PROPERTIES AND STATE OF THE ART OF HIGH POWER ULTRACAPACITORS

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Abstract
Today, ultracapacitors are a viable component for production-intent designs in the power electronics world. The need for highly reliable back-up and emergency power are creating significant markets for energy storage and power delivery. Electrical wind turbine pitch systems, uninterruptible power supplies and electronic products such as wireless communication devices and digital cameras are some of the many applications where ultracapacitors have been designed in.
Ultracapacitors are components which have properties of a complexe capacitor system which is sensitive to voltage, temperature and frequency. The understanding of their behavior is primordial to characterize and operate them.

INTRODUCTION

Engineers generally address peak power needs by designing the primary energy source to the size needed to satisfy peak demands, even if those demands occur for only a few seconds. Sizing an entire system for peak power needs, rather than for the “continuous” power requirement, is costly and inefficient. Such systems can be significantly improved by storing electrical energy from a primary energy source and then delivering that energy in controlled high power bursts only when high power is required (Figure 1). Such high power delivery provides electrical systems with dynamic power range to meet peak power demands for periods of time ranging from fractions of a second to several minutes.

With no moving parts, ultracapacitors provide a simple, solid state, highly reliable solution to buffer short term mismatches between power available and power required. This enables new functionality, reduces system size and cost and improves performance and reliability. Although batteries currently are the most widely used component for both primary energy sourcing and energy storage/peak power delivery, ultracapacitors increasingly are being used for energy storage and peak power delivery. The deficiencies of battery storage systems are multiple and they create many design challenges for engineers. Batteries have a poor low temperature performance, a very limited lifetime which results in repeated replacement throughout the life of the system, questionable reliability where safety demands are critical, and they are not designed to satisfy the most important requirements of power sources: to provide bursts of power over many hundreds of thousands of cycles [1].

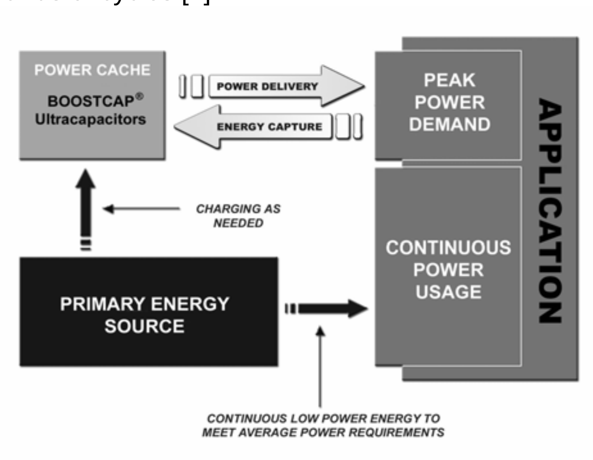

Figure 1: Peak power application model

When appropriately designed with a system approach, they offer excellent performance, wide temperature range, long life, and flexible management. To facilitate adoption of ultracapacitors for applications which require integrated packs consisting of multiple ultracapacitor cells, Maxwell provides fully integrated power packs that satisfy the energy storage and power delivery demands of large systems.

Any application that requires the storage of electrical energy and the discharge of peak power is a potential market for ultracapacitors. Our large cell ultracapacitors have been designed into industrial applications such as uninterruptible back up power systems, pitch systems of wind turbines and transportation applications such as hybrid buses and trucks, electrical rail systems and capacitive starting systems for diesel engines. Our small cell ultracapacitors have been designed into consumer electronics such as remote transmitting devices, digital cameras, bar code scanners, computer memory boards and transportation applications such as electrical rail alarm systems and electric actuators, or latches, for aircraft and automobile doors. Many of the end products into which our ultracapacitors have been designed for now are ramping into commercial production.

ULTRACAPACITOR PROPERTIES

The ultracapacitor measurement methodology is an open topic. Recently an addition to standard IEC 62391 has been submitted to the IEC organization to propose measurement methods for characterizing ultracapacitors. The basic difficulties are related to the capacitance and series resistance change with the applied voltage, the frequency or the temperature.

A lot of publications are dealing with supercap modelization. Most of them mixe the well-known de Levie transmission-line model [2] with a voltage dependant parallel-RC model, first described by Zubieta [3]. Similar models have been used by Dougal [4] and Belhachemi [5].

A recent paper [6] has shown that the capacitance is mainly driven by the space charge within the electronic conductor. The capacitance is indeed composed of a series connection,

one due to the space charge layer inside the conductor and the second to the Helmoltz layer in the electrolyte.
The capacitance is basically defined by the relation:

$$C_u = \frac{Q(U_c)}{U_c}, \tag{1}$$

where $Q(U_c)$ is the accumulated charge on the electrode at the voltage U_c, which in our case varies with the voltage applied at the capacitor terminals.

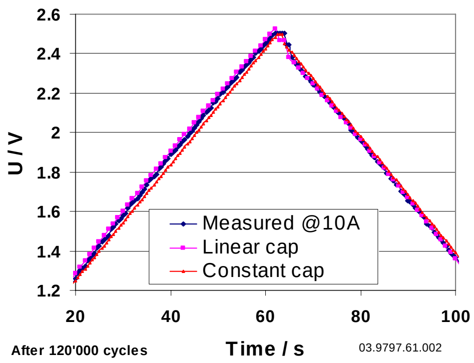

Figure 2: 10 A charging curve for the BOOSTCAP® type BCAP0350 with a nominal capacitance of 350F and a series resistance of 2.4 mΩ, measured after 120'000 cycles.

1. Voltage dependence

The capacitance can be described as the sum of a constant and a voltage dependent term,

$$C_u = C_o + K \cdot U_c, \tag{2}$$

where C_0 is the capacitance at 0 V. The current in the dc-limit is given by the classical relation

$$i = \frac{dQ}{dt}. \tag{3}$$

Taking into account the time dependency of the capacitance, it becomes

$$i(t) = (C_o + 2 \cdot K \cdot |U_c|) \frac{dU_c}{dt} \quad (4)$$

The differential capacitance value, C_{iu}, which is the capacitance found with a small ripple for a given bias voltage, is given by,

$$C_{iu} = C_o + 2 \cdot K \cdot |U_c| \quad (5)$$

and the nominal capacitance, C_n, is defined as the mean C_{iu} value between the nominal voltage U_n and half of its value $U_n/2$:

$$C_n = C_o + \frac{3}{2} \cdot K \cdot |U_n| \quad (6)$$

This relation states, that for a given voltage variation, higher currents are available in the higher voltage range.

2. Frequency dependence

The capacitance and the series resistance have values which are not constant over the frequency spectrum. The performance may be determined with an Impedance Spectrum analyser [7].

Basically the available capacitance is maximum at low frequency. This may be explained with the loger time available for the ions in the electrolyte to reach the surface which is located deep in the carbon pores. At higher frequency, only the superficial carbon surface is accessible for the ions. The capacitance is consequently much smaller.

The series resistance is composed of an electronic and a ionic part. The electronic contribution comes from the ohmic resistance in the conductor and in the carbon particles. The ionic contribution comes from the ions mobility in the electrolyte.

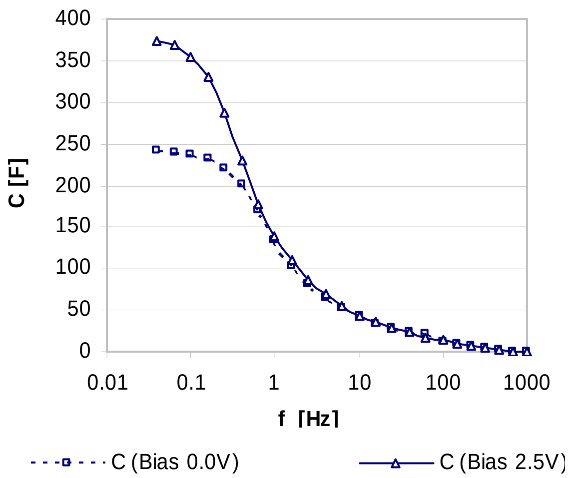

Figure 3: Capacitance frequency spectrum of a BCAP0350

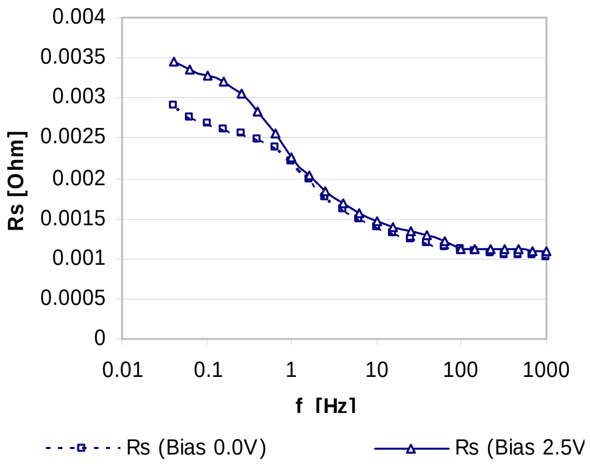

Figure 4: Series resistance frequency spectrum of a BCAP0350

3. Temperature dependence

Increasing the temperature will have the main effect to reduce the electrolyte viscosity and improve the accessibility of the surface for the ions. They will be able to reach deeper surface in a shorter time. Consequently the series resistance will be reduced and the capacitance will increase with the temperature. Several groups are working on the modelization of the temperature dependance of the supercapacitors and are giving parameters to fit their behavior [8, 9].

4. Efficiency of ultracapacitor

Recently Maxwell developed a new high performance 350-farad ultracapacitor with the size of a battery D cell. This cell combines high performance but low cost materials and a three piece assembly resulting in the lowest possible production costs. Thanks to the outstanding performance as well as the low cost design this cell is ideally suited for application such as automotive multiple zone electrical distribution systems, wind turbine pitch systems, medical systems and many high volume consumer applications.

Figure 5: BCAP0350

The BCAP0350 ultracapacitor efficiency is determined not by internal resistance alone but by how well its time constant matches the expected pulse duration of the application.

$$\eta \sim= 1 - 2(\tau / T) \quad (7)$$

where, R_s = ultracapacitor internal resistance, $\tau = R_sC$, and T = constant current charge or discharge duration.

The ultracapacitor time constant and “time” rating are determined using (2) and available specification data.

$$I/C = Vr/T \quad (8)$$

where, T= the constant current discharge time to fully deplete the ultracapacitor’s stored energy and Vr = the ultracapacitor’s rated voltage. Representative ultracapacitor specifications are listed in Table 1. Internal resistance used is a typical dc value since discharge pulse durations will be >1s to accommodate the load.

	Vr	m [g]	I [A]	C [F]	R_s [m]	W_e [J]	τ [s]	T [s]
BCAP0350	2.5	57	100	350	2.6	1094	0.91	8.8

Table 1: BCAP0350 preliminary specification data (Maxwell Technologies, Inc.)

The discharge efficiency of the BCAP0350 is shown in Figure 3 with pulse time, T, as a variable.

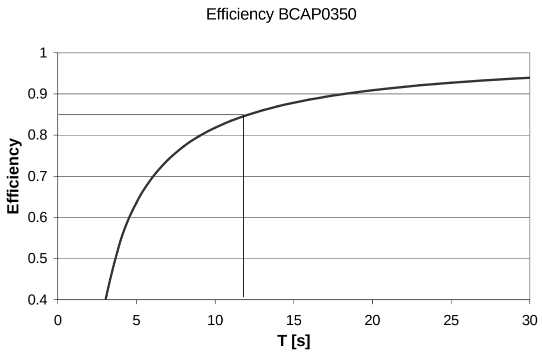

Figure 6: BCAP0350 discharge efficiency

To hold >85% discharge efficiency η_d the discharge pulse durations must be restricted to T_d = 11.5 s. Rearranging (2) and solving for current results in discharge currents of < 76 A for the cell. Discharging with these currents, for the stated discharge pulse time, results in a 100% depletion of the capacitor energy. It is common practice to extract 75% of the total capacitor energy, in which case the current magnitudes stated are proper for the "time" rating of the ultracapacitor. In this case, and using the data available from Table 1 the results in available output power are:

$$P_0 = (W_e * \eta_d) / T_d \qquad (9)$$

According to (3) the BCAP0350 is capable of sustaining a load of 80 W for 8 s while maintaining a discharge efficiency of greater than 85%.

APPLICATIONS

Short power failures, spikes or strong fluctuations in line voltage can seriously disturb complex and highly automated assembly lines and cause major damage. Here uninterruptible power supplies (UPS) are used to improve power quality and guarantee the reliability of power backups. In the future it will become even more important to secure critical loads, as the stability of power networks cannot always be guaranteed. It is impossible to exclude failures caused by short circuits, lightning strikes or storms, or by large loads being switched in and out. Powerful and quick-reacting UPS systems can prevent major damage in such cases.

1. UPS systems

The safest and most advanced solution is the online UPS, which completely decouples the line from the load. Sensitive and highly critical loads such as complex and sensitive manufacturing systems are secured exclusively by such online UPS systems.

During voltage sags or complete interruptions of the power supply, the energy has to be delivered by local energy storage devices. Lead-acid batteries, the conventional energy storage choice for UPS, can not be designed to bridge interruptions that last for seconds vs. many minutes. It is important to note that over 98% of power outages in the low voltage area last less than 10 s. Thus, in contrast to batteries, ultracapacitors are ideally suited to fulfil UPS requirements [3]. The strength of ultracapacitors lies in their ability to release energy with no delay for periods from a fraction of a second up to 30 seconds. With their guaranteed low residual current, long operating life, no maintenance or costly test runs, the ability of full discharge and the short recharging times for frequent power failures, ultracapacitors are an outstanding storage device as the key function in storing energy in high reliability systems.

2. Short term energy storage sytem

Maxwell recently developed a high reliability short-term Solid State Energy Storage (SSES) module used to provide 48 VDC bridge power. The SSES provides primary 48 VDC power during the start-up or transfer to generators, micro-turbines, fuel cells or other alternative primary or back-up energy sources. The SSES module incorporates a DC-to-DC boost converter that will reduce the slope of the ultracapacitor discharge to mimic a typical lead acid battery slope. When the primary 48 VDC source fails, the SSES module will begin to deliver power to the load until an alternative source or primary source returns. The discharge of the SSES module will begin just below the float level voltage and will continue to a low voltage shut-off. Optimum bridge time for the module is between seconds to minutes and is rated in watt minutes

The SSES modules incorporate long life, high reliability ultracapacitors that require no periodic maintenance and have an expected life of 10 years. The module incorporates a charging circuit that can rapidly recharge using excess energy from a 48-volt DC bus to charge up a bank of integrated energy storage ultracapacitors. The module can support in excess of 100,000 cycles regardless of depth of discharge. Designed as a rack mount device to fit the majority of telecommunication and data racks, it can be either flush or center mounted in a 19” or 23” racks.

3 Backup power

Ultracapacitors are perfectly suited for temporary backup power in electronic devices. Before ultracapacitor technology, batteries were the only source of backup power for functions such as computer BIOS settings, telephone and camera configuration settings, and secondary short-term emergency power when a primary power source is insufficient. However, because of their large capacity, ultracapacitors have become an alternative to batteries in applications where the ultracapacitor is charged from the primary power supply but functions as a backup power source when the primary source fails.

Figure 7: Backup examples using ultracapacitors: Memory boards, personnel transponders

4 Peak power

Ultracapacitors are ideal in supplying peak power in electronic devices. In these applications, ultracapacitors are used in tandem with batteries for systems that require both constant low power discharges for continual function and a pulse of power for peak loads. In fact, ultracapacitors have been used in a variety of applications, ranging from portable scanners for factory bar-code reading and automated meter reading (AMR) systems to digital cameras.

Figure 8: Peak power examples using ultracapacitors: Digital camera, AMR

Typically small sized ultracapacitors are used in AMR systems that are linked through a two-way communication architecture. Ultracapacitors provide many benefits over traditional energy storage components. By using ultracapacitors instead of Lithium Ion or Lead Acid batteries, the life expectancy of the power supply in AMR's is extended to over ten years – representing a one hundred to three hundred percent improvement over lead acid batteries. The PC10s in each unit (Figure 9) are also lighter and smaller, and facilitate a simpler design-in process due to the components' configuration, which allows them to be mounted flat on the board. Ultracapacitors are slightly more expensive in initial cost, but because the life of ultracapacitors is much longer, an overall cost savings of over two hundred dollars per unit is realized.

Similarly, in a digital camera application representative of a typical ultracapacitor-enhanced design, one PC10 ultracapacitor works with a battery to provide overall system power management. The ultracapacitor drives the initial power-up of the camera, and drives functions involved in composing photographs, such as microprocessor, zoom, and flash. The major high power peak demand was observed during the microprocessor activity, i.e. writing to the disk and the LCD operation. Here ultracapacitors in conjunction with basic inexpensive alkaline batteries achieve the same life cycle as expensive new high power batteries. By using the capacitor in parallel with the alkaline batteries, the overall system impedance will drop therefore allowing the battery to act as a pure energy source. Thus replaceable, low-cost off-the-shelf alkaline batteries can be employed, making the camera smaller, lighter, and truly portable.

Other current and potential portable ultracapacitor applications include two-way pagers, GSM-protocol cell phones, hand-held GPS systems, PDA's, and power tools, just to name a few. And as the demand for smaller portable devices increases, the flexibility, durability, and power of the ultracapacitor will help designers enhance product functionality while simultaneously decreasing size, proving the old adage that the best things come in small packages.

5 Wind turbine pitch systems

Advanced wind turbines consist of three-bladed variable speed turbines. The rotor blades are adjusted and controlled via three independent electro-mechanical propulsion units, the pitch systems. On a pitch controlled wind turbine the rotor blades are slightly turned out of the wind when the power output becomes too high. Conversely, the blades are turned back into the wind whenever the wind drops again. Thus aerodynamic efficiency and reduced loads on the drive train is assured, providing reduced maintenance and longer turbine life. To enhance the level of safety the newest wind turbine technology uses the wind not only to produce energy but also for its own safety. The converters feature aerodynamic braking by individual pitch control. The rotor attains the full braking effect with a 90 degree off position of all blades. Even if a blade pitch unit fails, the braking process is finished off safely by the other two rotor blades. To enhance the level of safety each of the autonomous pitch systems is equipped with an emergency power pack to immediately ensure the reliable functioning of the pitch system, for example in the event of a total power failure or for maintenance purposes. Due to their high reliability, efficiency and operating lifetime, ultracapacitors have been designed into pitch systems of many wind turbine manufacturers and pitch system designers.

Pitch systems are located in the rotating rotor hub of the wind turbine (Figure 9). The power supply and control signals for the pitch systems are transferred by a slip ring from the non rotating part of the nacelle. The slip ring first is connected to a unit which includes clamps for distributing power and control signals to the three individual blade drive units. Each of them consists of a switched mode power supply, a field bus, the motor converter, an emergency system, and the ultracapacitor bank. When the power supply is switched on, the ultracapacitor module is charged to its nominal voltage. Typical charging time is approximately 1 minute. The capacitor module has an energy content high enough to run the system for more than 30 seconds with nominal power. The ultracapacitor module is directly connected to the DC link of the motor converter.

Manufacturers continue to reach for the stars as installations grow ever larger. Megawatt class turbines dominate much of the actual world market, pushing the development of multi-megawatt turbines, as the offshore market may demand such installations. The largest turbines are able to produce power up to 5 MW with a rotor diameter of up to 110 m. To ensure the functioning of the fast blade pitch system even for such large installations, bigger emergency power packs have to be integrated. Maxwell’s integrated packs assembled with large ultracapacitors and rated at 300 VDC are perfectly suited to fulfil the requirements of MW size turbines.

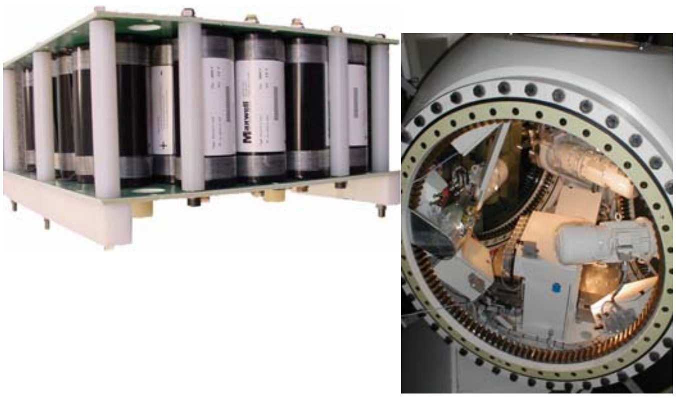

Figure 9: Rotor hub with independent electro-mechanical pitch propulsion units and emergency power pack containing 34 large cells rated at 2’700 F, a nominal capacitance of 78 F and a nominal voltage of 76 VDC

CONCLUSION

Maxwell is a global leader in commercializing ultracapacitor technology. BOOSTCAP® ultracapacitors are ideally suited for applications that require highly efficient energy storage and repeated bursts of electrical power lasting from fractions of a second up to several minutes. Today Maxwell’s ultracapacitors are commerically available, cost effective, and highly reliable for electronic systems.

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