Fundamentals of ambient energy transducers in energy harvesting systems

John Carpenter and Yogesh Ramadass, Texas Instruments
Sophisticated battery-operated electronic systems and self-powered devices recently have found diverse applications in existing autonomous and handheld objects. Significant advancements in CMOS process technologies and circuit techniques have reduced power consumption of circuits low enough to enable a new class of self-powered systems. These advancements are enabling emerging applications such as wireless micro-sensor networks, wearable medical electronics, industrial and home automation sensors, and electronic shelf labeling. Ideally, these systems can function without a battery. However, when a battery is still required, to the desire is to prolong battery life so that it does not need to be replaced during its lifetime. Understanding how energy transducers operate and how to extract power from them is essential to achieving either of these goals.

Self-powered systems require an energy source that keeps them going during their lifetime. Commercially available energy transducers can be classified into four broad categories based on the source of energy:

1) **Light**: Solar cells are composed of an array of p-n junctions and operate on the photovoltaic effect.
2) **Thermal**: Ambient thermal energy can be harvested using thermoelectric elements.
3) **Vibration:** Vibration harvesters use the mechanical energy present in vibrations through electromagnetic or piezoelectric means to produce electrical energy.
4) **Radio wave**: Radio wave harvesting works well with directed solutions, but for ambient energy there is not enough useful power for practical implementations.

Table I. Typical output power of energy harvesters

Energy Harvesting Sources	Environmental Location	Harvested Power	Harvester Consideration	Circuit Consideration
Light	Indoor	10 μW/cm²	Light intensity and wavelength	Low power efficiency, MPPT, single-cell operation
	Outdoor	10 mW/cm²		
Mechanical Vibration Piezoelectric	Human	4 μW/cm²	Amplitude of vibration and resonant frequency	AC/DC conversion, impedance matching
	Machine	250 μW/cm²		
Mechanical Vibration Electromagnetic	Human	50 μW/cm³		
	Machine	2 mW/cm³		
Thermal	Human	25 μW/cm²	Thermal gradient, heat flux	Low-voltage startup, high efficiency at sub-200 mV input
	Machine	10 mW/cm²		
Radio Waves	Background	0.1 μW/cm²	Distance from source and resonance of antennae	High efficiency low-voltage rectification
	Directed	1 mW/cm²		

Table I shows some typical power levels that can be obtained from the different energy transducers and key considerations of the harvester. In typical scenarios, average power output of ~10-50 μW/cm^2 can be expected from most harvesters. The power obtained is area-dependent and relies heavily on the space available for the harvester. Harvester characteristics can be described by using an example of a solar cell. The solar cell can be modeled as a current source in parallel with a diode, as shown in **Figure 1**. The shunting resistance models leakage and the series resistance models contact cell resistance.

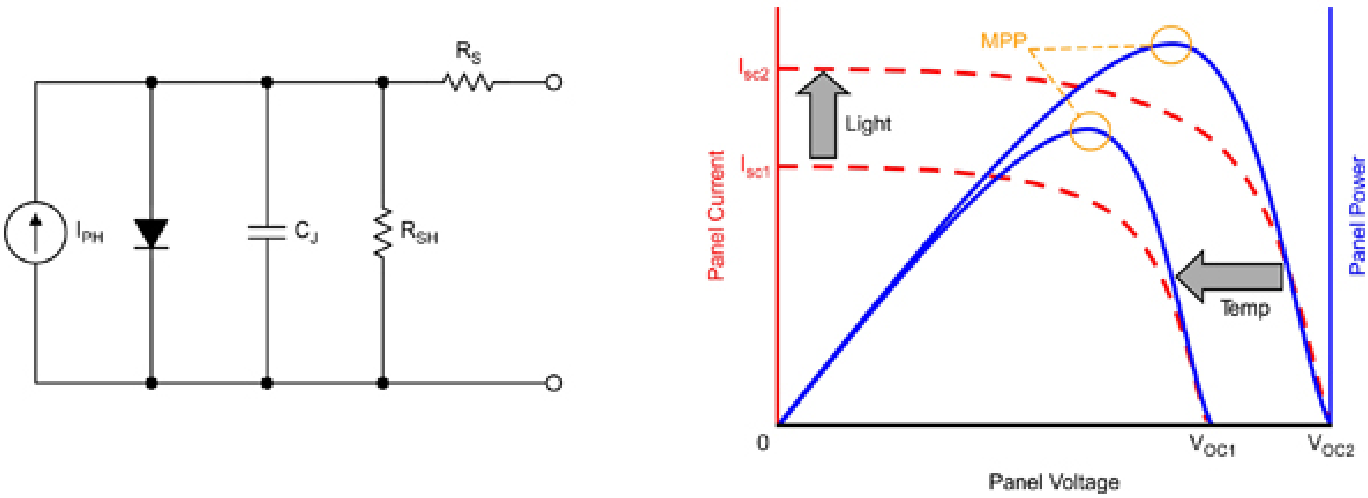

Figure 1. Electrical model of a photovoltaic cell and its characteristic curve.

When light impinges on the solar cell, the cell produces an electric current, IPH, which flows through the output. This current creates a voltage VOC at the output when the cell is open-circuited. Between the extremities of open and short-circuit, power can be extracted from the cell. In **Figure 1**, the red curve shows the current versus voltage characteristic of the solar cell. Increasing illumination increases the short-circuit current and has a slight effect on the open circuit voltage of the cell. The power obtained from the solar cell reaches a maximum at a particular voltage and tapers down on either side of this voltage. This is the cell’s maximum power point. It is a function of the incident illumination and other environmental factors such as temperature. Other transducers, owing to their high impedance characteristic, exhibit similar maximum power point (MPP) characteristics. As such, selecting a power management solution to operate at the MPP is a key consideration.

Thermoelectric generators (TEGs) are used to harvest ambient heat energy and generate an electrical voltage through the Seebeck effect [1]. The basic construction unit of a thermal harvester is a thermocouple. This thermocouple is composed of an n-type material electrically in series with a p-type material. When a temperature difference is applied across this material, heat begins to flow from the higher temperature surface to the lower temperature surface. Energy from the applied heat allows the free electrons and holes to move and form an electric potential. Commonly used thermal harvesters for power generation consist of p- and n-doped Bismuth telluride owing to its superior thermal properties. One p-n leg of this material generates around 0.2 mV/K difference between the hot and cold sides.

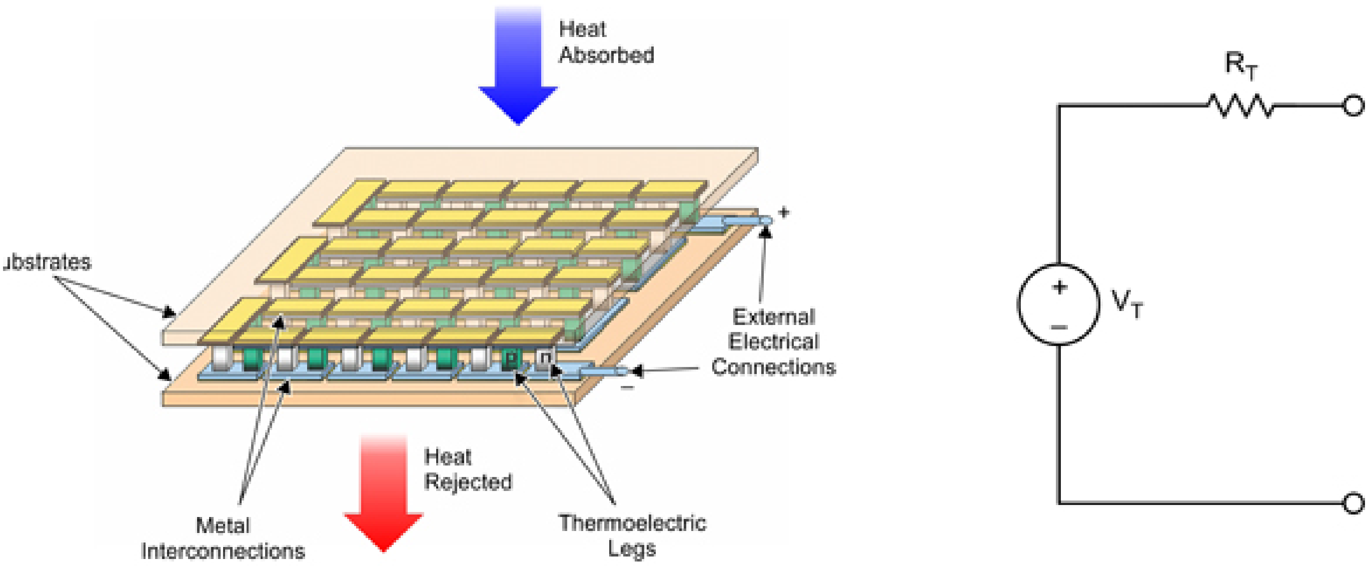

Figure 2. Thermopile array and a simple TEG electrical model.

To boost the output voltage and get more power (see **Figure 2**), many of these legs are connected electrically in series and thermally in parallel to form a thermopile capable of producing around 25 mV/K of temperature difference. The thermal harvester can be modeled electrically as a voltage source in series with a resistance where the open-circuit voltage is proportional to the temperature difference. The resistance arises from the metal interconnections and the resistance along the pellets. From this model, it is easy to see that in order to extract maximum power, controlling the impedance to match the load from the generator is required. An important aspect of thermal harvesters is that a proper heat flow system is needed around them to maintain the heat flux and, thereby, a healthy temperature difference. If the two sides of the TEG are allowed to reach thermal equilibrium, the electrical power output reaches zero.

A popular way to harvest ambient mechanical energy is to employ piezoelectric elements. An input vibration applied to a piezoelectric material as shown in **Figure 3** causes mechanical strain to develop in the device, which is converted to electrical charge. The equivalent circuit of the PE harvester can be represented as a mechanical spring mass system coupled to an electrical domain. Close to the resonant frequency of the device, we can transform the whole circuit to the electrical domain [2]. There is where the piezoelectric element, when excited by sinusoidal vibrations, can be modeled as a sinusoidal current source in parallel with a capacitance CP and resistance RP.

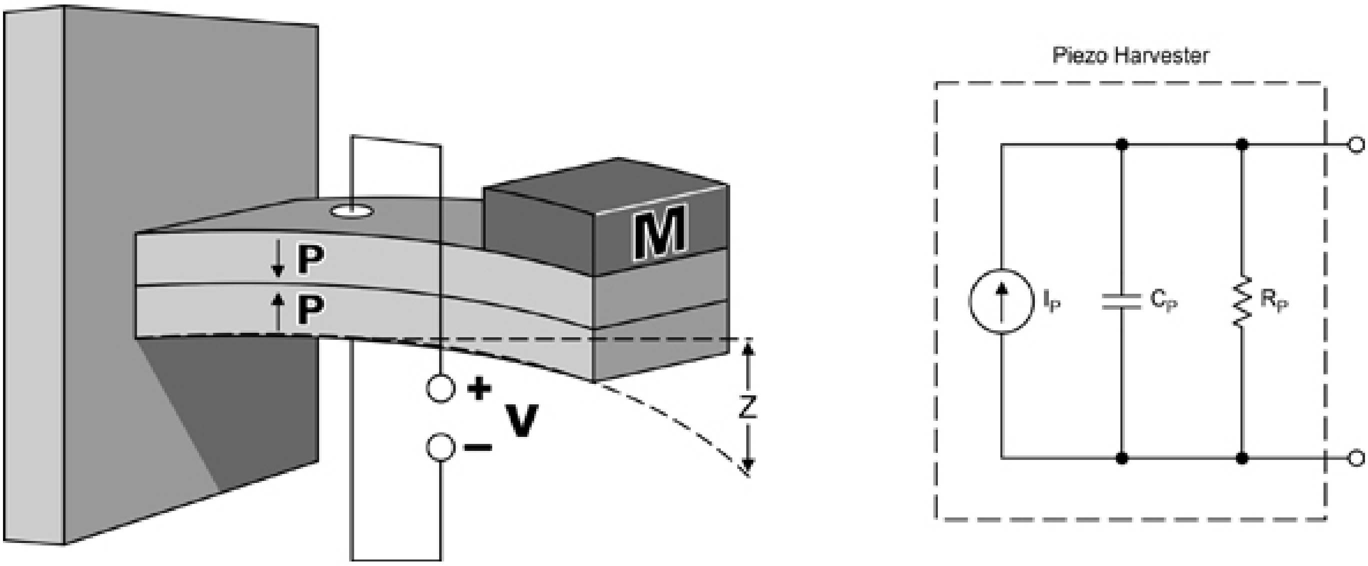

Figure 3. A piezoelectric element loaded with a mass and its electrical model.

Additionally, mechanical energy also can be harvested using electromagnetic harvesters that utilize motion through a magnetic field to produce electric energy. To maximize power output, the harvester is mechanically tuned to an optimized resonant frequency present within the application environment and the rectifier impedance is adjusted to match [2]. These devices are easier to scale to the desired power compared to the piezoelectric harvester. However, both mechanical energy transducers are essentially resonant in nature and operate over narrow frequency bands.

Conclusion

In summary, it is important to understand the characteristics of the energy transducer in order to optimize the energy extraction and make a viable energy harvesting system. Some key considerations for power management of energy transducers are the energy source profile, energy transducer characteristics, and power management performance. Matching a power management solution to extract the most power from the transducer and storing it at usable levels requires a good understanding of these key parameters. This aids in developing energy harvesting systems that perform optimally in their intended applications.

References

1. Seebeck effect: http://en.wikipedia.org/wiki/Thermoelectric_effect [1]
2. Y. K. Ramadass, “Energy processing circuits for low-power applications,” Ph.D. dissertation, Massachusetts Institute of Technology, Cambridge, MA, 2009
3. For more information on energy harvesting solutions from Texas Instruments, visit: www.ti.com/energyharvesting-ca [2].

About the Authors

John Carpenter, Jr., is a Design Engineer for Battery Management Solutions at Texas Instruments where he is responsible for system level integration and IC design with multifaceted circuits for mixed-signal applications in BICMOS processes. He received his MSEE and BSEE from the University of South Florida, Tampa. John holds 13 patents and is a Senior Member of IEEE, Senior Member Technical Staff for Texas Instruments, and a retired naval engineering duty officer for US Navy Reserves.

Yogesh Ramadass is an analog/mixed signal design engineer with the Battery Charge Management group at Texas Instruments. His current focus is on designing TI’s next generation energy harvesting interface circuits and low-power DC-DC converters. He received his SM and Ph.D. degrees from the Massachusetts Institute of Technology.

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