An off-chip input capacitor-less boost converter with fast MPPT for energy harvesting

Sangkwon Lee and Jinseong Jeong
School of Electrical and Computer Engineering, University of Seoul, 163 SeoulSiripdae-ro, Dongdaemun-gu, Seoul, Korea
a) jsjeong@uos.ac.kr

Abstract: In this paper, a boost converter with fast MPPT capability is proposed for energy harvesting applications. The sampling time for maximum power point voltage, $V_{MPP}$ of harvester device is extremely shortened by using inductor current conservation method and an off-chip input capacitor-less boost converter. The proposed boost converter is designed in a standard 0.13 µm CMOS process and compared with a conventional MPPT boost converter. The proposed architecture can sample $V_{MPP}$ more than 100 times faster than the conventional architecture. Power conversion efficiency of the harvesting system also improves due to the fast $V_{MPP}$ sampling. For the scenario used in this paper, the overall efficiency improves from 70% to 85%. This architecture can be applied to any energy harvesting systems and is especially effective when the ambient parameter such as temperature or light intensity changes relatively rapidly.

Keywords: energy harvesting, MPPT, boost converter, inductor current conservation, dual-boundary control

Classification: Integrated circuits

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1 Introduction

The maximum power point tracking (MPPT) is a critical ingredient in a boost converter for energy harvesting applications since the ambient energy from solar, thermoelectric or piezoelectric harvester is non-consistent [1]. Among various MPPT algorithms, the fractional open-circuit voltage method is widely employed to avoid power-hungry digital signal processors [2]. In this method, a fraction of the open-circuit voltage, $V_{OC}$ of harvester device is used as maximum power point voltage, $V_{MPP}$. For example, 0.5$V_{OC}$, 0.8$V_{OC}$, and 0.4$V_{OC}$ are used as a $V_{MPP}$ for thermoelectric, photovoltaic, and piezoelectric harvester, respectively [3]. In order to track the variation of temperature, light intensity, or vibration, $V_{OC}$ is periodically sampled and $V_{MPP}$ is updated accordingly.

Fig. 1 shows a conventional boost converter with MPPT capability in previous works [4, 5, 6] where a thermoelectric generator (TEG) is represented by a voltage source, $V_{TEG}$ with an internal resistance, $R_{TEG}$. In MPPT mode, the gates of $M_P$ and $M_N$, P and N are digitally controlled such that $V_{IN}$ is maintained around the $V_{MPP}$ which is $V_{TEG}/2$ in this case. An off-chip input capacitor, $C_{IN}$ is used at the input of boost converter to prevent excessive voltage ripple caused by MPPT. In sampling mode, $M_N$ is turned-off and the input current, $I_{IN}$ becomes zero after $t_1$ which is given by

$$t_1 = \int_{I_{MPP}}^{0} \frac{L}{V_{IN}(t) - V_{OUT}} dI_{IN}$$

where $I_{MPP}$ is equal to $V_{MPP}/R_{TEG}$. The $t_1$ is determined by an inductance, L and $C_{IN}$ since $V_{IN}(t)$ transition is delayed by $R_{TEG}$ and $C_{IN}$. Therefore, smaller $C_{IN}$ is preferred in sampling mode, however it causes excessive voltage ripple in MPPT mode. Now, the input of boost converter is open-circuit and $V_{TEG}$ is sampled for $t_2$. After sampling, MPPT is resumed by turning on $M_N$ and $V_{IN}$

![Fig. 1.](image-url)
goes back to around $V_{MP}$P. It also takes time $t_3$, according to similar equation as Eq. (1). During this period of time, $t_1 + t_2 + t_3$, the TEG is inefficiently loaded since $V_{IN}$ is out of MPPT range and significant amount of energy can be wasted if the temperature variation is so rapid that frequent $V_{MP}$ sampling is required. Therefore, it is desired to reduce $V_{MP}$ sampling time especially in power-desperate applications such as wireless sensor nodes.

In this paper, a boost converter with fast MPPT capability is proposed. $V_{MP}$P sampling time is extremely shortened without sacrificing MPPT performance by using inductor current conservation and removing the off-chip input capacitor, $C_{IN}$ in the boost converter.

2 Architecture of boost converter with fast MPPT

The proposed boost converter with fast MPPT capability is shown in Fig. 2(a) where $M_{N2}$ is used to make the input of boost converter as a virtual open circuit by conserving inductor current during sampling mode. In MPPT mode, $M_{N2}$ is off and the boost converter operates in the same way as in Fig. 1 except that the gates of the boost converter, P and N are controlled in a way such that the off-chip input capacitor, $C_{IN}$ can be removed.

Fig. 2(c) shows PWM signal generator with $V_{OC}$ sampling circuit where $V_{MP}$P and $V_{SAMP}$ are non-overlapping control signals to select either MPPT or sampling mode. In MPPT mode ($V_{MP}$P = HIGH), the gate control signals,
P and N are generated by comparing $V_{IN}$ with $V_H$ and $V_L$, which are reference voltages around $V_{MPP}$. A SR-latch enables that P and N nodes hold the previous state so that $V_{IN}$ remains between $V_H$ and $V_L$ as shown in Fig. 2(b). In this way, the amount of $V_{IN}$ ripple as well as its frequency can be controlled by proper selection of $V_H$ and $V_L$ without an off-chip input capacitor.

In sampling mode ($V_{SAMP} = \text{HIGH}$), the SR-latch is disabled and both $M_{P1}$ and $M_{N1}$ devices are turned-off. Instead, $M_{N2}$ is turned-on in order that the inductor current keeps flowing through $M_{N2}$ as illustrated in Fig. 2(a) as a current loop. Since $I_{IN}$ becomes zero instantaneously, $V_{IN}$ reaches $V_{TEG}$ rapidly with very short time delay which only depends on the parasitic capacitances and $R_{TEG}$. After sampling $V_{TEG}$, MPPT is resumed very quickly as well ($V_{MPPT} = \text{HIGH}$). Since $V_{IN}$ is higher than $V_H$, $M_{N2}$ is turned-off and $M_{N1}$ is turned-on. The conserved inductor current, $I_{MPP}$, which is equal to $V_{MPP}/R_{TEG}$, now flows from $V_{TEG}$ to the ground through $M_{N1}$ so that $V_{IN}$ goes back to $V_{MPP}$ almost instantaneously shown in Fig. 2(b).

3 Simulation results

In order to verify the performance of the proposed architecture, the boost converter with fast MPPT in Fig. 2 is designed and compared with the conventional MPPT boost converter in Fig. 1 using a standard 0.13 µm CMOS process with a supply voltage of 1.5 V. The TEG used has an internal resistance, $R_{TEG}$ of 5 Ω and a $V_{TEG}$ of 50 mV~500 mV, which is typical in wireless sensor node applications [7]. In this simulation, $V_{TEG}$ is sampled every 10 µs and total simulation time is 150 µs for both cases. It is assumed that $C_{OUT}$ is sufficiently large and the output voltage of boost converter is in steady state, i.e. $V_{OUT}$ is fixed at 1 V. Also, boost converters with the same size of device are used for both cases and an inductor of 17 µH is used.

For the sampling capacitors in Fig. 2(c), a capacitor of 50 pF is used for both $C_H$ and $C_L$. The values of $V_H$ and $V_L$ are selected to optimize the switching frequency of the boost converter and the MPPT performance together. Too much hysteresis for lowering switching frequency degrades the MPPT performance thereby the overall efficiency. In this simulation, a $V_H$ of 1.16$V_{MPP}$ and a $V_L$ of $V_{MPP}$ results in a switching frequency of about 1 MHz and shows the best overall efficiency. The corresponding values of $\alpha$ and $\beta$ are 0.72 and 1, respectively.

Fig. 3(a) shows voltage waveforms of $V_{IN}$ and $V_{SAMP}$ of the conventional circuit when $V_{TEG}$ is 100 mV (upper) and 500 mV (lower). A sampling time ($V_{SAMP} = \text{HIGH}$) of at least 1 µs is required to guarantee to sample the $V_{TEG}$ of 500 mV since it takes longer time for inductor current to become zero when the difference between $V_{IN}$ and $V_{OUT}$ is smaller (Eq. (1)). Also, after sampling, it takes more than 2 µs for $V_{IN}$ to settle to $V_{MPP}$. On the contrary, in the proposed architecture, shown in Fig. 3(b), a sampling time of 20 ns is enough for successful sampling regardless of $V_{TEG}$ variation since the inductor current is conserved and no RC delay is caused by the off-chip input capacitor. Considering sampling time and $V_{MPP}$ settling time together, the proposed
architecture shows more than 100 times faster performance than the conventional architecture.

In Fig. 3(c), the overall efficiency, $\eta$ and power transfer efficiency (PTE) of the conventional and proposed architectures are compared. The PTE is defined as

$$PTE = \frac{E_{IN}}{E_{AV}}$$

where $E_{AV}$ is available energy from TEG during one MPPT cycle which is 10 $\mu$s in this simulation and $E_{IN}$ is transferred energy from TEG to boost converter during the same cycle. Therefore, the PTE quantifies how well the MPPT is performed during one MTTP cycle. The proposed architecture shows almost ideal PTE performance whereas the conventional architecture shows worse PTE since MPPT is not well performed during $V_{MPP}$ sampling time. Also, the overall efficiency, $\eta$ can be calculated by

$$\eta = PTE \cdot \eta_{\text{BOOST}} = \frac{E_{OUT}}{E_{AV}}$$

where $\eta_{\text{BOOST}}$ is the efficiency of boost converter and $E_{OUT}$ is average output energy. In this simulation scenario, the overall efficiency improves from 70% to 85% over $V_{TEG}$ range from 100 mV to 500 mV.

Fig. 3. (a) $V_{IN}$ waveform of conventional MPPT boost converter (b) $V_{IN}$ waveform of proposed MPPT boost converter (c) Efficiency vs. $V_{TEG}$ of conventional and proposed architecture
In this scenario, a sampling interval of 10 µs is used to emphasize the efficiency improvement of the proposed architecture in such applications as temperature or light intensity changes rapidly. If longer interval can be used, the conventional architecture will have better efficiency, but not as good as the proposed architecture since the harvested energy is always wasted in longer period of sampling time than proposed architecture. It is very important to correct every bit of the harvested energy especially in power-desperate applications such as wireless sensor nodes.

4 Conclusion

In this paper, a boost converter with fast MPPT capability is proposed for energy harvesting applications. By using inductor current conservation method, the sampling time for maximum power point is extremely shortened, thereby improving the overall power conversion efficiency. Also, by using dual-boundary input controlled boost converter, the additional off-chip input capacitance is removed, which also improves the sampling time without sacrificing MPPT performance. This architecture can be applied to any energy harvesting systems and is especially effective when the ambient parameter such as temperature or light intensity changes relatively rapidly.

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