# SOLAR ENERGY HARVESTING

Low Power in a Compact Footprint

By Jeff Gruetter

Energy harvesting is by no means a new idea. The first hydroelectric plant which combined water and gravity to drive electricity generating turbines was built in 1882 and offered a relatively "green" and sustainable source of electric power on a very large scale. However, as this type of power source is greatly dependent on the natural terrain, large and expensive transmission networks are required. Since transmission losses rise with distance, this dramatically reduces the amount of available power. Nevertheless, in many instances only a few milliwatts of power are needed to power a wireless sensor node, so a much smaller scale solution is needed.

A much more cost-effective and electrically efficient solution is to keep the power source very close to the load creating a point-of-load design that eliminates transmission losses. However, in order to create these designs, there needs to be a readily available power source that can operate in remote areas, is cost effective and is self-sustaining, thereby requiring no servicing over many years.

The solution for these applications has re-introduced the concept of energy harvesting from a very different perspective, creating an emerging market for compact, predominantly wireless applications at the very low end
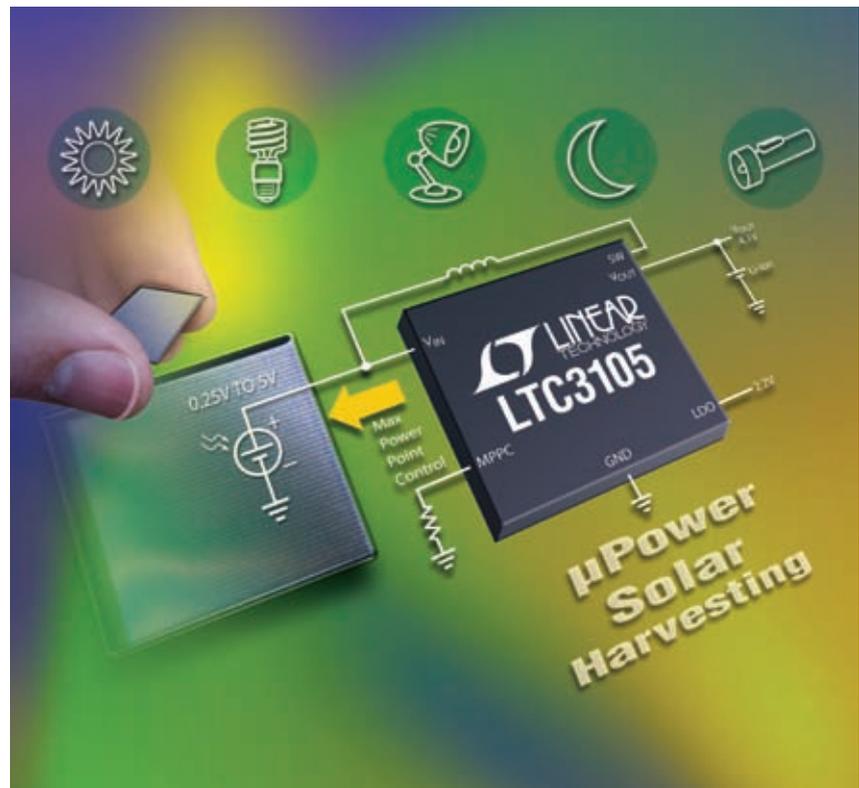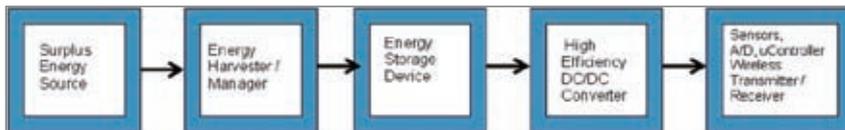
Figure 1: The five main blocks of a typical energy-scavenging system

of the power spectrum. These applications require output power that ranges from a few nanowatts to tens of milliwatts. Although non-traditional power sources such as solar cells (photovoltaic cells), thermoelectric generators (TEGs), thermopiles and piezoelectric transducers are known sources of electrical power, harnessing power from these sources has been challenging. Each of these require some type of power conversion circuit that can efficiently collect, manage and convert these alternative power sources into a more usable form of electrical energy to power sensors, microcontrollers and wireless transceivers. Whether the source voltage is very low and must be up-converted to be useful, or even rectified and then down-converted in some cases, specific energy harvesting circuits are necessary. Historically, these circuits have needed very complex discrete circuits with upwards of 30 components and yet still struggle to provide high enough efficiency to be of practical use. It is only recently that specialized energy harvesting power ICs have been introduced that can offer compact, simple and very efficient power conversion and management solutions.

These ultralow power solutions can be used in a wide array of wireless systems, including transportation infrastructure, medical devices, tire pressure sensing, industrial sensing, building automation and

asset tracking. These systems generally spend the majority of their operational lives in standby mode asleep requiring only a handful of µW. When awakened, a sensor measures parameters such as pressure, temperature or mechanical deflection and then transmits this data to a remote control system wirelessly. The entire measurement, processing and transmission time is usually only tens of milliseconds, but may require hundreds of mW of power for this brief period. Since the duty cycles of these applications are low, the average power that must be harvested can also be relatively low. The power source could simply be a battery. However, the battery will have to be recharged by some means or eventually be replaced. In many of these applications, the cost of physically replacing the battery makes it unfeasible. This makes an ambient energy source a more attractive alternative.

Emerging Nanopower Wireless Sensor Applications
In the case of building automation, systems such as occupancy sensors, thermostats and light switches can eliminate the power or control wiring normally required and use a mechanical or energy harvesting system instead. This alternative approach can also mitigate the costs of routine maintenance normally associated with wired systems in addition to eliminating the need for wiring to be installed in the first place, or

for regular battery replacement in wireless applications.

Similarly, a wireless network utilizing an energy harvesting technique can link any number of sensors together in a building to reduce heating, ventilation & air conditioning (HVAC) and lighting costs by turning off power to non-essential areas when the building has no occupants.

A typical solar energy scavenging system represented by the five main circuit system blocks shown in Figure 1 consists of a free energy source such as a small photovoltaic cell exposed to either direct sunlight or even indoor lighting. These photovoltaic cells are capable of generating over 50mW of electrical power per square cm of area, in peak sunlight and up to 100µW of electrical power in indoor lighting. However, the electrical energy they generate must be collected in a very specific manner using an energy harvesting circuit (see the second block in Figure 1) that can efficiently collect this low voltage energy and convert it into a more usable form, which can be used to continually charge a storage device. As the power generated by the solar cell will vary dramatically with the ambient lighting conditions, a rechargeable storage device such as a battery or supercap (block three in Figure 1) is required to provide continuous power when the ambient light is no longer available. In turn, the storage device, whether a battery or a supercap, combined with a simple step-down DC/DC converter (fourth block in Figure 1, which is usually not needed) can power downstream electronics while it is continually recharged.

The downstream electronics will usually consist of some kind of sensor(s), analog-to-digital converter, ultralow power microcontroller and wireless transceiver (fifth block in Figure 1). These components take the harvested energy, now in the form of a regulated power supply, and wake up a sensor to take a readings or a measurements, making this data available for transmission via an ultralow power wireless transceiver. The most recent generation of ultralow power wireless microcontrollers include multiple ADCs and an integrated wireless transceiver. They generally require current levels of 20mA to 35mA for periods as short as 1mS while measuring and transmitting, after which they go into a sleep mode requiring only 3.5µA of supply current minimizing the average power requirements.

Each circuit block in this chain has had a unique set of constraints that have impaired its commercial viability until recently. Although low cost and low power sensors and microcontrollers have been available for sometime, only recently have ultralow power transceivers been integrated with microcontrollers to offer very low power wireless connectivity. Nevertheless, the laggard in this chain has been the energy harvesting IC.

Existing implementations of the energy harvester block are a relatively low performance discrete configuration, usually consisting of 30 or more components. These designs have low conversion efficiency and high quiescent currents. Both
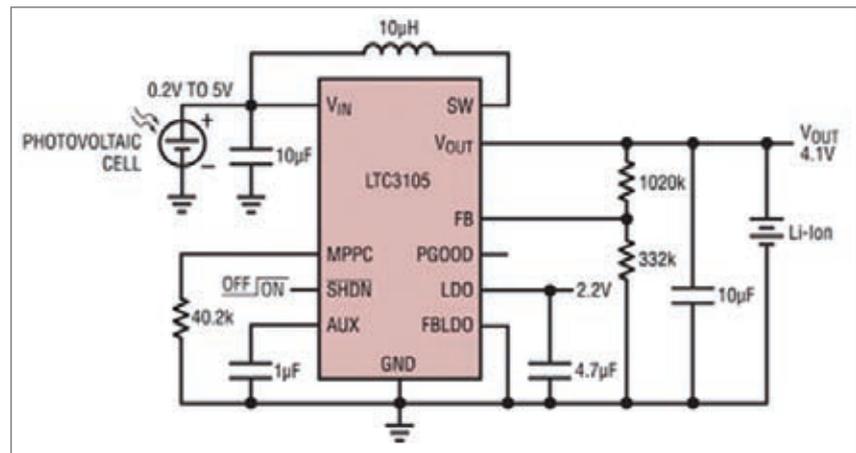

Figure 2: Single photovoltaic cell Li-Ion trickle charger

of these deficiencies result in the requirement for larger, more expensive batteries and solar cells compromising the performance of the end system. Without these larger storage elements, the low conversion efficiency will increase the amount of time required to power up a system, which in turn increases the time interval between taking a sensor reading and transmitting this data. High quiescent currents in the power conversion circuitry can severely limit the amount of "useable" energy that can be harvested and made available to the application load. Achieving both low quiescent current operation and high power conversion efficiency also requires a high degree of analog switchmode power supply expertise – which is rarely readily available.

The "missing link," if you will, has been a highly integrated DC/DC converter that can harvest and manage surplus energy from extremely low power sources. However, that has all changed.

Energy Harvesting Case Study
As an example, consider an energy harvesting-based industrial

monitoring system, such as a pipeline in the remote wilderness that needs to constantly monitor the flow rate, temperature and pressure of a pipeline for every 50-meter section of pipe. Each node has temperature, pressure and flow sensors built into the wall of the pipeline. Measurements must be taken and reported every five seconds. As the pipeline is hundreds of miles long, running power and information lines would be very expensive and subject to constant maintenance, potentially requiring expensive repairs. Replacing batteries periodically would also be very expensive due to their vast number and the ruggedness of the remote terrain. What is needed is a power source that can continually generate sufficient power, which is readily available and sustainable. One of the most popular and readily available energy sources would be a small solar cell combined with a storage device such as a battery or supercap to deliver continual power thru night time and poor weather conditions.

With the introduction of very low power sensors and microcontrollers with integrated
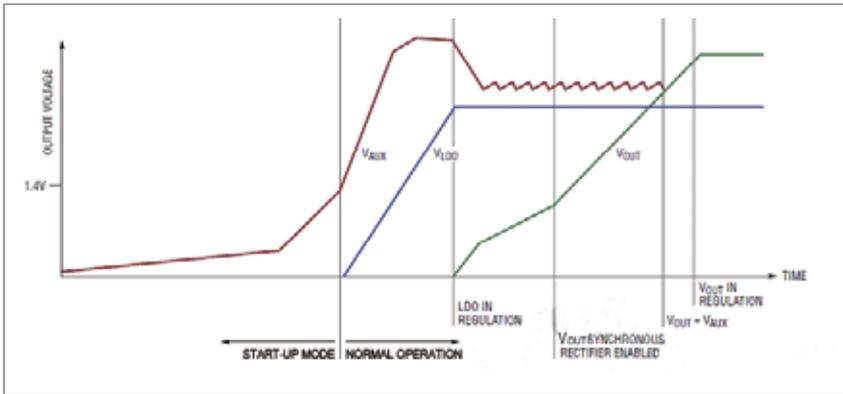
Figure 3: Typical LTC3105 start-up sequence

wireless transceivers, average power requirements have been dramatically reduced. This makes them ideal for energy harvesting powered applications. Their power requirements range from 10µW in sleep mode, to about 50mw to 75mW during processing and transmission (in 1ms to 2ms bursts). The microcontroller requires a consistent source of power typically at 2.2V whereas the wireless transceiver generally uses 3.3V. Although a single photovoltaic cell only 1cm2 in size can easily provide the required power, its output voltage ranges from 0.25V to only 0.6V, which is too low to power the rest of the system. This is where an energy harvesting IC comes into play. It must boost the very low voltage source to a level capable of charging a single cell Li-Ion battery, generally around 4.1V. Additionally, it must not pull too much current from the solar cell as it will collapse its internal voltage. As allowable current draw varies with illumination, the harvester IC must continually monitor the solar cell's voltage and limit current accordingly. Finally, the harvesting IC must be as efficient as possible over a very wide range of charging currents and require the minimum level of quiescent current while the

charging circuit is asleep in order to minimize the size of the battery.

The Energy Harvesting IC
Linear Technology recently introduced the LTC3105 - an ultralow voltage step-up converter specifically designed to dramatically simplify the task of harvesting and managing energy from low voltage, high impedance alternative power sources such as photovoltaic cells, TEGs (thermoelectric generators) and fuel cells. Its synchronous step-up design starts up from input voltages as low as 250mV, making it ideal for harvesting energy from even the smallest photovoltaic cells in less than ideal lighting conditions. Its wide input voltage range of 0.2V to 5V makes it well suited for a wide array of applications. An integrated maximum power point controller (MPPC) enables operation directly from high impedance sources, like photovoltaic cells, preventing the input power source voltage from collapsing below the user-programmable MPPC. Peak current limits are automatically adjusted to maximize power extraction from the source, while Burst Mode® operation reduces quiescent current to only 18µA, optimizing converter efficiency.

The circuit shown in Figure 2 uses the LTC3105 to charge a single-cell Li-Ion battery from a single photovoltaic cell. This circuit enables the battery to continually charge when the solar source is available, and in turn, the battery can power an application such as a wireless sensor node from the stored energy when the solar power is no longer available.

The LTC3105 has the capability to start with voltages as low as 250mV. During start-up the AUX output initially is charged with the synchronous rectifiers disabled. Once VAUX has reached approximately 1.4V, the converter leaves start-up mode and enters normal operation. Maximum power point control is not enabled during start-up; however, the currents are internally limited to sufficiently low levels to allow start-up from weak input sources. While the converter is in start-up mode, the internal switch between AUX and VOUT remains disabled and the LDO is disabled. Refer to Figure 3 for an example of a typical start-up sequence.

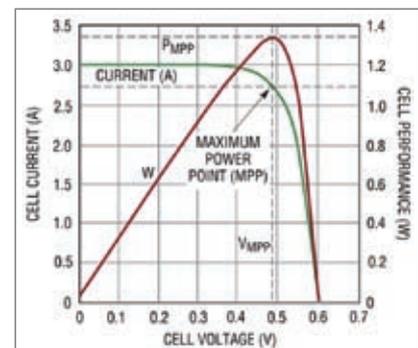When either VIN or VAUX is greater than 1.4V, the converter will enter normal operation. The

Figure 4: Typical maximum power point control point for a single photovoltaic cell

converter continues charging the AUX output until the LDO output enters regulation. Once the LDO output is in regulation, the converter begins charging the VOUT pin. VAUX is maintained at a level sufficient to ensure the LDO remains in regulation. If VAUX becomes higher than required to maintain LDO regulation, charge is transferred from the AUX output to the VOUT output. If VAUX falls too low, current is redirected to the AUX output instead of being used to charge the VOUT output. Once VOUT rises above VAUX, an internal switch is enabled to connect the two outputs together.

If VIN is greater than the voltage on the driven output (VOUT or VAUX) or the driven output is less than 1.2V, the synchronous rectifiers are disabled and operate in critical conduction mode, enabling regulation even when VIN>VOUT.

When the output voltage is greater than the input voltage and greater than 1.2V, the synchronous rectifier is enabled. In this mode, the N-channel MOSFET between SW and GND is enabled until the inductor current reaches the peak current limit. Once current limit is reached, the N-channel MOSFET turns off and the P-channel MOSFET between SW and the driven output is enabled. This switch remains on until the inductor current drops below the valley current limit and the cycle is repeated. When VOUT reaches the regulation point, the N- and P-channel MOSFETs connected to the SW pin are disabled and the converter enters sleep.

In order to power microcontrollers and external sensors an integrated LDO provides a regulated 6mA rail. The LDO is powered from the AUX output allowing the LDO to attain regulation while the main output is still charging. The LDO output voltage can be either a fixed 2.2V or adjusted via resistor divider.

The integrated maximum power point control circuit allows the user to set the optimal input voltage operating point for a given power source - see Figure 4. The MPPC circuit dynamically regulates the average inductor current to prevent the input voltage from dropping below the MPPC threshold. When VIN is greater than the MPPC voltage, the inductor current is increased until VIN is pulled down to the MPPC set point. If VIN is less than the MPPC voltage, the inductor current is reduced until VIN rises to the MPPC set point.

The LTC3105 incorporates a feature that maximizes efficiency at light load while providing increased power capability at heavy load, adjusting the peak and valley of the inductor current as a function of load. Lowering the peak inductor current to 100mA at light load optimizes efficiency by reducing conduction losses. As the load increases, the peak inductor current is automatically increased to a maximum of 400mA. At intermediate loads, the peak inductor current can vary between 100mA to 400mA. This function is overridden by the MPPC function and will only be observed when the power source can deliver more power than the load requires.

Input Undervoltage Lockout

In applications such as photovoltaic conversion, the input power source may be absent for long periods of time. To prevent discharge of the outputs in such cases, the LTC3105 incorporates an undervoltage lockout (UVLO) that forces the converter into shutdown mode if the input voltage falls below 90mV (typical). In shutdown, the switch connecting AUX and VOUT is enabled and the LDO is placed into reverse-blocking mode and the current into VOUT is reduced to 4μA typical. Reverse current through the LDO is limited to 1μA in shutdown to minimize discharging of the output.

Conclusion

The LTC3105 energy harvesting DC/DC converter is specifically designed to dramatically simplify the task of harvesting and managing energy from low voltage, high impedance alternative power sources such as photovoltaic cells, TEGs (thermoelectric generators) and fuel cells. Its unique design enables it to start up from input voltages as low as 0.25V, and provides very high efficiency over a wide range of input voltages and current levels. Onboard maximum power point control optimizes the energy extracted from a wide range of sources under a wide range of conditions. Its very simple and compact solution footprint makes it a straight forward power solution for a growing number of energy harvesting applications.

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