Design of a hybrid power system based on solar cell and vibration energy harvester

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Abstract. Power source has become a serious restriction of wireless sensor network. High efficiency, self-energized and long-life renewable source is the optimum solution for unmanned sensor network applications. However, single renewable power source can be easily affected by ambient environment, which influences stability of the system. In this work, a hybrid power system consists of a solar panel, a vibration energy harvester and a lithium battery is demonstrated. The system is able to harvest multiple types of ambient energy, which extends its applicability and feasibility. Experiments have been conducted to verify performance of the system.

1. Introduction

Wireless sensor network (WSN) plays a more and more important role in many industries[1]. With the development of manufacture technology, the volume of wireless sensor node tends towards micromation[2]. Although micro wireless sensor node consumes tiny power, it has very limited lifetime powered by batteries[3][4]. Wireless sensor network usually consists of a large amount of nodes distributed in a broad area[5] which build up communication internet. Since sensor nodes generally use traditionally secondary battery as power supply, it costs prohibitively to replace sensor node batteries at intervals.

Using renewable resource, such as solar energy[6][7], wind[8], motion[9], and temperature difference[10] will significantly extend working life of sensor node and lower the maintenance cost. Since vibration energy and solar energy is ubiquitous in most area, they are good candidate for outdoor wireless sensor nodes[11][12]. However, renewable energy harvester is easily affected by actual working environment and weather, research of hybrid power source containing both generator and storage devices has become a hot point. Furthermore, power system combined with multiple energy types such as solar cell and thermoelectric generator (TEG)[13][14], fuel cell and lithium battery[15], solar photo voltaic and wind turbine[16], etc. Energy scavenging aiming at different form from environment will enhance environmental suitability of power system, which will also gain more efficiency of energy transformation.

In this paper, a hybrid power system consists of a solar panel, a vibration energy harvester and a lithium battery is demonstrated. System structure is firstly introduced. Then, regulator circuit of each component is proposed to realize functional integration of the system. Based on this, energy management strategy is designed to promote system’s overall performance. Finally, experiments are conducted for verification.
2. Design of hybrid power management system

The power system includes two power generators, solar panel and vibration energy harvester, and an energy storage device, micro lithium battery. As output voltage of the power sources are improper for direct integration, corresponding converters are inherently necessary. A MSP430G2553 low power microcontroller is implemented in the system, in which proposed energy management strategy runs on it. System structure is presented in Figure 1.

![System energy flow route diagram](image)

**Figure 1.** System energy flow route diagram

The power system generates two power rails. One is 5V direct current which is used as primary output power line, the second is 3.6V direct current which is for microcontroller and other on-board peripherals. Both power rails are driven by the power components.

2.1. Solar panel regulator circuit

Due to low manufacturing cost[17] and relatively high efficiency, poly-Si solar panel is used as photovoltaic component, of which the parameters are presented in Table 1. Low drop-out regulator (LDO) is implemented to obtain stable 5V output. LDO is suitable for situations with high input voltage, under which the energy cost is relatively low and peripheral circuit is very simple. Texas Instruments (TI) LP2985-5.0 is selected as the LDO circuit, which has a very low leakage current of 850μA.

| Parameter Type                  | Value     |
|---------------------------------|-----------|
| Open circuit voltage            | 6.28V     |
| Short circuit current           | 0.15A     |
| Maximum power                   | 750mW     |
| Efficiency                      | 17%       |
| Size (length*width*thickness)   | 84×55×3mm |
The enable port is connected to microprocessor, which controls system structure dynamically. The output pin is connected to 5V power rail $V_{out}$, which supplies energy when LDO is enabled and enters high-resistance state when disabled.

2.2. Lithium battery regulator circuit design

When ambient solar energy is not sufficient for the system’s requirement, additional backup power supply is necessary to stabilize the system. A small lithium battery is integrated in the system, with model of CR2032, capacity of 230mAh and nominal voltage of 3V. A high efficiency boost converter is implemented to normalize output voltage of the battery, with model of Texas Instrument TPS61041-Q1 and quiescent current of 28uA (1μA when shut down). The inductor selection is restrict within equations as

$$f_{s,max} = \frac{V_{in,min} \cdot (V_{out} - V_{in})}{I_{peak} \cdot L \cdot V_{out}}$$  \hspace{1cm} (1)

$$f_{s,norm} = \frac{2I_{load} \cdot (V_{out} - V_{in} + V_d)}{I_{peak}^2 \cdot L}$$  \hspace{1cm} (2)

where $f_{s,max}$ and $f_{s,norm}$ respectively denote the maximum switching frequency and nominal switching frequency, $L$ represents inductance value, $V_d$ stands for Schottky diode drop-out voltage and $I_{peak}$ means the maximum switching current expressed as

$$I_{peak} = I_{lim} + \frac{V_{IN}}{L} \cdot T_{delay}$$  \hspace{1cm} (3)

where $T_{delay}$ is internal propagation delay time and $I_{lim}$ is DC current limit. With formula (1)-(3) and parameters given by manufacturer, inductance value range of $L$ can be calculated. Additionally, $L$ can be uniquely determined with the tradeoff between switching frequency and efficiency. Also, enable ports is connected to microcontroller for power management between output state and high impedance state.

2.3. Piezo vibration energy harvester regulator circuit design

Piezo vibration energy harvester is effective for low power wireless sensor devices. Its generated energy can be directly deposit in storage devices[18]. Piezo vibration energy harvester has a structure of cantilever with piezoelectric materials on both surfaces. When vibrationally excited, response of the cantilever beam is periodic, and output voltage of the energy harvester is alternating. The energy harvester implemented in system is Mide V25W with mass tip attached which lowers the resonant frequency to 45Hz. As vibration amplitude increases, the output peak-to-peak voltage ($V_{pp}$) can reach over 50V with 1g excitation. Linear Technology LTC3588 with low drop-out Schottky rectifier circuit resistant and high-efficiency step-down switching regulator integrates is implemented. The required inductance value can be derived from the equation

$$L = \frac{V_{out} \cdot (V_{in} - V_{out})}{V_{in} \cdot \Delta I_L \cdot f_{s,norm}}$$  \hspace{1cm} (4)

where $\Delta I_L$ is ripple current of inductor which values 30% of the maximum load current.

The Power Good signal is delivered to microcontroller when output reaches pre-programmed value of 5V (both D0 and D1 is tied to VIN2). Output enable function is realized by using PMOS with very low on resistance as switch.

2.4. Design of system internal power rail

A microcontroller with model of Texas Instruments MSP430G2553 is implemented to monitor states of each power source and executes respective control strategy. Energy management algorithm is programmed in the microcontroller, with very low current consumption and abundant low power mode (LPM). It is necessary to build up an internal power rail, since output voltage of power sources regulator is set to 5V, which exceeds the safe operation area of microcontroller and requires additional components for system to cold start with regulators disabled and microcontroller deactivated.
The schematic of internal power rail is shown in Figure 2. The power selector is realized by TPS22933 with a 3.6V LDO integrated, which stabilizes the output voltage of solar panel and battery. As output voltage of vibration energy harvester is high and alternative, it is not used for cold start of microcontroller. Multi-channel integrated 10-bit analog-to-digital converter of the microcontroller is used to monitor output voltages of lithium battery and solar panel for the further control.

2.5. Energy management strategy
During operation, output voltages of all modules are monitored and controlled as either power sources or high-impedance ports. Monitoring is realized via the built-in 10-bit ADC of the microcontroller, and control is realized via the enable ports of polar panel, vibration energy harvester and lithium battery with the energy management strategy shown in Figure 4, microcontroller decides the operation mode of each power source.
State of the vibration energy harvester can be obtained from the power good ports of LTC3588. Converting time of triple converting channels is about 12μs and interval period of sampling is set to 10ms, which are sufficient for double converting and data process. Interval of the converting is used to calculated change rate of output voltage which indicates availability of a power source.

Microcontroller detects open-circuit voltage of solar panel first. If the voltage reaches power good threshold, solar panel step-down regulator will be enabled and supply external load with 5V voltage. Meanwhile, output voltage variation is calculated within sampling cycle. If the voltage decreases rapidly and exceeds the threshold, it indicates that the power source is not sufficient for power load, and then solar panel converter will be shut down by setting the enable port to low (nearly ground voltage, 0V). In that case, even if piezo output shows power good state, lithium battery will be enabled as the piezo generator is far weaker than solar panel. On the other hand, when piezo is in resonance state, the energy collected is sufficient. Then the controller will enter low power mode (LPM) after finishing sampling and processing period which consumes several μA current and wait for next period or sudden power failing.

3. Results and discussion

3.1. Internal power rail and system cold start
Before output power rail is activated, microcontroller boots ahead and samples states of the power sources to ensure that the power system is capable to reach stabilization output. This procedure is called cold start during which power can be supplied by any part of the system sources, solar panel, vibration
energy harvester or lithium battery. Operating waveform of the 3.6V internal power rail powered by solar panel at 45500Lux illumination intensity is shown in Figure 4(a). Detailed data is listed in Table 2. As shown, higher optical power input leads to a shorter system start time and a higher open-circuit voltage. Operating waveforms of the 3.6V internal power rail powered by vibration energy harvester under acceleration of 1.5g are shown in Figure 4(b). Detailed data is shown in Table 3. Because the output power of vibration energy harvester is much lower than solar panel, start time becomes longer. The power good signal appears to be square-wave pulse since the output power is not fully sufficient for stabilization. When acceleration is over 2g, the power good signal is stable high level, which means the generated power is larger than internal consumption.

![Figure 4. Oscilloscope pattern of system internal power rail starts: (a) solar panel; (b) energy harvester](image)

**Table 2. Response time at different illumination intensity**

| Illumination intensity/Lux | Start time /ms | Open-circuit voltage of solar panel/V |
|---------------------------|----------------|--------------------------------------|
| 15000                     | 45             | 5.71                                 |
| 20000                     | 37             | 5.93                                 |
| 30000                     | 32             | 6.03                                 |
| 38000                     | 30.5           | 6.11                                 |
| 45000                     | 29.8           | 6.22                                 |

**Table 3. Response time at different acceleration stimulation**

| Acceleration | Start time /ms | Resonant frequency | PGOOD duty |
|--------------|----------------|--------------------|------------|
| 1.0g         | 360            | 47Hz               | 0%         |
| 1.5g         | 153            |                     | 21.8%      |
| 2.0g         | 114            |                     | 100%       |

3.2. Output power rail and wireless sensor node demonstrate

The output result of primary power rail supplied by solar panel is presented in Figure 5. Efficiency reaches up to over 90% with the output power of 600mW and output current of 150mA. When the illumination intense is around the same as outdoor daytime environment (40000Lux), the maximum output power can reach 620mW which is powerful enough for most wireless sensors with microcontrollers during data transmitting. When vibration acceleration is 2g, the vibration energy harvester gives a 4.7mW output power and 3.9mW actual output power with system convention efficiency of 83%, which can power up the internal microcontroller or CC2650 active mode without data transmitting. If ambient condition is changed dramatically, backup battery maintains the output power.
until either vibration energy or solar energy back online. As shown in Figure 6, hybrid power system implemented in this work can power up Texas Instrument CC2650STK Bluetooth sensor node.

Figure 5. Output power and efficiency of 5V power rail

Figure 6. Demonstration of supplying wireless node with hybrid power system

4. Conclusions
A hybrid power system consists of a solar panel, a vibration energy harvester and a lithium battery is demonstrated in this paper. The charge stored in lithium battery is significantly economized due to the strategy of renewable power sources supplying the load preferentially. Ambient solar energy and vibration energy are converted into electric energy, cached in super-capacity and exported with high quality via the strategy of energy management system. The lithium battery works only as back-up power source to cover circumstance where solar cell and vibration energy harvester cannot gather energy from environment. Experiments show that designed system has a maximum power output of 620 mW, which is sufficient for most wireless sensor node applications. The power of vibration energy harvester can reach 4.7mW, which can be used to supply low-power sensors and system working at standby mode. The life of battery is prolonged with few active time during sensor node working cycle.
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