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Harvesting ambient energy will make embedded devices autonomous

By Erick O. Torres and Gabriel A. Rincon-Mora, Courtesy of EE Times
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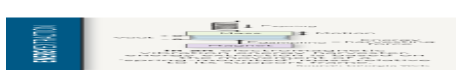
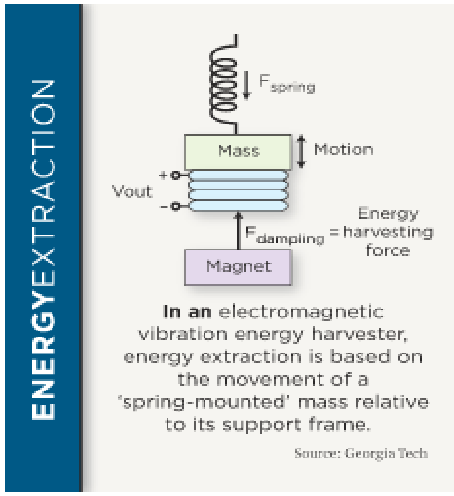
Modern electronics continues to push past boundaries of integration and functional density toward the elusive, completely autonomous, self-powered microchip. As systems continue to shrink, however, less energy is available on board, leading to short device lifetime (run-time or battery life). Research continues to develop higher-energy-density batteries, but the amount of energy available is not only finite but also low, limiting the system's life span, which is paramount in portable electronics. Extended life is also particularly advantageous in systems with limited accessibility, such as biomedical implants and structure-embedded micro-sensors. The ultimate long-lasting solution should therefore be independent of the limited energy available during startup. That's where a self-renewing energy source comes in, continually replenishing the energy consumed by the microsystem.

State-of-the-art microelectromechanical-system (MEMS) generators and transducers can be such self-renewing sources, extracting energy from vibrations, thermal gradients and light. The energy extracted from these sources is stored in chip-compatible, rechargeable batteries such as thin-film lithium-ion types, which power the loading application (for example, the sensor) via a regulator circuit. Since harvested energy manifests itself in irregular, random, low-energy bursts, a power-efficient, discontinuous, intermittent charger is required to transfer the energy from the sourcing devices to the battery. Energy that is typically lost or dissipated in the environment is therefore recovered and used to power the system, significantly extending its operational lifetime.

Energy harvesting is defined as the conversion of ambient energy into usable electrical energy. When compared with the energy stored in common storage elements, such as batteries and the like, the environment represents a relatively inexhaustible source. Consequently, energy-harvesting or -scavenging methods must be characterized by their power density, rather than energy density. Light, for instance, can be a significant source of energy, but it is highly dependent on the application and the exposure to which the device is subjected. Thermal energy, on the other hand, is limited because the temperature differentials across a chip are typically low. Vibration energy is a moderate source, but again dependent on the particular application.

Energy extraction from vibrations is based on the movement of a "spring-mounted" mass relative to its support frame. Mechanical acceleration is produced by vibrations that in turn cause the mass component to move and oscillate (kinetic energy). This relative displacement causes opposing frictional and damping forces to be exerted against the mass, thereby reducing and eventually extinguishing the oscillations. The damping forces literally absorb the kinetic energy of the initial vibration. This energy can be converted into electrical energy via an electric field (electrostatic), magnetic field (electromagnetic) or strain on a piezoelectric material. These schemes amount to harvesting energy from vibrations.





In an electromagnetic vibration energy harvester, energy extraction is based on the movement of a 'spring-mounted' mass relative to its support frame.

Source: Georgia Tech

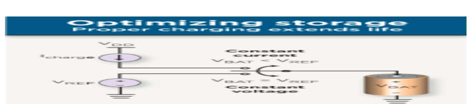
In electromagnetic-energy harvesting, a magnetic field converts mechanical energy to electrical. A coil attached to the oscillating mass traverses a magnetic field that is established by a stationary magnet. The coil travels through a varying amount of magnetic flux, inducing a voltage according to Faraday's law. The induced voltage is inherently small and must therefore be increased to viably source energy. Methods to increase the induced voltage include using a transformer, increasing the number of turns of the coil and increasing the permanent magnetic field. But each is limited by the size constraints of a microchip.

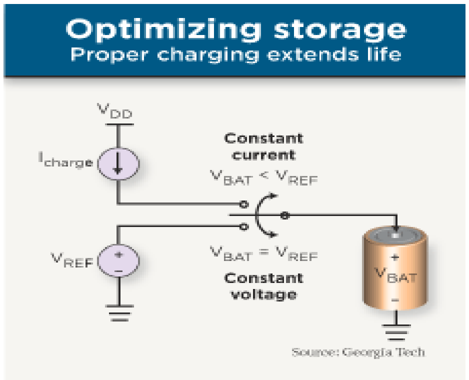
Piezoelectric energy harvesting converts mechanical energy to electrical by straining a piezoelectric material. Strain, or deformation, in a piezoelectric material causes charge separation across the device, producing an electric field and, consequently, a voltage drop proportional to the stress applied. The oscillating system is typically a cantilever-beam structure with a mass at the unattached end of the lever, since it provides higher strain for a given input force. The voltage produced varies with time and strain, effectively producing an irregular ac signal. Piezoelectric energy conversion produces relatively higher voltage and power density levels than the electromagnetic system.

Electrostatic (capacitive) energy harvesting relies on the changing capacitance of vibration-dependent varactors. A varactor, or variable capacitor, is initially charged and, as vibrations separate its plates, mechanical energy transforms into electrical energy. The most attractive feature of this method is its IC-compatible nature, since MEMS variable capacitors are fabricated with relatively mature silicon micromachining techniques. This scheme produces higher and more practical output-voltage levels than the electromagnetic method, with moderate power density.

Thermal gradients in the environment are directly converted to electrical energy through the Seebeck (thermoelectric) effect. Temperature differentials between opposite segments of a conducting material result in heat flow and, consequently, charge flow, since mobile, high-energy carriers diffuse from high- to low-concentration regions. Thermopiles consisting of n- and p-type materials electrically joined at the high-temperature junction are therefore constructed, allowing heat flow to carry the dominant charge carriers of each material to the low-temperature end, establishing in the process a voltage difference across the base electrodes. The generated voltage and power are proportional to the temperature differential and the Seebeck coefficient of the thermoelectric materials.

Large thermal gradients are essential to produce practical voltage and power levels. Temperature differences greater than 10 degrees C are rare in a microsystem, however, resulting in low voltage and power levels.





Photovoltaic cells convert incident light into electrical energy. Each cell consists of a reverse-biased pn+ junction, where light interfaces with the heavily doped and narrow n+ region. Photons are absorbed within the depletion region, generating electron-hole pairs. The built-in electric field of the junction immediately separates each pair, accumulating electrons and holes in the n+ and p-regions, respectively, and establishing in the process an open-circuit voltage. With a load connected, accumulated electrons travel through the load and recombine with holes at the p-side, generating a photocurrent that is directly proportional to light intensity and independent of cell voltage.

Research shows that photovoltaic cells can generate enough power to sustain a microsystem, though at lower power efficiencies than their macroscale counterparts, since the power needed to harvest the energy is a significant part of all the energy extracted (the area is small in microscale systems). A 3-D diode structure built on porous silicon helps increase efficiency by markedly increasing the device's exposed internal surface. Overall, photovoltaic energy conversion is a mature IC-compatible technology with higher power-output levels than other energy-harvesting mechanisms. Still, its power output strongly depends on environmental conditions-in other words, on varying light intensity.

Storing energy

The energy-harvesting system requires a charger capable of capturing and transferring intermittent low-energy bursts to a rechargeable battery-thin-film Li-ion batteries, in the case of chip-compatible solutions. Maximum battery life, capacity and energy content of a Li-ion battery is achieved by adopting a constant-current, constant-voltage charging scheme. Initially, a low preconditioning charging current is applied to the battery to ensure that the cell voltage is at least 2.7 V. Afterward, the constant-current phase follows with the application of a full charging current, until the battery voltage nears the end-of-charge voltage, typically between 4.1 and 4.2 V.

Subsequently, a voltage-controlled loop sources whatever little current is necessary to slowly pull the battery voltage to the end-of-charge voltage. The cell voltage increases quickly during the constant-current phase, before letting the system reach full capacity. Thus, fast-charging the cell by merely applying a constant charge current achieves only between 40 and 70 percent of its maximum capacity. As a result, both charging steps are required to fully charge the battery.

The charging circuit depends on the nature of the input energy to be stored. Mainly, the battery's charging current can be either continuous or discontinuous. Continuous-charging schemes may use linear and switching regulators. A linear regulator linearly controls the conductance of a series-pass device via a feedback loop to regulate the output against variations in load current and supply voltage, continuously supplying current. Like resistive voltage dividers, linear regulators can source voltages only below the input supply.

Switching regulators, on the other hand, can boost (step up) or buck (step down) the input voltage. In this latter scheme, fully on or off switching devices alternately store and deliver energy to the load via a combination of inductors and capacitors. Viewed from a different perspective, the LC components filter the inherent switching waveforms of the circuit, and the duty cycle of these waveforms is, in turn, normally regulated via a pulse-width-modulated controller or by another switching scheme. The supplementary filter and switching controller not only increase the complexity of the charger but also inject high-frequency noise to the output.

But the switching scheme used by these regulators achieves high power efficiency. That's because the switches incur negligible voltage drops, even at high current levels, thereby dissipating little power when compared with the series-pass device of the linear regulator. Although the circuit switches, the output is regulated and can continuously supply a charge current, albeit with a noisy ac ripple.

Discontinuous charging refers to applying alternating and discrete charge current pulses to the battery. The duty cycle of the pulsating current waveform gradually decreases as full charge approaches. Efficiency improves because periodic charge-current interruptions let ions diffuse and redistribute more evenly, thereby reaching higher levels of capacity. Adding a brief discharge pulse after each charging pulse further accelerates this diffusion process.

Each charging scheme depends on a continuous, steady energy source, so it's incompatible with intermittent and irregular sources like electrostatic energy harvesters and other vibration generators.

Unfortunately, the energy-harvesting sources supply energy in irregular, random bursts. Since none of the previously discussed charging circuits is compatible with intermittent low-energy bursts, a new alternative is required, which is what we are working on. The intermittent charger must wait until sufficient energy is accumulated in a specially designed transitional capacitor before attempting to transfer it to the storage device-in this case, the Li-ion battery.

For the full article and a list of references used, see the online version at www.powermanagementdesignline.com, and search for article ID: 164904186. More information about this article and our research can be found at www.rincon-mora.com/research.

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