MICRO-SCALE ENERGY HARVESTING

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Contents

Summary

Environmental energy sources abound in our immediate surroundings. Energy harvesting is a physical process by which the energy is collected from the environment. Examples of such energy sources include light, thermal gradients, vibrations, electromagnetic wave, etc. Harvesting electrical power from environmental energy sources is an attractive and increasingly feasible option for several micro-scale electronic systems such as biomedical implants and wireless sensor nodes that need to operate autonomously for long periods of time (months to years).

However, designing highly efficient micro-scale energy harvesting systems requires an in-depth understanding of various design considerations and tradeoffs. This book chapter provides an overview of the area of micro-scale energy harvesting and discusses the various challenges and considerations involved from a design perspective.

1. Introduction

As the world is more and more concerned with fossil fuel exhaustion and environmental problems caused by conventional power generation, renewable resources are becoming a focal point of the environmental movement, both politically and economically. Environmental energy sources abound in our immediate surroundings. Energy harvesting is a physical process by which the energy is collected from the environment. Examples of such energy sources include light, thermal gradients, vibrations, electromagnetic wave, etc. Harvesting energy from the surrounding environment is of growing interest to the research community, but in practice, design challenges limits its viability and ability to penetrate the market.

Nowadays, rapid advances in computing, communication, and integration has resulted in the emergence of a new class of ultra-low power applications. Examples of such systems include wearable or implantable biomedical devices [Yazicioglu 2009], wireless sensor nodes [Raghunathan 2004], etc. These systems are often required to operate for several months to years without the need of battery replacement, because frequent battery replacement may be infeasible (e.g., for biomedical implants) or prohibitively expensive (e.g., in a large sensor network). Energy storage element, e.g. battery, is extensively used for powering electronic systems. However, since the volume permitted for battery integration in these miniaturized systems is quite tiny (and hence very limited energy capacity), the energy storage element will be quickly depleted after a short time of system operating and these systems will become useless. Frequent battery replacement is impractical in these micro systems, since it is prohibitively expensive for large wireless sensor network that consist of hundreds to thousands of spatially distributed autonomous micro-sensor nodes, or it often requires invasive surgery (e.g., pacemaker batteries need to be replaced every six to seven years, on average). Loss of power in a biomedical implant due to a depleted energy storage element can have serious and potentially life threatening consequences. As a result, one key challenge in these systems is to conveniently provide the required power for long-lived, maintenance-free operation.

Environmental energy harvesting is an attractive option to alleviate the power supply challenge in these systems [Mateu 2005; Raghunathan 2005]. Examples of ambient energy sources are light, thermal, fuel, vibration, radio frequency waves, etc. While the basic idea of environmental energy harvesting has been extensively explored and applied at the macro-scale in the context of large systems such as solar farms, windmills, *etc.*, designing micro-scale energy harvesting systems involves several new challenges. Most of these challenges stem from the fact that the form-factor constraint in these systems mandates the use of miniature energy transducers (a few cm^3). As a result, the maximum power output of these micro-scale transducers is extremely small, often only a few mW. Therefore, the harvesting subsystem should be carefully designed to extract as much power as possible from the energy transducer and transfer it to the electronic system with minimal loss, which requires extremely energy efficient design techniques. Energy harvesting is an alternative method of providing power to these micro systems and has the potential to result in perpetual operation. This book chapter presents an overview of the various circuit design considerations and techniques involved in designing energy-efficient micro-scale energy harvesting systems.

In addition, energy harvesting also provides significant environmental benefits. For example, the large number of batteries discarded in solid waste landfills represents a long-term threat to groundwater and drinking water supplies due to heavy metal (e.g., mercury, cadmium) leakage. The use of energy harvesting in micro systems significantly prolongs overall battery life and in some cases, eliminates the dependence on batteries, and thus, directly contributes towards mitigating this problem.

Figure 1 shows the generic block diagram of a micro-scale energy harvesting system. It consists of five blocks: the micro scale energy transducer, the power converter, the control unit, the energy buffer, and the application unit. The energy transducer converts ambient energy into electrical energy, which is stored in the energy buffer (a rechargeable battery or a super capacitor) for powering the application unit (e.g., sensor node or biomedical implant). The energy transducer may be based on one energy conversion mechanism or a hybrid heterogeneous combination. The control unit plays a crucial role in maximizing overall system efficiency. It produces the required control signals for the entire system and ensures maximum power point (MPP) operation at all times by running a MPP tracking scheme. The goal of the power converter is to extract as much power (P_S) as possible from the energy transducer and pass on as much of it as possible (P_{EB}) to the output. In this chapter, each building block will be addressed and discussed in the following sections.

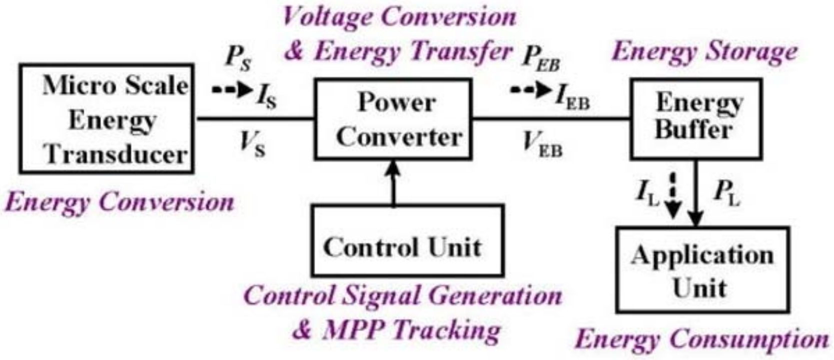


Figure 1. Block diagram of a micro scale energy harvesting system

The rest of this chapter is organized as follows. In Section 2, we briefly review the basic device physics and characterize the electrical behavior of various energy transducers. Design considerations and research progresses for energy-efficient power converters are introduced in Section 3. In order to enhance the charge transfer capability from ultra low voltage energy transducers, a tree topology charge pump is analyzed and discussed thoroughly. In Section 4, the previously proposed MPP tracking approaches are classified and addressed, followed by a discussion of harvesting-aware application unit design in Section 5. Finally, the conclusion is given in Section 6.

2. Energy Transducer Characterization

Environmental energy sources are ubiquitous in our immediate surroundings. Examples of such energy sources include solar radiation, air flow, mechanical motion/vibration, thermal gradients, radio frequency (RF) transmissions, etc. A variety of micro-scale energy transducers have been developed to convert energy from other modalities into electrical energy [Choi 2006; Chu 2006; Egbert 2007]. The dominant characteristic of energy transducers is their power density (Watt/cm^3). This is because transducers will never run out of energy (barring any hardware failures) as long as the environmental energy source is present, and hence, cannot be viewed as conventional capacity-limited energy sources (i.e., battery).

Table 1 shows the estimated power densities of a few commonly used energy-harvesting modalities [Raghunathan 2005]. While there has been (continues to be) extensive research from the device perspective to improve the cost, conversion efficiency, and power density of transducers, it is crucial for system designers to be aware of their electrical characteristics in-depth in order to understand their impact on the system being powered. Although various physical or mathematical models have been proposed to characterize micro scale energy transducers, these models are cumbersome, computationally intensive, and incompatible with circuit design or simulation software (e.g. Cadence or SPICE). Hence, in the remainder of this section, we provide an overview of various energy-harvesting modalities and describe how some of these transducers can be modeled from electrical perspective.

Harvesting technology	**Power density**
Solar cells (outdoors at noon)	15mW/cm^3
Piezoelectric (shoe inserts)	330μW/cm^3
Vibration (small microwave oven)	116μW/cm^3
Thermoelectric (10°C gradient)	40μW/cm^3
Acoustic noise (100dB)	960nW/cm^3

Table 1. Power densities of various energy harvesting modalities

2.1 Micro Photovoltaic Module

A photovoltaic (PV) cell is a device that converts the light energy directly into electricity by the photovoltaic effect. It is useful to create an electrically equivalent model that is SPICE-compatible. This model facilitates the design of remaining system building blocks (e.g. power converter or control unit) and enables system-level simulations and verification. This SPICE-compatible model allows system designers to simulate and observe the matching status between a power converter and an energy transducer.

Figure 2 shows the equivalent electrical circuit model of a micro PV module [Lu 2010b], which is composed mainly of a current source and a forward biased diode. $I_{\mathrm{PH,SC}}$ is the generated photocurrent by photovoltaic conversion, R_{S} is the parasitic series resistance, and R_{P} is the equivalent shunt resistance. I_{PH} and V_{PH} are the output current and terminal voltage of the PV module, respectively.

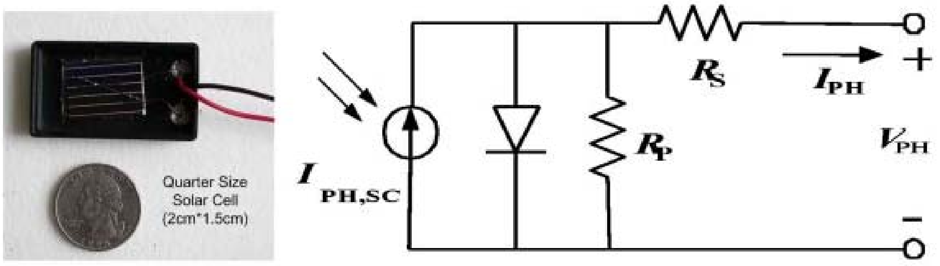
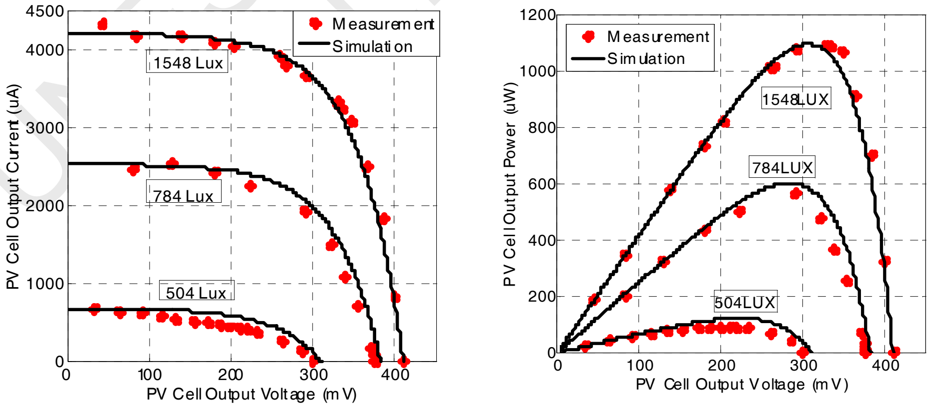


Figure 2. The electrical model of a PV module

Based on the circuit shown in Figure 2, the output current (I_{PH}) and power (P_{PH}) of a PV module can be expressed as

$$I_{PH} = I_{PH,SC} - I_{SAT}\left\{e^{\frac{q}{AKT}(V_{PH}+I_{PH}R_S)} - 1\right\} - \frac{V_{PH}+I_{PH}R_S}{R_P} \qquad P_{PH} = I_{PH}V_{PH} \qquad (1)$$

Here, I_{SAT} is the reverse saturation current, q is the electron charge, A is a dimensional factor, K is the Boltzmann constant, and T is the operating temperature. We conducted experiments using a commercial PV module (Model #1-100, SolarWorld Inc.) to validate this model. The PV module was characterized under weak light (indoor) conditions. The PV module was illuminated using a 40-Watt light bulb and the distance between them was adjusted to emulate changing light conditions. Various resistive loads were connected to the PV module and the output voltage and current were measured. Figure 3(a) plots the I-V curve of the PV module obtained using Eq. (1) and measured experimentally. We can see that the measured I_{PH} values fit well with the values predicted by the electrical model.



(a) **(b)**

Figure 3. (a) Measured I-V characteristic of a PV module (b) Output power vs. PV terminal voltage of a PV module

Figure 3(b) plots the output power (P_{PH}) of the PV module as a function of its terminal voltage. As is evident from the figure, for a given light irradiance, there exists an optimal output voltage (V_{MPP}) for the PV module at which P_{PH} is maximized (*e.g.*, 0.29V for 784*LUX*). This point on the *I-V* curve is the MPP. Note that the MPP changes significantly as the light intensity changes. The goal of MPP tracking schemes is to ensure that the PV module operates at its MPP at any given time. It can also be seen in Figure 3(b) that the harvested power is very limited (in the range of several hundred µW to 1.1mW). Obviously, we would like as much of this power as possible to be available to the load. Therefore, the power budget for an MPP tracking scheme in such a system is severely constrained (*e.g.*, at most a few µW), which requires the MPP tracking subsystem to be very carefully designed.

2.2 Micro Thermoelectric Generator

Micro TEGs are scalable, reliable and do not require any moving parts like vibration energy transducers. As a consequence, it is very appealing in micro scale energy harvesting systems, such as human body powered biomedical devices. Micro TEGs typically consist of multiple couples of p-type and n-type thermoelectric legs, which can output electrical energy by employing the temperature gradient between the hot surface (e.g., human body) and the cold surface (e.g., ambient air). These thermocouples are usually connected electrically in series and thermally in parallel to effectively make use of the limited surface area. When there is a temperature difference across a µTEG, seebeck effect causes the moving of charged carriers to generate a terminal voltage. Figure 4 illustrates the operation mechanism of a µTEG. The top layer of the µTEG is attached to a heat surface, while the bottom layer is placed near a cool surface. Due to the temperature difference, the electrons (or holes) in the N-type (or P-type) material flow towards the cool surface and forms a current.

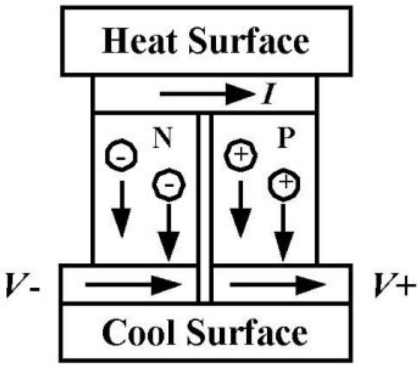


Figure 4. Illustration of operation mechanism of a µTEG

In [Egbert 2007], the figure of merit (FOM) of a micro TEG is defined as

$$Z = \frac{\alpha^2}{\lambda\rho} \tag{2}$$

Here α is the seebeck coefficient that is material dependent, λ is the thermal conductivity, and ρ is the electrical resistivity. Improving the FOM from a device or material perspective is one area of active research in thermoelectric community.

Micropelt MPG-D751 is a good example of small scale TEG devices. The current and voltage values for different ΔT across it were obtained by the simulation tool supported by the manufacturer and were plotted in Figure 5. The output power varies as a function of output voltage for different ΔT. The maximum output power is maintained when its output voltage is around half of the open circuit voltages (i.e. 0.31V for $\Delta T = 4K$, 0.23V for $\Delta T = 3K$). The open circuit voltage of a TEG is proportional to the number of leg pairs, the actual temperature difference ΔT and the seebeck coefficient α, as shown in the equation below:

$$V_{\mathrm{OC}} = \alpha \times N_{\mathrm{LEGPAIRS}} \times \Delta T \tag{3}$$

We can see that a TEG can be modeled as a voltage source in series with an internal resistor with the voltage source being proportional to ΔT. Such a model can be expressed using Eqs. (4) and (5), where β is a constant (i.e., internal resistor).

$$V_{\mathrm{TEG}} = V_{\mathrm{OC}} - \beta I_{\mathrm{TEG}} \tag{4}$$

$$\mathrm{P}_{\mathrm{TEG}} = V_{\mathrm{TEG}} I_{\mathrm{TEG}} = V_{\mathrm{TEG}} (V_{\mathrm{OC}} - V_{\mathrm{TEG}}) / \beta \tag{5}$$

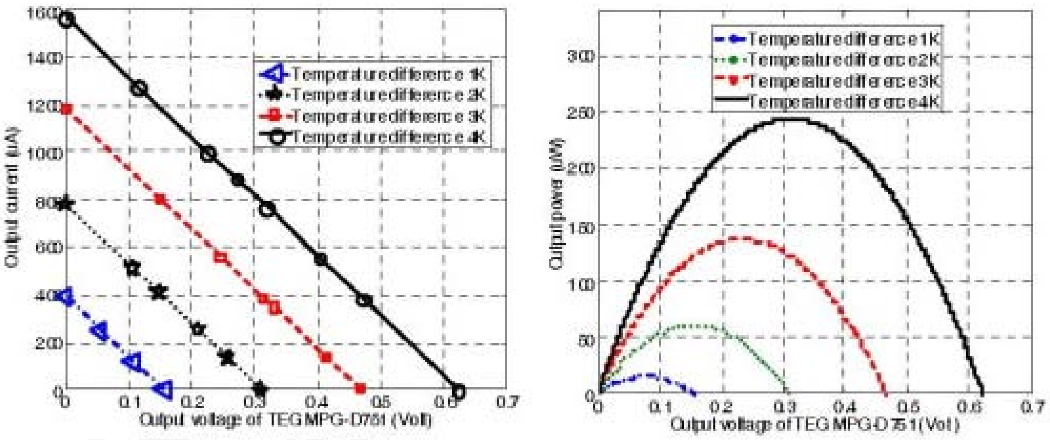


Figure 5. Simulation results of TEG MPG-D751 (ΔT=1~4K)

2.3 Micro Fuel Cell

Micro Fuel cell (µFC) is a viable alternative power source that converts fuel energy into electrical energy by chemical reaction of a fuel in the presence of a catalyst. µFC is considered as a green power source because the outputs of chemical reaction are environmental clean. The fuel has a much higher energy density. For example, theoretically the energy density of a methanol is five times higher than that of a lithium ion battery. Thus, it can achieve longer lifetime for the same weight or volume. With the advance of cutting-edge MEMS technology, researchers can shrink the size of fuel cells to chip dimension and integrate it with an integrated circuit (IC) to form a system-in-package (SIP) platform [Torres 2008]. In [Chu 2006], a silicon-based chip-scale fuel cell is fabricated and measured. Figure 6 shows a typical *V-I* characteristic (solid line) of a micro fuel cell. When the current density increases from zero, the µFC passes through three distinct operation regions: activation, ohmic and concentration polarization. Figure 6 also shows the estimated output power curve (dash line). It is obvious that there exists a maximum power point (MPP) in the region of ohmic polarization.

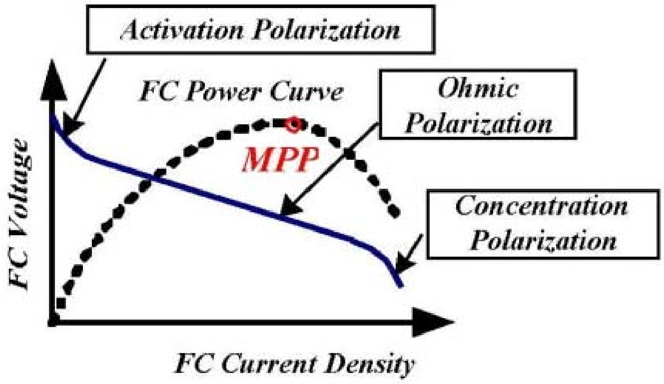


Figure 6. *V-I* and *P-I* characteristics of a micro scale fuel cell

Most existing fuel cell models assume constant fuel flow and unchanging concentration conditions [Yu 2004]. As a result, these models are only applicable to predict steady-state, time-independent behaviors. In [Chen 2008], a Cadence-compatible electrical model for a micro-scale direct methanol fuel cell (DMFC) was first developed to express the dynamic and steady state electrical behavior. This proposed electrical model is capable of prediction of runtime, large/small signal steady state or transient responses.

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Biography Sketches

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