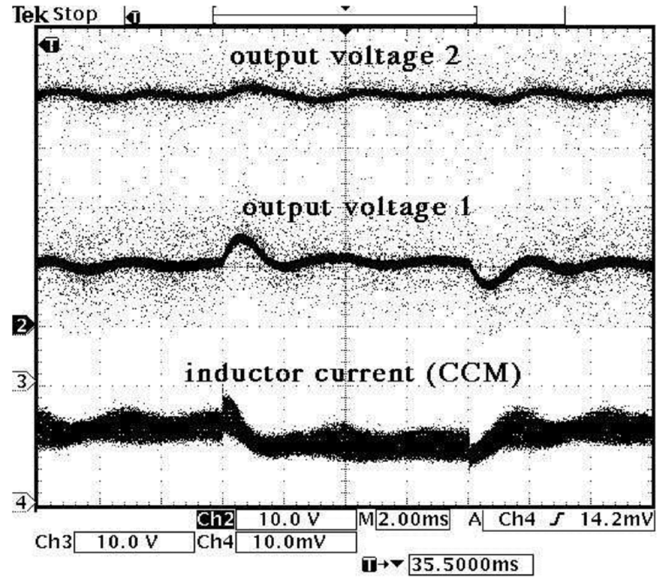


Fig. 7. Output transient responses for step changing input voltage. At $t = 6$ ms, $V_{\rm in}$ steps up from 12 V to 16 V, and at $t = 14$ ms, it steps down back to 12 V. Vertical scale: 10 V/div and 2 A/div. Horizontal scale: 2 ms/div.

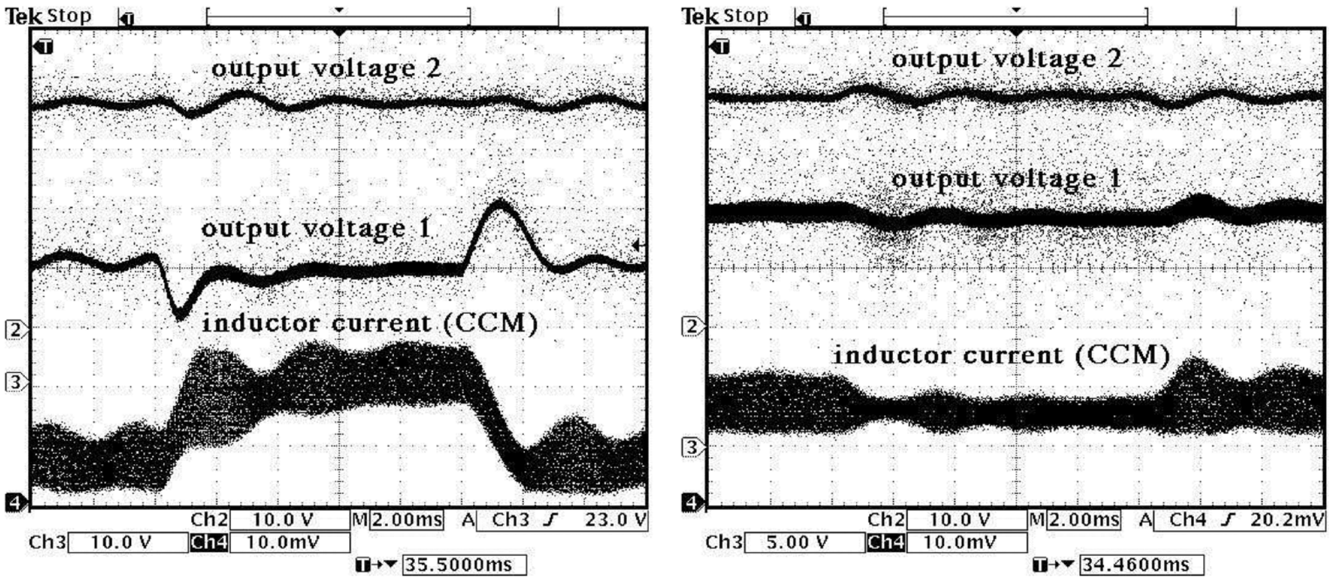
It is worth noting that the inductor current of the CCM converter is referenced at the turn-on instant, and hence its peak is generally unlimited (actually determined by the D^2T control). It is thus necessary to impose a peak limiter to limit the maximum switching period. This arrangement has been incorporated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

B. Results

Several tests have been performed to verify the operation of the proposed control. First of all, the steady-state output characteristics have been obtained by plotting the output voltages against load variations. Measured results are shown in Fig. 5(a) and (b).

Second, the control to output transfer characteristics are measured for different operating conditions. Typical results are shown in Fig. 6. These results demonstrate the stability of the inner current loop without the use of compensation ramp. Note that although the control-to-output characteristics are not perfectly linear, the application of feedback adequately provides good output regulation, as shown previously in Fig. 5.

Finally, the transient performance has been evaluated, including input regulation, load regulation and cross regulation. Results are shown in Figs. 7 and 8. In Fig. 7, the transient responses are recorded when the input voltage is stepped. In Fig. 8, the transient responses are recorded when the load resistances are stepped. Note that Fig. 8(a) and (b) reflect very satisfactory self load regulation performance as well as cross



(a) (b)

Fig. 8. (a) Experimentally measured transient responses for step changing loads with R_{o1} changing from 10 Ω to 35 Ω at t =4 ms, and back to 10 Ω at t =14 ms and (b) transient responses for step changing loads with R_{o2} changing from 50 Ω to 100 Ω at t =4.2 ms, and back to 50 Ω at t =14.2 ms. Vertical scale: 10 V/div and 2 A/div. Horizontal scale: 2 ms/div.

regulation performance, i.e., transient of v_{o1} (or v_{o2}) when R_{o2} (or R_{o1}) is stepped.[1]

V. 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. The simplicity of the control scheme allows easy integration in on-chip dc voltage regulators.

Acknowledgment

We wish to thank K.-C. Tang for his able assistance in the construction of the circuit prototype and the experimental measurements, and G. Koon, for her study of stability of an early version of the control scheme.

[1]The essential control applied to both converters is current-mode control. The small-signal characteristics of current-mode control have been extensively reported in the literature, and will be omitted in this paper. See, for example, [11]–[15].

References

[1] J. Sebastián and T. Veeda, "Double converter: A fully regulated two output dc-to-dc converter," in *Proc. IEEE PESC*, 1985, pp. 117–126.
[2] J. Sebastián, J. Uceda, M. Rico, M. A. Pérez, and F. Aldana, "A complete study of the double forward-flyback converter," in *Proc. IEEE PESC*, 1988, pp. 142–149.
[3] T. Charanasomboon, M. J. Devaney, and R. G. Hoft, "Single switch dual output dc/dc converter performance," *IEEE Trans. Power Electron.*, vol. 5, no. 2, pp. 241–245, Mar. 1990.
[4] P. T. Tang and C. K. Tse, "Design and implementation of a fully-regulated four-output two-switch one-controller power module," in *Proc. IEEE PESC*, Jun. 1996, pp. 823–828.
[5] D. Ma, W. H. Ki, C. Y. Tsui, and P. K. T. Mok, "Single-inductor multiple-output switching converters with time-multiplexing control in discontinuous conduction mode," *IEEE J. Solid-State Circ.*, vol. 38, no. 1, pp. 89–100, Jan. 2003.
[6] C. F. Lee and P. K. T. Mok, "A monolithic current-mode CMOS DC-DC converter with on-chip current-sensing technique," *IEEE J. Solid-State Circ.*, vol. 39, no. 1, pp. 3–14, Jan. 2004.
[7] R. Redl and N. O. Sokal, "Current-mode control, five different types, used with the three basic classes of power converters," in *Proc. IEEE PESC*, 1985, pp. 771–775.
[8] Q. Chen, F. C. Lee, and M. M. Jovanović, "Current-mode control for multiple-output converters," *IEEE Trans. Aerospace Electron. Syst.*, vol. 32, no. 4, pp. 1412–1420, Oct. 1996.
[9] *Modern Switching DC-to-DC Power Converter Circuits*, 1985.
[10] A. S. Kislovski, "Current-mode control: A unified model for open-loop instability," in *Proc. IEEE Applied Power Electron. Conf. Expo*, 1991, pp. 459–465.
[11] Q. Chen, F. C. Lee, and M. M. Jovanović, "Small-signal modeling and analysis of current-mode control for multiple-output forward converters," in *Proc. IEEE PESC*, 1994, pp. 1026–1033.
[12] Y. T. Chen, D. Y. Chen, and Y. P. Wu, "Small-signal modeling of multiple-output forward converters with current-mode control," in *Proc. IEEE PESC*, 1994, pp. 1019–1025.
[13] R. B. Ridley, "A new continuous-time model for current-mode control with constant frequency, constant on-time, and constant off-time, in CCM and DCM," in *Proc. IEEE PESC*, 1990, pp. 11–14.
[14] G. C. Verhgese, C. A. Bruzos, and K. N. Mahabir, "Averaged and sampled-data models for current mode control: A re-examination," in *Proc. IEEE PESC*, 1989, pp. 26–29.
[15] M. K. Kazimierczuk, "Transfer function of current modulator in PWM converters with current-mode control," *IEEE Trans. Circuits Syst. I*, vol. 47, no. 9, pp. 1407–1412, Sep. 2000.

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