True Grid Independence: Robust Energy Harvesting System for Wireless Sensors Uses Piezoelectric Energy Harvesting Power Supply and Li-Poly Batteries with Shunt Charger

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There is an emerging and potentially large market for wireless sensors. By their very nature, wireless sensors are chosen for use in inaccessible places, or for applications that require large numbers of sensors—too many to easily hardwire to a data network. In most cases, it is impractical for these systems to run off primary batteries. For example, a sensor for monitoring the temperature of meat as it is shipped would need to be mounted in a tamperproof way. Or, HVAC sensors that are mounted on every source of conditioned air would be far too distributed to feasibly use batteries. In these applications, energy harvesting can solve the problem of providing power without primary batteries.

Energy harvesting alone often does not produce sufficient power to continuously run the sensor-transmitter—energy harvesting can produce about 1mW–10mW, where the active sensor-transmitter combination may need 100mW–250mW. Harvested energy must be stored when possible, ready for use by the sensor/transmitter, which must operate at duty cycle that does not exceed the energy storage capabilities of the system. Likewise, the sensor/transmitter may need to operate at times when no energy is harvested.

Finally, if the stored energy is depleted and the system is going to shut down, the system may need to carry out housekeeping tasks first. This may include a shutdown message, or storing information in nonvolatile memory. Thus, it is important to continuously gauge available energy.

COMPLETE ENERGY HARVESTING SYSTEM

Figure 1 shows a complete system implementation using an LTC3588-1 energy harvester and buck regulator IC, two LTC4071 shunt battery chargers, two GM BATTERY GMB301009 8mAh batteries and a simulated sensor-transmitter modeled as a 12.4mA load with 1% duty cycle. The LTC3588-1 contains a very low leakage bridge rectifier with

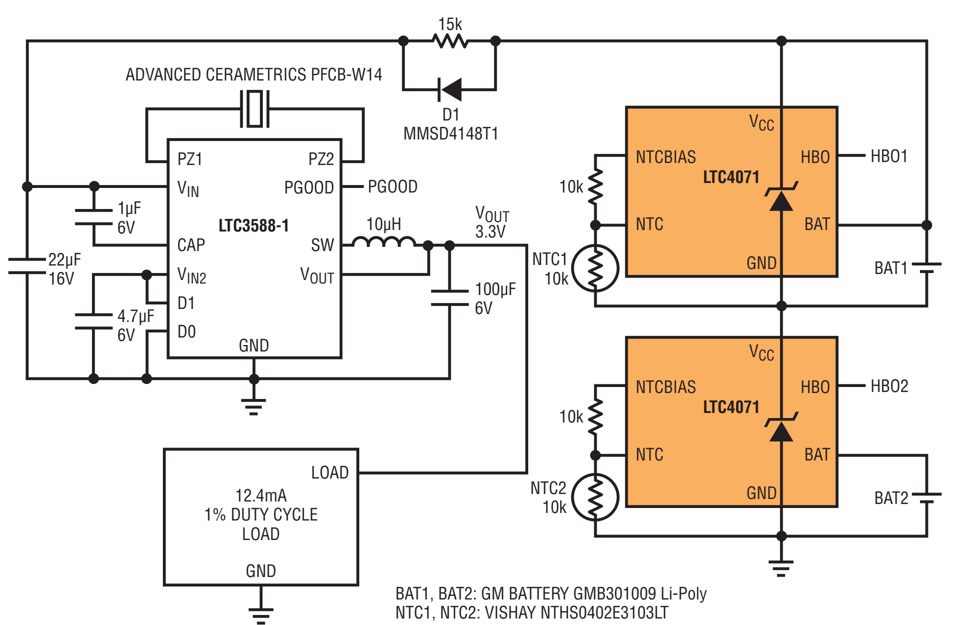

Figure 1. Complete piezo-based energy harvesting system is independent of the grid. This design uses thin film batteries to gather energy collected by the piezo for a wireless sensor transmitter, which operates on a 1% duty cycle.

With a few easy-to-use components, it is possible to build a complete compact energy-harvesting power subsystem for wireless sensor-transmitters.

inputs at PZ1 and PZ2 and outputs at V_{IN} and GND. V_{IN} is also the input power for a very low quiescent current buck regulator. The output voltage of the buck regulator is set by D1 and D0 to 3.3V.

The LTC3588 is driven by an Advanced Cerametrics Incorporated PFCB-W14 piezoelectric transducer, which is capable of generating a maximum of 12mW. In our implementation, the PFCB-W14 provided about 2mW of power.

The LTC4071 is a shunt battery charger with programmable float voltage and temperature compensation. The float voltage is set to 4.1V, with a tolerance on the float voltage of ±1%, yielding a maximum of 4.14V, safely below the maximum float allowed on the batteries. The LTC4071 also detects how hot the battery is via the NTC signal and reduces the float voltage at high temperature to maximize battery service life.

The LTC4071 is capable of shunting 50mA internally. However, when the battery is below the float voltage, the LTC4071 only draws ~600nA of current from the battery.

The GM BATTERY GMB301009 batteries have a capacity of 8mAh and an internal series resistance of ~10Ω.

The simulated sensor-transmitter is modeled on a Microchip PIC18LF14K22 and MRF24J40MA 2.4GHz IEEE standard 802.15.4 radio. The radio draws 23mA in transmit and 18mA in receive. The model represents this as a 12.4mA, 0.98% duty cycle (2ms/204ms) load, set with a self-clocked digital timer and a MOSFET switching a 267Ω resistor.

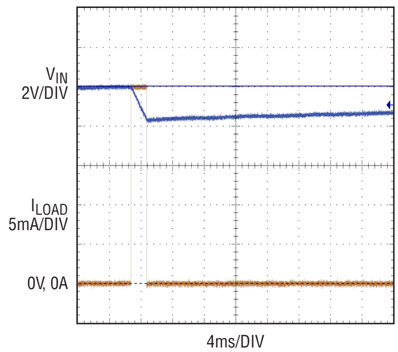

Figure 2. Charging with sensor-transmitter load

MODES OF OPERATION

This system has two modes of operation: charging-sending and discharging-sending. In charging-sending mode, the batteries are charged while the sensor-transmitter presents a 0.5% load. When discharging, the sensor-transmitter is operating, but no energy is being harvested from the PFCB-W14.

Charging-Sending

When active, the PFCB-W14 delivers power at an average of approximately 9.2V × 180µA ≈ 1.7mW. The available current must charge the battery and operate the buck regulator driving the simulated sensor-transmitter. The active sensor-transmitter draws 12.4mA × 3.3V ≈ 41mW at around 1% of the time, or about 0.41mW on average, leaving some current to charge the battery. Taking into account the 85% efficiency of the LTC3588 buck regulator, assuming an average V_{IN} of 9.2V (see Figure 2), and a buck quiescent current of 8µA, the average current consumed by the system without charging the battery is:

$$I_{AVG} = \frac{I_{SENSOR}}{\frac{V_{IN(AVG)}}{V_{OUT}} \bullet \eta_{BUCK}} \bullet DUTYCYCLE + I_{Q(BUCK)}$$

$$I_{AVG} = \frac{12.4\text{mA}}{\frac{9.2\text{V}}{3.3\text{V}} \bullet 0.85} \bullet 0.0098 + 8\mu\text{A} \cong 60\mu\text{A}$$

Harvested energy can drive the sensor-transmitter at a 0.5% duty cycle with about 120µA left to charge the batteries. The GMB301009 batteries have a capacity of 8mAh, so they completely charge from empty in about 75 hours.

Discharging-Sending

When the PFCB-W14 is not delivering power, the voltage at V_{IN} drops to approximately:

$$\frac{8.4 + 6.6}{2} = 7.5\text{V}$$

So the reflected load current calculation changes to:

$$I_{AVG} = \frac{12.4\text{mA}}{\frac{7.5\text{V}}{3.3\text{V}} \bullet 0.85} \bullet 0.0098 + 15\mu\text{A} \cong 78\mu\text{A}$$

The quiescent current of the buck regulator is higher because the regulator must switch more often to regulate from 7.5V versus 9.2V. At 78µA, with no energy harvested, the battery is discharged in approximately 115 hours. This indicates a charge storage capacity of >8.95mAh. These batteries when brand new could store approximately 12% more charge than rated.

A more serious problem is what happens when the battery is fully discharged. If current is drawn after the state of charge reaches zero, and the battery voltage drops below 2.1V, the battery is permanently damaged. Therefore the application must ensure that the battery voltage never falls below this limit. For this reason, the battery cutoff voltage is set to 2.7V or 3.2V to ensure some energy remains in the battery after the disconnect circuit has engaged.

Simply stopping the transmitter or disconnecting the load will not protect the battery, as the LTC4071 draws a quiescent current of approximate 600nA. Although this is extremely low, the total load, including the LTC3588-1, is nearly 2µA. A fully discharged battery will only be able to supply approximately 100µA before its voltage drops enough to damage the battery.

A disconnect circuit is necessary to ensure that the battery does not discharge in a reasonable amount of time. The LTC4071 provides an internal low battery disconnect circuit. This disconnect circuit was measured to provide <2nA of battery load at room temperature when activated. This leakage is typically dominated by PCB leakage. With only 2nA of battery drain current, the battery could survive for 50,000 hours in the disconnect state before the battery is damaged.

In Figure 3, the second battery (BAT2) is seen to disconnect 50 hours after BAT1 due to the 2µA load.

MEASURED RESULTS

The system shown in Figure 1 was measured in both operating modes discharging-sending (Figure 3) and charging-sending (Figure 4).

Discharging-Sending

In Figure 3 the voltages of the two batteries BAT1, BAT2 and V_{BUCK} are plotted against time with the batteries supplying all the system energy, none from the PFCB-W14 piezo.

The batteries slowly discharge until BAT1 activates the LBO threshold of its LTC4071, whereupon the disconnect circuit activates and disconnects BAT1 from all circuitry except the LTC4071 itself. This causes the voltage at V_{IN} of the LTC3588 to drop below the UVLO for the regulator, and the regulator shuts off.

The load on BAT2 is the 2µA quiescent current of the LTC4071 and the LTC3588. This small load slowly discharges BAT2 until the low battery disconnect of LTC4071 is activated and BAT2 is disconnected.

Charging-Sending

When the PFCB-W14 once again starts delivering power to the system, V_{IN} rises to 7V, which forward biases the body diodes of the disconnect FETs in the LTC4071. This charges the batteries until the reconnect threshold is reached, allowing batteries BAT1 and BAT2 to be reconnected. Looking at Figure 4, this can be seen as the voltage at V_{IN} snaps down to the battery stack voltage.

Since the voltage at V_{IN} is now $V_{BAT1} + V_{BAT2} + (180µA \times 15k) = 6.2V$, the buck regulator on the LTC3588 restarts and 3.3V is once again available.

CONCLUSION

With a few easy-to-use components, it is possible to build a complete compact energy-harvesting power subsystem for wireless sensor-transmitters. In this particular system a piezoelectric transducer supplies intermittent power, while two batteries store energy for use by the sensor-transmitter. An integrated disconnect switch protects the batteries from overdischarge.

This system can fully charge the battery in 75 hours, even while operating the sensor-transmitter at 0.5% duty cycle.

The batteries allow the system to continue operating the sensor-transmitter at 0.5% duty cycle for 115 hours after the PFCB-W15 stops providing power. If longer battery operating time is required, the sensor-transmitter duty cycle can be reduced to accommodate this need. ■

Figure 3. Discharge with battery undervoltage disconnect

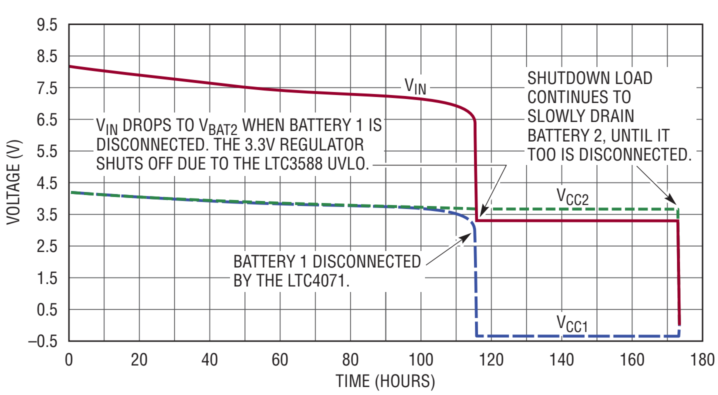

Figure 4. Battery disconnect recovery on charge