A 25-mV input boost converter with 91% MPPT efficiency for energy harvesting application

Sangkwon Lee and Jinseong Jeong

School of Electrical and Computer Engineering, University of Seoul, 163 Seoul siripdae-ro, Dongdaemun-gu, Seoul, Korea

Abstract: In this letter, a low input boost converter with continuous conduction mode is presented for energy harvesting application. The maximum power point tracking (MPPT) efficiency at low input voltage is improved by using the proposed input-ripple control technique. Fabricated in a 0.35 µm CMOS process, the boost converter generates an output voltage of 3 V from the input voltage as low as 25 mV. The measurement results show that the boost converter achieves an MPPT efficiency of 91% at 25-mV input and a peak power conversion efficiency of 82.7% at 250-mV input.

Keywords: boost converter, energy harvesting, MPPT, low input boosting, continuous conduction mode, boosting ratio

Classification: Integrated circuits

References

[1] Y. Zhang, et al.: “A batteryless 19 µW MICS/ISM-band energy harvesting body sensor node SoC for ExG applications,” IEEE J. Solid-State Circuits 48 (2013) 199 (DOI: 10.1109/JSSC.2012.2221217).

[2] E. J. Carlson, et al.: “A 20 mV input boost converter with efficient digital control for thermoelectric energy harvesting,” IEEE J. Solid-State Circuits 45 (2010) 741 (DOI: 10.1109/JSSC.2010.2042251).

[3] J. Mu and L. Liu: “A 12 mV input, 90.8% peak efficiency CRM boost converter with a sub-threshold startup voltage for TEG energy harvesting,” IEEE Trans. Circuits Syst. I, Reg. Papers 65 (2018) 2631 (DOI: 10.1109/TCSI.2018.2789449).

[4] J. Katic, et al.: “A dual-output thermoelectric energy harvesting interface with 86.6% peak efficiency at 30 µW and total control power of 160 nW,” IEEE J. Solid-State Circuits 51 (2016) 1928 (DOI: 10.1109/JSSC.2016.2561959).

[5] P.-S. Weng, et al.: “50 mV-input batteryless boost converter for thermal energy harvesting,” IEEE J. Solid-State Circuits 48 (2013) 1031 (DOI: 10.1109/JSSC.2013.2237998).

[6] A. Shrivastava, et al.: “A 10 mV-input boost converter with inductor peak current control and zero detection for thermoelectric and solar energy harvesting with 220 mV cold-start and −14.5 dBm, 915 MHz RF kick-start,” IEEE J. Solid-State Circuits 50 (2015) 1820 (DOI: 10.1109/JSSC.2015.2412952).
1 Introduction

Energy harvesting for self-powered electronic systems such as implementable medical sensors, often rely on ambient energy sources with low power and small output voltage. The output voltage of thermoelectric generator (TEG) can be less than 30 mV since the temperature difference between both sides of the TEG can only be a few ºC in wearable application [1, 2]. To power CMOS electronics with such low-voltage sources, discontinuous conduction mode (DCM) boost converter has been preferred since the power conversion efficiency at low input voltage is superior than that of continuous conduction mode (CCM) boost converter [3, 4, 5]. However, the DCM boost converter requires a large input capacitor which is essential for maximum power point tracking (MPPT) in order to extract the maximum available power from the TEG [6, 7]. Instead, the CCM boost converter with input ripple control shown in Fig. 1(a) has been most frequently employed to fabricate a miniature boost converter since it does not require a large input capacitor for MPPT [8, 9, 10]. While this architecture can track the maximum power point (MPP) with a simple feedback loop, a large ripple can appear at the input when low-voltage MPP is tracked since high boosting ratio makes the inductor current rapidly discharged, thus increasing the input voltage rapidly. This large ripple at the input degrades the MPPT efficiency as well as the overall power conversion efficiency since the inductor current can flow negatively. Therefore, to reduce the ripple voltage, the loop delay of the feedback loop must be minimized. Employing a fast comparator can reduce the loop delay, but at the expense of undesirable power consumption. In this letter, a new input-ripple control technique is proposed to improve MPPT efficiency and power conversion efficiency at low input voltage without designing a fast and power-hungry comparator.

2 Boost converter with input ripple control

Shown in Fig. 1(b), the input voltage of the boost converter, $V_{IN}$ tracks the MPP voltage, $V_{MPP}$ of the TEG, which is $V_{TEG}/2$ in fractional open-circuit voltage
method. If we define the positive propagation delay of the comparator, CMP as $T_{DLY,H}$ and the negative as $T_{DLY,L}$, a high-side ripple, $V_{RIP,H}$ and a low-side ripple, $V_{RIP,L}$, can be approximated as Eq. (1) and Eq. (2) assuming $V_{IN} \approx V_{MPP}$ and the voltage drop of the diode, $D_1$ is ignored.

$$V_{RIP,H} = R_{TEG} \cdot \frac{V_{STO} - V_{MPP}}{L_{BST}} \cdot T_{DLY,H}$$ (1)

$$V_{RIP,L} = R_{TEG} \cdot \frac{V_{MPP}}{L_{BST}} \cdot T_{DLY,L}$$ (2)

where $R_{TEG}$ is an output resistance of the TEG and $V_{STO}$ is an output voltage of the boost converter. It is noticed that when the input voltage is low, in other words, the boosting ratio, $V_{STO}/V_{MPP}$ is high, the $V_{RIP,H}$ is dominant component of the overall ripple, $V_{RIP}$, i.e. $V_{RIP} = V_{RIP,H} + V_{RIP,L} \approx V_{RIP,H}$. Therefore, to improve MPPT efficiency, or to reduce $V_{RIP}$, the positive propagation delay of the CMP, $T_{DLY,H}$ needs to be minimized. Motivated by the fact that the $T_{DLY,H}$ is a function of differential input, $V_{IN}(t) - V_{MPP}$, in this work, the CMP is accelerated by shifting $V_{MPP}$ down instead of designing a fast and power-hungry comparator. Shown in Fig. 1(c), the $V_{MPP}$ is shifted down by the amount of $\Delta V_{MPP}$ during the on-time of the diode, $D_1$. In this way, the CMP sees larger voltage difference at the input and therefore, $T_{DLY,H}$ is effectively reduced to $T_{DLY,H,NEW}$. Also, since the differential input becomes positive at the same time as the $V_{MPP}$ is shifted down, rising time of $V_{IN}$, $t_1$ in Fig. 1(b) becomes unnecessary which further reduces the $V_{RIP}$. Although the $V_{RIP}$ is reduced in the proposed technique, the $V_{IN}$ actually tracks $V_{MPP} - \Delta V_{MPP} \cdot p(t)$ where $p(t)$ is a pulse train with a duration of $T_{DLY,H,NEW}$. However, since the duty cycle of the $p(t)$ is very low, i.e. $T_{DLY,H,NEW} \ll t_2$ when the boosting ratio is high, this tracking error can be ignored.

### 3 Implementation

Fig. 2 shows an MPPT boost converter with the proposed input-ripple control technique where the SAMP signal triggers the MPP sampling circuit. In MPP sampling mode, both power transistors, $M_N$ and $M_P$ of the boost converter are turned off and the current of the inductor, $L_{BST}$ is fully discharged to $C_{STO}$ through a body diode, $D_{MP}$ of $M_P$. Once the input current of the converter, $I_{IN}$ becomes zero,
the open-circuit voltage of TEG, $V_{TEG}$ appears at $V_{IN}$ node and it is stored at $V_{SAMP}$ node of a capacitor, $C_{SAMP}$ by closing $SW_3$. At the same time, $SW_1$ is on and $SW_2$ is off in order to reset $V_{MPP}$ node. After sampling $V_{TEG}$, the $V_{SAMP}$ node is disconnected from $V_{IN}$ and $V_{MPP}$ becomes $V_{SAMP}/2$ by closing $SW_2$ (also, $SW_1$ and $SW_3$ are off) since the charge stored in $C_{SAMP}$ is shared by an identical capacitor, $C_{MPP}$. Once $V_{MPP}$ becomes $V_{TEG}/2$, the boost converter operates in MPPT mode. To pull down $V_{MPP}$ during the on-time of $MP$, a small coupling capacitor, $C_{CP}$ is placed between the $V_{MPP}$ node and the gate of $MP$. The amount of pulling down, $\Delta V_{MPP}$ can be calculated by

$$\Delta V_{MPP} = \frac{C_{CP}}{C_{MPP} + C_{SAMP} + C_{CP}} V_{STO}$$

since the $V_{STO}$ is used as a supply voltage of the circuits. In this work, $C_{CP}$ of 0.8 pF and $C_{MPP}$ ($C_{SAMP}$) of 60 pF are used and the corresponding $\Delta V_{MPP}$ is 20 mV with $V_{STO}$ of 3 V. In MPPT sampling mode, this coupling capacitance can disturb the charge sharing by

$$V_{MPP} = \frac{C_{SAMP}}{C_{MPP} + C_{SAMP} + C_{CP}} V_{SAMP} \approx \frac{C_{SAMP}}{C_{MPP} + C_{SAMP}} V_{SAMP}$$

but it can be ignored since $C_{CP}$ is much smaller than $C_{MPP}$ ($C_{SAMP}$).

### 4 Measurement results

Fig. 3 shows the proposed boost converter fabricated in a 0.35 µm CMOS process. In the measurement set-up, the TEG is is emulated by a power supply with a series resistance of 4 Ω and the output capacitor, $C_{STO}$ of 47 µF is pre-charged with a 3-V power supply. An off-chip inductor, $L_{BST}$ of 47 µH with a parasitic resistance of 280 mΩ and an off-chip capacitor, $C_{CP}$ of 0.8 pF are used to test functionality of the proposed technique. Fig. 4 shows the $V_{IN}$ and $V_{MPP}$ waveforms with and without $C_{CP}$ when $V_{TEG}$ is 50 mV. The maximum available power, $P_{AV}$ from the TEG can be calculated by

$$P_{AV} = \frac{V_{TEG}^2}{4R_{TEG}}$$
which is 156.25 µW in this case. Without $C_{CP}$, the $V_{IN}$ tracks a constant $V_{MPP}$ of 25 mV maintaining 18~53 mV while extracting 141 µW from the TEG. Also, indicated in Fig. 4(a), a reverse input current (higher $V_{IN}$ than $V_{TEG}$ means that the current flows back to the TEG through $R_{TEG}$) is observed due to rapid discharging of the $L_{BST}$ current. This reverse current returns the extracted power back to the TEG, thus degrading the overall power conversion efficiency. On the other hand, with $C_{CP}$, shown in Fig. 4(b), the ripple voltage is reduced and the $V_{IN}$ maintains 18~45 mV without the reverse current. The extracted power is improved to 151 µW which is 7.1% higher than without $C_{CP}$. Fig. 5(a) shows an enlarged view of the $V_{IN}$ and $V_{MPP}$ waveforms in Fig. 4(b). Initially, the $V_{MPP}$ is shifted down by 49 mV and settles to 5 mV ($V_{MPP} - \Delta V_{MPP}$). The main reason for this initial undershoot is that the parasitic resistance, $R_{ON2}$ of the charge sharing switch, $SW_2$ delays the charges being evenly distributed between $C_{SAMP}$ and $C_{MPP}$. The same response also happens when the $V_{MPP}$ returns to the original value. Although this overshoot is not desirable, the overshoot time is too short for the CMP to react since the switching time of the CMP is much longer. More sophisticated coupling and layout technique can improve this transient response. Fig. 5(b) compares the MPPT efficiency, $\eta_T$ and the power conversion efficiency, $\eta_P$ which is defined by

$$\eta_T = \frac{P_{IN}}{P_{AV}}, \quad \eta_P = \frac{P_{OUT}}{P_{AV}}$$

(6)

The MPPT efficiency is improved from 80.8~98.0% to 90.8~99.0% exhibiting about 10% improvement at low input voltages. Also, the power conversion efficiency is improved from 16.3% to 21.5% when the $V_{TEG}$ is 50 mV. The converter achieves a peak power conversion efficiency of 82.7%, while generating
12.9-mW output power when $V_{TEG}$ is 500 mV. Table I compares the proposed boost converter with previously reported thermal energy harvesters. Among the boost converters with CCM control, this work provides the highest boosting ratio of 120 at the minimum $V_{IN}$ of 25 mV, generating the highest output voltage of 3 V.

5 Conclusion

In this letter, a low input CCM boost converter with input-ripple control for energy harvesting application is introduced. The proposed technique efficiently improves the MPPT efficiency of the boost converter when the low-input voltage is boosted. The converter achieves 10% of improvement at the minimum $V_{TEG}$ of 50 mV ($V_{IN}$ of 25 mV) generating 3-V output voltage. The peak end to end efficiency of 82.7% demonstrates excellent maximum power transfer capability of the boost converter. Since this work can be implemented with one off-chip inductor and one output capacitor, the proposed technique can be applied to such applications which require small form-factor designs.

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