A 43% @0.1V efficiency self-sustaining solar energy harvester in indoor lighting

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Abstract. This paper presents a self-sustaining solar energy harvester (EH) based on 130nm process, which consists of a low voltage cold start (CS) circuit and a high efficiency boost charger. The CS circuit makes the boost charger self-sustaining and start the boost circuit from the 100mV input. An adaptive switch frequency modulation (SFM) and switch capacitor modulation (SCM) are proposed to minimize the switch loss and conduction loss of boost charger, thus reduce overall circuit power consumption. The proposed boost charger utilizes a dual voltage technique for reducing the power dissipation of the internal circuit. The efficiency of the boost charger ranges from 43% at $V_{IN} = 100mV$ to 65% at $V_{IN} = 300mV$.

1. Introduction
In recent years, IoT smart nodes are widely used in indoor environments. The self-sustaining of smart nodes has become an important indicator to measure the performance of power supply. Therefore, domestic and foreign scholar’s research on power supply is mainly focused on this field [1, 2]. Solar energy harvester becomes an attractive solution to power the IoT smart nodes, providing excellent battery lifetime and access of operation on small coin-cell battery. Because solar energy has higher power density than other sources, such as thermal and vibration [3]. In dim indoor environments, the light intensity is only 100~200lux. The output power generated by solar cell in indoor light environment is about 10uW/cm² when the output voltage is only 100~200mV. Harvesting from low input power faces a critical challenge, which is that low input power demands ultra-low power circuitry to reduce power consumption and achieve high efficiency. Further, the EH need low voltage cold start circuit to provide initial operating voltage for the boost charger to achieve EH system self-sustaining.
So far, a variety of energy harvester solutions for extracting energy from low-voltage, low-power sources have been proposed and obtained corresponding research results. A boost charger can be started with an input voltage of 35mV under the aid of a mechanical switch [4], however, the maximum efficiency achievable with an EH system is only 58%. The self-starting battery charger IC [5] achieves an efficiency of 80% at 0.5V but starts up at 330mV. In order to enable the boost charger to start at a low voltage, a self-starting boost converter based on a transformer structure is proposed in [6], achieving the input voltage at least 40mV. However, the shortcomings of the transformer-based structure are also clearly exposed. Considering the size and high integration of the chip, the use of a transformer increases the size of the EH, making it inconvenient for the EH system to integrate and increase the cost. These EH suggest solutions for extracting energy using photovoltaic cells in dim conditions. However, there are still unresolved issues in some areas, such as efficiency, start-up mechanisms, start-up voltage and harvester area.

2. Proposed solar energy harvester
The proposed solar energy harvester consists of two main modules, a cold start unit and a boost charger. In an indoor lighting environment, the cold start unit can operate under an input voltage (~100mV) obtained from a single solar cell output. Adaptive switch capacitor and frequency modulation reduces the dissipation of the power transistors and promotes the energy efficiency of the boost charger. In addition, the system uses a dual voltage supply to reduce the power dissipation of the internal circuit. The hysteresis adjustment is designed to provide a constant 3V output voltage for the smart nodes of the IoT network. Using EH to supply power for IoT applications can prolong battery lifetime by extending the energy source.

2.1 Architecture of the solar EH system
The architecture of EH is shown in Figure 1. It consists of an input-regulation boost charger that extracts energy from the photovoltaic cell and charges two off-chip capacitors (CSTOR & CVDDL). When the voltage on CVDDL falls below under-voltage (UV) threshold, the PMOS switch array between capacitor CSTOR and CVDDL turns on, then the VDDL voltage begins to rise. VDDL provides the supply voltage (1.6V) for the boost charger module in EH system. Charging is terminated when VSTOR reaches the over-voltage (OV) threshold. If the OV signal is invalid, the EH system restart. Due to the photovoltaic can experience the change of power density in the environment, thus, the PV output power changes accordingly. Illumination, ambient temperature and other variables affect the output of the photovoltaic cell, which in turn affects the maximum power point (MPP). The charger regulates the input voltage through the MPPT network as a part of the open circuit of the EH system. When the input voltage changes, the V_IN DETECT module generates a control signal that is sent to the charger to control the switch cap and switch frequency adjustments in switch array. The goal is to minimize switching loss and conduction loss under different input conditions, reducing power consumption overhead.
2.2 Low input cold start circuit

When the energy in the CSTOR is insufficient to drive the charger circuit, cold start as an auxiliary boost converter that raises the initial low input voltage to kick start the boost charger. Or after the VSTOR deeply discharges, the voltage is lower than the operation voltage of the boost charger, then the CS unit restarts. Figure 2 (a) demonstrates a brief circuit of the CS unit. The function of the cold start unit is to enable the EH system to start working at the output of single piece of solar cell (~100mV) under weak light conditions. It charges the CSTOR to 1.6V to power the main charger, which then cuts off the cold start and switches to the highly efficient boost charger circuit. The CS unit consists of a ring oscillator composed of a stacked inverter and a gate driver based on the output of charge pump. The structure of the stacked-inverter is depicted in Figure 2 (b). A ring oscillator using a stacked-inverter structure has higher DC gain and output voltage swing. Meanwhile, the OSC can work with a very low supply voltage (~50mV). The DC gain is obtained:

\[ A = \frac{(1 + A_1) \cdot g_{mp2} + (1 + A_3) \cdot g_{mn2}}{g_{dsp2} + g_{dsn2}} \]  

The high pulse output signal generated by the CP drives the LS_MOS, which together with the HS_MOS in the form of a body diode constitutes a boost converter. When the OSC enable signal ON is active, the pulse generator is activated then the charge pump (CP) is driven to raise the input voltage of EH system. The gate driver needs to reduce the equivalent resistance of the LS_MOS to improve conduction power consumption.

![Figure 1. Architecture of the solar energy harvester](image_url)

![Figure 2. (a) Circuit implementation of the Cold Start (b) Stacked-Inverter](image_url)
2.3 Main boost charger

When the cold start raises the voltage on CSTOR to 1.6V, the EH system mode switching circuit works, then the cold start turns off, and the main boost charger starts to work. Figure 3 reveals the architecture of the main charger that regulates the \( V_{IN} \) at the MPP of the EH and transfers the energy from PV to CSTOR. When the MPP_EN signal is pulled high, the sampling voltage (VSAMP) is obtained by periodically turning off the charger.

The input voltage \( V_{IN} \) can be boosted to the open circuit voltage of the EH. At the beginning of the sampling period of MPP, a voltage VSAMP (VSAMP=0.8\( V_{OC} \)) is acquired according to solar cell characteristics for MPP extraction during the remaining period. The charger designed in this paper is a synchronous rectification boost converter. Therefore, hysteresis regulation is used to achieve a constantly stable voltage output. When VSTOR is higher than 1.6V, the main charger enable-signal CHARGER_EN is pulled high. When the main charger is ON and \( V_{IN} \) exceeds VSAMP, the COMP1 triggers the digital logic block to turn ON the power switching transistors, in which the low side (LS) NMOS power transistor is turned on first. After a preset delay the low-side power switch will automatically turn OFF. Then the PMOS transistor turns ON and remains the state until the inductor current discharged to zero. If \( V_{IN} > VSAMP \), the cycle repeats, using the delay module to limit the on-time of the LS and HS switches to prevent current saturation in the inductor. The charger is turned OFF by the OV comparator COMP2 once VSTOR reaches the OV threshold set by the user.

![Figure 3. Charge architecture showing comparators and logic needed for operation;](image)

2.4 Adaptive SCM and SFM

The photovoltaic cell is used in indoor low-light environments, and as the EH input energy decrease, the difficulty of extracting excessively increases. The adaptive SCM and SFM are proposed to minimize the sum of switching loss and conduction loss in dim indoor environments. The light intensity determines the output current of the PV cell, which affects the on-time of LS and HS. The switch time of LS and HS transistor is given as equation (2), (3):

\[
T_{LS} = \frac{L \cdot I_{IN}}{V_{IN}} \quad (2)
\]

\[
T_{HS} = \frac{L \cdot I_{IN}}{V_{OUT} - V_{IN}} \quad (3)
\]

Where the \( V_{IN} \) and \( I_{IN} \) are the input voltage and input current of the boost charger, and L represents the
The goal behind this paper is to achieve a high power efficiency in caliginous environments. Figure 5 demonstrates the performance of the cold-start circuit, the figure shows that after the cold start circuit raises the VSTOR to 1.65V, the SWITCH signal is pulled high and the system operating mode switches to the boost charger circuit. The comparator hysteresis in the mode switching circuit pushes the flip point back 50mV. The output of the boost charger, over-voltage and inductor current are presented in Figure 6. The efficiency of the energy harvester in different input voltage from 0.1V to 0.5V is shown in Figure 7. In indoor low-light environment, the boost charger successfully achieves a power efficiency of 65% at 300mV input and 43% at 100mV. The proposed Energy Harvester was fabricated in a 130nm process of the global foundry. The layout graph is shown in Figure 8, it can be seen MIM capacitor layout occupies a large area.
A performance comparison is presented in Table 1. Compared to the boost charger in [7] and [8], the proposed solar EH has lower \( V_{\text{IN}} \), higher output voltage \( V_{\text{OUT}} \), and better power conversion efficiency. The boost charger in [7] is fully integrated, but its power conversion efficiency is significantly lower than [8] and this work. In addition, the circuit needs to provide an auxiliary voltage of 1.2V for the voltage doubler. In [8], although there is a lower input voltage and a higher output current, the output voltage is only 0.619V, which restricts the application scenario of the harvest system.

### Table 1. Comparison with prior state-of-the-art works

| Parameters            | [7] ISSCC’14 | [8] JSSC’15 | This work |
|-----------------------|--------------|-------------|-----------|
| Technology            | 180nm        | 130nm       | 130nm     |
| Fully int             | Yes          | No          | No        |
| Aux Volt              | 1.2V         | No          | No        |
| Modulation            | SFM          | NA          | SFM, SCM  |
| \( V_{\text{OUT}} \) | 2.2-5.2V     | 0.619V      | 3V        |
| CS Voltage            | 0.14V        | 0.15V       | 0.1V      |
| Efficiency            | 40%@0.25V*   | 34%@0.18V   | 43%@0.1V  |
|                       |              | 60%@0.3V*   | 65%@0.3V  |

*Extracted from the measurement results

### 4. Conclusion

The energy harvester system proposed in this paper is realized by high-efficiency charger and low input voltage cold start circuit. The input voltage is at least 100mV, and the power efficiency is 43% at this input voltage. When the input voltage climbs to 300mV, it achieves a peak efficiency of 65%.

### 5. References

[1] I. Lee, W. Lim, A. Teran, J. Phillips, D. Sylvester, and D. Blaauw 2016 21.4 A >78%-efficient light harvester over 100-to-100klux with reconfigurable PV-cell network and MPPT circuit ISSCC pp 370-371

[2] X. Liu and E. Sánchez-Sinencio 2015 An 86% Efficiency 12 \( \mu \)W Self-Sustaining PV Energy Harvesting System With Hysteresis Regulation and Time-Domain MPPT for IOT Smart Nodes JSSC Vol 50(6) pp 1424-1437
Acknowledgments

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