I. INTRODUCTION

Due to the applications of the wireless sensors [1], modern mobile devices [2], IoT (Internet of Things) [3], wireless sensor networks (WSN) [4], and roof-integrated PV (photovoltaic) systems [5], PV energy harvesting becomes an attractive technique because the solar energy possesses highest power density [6]. A 5 W PV panel with voltage ranging from 10 to 20 V is widely used in the applications of medical equipment and air monitoring systems [7]. In order to improving the efficiency of the PV energy harvesting, various MPPT (Maximum power point tracking) techniques are presented in the prior works [1]-[11] and [12]. The Incremental conductance method [8], the neural network and the fuzzy logic control method [9] compute the power and then trace the MPP (Maximum power point) using plenty of digital logic circuits, which needs the ADC and MCU. It results in a long tracking procedure and great cost. The analog power calculation method [10] and the perturb & observe (P&O) method (also called hill-climbing method) [3], [5], [6], [11] to achieve fast tracking and reduce the system cost by sensing the output current proportional to the output power and then determining the MPP. The tracking speed is further improved by using the sectored hill-climbing method [1], which analyzes and stores the features of the solar panel with an embedded resistor array to obtain the MPP. This method is a customized design to the specific solar panel. Besides, these methods require complex control circuits. The fractional open circuit voltage (FOCV) method uses simple control circuits to sense the open circuit voltage and detect the MPPT [3], [4]. However, the precision is sacrificed.

In this work, a 5 W solar panel with 10~20 V voltage is used as the energy source and a Li-ion battery of 3.6 V to 4.2 V is used as the energy storing device. By using the MPPT of P&O method, the adaptive constant current (ACC) mode with PWM control according to the output current of the solar panel is proposed. Moreover, the constant voltage (CV) mode is utilized when the Li-ion battery reaches the full-charged for protect the Li-ion battery. The proposed design is carried out using TSMC 0.5 um UHV process. The simulation results show that the peak MPPT tracking efficiency is 98% with the power throughput of 5 W and the switching frequency of 1 MHz.

II. THE PROPOSED HV ENERGY HARVESTING CIRCUIT WITH ACC/CV MODE AND MPPT CONTROL

Fig. 1 shows the block diagram of the proposed design, which includes a 5 W solar panel energy source, a Li-ion battery load with voltage from 3.6 V to 4.2 V, a Buck converter as the energy harvesting circuit and a MPPT control circuits to sense the open circuit voltage and detect the MPPT [3], [4]. However, the precision is sacrificed. 

In this work, a 5 W solar panel with 10~20 V voltage is used as the energy source and a Li-ion battery of 3.6 V to 4.2 V is used as the energy storing device. By using the MPPT of P&O method, the adaptive constant current (ACC) mode with PWM control according to the output current of the solar panel is proposed. Moreover, the constant voltage (CV) mode is utilized when the Li-ion battery reaches the full-charged for protect the Li-ion battery. The proposed design is carried out using TSMC 0.5 um UHV process. The simulation results show that the peak MPPT tracking efficiency is 98% with the power throughput of 5 W and the switching frequency of 1 MHz.

The MPPT Control circuit uses a Current Sensor to sense the output battery current, I_BAT. Besides, a Ramp&Clock Generator generates the required switching signal, Clk, and the ramp signal, V_ramp. The MPPT Controller and the PWM

Fig. 1 The block diagram of the proposed design.
then compared by the comparator, CMP1, to determine the operating power point. Referring to Fig. 3, the power point is adjusted by control signals, C(n), Q(n), and Q(n+1), which are generated by the XNOR gate and the DFF. C(n) of logic 1 refers to the current increased. Q(n) and Q(n+1) denote the changing direction of VCC in the last and the present cycle, respectively. Q(n) of logic 1 refers to the rising of VCC in the last cycle. Thus, the MPPT tracking process is achieved by repeating the loop composed of the paths 2, 3, 4, and 5, as shown in Fig. 3. Because the current is proportional to the power of the solar panel and the variation of IBA at each cycle is very small, the MPPT is achieved. Moreover, Q(n) is utilized to control the switches, sw1 and sw2, to determine that the node VCC is charged or discharged. Referring to Fig. 4, the MPPT control signal, VMPPT_PWM, is then generated and is used to adjust the output current, IBA, according to VCC and Vramp. Notably, sclk1 and sclk2 are the sampling signals. Besides, sclk3 is the triggered signal of the DFF.

B. CV Mode control with PFM

The CV Mode control circuit is showed in Fig. 5. With the comparator Comp3, VBAT is compared to the reference voltage, Vfull, which is 4.2 V to indicate that the Li-ion battery is full-charged. When VBAT is greater than Vfull, the output of the DFF is logic 1 such that the output signal, VPFM, keeps at logic 1. For VBAT < Vfull, the output of the DFF is logic 0 and VPFM is coupled to the clock signal, CLK, by the OR gate. The waveforms are illustrated in Fig. 6.

C. Current Sensor and ZCD

The Current Sensor is revealed in Fig. 7. By using the current mirrors of the transistors, M1 and MP, with the ratio of the feature size equaling to 1/K, the sensed internal current would be \( I_{\text{sen}} \), because the current through M1 and M2 are \( I_{\text{BAT}} \) and \( I_{\text{BIAS}} \), respectively. The output voltage, Vsen, is then expressed by the following equation. If \( I_{\text{BIAS}} \ll \frac{I_{\text{BAT}}}{R} \), Vsen would be linearly proportional to the battery current, IBAT:

\[
V_{\text{sen}} = \left(\frac{I_{\text{BAT}}}{K} - I_{\text{BIAS}}\right) \cdot R_{\text{sen}}
\]
D. Current Sensor and ZCD

Fig. 8 shows the schematic of the ZCD. When $V_x$ is pulled to 0V, the DFF is reset and $D_N$ becomes 0 V to turn MN off. When $V_x > 0V$, $D_N$ is coupled to the signal, $V_N$, provided by the Nonoverlap circuit for normal operation.

Fig. 6 The waveforms in the ACC mode and CV mode control

III. IMPLEMENTATION AND SIMULATION RESULTS

The proposed design is implemented using a typical 0.5 um UHV process. Fig. 9 shows the layout of the proposed design, where the area is 3600 \times 3480 \text{um}^2. The core area is 2073 \times 2295 \text{um}^2. Fig. 10 shows the simulated waveforms of the energy harvesting circuit in the charging process. With $I_{Ph}$ changing from 0.3 A to 0.1 A and then back to 0.1 A, the control signals, $C(n)$, $Q(n)$, and $Q(n+1)$, varies according to the MPPT process, as shown in Fig. 3. Besides, the output current, $I_{bat}$, is tracking the MPP and the battery voltage, $V_{bat}$, is increased at the same time. When $V_{bat}$ reaches 4.2 V, the energy harvesting circuit operates in the CV mode and the current, $I_{BAT}$, becomes very small to protect the Li-ion battery from over-charging. In this case, the circuit does not operates at MPPT because the efficiency of the solar panel is not the first priority. However, the PFM control is utilized to improve the efficiency of the buck converter at the light load.

The simulated enlarged waveforms of the control signals in ACC mode. $V_{MPPT \_PWM}$ is generated by comparing $V_{ramp}$ and $V_{CC}$, as shown in Fig. 2. The driving signal, $D_P$, is then coupled to $V_{MPPT \_PWM}$ based on the PWM control in ACC mode.

The simulated enlarged waveforms of the control signals of the CV mode is revealed in Fig. 12. The driving signal, $D_P$, is the result of the OR operation of $V_{MPPT \_PWM}$ and $V_{PFM}$. In the CV mode, $I_{BAT}$ reduces gradually to protect the battery. Moreover, the worst case of the peak MPPT efficiency is simulated to be 98% among the different processes of TT, FF, SS and the temperature variation of 0°C, 25°C, and 75°C.

Table 1 summarizes the performance comparison with several prior works. The proposed design provides the maximum operating voltage and the maximum power throughput. The FOM (Figure of merit) is given by considering the input voltage and the peak MPPT efficiency. The proposed design possesses the best performance.
TABLE I. COMPARISONS WITH PRIOR WORKS

<table>
<thead>
<tr>
<th>Publication</th>
<th>[1]</th>
<th>[5]</th>
<th>[6]</th>
<th>[10]</th>
<th>This Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>Year</td>
<td>BSC</td>
<td>PPE</td>
<td>VLISI-DAT</td>
<td>ISVLSI</td>
<td>SPIES</td>
</tr>
<tr>
<td>Technology</td>
<td>0.35µm</td>
<td>0.35µm</td>
<td>0.18µm</td>
<td>0.18µm</td>
<td>0.5µm</td>
</tr>
<tr>
<td>MPPT Method</td>
<td>Sectored Hill-Climbing</td>
<td>Quasi-P&amp;O</td>
<td>P&amp;O</td>
<td>P&amp;O</td>
<td>P&amp;O</td>
</tr>
<tr>
<td>Input voltage</td>
<td>0.5–2V</td>
<td>3.5–5.4V</td>
<td>0.5–1.1V</td>
<td>0.3–0.7V</td>
<td>10–20V</td>
</tr>
<tr>
<td>Output voltage</td>
<td>4.2V</td>
<td>NA</td>
<td>1.2–1.8V</td>
<td>NA</td>
<td>3.6–4.2V</td>
</tr>
<tr>
<td>Frequency (KHz)</td>
<td>500</td>
<td>530</td>
<td>NA</td>
<td>1000</td>
<td>1000</td>
</tr>
<tr>
<td>Power</td>
<td>0.5</td>
<td>27</td>
<td>0.045</td>
<td>0.15</td>
<td>5</td>
</tr>
<tr>
<td>Throughput (W)</td>
<td>99%</td>
<td>95%</td>
<td>90%</td>
<td>95%</td>
<td>98%</td>
</tr>
<tr>
<td>MPPT Efficiency</td>
<td>3.4</td>
<td>0.56</td>
<td>NA</td>
<td>NA</td>
<td>20</td>
</tr>
<tr>
<td>Power Consumption (mW)</td>
<td>1.625</td>
<td>0.45</td>
<td>1.43</td>
<td>2.373</td>
<td>12.53</td>
</tr>
<tr>
<td>Chip area (mm²)</td>
<td>1.98</td>
<td>5.13</td>
<td>0.99</td>
<td>0.665</td>
<td>19.6</td>
</tr>
</tbody>
</table>

Note: * The number indicates only the area of the control circuit of [5].

REFERENCES


IV. CONCLUSIONS

By using the MPPT and PWM control with ACC mode, the Li-ion battery is charged by the adaptive constant current based on the solar panel. The worst case of the peak MTTP efficiency is 98 % with the photocurrent from 0.1 A to 0.3 A among the various process and temperature simulation corners. Besides, the energy harvesting circuit enters the CV mode with PFM control when the voltage of Li-ion battery is close to 4.2 V to protect the battery from over-charging.

ACKNOWLEDGMENT

This investigation was partially supported by Ministry of Science and Technology, Taiwan, under grant MOST 108-2218-E-110-002-, MOST 108-2218-E-110-011 and MOST 108-2221-E-230-008-. The authors would like to express our deepest appreciation to TSRI (Taiwan Semiconductor Research Institute) in NARL (Nation Applied Research Laboratories), Taiwan, for the assistance of chip fabrication.

Authorized licensed use limited to: National Sun Yat Sen Univ. Downloaded on November 11,2020 at 01:48:28 UTC from IEEE Xplore. Restrictions apply.