TECHNICAL PAPER

Powering IoT Modules Using Solar Panels, Supercapacitors, and an Automatic Buck/Boost Controller IC

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Abstract

The use of IoT modules is exhibiting a high rate of growth because of their low cost, ease of implementation, and easily documented impact upon end-user efficiency, reliability, and cost. Manufacturers, installers, and end-users of IoT modules are seeking ways to power these devices and essentially create a set-and-forget module. Set-and-forget means a significant ongoing effort to eliminate batteries or extend the life of batteries powering IoT modules.

Manufacturers of IoT modules are working to reduce their designs' power consumption and also working with IC suppliers by requesting novel chipsets to provide quality power from harvested or scavenged sources.

This paper is an effort to document the performance and utility of supercapacitors when used in an IC that provides bidirectional buck-boost DC/DC regulation, supercapacitor cell charging and balancing functions, and automatic power switching to supercapacitors as primary power is lost.

POWERING IOT MODULES

USING SOLAR PANELS, SUPERCAPACITORS, AND AN AUTOMATIC BUCK/BOOST CONTROLLER IC

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INTRODUCTION

IC TECHNOLOGY

Integrated Circuit device progress seems to be mostly reflected in news of higher gate density, faster processing speed and power chips. While the faster CPU, more powerful FPGA, and larger memory chip are of great value and importance, the significant progress in making power conversion ICs is many times under-recognized. One example, of an easy to utilize, small, efficient, and practical power conversion IC is the LTC3110. The LTC3110 is a 2amp Bidirectional Buck-Boost DC/DC regulator and charge balancer.

It has a wide input operating voltage range from 1.8V to 5.5V and a selectable output/back-up voltage of 1.8V to 5.25V. While power is present, it provides power to the load, as well as balances and charges a supercapacitor stack. Then, upon input power loss, the LTC3110 automatically transitions to providing power derived from the charged supercapacitors. The power derived from the supercapacitors can be above, at, or below the supercapacitor level. Thus, maximum flexibility is given to designers for powering the end load.

One configuration of the LTC3110 could be to manage power from a solar panel, balance and charge multiple supercapacitors, and provide automatic switchover when the solar panel is unable to provide power for the load. Such a configuration could be a practical solution in providing power to IoT modules or in general, any RF system with battery/capacitor back-up. The LTC3110 is available in either 24 lead TSSOP or I plastic QFN measuring ~ 4x4mm and provides ~ 93% power conversion efficiency. This IC is an example of practical, easy to implement, power conversion controllers, perfect for IoT set-and-forget designs.

The other portion of set-and-forget designs is the supercapacitor.

SUPERCAPACITOR TECHNOLOGY

Supercapacitors or Electrochemical Double Layer Capacitors (EDLC) have rapidly become recognized as an acceptable solution for storing energy in a wide variety of applications. Great advances have been occurring in the world of supercapacitors and a review of their performance and progress is in order.

Supercapacitors are a compromise between traditional "dielectric" capacitors and batteries, as shown in figure 1.

Supercapacitors not only provide a high capacitance per unit volume, possibly more importantly they provide the ability to charge and discharge at exceptionally high rates of speed. Thus, the supercapacitors very high levels of current charge and discharge translate into an ability to deliver high specific power levels. This feature is one of supercapacitors most sought after features – massive specific power capability.

Another important feature is supercapacitors' high number of, charge-discharge cycles. One million cycles are not out of the realm of use conditions.

SUPERCAPACITOR TECHNOLOGY

It has been reported that supercapacitors are on a path to overtake batteries, providing safety, faster charging and size advantages while helping to eliminate complex battery management systems[1].

However, the extent to which that is true depends upon the charging source and circuit load. In the case of IoT modules – voltages are commonly low, typically <5V with 2.5V being a large percentage of the designs. Further, current loads are typically small and pulsed in nature. More discussions occur in the test description of this paper. From a materials point of view, a wide array of developments are on the horizon which may expand the available capacitance range by an order of magnitude (or more). But for this paper, acetonitrile (ACN) based devices are exclusively tested and discussed. Also, this paper assumes that the operating conditions required by end-use are within the supercapacitor operating range of -40°C to +85°C range.

Multiple form factors contribute to the ease of implementation of supercapacitors in end systems. Three form factors are common for designers to choose from as shown in figure 2.

PARAMETER / CHARACTERISTIC	SUPERCAPACITOR	LI-ION BATTERY
Charge Time	1To 10 Seconds	10 To 60 Minutes
Charge Cycle Life	1 Million	>500
Cell Voltage	2.1 To 3.3 Volts	3.6 To 4.2 Volts
Specific Energy (Wh/Kg)	5	100 To 200
Specific Power (W/Kg)	~10,000	1000 To 3000
Charge Temperature Range	-55°C To +90°C	0°C To +45°C
Discharge Temperature Range	-55°C To +90°C	-20°C To +60°C

Supercapacitor – Battery Comparison

Figure 1

RADIAL CAN SUPERCAPACITORS

These devices were chosen for this study since these devices offer designers maximum flexibility through:

- Multiple product series available
- Multiple voltage offering
- Ten different case sizes
- Highest number of capacitance values available

Radial can parts are commonly used in a single configuration for lower voltage designs or multiple cans configured to obtain the correct voltage/energy for higher voltage loads.

Multiple cans can be balanced via active or passive methods. Supercapacitor balancing is needed to ensure a long life for multiple supercapacitors used in series. Balancing each supercapacitor prevents damage to other supercapacitors in the stack through over-voltage.

POWERING IOT MODULES

SUPERCAPACITOR TECHNOLOGY

RADIAL CAN SUPERCAPACITORS

Passive balancing has the advantage of being the cheapest, smallest, and easiest to use since it's accomplished with a resistor. However, the big disadvantage is that passive balancing reduces efficiency since power is dissipated in the balancing resistor.

Active semiconductor balancing is most efficient and exacting, but its costs are more significant. The size required for active balance solutions varies greatly based upon the number of cells in need of balancing as well as the size of cell/ semiconductor types used in balancing.

CAPACITOR FORM FACTOR	CAPACITANCE	VOLTAGE	DIMENSIONS	TERMINAL OPTIONS	WEIGHT
Radial Can	1F To 3000F	2.7V To 3.0V	6.3 – 60mm Dia 12 – 138mm Long	• Solder In • Snap In • Cylindrical Lug • Screw In	~0.6g To ~504.0g
Radial Module	0.33F To 15F	5V To 9V	6.3 – 14mm Dia, 13.6-32mm W, 14-33mm L	• Radial Straight Lead • Radial Bent Lead	~1.35g To ~18.0g
Custom Module	100's To 1000 F	2.7V To ~200V	Custom Package	Custom Options	Custom

Supercapacitor Form Factor Options – Figure 2

RADIAL MODULE PACKAGE

The supercapacitor packaging discussion would be incomplete without a discussion of other package options. Radial modular packages are manufactured by series connecting two to three radial can capacitors and packaging them into a "module". These packages offer maximum efficiency of package density and a higher voltage, which is commonly very attractive for use in simplifying design in higher voltage battery applications. As commented on in prior paragraphs, radial modules can be balanced or unbalanced and have options for hard-shell or heat-shrink packaging depending upon if end users need enhanced reliability.

CUSTOM MODULE PACKAGES

Custom modules are made using combinations of radial can supercapacitors, and commonly involve the need for charge control and cell balancing. Custom modules can have massive energy ratings and can be made to provide direct replacement of batteries in a wide variety of applications. Examples range from LED-based lighting to wirelessly charged specialty equipment – pallet trucks, forklifts, industrial robots, etc.

SUPERCAPACITOR TECHNOLOGY

SUPERCAPACITOR RELIABILITY

Supercapacitors need to be properly derated to achieve long-term reliable operation regardless of the specific package configuration. Previous work by DeRose et al.[2] shows that supercapacitor reliability is a function of applied voltage and temperature. In their work, a variety of ACN chemistry supercapacitors were subjected to a matrix test where voltage, temperature, and humidity stress levels were varied while the DUTs capacitance and ESR were measured to determine stress effects.

A series of graphs that show MTTF in years vs applied voltage and applied temperature was developed from test data obtained from testing. These graphs indicate that expected life more than doubles for every 10°C lower operating temperature. Life doubles again for every reduction of 0.1V lower operating voltage. The results are shown in figure 3.

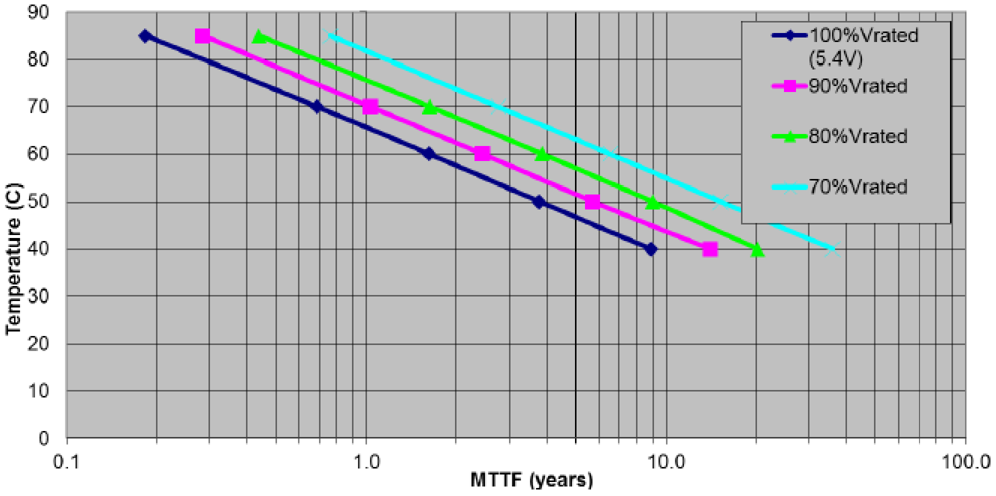


Figure 3

MTTF Years at Various Voltages and Temperatures for ACN Material 5.4V/5.0V Rated Supercapacitors

SUPERCAPACITOR SIZING

When it comes to the sizing of supercapacitors for battery hold up or replacement, the BOM cost and PCB volume tend to be dominated by the supercapacitors as pointed out by Analog Devices Holtkamp and Alonso[3]. The key to an efficient design is to provide for the peak power needs without excessive conservatism. Excessive conservatism results in increased part cost and PCB volume.

To meet the power hold up requirements of any project, the energy of the stack must be > than the energy of the load.

The extent to which designers must be conservative is impacted by the use of the supercapacitor's temperature, and the quality of charge voltage since both directly affect cell reliability.

SUPERCAPACITOR TECHNOLOGY

SUPERCAPACITOR SIZING

In our particular circuit, the LTC3110 will provide a well-regulated and balanced voltage on the cell. Therefore, the reliability of the supercapacitor storage 'bank' will not be negatively impacted by charging voltage stability in our tests. Whenever charge sources exhibit wildly swinging voltages the cell stack will need to be de-rated by a higher series stack voltage (more supercapacitors in series) or some form of added voltage regulation.

There are added factors impacting the conservatism of the cell size chosen. Assuming temperature and voltage derating have already taken place, 3 added factors must be considered for sizing:

Aging Effects of the Supercapacitor – Generally when a supercapacitor hits EOL its capacitance drops to 70% of the specified value and its ESR goes to 200% of specified ESR. Capacitor aging must be taken into account, in order to provide Energy Stored > Energy Needed.

Converter Efficiency – The converter efficiency is a direct function of the PMIC chosen.

Drop out Voltage of the IC Power Management IC – The dropout voltage is the point at which the capacitor's voltage is too low to power the PMIC. This voltage is PMIC dependent.

The particular tests conducted in this study did not concentrate on any specific cell sizing since tests were conducted at 25°C using a well-balanced and stable voltage to each supercapacitor. The tests were conducted on a short-term basis where aging effects do not even start to be apparent. Converter efficiency and drop out voltages were all the same in comparisons since the LTC3110 was used in all test cases.

TEST PROCEDURE

TEST BOARD DESCRIPTION

The purpose of this investigation is to show that supercapacitors are well suited to create a set-and-forget power source when used along with a solar panel and bidirectional regulator/ charge balancer.

All tests were conducted on an Analog Devices DC1964A demo board (see figure 4). This evaluation board is based upon the LTC3110 chip. When the system rail is powered, the LTC3110 charges and balances two supercapacitors for backup energy storage, in addition to powering the load.

However, when the system power is eliminated, the LTC3110 reverses direction, immediately using the stored energy to power the downstream load as it extracts energy from the supercapacitors down to the drop out voltage of the IC as measured on the supercapacitor bank. Our testing was based upon two values of 2.7V cylindrical can supercapacitors - 1F and 7F.

These capacitors were chosen along with two current loads of 50mA and 100mA, at a 1ms on / 9ms off (10% duty cycle). The capacitor values, current load, and duty cycle test matrix allow readers to extrapolate power supplied for other known loads and duty cycles while limiting the test duration to record data.

Figure 4: DC1964A Demo Board Based Upon LTC3110 2A, Bidirectional Buck-Boost DC/DC Regulator and Charge/Balancer

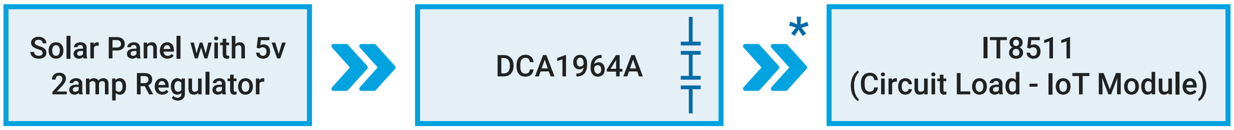
TEST PROCEDURE

TEST SET UP

A low cost industrial solar panel was chosen to drive a 5V 2amp regulator which served as input power to the DC1964A evaluation board. An ITECH IT8511 DC electronic load was placed on the DC1964A evaluation board and data was recorded for loads of 50mA and 100mA at a 10% duty cycle 1ms on, 9 ms off. The test configuration is shown below in figure 5.

It should be noted that although the capacitors chosen in the test matrix were 1F and 7F, these capacitors are placed in a series stack to double their voltage. In that configuration, their capacitance drops to 0.5F and 3.5F.

Although there are various added configurations and features available on the DC1964A evaluation board, the board was used in its simplest of configurations to show the ease of creating a set-and-forget power source based upon solar harvesting and supercapacitor storage. The IT8511 was configured to represent the power use from an IoT module and data was recorded in real-time after the capacitor stack had been charged by the solar panel and then that source of power was removed from the DC1964A board.



* Automatically Switched Power From LTC3110

Figure 5
Test Configuration

TEST RESULTS

The selection of load currents, duty cycles, and capacitance values to test was driven by approximate needs obtained by a survey of some IoT designers. Graphs 6a, 6b compare the charge/discharge characteristics of the 0.5F and 3.5F stacks when under testing at 25°C, 50mA, and 100mA load. Supercapacitors were charged and maintained charge based upon the input of the solar panel to the DC1964A. Once power was removed the IC routed power from the supercapacitor to the load. The voltage of the supercapacitor stack was monitored during this discharge state and plotted vs time to provide readers a measure of usable output voltage from the IC-based upon the capacitor charge state.

In all test cases, only the AVX supercapacitor was on the evaluation board to provide a charge reserve for output power to be pulled from. Although the test could have been performed hundreds of thousands of times testing was limited to < 10 cycles of charge/discharge due to time limitations and the fact that supercapacitors exhibit an ability to be charged and discharged many hundreds of thousands of times without measurable wear out. A comparison of capacitor stack value, volume, weight vs power hold up time in seconds, at 10% duty cycle for 50mA, and 100 mA loads is shown in figure 7.

POWERING IOT MODULES

TEST PROCEDURE

Typical Charge/Discharge Curve of Capacitor Stacks

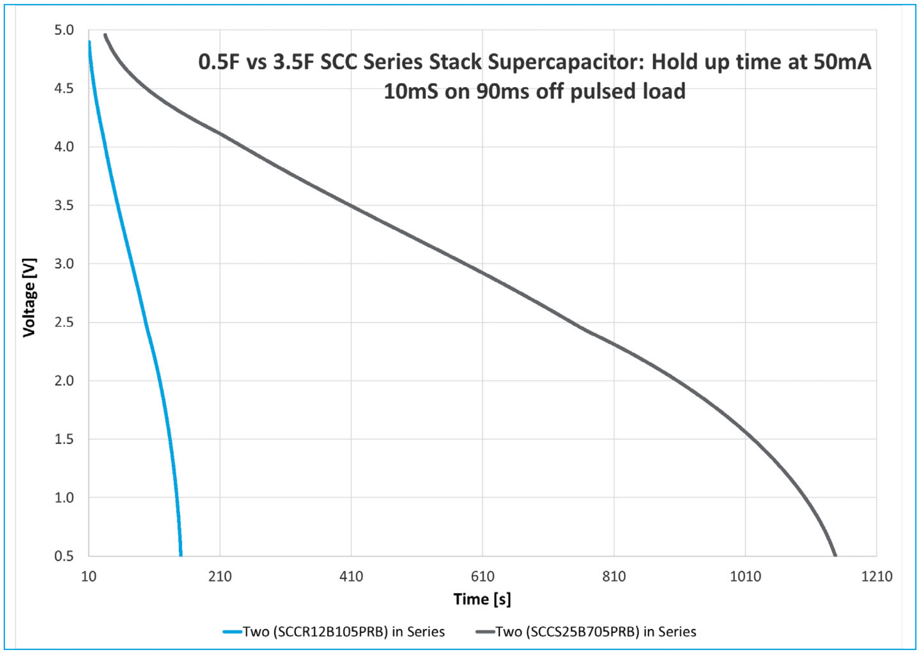


Figure 6A
0.5F vs 3.5F stack at 50mA load

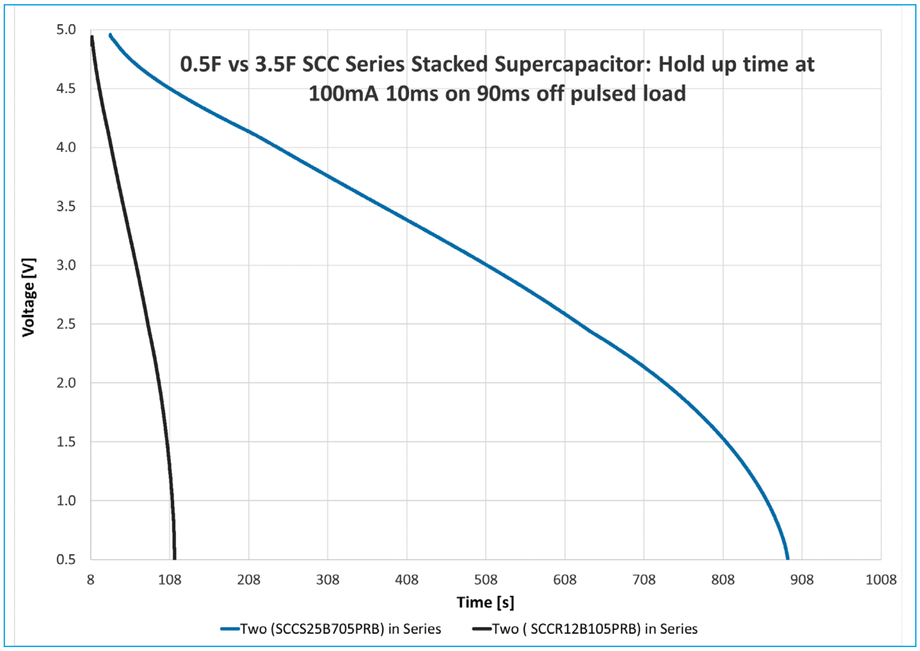


Figure 6B
0.5F vs 3.5F at 100mA load

TEST PROCEDURE

CAPACITOR STACK VALUE (F)	CAPACITOR STACK VOLUME (cc)	CAPACITOR STACK WEIGHT (g)	VOLTAGE HOLD UP TIME (S) AT 50 MA LOAD	VOLTAGE HOLD UP TIME (S) AT 100 MA LOAD
0.5	1.20637	1.8152	140.05	105.79
3.5	3.92699	5.93161	1,111.89	857.12

Figure 7
Capacitor Stack Properties vs Hold Up Time Under Different Loads

SUMMARY

The concept of set-and-forget IoT modules is very attractive to IoT end-users. Progress in power management semiconductors has created multiple families of small, high-efficiency ICs that are ideal for use in long-life power source scenarios. Supercapacitors compare favorably to Li-Ion batteries in terms of speed of charge/discharge, the number of charges, operating temperature range, and specific power. Supercapacitors do suffer from an energy density < 1/10 of Li-Ion batteries.

Even with the specific energy disadvantage, supercapacitors can provide very reliable energy storage which may be called upon when primary power sources are eliminated in a portion of loads that exist.

Though it is unlikely that all particular power requirements of IoT modules will be directly addressed in this study, a general example of the simplicity of implementation will encourage end-users to strongly consider a combination of energy harvesting and supercapacitors as a power source in set-and-forget IoT modules.

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[1] Leopold, Supercapacitors Ussurp Batteries, EET Asia July 2020

[2] Holtkamp, Alonso, Energy storage using supercapacitors: How big is enough, Analog volume 54 No3, July 2020

[3] DeRose, Reliability of Supercapacitors, AVX.com, 2018

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