Highly efficient and wide input range maximum power point tracking circuit with coarse and fine stages for energy harvesting systems

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This letter presents a highly efficient and wide input range maximum power point tracking (MPPT) circuit for energy harvesting systems (EHSs). The conventional MPPT circuit shows attenuation of the power conversion efficiency (PCE) at low input voltages due to insufficient distribution of conversion ratio (CR) in switched capacitor (SC) dc–dc converters. To overcome this critical issue, the proposed circuit implements coarse and fine stages to increase the number of CR. The proposed MPPT operation can be accurately achieved with CR tuning only (without switching frequencies), which results in high PCE. This work is fabricated in the 180-nm CMOS process and measured with the commercial photovoltaic (PV) cells to demonstrate the advantages of the proposed circuit. The measurement results show that the EHS achieves a flat and improved PCE over a wide input range of 0.4 to 1.6 V. The PCE is as high as 88% for an output power below 50 μW and the active area occupies 1.2 mm^2.

Introduction: Switched capacitor (SC) dc–dc converters are commonly used in maximum power point tracking (MPPT) circuits for low power and fully integrated energy harvesting systems (EHS) [1–3]. However, the main disadvantage of this converter is its unavoidable loss due to single conversion ratio (CR). The CR is intrinsic to its structure and induces a charge redistribution loss (CRL) [4]. This loss limits the optimal harvestable voltage to a narrow range and cannot handle a wide input voltage range of photovoltaic (PV) cells. Therefore, a reconfigurable SC dc–dc converter is required to eliminate the CRL.

The MPPT circuit must adjust the impedance of the converter to extract the maximum power to the load, because the maximum power point (MPP) of PV cells is a dependent variable of the environment (light irradiance, temperature etc.). For a reconfigurable SC dc–dc converter, there are three parameters (CR, switching frequency, and capacitance) that can be utilized for the tuning process [5]. For example, the CR and switching frequency tuning parameters are used in [3]. Although the MPPT circuit in [3] sufficiently eliminates the CRL and achieves high tracking accuracy, it still shows attenuation of the power conversion efficiency (PCE) at low input voltages due to insufficient CR distribution over a wide input voltage range. In addition, the MPPT in [3] also uses switching frequency as a tuning variable, which causes a large power.

To overcome these issues, a highly efficient and wide input range MPPT circuit is proposed. In this work, the SC dc–dc converter is divided into two stages (coarse and fine) that are tuned separately during the MPPT procedure. By cascading the two stages, a numerous CR can be obtained and distributed over a wide input voltage range. In addition, the fine stage allows the MPPT procedure to be performed accurately with only the CR tuning, resulting in less power loss compared to conventional works.

Conventional MPPT circuit and its limitation: The block and timing diagrams of EHS with a conventional MPPT circuit are shown in Figure 1 [3]. The constant-on-time (COT) block regulates the output voltage V_{OUT} by switching SC dc–dc converter ON and OFF according to control signal S_{EN}. Meanwhile, the 'power tracking' unit finds the MPP of the EHS by tuning the CR and switching frequency. The detailed MPPT procedure is as follows. The peak output voltage $V_{OUT,PK}$ (the sampled value at the end of the ON period) is used as information about the output power P_{OUT}, and the correlation between $V_{OUT,PK}$ and P_{OUT} is defined as

$$P_{OUT} \propto \frac{V^2_{OUT,PK}}{\ln(V_{OUT,PK}) + V_{OUT,PK}} \quad (1)$$

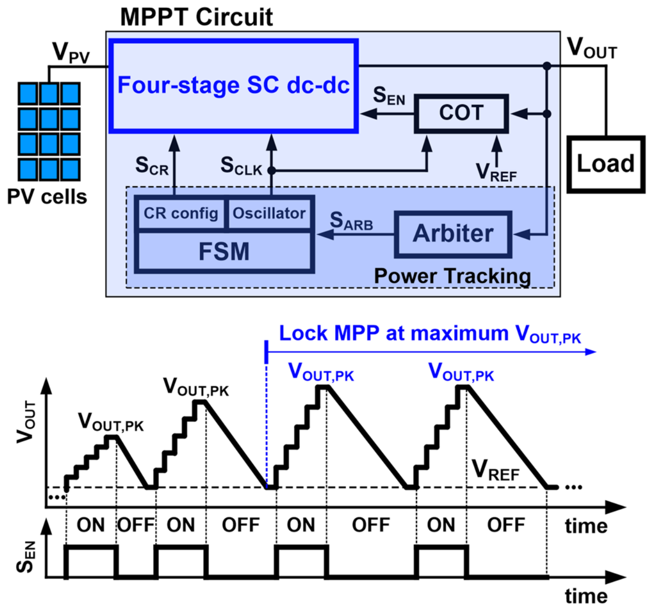

Fig. 1 *Block and timing diagrams of EHS with conventional MPPT circuit. EHS, energy harvesting systems; MPPT, maximum power point tracking.*

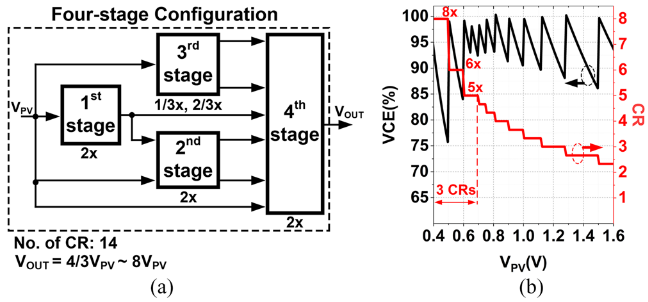

Fig. 2 *(a) Four-stage configuration of SC dc–dc converter in conventional MPPT circuit. (b) VCE and CR versus input voltage. CR, conversion ratio; SC, switched capacitor; VCE, voltage conversion efficiency.*

Equation (1) means that $V_{OUT,PK}$ can be used as power indicators. The $V_{OUT,PK}$ is sampled and stored by 'Arbiter'. Then, the $V_{OUT,PK}$ is evaluated while CR and switching frequency are tuned continuously by finite state machine (FSM) unit. Eventually, the MPPT circuit locks the optimal CR and switching frequency at the maximum $V_{OUT,PK}$ when the MPP is found. In this conventional work, a four-stage SC dc–dc converter is implemented to obtain less CRL through many CRs. However, there are two important issues that affect the overall performance of EHS. First, as shown in Figure 2a, the conventional circuit uses a four-stage SC dc–dc converter to provide 14 CRs. The first and second stages double the input voltage. The third stage provides a 1/3× or 2/3× fractional CR. The forth stage combines the previous-step results and uses a voltage doubler to boost the voltage. By cascading the stages and selecting their input connections through a demultiplexer, the 14 CRs from 4/3× to 8× can be obtained. As illustrated in Figure 2b, it can be seen that voltage conversion efficiency (VCE) is still lowered at low input voltage, although it is better than the singe CR case. Note that the VCE represents the PCE with CRL. This significant problem is caused by the small number of CRs at low input voltages. Specifically, there are only three CRs (5×, 6×, 8×) for the input voltage range of 0.4 to 0.7 V. In the other word, at low input voltages, the CR distribution is not sufficient to eliminate the CRL. Moreover, it is difficult to extend the number of CRs with this architecture for better VCE performance. Therefore, many stages have to be added to provide more CR, which causes large converter losses due to the use of more capacitors and switches. Second, the conventional work also uses the switching frequency as a fine-tuning parameter. This helps the MPPT circuit to determine the MPP due to the correlation between the switching frequency and the impedance of SC dc–dc converter. However, since the MPPT circuit captures a high switching frequency during operations, the switching loss of the converter increases rapidly.

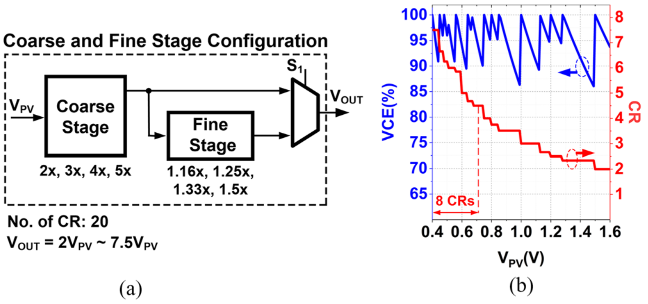

Fig. 3 *(a) Coarse and fine stages configuration of SC dc–dc converter in proposed MPPT circuit. (b) VCE and CR versus input voltage*

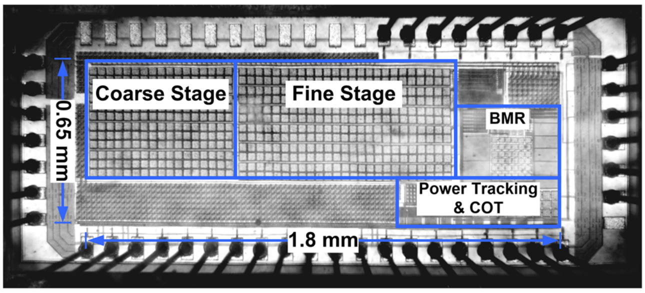

Fig. 4 *Die micrograph*

Proposed MPPT circuit: To solve the aforementioned problems, the proposed SC dc–dc converter adequately obtains sufficient number of CRs by dividing it into two stages (coarse and fine) to improve the CR distribution over a wide input range. The stage configuration of the SC dc–dc converter is shown in Figure 3a. In the coarse stage, four step-up integer CRs (2×, 3×, 4×, 5×) are implemented, covering a wide input voltage range from 0.4 to 1.6 V with an output voltage target of 3 V. And in the fine stage, four step-up fractional CRs (1.16×, 1.25×, 1.33×, 1.5×) are implemented to fine-tune the impedance of the converter during the MPPT procedure. With eight CRs in the coarse and fine stages and a proper connection, a total of 20 CRs can be obtained. For instance, if the output of coarse stage is directly connected to the load, four CRs of 2×, 3×, 4×, and 5× are achieved. And, when the output of the coarse stage is connected to the input of the fine stage, 16 extended CRs can be also obtained. Therefore, sufficient CRs are achieved by stacking the two stages together and distributed over wide input voltage range. Figure 3b shows the VCE and CR versus input voltage of the proposed MPPT circuit. As shown in the figure, there are eight CRs for an input range of 0.4 to 0.7 V. Therefore, better VCE can be achieved at low input voltages compared to the conventional work, and the VCE always stays above 85% within the input voltage range of 0.4 to 1.6 V. In the MPPT procedure, because many CRs are obtained by using coarse and fine stages, the high tracking efficiency can be achieved without switching frequency tuning. Instead, a fixed and low switching frequency of 200 kHz is used in this work to reduce the dynamic and the switching loss of the converter. In conventional work, depending on the environment condition, the switching frequency tuning forces the system to use a frequency of 1 MHz which results in large power loss. To find the MPP precisely, the coarse, fine stage are tuned individually, the CR of coarse stage is tuned first to find the local MPP. Then, the MPPT circuit tunes the CR of fine stage to find global MPP. Eventually, the circuit locks the global MPP and uses it for the system.

Measurement results: The proposed MPPT circuit is fabricated in the 180-nm CMOS process. The die micrograph is shown in Figure 4. It occupies an active area of 1.2 mm^2. The performance of the proposed circuit is demonstrated with the commercial PV cells (4 × KXOB25). The transient response of the MPPT circuit is measured to verify the behaviour of the output voltage regulation and the MPP-tracking performance. Figure 5 shows the tracking waveforms including V_{OUT}, V_{PV}, and control signal (S_{MPPT}, $S_{TRIGGER}$). A stable output voltage V_{OUT} is

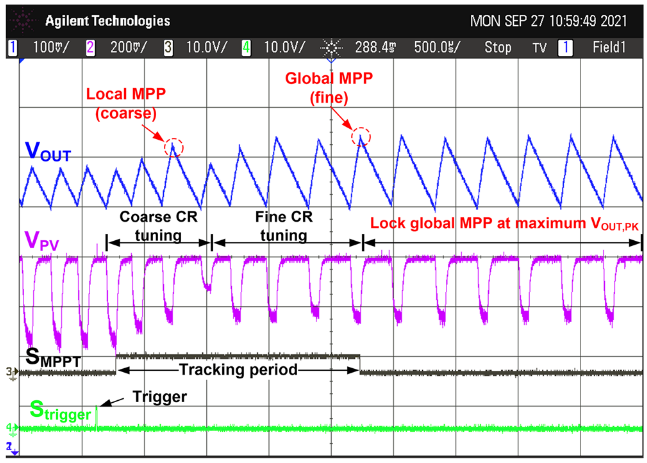

Fig. 5 *Tracking waveforms of proposed MPPT circuit*

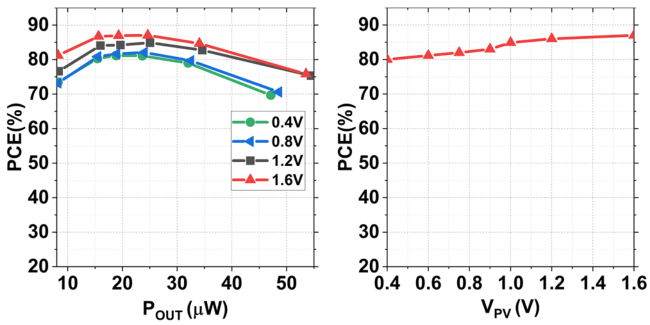

Fig. 6 *(a) Measured PCE versus output power with four different configurations of PV cells. (b) measured PCE versus input voltage. PCE, power conversion efficiency; PV, photovoltaic.*

Table 1. Performance comparison

Parameters	[3] JSSC 16	[1] TCAS 18	[2] JSSC 18	This work
Technology (nm)	180	180	65	180
No. stage	4	-	-	**2**
MPPT tuning	CR frequency	CR frequency	CR frequency	**CR only**
Output power (μW)	< 50	< 35	< 300	< 50
Max. PCE (%)	81	72	88	**88**
PCE (%)@0.45 V	40	-	-	**80**
Active area (mm^2)	2.3	0.6	0.54	1.2

produced as shown. When a MCU generates a trigger signal $S_{TRIGGER}$ which is used to detect the change of environment condition, the MPPT circuit starts finding MPP by setting S_{MPPT} to high level. The CR of coarse stage is first tuned from 5× and captured the local MPP at CR of 3×. Then, CR of fine stage is tuned from 1.5× and captured the global MPP at CR of 1.33×. The tracking waveforms verify that the MPP is correctly captured as the highest $V_{OUT,PK}$ is locked after the MPPT procedure. The PCE values of the proposed MPPT circuit are measured with four different configurations of PV cells (0.4, 0.8, 1.2, and 1.6 V), as shown in Figure 6a. The MPPT circuit uses the CR tuning parameter to extend the input range. Therefore, the system with the proposed MPPT circuit can cover a wide input range from 0.4 to 1.6 V. The peak PCE of 88% is obtained with 1.6-V PV cells. Within the output power range from 10 to 50 μW, the PCE is always higher than 70%. Figure 6b shows the PCE as a function of input voltages. Thanks to the proposed circuit, the PCE is almost flattened over a wide input voltage range unlike [3]. In addition, the switching frequency of SC dc–dc converter is fixed at a low frequency of 200 kHz. Thus, the dynamic power consumption is relatively small. The total power consumption of the MPPT circuit is 1.1 μW. The performance of the proposed MPPT circuit is compared with the state-of-the-art circuits as shown in Table 1. The proposed circuit achieves competitive or higher PCE to that of prior works [1–3]. More importantly, this work provides much higher PCE at low input voltage.

Conclusion: This letter proposes a highly efficient and wide input range MPPT circuit for EHS. In the proposed circuit, by using coarse and fine stages, the 20 CRs are obtained, and they are distributed over a wide input voltage range. Therefore, the PCE of EHS is flattened and improved for the input voltage range of 0.4 to 1.6 V. Furthermore, the power consumption of the MPPT circuit is sufficiently reduced by using CR tuning only in the MPPT procedure. This work is fabricated in the 180-nm CMOS process and measured with commercial PV cells to demonstrate the advantages of proposed circuit. The achieved PCE is as high as 88% for an output power below 50 μW.

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