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WHITE PAPER

DESIGN CONSIDERATIONS FOR ULTRACAPACITORS

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Maxwell's ultracapacitors are increasingly being utilized in consumer electronics, traction, automotive, telecoms and industrial, with applications including pulse power, bridge power, main power and memory backup. These two applications can be group into either static or dynamic applications. Static applications will be able to last a given time, while dynamic applications will be effected by cycle life.

This document provides an overview of some of the key performance characteristics and design issues of ultracapacitors. Product datasheets, tools for sizing ultracapacitors to an application, application notes and white papers are available at our website (www.maxwell.com). It is recommended to contact Maxwell for assistance and more detailed information before commencing any design. Maxwell is committed to RoHS compliance and providing product satisfying Directive (2002/95/EC) limiting use of hazardous substances in electrical and electronic components, as well as complying with all relevant safety and quality standard. Please contact Maxwell for more information.

1. Temperature effects

The performance of Maxwell Technologies ultracapacitors is very stable over a wide operating temperature due to the chemistry and physical make-up of the products. An advantage of the ultracapacitors' organic based electrolyte is its low freezing point allows for good performance down to -40C. This enables the ultracapacitors to be utilized over a wide range of temperatures, with relatively unaffected performance. Plots of capacitance and resistance change as a function of temperature are available on request and on the datasheets.

2. Lifetime and performance changes over time

Ultracapacitor life is predominantly affected by a combination of operating voltage and operating temperature with temperature being the dominant contributor. The ultracapacitor has an unlimited shelf life when stored in a discharged state and benign environment. When referring to ultracapacitor life the data sheets reflect the change in performance which can be seen as a decrease in capacitance and/or increase in resistance. The ultracapacitor does not experience a true end of life rather the performance continually degrades over the life of the use of the product and is a soft end of life.

The typical degradation behavior of the ultracapacitor resembles that of an exponential decay. The majority of the performance change occurs during the initial use of the ultracapacitor and this performance change then levels off over time. The most dramatic effect of the life degradation is on the internal resistance of the device.

In many applications, such as UPS, the ultracapacitors will be maintained at working voltage until needed. Mean Service Life estimates are available on request that show the degradation in rated capacitance for ultracapacitors held at typical working voltages for long periods of time, and at different temperatures. There is a influence of life by temperature; decreasing every 10C has a doubling effect on life for example.

3. Cycling

From cycle testing performed on the products, under typical conditions the product is expected to provide in excess of 1 million duty cycles with an approximate 20% reduction in rated capacitance. This cycle is a 50% voltage depth of discharge (or 75% energy usage) at room temperature. More details of the testing and plots of capacitance versus cycles are available on request. In harsher applications, cycling applications can result in shortened lifetimes.

4. Frequency response

Ultracapacitors have a typical time constant of approximately one second. One time constant reflects the time necessary to charge a capacitor 63.2% of full charge or discharge to 36.8% of full charge.

The time constant of an ultracapacitor is much higher than that of an electrolytic capacitor. Therefore, it is not possible to expose ultracapacitors to a continuous ripple current as overheating may result. The ultracapacitor can respond to short pulse power demands, but due to the time constant the efficiency or available energy is reduced.

5. Voltage

Ultracapacitors are capable of operating between their rated voltage and zero volts. Occasional spikes above the rated voltage will not immediately affect the capacitor. Depending on the frequency and duration of voltage spikes the life will be reduced.

Efficient utilization of the available energy and power storage is achieved with the widest operating voltage range use. Most electronics have a minimum voltage threshold for utilization, limiting the effective utilization voltage of the capacitor although there is no limitation in the capacitor itself. Since the energy in the capacitor is proportional to the voltage squared according to $E = \frac{1}{2} C V 2$.

It is possible to utilize approximately 75% of the available energy if the application utilizes from the rated voltage to ½ rated voltage of the capacitor. However, this is not always possible due to system limitations.

De-rating the voltage provides a benefit to ultracapacitor lifetime. It is not as significant as temperature de-rating, but a .1 lowering of voltage helps extend life.

6. Polarity

Unlike many batteries the anode and cathode of an ultracapacitor are comprised of the same material. If the positive and negative terminal and casing are also comprised of similar materials, then theoretically the ultracapacitor has no true polarity.

For manufacturing and consistency purposes the terminals are marked with polarity. It is recommended practice to maintain the polarity although catastrophic failure will not occur if the ultracapacitor is reversed charged for some reason. If the ultracapacitor has been conditioned for charge in a certain direction and then is changed, the life can be reduced due to this conditioning. For the PC10 product the case is comprised of stainless steel. Due to the corrosion potential it is required to maintain the polarity indicated on the products, and reverse polarity will cause accelerated life reduction.

7. Charging

Since the energy storage mechanism of the ultracapacitor is not a chemical reaction, charging/discharging of the ultracapacitors can occur at the same rate. Therefore, the rated current for the ultracapacitor applies for both charge and discharge. The efficiency of charge and discharge are in practical terms the same. A variety of methods are possible for charging of the ultracapacitors. This may be either through constant current or constant power charging via a dc source or through ac charging methods. A separate application note is available discussing different methodologies for ultracapacitor charging.

8. Series connection and balancing

Since the individual ultracapacitor cell voltage is relatively limited compared to the majority of application requirements, it is necessary to series connect the ultracapacitors to achieve the voltage required. Because each ultracapacitor will have a slight tolerance in capacitance and resistance it is necessary to balance, or prevent, individual ultracapacitors from exceeding its rated voltage.

Balancing can be achieved through two different methods, active balancing or passive balancing:

- Active balancing schemes are varied. Maxwell has adopted a balancing method based on a threshold and dissipates technique. Once a cell comes into range the circuit is turned on and this will increase the leakage current. The maximum current during balancing varies by product. Refer to the product data sheet or product manual for more information. There is another applications note for reference too.

- Passive balancing implies no variation in the voltage regulation as a function of the ultracapacitor condition. The most typical method of passive balancing utilizes resistors in parallel with the ultracapacitors. This method will have a higher leakage current.

A variety of interconnect methods are employed with the various product offerings. They range from buss bar interconnecting to soldering. In general the larger the cell capacitance the more critical the cell interconnects becomes. The larger capacitance devices have internal resistances on the order of a few hundred micro ohms. A poor interconnection can have more resistance than the internal resistance of the device itself. Larger devices will generally be required to carry larger currents, thus necessitating reliable interconnects.

9. Efficiency

Unlike batteries, the ultracapacitor has the same efficiency during charge or discharge. This enables the ultracapacitor to be recharged quickly without current limiting as long as the current is within the rated current for the device.

The only efficiency losses associated with ultracapacitors are due to internal resistance of the device resulting in IR drop during cycling. For most uses the ultracapacitor efficiency is in excess of 98%. For high current or power pulsing the efficiency is reduced. Typical efficiency under high current pulses is still greater than 90%.

10. Thermal Properties

For minimum performance influence over the life of the application it is necessary to maintain the ultracapacitor core temperature within the rated temperature range of the device. The lower the temperature is maintained the better for life considerations.
All products are provided with an electrically insulating shrink sleeving around the capacitor body. For this reason and since all current passes through the capacitor terminals, cooling at the capacitor ends or terminals is the most efficient means for cooling of the capacitor.

Depending on the duty cycle of the application cooling can be accomplished via heat sinks (conduction), air flow (convection) or a combination of the two. Consideration should be made for the duty cycle and resulting capacitor temperature as well as the anticipated ambient temperature the device will be operating under. The combination of the two should not exceed the operating temperature for the ultracapacitor.

More information and advice on thermal performance and design considerations is provided for each product on the data sheet.

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Charging of Ultracapacitors

Charging of ultracapacitors is simple while at the same time may present some unique challenges. Unlike batteries, ultracapacitors may be charged and discharged at similar rates. This is very useful in energy recovery systems such as dynamic braking of transport systems. Here are a few characteristics of ultracapacitors that should be kept in mind when integrating/designing a charging system for the intended application.

An ultracapacitor with zero charge looks like a short circuit to the charging source. Most low cost power supplies fold back the output current in response to a perceived short circuit, making them unsuitable for charging of ultracapacitors.

Ultracapacitors have a low series inductance allowing easy stabilizing with switch mode chargers.

The RC time constant of passive charging networks is usually too long. Therefore, linear regulators are inefficient components for ultracapacitor charging. Covered in this application note are recommendations for constant current charging, constant power charging, and AC line charging.

Constant Current Charging

A DC-to-DC constant current regulator is the simplest form of active charging. Either a buck or boost regulator may be used depending on the application. A buck regulator is the preferred topology due to the continuous output charge current. The power losses or ultracapacitor heating is proportional to current squared times the duty cycle. Therefore, an ultracapacitor module with an I^2 rating of 40,000 may be charged at 200 amps using a buck converter with low ripple current, whereas, the same module could only be charged at 141 amps from a boost converter at a 50% duty cycle (282A squared times a 50% duty cycle $\cong$40,000).

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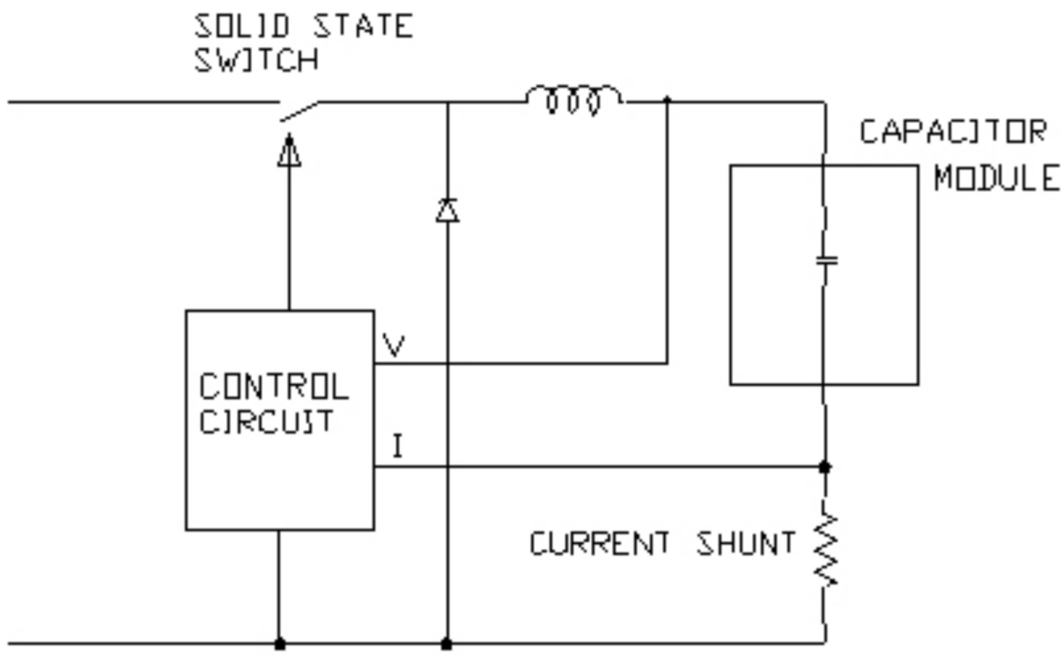

Figure 1: Constant Current Charging Schematic

A simple constant current charger may be built with standard power supply IC's. The current limit would be set to the required charge current and the voltage limit would be set to the maximum required voltage. An example circuit layout is provided in figure 1.

Constant Power Charging

When charge time is critical, constant power charging provides the fastest charge method. Constant power charging can transfer all the available power from the charge source into the energy storage capacitors.

Drawing a constant current from the source at a constant voltage is a simple implementation of constant power charging. This usually requires that a maximum switching current of 2.5 times the nominal be established to prevent overloading the switching circuitry when the ultracapacitor voltage is below 40% of maximum. An example schematic is provided in figure 2 (patent pending).

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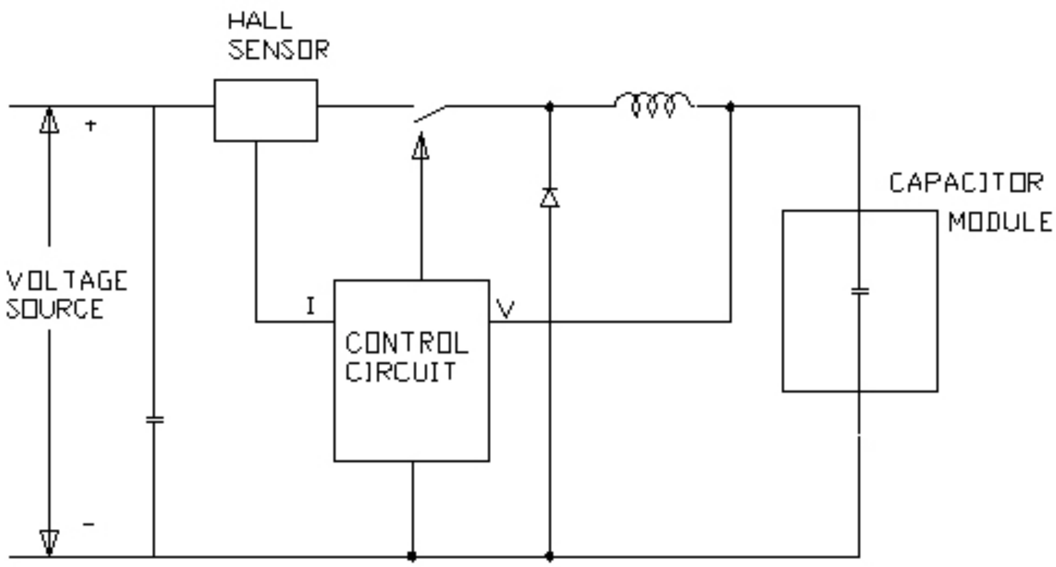

Figure 2: Constant Power Charging Schematic

To quantify the significance of constant power charging the following example is provided and illustrated in figure 3. A 100 farad, 50 V module is charged from a 50 V, 20 amp power supply. In the constant current waveform the module is charged at the maximum power supply current of 20 amps. In the constant power waveform the module is charged at a constant 1000 watts. The maximum charge current from the constant power charger was set at 50 amps.

The constant 20 amp charge current required 250 seconds to charge the module to 50 volts. The 1000 watt constant power charger required 145 seconds to charge the module to 50 volts. For the constant power waveform 50 amps charging current was utilized until the ultracapacitor module voltage reached 20 V with this limit is set by the switching circuitry.

Constant power charging is very useful in dynamic braking systems. This allows a constant power to be extracted from the vehicle's momentum and transferred to stored electrical energy.

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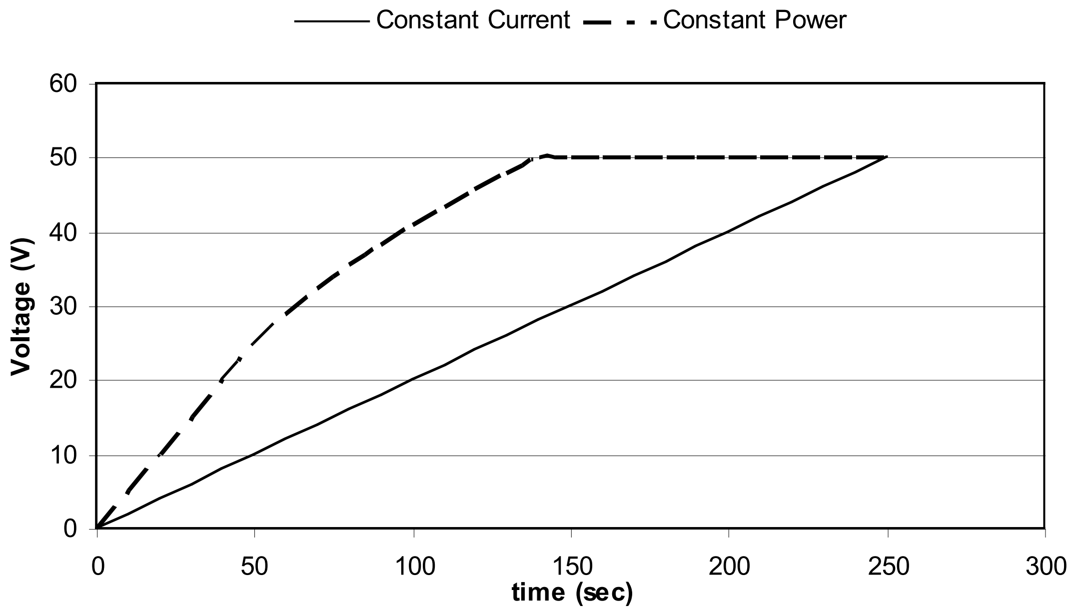

Figure 3: Constant Current vs. Constant Power Charging Time

<u>Isolated AC Line Charging</u> (U.S Patent 6,912,136 – Thrap)

It is often difficult to cover the wide dynamic range requirements for charging ultracapacitors from a varying AC power line. The circuit illustrated in figure 4 uses the L/V characteristics of the switching transformer to set the switching frequency permitting the circuit to provide full output current at zero volts with no risk of saturating the magnetics.

The switch Q1 turns on, charging the primary of T1 to a preset current limit. The switch Q1 then turns off permitting the energy stored in T1 to discharge through D1 into the ultracapacitor module, C1. When the secondary current has discharged to a preset lower limit then Q1 will turn on again repeating the cycle. The time required to charge T1 is inversely proportional to the instantaneous line voltage while the time required to discharge T1 is inversely proportional to the ultracapacitor voltage at C1. The combination of low line voltage and low ultracapacitor voltage will produce the lowest switching frequency. The highest switching frequency occurs at the peak of the AC power line at maximum voltage and full charge voltage on the ultracapacitor. Depending on the application the switching frequency can cover a range of 20:1. When C1 reaches its maximum voltage then the voltage sensor will drive the control circuit into discontinuous operation.

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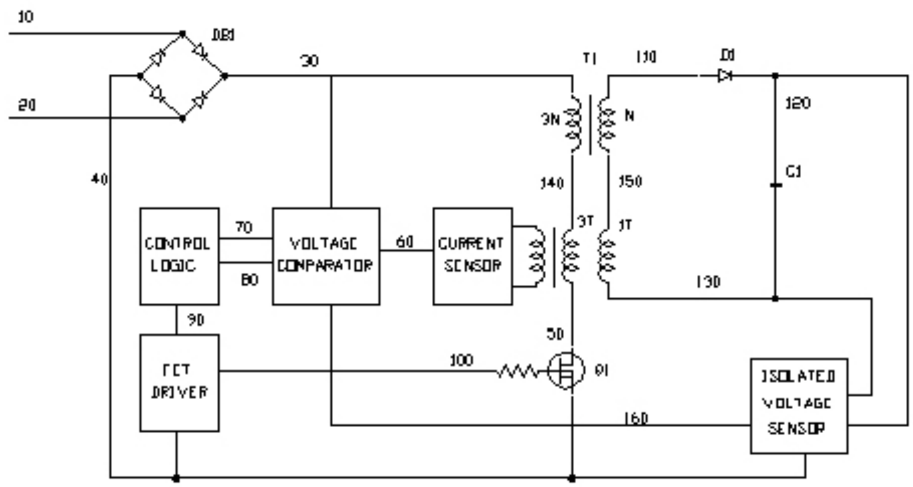

Figure 4: AC Charging Schematic

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