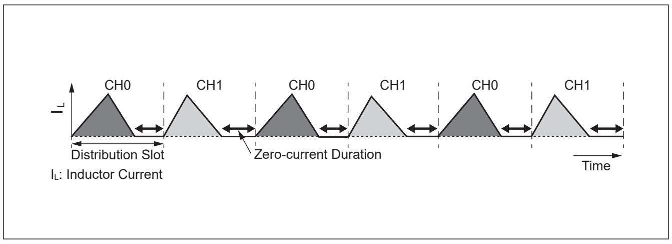
Technical Review Vol.7

SIMO DC-DC Converter with High Efficiency over Wide Load Range for IoT Devices

A wireless sensor node for Internet of Things (IoT) devices is mostly in standby mode, in which its power consumption is less than 1 mW, and only enters active mode intermittently when performing data communication, at which time its power consumption increases to several tens of mW. Hence, single-inductor multiple-output (SIMO) DC-DC converters for IoT devices must achieve high conversion efficiency over a wide range of loads.
In response to this market requirement, Toshiba Electronic Devices & Storage Corporation has been developing a SIMO DC-DC converter equipped with two new technologies: (1) a maximum-on-time (MOT) control technology, and (2) a channel-consolidated multiple-switching (CCMS) control technology. Experiments on a prototype chip fabricated using 65-nm complementary metal-oxide-semiconductor (CMOS) process technology have verified that its peak conversion efficiency is 86.3% and its conversion efficiency over a wide load range from 1 μW to 50 mW is 65.3% or more. The new SIMO DC-DC converter is expected to contribute to lengthening of the operating time of IoT devices powered by coin-type lithium-ion batteries.

1. Introduction

Wireless sensor nodes are being used for various IoT applications. Since the ICs in IoT devices are generally powered by coin-type lithium-ion batteries, low-power operation using minimum supply voltage is required. SIMO-type DC-DC converters (hereinafter abbreviated as SIMO-DCDCs) capable of delivering a range of voltages with only one external inductor and contributing to the reduction in cost and volume of the devices are receiving attention.



(Figure 1) : Inductor current waveform for the case of two outputs in discontinuous conduction mode (DCM)

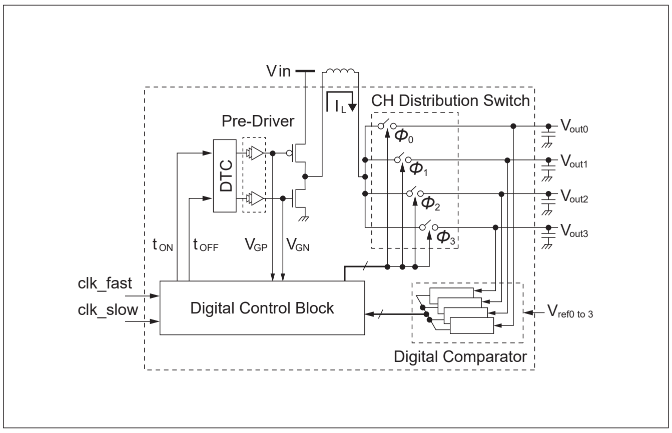
Since wireless sensors often have active and standby modes running at different power consumption levels, SIMO-DCDCs must support a wide load range with high conversion efficiency. In active mode, accurate control of power supply voltage at heavy load is required since the sensing precision decreases with power supply voltage fluctuations. As shown in Figure 1, the discontinuous conduction mode (DCM) can prevent voltage fluctuation by isolating each output channel (CH) of the SIMO-DCDC using the zero-inductor-current duration. As this duration is increased, however, the maximum output power decreases. In standby mode at light load, the power consumption drops to below 1 μW. The sensor node is in standby except for waking up only intermittently to active mode. Thus, the conversion efficiency of the SIMO-DCDC at light load greatly affects battery life. Conventional SIMO-DCDCs not designed for IoT applications are unable to support such a wide load range with practical efficiency [1] [2].

A maximum-on-time (MOT) control technology that raises the upper limit of output power under heavy loads and a channel-consolidated multiple-switching (CCMS) control technology that improves conversion efficiency under light loads are proposed.

This review outlines the SIMO-DCDC and the results evaluated using a prototype on-chip digital control SIMO-DCDC.

2. Overview of the SIMO-DCDC

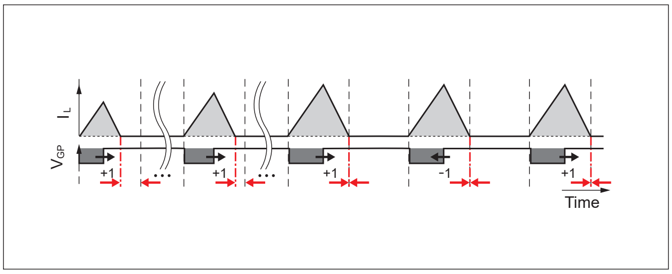
As shown in Figure 2, the SIMO-DCDC under development generates four output voltages (V_{out0} to V_{out3}) from the input voltage (V_{in}). Each of the output voltages is compared with the reference voltage (V_{ref0} to V_{ref3}) by a digital comparator, and when the output voltage falls below the reference voltage, DTC (Digital-to-Time Converter) and the pre-driver operates the PMOS (P-type Metal Oxide Semiconductor) and the NMOS (N-type Metal Oxide Semiconductor) transistors according to the on and off time codes (t_{ON}, t_{OFF}), respectively. Inductor current (I_L) is supplied to one of the CH's in accordance with the drive signal (Φ_0 to Φ_3) of the CH distribution switches for each switching cycle of PMOS and NMOS. In order to maintain high conversion efficiency over a wide load current range, an externally supplied high-frequency clock (clk_fast) and a low-frequency clock (clk_slow) are used, for heavy loads and light loads, respectively.



(Figure 2) : Block diagram of prototype SIMO DC-DC converter

2.1 MOT control technology to improve the upper limit of output power under heavy load

In order to increase the maximum output power of the SIMO-DCDC running in DCM mode, the zero-current duration should be minimized. To minimize the zero-current duration, the on-time is adjusted such that I_L becomes zero at the end of each CH distribution slot. Such a DCM operation is called a boundary conduction mode (BCM). Traditionally, an analog circuit was employed to determine the on-time to operate a DC-DC converter in the BCM operation [3] where the zero-current duration was not directly controlled. Due to process and temperature variations, the zero-current duration fluctuated and could not be minimized.

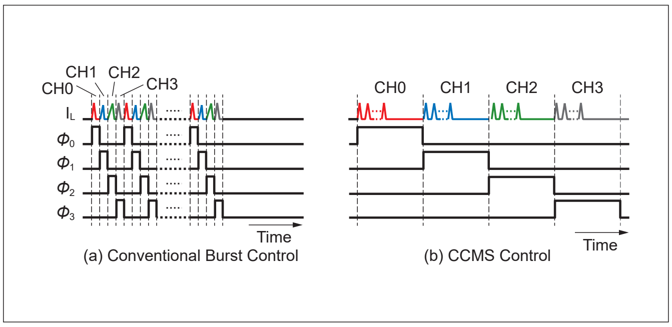


(Figure 3) : MOT control to minimize zero-current duration under heavy load

In order to achieve precise BCM operation, the MOT control technology is developed. As shown in Figure 3, if I_L becomes zero before the boundary of each CH distribution slot, the time code of the ON time is incremented by one step, which is several nanoseconds. On the other hand, if I_L does not become zero during the step before the slot boundary, the ON time is reduced by a step. The zero current duration converges to zero when this operation is repeated for each switching cycle. This zero current duration is fed back using a digital circuit and the upper limit of the output power can be maximized for heavy loads regardless of any variations in external factors such as connected devices, input-output voltage, process and temperature.

2.2 CCMS control technology to improve conversion efficiency at light load

The power consumed by the digital comparators is one of the dominant causes lowering efficiency at light load. This is reduced by lowering the operation frequency using burst control. In the SIMO-DCDC, it is necessary to further reduce the driving power of the CH distribution switch. When a conventional burst control is simply applied to the SIMO-DCDC, however, the CH distribution switches are driven every time I_L is supplied, resulting in power losses (Figure 4 (a)). With the newly developed CCMS control technology, the number of times the CH distribution switches are driven is reduced by changing the CH distribution order and continuously supplying I_L to a specific CH, thereby reducing the power loss (Figure 4(b)).



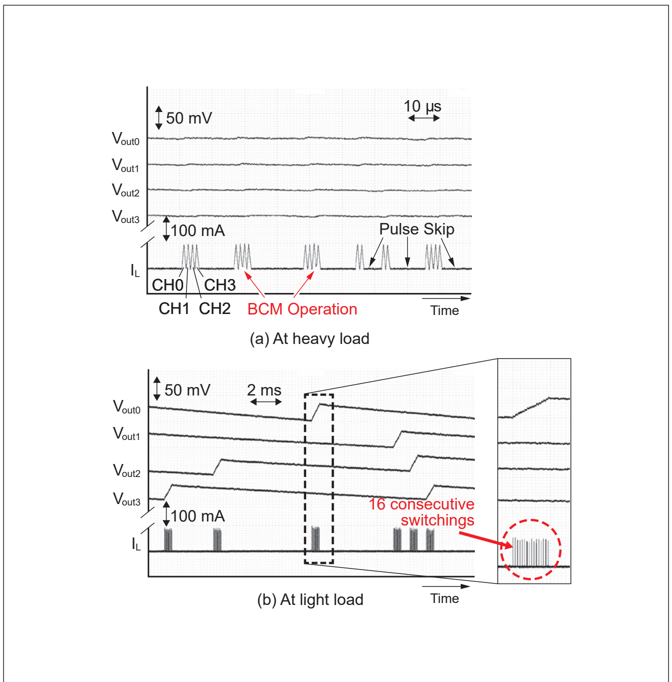
(Figure 4) : CCMS control to reduce channel distribution switching frequency under light load

3. Evaluation results

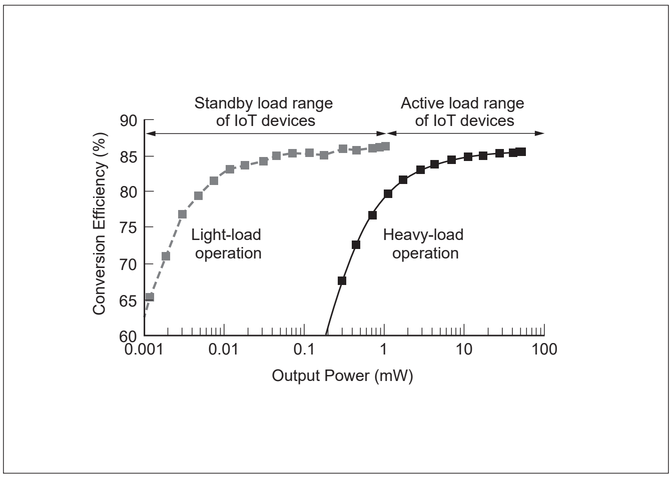
The on-chip digital control SIMO-DCDC equipped with MOT control technology and CCMS control technology was prototyped using a 65-nm standard CMOS (complementary MOS) process and the performance was evaluated.

Figure 5 (a) shows the waveforms of I_L and output voltages under heavy load where the load current of each CH is 3 mA. For this test, V_{out0} to V_{out3} were set to 1.3 V, 1.2 V, 1.1 V, and 1.0 V. BCM operation was realized by MOT control, and I_L was maximized. Unnecessary pulses are skipped, and the driving power of PMOS and NMOS was also reduced. Figure 5 (b) shows waveforms at light load when the load current of each CH is 50 μA. Sixteen consecutive switchings are made by CCMS control, and the voltage of the corresponding CH rises during the switching operation. The frequency of operation of the CH distribution switch was reduced to 1/16 compared with the conventional technique.

Figure 6 shows the relationship between the total output power and conversion efficiency when V_{in} is 2.7 V. The maximum output power operation was 53 mW, and the conversion efficiency was maintained above 80% up to about 1 mW. The maximum conversion efficiency at light load operation was 86.3%, maintaining the efficieny above 80% up to 5.2 μW and 65.3% at 1.1 μW. It was confirmed that the conversion efficiency is maintained at above 60% at output power from 1 μW to 50 mW by selectively using heavy load operation and light load operation.



(Figure 5) : Experimentally obtained waveform data at time of heavy-load and light - load operations



(Figure 6) : Conversion efficiency and total output power of prototype SIMO DC-DC converter

Table 1 shows a performance comparison between the SIMO-DCDC under development and the conventional SIMO-DCDCs, [1] [2] which have a conversion efficiency above 60% and a wide output power range. Using the developed technologies, the output power range is extended by two orders of magnitude compared with conventional implementations.

(Table 1) : Comparison of performance of conventional and prototype SIMO DC-DC converters

	Performance Specifications		
	Prototype	Conventional A [1]	Conventional B [2]
Manufacturing Process	65 nm CMOS	0.25 μm CMOS	65 nm CMOS
Input Voltage (V)	1 .8 to 3.6	2.7 to 5.0	2.7 to 3.6
Output Voltage (V)	0.6 to 1.8	1.2 / 1.8	1.8 / 1.2
External Inductor (μH)	10	4.7	4.7
External Capacitor (μF)	47	47	4.7
Peak Efficiency (%)	86.3	87	91
Light-load Efficiency (%)	65.3(1.1 μW)	60(1.8 mW)＊1	approx.62 (15 mW)＊1
Output Power Range for Conversion Efficiency > 60% (digit) ＊2	4.7 (1 μW to 50 mW)	2.7＊1 (1.8 mW to 840 mW)	1.8＊1 (15 mW to 900 mW)

＊1 : Estimated from the published data
＊2 : Logarithm of the ratio between maximum power and minumum power

4. Conclusion

A prototype on-chip digital control SIMO-DCDC converter equipped with newly developed MOT and CCMS control technologies suitable for IoT devices was developed. The measurement results showed that a maximum conversion efficiency of 86.3% is achieved with a practical operating efficiency of 65.3% or more within a wide load power range from 1 μW to 50 mW.

As a technology enabling more efficient use of power, IoT applications supporting the Bluetooth® Low Energy (BLE) standard are being considered where low-power-consumption ICs running on coin-type lithium-ion batteries would contribute to the extension of the operating time.

References

(1) Xu, W. et al. A Dual-Mode Single-Inductor Dual-Output Switching Converter with Small Ripple. IEEE Trans. Power Electron. 2010, 25, 3, pp.614 − 623.
(2) Lee, Y. H. et al. Interleaving Energy-Conservation Mode (IECM) Control in Single-Inductor Dual-Output (SIDO) Step-Down Converters with 91% Peak Efficiency. IEEE J. Solid-State Circuits. 2011, 46, 4, p.904 − 915.
(3) Fu, W. et al. A DCM-only buck regulator with hysteretic-assisted adaptive minimum-on-time control for low-power microcontrollers. IEEE Trans. Power Electron. 2016, 31, 1, p.418 − 429.