A hysteretic buck converter with fast transient response

Min Gyu Jeong and Jin Gyu Kang Chang Sik Yoo
Integrated Circuit Lab. Department of Electronic Engineering, Hanyang University
E-mail: cmg3256@hanyang.ac.kr

Abstract - A current-mode hysteretic buck converter is described in which inductor current is sensed by an RC network. The inductor current sensing RC network is reset multiple times per switching clock period. The multiple reset allows the RC network to have time constant much smaller than switching clock period and therefore occupy small silicon area. The multiple reset also removes DC-output offset which is dependent on load current and improves the load transient property. The current-mode hysteretic buck converter is implemented in a 65-nm CMOS process and the converter operates in 0.6~2.0-V output from 3.3-V input with 1.5-A maximum load current. The recovery time for step-up load transient is 3.4-μs under 0.9-A/0.1-μs load change and the measured peak power efficiency is 96.3-%.

Keywords – Current-mode hysteretic buck converter, DC-output offset dependent on load current, Multiple reset operation

I. INTRODUCTION

Recently, as the demand for portable devices increases, the various applications including RF circuit, LED display and memory are integrated on a single chip. Each application requires reliable supply voltage for its performance. Thus, the power management IC (PMIC) is required for providing reliable supply voltage to each application with high power efficiency and high transient speed.

The switched-inductor DC-DC converter is known to provide the best possible power efficiency among various types of DC-DC conversion topologies. The control scheme of the converter determines its general property such as transient response, regulation accuracy and chip-area. The PWM control scheme usually shows slow transient response and requires large chip-area due to its frequency compensation network. Whereas the hysteretic control scheme has area-effective and immediately respond property when a step-up load transient or step-down load transient occurs because it operates only with a hysteretic comparator and no passive frequency compensation network is required. However, for voltage-mode hysteretic control, the output ripple of a DC-DC converter must be large enough, and the output capacitor requires large equivalent series resistance (ESR). To ensure that the converter doesn’t have large output ripple, hysteretic control can be performed with the ramping inductor current waveform of a DC-DC converter. [4]. This type of control technique, called current-mode hysteretic control, is typically implemented with an inductor current sensor, which is usually realized as an RC network across inductor. In the current-mode hysteretic converter, the time-constant of inductor current sensing RC network determines the switching frequency and requires large silicon area for the switching frequency below 1-MHz. Also, the series resistance R_DCR_1 of the inductor causes large DC output error dependent on load current.

Several hysteretic converters have been studied in [1]-[3]. But the converters do not fully resolve those problems. In [1], by adding AC-coupling capacitor, DC-offset is mostly removed. However, the converter requires large chip-area for AC-coupling capacitor and has slow transient response due to the low-pass filtering of βV_0 by R_c and C_c. In [2] and [3], based on error voltage feedback control, DC-offset is removed. But, the converter also has slow transient response due to the integrator for error voltage feedback, especially in large load step change.

This paper discusses a current-mode hysteretic buck converter where the inductor current sensing RC network is reset multiple times per switching clock period. With the multiple reset operation, the inductor current sensing RC network could have much smaller time constant for achieving the same switching frequency. Section II describes architecture of the proposed current-mode hysteretic converter. The circuit implementation and the experimental results are given in section III and IV, respectively. Finally, Section IV concludes this paper.

![Fig. 1. Structure of conventional hysteretic buck converter with current-mode control](image-url)
II. THE PROPOSED CURRENT-MODE HYSTERETIC CONVERTER

Fig. 1 shows the block diagram of the conventional hysteretic buck converter with current-mode control. Its controller is composed of one hysteretic comparator, RC network and the drivers. The feedback signal $V_{FB}$ is locked between hysteretic reference levels $V_H$ and $V_L$ shown in Fig. 2. The converter switches power transistor when $V_{FB}$ touches either $V_H$ or $V_L$. The current-mode hysteretic structure was adopted in Fig.3, which is block diagram of the proposed current-mode hysteretic converter. Unlike the previous works [1]-[3], the power transistors of the proposed hysteretic converter are switched after $V_{FB}$ touches $V_H$ or $V_L$ three times consecutively as shown in Fig. 4. The inductor current sensing RC networks is reset three times by $V_{UP}$ to turn on the nMOS power transistor $M_N$ and reset three times by $V_{DN}$ to turn on the pMOS power transistor $M_P$. When the feedback signal $V_{FB}$ touches either $V_H$ or $V_L$, the capacitor $C_{SEN}$ of the inductor current sensor is shorted and reset, removing the DC-offset problem of RC-network caused by $R_{DCR_L}$. In addition, the multiple-reset of the inductor current sensing RC network would occupy a smaller silicon area, with the time constant $R_{SEN} \times C_{SEN}$ of the inductor current sensor to be much smaller than the switching clock period $T_{SW}(=T_{ON}+T_{OFF})$. The simulated steady-state waveforms of the proposed hysteretic buck converter are shown in Fig. 5 when input voltage $V_{IN}$ = 3.3-V, output voltage $V_{OUT}$ = 2-V and load current $I_{LOAD}$ = 0.5-A. The power transistors of the converter are switched after $V_{UP}$ or $V_{DN}$ is generated three times consecutively. With the multiple-reset operation, the DC-offset which is proportional to load current is removed.
III. CIRCUIT IMPLEMENTATION

A. Driver

The schematic of driver is shown in Fig. 6. To prevent the short through current in the synchronous converter, the dead-time circuit split the duty cycle signal CLK_SWR into two non-overlapping signal VN and VP, which control nMOS power transistor and pMOS power transistor respectively. The dead-time is controlled by capacitance C1 and C2. Charging time and discharging time of which determines non-overlapping time between VN and VP. The dead-time is long enough to ensure that there is no turn on of the nMOS power transistor and pMOS power transistor simultaneously. The inverter chain is used for driving the large gate capacitance of the nMOS power transistor and pMOS power transistor and generates gate driving signal VGL and VGH.

B. Comparator

The schematic of the comparator is illustrated in Fig.7. The performance of the comparator dominantly effects to the output voltage of the hysteretic converter. The comparator adapts two-stage amplifier structure for the fast comparison between two inputs, V_INN and V_INP. In addition, the input transistor for the comparator is based on pMOS that support the input range of the comparator from 0.6-V to 2.0-V in the supply voltage of 3.3-V.

C. Start-up

When the output voltage V_OUT is outside the window defined by V_H and V_L at start-up, for example, either one of the comparator outputs V_UP and V_DOWN is HIGH for a long time but neither V_UP_CNT nor V_DOWN_CNT is generated, meaning no switching of the power transistors. To ensure the switching of the power transistors even at this condition, the start-up block in Fig. 3 generate the pulses V_UPST and V_DOWNST with the comparator outputs V_UP and V_DOWN, respectively when the pulse widths of V_UP and V_DOWN are larger than τ. The magnitude of τ has to be larger than the pulse widths of V_UP and V_DOWN generated during normal operation to avoid the false switching of the power transistors.

IV. EXPERIMENTAL RESULT.

The proposed current-mode hysteretic buck converter has been implemented in a 65-nm CMOS process. The inductor and output capacitor are 2.2-μH and 10-μF, respectively. The converter operates at a 3.3-V input voltage. The output voltage ranges from 0.6-V to 2.0-V with 1.5-A maximum load current. At the step-up load transient from 200-mA to 1.1-A and inclination of 900-mA / 0.1-μs, the output voltage is recovery to desired level in less than 3.4-μs as shown in Fig.8. The measured power efficiency is plotted versus the load current in Fig. 9. The peak power efficiency is 96.3-% when the load current is 300-mA and the output voltage is 2.0-V. The performance of the proposed converter is summarized and compared with other hysteretic converters in Table I.
IV. CONCLUSION

This paper describes a current-mode hysteretic buck converter in which the inductor current is sensed by an RC-network. The multiple-reset of the inductor current sensing RC network reduces silicon area, with the time constant of the inductor current sensor to be much smaller than the switching clock period. In addition, the reset operation removes DC-out offset dependent on load current. The hysteretic buck converter is implemented in a 65-nm CMOS process. The converter operates at a 3.3-V input voltage. The output voltage ranges from 0.6-V to 2.0-V with 1.5-A maximum load current. The peak power efficiency is measured to be 96.3-\%.

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REFERENCES


Min Gyu Jeong received the B.S. and M.S. degrees in electronics and computer engineering from Hanyang University, Korea, in 2013 where he is currently pursuing his Ph.D. degree. His main research interest includes power management integrated circuit and system design.

Jin Gyu Kang received the B.S. and M.S. degrees in electronic engineering from Hanyang University, Korea, in 2014 and is currently working toward the Ph.D. degree at Hanyang University. His main research interest includes power management integrated circuit and system design.

Chang Sik Yoo (S’92-M’00) received the B.S. (with the highest honors), M.S. and Ph.D. degrees in electronics engineering from Seoul National University, Seoul, Korea, in 1992, 1994, and 1998, respectively. From 1998 to 1999, he was a Member of Research Staff at Integrated Systems Laboratory (IIS), Swiss Federal Institute of Technology (ETH), Zurich, Switzerland, where he was involved in the research on CMOS RF circuits. From 1999 to 2002, he was at Samsung Electronics, Hwasung, Korea. Since 2002, he has been an Associate Professor at Hanyang University, Seoul. His research interests include CMOS RF transceiver design, mixed-mode CMOS circuit design, high-speed interface circuit design, and power management IC design. Dr. Yoo is the winner or co-winner of several technical awards including the Samsung Best Paper Bronze Award in 2006 International SoC Design Conference, the Silver Award in 2006 IDEC Chip Design Contest, the Best Paper Award in 2006 Silicon RF IC Workshop, and the Golden Prize for research achievement in the next generation DRAM design from Samsung Electronics in 2002. He is a member of the technical committee of IEEE International Solid-State Circuits Conference (ISSCC), the Very Large Scale Integration (VLSI) Circuits Symposium (SOVC), and the European Solid-State Circuits Conference (ESSCIRC).