Integrated Direct Output Current Control Switching Converter using Symmetrically-Matched Self-Biased Current Sensors

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Abstract -- A non-inverting flyback converter using an integrated symmetrically-matched self-biased current sensor was fabricated in a 0.35μm CMOS process. It operates in pseudo-continuous conduction mode and employs a direct output current control scheme to achieve excellent line transient response. The converter switches at 1MHz with an input of 1.2V to 2V to give an output of 1.5V and delivers 250mA.

I. Introduction

The controller of a DC-DC switching converter with voltage feedback is simple, but neither the inductor nor the output current is monitored, and the loop response is slow. Dynamic performance could be enhanced by employing current feedback, but slope compensation for the current loop is required to avoid sub-harmonic oscillation. Switching converters operating in the discontinuous conduction mode (DCM) do not exhibit sub-harmonic oscillation, because the inductor current starts from zero in every switching cycle. By raising the current floor to a non-zero value, the technique of pseudo-continuous conduction mode (PCCM) can be used to enhance the current handling capability [1].

The input voltage of a power converter with multiple sources changes from time to time, and spikes at the output are unavoidable. A control scheme that monitors and controls the output current directly may regulate the output voltage independent of the input voltage. In this paper, a direct output current control non-inverting flyback converter is proposed, and exhibits excellent rejection to abrupt line changes.

II. Direct Output Current Control Converter

The proposed direct output current (DOC) control non-inverting flyback converter operates in PCCM is shown in Fig.1. The supply voltage V_{IN} may vary from 2V down to 1.2V, while the converter maintains an output voltage at V_{OUT}=1.5V. Every switching period is divided into three phases. In Phase 1, switches S_1 and S_3 are closed, charging the inductor at a rate of $di/dt=V_{in}/L$, until it reaches the peak current I_{PK} that is controlled by the output of an error amplifier. In Phase 2, S_2 and S_4 are closed, discharging the inductor at $di/dt=-V_{out}/L$. When the inductor current drops to the predefined freewheeling level I_{FW}, the converter enters Phase 3. In Phase 3, S_2 and S_4 are closed, and the inductor current freewheels at I_{FW} until the period expires. The current flow is shown in Fig.1(a) and the inductor current waveform is shown in Fig.1(b).

Charge is delivered to the output in Phase 2 only, and the average output current is proportional to the shaded area shown in Fig.1(b) that can be controlled by changing I_{PK} through the control loop. Therefore, the output current is directly controlled. If the input voltage changes suddenly, the ramp up slope in Phase 1 is changed. Yet, as both I_{PK} and I_{FW} are not changed in a time frame of one cycle, the shaded area in Phase 2 is not affected (Fig.1(b)). Hence, the output voltage is not disturbed by a sudden change in V_{IN}, and excellent line transient response is achieved.

III. Control Scheme Implementation

The system block diagram of the proposed converter is shown in Fig.2. All switches are MOS transistors. The output voltage is scaled by a resistor string and compared to the reference voltage through a compensation circuit realized by an op-amp. The output of the error amplifier controls the peak inductor current. The functional block Logics & Drivers controls the switching sequence of the power stage. Inductor current information is extracted by sensing the current that passes through transistors M_{N1} and M_{N2} utilizing a MOS transistor scaling technique [2]. By sensing either M_{N1} or M_{N2}, the inductor current can be sensed all the time. It should be noted that in Phase 3 when the inductor current is freewheeling, both M_{N1} and M_{N2} conduct, but M_{N2} is chosen to be sensed such that there is no hand-over problem at the start of Phase 1.

IV. SM Self-biased Current Sensor

A symmetrically-matched (SM) self-biased voltage mirror current sensor (Fig.3) [3, 4] is employed in the design. Using a time-multiplexing technique, the voltage-mirror core can be reconfigured in sensing both the switch and diode currents, and hence, the complete inductor current can be sensed without additional loss. The voltage mirror core consists of M_{1A} to M_{4A} and M_{1B} to M_{4B}. Let switches S_{X2} and S_{Y2} be closed, such that the current of M_{N2} is sensed by M_{S2}, with $M_{N2} : M_{S2} = N : 1$. Consider a large inductor current I_L injected into M_{N2} at node V_{SW2}. With $(W/L)_{1A} = (W/L)_{1B}$, $I_{d1A} = I_{d1B}$ are injected into M_{2A} and M_{2B}. Now, M_{2A}, M_{2B} : M_{4A}, M_{4B} = 1 : M, such that $M_{2A}+M_{4A}$ are matched with $M_{2B}+M_{4B}$, and currents of $(M+1)I_{d2A}$ are injected into M_{N2} and M_{S2}. The matching forces V_Y to be equal to V_X, thus achieving the voltage mirror function, and the current ratio $I_{N2} : I_{S2}$ is N : 1, or $I_{S2} = I_L/(N-1)$. This sensed current is mirrored by M_5 for peak current control (using R_{sen}). The X branch and the Y branch are biased with $I_L/(N-1)$, and hence, the larger the I_L, the larger the bias current, and the faster the voltage mirror. The matching is so accurate that even the large-signal analysis using MOS equation with channel length modulation cannot reveal any difference between the corresponding terminal voltages of any paired transistors. Hence, the sensing accuracy surpasses all prior current sensors. For a sensing ratio of 1000 to 1, an inductor current of 1mA can be sensed accurately. By closing switches S_{X1} and S_{Y1}, the switch current of M_{N1} is sensed by M_{S1}, and

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the same voltage mirror core is reused. Yet, the connections for M_{N1} and M_{N2} are different, as shown in Fig.3, because M_{N1} is sourcing while M_{N2} is sinking the inductor current.

V. Measurement Results

The converter was fabricated and tested. Fig.4 shows the inductor current and the corresponding current sensor output voltage. Complete inductor current information was sensed and scaled accurately at a switching frequency of 1MHz. Fig.5 shows the line transient response. The supply voltage changed by 400mV but the output voltage showed no observable changes. Fig.6 shows the load transient response of the DOC control converter. The output voltage settled in 120µs when the load current changed from 50mA to 250mA, and 60µs when the load current changed from 250mA back to 50mA.

VI. Conclusions

A direct output current control scheme for switching converters in incorporating the current control loop with the pseudo-continuous conduction mode of operation was proposed. The DOC control converter was designed and demonstrated excellent line transient response. An accurate and fully-integrated current sensor is employed. The complete design was realized and verified by measurement results.

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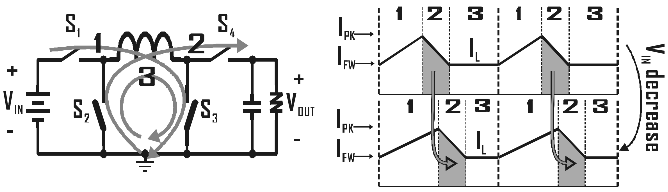


(a) (b)

Fig.1 (a) PCCM flyback converter current flow and (b) corresponding inductor current waveforms

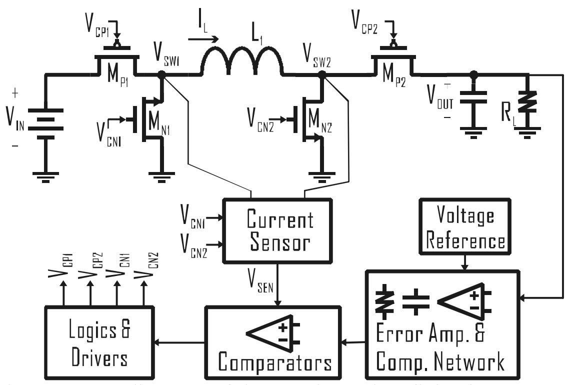


Fig.2 System diagram of the non-inverting flyback converter

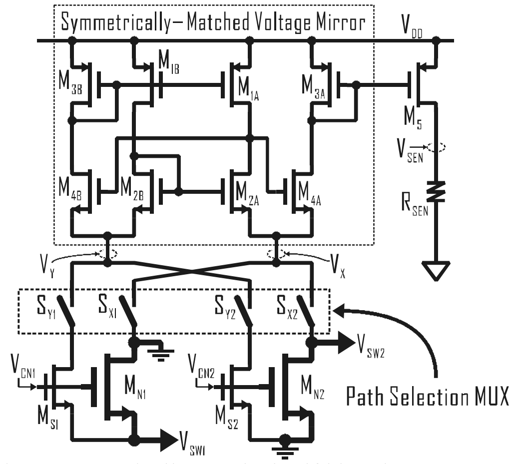


Fig.3 Symmetrically-matched self-biased current sensor

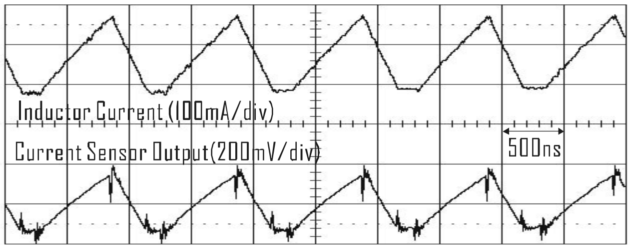


Fig.4 Measured inductor current and sensed current waveforms

Fig.5 Line transient response of DOC control converter

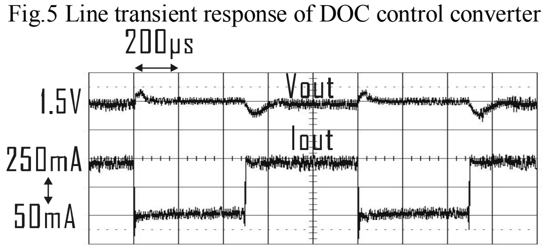
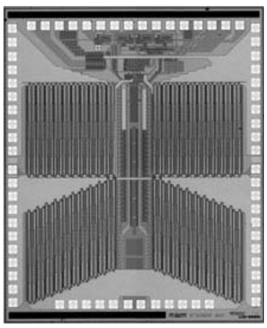


Fig.6 Load transient response of DOC control converter



Die Size	2.46mm × 2.82mm
Technology	0.35µm CMOS 4Metal-2Poly
Inductor	4.7µH (off-chip)
C_{out}	47µF (off-chip)
f_{switch}	1MHz
V_{in}	1.2V to 2V
V_{out}	1.5V
Max. I_{out}	250mA

Fig.7 Converter specifications and chip micrograph