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Energy Harvesting System for Wireless Sensor Nodes from Ambient Sources

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Abstract: ***Generally in case of Wireless sensor networks (WSNs) for energy scavenging and supplying purpose portable and limited energy source, such as batteries, power suppliers are used. Except energy, a sensor node is essentially useless and cannot contribute to the utility of the network as a whole. That's why, substantial research efforts have been made on designing energy-efficient wireless sensor networking protocols to maximize the lifetime of nodes used in network to collect different types of data. As , there are different kinds of Wireless sensor networks applications where sensors nodes are required to operate for much long durations (like years or even decades) after they are deployed. Examples include environmental/habitat monitoring and structural health monitoring of critical infrastructures and buildings, where batteries are hard or impossible to replace or recharge. Then, different approaches has been made to empowering wireless sensor nodes is being studied, one of which is to convert the ambient energy from the environment into electricity to power the sensor nodes so they can quickly sense and transmit the data. In this paper, we propose a methodology for harvesting energy on sensor nodes from ambient sources like solar and wind harvester with maximum power point tracking for self-powered wireless sensor network (WSN) nodes. We focus on maximizing the harvester's efficiency in transferring energy from solar panel, wind mill to the energy storing device. This model predicts the instantaneous power collected by the panel helping the harvester design and optimization procedure. Experimental results based on the presented design guidelines demonstrate the effectiveness of the adopted methodology. This design procedure helps in boosting efficiency. The application also focus on how the ambient sources extend the battery life.***

Keywords: *WSN; ambient energy, PV cells,* RFM's, LPR2400ERA, LDO, FET

1. Introduction

One of the most important issues in the field of Wireless Sensor Network is energy. Energy supply has been the greatest limiting factor on wireless sensor networks (WSN). Batteries today can power a sensor node for only a few hours at 100% duty cycle[1]. Much of the research on wireless sensor networks has assumed the use of a portable and limited energy source, batteries, to power sensors and focused on extending the lifetime of the network by minimizing energy usage. Portable energy sources like batteries will experience current leakages that drain the resource even when they are not used; furthermore, any flaws in the packaging due to long term wear and tear can result in environmental problems. A wireless sensor network that is not dependent on a limited power source (like a battery) essentially has longer lifetime than traditional ones. Failure due to other causes (like structural hardware damage) can be overcome by self- organization and network re-configuration[2]. This study has motivated the quest for an alternative source of energy to power WSNs especially for applications that require sensors to be installed for long durations (up to decades) or embedded in structures where battery replacement is impractical. At the same time, many sensing environments provide sufficient energy in the form of sunlight, wind, vibration, and even water flow that can be harvested for powering the sensor nodes indefinitely. In this paper, we first provide a survey of research on energy harvesting for wireless sensor networks from natural sources. This has motivated researchers to design energy harvesting capabilities in their sensing systems. The issues are harvesting *efficiency*, *autonomy* of harvesting control, and *expandability* to multiple energy sources.

2. Literature Review

Different types of energy harvesting systems for wireless sensor systems have been proposed for different uses. Most of them use solar panels as their ambient power source, and they use batteries and super capacitors for energy storage. This section reviews some of the recently proposed energy harvesting systems and shows the characteristics of the ambient power sources. The use of renewable energy to generate electricity is not a new concept. Renewable energy that is being harvested to generate electricity today includes solar, wind, water and thermal energy. Harvesting energy for low-power (and possibly embedded) devices like wireless sensors presents a new challenge as the energy harvesting device has to be comparable in size (i.e. small enough) with the sensors[3]. There are complex tradeoffs to be considered when designing energy harvesting circuits for WSNs arising from the interaction of various factors like the characteristics of the energy sources, energy storage device(s) used, power management functionality of the nodes and protocols, and the applications' requirements[4].

A. Solar Energy

Solar power is the most available and efficient source among the different forms of energy harvesting. But, it has the disadvantage of being able to generate energy only when there is sufficient sunlight or artificial light; furthermore, existing systems were not designed for use with low power WSNs. So it requires new research efforts. With the envisioned indoor WSN applications, a system has been developed to address the needs of WSNs deployed in indoor environments (e.g. hospital and industrial) where lights are operational at close to 100% duty cycle [5]. To ensure that energy is not unnecessarily lost during the transfer from the harvester to the wireless sensor, a low power-maximum power point tracker circuit has been proposed to efficiently transfer the harvested solar energy to rechargeable batteries even in non-optimal weather conditions. Another effort conducted empirical and mathematical analysis of two micro-solar power systems and used the results to propose design guidelines for micro- solar power systems for WSNs

B. Thermal Energy

Another important ambient resource for energy is Thermal sources. Electric energy can be generated when there is a temperature difference between two junctions of a conducting body. This type of energy harvesting uses temperature differences or gradients to generate electricity. To address the needs of telecommunications and other embedded applications, design of small-structure thermoelectric devices has been proposed in [6]. Due to the lack of moving parts in thermal energy harvesting devices, they tend to last longer than vibration-based devices [8].

C. Wind

Wind can be an alternative source for natural energy There are so many places where most of the time sunlight is unavailable. And it is mostly cloudy and windy. By installing windmill electricity and charge can be produced. Thus it can be also used to harvest energy in WSN nodes.

D. Commercial Energy Harvesters

Energy harvesting devices are becoming available commercially. E.g., a Solar Energy Harvesting development kit, produced by Texas Instruments (http://www.ti.com), can be used to create perpetually powered wireless sensor net- works based on their ultra-low power components. It can produces vibration-based energy harvesters that can replace batteries and be used to power wireless sensor nodes. Details on other commercially available energy harvesters for sensor nodes are available in [6].

3. Methodology and implementation

Solar provides an excellent source of energy for wireless systems that have no access to fixed power. Solar energy is abundant, present in all but the most northern-reaching climes and dependable for the foreseeable future (>1 billion years). Solar or Photovoltaic (PV) cells continue to improve at a rapid pace, both in terms of higher efficiencies and lower production costs. On average, the amount of solar energy falling onto a square meter at the equator of planet earth is 1000 w/m^2. This number varies wildly depending on circumstances and location but illustrates the point that solar energy can provide significant amounts of power for outdoor wireless applications. RFM has designed two solar power energy harvesting supplies for our LPR2430ERA wireless module. The LPR2430 is a 100mW 802.15.4 wireless sensor module[2][7]. This work explains the technical approach and design choices used to design the harvesting supply. The circuits discussed in this work have been implemented in prototype designs and have been working in an outdoor environment for more a certain time.

A. Energy source: The PV Cell

At its most basic, the equivalent circuit of a PV cell is that of a photon-controlled current source in parallel with a diode. Figure 1 show that basic configuration plus parasitic resistances. These model the various losses in the cell and are of secondary importance. For our purposes, the current source and the diode are the key elements to consider when designing the power harvester. PV cells are rated to produce a given current and voltage output when illuminated with a standard light level (irradiance) of 1000 Watts/m^2 at room temperature. The current produced by the cell is directly proportional to the active area of the cell (in m^2), the amount of light falling in that area and the conversion efficiency of the cell. The voltage across a single PV cell is a function of the current through it (Id) and obeys the standard semiconductor diode equation. Open circuit voltage across a single cell is usually about 0.6 volts. Note that while one cell will suffice for many applications, most of the time, cells are stacked in series and/or in parallel to provide higher currents or voltage for a given light level[8].

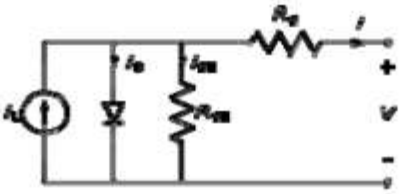

Figure 1: Ideal PV circuit

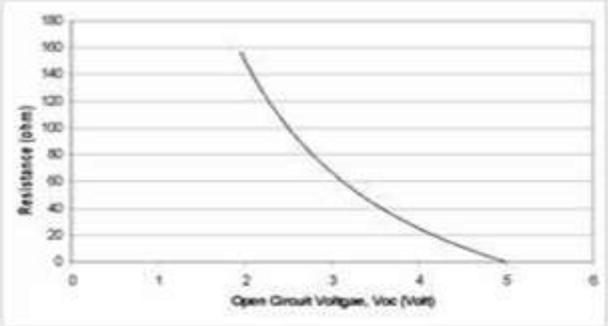

Figure 2 (a): I/V characteristics of a series-stacked PV cell

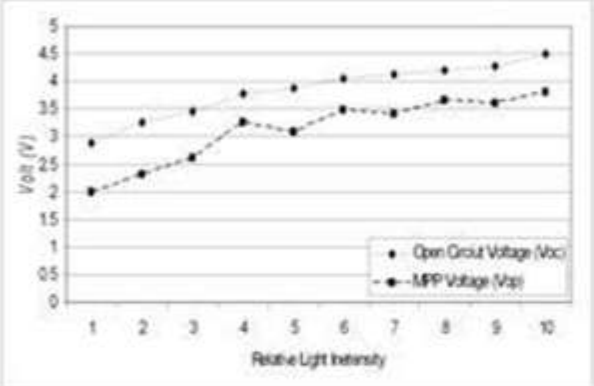

Figure 2 (b): PV cell when illuminated with 1000 Watts/m^2

Figure 2 shows the I/V characteristics of a series-stacked PV cell when illuminated with 1000 Watts/m^2. Note that the output voltage of the cell remains reasonably constant as current drawn from the cell is increased from 0 to 30 mA.

Past that point though , the cell voltage collapses and the output voltage drops to 0 volts. Conversely, the cell voltage peaks at ~2.6 Volts at room temperature when no current is drawn from the cell. This characteristic is typical for all PV cells and we've found it useful to think of the devices as current limited voltage sources. As long as the current pulled from the cell is somewhat less than its short circuit limit (30 mA in this case), the cell can be considered to be a constant voltage source with moderate internal resistance. Note that this characteristic will have some bearing on the choice of power conditioning circuitry following the PV cells. For the purposes of this app note, we'll simply state that PV cells come in only two flavors: thin film and crystalline silicon. Both differ in efficiency and form factor. This is a gross over-generalization but it is fairly safe to say that Thin film cells are flexible, fairly inexpensive but have low (3% to 5%) efficiency when converting photons to electrons. Crystalline cells are usually rigid (inflexible), higher cost and higher (15% to 20%) efficiency. The choice of cell is dictated by the amount of available sunlight, form factor (volume and area) and cost[9].

B. Energy Storage

Since our PV cells can only collect energy during the day, some provision for energy storage must be made to power the modules when no light is available. After considering many battery technologies, we chose to use a Lithium Ion secondary cell for our storage element. Li-Ion batteries have excellent energy storage capacity, long charge/discharge lifetime characteristics, low internal resistance and exhibit very little self-discharge. They have the additional virtue of providing 3.6 volts – a very handy value for powering 3.3 volt modules. The size of the battery is completely dependent on the current drawn by the wireless module[9].

C. Energy Conversion Circuitry

The type of circuitry used to convert solar energy to electricity to power our wireless module is driven by the voltage rating of PV cell and the voltage requirements of the wireless module. RFM's LPR2400ERA wireless module requires at least 3.3 volts for proper operation. PV cells come in all flavors and the choice of voltage ranges from 0.6 volts to tens of volts. If the cell voltage is rated below 3.3 volts, then a boost switcher will be required. Conversely, if the PV voltage is higher, either an LDO or buck switcher is required. In both solar harvesters we constructed, the PV cell voltage was lower than what was needed to power our module and charge our battery so we used boost regulators.

D. Circuit Implementation

When adequate sun is present, the PV cells supply power to the switcher at a nominal 3.0 volts. The particular PV cells we chose for the first harvester prototype produced a composite 125 mA output current. We needed at least 4.5 volts to operate our Li-Ion charging IC so we used a voltage boost IC to translate the PV cell voltage up to 4.75 volts to provide some head room. Peak current for our wireless module was 125 mA so the switcher was sized appropriately. The Li-Ion charging circuit was set to provide a constant charging current of 10 mA to the battery. The Diode and P-channel FET circuit on the right side of Figure 3 selects either the switcher output or the battery voltage depending on time of operation. During the day when the PV cells are operating, the switcher produces 4.75 volts. This is higher than the 4.2 volts across the Li-Ion battery so the P-channel FET is back- biased and the Schottky diode provides current to the load. After dark, the PV cells are off and the switcher produces 0 volts. The 4.2 volts across the battery is now higher than the switcher output. The P-channel FET switch turns on, the Schottky is back-biased and power flows from the battery to the load. Next morning, the PV cells crank up at first light, the switcher starts producing 4.75 volts, the P-channel FET turns off, the Schottky turns on and the circuit is again solar powered. The 1 Farad super cap on the left and the 1000 uF electrolytic Capacitor on the right serve as charge reservoirs to buffer current spikes produced when the module transmits an RF signal. The Super cap reservoir allows us to use PV cells rated at 125 mA to power circuitry that consumes higher peak currents. As long as the transmit bursts are reasonably short, the super cap will fill the gap and provide the necessary energy. Finally, note that most super caps are rated to 2.5 volts. We used two in series to handle the 3.0 output voltage from the PV cells[10].

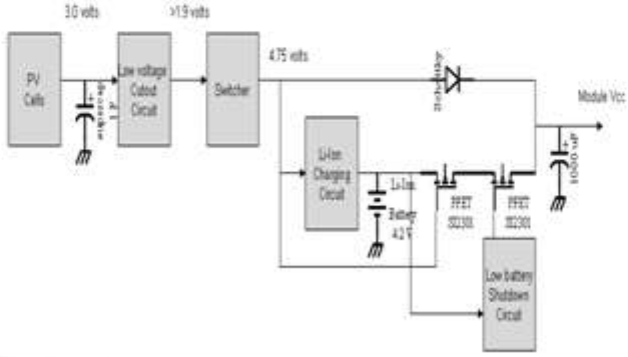

Figure 3: Basic block diagram of solar powered energy harvester

4. Result and Analysis

The Low Voltage Cutout circuit fixed a problem we found early on with the first prototypes of this circuit. When the harvester started up under low light conditions, the boost switcher would initially draw excessive current from the cells and the cell's output voltage would collapse to ~0 volts. With the PV cells shorted out, the boost switcher couldn’t start properly and the circuit was locked down tight. This condition would continue until the cell was disconnected from the switcher. Start up under brighter light was more reliable as the PV cells could source the current needed by the boost switcher at start up. The appropriate cut-in voltage was determined empirically. We found that any voltage above 2.2 volts avoided the lockup problem. We used a standard voltage monitoring IC to measure the PV cell voltage and a P-channel FET to act as series switch[11]. The schematic and BOM has details of the actual implementation. There is one slight trick to the battery disconnect circuit. Refer to the schematic in the appendix and note that after the NCP303 voltage monitor turns off FET Q3, it will never turn back on until the PV cells start producing power again. This ensures that the battery stays disconnected from the load until power is available. See the schematic and BOM for exact implementation [12]. The RFM Engineering group has built two solar powered sensor radios using the techniques outlined in this app note. Both units have been running continuously since November of 2009. Each unit was designed slightly differently so we could investigate technology differences between PV cells and batteries. Unit One uses 5 Thin Film PV cells and 1 coin-cell Li-ion battery. [13]Unit Two uses 4 crystalline PV cells and an AA Li-ion battery. After 4 months, both systems continue to perform well. The Crystalline and Thin Film PV cells appear to be sized about right for our energy consumption needs. We have decided that a product based on these prototypes would probably use the AA battery to provide greater energy storage in case of extended dark weather.

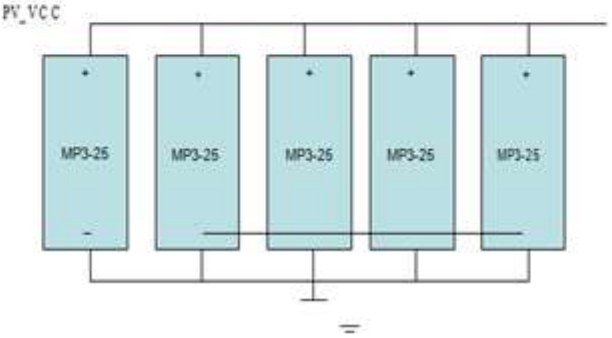

Figure 4: Crystalline PV Cell Stack up.

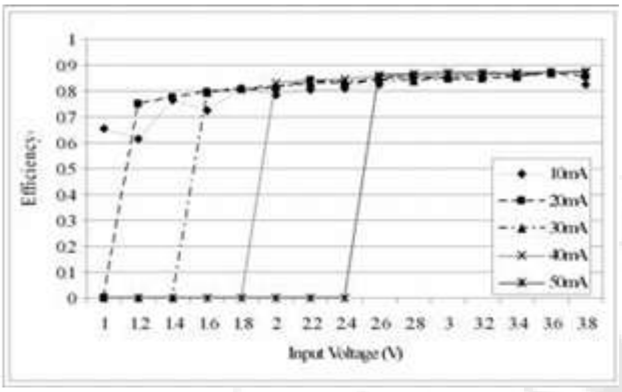

Figure 5: Measured conversion efficiency of LTC3401 at V_{out} =4.1V

5. Conclusion

In this paper, we have presented an optimization methodology allowing maximizing the efficiency of solar harvester for self-powered WSN devices. This methodology relies on compact models of both the PV module and the harvesting circuit, which implements an analog MPPT technique already proposed in the literature. The model of the PV module is discussed in detail, and a simplified parameter extraction procedure is proposed[14]. Useful guidelines are presented to optimize the harvester circuit design, which allow to significantly improve the whole harvester efficiency, which is crucial in WSN applications. Noticeably, the harvester implemented using commercial components features a high efficiency (85%), which to our knowledge is the highest ever reported in the literature. It is worth noting that this methodology is not limited to self-powered WSN nodes; it can easily be applied to embedded systems to extend the battery lifetime, and it can also be used to optimize the design of harvesting ICs. The final goal of this paper will be the implementation of an IC harvester able to efficiently work on a wide range of light conditions. For this reason, design information about the needed passive components is a key aspect, because a tradeoff between harvester performances and physical implementation will be needed to keep the silicon costs below a bearable threshold.

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