Analysis of the TEG Maximum Power Point Tracking Operation with Continuously Scalable-Conversion-Ratio SC Converter

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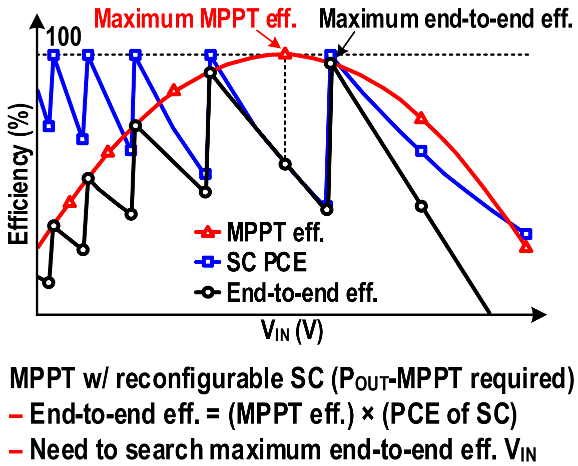
***Abstract* – This paper analyzes the output power of the thermoelectric generator (TEG) and continuously scalable-conversion-ratio SC converter for achieving low-power maximum power point tracking (MPPT) with switched-capacitor (SC) converter. In state-of-the-art SC energy harvesting interfaces, they transfer harvested power inefficiently due to fixed conversion ratios. Therefore, the proposed MPPT method harvest power based on the conventional open circuit voltage method, without additional open circuit voltage sampling period. The proposed energy harvesting converter is designed in a 180 nm CMOS process and is measured to prove that the power can be transferred properly with the analyzed power conversion modes.**

***Keywords*—DC-DC converter, Energy harvesting, Internet of Things**

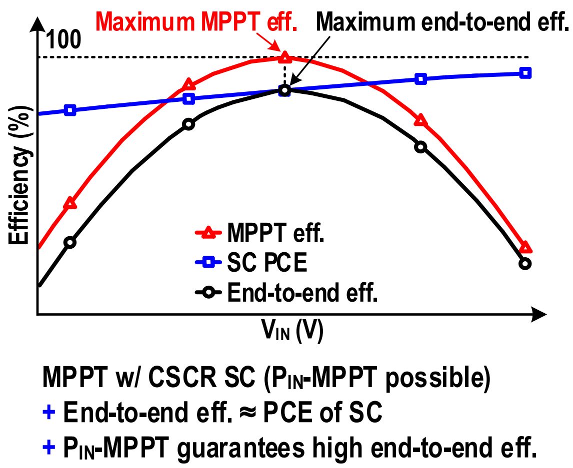
I. INTRODUCTION

Thermoelectric generators (TEGs) are suitable energy harvesting (EH) sources for small and reliable wireless sensor applications, as they are scalable to a small volume and supply stable power from a constant heat source [1], [2]. For higher power conversion efficiency (PCE), inductors were commonly used to match the output impedance of the EH sources. However, since the huge volume of the off-chip inductor limited the form factor of small IoT devices, switched-capacitor (SC) converter EH interfaces have been thoroughly studied for the implementation of small sensors [3]–[6].

Unlike inductor-based converters, fixed VCRs of conventional SC converters drop the converter PCE faster than the MPPT efficiency as V_{IN} changes, as shown in Fig. 1(a). Therefore, in typical battery-employing SC interfaces, the SC converter should be highly reconfigurable to perform voltage conversion between the input (V_{IN}) and output (V_{OUT}) voltages and between V_{OUT} and the battery voltage (V_{BAT}). wide output voltage range of EH sources. However, as the SC converters become more reconfigurable, the increase of output series resistance and gearbox control power limit the overall PCE of EH interfaces. Therefore, conventional reconfigurable SC converters need to track the global maximum end-to-end efficiency point through P_{OUT} sensing. Nevertheless, state-of-the-art SC maximum power point tracking (MPPT) converters operate by sensing the input power (P_{IN}) of a DC–DC converter without considering the efficiency degradation due to the fixed voltage conversion ratio (VCR) or by tracking the global maximum end-to-end efficiency point through sensing the output power (P_{OUT}). These MPPT schemes require high static MPPT control power, and cost output regulation performances.



(a)



(b)

Fig. 1. Conceptual end-to-end efficiency considerations with (a) reconfigurable and (b) CSCR SC converters

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Also, conventional EH SC converters carry out power conversion over a wide range of P_{OUT} using fixed capacitance resources, which leads to a low end-to-end efficiency and low maximum P_{OUT} ($P_{OUT,MAX}$) [3], [6]. Thus, a novel power conversion scheme appropriate for wireless sensor applications is required for high-performance EH SC converters.

In 2019, a single-topology continuously scalable-conversion-ratio (CSCR) SC converter that exhibits relatively constant PCE over wide V_{OUT} range was introduced in [7], as shown in Fig. 1 (b). Although the paper proposed a step-down converter, the relatively constant PCE over the wide voltage conversion ratio (VCR) of the converter is a common characteristic of CSCR SC converters, and is used as a key factor in implementing a power-efficient EH interface in this work.

Thus, this work analyzes an output power of the TEG, conventional reconfigurable SC converter, and CSCR step-up SC converter, and discusses the MPPT scheme that is appropriate for the SC energy harvesting interfaces. Also, the paper introduces a novel lower-power MPPT scheme implemented by associating the theoretical output power of the TEG and CSCR SC converter.

This paper is organized as follows. Section II describes the prior-art reconfigurable SC converters and CSCR SC converter, and analyzes the output power of them. Section III explains the designed converter, Section IV shows the measurement results, and Section VI concludes the paper.

II. OUTPUT POWER ANALYSIS FOR TEG EH INTERFACE WITH SC CONVERTER

A. Prior Art

Studies about SC-based energy harvesting interfaces mostly focused on improving the power conversion efficiency by implementing the low-power MPPT schemes [3], [6], with cascaded SC converter interfaces, as shown in Fig. 2.

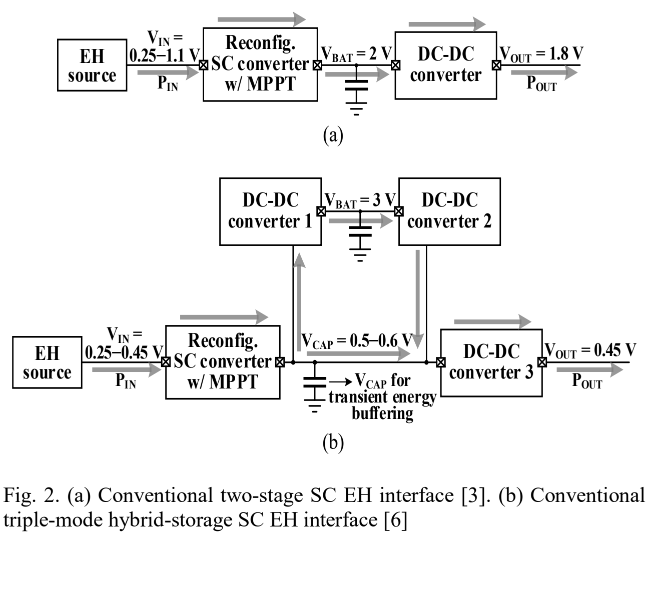

Fig. 2. (a) Conventional two-stage SC EH interface [3]. (b) Conventional triple-mode hybrid-storage SC EH interface [6]

However, assuming the conventional reconfigurable SC converter is operated with ideal power switches, the output power of the SC converter is limited by its slow-switching limit of current operating VCR mode. Therefore, the ideal output current transferred to V_{OUT} from SC converter can be derived theoretically by calculating the slow-switching limit impedance, which exhibits sawtooth waveform in VCR vs. P_{OUT} graph.

Fig. 1(a) shows the simplified concept of end-to-end efficiency with reconfigurable SC converters, which inevitably degrades the end-to-end efficiency due to multiple VCRs.

B. Theoretical end-to-end efficiency consideration with TEG and CSCR SC converter

As introduced in the introduction, Fig. 3 shows the analysis of the output power of TEG and CSCR SC converter. In 2019, a single-topology continuously scalable-conversion-ratio (CSCR) SC converter is introduced to convert input power with a relatively constant power conversion efficiency (PCE) over a wide VCR range. and CSCR SC converters. Therefore, the product of the MPPT efficiency and PCE of CSCR SC converter does not degrade end-to-end efficiency severely, unless the MPPT efficiency is always maintained highly. Moreover, the relatively constant end-to-end efficiency due to the VCR ratio of CSCR SC converters enables them to operate with P_{IN}-MPPT methods, which are easily implemented and do not require any additional power-consuming P_{OUT}-sensing circuits.

Considering P_{IN}-MPPT methods, OCV MPPT is one of the most widely used MPPT schemes because of its high MPPT efficiency and simple circuit implementation [9]. However, the conventional OCV MPPT method requires a long OCV-capture time to charge an OCV-capturing capacitor with small input currents [10]. Moreover, the OCV-capturing capacitor should be sufficiently large to maintain the maximum power point (MPP) voltage from leakage currents for a long time, and an offset-compensated static comparator is required to maintain the MPP state accurately for low-V_{IN} interfaces.

To overcome the aforementioned issues of conventional OCV methods, the proposed MPPT scheme is designed to operate without either a direct OCV-capture period or V_{IN}-connected comparator, as shown in Fig. 3. On the basis of the output power characteristics of the TEG (P_{TEG}) [2], the input power equation of CSCR SC converters (P_{CSCR}) [8], and the reasonable assumption that the ideal MPP voltage of the TEG ($V_{TEG,MPP}$) is half of the OCV voltage of the TEG ($V_{TEG,OC}$) [9], the required operating frequency of the CSCR SC converter (f_{SW1}) for ideal MPPT operation can be expressed as,

$$f_{SW1} = \frac{V_{IN}}{R_{TEG} C_{CSCR} V_{OUT}} \tag{1}$$

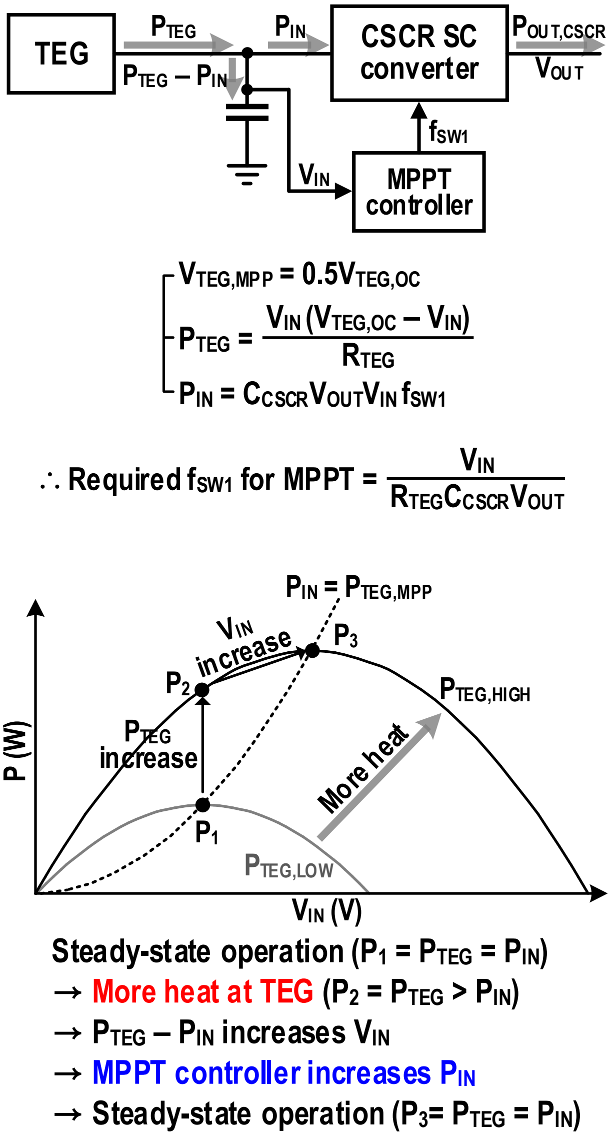

Fig. 3. Theoretical end-to-end efficiency consideration with TEG and CSCR SC converter

where R_{TEG} is the internal resistance of the TEG, and C_{CSCR} is the total flying capacitance of the CSCR SC converter. Therefore, the MPPT controller of the proposed interface is designed to generate value of f_{SW1} that is proportional to V_{IN}.

III. CIRCUIT IMPLEMENTATIONS

Fig. 4 shows the top diagram of the proposed SC interface that shows the novel MPPT operation based on the above analysis. The proposed SC converter interface employs a step-down CSCR SC that extracts power from a 0.1–0.5 V TEG, regulates a 0.75 V output load, and manages a 1.2–1.45 V battery.

The overall interface consists of the proposed MPPT controller, non-overlapping phase generator, decoder, level shifter, gate driver, and step-down CSCR SC converter. For preventing the short-through current between operating phases, the converter operates with non-overlapped phase

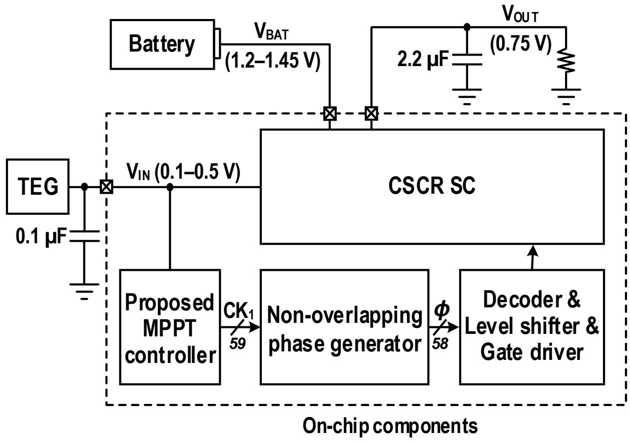

Fig. 4. Top diagram

signals (ϕ), which is generated by the output clock signals (CK_1) of the proposed MPPT controller. The proposed MPPT controller is designed to generate frequency of the CK_1 signal to be equal to the f_{SW1}, derived in Section II.

Unlike the conventional open-circuit voltage method, the proposed interface does not require additional open-circuit voltage sampling circuit, improving the MPPT efficiency. Thus, for showing the accuracy of the proposed MPPT method, the proposed interface employs off-chip capacitor of 0.1 μF, which can rather be replaced by smaller capacitors in small sensor applications.

IV. MEASUREMENT RESULTS

The chip micrograph of the proposed converter is shown in Fig. 5. The total chip area is approximately 7.25 mm^2. Both MIM and MOSFET capacitors are used for power conversion operation with high power density. The controller is located in the middle of the chip to operate the power switches of the converter at the same time as possible, and the power switches are located at the right and left side of the controller to reduce the parasitic capacitance of the gate drivers.

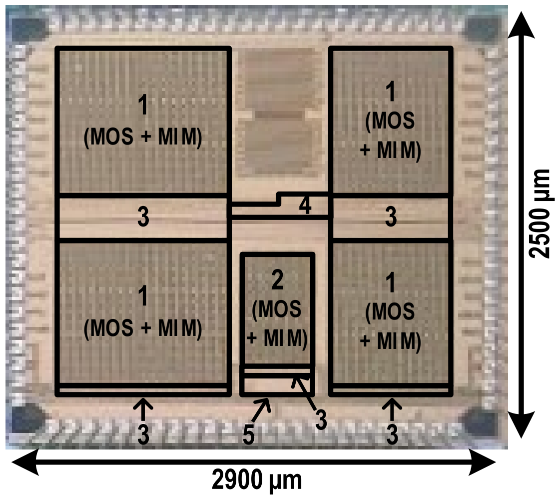

Fig. 5. Chip micrograph

TABLE I. Specifications of the measured CSCR SC converter

Parameter	Value
Process	180 nm
# of V_{IN}s	2
# of V_{OUT}s	2
Flying capacitor	7.8 nF
Input capacitor	0.1 µF
Output capacitor	2.2 µF
Switching frequency	> 10 kHz

Table I presents the summarized specifications of the measured CSCR SC converter. As shown in the table, the converter is designed comparable specifications to the state-of-the-art SC converter-based MPPT EH interfaces [3], [9]. The converter was designed using TSMC 180 nm technology, and employs flying capacitor of 7.8 nF, 0.1 µF input capacitor, and 2.2 µF output capacitor.

Fig. 6 shows the measured transient response of the proposed interface. As shown in the waveform, the proposed interface successfully regulates V_{IN} close to the half of the open circuit voltage of the TEG ($V_{TEG,OC}$) during transient open circuit voltage change.

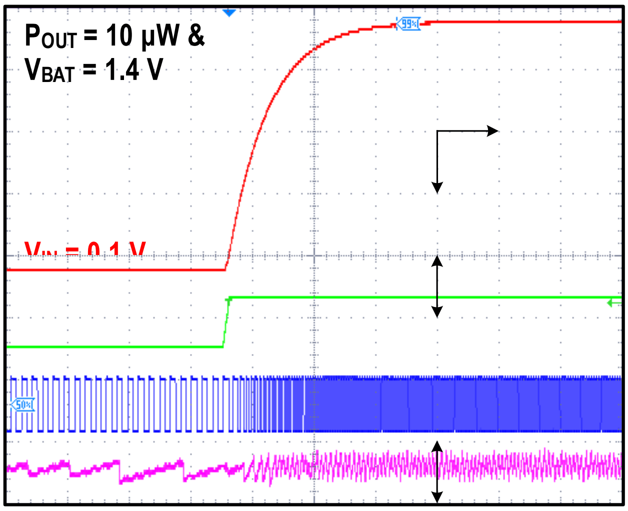

Fig. 6. Transient response.

V. CONCLUSION

An analysis for designing a low-power SC-based MPPT EH interface was introduced. Through formula analysis, the proposed interface is proven to harvest the TEG power with low static MPPT control power. Additionally, the measured waveform of the proposed interface shows that the proposed converter successfully tracks the $V_{TEG,OC}$ and proves that the above analysis is feasible.

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