A Monolithic Buck Converter With Near-Optimum Reference Tracking Response Using Adaptive-Output-Feedback

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Abstract—A monolithic output-ripple-based buck converter with adaptive output and ultra-fast reference tracking is presented. Fixed-switching-frequency V^2 -control is used in steady-state operation; while its speed limitation during reference tracking is eliminated by employing end-point prediction, a novel oscillator with clock-holding function, and the proposed adaptive-output-feedback (AOFB)-scheme. The AOFB-scheme is obtained from a detailed analysis of the dynamics of general output-ripple-based controller during reference tracking. Then, an adaptive feedback voltage which satisfies the switching criterion for optimum switch control in reference tracking is formulated, and is incorporated into the controller design. The resultant single ON/OFF-switching during reference tracking is very close to the optimal solution for fast reference tracking. Moreover, it also leads to the lowest switching loss and minimized conduction loss at the fastest tracking speed, making the converter very suitable for adaptive-output applications.

Fabricated in a 0.35 μm CMOS process, the 3-V input prototype chip exhibits stable operation across a wide output range of 0.7–2.4 V. High tracking speed within 10 $\mu\text{s}/\text{V}$ is measured with different output voltages and output voltage steps. Maximum efficiency of 96% is obtained at 260 mA output current, while maximum output current is 800 mA.

Index Terms—Dynamic voltage scaling, end-point prediction, output-ripple-based control, reference tracking, V^2 -control.

I. INTRODUCTION

THE prevalence of battery-operated portable devices like cellular phones and media players creates a great demand for high-quality switching DC-DC converters. The desirable qualities generally include high efficiency, small volume, tight static and dynamic regulations, and low EMI noise. Regarding efficiency, a recent low-power VLSI technique namely dynamic voltage scaled (DVS) calls for a new type of “adaptive power supply” [1]–[5], which requires its output voltage to track the reference voltage when the latter has a step change. As a result, two new parameters, namely transition (tracking) time and transition energy, are introduced to characterize the power supply’s performance on speed and energy conservation during reference tracking [4]. Obviously, too long transition time may reduce energy saving of a DVS system or adds considerable latency to resume high-speed operation. Meanwhile, too large

transition energy adds significant overhead to the energy saving by DVS.

Unfortunately, few literatures discuss the performance of switching converters (using different control methodologies) applied in a DVS system in detail. There are some recent works [6], [7] discussing the design of controller for DVS; but all of them are digital controllers, which usually involves large and sophisticated look-up tables and digital structures typically not familiar to analog circuit designers. On the other hand, output-ripple-based control, e.g., hysteretic and V^2 [8]–[10], which exhibits the fastest load transient response among common analog controls, remains rarely explored regarding to their performance in a DVS system. This paper aims to bridge this gap by considering a V^2 -controlled buck converter. V^2 -control is chosen because of its tight regulation and fixed switching frequency [9], [10]. After a close examination of its circuit structure and the ideal dynamics during reference tracking, the conventional V^2 -control is found to have poor transition time. Hence, a buck converter based on a modified V^2 -control is proposed in this paper. By using the end-point prediction (EPP) scheme [11], a novel oscillator with clock-holding function, and the proposed adaptive-output-feedback (AOFB) technique, the proposed buck converter achieves an ultra-fast reference tracking speed for a wide range of reference transition scenarios under different output voltages and voltage steps. Not only does the converter achieve the fastest tracking time, but also has the two unique characteristics during reference tracking: absence of overshoot/undershoot in output voltage and inductor current, and minimum number of switching activities (single ON/OFF-switching). These features reduce the conduction loss and minimize the switching loss during tracking period, thus transition energy is also considerably conserved under the condition of fastest transition time.

This paper is organized as follows. Section II reviews the conventional fixed-frequency V^2 -controlled buck converter and its limitation. Section III presents the improved reference tracking performance using the EPP scheme and its pitfall. Section IV analyzes the dynamics during reference tracking, which leads to the need for a novel oscillator design and the proposed AOFB-scheme. Circuit implementation of major building blocks is discussed in Section V. Section VI presents the measurement results and compares with state-of-the-art adaptive DC-DC converters.

II. REVIEW OF V^2 -ARCHITECTURE

Fig. 1 shows the conventional fixed-frequency V^2 -architecture [9]. It has two distinct characteristics different from

Manuscript received January 29, 2007; revised June 29, 2007. This work was supported in part by the Research Grant Council of Hong Kong SAR Government under Project 617705.

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Digital Object Identifier 10.1109/JSSC.2007.907169

Fig. 3. Simulated reference down-tracking of V^2 architecture with EPP.

when clock is issued as soon as $V_{\text{pwm_rmp}} < V_{\text{pwm_rf}}$ at t_1 (design of this clock circuit is covered in Section V). It can be concluded that end-point prediction speeds up tracking, but it does not guarantee proper reference tracking (e.g., absence of undershoot/ overshoot). Fig. 3 shows that direct comparison of PWM ramp signal and PWM reference signal is not a good criterion for determining switching activities during reference tracking. The dynamics behind reference tracking will be thoroughly analyzed in next section to formulate the criterion for proper reference tracking.

V_o undershoot during reference tracking should be avoided as it increases the transition time, and most importantly, affects the reliability of the digital circuits due to the lower supply voltage. Other adverse effects shown in Fig. 3 are too low i_L at t_1 and the following i_L overshoot for replenishing the lost charge in C_o . Both of these effects increase conduction loss during transition and should be avoided.

IV. PROPOSED AOFB SCHEME

The model in Fig. 4 is used to derive the condition for optimum reference tracking in general output-ripple-based controller. Reference tracking starts at t_0 and ends at $t_1 + t_2$ ($t_0 = 0$ for easy discussion). Steady state current ripple in i_L is neglected as it is small compared with the peak change of i_L ($\Delta i_{L,\text{rf}}$) during reference tracking. Thus, the steady-state V_o ripple is also neglected. V_{C_o} is the voltage across C_o , which is V_o before reference tracking, and $V_o - \Delta V_o$ after reference tracking. Assuming load current i_{ld} is unchanged, i_L equals i_{ld} before and after reference tracking. The optimum reference tracking happens when i_L experiences a straight decrease from t_0 to t_1 (period A), followed by a straight increase from t_1 to $t_1 + t_2$ (period B) back to its original level, such that V_{C_o} moves down by ΔV_o at $t_1 + t_2$ (single ON/OFF-switching) [6]. This is equivalent to using a near-triangular i_L profile to remove the charge of $C\Delta V_o$ in $t_1 + t_2$ seconds. i_L profile is not strictly triangular as the slope of i_L in periods A and B are not constant but depends on a varying quantities $V_o(t)$. However, for deriving an optimum reference tracking criterion that is useful

for design purpose, the average slope in periods A and B can be defined as

$$-m_2 = \frac{-V_{o,\text{eff}}}{L} \quad (2)$$

$$m_1 = \frac{V_i - V_{o,\text{eff}}}{L} \quad (3)$$

where $V_{o,\text{eff}}$ is around the middle value between V_o and $V_o - \Delta V_o$. Then, since the decrease of i_L in period A is equal to the increase of i_L in period B, we have

$$m_2 t_1 = m_1 t_2. \quad (4)$$

Making use of the fact that the shaded area represents the removed charge $C\Delta V_o$, and (2)–(4), optimum time for switching power-MOSs (t_1) can be derived as

$$t_1 = \sqrt{\frac{2C_o L (1 - D) \Delta V_o}{V_{o,\text{eff}}}} \quad (5)$$

where $D = V_{o,\text{eff}}/V_i$. It can be seen that the relation between t_1 and many quantities like D and ΔV_o is very sophisticated. There is no simple way to directly compute t_1 using simple circuits, unless a large look-up table implemented in digital FPGA (which is the approach used in previous works [6], [7]). Moreover, the previous work [6] did not implement a controller to close the loop for output regulation. Thus, the possibility of incorporating the above criterion into controller design needs to be investigated. Since the switching criterion in V^2 -control is $V_{\text{pwm_rmp}} < V_{\text{pwm_rf}}$, the change of $V_{\text{pwm_rmp}}$ at t_1 is derived as

$$\Delta V_{\text{pwm_rmp}}(t_1) = b \{ \Delta V_{R_c}(t_1) + \Delta V_{C_o}(t_1) \} \quad (6a)$$

$$= b \left\{ R_c m_2 t_1 + \frac{1}{C_o} \int_0^{t_1} (m_2 t) dt \right\} \quad (6b)$$

$$= b \left\{ R_c \sqrt{2C_o \Delta V_o m_2 (1 - D)} + (1 - D) \Delta V_o \right\} \quad (6c)$$

where (6c) is obtained by substituting (5) and (2). Given that $\Delta V_{\text{pwm_rf}} \approx b \Delta V_o$, we propose to add the following adaptive-output-feedback-voltage to $V_{\text{pwm_rmp}}$ in period A:

$$V_{\text{aofb}} = -k \cdot D \Delta V_o \quad (7)$$

where

$$k = b \left[1 - R_c \sqrt{\frac{2C_o m_2 (1 - D)}{D^2 \Delta V_o}} \right]. \quad (8)$$

The effect is like adding an adaptive voltage V_{aofb} to V_{fb} to meet switching criterion ($V_{\text{pwm_rmp}} < V_{\text{pwm_rf}}$) at t_1 . Fig. 5 illustrates this idea. At t_0 when $V_{\text{pwm_rf}}$ transits, V_{aofb} is added to $V_{\text{pwm_rmp}}$, so that switching occurs at t_1 and V_o settles properly; otherwise, switching may happen at a later time (t_1') and V_o undershoot may occur. Finally, it should be noted that V_{aofb} is removed from $V_{\text{pwm_rmp}}$ at $t_1 + t_2$ when i_L returns to steady-state level; otherwise, $V_{\text{pwm_rmp}}$ will experience an offset in steady-state.

Fig. 8. Proposed oscillator with clock-holding function.

V. CIRCUIT IMPLEMENTATION

Fig. 7 shows the proposed buck converter. EPP, a novel oscillator, and AOFB scheme are the new features. They are described in details in the following sections.

A. Proposed Oscillator

In the trailing-edge modulated converter, the logic is set by a periodic clock signal, while the reset input is the output of PWM comparator. In reference up-tracking, a reset signal can be issued instantly after the switching criterion is fulfilled. However, in reference down-tracking, the logic can only be set at the next clock following the optimum switching time. Hence, delay occurs. A novel oscillator with clock-holding function is thus proposed to optimize reference down-tracking.

Fig. 8 shows the proposed oscillator and its timing diagram. In steady-state, its operation is the same as a previous work [12]. Yet, during reference down-tracking, its clock can be held high until optimum switching time determined by AOFB-scheme. In the timing diagram, V_{rf_sc1} down-transits at t_a , so that PWM comparator output, V_{rst} , turns high. When the next clock pulse (clk) comes at t_b , Hld_clk turns high. Then the oscillator enters the “clock-holding” state by stopping the feedback of clk to M_{sh} , turning M_{sh} off and clamping V_{tmp} to v_m which is around middle of v_h and v_l (the upper and lower bounds of ramp signal). Hence, V_{tmp} stays in between v_h and v_l , and keeps clk to stay high when Hld_clk is high. Due to the reset-dominant nature of the logic, the converter stays in reset state regardless of the clock. This clock-holding state lasts until V_{rst} turns low

at t_c (i.e., $V_{pwm_tmp} < V_{pwm_rf}$). Then, Hld_clk is cleared, and the oscillator resumes its operation, with V_{tmp} ramping down to v_l and resetting clk at t_d . Since clk remains high at t_c (and until t_d) when optimum switching criterion is fulfilled, the logic is set instantly without the delay in conventional oscillator.

B. AOFB Implementation

Fig. 9 shows the main components inside AOFB-generator. Section IV showed that circuits extracting V_{rf_sc1} transition time, steady-state i_L , duty-ratio, and V_{rf_sc1} step size are required. They are implemented in simple circuits as described below.

V_{rf} -transition-detector comprises two comparators to detect the sudden transit of V_{rf_sc1} (i.e., start of reference tracking). Offset is built into the comparators to prevent false alarm. This detector is needed for an external analog V_{rf_sc1} signal and can be removed if the command of reference transition is provided by digital load. Two outputs of the detector, Rf_dn_dt and Rf_up_dt, trigger T_{Rf_trn} logic to start the process of reference down- and up-tracking, respectively.

T_{Rf_trn} logic marks the start and the end of the reference tracking. The process of reference tracking is signaled by the active high “Rf_trn” and is ended by inductor current i_L returning to its original steady-state ($t_1 + t_2$ in Fig. 5). The time instant $t_1 + t_2$ is detected by the following mechanism: a sample-and-hold (S/H) following a forward inductor current sensor (shown in Fig. 7) periodically samples the inductor current value at steady-state. When Rf_trn turns high, S/H holds the inductor current value before reference tracking and this value is compared with

Fig. 9. Main components in AOFB-generator.

the contemporary inductor current to determine when i_L returns to its original value. When this happens, it is signaled by “ $i_{L_hi_ave}$ ” and its complement. The current sensors used are similar to a previous work [13] for its simplicity, accuracy, and ability to sense in the conduction periods of both power transistors. Both forward- and reverse- i_L over-current protections are done (using signals “ i_{L_hi} ” and “ i_{L_low} ” in Fig. 7) since large forward and reverse inductor currents are necessary for fast reference tracking.

Duty-ratio generator generates duty-ratio D and its complement $1 - D$, which are used in reference down- and up-tracking, respectively. They are obtained by two sets of cascaded 4-stage low-pass filter acting on the pre-buffered switch gate-drive signal pg' . The outputs are then selected by Rf_dn and Rf_up .

The analog core of AOFB-scheme is shown in Fig. 10. The multiplier of duty-ratio and reference step size is a simple switched-capacitor circuit making use of the principle that charge being the product of current and time. Hence, the ΔV_{rf} -extractor is a V-I converter that outputs constant current, which is proportional to ΔV_{rf_scl} ; while duty-ratio is translated to time by a voltage-to-time converter (V-T converter). Their operations are explained as follows.

In steady-state, M01-M06 in ΔV_{rf} -extractor conducts current of $V_{rf_scl}/R\Delta_{vrf}$ so that C_{hd} samples information of V_{rf_scl} . At t_0 when Rf_trn turns high, switch $sw1$ opens and original V_{rf_scl} information is held in C_{hd} . Then, M03 keeps sourcing previous current while M06 sinks current corresponding to new V_{rf_scl} . Difference between these two currents is injected into C_{aofb} in multiplier via T_{mult} switch when T_{mult} remains high. T_{mult} is modulated by V-T converter such that it is a pulse that starts when Rf_trn goes high, and its duration is directly proportional to the output of the duty-ratio generator, V_{dr} . The multiplier's output (V_{aofb}) is reset to v_l in steady-state, and it only

performs multiplication when Rf_trn is high. It can be proved that after the T_{mult} pulse, change of V_{aofb} is given by

$$\Delta V_{aofb} = \frac{b\Delta V_o V_i DC T_{mult}}{R\Delta_{vrf} C_{aofb} I_k} \propto D\Delta V_o. \quad (9)$$

Thus, the circuit implements AOFB-scheme, in which parameters V_i , C_{aofb} , C_{Tmult} , $R\Delta_{vrf}$, and I_k determine k in (7). Meanwhile, in this design the duration of reference tracking (i.e., $t_1 + t_2$) is around a few microseconds, while the time to the optimum switching time (t_1) can be less than two microseconds. Hence, another constraint of design is $T_{mult} < 0.5 \mu s$ so that multiplication ends before switching time t_1 . At $t_1 + t_2$ when Rf_trn turns low, the process of reference tracking is over, and V_{aofb} is reset to v_l . The addition of V_{aofb} to V_{pwm_rmp} is via voltage-to-current converter (similar to [12]) with one input being V_{aofb} and another input being v_l . Thus, both positive and negative ΔV_{aofb} additions can be done which are required in reference up- and down-tracking, respectively. All of the AOFB circuits, including current sensors, are integrated on-chip.

VI. EXPERIMENTAL RESULTS

The proposed buck converter was implemented in AMS 0.35 μm CMOS process. Fig. 11 is the die photo of the prototype, which has a dimension of $1.65 \mu m \times 1.1 \mu m$, including pads. The prototype works with input voltages ranging from 1.8 V to 3.3 V, while inductor and output capacitor chosen to be 4.7 μH and 9.4 μF (with 0.1 Ω ; ESR), respectively. Unless otherwise stated, all of the following results are obtained using input voltage of 3 V, and resistive load. Table II shows the static performance summary of the prototype; in particular, the tight load regulation of 1.25 mV/A is due to the high open-loop gain of the amplifier (~ 60 dB); while about half of output ripple voltage (~ 18 mV) is due to equivalent series inductance (ESL)

Fig. 10. Schematic and timing diagram of analog core of AOFB-generator.

Fig. 11. Die photo of proposed V^2 -controlled buck converter.

on PCB. Fig. 12 shows the measured efficiency, which has a maximum of 96% at 260 mA load current.

Fig. 13 shows the measured load transient. At $V_o = 1.8$ V, a load current step of -700 mA can be settled in only $3 \mu\text{s}$. The clock-holding function is verified as it is noted that Hld_clk stays high during V_o slewing down; and as soon as it turns low, a clock pulse is issued so that i_L increases instantly without delay. The response of a positive load current step is similarly fast, so it is not shown here for limited space.

Fig. 14 shows the measured reference up-tracking of V^2 -architecture with EPP. Undesirable effects including overshoot

Fig. 12. Measured power conversion efficiency of the prototype.

of V_o , too large peak i_L and its subsequent undershoot are seen. As a comparison, Fig. 15 shows the case when AOFB-scheme is employed. The addition and removal of V_{aofb} on V_{pwm_rmp} is clearly seen on the buffered V_{pwm_rmp} test signal. As a result, all of the above undesirable effects are removed and the benefits of lower transition energy and an ultra-fast transition time, t_{rf_tk} , of $4 \mu\text{s}$ are achieved. The comparison in reference

TABLE II
SUMMARY OF STATIC PERFORMANCE OF THE PROTOTYPE

Technology	AMS 0.35- μm CMOS process
Switching frequency	1MHz
Input voltage	1.8V to 3.3V (nominal 3V)
Maximum output current	800mA
Power conversion efficiency	max. 96% @ $V_o = 2.1\text{V}$
Line regulation	9mV/V @ $V_o = 1.5\text{V}$
Load regulation	1.25mV/A
Output voltage range	0.7V – 2.4V
Output ripple voltage	35mV @ $V_o = 1.8\text{V}$
Chip area	1.65mm x 1.1mm (including pads)

Fig. 13. Measured load transient ($V_o = 1.8\text{V}$, load current from 760 mA to 60 mA).

Fig. 14. Measured reference up-tracking of V^2 with EPP only (V_o : 0.9 V – > 1.17 V).

down-tracking between V^2 -control with and without AOFB is similar and is not detailed here for brevity.

Figs. 16–19 shows the measured reference tracking of AOFB- V^2 -architecture under different V_o s (i.e., different D s) and ΔV_o s using the worst case k -value as mentioned in Section IV. As expected, no undershoot/ overshoot of V_o is seen and the over-designed k -value only slows down the non-worst-case (i.e., smaller ΔV_o or lower D in reference down-tracking/higher D in reference up-tracking) a little bit. In all cases, reference tracking finishes in 5 μs for steps as large

Fig. 15. Measured reference up-tracking of V^2 with EPP & AOFB (V_o : 0.9 V – > 1.17 V).

Fig. 16. Measured reference up-tracking (same ΔV_o , different D s).

Fig. 17. Measured reference down-tracking (same ΔV_o , different D s).

as 500 mV. Larger step requires higher peak i_L exceeding the over-current limit, which turns the optimum near-triangular i_L profile into a chopped one. As this is not the case of optimum reference tracking, the result is not shown here. Yet, the prototype still undergoes larger step reference tracking with a sub-optimum speed limited by maximum i_L .

Table III shows the comparison of this work and some prior adaptive converters. Typically, the figure-of-merit, $t_{\text{rf-tk}}/\Delta V_o$, is used as a measure of tracking speed. Yet, as shown in Section IV, optimum tracking time scales with $\sqrt{LC_0}$, which

TABLE III
COMPARISON OF ADAPTIVE SWITCHING CONVERTERS.

Design	[4]	[14]	[15]	[16]	[17]	This Work
FOM _{conventional} ($\mu\text{s}/\text{V}$)	26.92	292	80	12.25	41.67	10
FOM _{ctl} ($1/\sqrt{V}$)	8.54	14.6	4.42	2.73*	35.64	1.06
Output range(V)	1.2-3.8	0-0.5	1.1-2.3	0.9-2.5	1.3-1.9	0.7-2.4
Max efficiency (%)	90	92	95	93.7	N/A	96
CMOS process (μm)	0.6	0.35 SOI	0.25	0.5	N/A	0.35
Area (mm^2)	5.44	6	1.43	2.31	N/A	1.815

* L, C_o estimated from steady-state ripple voltage and current

Fig. 18. Measured reference up-tracking (different ΔV_o s, same D).

Fig. 19. Measured reference down-tracking (different ΔV_o s, same D).

is an indicator of the power stage's speed and $\sqrt{\Delta V_o}$, but not ΔV_o . Hence, we propose a new figure-of-merit to reflect the actual reference tracking speed of the controller:

$$\text{FOM}_{\text{ctl}} = \frac{t_{\text{rf-tk}}}{\sqrt{\Delta V_o LC_o}}. \quad (10)$$

It should be noted that the unit of FOM_{ctl} is $1/\sqrt{V}$ as tracking time is normalized by the time constant of power stage. The proposed AOFB- V^2 -architecture achieves the lowest FOM_{ctl}, i.e., the fastest transition speed of the controller compared to prior arts.

VII. CONCLUSION

A high-performance V^2 -controlled buck converter suitable for DVS applications is presented and proven by experimental results. In addition to the original merits of V^2 -control including easy compensation, fast load step response, tight regulation, and fixed switching frequency, performance metrics important for DVS systems like fast tracking time, low switching loss and conduction loss during reference tracking are also achieved thanks to the employment of end-point prediction, a novel oscillator and the proposed AOFB-scheme. The dynamics of reference tracking is analyzed, and the criterion for optimum reference tracking is introduced, which can also be extended to other output-ripple-based converters such as hysteretic control.

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