Low-Power Switched-Capacitor Converter Design Techniques for Small IoT Systems

Wanyeong Jung, Dennis Sylvester, David Blaauw
University of Michigan
Ann Arbor, MI, USA
wanyeong@umich.edu

***Abstract*—The small system size and low power level of recent small IoT (Internet of Things) systems render a switched-capacitor power converter more favorable than a traditional inductive converter because of its easy integration on chip and control for low power output. This paper presents a number of low-power switched-capacitor techniques for solving challenges of a millimeter-scale real IoT system, including energy harvesting from a photovoltaic (PV) cell and voltage regulation from battery voltage to multiple system-required voltages. Efficient converter topologies and a regulation scheme realize efficient power conversion over a wide range of powers, including as low as several nanowatts.**

Keywords—switched capacitor; DC-DC conversion; energy harvester; power management unit; internet of things

I. Introduction

As technology scaling has improved the size, cost and energy dissipation of a wide variety of circuits, more and more functions have been integrated into systems with small form factors, leading to the emergence of many small Internet of Things (IoT) systems. In recent years, many different mm-scale applications have been described, such as temperature sensing [1] and imaging [2]. However, the components for power regulation in these systems, an essential part of most wireless systems, are relatively difficult to scale down while maintaining efficiency because their performance largely depends on the quality of the accompanying energy-storage devices. In addition, the requirement for reduced quiescent power in these small systems, due to reduced power and energy availability, renders the design of the power regulation components more challenging.

In this paper, some design choices and techniques for energy harvesting and power management in a real, small IoT system are presented. Switched-capacitor (SC) converters are adopted for their small size and low quiescent power. Cascaded converter topologies enable a fine ratio configuration. Wide-range feedback frequency control maintains high efficiency in a variety of operating conditions.

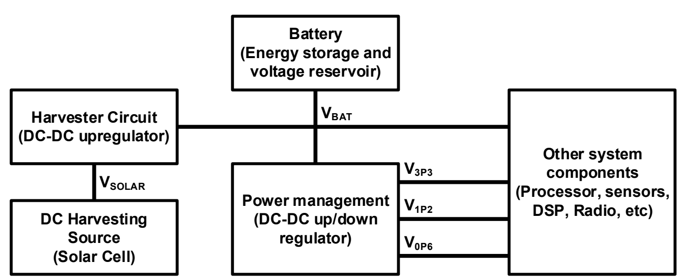
II. System Specification and Requirements

A. General system description

Fig. 1 shows a system with power regulation parts. We assume a mm-scale system with an ultra-low power standby mode of approximately 10 nW power dissipation including a battery and energy harvester for sustained operation without external power supply [2]. A thin-film Li battery and several silicon layers, each approximately 1-2 mm^2 thick, are stacked to form a wireless sensing platform with ~1 mm^3 overall volume. The harvesting circuit realizes DC-DC voltage upconversion from a DC harvesting source, such as a photovoltaic cell or a thermoelectric generator, to charge the battery. The system's battery serves as an energy storage device as well as a voltage reservoir so that the shared V_{BAT} node among different components is maintained regardless of the operating condition of each component and the design and operation of the energy harvester and the power management unit (PMU) can be decoupled. The energy stored in the battery is used to power the other system components. The PMU converts the battery voltages needed by the system components.

Due to size constraints, the use of additional off-chip energy storage components is less desirable for voltage conversion. Thus capacitive voltage conversion is preferred over inductive conversion because much larger inductance is usually required for efficient power conversion at nanowatt power levels [3-4] than on-chip inductors are capable of.

Fig. 1. IoT system with emphasis on power regulation parts.



B. Harvesting source and harvester specifications

Even assuming the use of a DC harvesting source, the design of the actual harvesting circuit can vary substantially according to the type of harvesting source because they vary with respect to their output voltage, current characteristics and optimum power points. In this paper, we assume the use of a silicon photovoltaic cell for harvester design optimization. Therefore, according to the measured performance results of a 0.84-mm^2 silicon solar cell shown in TABLE I. , we set the following rough specifications for the harvesting circuit: an

978-1-5386-3974-0/17/$31.00 ©2017 IEEE

input voltage range of 200-450 mV and an output power range from a few nanowatts to several microwatts. The overall IoT system standby power can be as low as 10 nW, so harvesting even a few nanowatts can substantially increase the system operation time and thus is desired. In addition, it is preferable for this harvester to have a self-startup capability from a cold state so that it can restore the operation of the whole system even if the battery is completely discharged during remote operation.

TABLE I. MEASURED PERFORMANCE OF 0.84 mm² SI SOLAR CELL [5]

Light Illuminance	Description of light level in usual case	Short circuit current	Voltage around maximum power point	Maximum output power
214 lux	Dim room light	30 nA	0.235 V	6.8 nW
1.1 klux	Bright room light	175 nA	0.28 V	47 nW
11 klux	Daylight	1.9 μA	0.35 V	0.63 μW
100 klux	Direct sunlight	14 μA	0.41 V	5.5 μW

C. *Voltage regulation for other system components*

Additional energy-conserving techniques can be applied to the design of other system components to improve the energy efficiency of the whole system, and the PMU must support these designs efficiently. First, the system has a very low standby power of approximately 10 nW, requiring high conversion efficiency for the PMU down to 10 nW output power. Second, three different power supplies with different voltage levels are used to assign the optimum supply voltage, among the 3 supplies, to each block. For example, several main digital circuits, including chip-to-chip communication, use 1.2 V supply voltage. Some low-power circuits use 0.6 V supply voltage to reduce leakage and dynamic power. Some analog blocks and radio circuits use 3.3 V supply voltage as they need relatively high voltage swing and power consumption.

A system's active power depends on the activated system's functions and typically ranges from a few microwatts to tens of microwatts [1-2]. Therefore, the PMU is designed to sustain output power up to several hundred microwatts to allow for some design margin and expandability of system functions in the future.

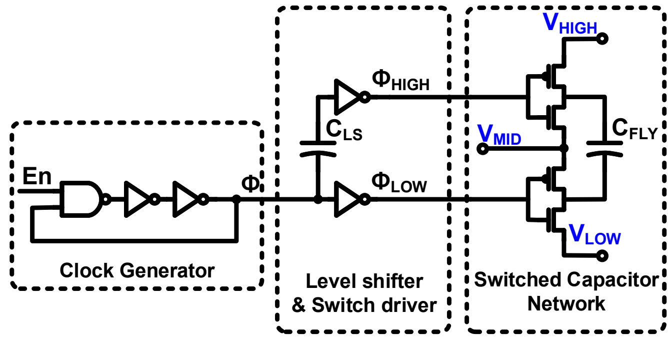
III. DESIGN AND IMPLEMENTATION DETAILS

The power converters for the energy harvester and PMU are designed and implemented according to the specifications defined in the previous section. They use a switched-capacitor DC-DC conversion scheme to achieve low-power operation within a small space.

A. *Unit switched-capacitor converter design*

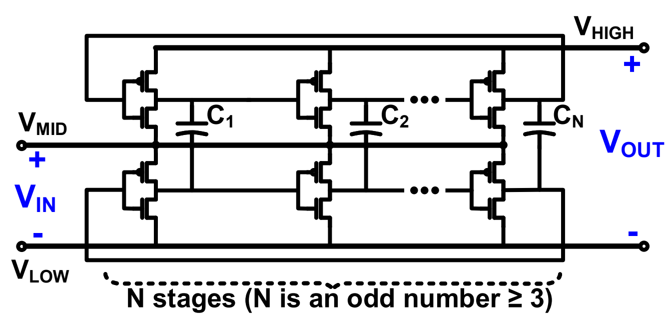
Most switched-capacitor designs for the harvester and PMU in this paper are based on the simple 1:2 converter structure shown in Fig. 2. A flying capacitor C_{FLY} switching between V_{LOW} and V_{MID} and V_{MID} and V_{HIGH} keeps the voltage differences between these couples at a similar level, generating V_{MID} at the level in the middle of the other two voltages or either V_{HIGH} or V_{LOW} outside the input voltage range when the corresponding other two voltages are used as inputs.

Fig. 2. Basic structure of 1:2 switched-capacitor converter. [5]



This basic structure is modified for specific purposes in each converter design. Voltage upconversion is required in the energy harvester, so this converter is configured to output V_{HIGH} with inputs at the other two terminals, V_{MID} and V_{LOW}. In addition, level shifting and clock delivery parts are combined into the switched capacitor network to guarantee its self-startup capability, as shown in Fig. 3. This structure, referred to as a self-oscillating voltage doubler [5], also improves efficiency, especially at a low input power level, by saving the extra power consumption that would be necessary for external clock generation and level shifting.

Fig. 3. Self-oscillating voltage doubler used in harvester. [5]



On the other hand, voltage downconversion is mainly used in the voltage regulator, so the V_{MID} terminal is set as the output. In this implementation, self-startup is no longer an issue because V_{BAT} is always available whenever the PMU needs to operate, but ensuring its efficient conversion at higher active output power levels becomes important. For this purpose, the switched capacitor network is driven by cross-coupled level shifters [6-7] to maintain consistently high switch conductance regardless of input and output voltage levels.

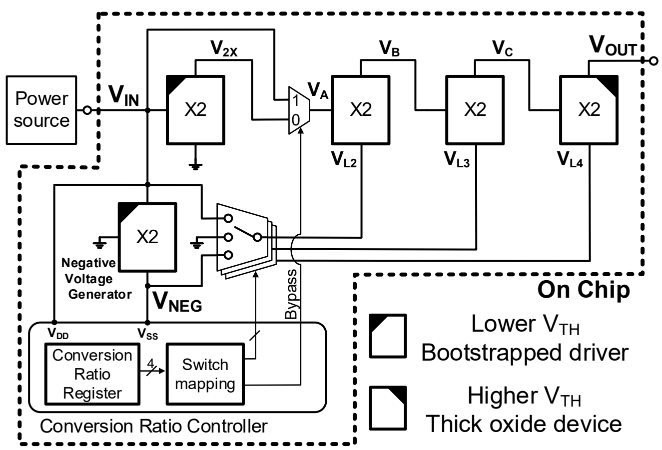
B. *Converter configuration for proper conversion ratio*

In contrast to an inductive voltage conversion, where the output voltage can be easily regulated by PWM of switching signals, the conversion ratio of a switched capacitor converter is fixed at a specific ratio. To overcome this drawback of the switched-capacitor conversion scheme, many converter topologies with ratio reconfigurability have been presented [7-9]. The converters in this paper adopt cascaded converter topologies because the reconfigurable ratios can be infinitely expanded by simply increasing the number of cascaded stages, and each stage can be designed based on a simple unit converter structure.

In the harvester, four 1:2 upconverters are cascaded [5] as shown in Fig. 4 so that the overall conversion ratio is 16×. In addition, by changing V_{LOW} of each converter stage from V_{SS} to V_{IN} or $-V_{IN}$, the output of the converter can decrease or increase by V_{IN}, respectively. This voltage change is amplified 2× as it passes through each stage to the final output; therefore, any integer ratio can be essentially achieved by changing the V_{LOW}s into the converters in a binary-like manner. $-V_{IN}$ is generated by supplying V_{SS} and V_{IN} into V_{MID} and V_{HIGH} of another 1:2 converter.

These five converters in the harvester have different nominal operating voltages and output current ranges, so each converter is additionally optimized for its unique operating condition. The first stage and negative voltage generator use low-threshold devices for smooth operation with a small input voltage. The output swings of the switch drivers are multiplied by bootstrapping to additionally improve the switch conductance as well as suppress the leakage. V_{LOW} of the first stage is fixed at V_{SS} because its operating condition varies too much when other voltages are supplied. Instead, the first stage can be bypassed by an additional mux when the input voltage is high enough. In this case, the V_{LOW} voltage of the second stage is fixed at $-V_{IN}$, so the voltage swing of the second stage can be always kept similar to or higher than $2V_{IN}$. As a result, the conversion ratio can be 9× to 23× in this implementation, which is sufficient to cover a voltage upconversion from a 200–450 mV solar cell voltage to a Li battery voltage of ~4 V. The final stage uses IO devices with thick gate oxide for device protection and low leakage with high input voltages.

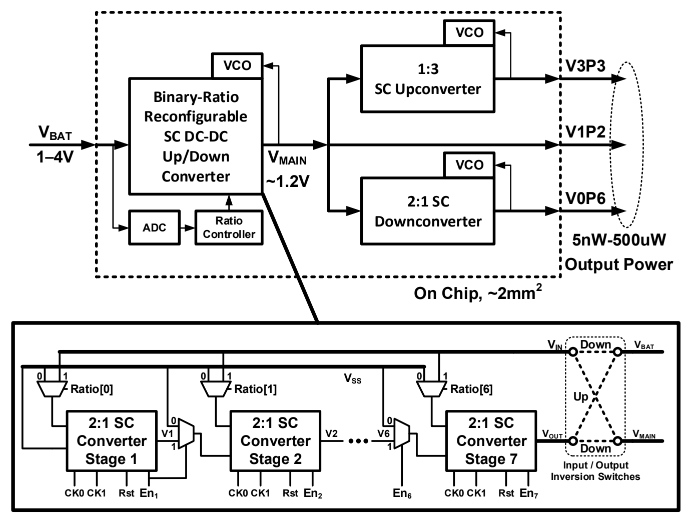
Fig. 4. Overall energy harvester architecture. [5]



The PMU converts the battery voltage into three different system voltages. Fig. 5 outlines the basic conversion scheme for this purpose [6]. First, the main system voltage of ~1.2 V is generated from the battery voltage, V_{BAT}. Seven 2:1 downconverters are cascaded for ratio configuration for this conversion (Fig. 5, bottom). Similar to the cascaded structure in the harvester, one input of a converter is connected to the output of the previous stage, and the other input is chosen between V_{IN} and V_{SS} [9]. In contrast to the harvester, where changes in an earlier stage are amplified on the output, a voltage change made at a stage of this downconverter is diminished by 2× as it passes through each stage to the output, so the voltage selection at the final stage has the most significant reduction. As a result, this converter can have a conversion ratio of any 7-bit binary fraction between 0 and 1. This fine-resolution ratio tuning provides a way to find a conversion ratio with good efficiency over a wide range of battery voltage levels (1.5 to greater than 4 V), ensuring efficient operation with any Li battery state of charge as well as with some other types of batteries. In addition, a switch for input-output inversion of this 7-bit binary converter enables voltage upconversion with this converter as well as downconversion, so the available V_{BAT} range is further extended to below 1.2 V. An ADC periodically measures V_{BAT} and adjusts the conversion ratio to a proper value.

After the main 1.2 V voltage, V_{MAIN}, is generated, a 1:3 Dickson upconverter and a 2:1 downconverter receive V_{MAIN} and convert it to 3.3 V and 0.6 V, respectively. The higher efficiency and smaller required area of these fixed simple-ratio conversions minimize the overhead of this extra conversion. Additionally, a large portion of the power output from V_{MAIN} directly passes to the main system voltage output *V1P2*, further minimizing the effect these extra conversion losses have on the whole system.

Fig. 5. Overall PMU architecture. [6]



C. Feedback frequency regulation for maintaining efficiency

To achieve a high conversion efficiency of a switched-capacitor converter operating with a slow switching frequency [10], the power losses in the converter are categorized into three main categories according to their relationship with the switching frequency of the converter: switching loss, which is proportional to the frequency; conduction loss with inverse proportionality to the frequency; and constant leakage. Then, because of the inversely proportional relationship between the switching and conduction losses, minimum power loss is achieved at the frequency where these two losses are balanced [5]. A converter shows a similar ratio between the input and output voltages at this balanced point within a wide power range, so this ratio can be used for feedback control of the switching frequency to maintain high efficiency.

Frequency tuning for a wide power range results in a wide range of frequency change. The feedback control shown in Fig.

6 (left) enables stable and efficient operation within this wide frequency range. A wide-range VCO consisting of leakage-based delay elements (Fig. 6, right) [1, 5] provides a switching frequency for an SC converter. Tunable leakage paths are added to the delay elements and are controlled by a charge-pump output. This charge pump is feedback-controlled to keep the ratio between the input and output voltages at approximately *K*, which can be optimally trimmed separately in each converter by a simple voltage divider. As an exception, V_{MAIN} must be regulated to stay at approximately 1.2 V, so it needs a proper conversion ratio adjustment of the binary converter for high efficiency.

A drop detector is added into the regulation loops in the PMU converters to respond faster to the input voltage drop. When a low-power analog amplifier in the drop detector detects an output voltage drop below a certain threshold, it immediately changes the charge pump output, driving the VCO frequency to its maximum so that the output voltage is quickly recovered. Once recovered, the drop detector is reset, and the frequency is settled back down by the main feedback control.

Fig. 6. Feedback frequency regulation scheme (left) [6] and a leakage-based delay element for wide-range frequency tuning in VCO (right) [5]

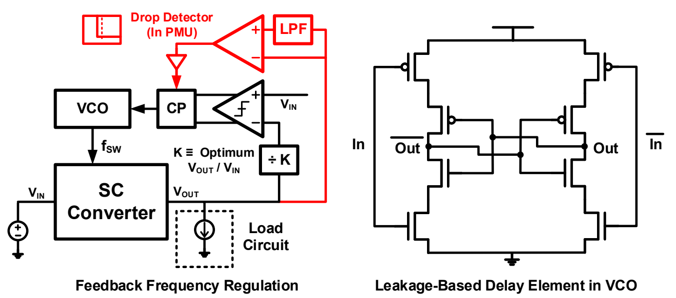


Fig. 7. Die micrograph of the energy harvester (left) [5] and PMU (right) [6]

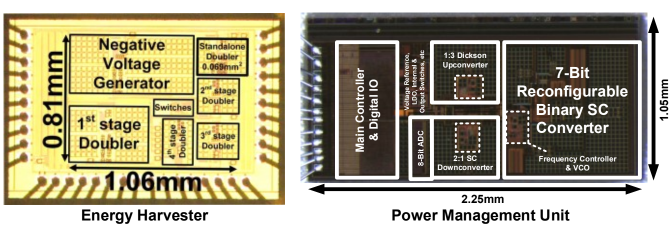
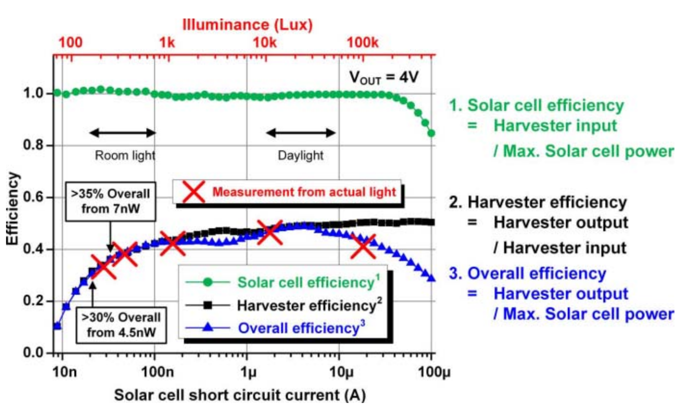


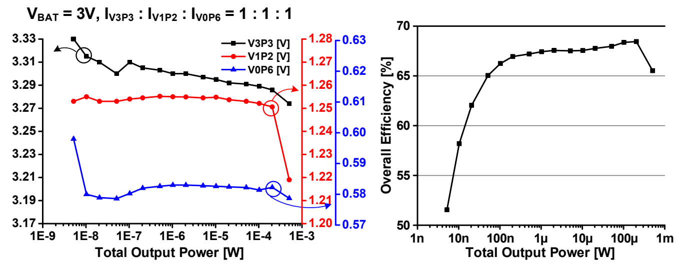
Fig. 8. Measured results of the harvester with a 0.84 mm^2 Si solar cell [5]



IV. RESULTS

The energy harvester and PMU are fabricated in 0.18 μm CMOS (Fig. 7). Each test chip has ~2 mm^2 area and can be easily incorporated into a small stacked system. The measured results in Fig. 8 and Fig. 9 (excerpted from [5] and [6], respectively) show its wide operation range with low quiescent power that fulfill the original specification for the system. The overall conversion efficiency of each circuit is maintained at an acceptable level at this low power level.

Fig. 9. Measured results of the PMU. [6]



REFERENCES

[1] M. Fojtik, D. Kim, G. Chen, Y.-S. Lin, D. Fick, J. Park, M. Seok, M.-T. Chen, Z. Foo, D. Blaauw, and D. Sylvester, "A millimeterscale energy-autonomous sensor system with stacked battery and solar cells," IEEE J. Solid-State Circuits, vol. 48, no. 3, pp. 801–813, Mar. 2013.

[2] Y. Lee, S. Bang, I. Lee, Y. Kim, G. Kim, M. H. Ghaed, P. Pannuto, P.Dutta, D. Sylvester, and D. Blaauw, "A modular 1 mm die-stacked sensing platform with low power inter-die communication and multi-modal energy harvesting," IEEE J. Solid-State Circuits, vol. 48, no. 1, pp. 229–243, Jan. 2013.

[3] S. Bandyopadhyay, P. P. Mercier, A. C. Lysaght, K. M. Stankovic, and A. P. Chandrakasan, "A 1.1 nW Energy-Harvesting System with 544 pW Quiescent Power for Next-Generation Implants," IEEE J. Solid-State Circuits, vol. 49, no. 12, pp. 2812-2824, Dec. 2014.

[4] A. Paidimarri and A. P. Chandrakasan, "A Buck Converter with 240pW Quiescent Power, 92% Peak Efficiency and a 2×106 Dynamic Range," IEEE ISSCC Dig. Tech. Papers, 2017, pp. 192–193.

[5] W. Jung, S. Oh, S. Bang, Y. Lee, Z. Foo, G. Kim, Y, Zhang, D. Sylvester and D. Blaauw, "An Ultra-Low Power Fully Integrated Energy Harvester Based on Self-Oscillating Switched-Capacitor Voltage Doubler," IEEE J. Solid-State Circuits, vol. 49, no. 12, pp. 2800–2811, Dec. 2014.

[6] W. Jung, J. Gu, P. D. Myers, M. Shim, S. Jeong, K. Yang, M. Choi, Z. Foo, S. Bang, S. Oh, D. Sylvester and D. Blaauw, "A 60%-Efficiency 20nW-500μW Tri-Output Fully Integrated Power Management Unit with Environmental Adaptation and Load-Proportional Biasing for IoT Systems," IEEE ISSCC Dig. Tech. Papers, 2016, pp. 154–155.

[7] S. Bang, D. Blaauw and D. Sylvester, "A Successive-Approximation Switched-Capacitor DC–DC Converter With Resolution of $V_{IN}/2^N$ for a Wide Range of Input and Output Voltages," IEEE J. Solid-State Circuits, vol. 51, no. 2, pp. 543–556, Feb. 2016.

[8] H.–P. Le et al., "A Sub-ns Response Fully-Integrated Battery-Connected Switched-Capacitor Voltage Regulator Delivering 0.19W/mm2 at 73% Efficiency," ISSCC Dig. Tech Papers, 2013, pp. 372-373.

[9] L. G. Salem and P. P. Mercier, "A Recursive Switched-Capacitor DC-DC Converter Achieving 2N−1 Ratios With High Efficiency Over a Wide Output Voltage Range," IEEE J. Solid-State Circuits, vol. 49, no. 12, pp. 2773–2787, Dec. 2014.

[10] M. D. Seeman and S. R. Sanders, "Analysis and Optimization of Switched-Capacitor DC–DC Converters," IEEE Transactions on Power Electronics, vol. 23, no. 2, pp. 841-851, Mar. 2008.