Thermal and solar energy harvesting boost converter with time-multiplexing MPPT algorithm

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Abstract: A single-inductor, dual-input, and dual-output boost converter harvesting thermal and solar energy with a novel time-multiplexing maximum power point tracking (MPPT) algorithm is proposed in this paper. The proposed boost converter harvests energy from thermoelectric generator (TEG) and photovoltaic cell (PV cell) and applies the harvested power to the load and battery. The proposed MPPT algorithm controls the effective frequency of energy harvesting from TEG and PV cell by time multiplexing. As a result, the MPPT can be achieved using a single system clock frequency. The reduced number of required system clock frequencies can leads to power and area savings owing to the reduced clock generation circuits. The proposed boost converter is designed using 65 nm CMOS process technology and evaluated using the HSPICE simulation. The peak power conversion efficiency of the proposed boost converter is 78%.

Keywords: energy harvesting, MPPT, boost converter, time multiplexing

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1 Introduction

As the interest on the wireless sensor node (WSN), which is the core enable technology of internet-of-things (IoT), increases, the interest on the energy harvesting is also increases. The energy harvesting provides sustainable power to the WSN by harvesting energy from ambient sources. It largely extends the lifetime of the WSN and thus reduces the cost of maintenance. Several WSNs, whose power is generated from energy harvesting, are published [1, 2, 3, 4].

However, the supplied power from energy harvesting is inherently limited by the environmental condition. Thus, the multiple-source energy harvesting approaches [5, 6] have been published to diversify the energy source and to secure the reliability of the system. The issue in multiple-source energy harvesting approach is to achieve the maximum power point tracking (MPPT) for each energy harvesting sources.

The MPPT is to match the input impedance of the DC-DC converter with the output impedance of the energy harvesting source. [5, 6] have time-slots for each energy harvesting source and harvest energy from the source during the dedicated time-slot. The input impedance of a multiple-source energy harvesting DC-DC converter seen at the output of the energy harvesting source “A” \( Z_{IN-A} \) can be expressed as below [5].

\[
Z_{IN-A} = \frac{2 \cdot L}{t_1 \cdot \alpha_A \cdot f_{s-A} \cdot \left( 1 + \frac{t_2}{t_1} \right)^{-1}}
\]

where \( L \) is the inductance of the inductor in power stage, \( t_1 \) and \( t_2 \) are the on time of the NMOS and PMOS power FETs, \( \alpha_A \) is the portion of the time-slot for the source “A” compared to the entire time-slot, and \( f_{s-A} \) is the switching frequency of the DC-DC converter when it harvests energy from the source “A”, respectively. In [5], the time-slots for each energy harvesting source are fixed, i.e. \( \alpha \) in Eq. (1) is fixed for each energy sources. Then, the MPPT is achieved by adjusting \( f_s \) in Eq. (1) for the respective energy sources. As a result, each energy source operates in difference switching frequency and thus requires dedicated clock generation circuits. In [6], on the other hand, switching frequency of all energy sources are fixed and the time-slot, i.e. \( \alpha \) in Eq. (1), for each energy source is adjusted for MPPT. The approach in [6] can reduce the required clock generation circuit to one...
but the MPPT efficiency is not optimal since MPPT cannot be simultaneously achieved for multiple energy source only by controlling $\alpha$.

In this paper, a time-multiplexing based MPPT algorithm which can achieve MPPT simultaneously for multiple energy sources with one single clock generation circuit is proposed. The proposed MPPT algorithm is applied to the single-inductor, dual-input, and dual-output boost converter harvesting energy from thermal and solar sources. The rest of this paper is organized as follows. In section II, the structure and operational details of the proposed boost converter is described. In section III, the simulation results showing the performance of the proposed algorithm and boost converter are given and section IV concludes this paper.

2 Proposed boost converter with time-multiplexing MPPT algorithm

The structure of the proposed boost converter is shown in Fig. 1. The proposed boost converter consists of the power stage, the CLKN generator with the proposed time-multiplexing MPPT controller, and the CLKP generator with zero-current detectors (ZCDs). The operation of the proposed boost converter is as follows.

The operation of the proposed boost converter consists of phase A and B. The phase A starts with the initiating the operation of the proposed boost converter and conducts MPPT for the energy harvesting from thermoelectric generator (TEG). The energy harvesting from TEG is activated and that from the photovoltaic (PV) cell is deactivated in phase A. MPPT-TEG block in CLKN generator adjusts the frequency of the CLKN for MPPT of the energy harvesting from TEG. The frequency of CLKN is adjusted by controlling CODEPrelock which determines the period of CLKN during the phase A. With the assumption that the output of the
The proposed boost converter, $V_{\text{OUT}}$, is much larger than the output of the TEG, $t_1$ in Eq. (1) becomes much larger than $t_2$. Then the input impedance of the proposed boost converter seen at the output of the TEG can be derived as below from Eq. (1)

$$Z_{\text{IN-TEG}} = \frac{2 \cdot L}{t_1 \cdot f_{\text{TEG}}}$$

$t_1$ is fixed because the proposed CLKN generator block operates in constant-on-time topology [7]. Thus, by adjusting the frequency of CLKN, the MPPT for TEG can be achieve. The achievement of MPPT is determined by comparing $V_{\text{comp,TEG}}$, which is the half of the open-circuit voltage of TEG, and low-pass filtered $V_{\text{IN-TEG}}$ as described in [8]. $V_{\text{comp,TEG}}$ is half of the open-circuit output voltage of TEG. After the MPPT for TEG is achieved, LOCK$_{\text{TEG}}$ becomes HIGH and the phase B begins. In phase B, the proposed time-multiplexing MPPT algorithm is applied for the MPPT of solar energy harvesting. Fig. 2 shows the principle of the proposed time-multiplexing algorithm.

In phase B, the energy harvesting from PV cell is also activated. The energy harvesting from TEG alternates with that from PV cell by applying SEL$_{\text{TEG}}$ and SEL$_{\text{PV}}$ alternatively as shown in Fig. 2. The MPPT for solar energy harvesting can also be achieved by controlling the frequency of the CLKN. However, the changes in the frequency of CLKN and the alternating operation can break the MPPT for TEG which is achieved in phase A. Thus the proposed time-multiplexing MPPT algorithm changes the ratio of executing energy harvesting from TEG and PV cell when controlling the frequency of CLKN. Let’s assume that the frequency of CLKN when MPPT for TEG is achieved at the end of phase A as $f_{\text{TEG-LOCK}}$, the frequency of the CLKN in phase B as $f_{\text{CLKN-B}}$, and the portion of executing energy harvesting from TEG in phase B as $a$. Then the portion of executing energy harvesting from PV cell becomes $1-a$, and the input impedances of the proposed boost converter seen at the output of the TEG and PV cell in phase B; $Z_{\text{IN-TEG-B}}$ and $Z_{\text{IN-PV-B}}$, respectively, can be expressed as below

![Fig. 2. The waveform of the proposed boost converter (a) when MPPT for TEG is locked in phase A and (b) during the time-multiplexing MPPT for solar energy harvesting in phase B.](image)
where $t_{1,\text{TEG}}$ and $t_{1,\text{PV}}$ are the on time of MN when harvesting energy from TEG and PV cell, respectively. If $\alpha$ in Eq. (3) and (4) is adjusted to maintain the following Eq. (5)

$$\alpha = \frac{f_{\text{TEG-LOCK}}}{f_{\text{CLKN-B}}}$$

Then, $Z_{\text{IN-TEG-B}}$ in Eq. (3) becomes as following Eq. (6).

$$Z_{\text{IN-TEG-B}} = \frac{2 \cdot L}{t_{1,\text{TEG}} \cdot f_{\text{CLKN-B}}}$$

Thus, MPPT for solar energy harvesting can be achieved by adjusting $f_{\text{CLKN-B}}$ while maintaining the MPPT for thermal energy harvesting achieved in phase A. In this way, the proposed time-multiplexing MPPT algorithm can achieve MPPT for energy harvesting from TEG and PV cell simultaneously with a sole frequency of CLKN. $f_{\text{CLKN-B}}$ when MPPT for both energy harvesting from TEG and PV cell is achieved ($f_{\text{CLKN-B-LOCK}}$) can be derived as follows from Eq. (3), (4), and (5)

$$f_{\text{CLKN-B-LOCK}} = f_{\text{TEG-LOCK}} \cdot \left(\frac{t_{1,\text{TEG}} \cdot R_{\text{TEG}}}{t_{1,\text{PV}} \cdot R_{\text{PV}}} + 1\right)$$

where $R_{\text{PV}}$ and $R_{\text{TEG}}$ are the output impedances of the PV cell and TEG, respectively.

The electrical models of the TEG and PV cell, which are used in the design and verification of the proposed boost converter, are shown in Fig. 3 [5]. Because the TEG is modeled by a single internal resistor as shown in Fig. 3(a), the output impedance of the TEG remains constant even though the temperature difference across the TEG changes. Thus, as long as Eq. (5) is satisfied, the MPPT for the TEG is always achieved. On the other hand, the electrical model of a PV cell contains a diode, which is non-linear elements, as shown in Fig. 3(b). It means that the output impedance of the PV cell changes as the irradiance power varies. Thus, it is required to periodically perform the MPPT for the PV cell. This is the reason why the MPPT for the energy harvesting from the TEG is performed before that from the PV cell in the proposed boost converter. Although the environmental conditions change after the phase B, the output impedance of the TEG does not change.
Therefore, MPPT for both the TEG and PV cell can be achieved by only performing phase B again. As a result, the proposed boost converter can track the changes in the environmental conditions and can quickly achieve the MPPT for both TEG and PV cell again.

The controller for the abovementioned proposed time-multiplexing MPPT is realized as follows. First, CODEPrelock at the end of phase A is sampled in SAR-CTRL of CLKN generator in Fig. 1 when LOCKTEG becomes HIGH. Then, CODEPostlock, which determines the period of CLKN during the phase B, is adjusted to make $f_{\text{CLKN-B}}$ become same with $f_{\text{CLKN-B-LOCK}}$ in Eq. (7). The CODEPostlock making $f_{\text{CLKN-B}}$ become same with $f_{\text{CLKN-B-LOCK}}$ is found using successive approximation register (SAR) algorithm. First, CODEPostlock is set to half of the sampled CODEPrelock, which is sampled at the end of phase A and the MSB of CODEALPHA is set to HIGH. Then the achievement of MPPT is determined using the fractional open circuit voltage (FOCV) sensing scheme in [9]. $V_{\text{comp-PV}}$, which is 0.8 times of the open-circuit voltage of PV cell, is compared with the low-pass filtered $V_{\text{IN-PV}}$ to determine the MPPT for solar energy harvesting is achieved or not. If $V_{\text{IN-PV}}$ is smaller (larger) than $V_{\text{comp-PV}}$, it mean that the input impedance of the power stage, $Z_{\text{IN-PV-B}}$ in Eq. (4), is smaller (larger) then $R_{\text{PV}}$. Thus, $f_{\text{CLKN-B}}$ in Eq. (4) has to be reduced (increased) to increase (decrease) $Z_{\text{IN-PV-B}}$. Then, CODEPostlock is added (subtracted) by the quarter of the sampled CODEPrelock to reduce (increase) $f_{\text{CLKN-B}}$ and the MSB of CODEALPHA remains HIGH (is set to LOW). Then, the next MSB of CODEALPHA is set to HIGH and the next operation cycle of SAR begins. After the SAR algorithm ends, CODEPostlock making $f_{\text{CLKN-B}}$ become same with $f_{\text{CLKN-B-LOCK}}$ and corresponding CODEALPHA are found. The resultant CODEALPHA contains information on $\alpha$ in Eq. (3), (4), and (5). If CODEALPHA is 5bit-wide and 20 after the SAR algorithm ends, it means that $\alpha$ is 0.625; 20 divided by 32. In this condition, the energy harvesting from TEG and PV cell has to be performed 20 and 12 times, respectively, during the 32 cycles of CLKN. However, if energy harvesting from TEG and PV cell is performed 20 and 12 time successively, $V_{\text{IN-TEG}}$ and $V_{\text{IN-PV}}$ may be reduced too much below the $V_{\text{comp-TEG}}$ and $V_{\text{comp-PV}}$, respectively, at which the maximum power is harvested. This phenomenon can also occurs when the energy harvesting from multiple source is performed in the dedicated time slots as in [5, 6]. Therefore, a first-order delta sigma modulator (DSM) is used in the proposed boost converter to generate SELPV and SELTEG based on the CODEALPHA. DSM generates bit-stream with minimized successive HIGH or LOW and average value of $\alpha$. Thus, DSM keeps $V_{\text{IN-TEG}}$ and $V_{\text{IN-PV}}$ near the $V_{\text{comp-TEG}}$ and $V_{\text{comp-PV}}$, respectively, and makes the propose boost converter operate at maximum power point at all time.

The CLKP generator in Fig. 1 generates CLKPLOAD and CLKPBAT for PMOS power FETs in the power stage to deliver the inductor current to battery or load. Whether the harvested energy is delivered to load or battery is determined by the voltage level of $V_{\text{OUT}}$. $V_{\text{OUT-COMP}}$ compares $V_{\text{OUT}}$ and $V_{\text{REF}}$, the reference voltage, and generates CLKNLOAD and CLKNBAT which are used for generating CLKPLOAD and CLKPBAT, respectively. The LOW pulse-width of CLKPLOAD and CLKPBAT are determined by the four ZCDs. The principle of zero inductor current sensing is based on sampling $V_X$ with delayed CLKPLOAD or CLKPBAT as in [8].
Four ZCDs are used in the proposed boost converter because there are two energy sources, PV cell and TEG, and two current sink, the load and battery. Thus, considering all combinations where the energy is harvested from and where the harvested energy is delivered to, four ZCDs are used. Only one of the four ZCDs, which is selected by SELTEG or SELPV and to which CLKPLOAD or CLKPBAT pulse is applied, is activated in a switching cycle of the proposed boost converter.

3 Simulation results

The proposed boost converter with the time-multiplexing MPPT algorithm is designed using 65 nm CMOS technology and verified using HSPICE simulation. VDD and VOUT of the proposed boost converter is 1 V. The capacitances of the CIN_TEG, CIN_PV, and COUT are 80 µF, 80 µF, and 40 µF, respectively, and the inductance of L is 2.5 µH.

The TEG and PV cell in [10] and [11], respectively, are modeled based on the electrical models in Fig. 3 and used in the simulation. The 45 TEGs connected in parallel, whose dimension is $2.1 \times 3$ cm$^2$ in total, and 1 PV cell, whose dimension is $2.1 \times 0.7$ cm$^2$ are used for thermal and solar energy harvesting, respectively. The $t_{1\text{-TEG}}$ and $t_{1\text{-PV}}$ are 15 µs and 10 µs, respectively. The specific parameter values of the electrical models of TEG and PV cell used in the verification of the proposed boost converter are summarized in Table I. In addition, Fig. 4 shows the I-V characteristics and the extractable powers of the TEG and PV cell used in the simulation. $Z_{MPP}$ and $Z_{MPP1}$ to $Z_{MPP3}$ are the input impedance of the DC-DC converter at which the maximum power is harvested from the TEG and PV cell, respectively. As mentioned in Section 2, $Z_{MPP}$ remains constant because the output

| Power Source | Parameter | Value |
|--------------|-----------|-------|
| TEG          | RTEG      | 375 Ω (single cell) |
|              |           | 8.33 Ω (45 cells in parallel) |
|              | S (Seebeck coefficient) | 140 mV/K |
| PV Cell      | RS        | 600 mΩ |
|              | RP        | 5 kΩ  |

Fig. 4. I-V characteristics of (a) the TEG and (b) the PV cell in various environmental conditions
The impedance of the TEG does not change even if the temperature difference across the TEG changes. However, the input impedance of the DC-DC converter at which the maximum power is harvested from the PV cell changes from $Z_{MPP1}$ to $Z_{MPP3}$ because the output impedance of the PV cell changes as the irradiance on the PV cell changes.

Fig. 5 shows the waveform of the proposed boost converter at various operating conditions with corresponding $\alpha$ and $f_{CLKN-B-LOCK}$. Because $Z_{MPP}$ is always constant as shown in Fig. 4(a), the variation in the temperature difference applied to the TEG ($\Delta T$) doesn’t affect $\alpha$ and $f_{CLKN-B-LOCK}$ as shown in Fig. 5(a) and (b). However, the input impedance of the proposed boost converter at which the maximum power is harvested from the PV cell varies according to the irradiance energy as shown in Fig. 4(b). Therefore, if the irradiance energy changes, the

![Waveform of the proposed boost converter](image)

**Fig. 5.** Waveform of the proposed boost converter with (a) $\Delta T = 3^\circ C$ and irradiance energy $= 350 \text{ W/m}^2$, (b) $\Delta T = 5^\circ C$ and irradiance energy $= 350 \text{ W/m}^2$, and (c) $\Delta T = 5^\circ C$ and irradiance energy $= 100 \text{ W/m}^2$.

![Power conversion efficiency](image)

**Fig. 6.** The power conversion efficiency of the proposed boost converter for various input power of TEG and PV cell.
\( f_{\text{CLKN-B-LOCK}} \) and \( \alpha \) change following the Eq. (4) and the changes in \( f_{\text{CLKN-B-LOCK}} \) and \( \alpha \) are shown in Fig. 5(b) and (c). In addition, owing to the DSM of the propose boost converter, the energy harvesting from TEG and PV cell conducted alternatively.

Fig. 6 shows the power conversion efficiency of the proposed boost converter. The power consumption of the controller of the proposed boost converter is only 15.234 \( \mu \)W. Most of the power losses come from switching and conduction loss. The peak power conversion efficiency is 78%.

4 Conclusions

In this paper, a single-inductor, dual-input, and dual-output boost converter harvesting thermal and solar energy with a novel time-multiplexing MPPT algorithm is presented. The proposed time-multiplexing MPPT algorithm enables the boost converter to achieve MPPT for both thermal and solar energy harvesting with only a single clock frequency. It can improve the efficiency of the system and reduce the core area by decreasing the required number of clock generator and its control circuits. The adoption of DSM helps the proposed boost converter to operate more close to the maximum power point. The proposed boost converter is designed and evaluated using 65 nm CMOS technology and 78% of peak efficiency is achieved.

Acknowledgments

This research was supported by the Basic Science Research Program through the National Research Foundation of Korea (NRF) funded by the Ministry of Education (NRF-2014R1A1A2055640).