Energy Harvesting System with Multiple Inputs

O Setyawati¹, Taufik² and A Satriya³

¹ Electrical Engineering Department, Brawijaya University, Indonesia
² Electrical Engineering Department, Cal Poly State University, San Luis Obispo, CA
³ Electrical Engineering Department, University of Jember, Indonesia
E-mail: osetyawati@ub.ac.id

Abstract. Energy scavenging system that can harvest from multiple energy sources has been considered and remains a promising research topic. This paper presents characterization of a multiple input energy harvesting system for Wireless Sensor Network and evaluation of battery state of charge utilized in the system. The system under study automatically selects the highest voltage value from among connected harvested energy sources to determine which of the multiple sources will supply energy to charge the system’s battery and any operating load. By means of the coulomb counting method in the wireless application board and under the regulated maximum input voltage of the application board of 3.3 V, the state of charge (SOC) of the system battery was observed to study the functionality and effectiveness of the multiple input energy harvesting system. Further hardware test results show approximately 0.013% of SOC is obtained.

1. Introduction

Energy scavenging system that harvests from multiple energy sources continues to attract interests among researchers. One application that may benefit from the use of multiple input energy harvesting system is Wireless Sensor Networks (WSN). This is largely because WSN sensors operate at relatively very low power. A hierarchical illustration of energy harvesting system for the WSN utilizing various energy sources is shown in figure 1 [1]. As the figure suggests, finding alternative ways of sourcing energy for WSN sensors has become an interesting research challenge. Consequently, the development of low-power energy harvesting system to provide tens to hundreds of milliwatts for these sensors constitutes a major focus of activity [2][3].

Some sources of micro-energy harvesting come from motion or vibration or mechanical energy, electromagnetic (RF) energy, thermal energy, micro flow energy, solar or light energy, and biological energy. Other schemes are based on subjects that provide the energy such as human or animal energy source, and energy provided by the surrounding environment [4]. Many of these methods have been previously investigated for their potential in becoming energy sources such as vibration and pressure energy scavenging [5], radio frequency energy [6], and thermoelectric energy [7]. Due to the small amount of energy produced by the majority of these sources, it is imperative to choose sensor types having the lowest amount of required energy consumption. Further help in efficiently utilizing the energy can be done by managing the energy consumption through an automatic switch or duty-cycling technique for on-demand operating system. This duty-cycling method however is mostly suitable for a system that changes its state infrequently. The performance of the duty-cycling technique for the indoor and the outdoor photovoltaic cells-based energy harvesting has been investigated [8]. In the solar cell case, focusing more light onto the cell area will obtain more power. However, solar cells do not offer ease of scalability. This is unfortunate since scaling up of energy harvesting source is
important in many practical situations when there is a need to install additional devices that are much simpler to add or scale up such as those employed in WSN’s.

Figure 1. Energy harvesting sources in WSNs [1].

WSN involves some sensor nodes capable to transmit and receive data. Sometimes these nodes are distributed to several different locations and they might be hard to access. For reliable WSNs deployed in forests, as an example, the sensor nodes should utilize some form of energy source from the surrounding environment for their batteries. This in turn requires electronic system that can process low power and ensure long battery lifetime. However, managing the energy harvested from the environment presents a major challenge, especially for an environment such as tropical forest where light nor temperature nor wind showing significant difference throughout long time span. Therefore, it is crucial to ensure the harvested energy is sufficient for the WSN system. To obtain a certain required power level, either the capacity of harvested energy sources should be increased or the application devices need to be scaled [1].

Vibration, pressure and human activity can be categorized in general as mechanical or kinetic energy. The way to harvest energy depends on available methods. For example, piezoelectric is the method whereby pressure to electricity is desired to get the energy. Another example is electrostatic which converts capacitance to electric energy and it is quite popular for use in micromachined devices. Electromagnetic waves output radiant energy, e.g. light and RF signals. Solar cells or photovoltaic can harvest light energy from the sun, and many researches have been putting efforts to improve solar cell technology that can provide wide range of power, from high to low power applications. RF signals either dedicated from a certain transmitter to its receiver or waste signals (scattered from ambient, e.g. Wi-Fi or base station) can be used for generating energy. Energy from thermal, and fluid flow (water and wind) are available from ambient as well. Thermoelectric and pyroelectric transducer can be used to convert temperature differences into energy. In addition to these, temperature difference between human body heat and its environment can also be harvested as an energy source [9].

The use of multiple sources of harvested power or generic sources of harvesting system is promising but challenging. It is promising due to the ability to provide alternate forms of energy required by each sensor node in WSN. However, it is also challenging since advanced and very efficient energy management system is highly required.

2. Energy Harvesting System for Wireless Sensor Network in Agricultural Applications

In a WSN system, normally battery works as the main source for a sensor node whose lifetime depends heavily on sensor equipment depending on the application and by the processing and
communication units. This battery typically has lifetime of a few years, after which it has to be replaced with a new one. This causes additional operating cost for the system and inconvenience especially when the WSNs are in remote location or installed in hard to access part in a system. The main purpose of providing an energy harvesting system for WSNs is therefore to replace the battery as the main source, and hence the WSNs will rely on ambient and/or external energy sources. Furthermore, if the WSN still employs the battery, then the energy harvesting system will complement the battery in providing the needed energy, thus lengthening the lifetime of the battery or making battery replacement less frequent.

In this project, the study of an efficient energy harvesting system for micro-sensors in WSN for agricultural applications was conducted. A new energy harvesting test-bed utilizing the latest and greatest power electronics technology was investigated to demonstrate maximum gain in energy production.

Providing adequate energy harvesting system, for instance for the WSN of the microclimate system and for the automatic hydroponic systems, is necessary in order to prolong system’s lifetime. Therefore, designing the multiple input energy harvesting system by employing different ambient energy sources is inevitable to achieve high efficiency and low cost. For the microclimate monitoring and hydroponic systems, energy harvesting is ideal since it would be implemented once and the system needs to have long lifetime, and their sensors (temperature, humidity, light) should have low energy requirements.

For the aforementioned agricultural applications, combining energy sources such as solar, thermal and wind sources should be adequate for the energy harvesting system. Such approach will be beneficial since thermal energy source has efficiency only up to 6%. However, new materials and modules can lead to 10% [1]. The idea for combining energy sources emerges from the expectation to meet generic harvesters challenging advanced power management techniques. Therefore, in this study the focus of the experiments was to investigate the operation and determine the characteristics of available multiple sources used in an energy harvesting system, including the state of charge of the system battery.

3. Hardware Test Setup

Experimental setup utilized prototyping kit DC2509A (Analog Device Inc.) and DC2344A (Wuerth Electronics) power boards, connected to a DC2321A as the load. The DC2509A provides four ICs that interface with solar cell, thermal electric generator, and multiple inputs with primary and secondary batteries respectively. The DC2344A has the same ICs, and two transducers i.e. solar cells and thermal electric generator. The DC2509A board provides no transducers; however, the experiment was performed by giving an external input power via turrets. Furthermore, the DC2321A is equipped with the coulomb counter to provide the ability to monitor continuously the battery’s charge, temperature, voltage and current.

Procedure for output voltage measurement of LTC3106 in both modules was accomplished. The battery output voltage of 3.3 V was obtained by giving the solar cells approximately 400 lux (lamp) to DC2344A, and input power to DC2509A with input voltage varied from 10 V to 16 V. LTC3106 works only for the solar transducer, and LTC3107 only for thermal electric generator. Tests for applying more than one input power supply was conducted using LTC3330 if the primary battery was being investigated or LTC3331 for the secondary battery.

Figure 2 shows the block diagram of hardware measurement set up. The energy harvesting (EH) system or power board, can harvest from solar, piezoelectric, or magnetic sources. The LTC3330 (i.e. primary battery of the module is used) with two given inputs at AC1 and AC2 was investigated to characterize the multiple inputs of the EH system. Measurements of the state of charge and input current were performed at 10 V and from 10 V up to 16 V given input, respectively. The LTC3330 consists of an EH supply with a buck DC-DC converter, and a primary cell input battery which gives power to a buck-boost DC-DC converter. These converters route the energy from the sources to a single output. The buck-boost converter works only when there is no supply from the EH power.

Figure 3 depicts the laboratory set up for measuring input current, as the energy (or voltage) applied to the power board input turrets. Two energy sources can be connected to LTC3330 if primary battery or LTC3331 if secondary battery was used. However, the IC routed only the source with the highest
voltage to a single output of the board. Output of the EH system, recorded to be at 3.3 V, was received by the DC2321A application board. The board is provided by E-Ink display, and GUI application using QuickEval software where data can be stored. GUI main form showed the status of mote, IC, network and battery. Signal EH_ON high means that input EH is used; hence, the buck switching regulator works. Buck-boost regulator is functional if input battery used. The mote/application board status presented also the battery status screen, showing a negative image (white background with black text) indicating that charge goes to the battery instead of drawn (for secondary battery), while the positive image is showing the discharging process of the battery.

4. Results and Discussion
Figure 4 shows measurement results of the input current by giving a fixed 10 V to one input turret while at another turret the voltage was varied from 10 V up to 10.1 V with 5 mV step. These two input sources were applied to LTC3330, and since only the source with the highest voltage was selected by the application board, the input current was observed. When both sources had 10 V, the current of each input was approximately 1.6 µA. The source with fixed input revealed decreasing current, 1.6 µA down to 0.11 µA, and reached 0 µA as the differences between the sources reached 0.10 V. Measurements were also conducted for 16 V applied input voltage for the same IC.
Figure 5. Graphic of ΔSOC (%) as a function of time (s) for the primary battery.

Figure 6. Graphic of charge (mC) of the primary battery as a function of time (s).

SOC or maximum charge presented inside the battery in percentage can be evaluated using direct measurement, adaptive systems, and book-keeping methods [10] [11]. Coulomb counting technique is one of the book-keeping methods that is known as battery current integration. Coulomb (C) is the unit of electric charge equal to one ampere-second (A.s). The equation shown next is given in order to determine SOC; it is the coulomb counting where the discharging current of battery is used for the estimation.

For this study the change in SOC was measured. Carrying out equation (1) and then rearranging yields the change in SOC or ΔSOC equation as shown in equation (2). The $C_{\text{rated}}$ in both equations is the battery capacity, and for the sampling results shown in figures 5, i.e. the primary battery capacity, $I_b$ and $I_{\text{loss}}$ were the battery current and current consumed by the loss [10].

\[
SOC = SOC(t_0) + \frac{1}{C_{\text{rated}}} \int_{t_0}^{t_0+\tau} (I_b - I_{\text{loss}}) dt
\]

\[
\DeltaSOC = \frac{\Delta I}{C_{\text{rated}}}
\]

The data recorded by QuickEval software captured status of each IC, for instance if LTC3330 worked its status was indicated by PGOOD equal to 1, where the primary battery charge was monitored. Therefore, the current used by the battery is also shown. Output voltage from the power system was 3.3 V, which enabled DC2321A application board to work. The primary battery, a 240 mAh CR2032 lithium coin type using LTC3330, was monitored by coulomb counter in DC2321A, and the results are shown in figures 5 and 6, as the change of SOC (ΔSOC) wherein the negative sign indicated battery discharging process, and the charge condition of the battery, respectively. The data were captured every 5 seconds, this length of time $t$ is sufficient since the average current of 0.022 mA was measured through the coulomb counter, according to the equation (given in DC2321A manual sheet) $t \geq \frac{2(36.22 \mu C)}{22 \mu A}$. After 240 s the power input was applied, indicated by EH_ON status equal to 1.

The ΔSOC means that the obtained value was relied only on the change of charge and the capacity of battery, or the initial SOC$(t_0)$ subtracted by SOC (equation (1)), as previously explained. The battery was discharging when there was no energy harvested; in case of DC2509A no input was applied to
their turrets. An applied input turret (voltage) was indicated by EH_ON equal to 1, as it happened the battery current equal to 0 was obtained. This discharging condition of the primary battery was monitored as well in the battery status GUI, i.e. the black background with white text. The ΔSOC can be represented by monitoring the current, and by using the charge to determine for the average of ΔSOC, approximately 0.013% was achieved for the primary battery. During the measurement of the observed temperature, voltages at primary battery and at secondary battery were 21°C, 3.3 V and 3.9 V, respectively.

5. Conclusion
Determination of the change of SOC (ΔSOC) of battery, and characteristics of multiple sources in an energy harvesting system has been presented in this study. CCTR (coulomb counter function) provided in EH/power board can be switched to perform the observation of charge of battery used by the ICs. LTC3330 was used to investigate ΔSOC resulted in 0.013% that was achieved for discharging of the primary battery of EH system. Results from the input current measurements demonstrate the ability to interface the EH system with multiple energy sources, simulated by the use of bench power supplies. More specifically, the EH selects the source with the highest voltage to supply the energy. This presents a shortcoming of the EH since this method implies only one source of the multiple sources at any given time is supplying the power. An improved technique such as a true multiple input single output converter could be utilized to maximize energy production for the EH system.

6. References
[1] Shaikh F K and Zeadally S 2016 Energy harvesting in wireless sensor networks: A comprehensive review Renewable and Sustainable Energy Reviews 55 1041
[2] Warneke B A and Pister S J 2002 Proc. of Electronics, Circuits and Systems vol 1 p 291
[3] Yeatman E M 2007 Applications of MEMS in power sources and circuits Journal of Micromechanics and Microengineering 17 S184R
[4] Harb A 2011 Energy harvesting: State-of-the-art Renewable Energy 36 2641
[5] Fang H B et al 2006 Fabrication and performance of MEMS-based piezoelectric power generator for vibration energy harvesting Microelectronics Journal 37 1280
[6] El-Anzeery, El-Bagouri, Guindi R 2012 IEEE Int. Power Engineering and Optimization Conference (Melaka, Malaysia) p 209
[7] Maharaj S and Govender P 2013 Proc. of the 21st Domestic Use of Energy Conference (DUE) pp 1-6
[8] Jad O, Razvan S and Fabrice V 2016 IEEE 13th Int. Conf. on Mobile Ad Hoc and Sensor Systems p 183
[9] Kamarul Z P et al 2016 IEEE 3rd Int. Symp. on Telecommunication Technologies (Kuala Lumpur) p 53
[10] Murnane M and Ghazel A 2017 A closer look at State of Charge (SOC) and State of Health (SOH) estimation techniques for batteries Analog Devices Technical Article (2017)
[11] Pop V, Bergveld H, Notten P, and Regtien P 2005 State of the art of battery state of-charge determination Measurement Science and Technology 16 R93

Acknowledgments
We thank Fulbright fellowships for the financial support during the short-term research/visiting scholar period for conducting the work at Cal Poly State University, San Luis Obispo, USA.