HOW2POWER TODAY
Your Power Design Newsletter

Exclusive Technology Feature

ISSUE: December 2018

Need Uninterrupted Power? Let A Supercapacitor Come To The Rescue

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As every system around us is becoming more and more intelligent, always-on devices are becoming the norm. Disconnecting or removing the power source from these circuits, such as the removal of the supply line or the system's battery, creates a blackout event. When this occurs, it is possible to lose critical data, leaving the system engaging in its last microsecond gasp as it attempts to back up critical data.

Enter the superhero, also known as the supercap or supercapacitor. A supercap, akin to an insurance policy, deflects a crash condition by providing a temporary backup current source for a short period of time. This sounds encouraging, but some of its characteristics, without the helping hands of power converters, can inhibit a smooth recovery.

The design solution presented here starts with a short description of the supercap's capabilities. Comparisons with Li-ion batteries and tantalum capacitors help to put the supercap's characteristics in perspective. The article then shows how to use a supercap as a real-world charge and discharge solution in a power backup application. In particular, the use of a boost function to overcome supercap voltage limitations and extract more of the supercap's usable energy is explained. Formulas for calculating backup time and selecting the supercap value are given. Finally, an integrated design solution based on the MAX38888 backup power regulator is presented.

While a supercap is used as an example, a large tantalum capacitor bank can also be used. Supercapacitors simply provide more capacitance in the same footprint. Some of you may be wondering why not a Li-ion (Li+) battery? While a Li+ battery serves as a good rechargeable backup power source, it is heavy, takes a long time to charge, has a limited lifespan, and needs special circuitry or algorithms to charge or discharge thereby making it expensive for short-term power backup.

Supercap Characteristics

A supercap is a high-capacity capacitor that is available with lower rated voltage limits and has the capability of very high capacitance values. The other advantages are its high energy density, low dc effective-series-resistance (dc ESR), and linear charge/discharge of voltage vs. current. So, let's take some time to compare the supercap, standard capacitor and battery.

The capacitance of the supercap is several hundred times higher than standard capacitors. These higher capacitance values facilitate the storage of large amounts of energy.

The energy storage is the amount of energy that a device (capacitor or battery) can hold. Energy storage density is usually described as milliwatt-hours-per-gram (mWh/g). The supercap's moderate energy storage density allows it to be used in multiple applications as a short-term power source. The energy storage of an electric double layer capacitor (EDLC) or supercap (also referred to as an ultracapacitor or ultracap) is between that of the standard capacitors (tantalum, ceramic, aluminum, film, silicon, electrolytic, etc.) and batteries.

The measurement of a capacitor or battery equivalent series resistance (ESR) can occur near dc or at higher frequencies, such as 100 kHz. Generally, the claimed capacitor's ESR values have test frequencies on the higher side. The near dc ESR value is significant in most supercap and battery applications because the charging or discharging currents are usually near dc events. The ESR generates a low-voltage error with the supercap's charge and discharge currents. The table below summarizes the key specifications that differentiate supercaps, tantalums, and batteries from one another.

Batteries and supercaps both store electrical energy. The widely used battery has a better energy density. However, it is possible to quickly charge and discharge the high-power density supercap.

Table. Comparison of the supercap, tantalum capacitor, and battery.

	Maximum capacitor value	Energy storage (mWh/g)	ESR (mΩ)
Supercap	12,000 F	4 to 9	40 to 800
Tantalum capacitor	25 µF	0.1 to 0.3	100 to 25,000
Li-ion battery	~1200 F	100 to 265	~80

The supercap does an adequate job bridging the gap between standard capacitors and batteries. These characteristics position it as a good candidate for a temporary backup source due to its high capacitance and moderate energy density.

Supercaps For Power Backup

When provided with sufficient charge, the supercap delivers a limited amount of energy to existing circuits in the event of power supply blackout. Consider a portable application where the battery is the main power source and the supercap is the backup (Fig. 1).

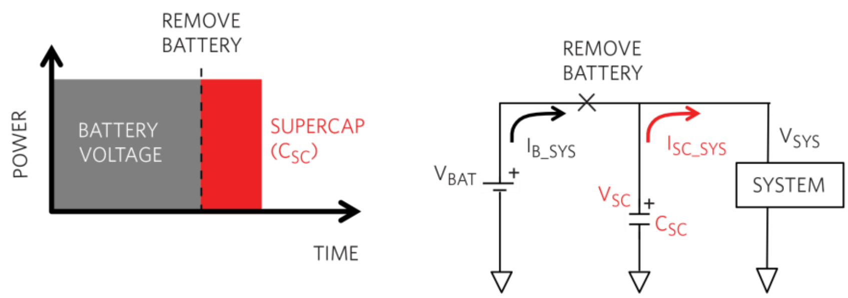

Fig. 1. At the time of battery removal, the circuit uses a supercap to provide enough current to help with millisecond system backup.

In Fig. 1, time is the most valuable commodity for the supercap since it will not last forever. However, if correctly chosen, the supercap sustains the circuit's power long enough for backup recovery activities to quickly occur.

Fig. 2 shows a general timing diagram for Fig. 1's block diagram. In Fig. 2, the supercap (C_{SC}), with a battery insertion in the circuit, momentarily collects an insurance of charge while reaching the battery's voltage level. This typically costs a subpercentage amount of the battery charge reservoir. The system is powered by the battery's voltage (V_{BAT}) and current (I_{B_SYS}). Once the supercap voltage (V_{SC}) reaches V_{BAT}, C_{SC} then enters its idle phase, holding its charge with I_{SC} equaling zero.

The system holds the supercap idle condition for the duration of the device's operation until the removal of the battery. Depending on the equipment's usage of power, the idle time can be days, months, or years. With the removal of the battery, the system backup begins. During this short duration of time, C_{SC} provides the added assurance of current (I_{SC_SYS}) and the supercap voltage source (V_{SC}) to the system for a quick backup recovery. This connection persists until the system ICs start to collapse by reaching their minimum power supply voltage.

Although the supercap temporarily sustains the power supply voltage, there are some shortcomings, such as unused energy and limitations of the supercap family's maximum voltage.

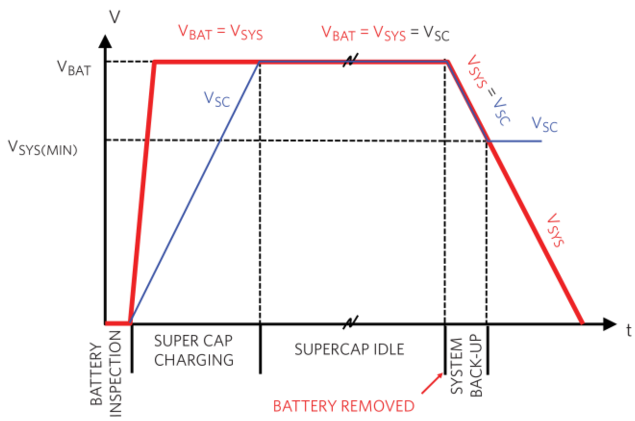

Fig. 2. Installing a battery allows the supercap to charge, enabling limited power when the system battery is disconnected.

Unused Supercap Energy

The system's minimum power supply leaves unused energy in the supercap. For example, if V_{BAT} equals 3.3 V and the $V_{SYS(MIN)}$ equals 2.7 V, 66% of the usable energy remains.

Maximum Voltage Limitations

Currently, the average supercap voltage is between 2.5 V and 2.7 V. These voltages limit the type of systems where they can be used unless these capacitors are stacked or placed in series. For instance, two stacked 2.7-V supercaps can provide 5.4 V. However, the total capacitance of these series capacitors lessens by $C_{SC} = (C_1 \times C_2)/(C_1 + C_2)$, where C_1 equals C_2. With this formula, the total capacitance is 50% less than C_1 or C_2, so C_1 and C_2 must be twice the design's supercap value.

Additionally, the PCB layout geometries and application cost will increase. Two supercaps instead of one increases the size by 4x, because now each of the two larger capacitors (C_1 and C_2) are twice the size of the single smaller (C_{SC}) capacitor. An additional cost to the stacked supercap scenario is that series capacitors require cell balancing circuits to even out tolerance differences in capacitance, resistance, and leakage current.

Increasing Supercap Efficiency

Let's take a second look at a backup design. As discussed, the issues are to use more of the supercap's energy and to overcome the maximum voltage limitations. The circuit in Fig. 3 overcomes both of the previous shortcomings.

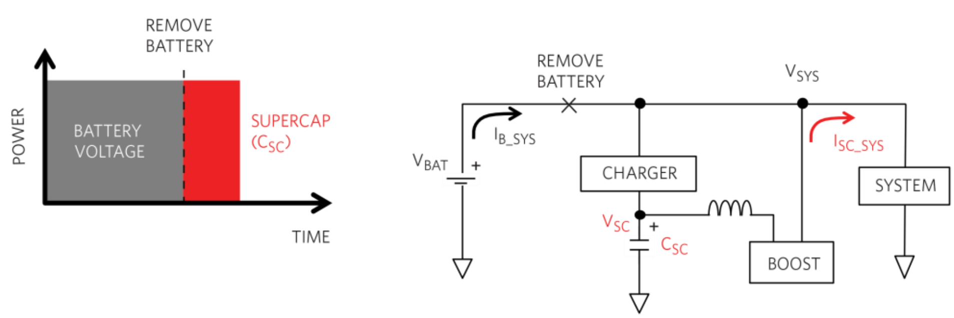

Fig. 3. With a boost converter added to the charger circuit, the supercap voltage is independent of the system supply voltage (V_{SYS}).

In the circuit shown in Fig. 3, the unused supercap energy is tapped using a boost function. The boost function generates the system current (I_{SC_SYS}) from the supercap (C_{SC}) while maintaining a constant system power supply voltage (V_{SYS}). Now the configuration allows the supercap voltage to be independent of the system voltage and dependent on the boost converter's minimum allowable input voltage, which is considerably lower than the required system voltage (V_{SYS}). This lower voltage allows the use of more charge.

The charger completes the picture of the V_{SC}'s independence from the battery voltage (V_{BAT}). The implementation of a charger function meets the supercap input lower voltage requirements and provides an initial charge. This device can be a supervisor IC (including resistors and FETs), a low-dropout linear regulator (LDO with reverse current protection), a buck converter (with a reverse-current protection), or a supercap backup IC.

Fig. 4 illustrates an example of a timing diagram for the circuit in Fig. 3. The variables for Fig. 4 are I_{SC_SYS} = 500 mA, V_{SC_INI} = 2.7 V, V_{SC_FIN} = 1.5 V, and t_{BKUP} = 3.8 ms. The value of C_{SC} is approximately 2.3 mF.

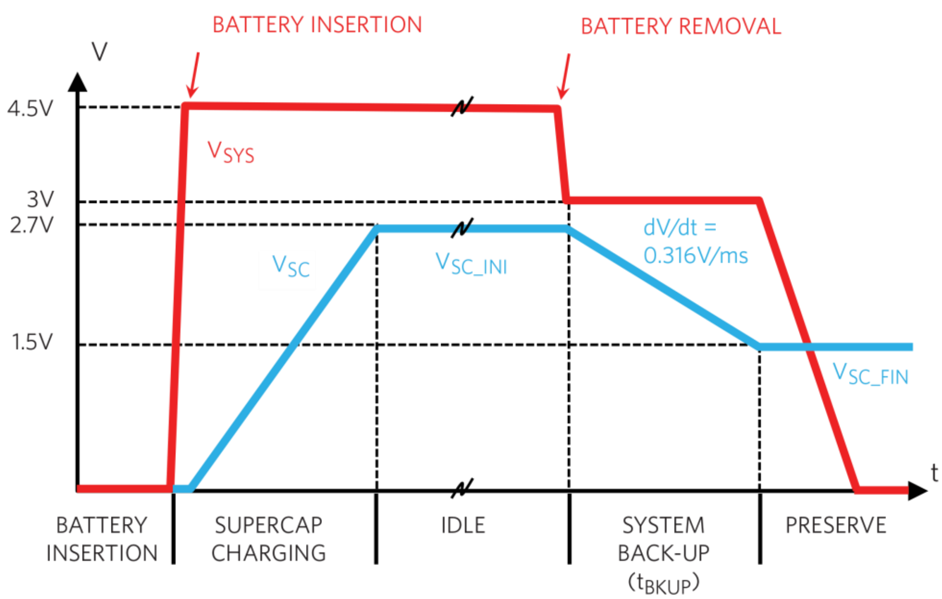

Fig. 4. At the start of the timing diagram, a buck converter charges the supercap. Near the end, a boost converter uses the supercap to provide the system voltage (V_{SYS}) and system current (I_{SC_SYS}).

In Fig. 4, an installed battery drives the system voltage (V_{SYS}) to a 4.5-V level, thus entering the supercap charging period. While V_{SYS} equals 4.5 V, the charger provides current to the supercap until it reaches its full voltage of 2.7 V. Once the voltage (V_{SC}) reaches its specified nominal voltage of 2.7 V, the supercap charging activity enters an idle period where the current (I_{SC}) equals 0 A.

A battery removal event is detected when the V_{SYS} voltage falls and crosses a preprogrammed 3.15-V level, causing the circuit to enter the system backup period (t_{BKUP}). During the backup period, the boost dc-dc converter turns on to provide 3 V from V_{SC} to the V_{SYS} node as well as producing the system's required 500-mA current (I_{SYS}).

During the system backup period, V_{SYS} remains at 3 V, however the supercap voltage (V_{SC}) declines at approximately 0.316 V/ms and the backup time (t_{BKUP}) equals:

$$t_{BKUP} = \frac{0.5 \times C_{SC}\left(Eff \times \left(V_{SC\_INI}{}^{2} - V_{SC\_FIN}{}^{2}\right)\right)}{V_{SYS} \times I_{SC\_SYS}} \quad (1)$$

where Eff is the boost converter efficiency.

Theoretically, if Eff = 1, 3.8 ms expires during the implementation of power-down recovery operations and the progression of the supercap's voltage from 2.7 V to 1.5 V. For three 1.5-V AA alkaline titanium batteries (capacity totaling 5.52 Ah), this 3.8-ms recovery time requires ~1.15 m% of the batteries' current. This is a great ultra-low-cost strategy!

In reality, this time value is closer to 3 ms taking into account the supercap ESR loss and the actual boost efficiency. With this configuration, the system uses 70% of the usable supercap energy with only 30% remaining.

When the supercap voltage reaches 1.5 V, the boost converter switches off and allows the system to ramp down to 0 V. This type of regulation stabilizes the system voltage long enough for the processor to implement data saving activities.

Supercap Selection Process

For the supercap selection process, there are two primary electrical specifications and three system specifications, which are the rated voltage (V_{SC}) and capacitance (C_{SC}). The three system specifications are the system's nominal power (V_{SYS} x I_{SYS}), the boost converter's minimum voltage ($V_{SC(MIN)}$), and the required system recovery time for a power outage event (t_{BKUP}).

These specifications determine the supercap capacitive value, where:

$$C_{SC} \geq \frac{2 \times V_{SYS} \times I_{SC\_SYS} \times t_{BKUP}}{Eff \times \left(V_{SC\_INI}{}^{2} - V_{SC\_FIN}{}^{2}\right)} \quad (2)$$

For example, if I_{SC_SYS} = 500 mA, V_{SC_INI}= 2.7 V, V_{SC_FIN} = 1.5 V, and t_{BKUP} = 3.8 ms, the value of C_{SC} is approximately 2.3 mF.

Integrated Solution

An example of an integrated solution for this design problem includes a reversible buck and boost converter on chip. The MAX38888[1] is the first in the Continua family of backup power regulators. This compact solution outperforms the discrete solution by providing lower power consumption and a small form-factor that only requires one inductor (Fig. 6).

In Fig. 6, with the main battery removed, a boost converter holds V_{SYS} or the system load at a constant voltage while the supercap provides the input current and voltage to the boost converter. When the battery is back in the circuit, the system load reverts to normal operation while the buck converter recharges the supercap. This system is operational if the specified supercap voltage is less than the required minimum V_{SYS} value.

The MAX38888 can be evaluated using the MAX38888EVKIT evaluation kit[2] and uses tools to pick a supercapacitor.

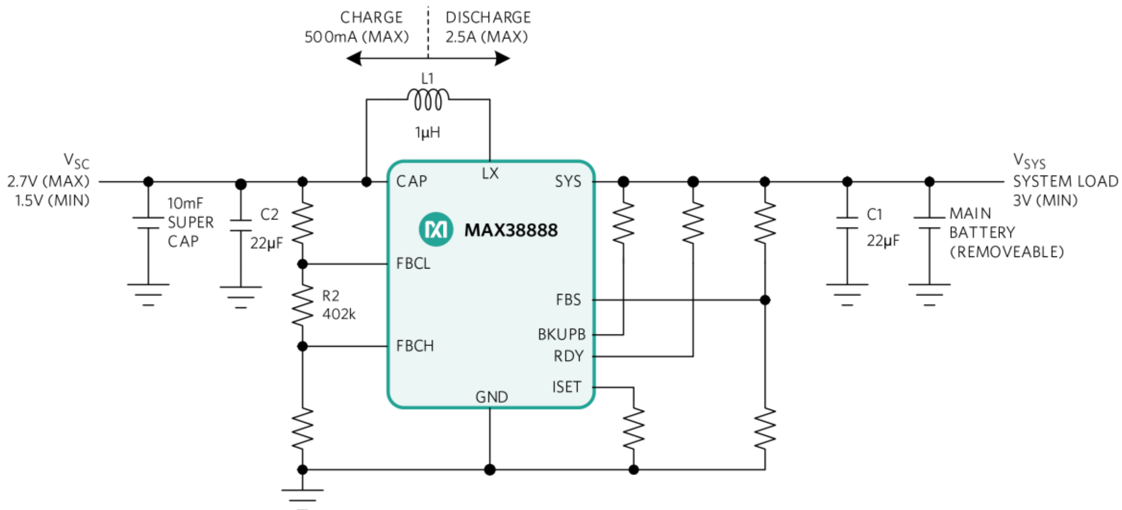

Fig. 6. The supercap charging process uses a buck converter (V_{SC} side of the circuit) while the discharge process uses a boost converter (V_{SYS} side of the circuit).

Conclusion

The often misunderstood supercapacitor is not a battery replacement which provides long-term energy, nor is it used as a capacitor in the frequency signal chain or as a bypass element. Supercaps can very effectively bridge power gaps that last for a few milliseconds or even up to a few minutes.

Battery-powered handheld computers, fire panels, electric meters, home automation, and cameras benefit from the combination of the supercap's very high capacitance and very low ESR, providing new methods for solving common backup power problems. To make effective use of the supercap's capability, a buck and boost regulator device proficiently transfers power between the supercap and the system supply rail. This strategy elongates a system's blackout recovery time from a few microseconds to a more comfortable range of several milliseconds to minutes.

References

1. MAX38888 2.5V–5.0V, 0.5A/2.5A Reversible Buck/Boost Regulator for Backup Power Applications.
2. MAX38888EVKIT Evaluation Kit for the MAX3888.

About The Author

Bonnie Baker is a seasoned analog, mixed signal and signal chain professional and electronics engineer. She has published and authored hundreds of technical articles in industry publications. Baker is also the author of A Baker's Dozen: Real Analog Solutions for Digital Designers as well as coauthor of several other books. In past roles, she worked as a modeling, strategic marketing, IC architect, and designer engineer. Baker has a masters of electrical engineering from University of Arizona, Tucson, Arizona and a bachelor's degree in music education from Northern Arizona University in Flagstaff, Ariz. She has also planned, written, and presented hotel and online courses on engineering topics, including ADC, DAC, operational amplifier, instrumentation amplifier, SPICE, and IBIS modeling topics.

For more information on supercapacitor charging circuits, see How2Power's Design Guide, and do keyword searches on "supercapacitor" and "ultracapacitor".