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Solar powered micrometeorite sensors using indoor ambient light for the International Space Station

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Abstract

Sensors for detecting micrometeorite impact locations and magnitudes as well as pressure vessel leaks have been under investigation for some time by the NASA Langley Research Center and other related entities. NASA has been investigating the use of the Distribution Impact Detection System (DIDS) for use on the International Space Station (ISS). However, the DIDS currently requires thionyl chloride lithium batteries which pose explosion and toxicity hazards, and replacing batteries is tedious and utilizes scarce man-hours. Carrying replacement batteries into space is also expensive. To hardwire new sensing devices into the ISS while in orbit would be time consuming. To overcome this problem, high efficiency GaAs solar cells have been studied under low light conditions comparable to those found inside the ISS. The cells were also studied for temperature dependence. Solar concentrators were investigated for possible use with ambient lighting. The power generated by the cells was stored in a large 300 F supercapacitor. A DC to DC boost regulator was modified to produce an output voltage of 3.55 V that is required by the DIDS. The successful operation of the DIDS with ambient light power, supercapacitor energy storage, and boost regulation was demonstrated.

Keywords: Solar cell; Sensor; Space station; Micrometeriote; Photovoltaics; Ambient light

1. Introduction

Sensors are found in all areas of aerospace research for applications ranging from monitoring temperature, strain, vibration, etc. Networks of wireless sensors are being introduced in many new areas (Brush, 2007). Since the Columbia disaster there is an increased desire for improved monitoring of all areas of spacecraft. To meet this need there has been research into wireless sensing devices that can be implemented in the Shuttle, International Space Station (ISS), aircraft, and all other future manned or unmanned spacecraft.

The devices typically require fairly low power and are getting more efficient, yet there will always be some finite power requirements that must be considered. The only fundamental limitations of autonomous sensors are their energy storage capabilities and the amount of power that can be harvested from their environments (Jeong et al., 2007). For active wireless sensing devices, non-rechargeable batteries are the most common power source. It is not always possible or easy to replace non-rechargeable batteries due to location or manpower constraints. To overcome these problems, power harvesting devices that either power the device directly or store energy in the form of capacitive or rechargeable battery storage are possible solutions. An ambient lighting powered wireless sensing device that monitored environmental conditions has been developed (Lee, 2008). The device was implemented in a store where light was always available. The power storage problem was circumvented by having constant lighting available. For these

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types of devices, supercapacitors have a large energy density and are typically used. Supercapacitors are superior to batteries in that they are better at delivering bursts of energy and charge faster at a wider range of voltages.

Power harvesting has many possible options such as thermoelectric, piezoelectric, micro-magnetoelectric and photoelectric. Thermoelectric and piezoelectric devices have the highest power density (Hande et al., 2007). Thermoelectric devices, however, are large, require a significant temperature gradient and are comparatively expensive. Piezoelectric devices require significant vibration for useable power output which is not always available. Photovoltaic cells are second to thermoelectric devices in power density, are much cheaper, and usually require only ambient light to operate. Although solar cells have lower power density, they are rapidly becoming more efficient. Advanced solar cells combined with supercapacitor energy storage would provide a viable and cheap alternative to batteries and would eliminate the maintenance requirement to replace batteries in areas where a light source is available.

The biggest problem with using solar power harvesting indoors is the low usable light power. There has been limited research in solar cell performance under ambient lighting conditions. The results show dependencies, but show very low efficiencies (Reich et al., 2009). Solar cells are designed to operate with 1 Sun (0.1 W cm^{-2}). In interior spaces the level of lighting is several orders of magnitude smaller, around 1–3 m Sun (Randall et al., 2005). Computer modeling of solar cell performance has been performed to show low-level efficiencies, and similar results have been theorized, but do not take into account real-world variations such as spectral shifts (Kerr and Cuevas, 2004). At these low lighting levels, angle of incidence and spectra distribution are significant factors (Stamenic et al., 2004). This presents unique challenges in designing and implementing solar cells or panels because they cannot be modeled in the same manner as can solar cells designed for exterior sunlight exposure.

One wireless solar-powered sensor placed the solar cells inside of a lighting fixture (Hande et al., 2007). Although this will provide much higher intensities and efficiencies, such placement of cells or devices is not usually practical due to sensing needs. For powering of the DIDS inside the ISS, lighting power would not be constant and the location would likely not be in close proximity to fluorescent fixtures.

2. Experimental method

The Distributed Impact Detection System (DIDS) was developed by Invocon, Inc. and is planned for use in micrometeorite detection. The manufacturer specified steady state current for the device was 60 μA at ~3.3 V, needing ~200 μW (Invocon, 2009). The device was monitored to test and verify the power usage under different modes of operation. The test setup in Fig. 1 was used.

The power supply used was an HP model 6203B and DC voltage was measured with a generic digital averaging multimeter to ensure the device voltage remained in specifications and to prevent damage. The test was performed again with a Lecroy Waverunner LT344L oscilloscope in place of the multimeter to observe the relative waveforms for each operational mode and transition.

Spectrolab, Inc. provided two of their Ultra Triple Junction (UTJ) GaAs solar cells for this research. The UTJ cell is designed as a multiple junction cell with a germanium substrate and GaAs and $GaInP_2$ active layers. The total surface area of the combined two cells was ~48.6 cm^2. The cells were designed to operate at 28.3% minimum efficiency at 1 Sun of illumination at AM 1.5 (Spectrolab, 2009). The Spectrolab, Inc. solar cells are one of the highest efficiency cells commercially available. They were not designed to operate at ambient indoor lighting levels, and no low light level data was available. The two cells were mounted in parallel to add current as shown in Fig. 2.

Ambient room lighting power was measured with a Thorlabs PM30 power meter attached to a Thorlabs

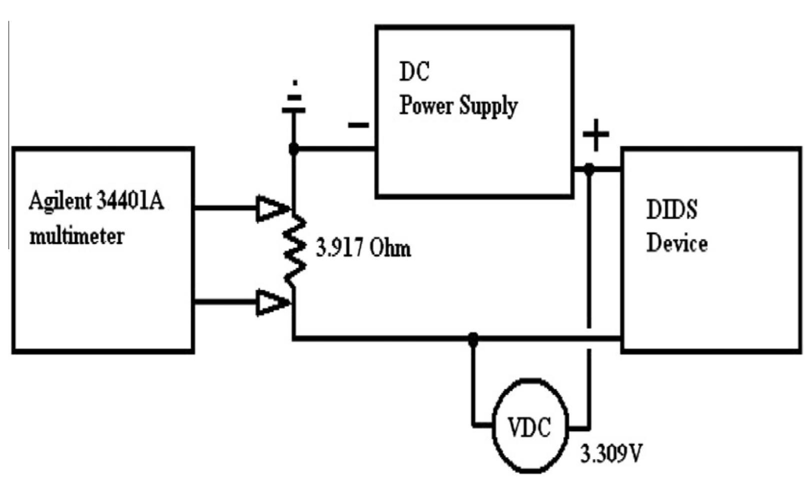

Fig. 1. DIDS device test setup.

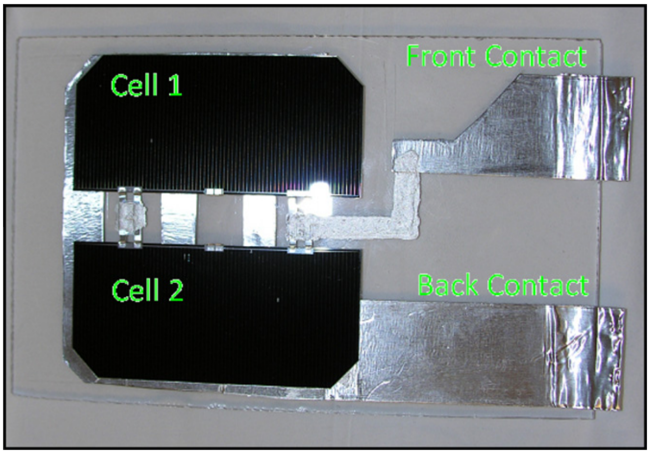

Fig. 2. UTJ solar cells mounted in parallel on plexiglas.

S120B silicon sensor head. The spectrum of fluorescent lights is generally centered near 560 nm. Actual numbers for the ISS lighting is not available but it is confirmed that commercially available fluorescent lamps are being used on the ISS. These values were checked against the lab lighting values to ensure consistency. Because the ISS uses fluorescent lamps, the spectrum was assumed to be similar. An 11″ × 11″ Fresnel concentrator was used to increase incident lighting power density. Temperature data was obtained by heating the cells with a heatgun and measuring open circuit voltage (V_{oc}) and temperature while the cells cooled.

For power storage the best option was determined to be a supercapacitor. This type of storage has benefits over a rechargeable battery in that is does not need complex charging circuitry, and has benefits over traditional capacitors (paper, ceramic, etc.). They store much more energy, allowing for lengthier discharges when under heavy use or when charging power was not available. Several sizes were acquired ranging from 0.5 F up to 300 F so that testing could determine the smallest size useable as they are generally bulky and size/weight constraints are important when sending something into orbit or installing it on the ISS or shuttle.

A power conditioning system was needed to maintain an output voltage of 3–3.6 V, to meet the operational voltage requirement of the DIDS device. The Linear Technology LT1307 3.3 V DC-DC Boost regulator was found to be relatively well suited to this particular application. The regulator was adjusted to give 3.55 V output with varying input voltage as shown in Fig. 3.

The rectifier used for the regulator was an MBR0520L Schottky barrier diode and was chosen for its low voltage and high switching speed. All capacitors in the circuit were chosen to be generic ceramic capacitors due to leakage concerns affecting efficiency (electrolytic capacitors typically exhibit much greater leakage than ceramics). The regulator was tested across different input voltages and static resistive loads and efficiencies were calculated.

The solar cells were connected to the largest supercapacitor acquired (300 F) through another diode (MBR0520L) that protected the solar cells from reverse current as shown in Fig. 4. The 300 F supercapacitor was the largest acquired due to increasing physical dimensions with increasing capacitance, and it was already about the size of a "D" cell battery. Cost also increases exponentially with increases in capacitance. A voltage drop of ~0.3 V was observed, making it ideal for such an application. The supercapacitor was attached to the output side of the regulator. The capacitor was pre-charged to ~1.3 V to speed-up the lengthy charging cycle. The entire setup was checked on a static load of 32.5 kΩ at 3.55 V regulated voltage which gave a test load current of ~100 μA which was in the range of the DIDS current.

After initial operational check, the DIDS device was attached for powering. It was cycled through all of its primary operating modes and the voltage on the supercapacitor was monitored as was the voltage on the DIDS to insure that a limit was not exceeded. Longer tests were performed with the static load in place to determine charging and discharging trends.

3. Results and discussion

The DIDS was tested for power use and compared with the manufacturer provided data. The results are shown in Table 1.

An example of a common transient cycle can be seen in Fig. 5, which visually shows the DIDS wirelessly transfer a

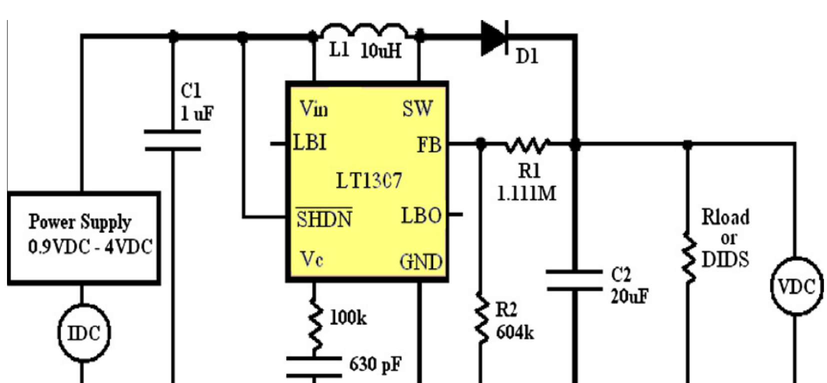

Fig. 3. Linear technology LT1307 regulator setup for 3.55 V.

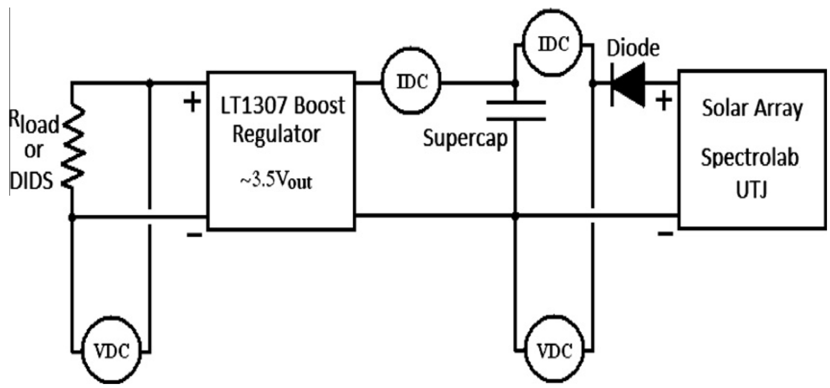

Fig. 4. Full implementation test setup.

Table 1
DIDS power use test results.

	Measured current (mA)	Manufacturer data (mA)	Power at 3.5 V (mW)	Time (Ave.)	Energy (J)
Trigger mode	0.059	0.06	0.207	–	–
Idle mode	0.059	Not provided	0.207	–	–
Event average (trigger and query)	38.3	10–80	134.1	2 s	0.27
Remote file download average	35.7	28	125.0	8 s; 4 s active	1

file to the computer. This and other transients are relatively major in comparison to steady state operations.

The solar cell low lighting testing results showed that at ambient lighting levels, the solar cell light conversion efficiency could be expected to be ~12% vs. ~28% at 1 Sun. Under ambient light power, the open circuit voltage (V_{oc}) was ~1.8 V and the short circuit current (I_{sc}), was ~550 μA. A solar concentrator, 11″ × 11″ Fresnel lens, showed an increase of incident ambient lighting power density by a factor of 6.

Results from the temperature study are shown in Fig. 6.

Changes in open circuit voltage with temperature were found to be −3 mV/°C for a monocrystalline silicon solar cell, −9 mV/°C for a single TASC cell, and −7 mV/°C for the UTJ array. These numbers were in agreement with the theoretical values which are found using the standard bandgap equation (Goetzberger et al., 1998). Testing for a wider range of temperatures is not necessary because the expected temperature range within the space station is 18–27 °C (ISS Factsheet, 2011), and the experiment is meant only to show the dependence on the theoretical value.

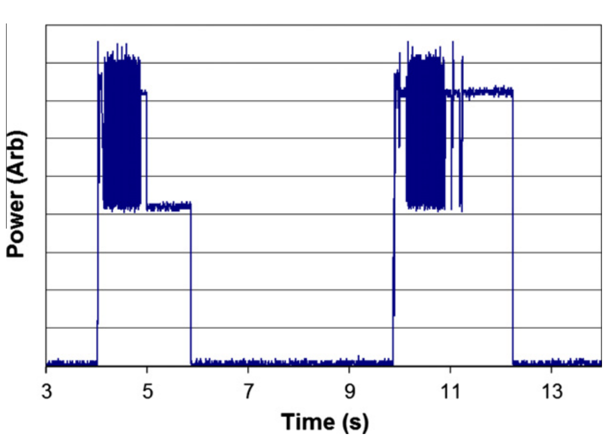

Fig. 5. DIDS file transfer waveform power consumed.

The supercapacitor leakage tests showed that they would all maintain above 50% of their charge for over two weeks. Without available light, they would remain charged for extended periods of time and leakage rates would be necessary for storage planning. Typical results gathered can be seen in Fig. 7. The presented results are for 200 F and 4.7 F supercapacitors.

The regulator efficiencies shown in Fig. 8 were comparable to those provided by the manufacturer data of peak efficiency at ~80% (Linear, 2009). The manufacturer suggested components were used to achieve high efficiency. The only deviation from the manufacturer setup was the value of R1 in Fig. 3 which was used to increase output voltage from 3.3 V to 3.55 V. The lower experimental efficiency of ~70% is likely due to quality variations from the manufacturing process.

The manufacturer provided quiescent current for the LT1307 at 3.3 V was 50 μA (Linear, 2009). The measured quiescent current ranged between 65 μA and 75 μA regardless of the input voltage. These results combined with the actual efficiency data made the Linear Technology LT1307 regulator well suited for this application.

Regulator output voltage relative to input voltage, seen in Fig. 9, shows that we would have useable voltage for our DIDS across the range of input voltages expected from the solar cells (<2 V).

The UTJ solar cells showed the capability of charging the 300 F supercapacitor, powering the regulator, and powering subsequent loads that would be necessary to operate the

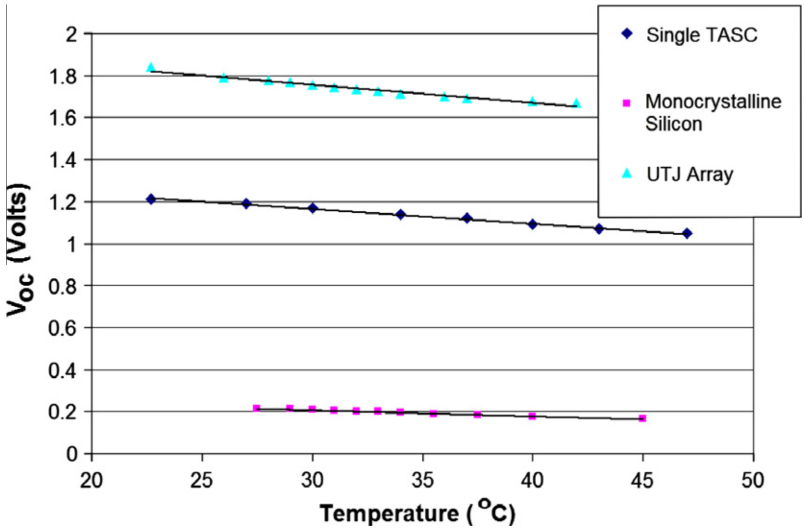

Fig. 6. V_{oc} vs. temperature for several cells.

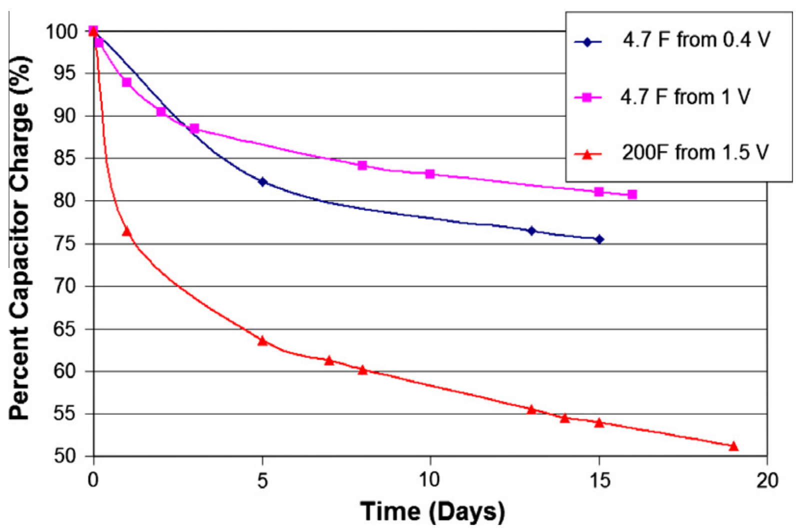

Fig. 7. Supercapacitor leakage curves for 4.7 F and 200 F supercapacitors from varying initial voltages.

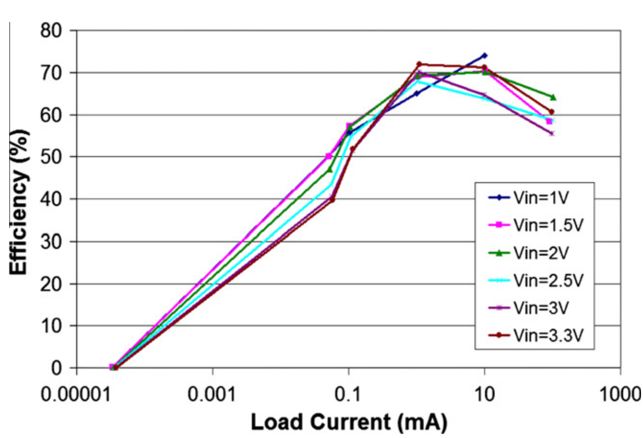

Fig. 8. Test results for regulator efficiency vs. load current.

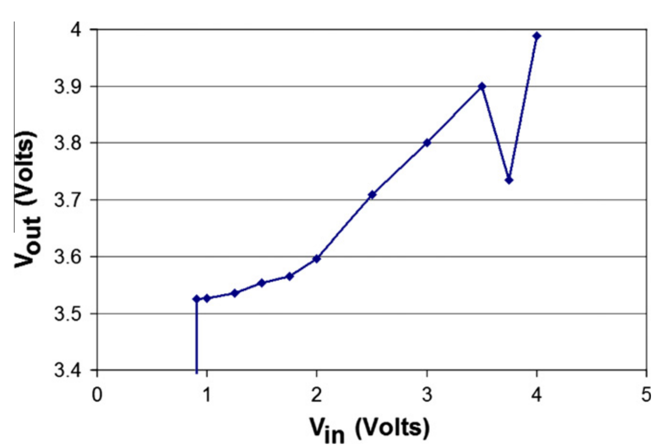

Fig. 9. LT1307 output voltage vs. input voltage.

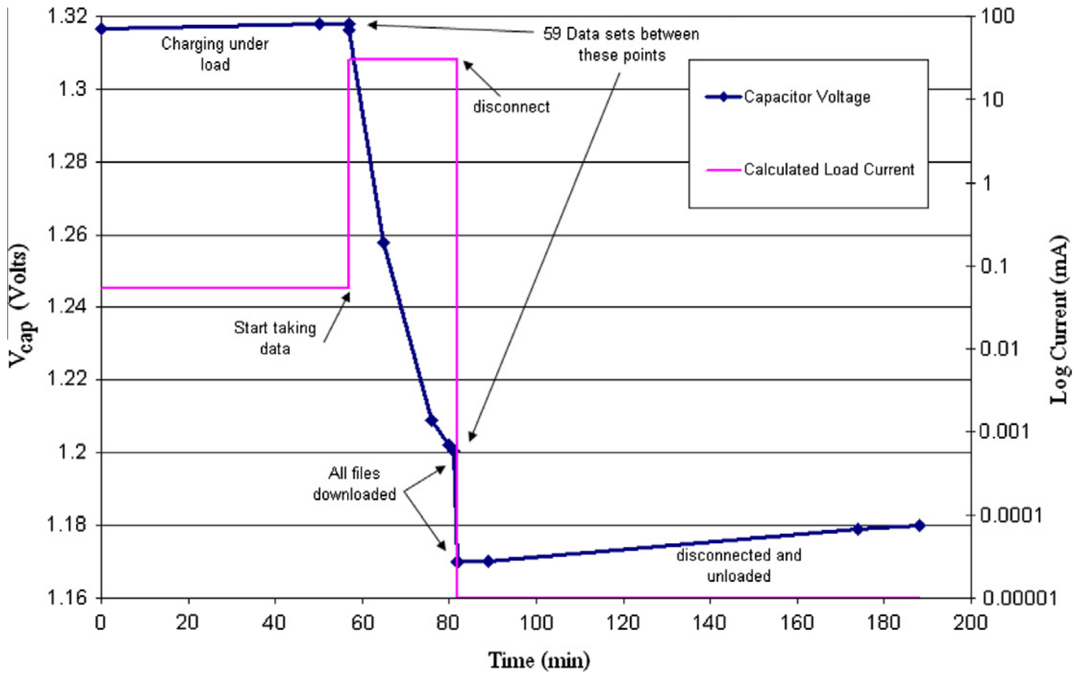

Fig. 10. Complete implementation with DIDS test results shown.

device. The DIDS device was attached and tested through a large number of cycles, demonstrating capacity to perform under intensive loads. The entire DIDS trial is shown in Fig. 10 and represents a larger number of collected data sets than would be used in operation on the ISS (59 sets in ~20 min vs. ~2 sets per month expected (Stella, 1991)).

4. Summary

- The UTJ solar cell array is ~12% efficient at ambient room lighting levels (1–3 m Sun) with $V_{oc} - 1.8$ V and $I_{sc} - 550$ μA; while at 1 Sun it is ~28% efficient with $V_{oc} - 2.67$ V and $I_{sc} - 85$ mA (Spectrolab, 2009).
- In ambient room light, a UTJ solar cell 2-cell array can charge a 300 F supercapacitor to 1.6 V, ~384 J in ~14 days.
- At 1.6 V a 300 F supercapacitor can power a Linear Technology LT1307 regulator and Distributed Impact Detection System (DIDS) (with no impacts detected) for ~7 days.
- Average power consumption of the DIDS device is ~245 μW over the expected monthly cycle. The DIDS requires an input voltage in the range of 3.0–3.6 V.

5. Conclusion

The solar power technology presented here was shown to provide power to devices using ambient light. Solar cell efficiencies are relatively low in an indoor environment. Adding more solar cell surface area to a setup or increasing the incident light would greatly increase the power handling capability. With higher power devices such as wireless sensors and remote-controls, standard solar technology used in typical indoor applications is not suitable. The process of communications takes a much larger amount of power which is the primary reason this method of powering in sensors is not more prevalent. In transmit mode, even the DIDS power is too high to be to be used for long periods of time with the setup. The supercapacitor power storage allows for periods of no light. With available light, the devices can provide power indefinitely to the sensor. Leakage accounts for most of the power consumption in low power logic devices such as solar wristwatches and calculators. The concept shows potential for replacing batteries, not only in this particular application, but in many sensing applications and for other low-power wireless devices. There will be a place for this technology in many future applications.

Acknowledgement

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