An 84% efficient boost-converter using 0.57 nW/kHz relaxation oscillator-based MPPT for biomedical energy harvesting applications

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Seneke Chamith Chandrarathna, Bui Huu Nguyen, and Jong-Wook Lee*

Department of Electronics and Information Convergence Engineering, Kyung Hee University

요 약

This brief presents an ultra-low power DC-DC boost converter for interfacing high impedance energy harvesters. The interface system implemented in a 180 nm standard CMOS process with a thick metal option can be initialized using 280 mV of input or 915 MHz RF signal at -14.5 dBm. The system also employs a maximum power point tracking (MPPT) algorithm and a zero current sensing controller (ZCS), which are realized by using a 0.57 nW/kHz relaxation oscillation-based delay controller. The boost-converter has been successfully tested using a voltage source with a 15 kΩ series resistance and achieved end-to-end efficiency of 84% at 130 mV of input while regulating output at 1.8 V.

Ⅰ. Introduction

As a promising long-time sustainable sensor, the battery-powered system may not be adequate. Therefore, alternative energy sources such as thermal, solar, or mechanical might be a solution depending on the applications. However, for the implantable or ingestible sensors, those energy sources are typically limited inside the human body. Besides, inside the human body can also be considered as a biocompatible energy source [1]. Depending on the pH and size of the electrodes (4 mm^2), the available power density in gastrointestinal (GIT) is about 150 nW/mm^2. A single-chip solar energy harvesting system presented in [2] explains the feasibility of using solar cells for biomedical implant applications.

The primer key challenge of harvesting energy inside the human body is a lower power budget, typically a few μW. In the previous works, a boost converter for GIT energy harvesting presented in [3] achieves power consumption of 16.8 nW while extracting 703 nW of available power. The input impedance of this work is limited between 1- 3 kΩ. In [2], a charge pump based energy harvesting system is presented, and it delivers an output power of 1.65 μW at 64% efficiency. However, the system does not employ a maximum power point tracking (MPPT)

Another issue is that the self-startup technique at the low voltage of the input (V_{IN}). In [1], RF power has been used for initiating the self-startup. However, due to the attenuation through the body, the usage of RF power sometimes will be tricky.

To tackle these challenges, we proposed an ultra-low-power (ULP) boost converter with a MPPT algorithm and a zero-current-sensing (ZCS) controller. The MPPT can sustain the boost converter under a relatively high input impedance of 15 kΩ at 25 mV of V_{IN}. The peak end-to-end (η_{EtE}) efficiency of the boost converter is 84% while delivering 2.9 μW of the output power at 130 mV of V_{IN}, and the total power consumption of the system is less than 10 nW at 50 mV of V_{IN}.

Ⅱ. Design

Fig. 1(a), (b), and (c) show the various types of energy harvesting topologies utilized inside the human body, where the low power assist exists. Therefore, we proposed system architecture, including a ULP boost converter. Besides, to detect the activities in the human body, a biomedical circuit is also presented, which can transfer data through the RF power [1] and [3].

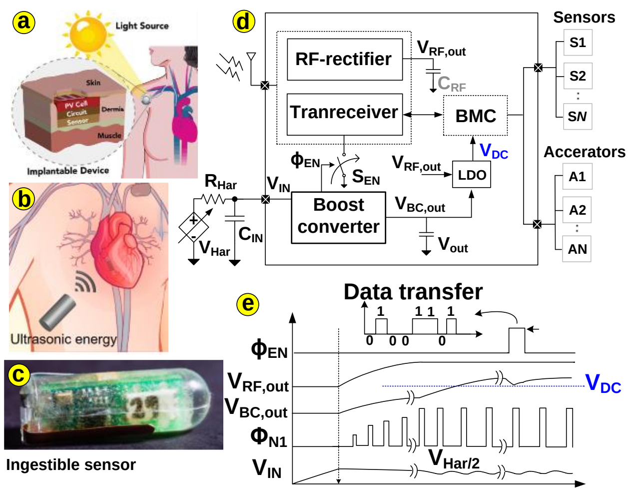


Fig.1 Energy harvesting devices inside the human body (a) implant solar cells, (b) implant piezo materials, and (c) ingestible sensor. The proposed energy harvesting and sensing system (d) overall block diagram and (e) typical waveforms.

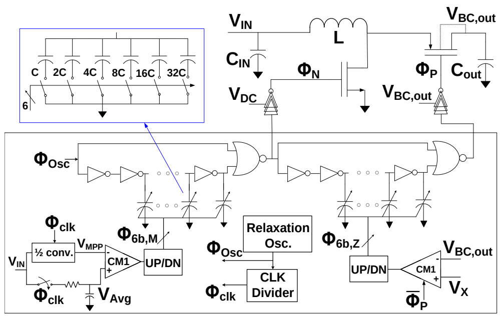
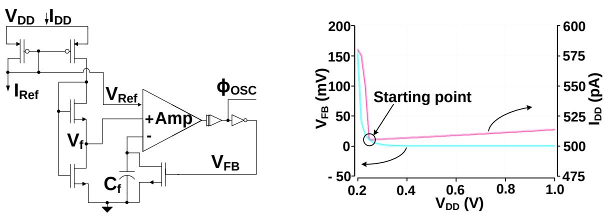


Fig.2. Proposed boost converter with MPPT and ZCS controllers.

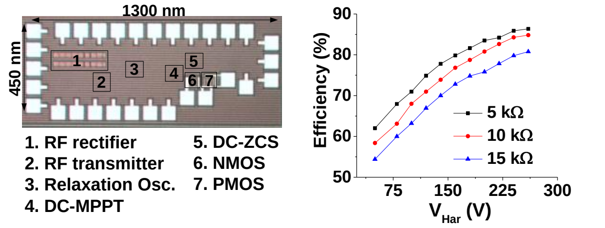
The high voltage energy source has been emulated using a voltage source V_{Har} with a series resistance of R_{Har}. The boost converter consists of an MPPT controller, a ZCS controller, and two power switches (S_{N1} and S_{P1}). The input needs a capacitor C_{IN}, which buffers the V_{IN}. Using the RF kick-start or the cold-start at 280 mV, the boost converter can be initialized. Then, the MPPT controller adjusts the input impedance of the converter R_{IN} ($\sim 2L/f_S.t^2_{ON}$), while increasing output of the converter ($V_{BC,out}$) to 1.8 V. Besides, an LDO is used to regulate $V_{BC,out}$ to 1.2 V, which also acts as V_{DD} and input for the BMC.

Fig. 2 shows the schematic of the proposed boost converter. It mainly consists of delay-controlled MPPT (DC-MPPT), delay-controlled ZCS (DC-ZCS), and a pW power relaxation oscillator. After starting up, V_{IN} is sampled at VHar/2, which is the MPPT condition. When V_{IN} has a small change, comparator CM1 will count up or down to adjust the on-time of S_{N1} (t_{ON}). The pair of five 6-bit capacitor arrays improve the resolution of the tracking ranges to realize the wide ranges of source variation 1-20 kΩ and the load variation 10 kΩ- 1 MΩ, respectively.



(a) (b)

Fig.3. (a) schematic of relaxation oscillator and (b) variation of the driven current I_{DD} as a function of V_{DD}.



(a) (b)

Fig.4. (a) chip micrograph and (b) variation of end-to-end efficiency as a function of V_{Har}.

Fig. 3(a) shows the proposed relaxation oscillator, and it has been realized by using a single-stage amplifier and a voltage reference. As the waveforms are shown in Fig. 3(b), the minimum starting voltage of the oscillator is 280 mV. Fig. 4(a) shows the chip micrograph of the overall system. Fig. 4(b) shows the measured η_{EtE} efficiency as a function of V_{Har}, illustrating that the peak η_{EtE} of 84% achieves at 130 mV of V_{IN} (~ $V_{Har}/2$).

Ⅲ. Conclusion

In this work, we investigated the ULP boost converter for biomedical applications. The converter fabricated in a 180 nm CMOS process delivers 2.9 μW of the output power at 130 mV of V_{IN}, and the total power consumption of the system is less than 10 nW at 50 mV of V_{IN}.

ACKNOWLEDGMENT

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REFERENCES

[1] P. Nadeau, et al., "Prolonged energy harvesting for ingestible devices," Nat. Biomed. Eng., vol. 1, no. 2, pp. 1–8, Feb. 2017.

[2] Z. Chen, et al., "A Single-Chip Solar Energy Harvesting IC Using Integrated Photodiodes for Biomedical Implant Applications," IEEE Trans. Biomed. Circuits Syst., vol. 11, no. 1, pp. 44–53, Feb. 2017.

[3] S. C. Chandrarathna and J.-W. Lee, "16.8 nW ultra-low power energy harvester IC for tiny ingestible sensors sustained by bio-galvanic energy source," IEEE Trans. Biomed. Circuits Syst: Reg. Papers, vol. 4565.