A Solar Energy Harvester with an Improved MPPT Circuit for Wearable IoT Applications

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ABSTRACT

One of the main issues of wearable IoT devices is the limited battery technology. Energy harvesting will be a key development for health and fitness oriented wearable devices that can measure signals continuously. In this paper, an analog maximum power point tracking (MPPT) circuit is presented to power a wearable pulse sensor with a Bluetooth low energy (BLE) module for transmission. The proposed MPPT algorithm uses only the output current to extract the maximum power from a flexible solar panel. The whole energy harvesting system was implemented and tested. Experiment results validate that the solar energy harvester has an overall efficiency of 66.5% and can provide sufficient power for the measurement of the pulse sensor and transmission with a BLE module.

Keywords

Energy harvesting; photovoltaic; MPPT; wearable sensor; Bluetooth low energy

1. INTRODUCTION

One of the key developments in wearable IoT applications is the energy harvesting technique [1], which provides solutions to extend the lifetime of batteries or directly supply energy for the wearable sensors in the IoT applications and deployments. Solar energy is one of the most favourable energy sources because it provides a higher power density than other sources, such as the piezoelectric, thermoelectric and radio frequency [2]. However, the power from a solar panel depends on its operating conditions. There exists a maximum power point of each solar panel, which changes with the environmental irradiance and temperature conditions. As a result, the maximum power point tracking (MPPT) circuits are essential in the solar energy harvesting systems.

There have been many researches on tracking the maximum power point of solar panels [3, 4]. Conventional MPPT algorithms, like perturb and observe (P&O) and incremental conductance (IC), require both the photovoltaic (PV) voltage and current to track the maximum power point [5, 6]. Though the open circuit voltage (OCV) algorithm or the short current circuit (SCC) algorithm needs only one parameter of the solar panel to operate, their tracking is ”quasi” and cannot extract energy when the circuit is open or short [7, 8]. In this paper, an MPPT algorithm only based on the output current is proposed. Due to its analog design and only sensing the current at the output side, the implementation of this MPPT circuit is simplified and can be integrated with proper CMOS technology.

To validate the performance of the proposed MPPT algorithm, a pulse sensor circuit with wireless Bluetooth low energy (BLE) transmission is connected as a load for the real life application. The pulse sensor is implemented with an off-the-shelf piezo sensor [9]. With the BLE module, the sensor can transmit the pulse data to a terminal device (e.g. smartphones), which monitors user's health condition.

The rest of the paper is organised as follows. The next section presents the analysis and design of the proposed MPPT circuit. Section 3 introduces the implementation of the pulse sensor and BLE module. Experiment results of the whole energy harvesting system are demonstrated in Section 4 and Section 5 gives the conclusion of the paper.

2. SOLAR ENERGY HARVESTER

As the solar panel is a nonlinear device, it has an optimal working point at a certain irradiance and temperature condition. Usually a DC-DC converter is employed to regulate the output of the solar panel. The MPPT control circuit keeps adjusting the duty cycle (D) of the converter to track the maximum power point of the panel.

2.1 Proposed MPPT Algorithm

Figure 1 shows the block diagram of the proposed energy harvesting system, where a boost converter is used to connect the solar panel and the output load. The relationship of the voltage and current between the panel and load is:

$$V_{out} = \frac{1}{1-D} V_{PV}, \tag{1}$$

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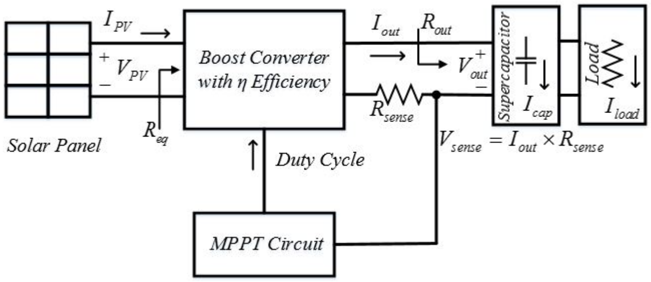

Figure 1: Block diagram of the solar energy harvesting system.

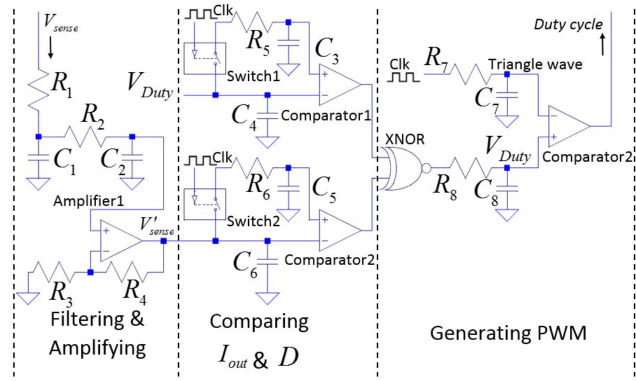

Figure 2: Schematic of the MPPT control circuit.

Table 1: Relationship of I_{out} and Duty Cycle

I_{out}	D	Next D
Increase (1)	Increase (1)	Increase (1)
Increase (1)	Decrease (0)	Decrease (0)
Decrease (0)	Increase (1)	Decrease (0)
Decrease (0)	Decrease (0)	Increase (1)

and

$$I_{out} = (1 - D)I_{PV} \tag{2}$$

Therefore the equivalent resistance seen by the solar panel through the converter is:

$$R_{eq} = (1 - D)^2 R_{out} \tag{3}$$

The MPPT control circuit will keep tuning the duty cycle of the converter until R_{eq} equals the load resistance of the solar panel at the maximum power point.

To calculate the maximum power, conventional MPPT algorithms (P&O and IC) need to multiply the sensed V_{PV} and I_{PV} at the input side of the converter. The proposed MPPT algorithm only measures the I_{out} at the output side without any multiplication [10]. If there is a fixed resistive load, the output power is:

$$P_{out} = I_{out}^2 R_{out} \tag{4}$$

For a boost converter with efficiency of η, the power from the solar panel will be:

$$P_{PV} = \frac{I_{out}^2 R_{out}}{\eta} \tag{5}$$

From (5) it can be seen the power from the solar panel is maximized when I_{out} is maximum. The MPPT control circuit changes D according to the comparison result between I_{out} and its previous value. If I_{out} increases, then change D in the same direction; otherwise change D in the opposite direction. The relationship of I_{out} and D is summarised in Table 1, which can be expressed by an "XNOR" logic.

For a varying resistive load or a supercapacitor, it can be approximated as a stair-case: the MPPT circuit will track the maximum power of the solar panel as the load is constant during a short period of time. As long as the change of the load does not exceed the convergence time of the MPPT circuit, the aforementioned analysis is still applicable.

2.2 Design of the MPPT circuit

The implementation of the proposed output current based analog MPPT circuit is demonstrated in Figure 2. Firstly the V_{sense} ($I_{out} \times R_{sense}$) is filtered through a low-pass filter (R_1, R_2, C_1&C_2) to remove high frequency noise. Since V_{sense} is really small it needs to be amplified to $V_{sense}^{'}$ by Amplifier1. $V_{sense}^{'}$ is then separated into two paths: one is directly connected to the inverting input of Comparator2; the other is connected to the noninverting input of Comparator2 through the clock-controlled Switch2 and delayed by an RC circuit (R_6&C_5). This configuration compares the present value of $V_{sense}^{'}$ (inverting input) with the delayed value of $V_{sense}^{'}$ (noninverting input). The result of Comparator2 shows the changing trend of $V_{sense}^{'}$, which represents the trend of I_{out}. The same topology applies to the measurement of the duty cycle (V_{Duty}) of the converter.

The results of Comparator1&2, representing the trend of D and I_{out} respectively, are fed into the XNOR gate, which determines whether to charge C_8 or not. The voltage of C_8 (representing the duty cycle value) is compared with a triangle wave (generated by R_7, C_7 and a clock), producing a variable duty cycle PWM signal to drive the boost converter. The duty cycle of the converter is changed continuously by the above process until the solar panel reaches the maximum power point. Then the duty cycle varies within a certain range, making the solar panel operates around the maximum power point with small oscillations.

3. WEARABLE PULSE SENSOR WITH BLE

3.1 Design of the Pulse Sensor

Figure 3 depicts a simple implementation of the pulse sensor, which consists of a piezoelectric transducer, an amplifier and an active low-pass filter. A commercial piezoelectric PVDF polymer, the LDT1-028K from Measurement Specialities®, is attached to the wrist to sense the pulse signal. The signal is then biased to a reference voltage (V_{ref}) by a large resistor R_1 and amplified by Amplifier1. The output of the pulse signal is:

$$V_{pulse} = V_{piezo}(1 + \frac{R_3}{R_2}) + V_{ref} \tag{6}$$

The right part of this schematic is a 2nd order active low-pass filter. Through this filter, the high frequency noise is

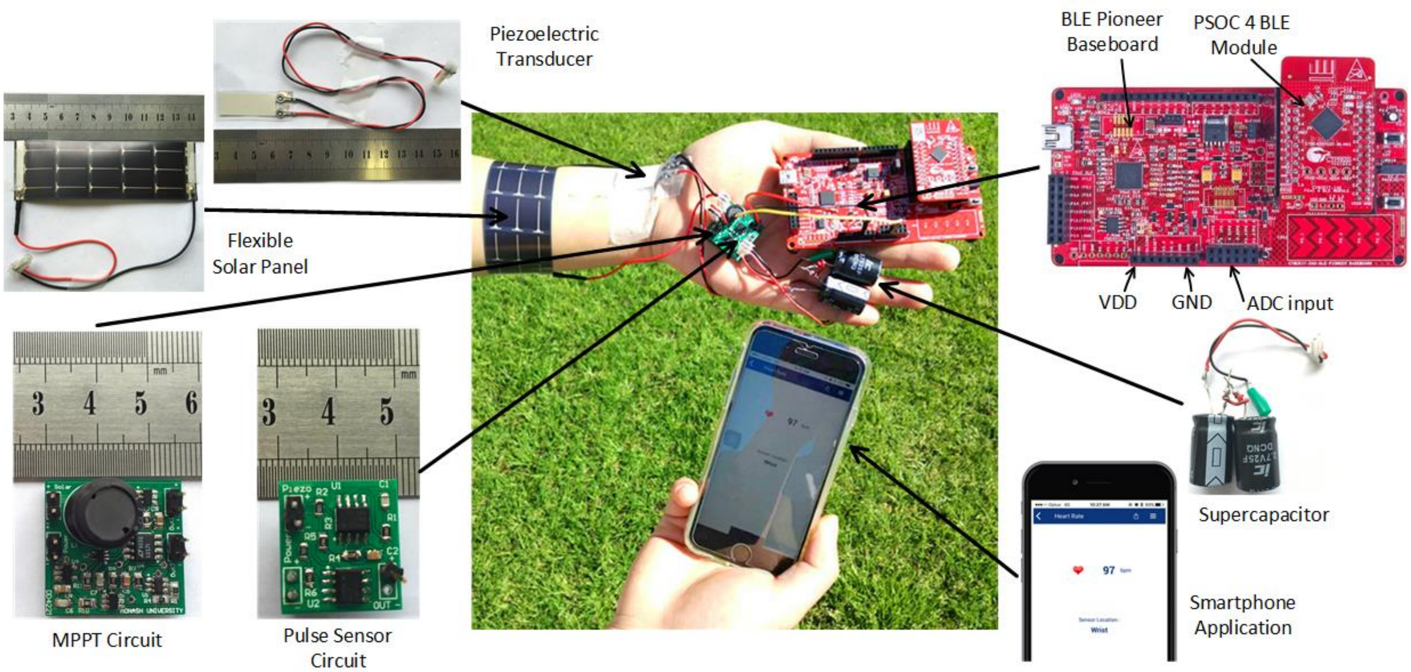

Figure 4: The setup of the solar energy harvesting system with a pulse sensor and BLE module.

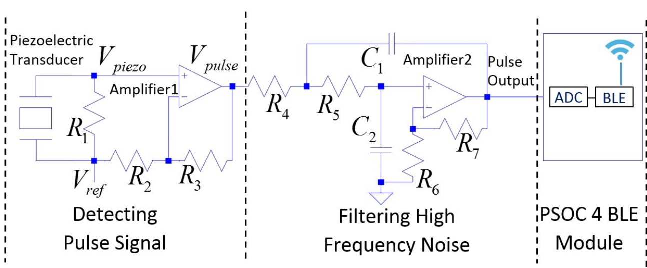

Figure 3: Schematic of the pulse sensor and BLE.

eliminated. The pulse signal is then sent to the BLE module for wireless transmission.

3.2 Bluetooth Low Energy Transmission

Bluetooth low energy, also known as Bluetooth Smart, is an emerging wireless transmission technique developed by Bluetooth Special Interest Group [11]. Due to its extreme low power consumption and multiple applications, BLE is expected to be equipped into billions of electronic devices for use in wearable IoT devices in the next few years [12].

In this work, PSOC 4 BLE Module from Cypress® is chosen for the wireless data transmission. The BLE module along with the pioneer baseboard is shown in Figure 4. Its working voltage is 3.3-5 V with the transmitting current less than 15 mA. For this application, the BLE module is always active to transmit real time data. For lower power applications, it can be configured with sleep or deep-sleep mode, which consumes less than 3 mA or 15 μA, respectively. In this work, a smartphone application is designed for receiving the pulse signals from the sensor.

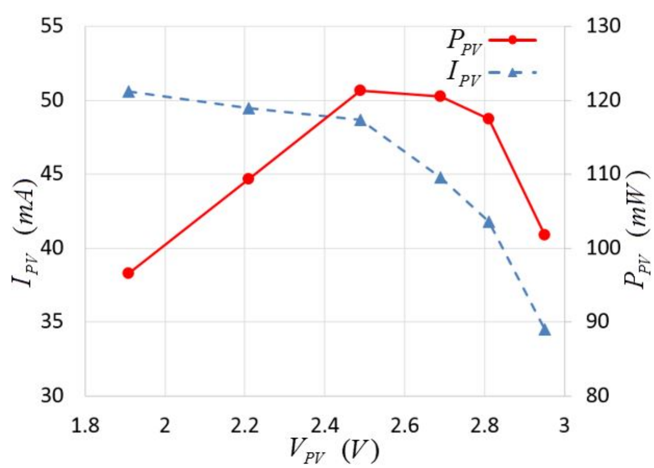

Figure 5: The I-V & P-V curves of the flexible solar panel under common sunlight.

4. EXPERIMENTAL RESULTS

Figure 4 shows the setup of the proposed solar energy harvesting system and the pulse sensor with BLE. The MPPT circuit is fabricated and tested with a flexible solar panel, the MP3-37 from Sundance Solar®. Unlike conventional rigid solar panels, it can conform to the contour of a human body. Therefore the solar energy harvester is suitable for wearable devices. The MPPT circuit controls the flexible solar panel to operate at the maximum power point and supply energy to the pulse sensor and BLE module. It also charges a 12.5 F supercapacitor to store the backup energy for use without light. In the meantime, the pulse sensor detects the real time pulse signal and sends it to a smartphone APP through wireless BLE transmission.

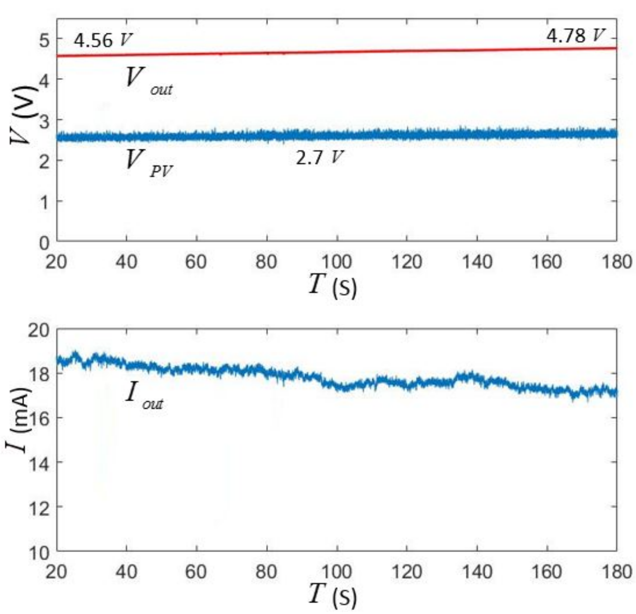

Figure 6: Experimental result of charging a 12.5 F supercapacitor with the MPPT circuit.

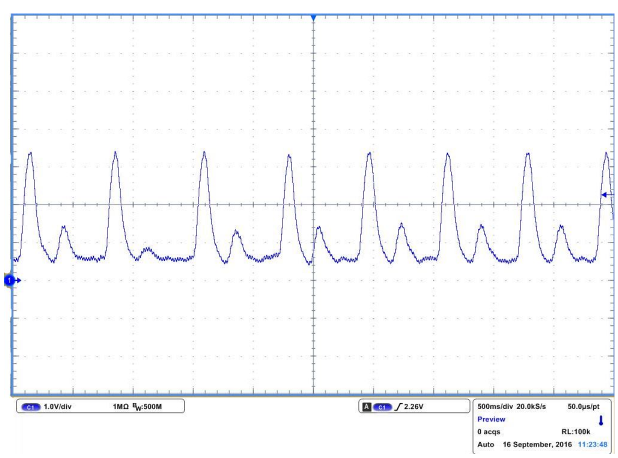

Figure 7: Experimental result of detecting the pulse signal with the pulse sensor.

4.1 Solar Energy Harvester

The first experiment was done outdoor testing the characteristic of the solar panel in the sunlight. Figure 5 depicts the I-V and P-V curves of the solar panel at the experimental condition. It can be seen the maximum power point of the panel is between 2.5 V and 2.7 V of the solar panel (the maximum power is 120.7 mW) at that condition.

Figure 6 shows the experiment result of charging a 12.5 F supercapacitor (two 25 F supercapacitor in series) with the proposed MPPT control circuit. The solar panel operated around 2.7 V while the supercapacitor was charged from 4.56 V to 4.78 V in 160 s. I_{out} is the output current to charge the supercapacitor. The output power from the solar panel is fixed at that irradiance condition, so I_{out} is decreasing with the increase of the supercapacitor's voltage. According to the analysis in Section 2, I_{out} is at its maximum value

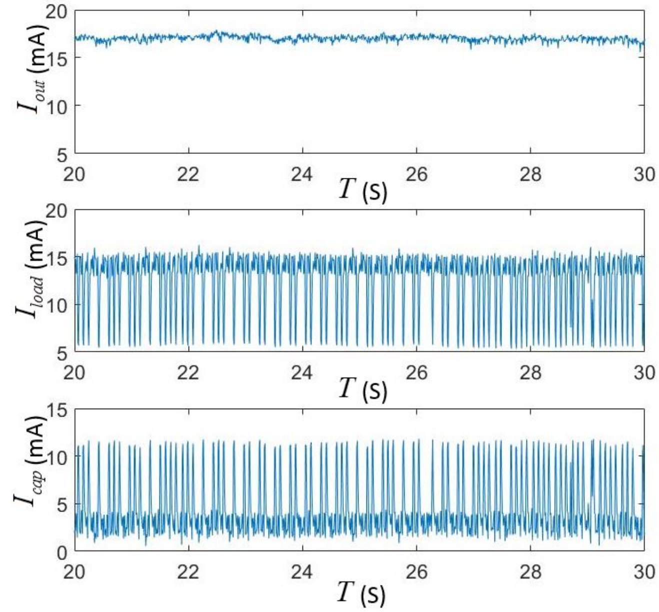

Figure 8: Experimental result of powering the pulse sensor and BLE while charging a supercapacitor.

for each constant supercapacitor's voltage during a short period of time. The charging power and overall efficiency of the solar energy harvesting system is 80.3 mW and 66.5%, respectively. The major power loss is due to the resistance of the inductor and voltage drop of the Zener diode used in the boost converter.

4.2 Self-powered Pulse Sensor with BLE Transmission

The pulse sensor was tested with the piezoelectric transducer attached to the wrist with the palm facing upwards. The experiment was performed without any wrist motion to get rid of artificial disturbances. Figure 7 shows that the sensor can successfully detect the pulse signal and eliminate high frequency noise. As the BLE module was active all the time for transmitting data, the overall power consumption of the pulse sensor and BLE was around 70 mW.

Figure 8 shows the experimental result of the MPPT circuit powering the pulse sensor and the BLE module from 20 s to 30 s. I_{out} is the overall output current through the converter, which consists of I_{load}, the current supplying the load (pulse sensor and BLE), and I_{cap}, the current charging the supercapacitor. During the experiment, the pulse sensor kept monitoring the pulse signal and transmitting it to a smartphone, while the supercapacitor was charged from 4.76 V to 4.79 V in 200 s. The charging power was around 8.9 mW, considering the power consumption of the pulse sensor and BLE module, it corresponded to the results of charging the supercapacitor alone.

5. CONCLUSIONS AND FUTURE WORK

This paper presents a solar energy harvesting system with an improved MPPT algorithm for wearable sensor applications. The proposed analog MPPT circuit needs only the output current for tracking the maximum power point, making the implementation of the circuit simpler. The experiment results demonstrate that the efficiency of the energy harvesting system is 66.5%. The MPPT circuit is applied to power a pulse sensor, which can transmit the real time pulse data to a smartphone through a wireless BLE module. The proposed system can be used to monitor people's health condition in daily life. The MPPT circuit with the flexible solar panel can also be applied to other wearable devices.

6. ACKNOWLEDGMENT

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