Implementing Energy Harvesting in Embedded System Designs

Energy harvesting technology is rapidly emerging as a viable power supply option for embedded system designers, enabling wireless sensors to be used in applications that previously were not feasible with conventional battery-powered designs. For example, an energy harvesting power supply enables a system designer to easily build an ultra-slim wireless sensor with a range of more than 100 meters and a lifespan of more than 20 years.

As with any new technology, there are lessons to be learned when deploying a wireless sensor powered by an energy harvesting source. Let's take a closer look at how to design an embedded system for perpetual operation that's capable of surviving the initial power-on reset, as well as how to extend the lifespan of that self-sustaining embedded system. We will also examine the trade-offs between rechargeable thin film batteries and conventional high-capacity, long-life primary batteries.

Designing Embedded Systems for Perpetual Operation

The ultimate goal of an energy harvesting system is to achieve perpetual operation. The term perpetual operation brings to mind an "ideal pendulum," which, when placed in motion, never stops swinging. An energy harvesting system can achieve perpetual operation by ensuring that the harvested energy meets or exceeds the energy expended by the system during operation.

Energy management is a critical aspect of designing an energy harvesting system. The first step is to determine the available power output of the harvester. Commercially available energy harvesters convert solar, mechanical or thermal energy into electrical energy. Solar energy harvesters have the highest power density and are capable of harvesting 15 mW/cm^2 of surface area. Maximizing the output power of the energy harvester is critical to building a robust energy harvesting system.

Equally important in designing an energy harvesting system is characterizing and minimizing the power consumption of the embedded system. Low power consumption can be achieved by selecting components with low leakage specifications and by using an ultra-low-power microcontroller (MCU) like Silicon Labs' Si10xx wireless MCU. Most of the techniques used to achieve low-power operation in battery-powered systems can be used to minimize power consumption in energy harvesting systems.

Let's look at an example of a solar-powered wireless sensor node transmitting data once every 20 minutes at an average current of 10 µA. The system is equipped with a solar panel that provides 50 µA of continuous current during daylight hours. The net current available to charge the battery during daylight hours is 40 µA, and at night the battery is discharging at a rate of 10 µA. As shown in Figure 1, the energy harvesting system will achieve perpetual operation as long as the system is exposed to at least 4.8 hours of daylight each day.

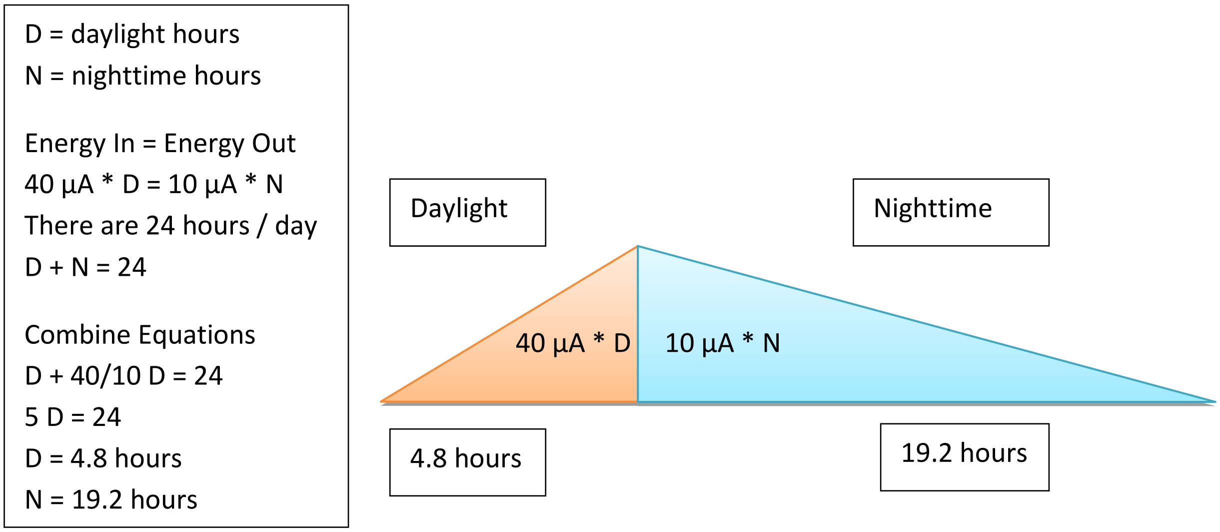

Figure 1. Number of Daylight Hours Required to Achieve Perpetual Operation

Two Classes of Energy Harvesting Systems

There are two classes of energy harvesting systems capable of achieving perpetual operation, and each one varies in its energy storage mechanism. The first type harvests and accumulates energy over a long period of time and uses a very low-leakage, high-capacity energy container, such as a thin-film battery. Perpetual operation is achieved by balancing the average energy harvested and the average power consumed. This class of energy harvesting system is the most flexible and typically expends power in short bursts of high-power consumption. These systems spend a majority of the time in a low-power sleep mode, are always powered and harvest energy at all times. An example of this type of system is a solar-powered wireless sensor node.

The second type of energy harvesting system stays in an unpowered state until a pulse of energy is detected, harvested and stored in a low-impedance energy container, such as a capacitor. After a brief power-on reset, the system performs the necessary system functions using the limited energy collected from the energy pulse. Perpetual operation is achieved by balancing the total energy expended in performing a task and the energy harvested in a single pulse. An example of this type of system is a wireless light switch that uses the energy generated by the mechanical switch to transmit an RF signal to a receiver located at the light fixture.

Surviving the Power-On Reset

The power-on reset for an energy harvesting system is analogous to the initial push of a pendulum that sets it in motion. Designing an energy harvesting system to survive the power-on reset and occasional brownout condition is essential for a system’s long-term robustness. Many embedded systems require storage and transportation prior to being activated by the end user. Care should be exercised to ensure that sensitive components are protected during transport and storage.

During storage, most energy harvesting systems do not harvest enough energy to sustain perpetual operation. If the system is allowed to run during storage, all energy will eventually be depleted, potentially over-discharging and causing damage to sensitive energy storage elements, such as thin-film batteries. The solution is to create a safe “storage mode” that disconnects the energy storage element from the system until it is activated. For example, a shunt battery charger with a battery disconnect provides protection against over-discharge during storage or when a brownout condition is detected. Using a shunt battery charger with a battery disconnect greatly simplifies the design and adds robustness to the energy harvesting system.

Most embedded systems require significantly more energy to get through a power-on reset than during normal operation. An energy harvesting power supply typically is unable to supply enough instantaneous energy to get the system through a power-on reset. To survive the initial power-on reset, an energy harvesting system must delay the start of the power-on reset until it is able to accumulate sufficient energy in a capacitor to get the system through its reset.

Figure 2 shows an example circuit design that can enable a power-hungry embedded system to go through a power-on reset using only harvested energy. Starting from the unpowered state, the primary energy storage element is disconnected from the system by the battery protection circuit. The energy harvester alone charges the capacitor, which will later be used to supply energy for the power-on reset. A supply voltage monitor and regulator gate the power supply to the embedded system to minimize its power consumption while the capacitor is charging.

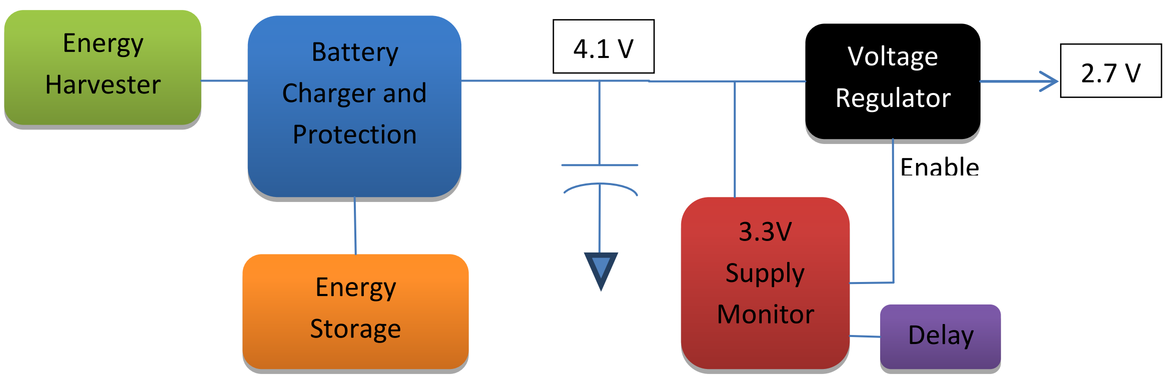

Figure 2. Surviving the Initial Power-On Reset Circuit Diagram

After some time, the capacitor voltage will reach a trip point that triggers the supply monitor to initiate the power-on reset sequence. The supply monitor ideally has a programmable delay that provides additional time for the capacitor to charge before enabling power to the embedded system. When the voltage regulator is enabled, the capacitor is discharged into the embedded system, allowing it to complete its power-on reset and enter a low-power sleep mode.

Once the battery charger detects sufficient voltage on the input capacitor, it reconnects the energy storage element to the system, and the energy harvesting system is in full operation, similar to a swinging pendulum. Figure 3 shows an example of this system implemented in an energy harvesting reference design from Silicon Labs.

Figure 3. Example of Energy Harvesting Reference Design

Extending the Lifespan of an Energy Harvesting System

Just as even the best pendulum will eventually stop swinging due to friction and air drag, an energy harvesting system will eventually stop operating. Numerous situations can cause an energy harvesting system to stop operating, and being aware of these situations and addressing them during the design phase may extend its lifespan.

Battery-operated systems reach their end of life when they run out of stored energy. Although energy harvesting systems designed to operate perpetually do not run out of energy, their components may degrade to the point where they can no longer store or supply sufficient energy to power the system. In an energy harvesting system, the most common degradable component is typically the energy storage element. When using a thin-film battery, it is important to avoid over-discharging the battery and to follow the manufacturer's guidelines for maximizing its lifespan. One technique used to prolong thin-film battery life is to add a large decoupling capacitor in parallel with the battery to minimize fluctuations in load current experienced by the battery.

Energy harvesting systems are susceptible to mechanical and design failures. To protect against mechanical failures, the system may be encapsulated or placed in a high-quality enclosure that is resistant to the environmental conditions in which the embedded system will be used. Testing the embedded system in a variety of environmental conditions and allowing sufficient margin for design parameters can extend the life of an energy harvesting system. In addition, following best practices in software design and keeping the energy harvesting system as simple as possible provides numerous benefits and can enhance a system's longevity.

Design Trade-Offs: Thin Film Batteries vs. Conventional Batteries

Conventional batteries, such as coin cells, AA lithium batteries and lithium-thionyl-chloride batteries have been used for many years in embedded systems requiring long life spans. The introduction of thin-film batteries has created a new option for system designers with trade-offs in cost, size and safety. With developers under constant pressure to reduce system costs, economical coin cell batteries may appear to be the optimum solution for reducing manufacturing costs and getting products to market quickly. However, there is a hidden cost associated with coin cell batteries when it comes time to replace them. If you consider that a thin-film battery has a total lifetime energy storage capacity of more than thirty CR2032 coin cells, you will quickly conclude that the initial cost of a thin-film battery is miniscule compared to the cost of replacing a coin cell thirty times over the life of an embedded system.

When considering battery size, thin-film batteries have the thinnest profile (as small as 0.17 mm) of any battery type. The total lifetime capacity of thin film batteries is equivalent to four lithium “AA” batteries or a single “C” size lithium-thionyl chloride battery. Thin-film batteries are well suited for space-constrained embedded systems that require an ultra-thin profile and long battery life.

In addition, thin-film batteries do not pose safety concerns, such as flammability and explosion hazards, associated with large conventional batteries. Since they are rechargeable, thin-film batteries only store a portion of their total lifetime capacity at any given time. This makes the battery much safer if it is accidentally shorted or exposed to extreme heat or an open flame. Thin-film batteries also result in much less waste than large conventional batteries, which often end up in landfills instead of being recycled.

Summary

Energy harvesting technology has grown quite popular and is expected to become even more prevalent in the coming years thanks to the many benefits it provides to embedded system designs. Properly designed energy harvesting systems are capable of operating perpetually once they overcome their initial power-on resets. With careful system design, the lifespan of an energy harvesting system can be extended to more than 20 years. Thin-film batteries are often used in energy harvesting systems for their ultra-thin profile and low leakage characteristics. The flexibility of designing a self-sustaining embedded system without requiring mains power or conventional replaceable batteries creates new application possibilities and opens new frontiers for embedded system development.