Integrated Single-Inductor Dual-Input Dual-Output Boost Converter for Energy Harvesting Applications

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Abstract— An integrated single-inductor dual-input dual-output (SI DIDO) boost converter for energy harvesting applications was designed in a 0.35 μm CMOS process. It provides two regulated output voltages for the load and the charge storage device, and two sources, the energy harvesting source and the charge storage device, are multiplexed to serve as the input. The implementation has several special features. (1) The input power MUX is driven by an internal charge pump for a larger gate drive to save area. (2) The power stage is implemented with an active diode core to eliminate gate drive circuitry. (3) A 1:7 timeslot scheduling with a fixed peak inductor current is adopted to deliver energy to the two outputs with a large difference in load currents. The proposed converter could operate at 1V with up to 85% efficiency at 200mW.

I. INTRODUCTION

Energy harvesting could provide a micro-sensor application with essentially a lifetime of power source, and there are many power management issues to be solved for efficient energy conversion [1]. When the energy-harvesting source is available, it provides energy directly to the micro-sensor and excessive energy can be stored in a charge storage device (a rechargeable battery or a super-capacitor). Energy can be retrieved from the charge storage device once energy harvesting is interrupted, thus extending the operation time of the micro-sensor. For an intermittent power source, the supply voltage could drop to zero frequently. To deal with this problem, a single-inductor dual-input dual-output (SI-DIDO) boost converter that operates in discontinuous conduction mode (DCM) is designed [2]. When the power source is available, it provides energy to the load (the primary output), as well as charging up a charge-storing device (the secondary output) such as a rechargeable battery. When the power source is absent, the energy harvester (the primary input) will be disconnected from the converter, and the energy storage device (the secondary input) will be multiplexed to serve as the supply voltage to the load through the converter. Depending on the nature of the power source, the inductor may charge up the two outputs with different activation cycles.

II. SYSTEM IMPLEMENTATION

In this research, we assume an energy-harvesting source

with an output voltage of approximately 1V, the nominal rechargeable battery output voltage is 1.2V, and the portable device needs a 2.4V supply. Straightforward implementation of the power management scheme is shown in Fig. 1. The obvious disadvantage is that the power from the power source has to pass through two converters before reaching the load, sacrificing the efficiency.

Fig. 1 Straightforward implementation

Our proposed implementation of SI DIDO boost converter with time multiplexing control loops is shown in Fig. 2 [2]. It needs only one inductor and 5 MOS power transistors. This method reduces area on PCB without greatly sacrificing efficiency when compared with the previous case.

Fig. 2 Implementation with SI DIDO boost converter

The system diagram of the proposed converter is shown in Fig. 3. Both of the two sub-converters are boost converters. Sub-converter A (boost-A) is for the load and sub-converter B (boost-B) is for the rechargeable battery. Let us use boost-A for discussion. The main switch is the power NMOS M_N , and the "diode" is realized by a power PMOS M_{Pa} . Synchronous rectification is achieved not by a dead-time control circuitry for M_N and M_{Pa} , but by employing the active diode technique for M_{Pa} [3]. This self-regulating scheme is best for isolating the control circuitry of sub-converters A and B as much as possible.

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Fig. 3 System diagram of SI DIDO boost converter with control loop

Voltage regulation is realized by sensing the scaled output voltage bV_{oa} and feeds it into a PWM controller. The two feedback loops are multiplexed to the M_N control block to generate the gate drive for M_N . As both sub-converters are designed to work in DCM, the node V_x will exhibit serious ringing when all switches are opened. Hence, ringing suppression technique is employed by shorting the inductor with a C-switch S_{ring} [4]. The two inputs of the main converter are selected through a power multiplexer P_MUX. The power switches are realized by power NMOS instead of power PMOS to save silicon area (Sec. III). Important circuit implementation issues are discussed below.

III. CIRCUIT IMPLEMENTAION

A. Input Power Multiplexer

The input power multiplexer could be implemented with power PMOS. A $0.35\mu\text{m}$ process is used and the threshold voltages are $V_{tn} = |V_{tp}| = 0.7\text{V}$. With an input voltage of 1V to 1.2V, the gate overdrive voltage is only 0.3V to 0.5V, and that would need a very large power PMOS. To save silicon area, we consider using power NMOS that have a higher mobility than PMOS ($\mu_n = 3\mu_p$). The power NMOS are driven by a much higher regulated voltage V_{QP} generated by an on-chip pulse-frequency 5X charge pump. The schematic is shown in Fig. 4. For $V_{QP} = 3.6\text{V}$ and suppose that the original PMOS P_MUX and the proposed NMOS P_MUX are passing the same current with the same $|V_{ds}|$, then

$$\mu_p C_{ox} (W/L)_p (1.2 - 0.7) = \mu_n C_{ox} (W/L)_n (3.6 - 0.7) \quad (1)$$

$$(W/L)_p / (W/L)_n = 17.7 \quad (2)$$

Thus, the size of a power PMOS is 17.7 times the size of an equivalent power NMOS. Including the area consumed by the charge pump, the area saving is 12.5 times if power NMOS are used.

B. 1:7 Time-Scheduling of Sub-Converters

In this application, the energy-harvesting source is available most of the times, and the rechargeable battery only needs to supply energy intermittently. Hence, the SI-DIDO boost converter delivers power to the two outputs with a large difference in load currents. Both sub-converters work in DCM to minimize cross-regulation [5]. The time-scheduling scheme of the inductor currents is shown in Fig. 5, with the system clock switching at $f_s = 1/T$ (300kHz). Seven out of eight pulses are supplying power to the application (V_{oa}), and the eighth pulse to the rechargeable battery (V_{ob}).

Fig. 4 Power multiplexer with 5X charge pump

Fig. 5 Time scheduling for boost-A and boost-B

Fig. 6 Compensation network for boost-A

Fig. 7 Bode Plots of A(s) and h(s) of (a) V_{oa} and (b) V_{ob}

Fig. 8 Bode Plots of T(s)=A(s)h(s) of (a) V_{oa} and (b) V_{ob}

The average power of V_{oa} and V_{ob} are computed to be

$$P_a = V_{oa} \times I_a = \frac{7}{16} \cdot \frac{V_s^2}{L f_s} \cdot \frac{D_{lb}^2 M_b}{M_b - 1} \quad (3)$$

$$P_b = V_{ob} \times I_b = \frac{1}{16} \cdot \frac{V_s^2}{L f_s} \cdot \frac{D_{la}^2 M_a}{M_a - 1} \quad (4)$$

Thus, the maximum power from the converter is

$$P_{total} = P_a + P_b = \frac{1}{16} \cdot \frac{V_s^2}{L f_s} \left[\left(\frac{M_a - 1}{M_a} \right)^2 \frac{M_a}{M_a - 1} + \left(\frac{M_b - 1}{M_b} \right)^2 \frac{7M_b}{M_b - 1} \right] \quad (5)$$

C. Compensation of Sub-Converters

As output V_{oa} and V_{ob} are isolated from each other, they can be treated as outputs of two independent converters. The loop gain of each output is simply the loop gain of a single-input single-output boost converter in DCM, and is given by:

$$T(s) = A(s) \times h(s) \quad (6)$$

$$= A(s) b \frac{2V_o}{V_m(2M-1)} \sqrt{\frac{M-1}{KM}} \frac{1+sR_{ESR}C_o}{1+s\frac{M-1}{2M-1}R_oC_o} \quad (7)$$

where A(s) is the transfer function of the error amplifier with the compensation network, h(s) is the control-to-output transfer function of the converter, b is the scaling factor, R_o is the output loading resistor, C_o is the output filtering capacitor, R_{ESR} is the ESR, V_m is the peak-to-peak voltage of the ramp signal, and K = 2L/R_oT_e, where T_e is the equivalent clock period of the specified output. Thus, assuming T is the period of clock signal, T_e of V_{ob} is 8T. In addition, T_e of V_{oa} is equal to 8T/7, because the pattern of the inductor current related to V_{oa} is periodic, and after averaging the inductor current pattern, T_e is a little bit larger than T, which is 8T/7.

Eq. (7) shows a low frequency pole (-[2M-1]/[(M-1)C_oR_o]) and a high frequency zero (-1/C_oR_{ESR}) in h(s) of each output. To make sure that the sub-converter is stable, compensation by pole-zero cancellation is used, and the amplifier with the associated Type II compensation network is shown in Fig. 6. Assuming that the amplifier has infinite gain, the transfer function is

$$A(s) = \frac{1+sC_2R_2}{s(C_1+C_2)R_1[1+s(C_1 \parallel C_2)R_2]} \quad (8)$$

where the low frequency zero is at -1/C₂R₂, the high frequency pole is at -1/[(C₁||C₂)R₂] and the first pole is at 0. The low frequency pole (-[2M-1]/[(M-1)C_oR_o]) of h(s) changes with the load current, and the low frequency zero (-1/C₂R₂) generated by A(s) is fixed. If the maximum load current is less than 10 times of the minimum load current, the converter is stable for all condition. Fig. 7 and Fig. 8 show how the low frequency zero and the high frequency pole of A(s) compensating the low frequency pole and the high frequency zero of h(s) respectively. The phase margin of converter is 80° and 88° for V_{oa} and V_{ob}.

IV. SIMULATION RESULTS

Functionality and performance of the proposed SI-DIDO boost converter is verified with the post-simulation results. The overshoots of V_{oa} and V_{ob} at startup are 12% and 6% respectively, which is a little bit large, but should be acceptable in most applications, because overshoots only occur for a very short time. Fig. 9 and Fig. 10 show the cross regulation of both outputs. The power level of V_{oa} is much higher than that of V_{ob}. Therefore, the transient of V_{ob} did not affect V_{oa}, but the transient of V_{oa} induced glitches to V_{ob}. However, the proposed converter is well compensated and stable.

Table 1 shows the performance summary of the proposed converter and the efficiency plot (Fig. 11) shows that the efficiency of the SI-DIDO boost converter is 85% with an output current of 30mA at V_{oa} and 10mA at V_{ob}. We also simulated the case when the input voltage of the P_MUX is 1V sourcing a current of 0.8A, then the output voltage of the P_MUX is 0.965V, a reduction of efficiency by 3.5% due to the P_MUX alone. The improvement of the output voltage of the MUX is less than 1% even the size of the power NMOS is doubled.

V. CONCLUSION

An integrated SI DIDO boost converter was developed to cater for an intermittent power source. It consists of two sub-converters providing two regulated outputs for the load and the

Fig. 9 Cross regulation transient response due to change in I_o of V_{ob}

Fig. 10 Cross regulation transient response due to change in I_o of V_{oa}

Fig. 11 Efficiency plot of SI-DIDO boost converter

charge storage device, and the energy harvesting source and the charge storage device are the two inputs that are multiplexed to serve as the input to the sub-converters that power up the load, using only one inductor. Several novel features are implemented. The SI-DIDO boost converter was designed and sent for fabrication using a $0.35\mu\text{m}$ CMOS process. Extensive simulation results confirmed that the SI DIDO converter could choose between two inputs (1V and 1.2V) and give two regulated output voltages, 1.2V at 15mA and 2.4V at 80mA, with no observable cross-regulation. The 2.4V output was for the load, and the 1.2V was for the charge storage device. Ringing suppression circuitry was implemented, and the efficiency of the converter could be as high as 85%.

TABLE I. PERFORMANCE SUMMARY OF SI-DIDO CONVERTER

	Simulation Result
Technology	AMS $0.35\mu\text{m}$ CMOS process
Inductor	$2.2\mu\text{H}$
Filtering capacitor	$30\mu\text{F}$
Switching frequency	300kHz (Clock), 262.5kHz (V_{oa}), 37.5kHz (V_{ob})
Input supply voltages	1V or 1.2V
Output voltages	1.2V and 2.4V
Output ripple voltage	$<42\text{mV}$
Load currents	20mA – 80mA (V_{oa}), 5mA – 15mA (V_{ob})
Line regulation	10.6mV/V (V_{oa})
Load regulation	0.16mV/mA (V_{oa}), 0.2mV/mA (V_{ob})
Load transient response (20mA to 80mA – V_{oa}) (5mA to 15mA – V_{ob})	1ms (V_{oa}) 0.5ms (V_{ob})

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