An Inductor-less MPPT Design for Light Energy Harvesting Systems

Authors: Hui Shao, Chi-Ying Tsui and Wing-Hung Ki

Department of Electronic and Computer Engineering
The Hong Kong University of Science and Technology
Hong Kong SAR., P. R. China
Introduction

- Energy harvesting techniques – to extend the device lifetime for micro-system designs
  - Solar energy: The most popular because of its ubiquitous spreading, high power density, etc.

- Previous works of solar systems
  - Maximum Power Point Tracking (MPPT)
    - Extract maximum power from solar cell
  - MPPT using DC-DC converter
    - Inductors are costly
  - Strong sunlight assumption
    - Low light condition
      - Voltage step up needed

- Our work: Inductor-less MPPT Design
System Description

Under low light condition:
Charge pump steps up the voltage (Inductors avoided)

Light energy →
Electrical energy

PV Cells

Power Management Circuit

Charge Pump

V_{PH} → V_{CLK} → V_{CLK} → V_{VCO} → V_{OUT}

Optimal Power Tracking Unit

Control Unit

V_{VCO}: Change the charge pump switching frequency based on the V_{VCO} value

1. Energy buffer for system continuous operation
2. Voltage clamper to fix system output voltage

Track the maximum output power point:
1. Monitor the power from the charge pump
2. Adjust V_{VCO} to maximize the output power based on generic hill climbing algorithm

Maximizing system output power = Maximizing system output current
System Operating Behavior

- **System output current is determined by** $I_{PH}$ and $I_{loss}$
  
  $I_{CP,O} = \frac{1}{N+1} \left\{ (1 - \frac{C_E}{\alpha})I_{PH}(V_{PH}) - I_{amp} \right\} - \left( \sigma + \frac{C_E\beta}{\alpha} \right) f_{CLK}$

- **System MPP is usually different from PV cells’ MPP**
  
  - $f_{CLK} = 0$
    - $I_{PH} = 0$, $I_{loss} = 0$
      - $I_{CP,O} = 0$
  
  - $f_{CLK}$ increases
    - $(I_{PH} \uparrow) > (I_{loss} \uparrow)$
      - $I_{CP,O} \uparrow \uparrow$
  
  - $f_{CLK}$ increases
    - $(I_{PH} \uparrow) < (I_{loss} \uparrow)$
      - $I_{CP,O} \downarrow \downarrow$

- **System MPP can be tracked by implementing hill climbing algorithm with tuning $f_{CLK}$**

![Diagram](image-url)
System Maximum Output Power Control

Current sensor: monitor system output current, reflect it by $V_S$

Decision Generation Circuit: Check if $V_S$ (or $I_o$) maximum and tune $V_{VCO}$ based on generic hill climbing algorithm

Low power techniques are implemented to reduce the circuit power overhead

Current sensor: $I_o/N$ → $V_O$ → $V_{O1}$ → $N-1$ → $M_{W1}$ → $S_S$ → $MP_1$ → $M_{W2}$ → $S_S$ → $MP_2$ → $V_{OUT}$

Current sensor: monitor system output current, reflect it by $V_S$

Decision Generation Circuit: Check if $V_S$ (or $I_o$) maximum and tune $V_{VCO}$ based on generic hill climbing algorithm

Low power techniques are implemented to reduce the circuit power overhead

Current sensor: $I_o/N$ → $V_O$ → $V_{O1}$ → $N-1$ → $M_{W1}$ → $S_S$ → $MP_1$ → $M_{W2}$ → $S_S$ → $MP_2$ → $V_{OUT}$

Current sensor: monitor system output current, reflect it by $V_S$

Decision Generation Circuit: Check if $V_S$ (or $I_o$) maximum and tune $V_{VCO}$ based on generic hill climbing algorithm

Low power techniques are implemented to reduce the circuit power overhead

Current sensor: $I_o/N$ → $V_O$ → $V_{O1}$ → $N-1$ → $M_{W1}$ → $S_S$ → $MP_1$ → $M_{W2}$ → $S_S$ → $MP_2$ → $V_{OUT}$

Current sensor: monitor system output current, reflect it by $V_S$

Decision Generation Circuit: Check if $V_S$ (or $I_o$) maximum and tune $V_{VCO}$ based on generic hill climbing algorithm

Low power techniques are implemented to reduce the circuit power overhead

Current sensor: $I_o/N$ → $V_O$ → $V_{O1}$ → $N-1$ → $M_{W1}$ → $S_S$ → $MP_1$ → $M_{W2}$ → $S_S$ → $MP_2$ → $V_{OUT}$

Current sensor: monitor system output current, reflect it by $V_S$

Decision Generation Circuit: Check if $V_S$ (or $I_o$) maximum and tune $V_{VCO}$ based on generic hill climbing algorithm

Low power techniques are implemented to reduce the circuit power overhead
Experimental Results

- Test chip was fabricated in AMS 0.35μm process
  - Source: 2 mono-crystalline solar cells (area: 6cm x 6cm)
  - Charge pump: 1-stage voltage doubler
  - Load: a 125mAh Li-ion rechargeable battery
Measurement Results

- Operation of the optimal power tracking unit (OPTU)
  - Disable OPTU: Tune $f_{\text{clk}}$ to check the system ideal MPP
  - Enable OPTU: Auto-track the system MPP well

![Graph showing system output current vs. charge pump switching frequency]

**System output current vs. charge pump switching frequency**
Experimental Results

Comparison of system output power & power efficiency at the system ideal MPP and when applying MPP tracking control scheme

<table>
<thead>
<tr>
<th>light intensity</th>
<th>system ideal maximum $P_{OUT} / \eta$</th>
<th>system $P_{OUT} / \eta$ with MPPT</th>
</tr>
</thead>
<tbody>
<tr>
<td>368 LUX</td>
<td>106.63 $\mu$W / 53.65 %</td>
<td>100.72 $\mu$W / 50.65 %</td>
</tr>
<tr>
<td>706 LUX</td>
<td>332.99 $\mu$W / 64.60 %</td>
<td>327.49 $\mu$W / 63.24 %</td>
</tr>
<tr>
<td>1141 LUX</td>
<td>533.02 $\mu$W / 67.22 %</td>
<td>528.76 $\mu$W / 67.08 %</td>
</tr>
<tr>
<td>1734 LUX</td>
<td>779.24 $\mu$W / 66.95 %</td>
<td>775.50 $\mu$W / 66.82 %</td>
</tr>
</tbody>
</table>
Measurement Results

- Under same light intensity
  - $V_{VCO}$ oscillates around the system MPP
- When light intensity changes
  - $V_{VCO}$ tracks the light change and goes to the new MPP

![Diagram showing light intensity and $V_{VCO}$ oscillations]

System MPP tracking when light intensity changes