SkelCap User Manual

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Introduction

The SkelCap ultracapacitors offer industry-leading performance with specific power up to 112 kW/kg and specific energy up to 6.8 Wh/kg. The SkelCap cells are available at 2.85 V from 500 F to 3200 F rated capacitance cells, with a very low ESR. This document provides general safety, handling and system integration guidelines for SkelCap cells and stacks. All SkelCap ultracapacitors are manufactured in the EU.

Safety warnings

- **Never short-circuit the cell/stack terminals as any (even residual) voltage can cause injury (in case of large stack even fatal electrical shock)! Always check to ensure the cell/stack is discharged before handling.**
- Do not crush, smash or disassemble the ultracapacitors.
- Do not handle or operate ultracapacitors on conductive surfaces and always protect surrounding electrical components from incidental contact.
- In case of electrolyte leakage, avoid contact with eyes and skin or ingestion and keep away from fire sources.
- Ultracapacitors may rupture if overcharged or heated above the specified upper temperature limit. Avoid operating outside of the specified operating voltage/temperature limits.
- Avoid high temperatures, high humidity, exposure to direct sunlight, shock and/or vibration, and direct contact with water, corrosive and/or toxic substances or other chemicals during long-term storage.

1. General safety and handling guidelines

1.1. Residual voltage and handling of ultracapacitors

In the last stage of production, following the quality control testing (i.e., capacitor conditioning), ultracapacitors will be discharged to 0 V. However, due to charge redistribution effects, ultracapacitors will regain a voltage of approximately 250 mV.

For safe assembly, storage and testing of ultracapacitors, do not use electrically conductive surfaces. On a conductive surface the ultracapacitors may be short-circuited. If an ultracapacitor stack is fully charged and placed on an electrically conductive surface, sparks and short circuits that could lead to a fire may occur.

1.2. Overvoltage

The rated voltage of an ultracapacitor is the upper voltage limit at which the rate of the system degradation is within acceptable limits for long-term application, with the stability of the electrolyte solution as the main limiting factor. The rated voltage of SkelCaps is 2.85 V. If the capacitor is charged beyond the rated voltage, i.e., overvoltage is applied, the rate of degradation increases. In most cases, this is not a safety hazard as the cells tolerate short periods of overcharging reasonably well. There should be no observable negative effects if the cell is accidentally overcharged—for example, to 0.15 V beyond the rated voltage for 12 hours at room temperature. In the worst-case scenario, the capacitor is constantly charged with no voltage control, leading to severe overvoltage. Overvoltage results in formation of gaseous degradation products inside the hermetically sealed ultracapacitor casing, especially at a temperature close to or above the upper operating temperature limit (+65 °C for SkelCaps). That, in turn, causes pressure buildup and eventually rupture of the preset breakpoint relief in the ultracapacitor casing wall. The opening of the preset breakpoint relief may take anywhere from minutes to weeks, depending on the current used to charge the cell and the resulting overvoltage extent.

1.3. Overtemperature

The defined operating temperature range for SkelCaps is between –40 ºC and +65 ºC. In this range the energy storage processes are sufficiently effective and allow long-term use. The safety hazards of overtemperatures (i.e., above +65 ºC) are related to the pressure levels inside the capacitor's casing. The rated maximum operating temperature is partly limited by the close boiling point of the electrolyte but more importantly by the electrochemical instability of the electrolyte under applied voltage above the upper limit for capacitor temperature. Exceeding the specified operating temperature upper limit will cause the capacitor's internal pressure to increase, especially at (or close to) rated voltage state-of-charge. At temperatures below –40 ºC, the electrolyte in the capacitor freezes and the device loses its functionality. When returned to the defined operating temperature range, capacitor functionality is recovered, though with a notable loss of performance.

It is important to note that ultracapacitors heat up during operation, i.e., continuous cycling or cycling with short idle periods, due to their internal resistance. The temperature difference between the capacitor and the operational environment depends on the applied current as well as the thermal properties of the capacitor and must be considered when designing a system.

1.4. Preset breakpoint relief (safety valve)

A machined preset breakpoint relief is located on the bottom part of the SkelCap's aluminum casing wall (Figure 1). Its purpose is to provide a predetermined point for capacitor casing failure (opening) if the capacitor has been misused for a period long enough to cause an extreme internal pressure buildup. The preset breakpoint relief (i.e., safety valve) has been designed to open when the capacitor internal pressure exceeds 12±2 bar. When designing systems, the breakpoint should be placed facing away from any sensitive components, such as circuit boards, and away from direct access points for personnel as electrolyte vapors may be released during the rupture of the breakpoint. Note, however, that there is a limited amount of free-flowing bulk electrolyte (i.e., electrolyte not adsorbed in the carbon or separator) inside the capacitor.

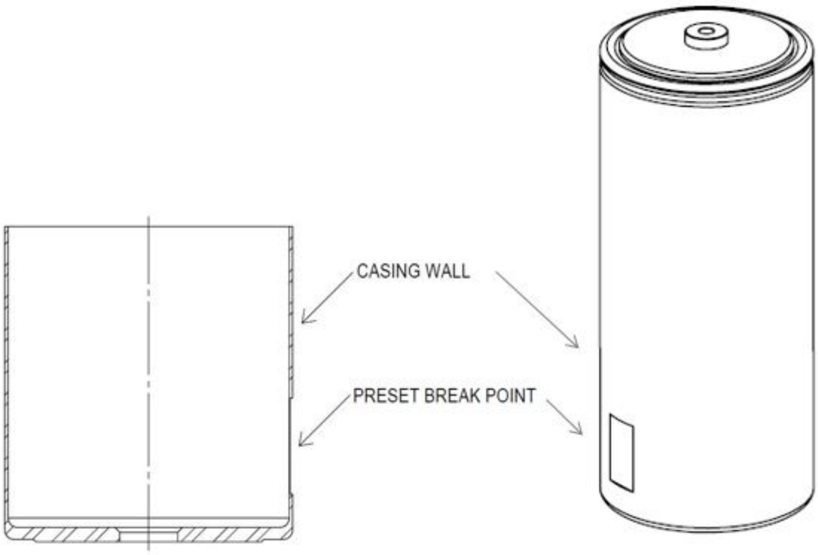

Figure 1. SkelCap casing model with machined preset breakpoint relief.

1.5. Short circuits

Short-circuiting a charged ultracapacitor must be avoided as it can generate a current in the range of several kiloamperes. If the short circuit occurs in a series-connected module, the very high current that drains through the short circuit may cause severe heating of the module's components with the highest resistance.

The short circuit can damage wires and welds, i.e., the wires and/or the insulation of wires may melt or catch fire. Also, the welds may be heated enough to melt the aluminum casing of the capacitor, resulting in cell opening and possible electrolyte evaporation and combustion. Therefore, especially in the case of modules, the cause of the short circuit must be removed as soon as possible, but only **if it is safe to do so**. The capacitor(s) of concern should be immediately disconnected from the system they are powering.

An incidental, temporary short circuit (e.g., a technician accidentally connects the positive and negative terminals with a screwdriver) may generate sparks and **very rarely** a small piece of molten aluminum may separate from the capacitor/module. If any maintenance is necessary, the module/cells must be discharged and short circuited before maintenance.

1.6. Connecting charged or uncharged ultracapacitors with a DC link

Never connect ultracapacitors or ultracapacitor stacks directly to a DC-bus or other equipment if the voltage difference between the two systems is more than 10%. If the voltage difference is higher than 10%, there is a high risk of burning down cables, fuses, contactors, switches or other power electronic devices. Use proper pre-chargers and other devices to limit the inrush current values to protect your devices.

1.7. Discharging instructions

Ultracapacitors can be discharged to 0 V without affecting their lifetime.

Ultracapacitors and modules can be safely discharged in two ways:

a) The cells/modules can be connected to a circuit with a variable resistor that can handle the load from the cell/module (passive load). Using this method, the polarity of the cells cannot be reversed because there is no active supply of current. On the other hand, this method is rather slow in the lower voltage region.

b) The cells/modules can be discharged with an active galvanostatic discharger. However, it must be remembered that galvanostats can discharge the cells completely and then proceed to negative voltages, i.e., cause reversed polarity. This becomes an issue for unbalanced or poorly balanced modules or systems, where one capacitor may be discharged much quicker than others, causing negative voltage on the former.

Using breaking resistors that are sized to meet a discharge time of three minutes or more (in case of single cells or modules) is strongly recommended. Please note that the resistor's power, voltage and thermal capacitance need to be calculated properly to avoid burning down the resistor. If there is a need for the discharge time to be under three minutes, a temperature rise calculation is essential to avoid exceeding the specified temperature limits.

1.8. Reversing polarity

Unlike batteries, the positive and negative electrodes of an ultracapacitor are made of the same material. Also, the terminals and the casing of the ultracapacitor are generally composed of similar materials. Thus, the cell has no true polarity before charging it for the first time during standard quality control.

All cells have been electrically tested before dispatched from the manufacturing plant. During the electrical testing, cell polarities will be defined and marked on the cell label with a "+" and

"–" sign. Once the positive and negative polarities are defined for either electrode, the initial charge direction, i.e., the initial polarity, should be followed for the best performance.

No catastrophic failure will occur if the polarity of the cell is reversed. However, reversing the polarity does have an immediate and irreversible negative effect on the cell's capacitance and resistance (and therefore also on lifetime). The magnitude of the negative effect depends on the extent of the reverse polarity voltage applied to the cell. Skeleton Technologies strongly advises users to avoid reversing the polarity.

1.9. Flammability

In the case of a cell opening due to internal pressure increase or mechanical damage, leakage of the electrolyte is possible. It must be noted that only a spark (or other source of fire) is necessary to ignite the electrolyte, which is a volatile and flammable liquid. In case of fire, the capacitor's internal pressure increases until the breakpoint relief opening. Most of the electrolyte in the cell is adsorbed in the active carbon and separator and is therefore rather inactive in terms of flammability, even if the cell is opened. The amount of free electrolyte is in the range of couple of milliliters in the largest cells; thus, the potential for a large-scale fire is very low. If the electrolyte of an opened capacitor catches fire, it burns in a few seconds. In accordance to the IEC60695-11-5 standard, the SkelCap ultracapacitor's electrolyte burns in less than 30 seconds, generally in less than five seconds.

1.10. Chemical compatibility of sealing material

The electrical isolation gasket between the ultracapacitor's casing and lid is made from EPDM-type rubber, for which the chemical compatibility with various substances can be checked from this online database: http://www.utexind.com/resources/chemical-compatibility-lookup/.

1.11. Disposal considerations

For disposal of ultracapacitors, please check regional laws and guidelines. SkelCap ultracapacitors consist of aluminum, rubber, carbon, paper and electrolyte containing acetonitrile. No heavy metals are used.

Also, please check the Material Safety Data Sheets at Skeleton Technologies web page: http://www.skeletontech.com/downloads.

2. System integration guidelines

2.1. Connecting the ultracapacitors in series and in parallel

To determine the amount and the type of ultracapacitors necessary for a specific application, as well as the capacitor connection and control-circuit requirements, several parameters must be considered: the upper and lower limits of the operating voltage, the peak and average power (or the peak and average current values), the required runtime at the defined current, the temperatures of the environment and the operating cell, and the expected lifetime for the defined operating conditions.

2.1.1. Connecting in series

Ultracapacitors are connected in series to obtain the application-defined operating voltage of a module or system. The number of cells, $\#cells$, required to obtain the system's voltage, V_S, is determined from the ultracapacitor's rated voltage, V_R, according to

$$\#cells = \frac{V_S}{V_R}$$

where the resulting $\#cells$ is rounded off upwards to avoid overcharging the cells connected in series.

If the average application current, I_{AV}, the required runtime (discharge time), dt, and the upper and lower operating voltages, V_{max} and V_{min}, are known, the required system capacitance can be calculated as

$$C_S = I_{AV}\frac{dt}{dV} = I_{AV}\frac{dt}{V_{max} - V_{min}}.$$

The system's total capacitance can also be calculated from the capacitances of individual cells as follows:

$$\frac{1}{C_S} = \frac{1}{C_1} + \frac{1}{C_2} + \ldots + \frac{1}{C_n}$$

where $n = \#cells$. If $C_1 = C_2 = \ldots = C_n$, the type of ultracapacitor to use, i.e., the required capacitance of a single ultracapacitor, C_{UC}, is therefore defined as

$$C_{UC} = \#cells \times C_S.$$

If the capacitors are connected in series, the residual voltage of 250 mV on shipped individual cells is cumulative, meaning that for 10 capacitors in series, a total voltage of 2.5 V is reached in a module or system. To avoid this, the cells can be short-circuited separately beforehand for an hour (e.g., by connecting the two terminals via a wire) or the cumulative residual voltage must be considered while handling the module (avoid short-circuiting the module).

2.1.2. Connecting in parallel

If the calculated necessary capacitance per single ultracapacitor (to obtain the required runtime) in a series-connected module or system exceeds that available in the product range, capacitors can be connected in parallel to increase the system capacitance and current ratings. Ultracapacitors connected in parallel have equal voltage, i.e., 2.85 V per cell, and the total capacitance of the system is the sum of the capacitances of individual cells: $C_S = C_1 + C_2 + \ldots + C_n$. This also applies for parallel-connected stacks.

There are no special safety hazards related to the cells connected in parallel.

Regardless of connection type (series or parallel), the module or system's total energy increases with the increasing number of capacitors. Total energy can be calculated as $\#cells$ times an individual cell's energy.

2.2. How to laser-weld ultracapacitors to bus-bars

Skeleton Technologies' ultracapacitors should be welded to bus-bars only by the laser-welding process. Please see the technical note "Technical Note – Ultracapacitor Series Welding Guidelines" on Skeleton Technologies web page: http://www.skeletontech.com/downloads.

2.3. How to isolate ultracapacitors in a module

As the shipping (residual) voltage of an ultracapacitor is ~250 mV, it is recommended to discharge the cells to zero volts prior to assembling a system or module. Short-circuiting a charged cell or an ultracapacitor pack can cause severe burns and/or injuries.

For ultracapacitors in modules with metal casings, isolation of the capacitors from the module casing by nonconductive materials is required. In particular, thermal pads are a good option as they isolate the ultracapacitors while being good thermal conductors. Thermal pads from manufacturers such as t-Global can easily be found and bought from Internet stores such as Farnell or Digi-key.

Ultracapacitor packs must be transported in the uncharged state, protected against short-circuiting or, alternatively, have a strap connecting the terminals. The transportation of ultracapacitors is governed by Regulation UN 3499 according to the IATA special provision A186.

2.4. How to construct module cooling

While a system or module is in use, heat is generated due to its internal resistance. The amount of heat produced depends on the current and resistance. The majority of the heat is dissipated through the terminals of the cells. Therefore, in a module that heat can be transferred through thermal pads from bus-bar to outer casing. It is important to monitor the temperature of every cell, as the cell casing temperature should not exceed +65°C. If the upper limit of the operating temperature range is exceeded, the lifetime of the cell will be reduced significantly. The type of cooling system applicable depends on the required current and the total electrical resistance of the ultracapacitor module. For low-current applications, regular convection cooling may be sufficient; for high-current applications, forced convection cooling or liquid cooling may be used.

In Figure 2, a cross-section of a simplified module can be seen. Individual cells are connected by bus-bars. Thermal pads are placed on top of the bus-bars to electrically insulate the bus-bars from the outer casing. Thermal pads are also used to carry the heat generated by the capacitors to the outer casing, where the heat is dissipated.

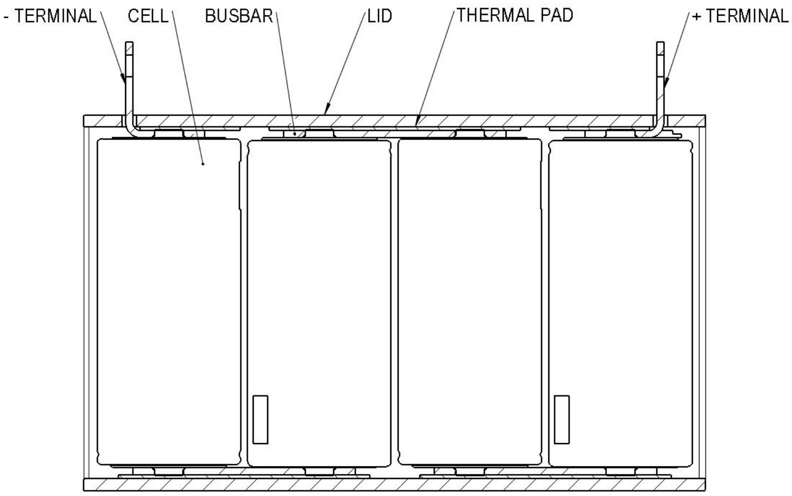

Figure 2. Illustrative picture of module containing four SCA3200 cells connected in series.

The average current value $I_{\Delta T}$ (A), corresponding to a given temperature rise, can be calculated as follows:

$$I_{\Delta T} = \sqrt{\frac{\Delta T}{R \times R_{th} \times 0{,}001}}$$

where ΔT is the temperature rise for the module (K), R is the combined electrical resistance of the module (mΩ) and R_{th} is the combined thermal resistance of the module (K/W).

2.5. Cycle life and lifetime

The end-of-life (EoL) parameters for SkelCaps are defined as a 20% decrease in capacitance and/or 100% increase in resistance from the respective rated values. The cycle life of an ultracapacitor shows the number of cycles between rated voltage and half-rated voltage at 25 °C until EoL (defined as a minimum of 1,000,000 cycles), and the lifetime shows the hours of operating at the rated voltage and upper working temperature limit until EoL (defined as a minimum of 1,500 hours). The temperature of the surrounding environment and the temperature increase due to the ultracapacitor's internal resistance while operating define the requirements for the cooling-system design to achieve the desired long-term stability for the module or system. The closer the average operating conditions are to the rated voltage value and to the upper limit for temperature, the quicker system degradation occurs.

Ultracapacitors or modules have a lifetime of a minimum of 1,500 hours at operating conditions of rated voltage and +65 °C. At 25°C, the ultracapacitor's usage time is 10 years. For more detailed information, please contact info@skeletontech.com.

2.6. How to monitor module health

The life expectancy of ultracapacitor modules is affected mostly by two parameters: temperature and voltage. These parameters need to be measured and monitored throughout the system's lifetime. If there is a limited number of temperature sensors used in the modules, they must be placed at the hottest spots. The temperature variation between the hottest and the coldest ultracapacitor can vary several degrees in large-sized modules. As this will lead to uneven degradation of cells, a module should be designed to keep this variation as low as possible. To determine the hottest spot(s) in the module, a simulation of the module's mechanical-electrical design is recommended.

The control system of the module should be able to switch off charging and even discharge the module if overtemperature or overvoltage is detected. The monitoring system should output data frequently enough so that the surge voltage is never achieved on any of the cells, as this may damage the cells irreversibly. The temperature monitoring may be less frequent as the temperature will not change as rapidly due to the system's thermal capacity.

2.7. How to balance the module

There are several ways to balance an ultracapacitor module. The voltages of ultracapacitors go out of balance due to small variations in their parameters, i.e., the capacitance and leakage current. Small imbalances in the system would be acceptable if they did not affect the life expectancy. However, a difference of 0.15-0.2 V between individual ultracapacitor voltages can reduce module life by roughly two times.

2.7.1. Passive balancing

The simplest balancing method is passive balancing. The concept employs a resistor in parallel with each of the cells to reduce the variation of leakage current. During steady state, the variation of leakage current causes voltage imbalances between the cells, which ultimately affects the life expectancy of the module. Hence, the imbalances must be reduced. Passive balancing will not, however, balance the voltage variation caused by the capacitance differences arising during charge or discharge. Thus, passive balancing is generally used in tandem with active overvoltage protection, which draws energy from ultracapacitors that have reached a set voltage level (usually the rated voltage value). It should be noted that the simplest balancing methods do not allow any control over the balancing process and therefore will not optimize the lifetime of the module.

2.7.2. Active balancing

The balancing system used by Skeleton Technologies is an active controlled balancing that enables complete control over the balance of the module. This is achieved by measuring the voltage of each cell and subsequently controlling the energy flow in the way that allows the system to be balanced as quickly as possible. This also allows to change the accuracy of balancing and set point as needed. The active balancing method gives the user the best possible control of the system and helps extend the life expectancy of the module(s).

2.7.3. Optional balancing method

An optional solution for balancing the module is using the active controlled method, but instead of the excessive energy being bled off, it is transmitted from the most-charged to the least-charged ultracapacitor. This allows one to keep heat dissipation to a minimum and thus enables quicker balancing of the module. The method is used rather rarely, though, due to the high cost and complexity of the system.

2.8. Connection considerations for modules

In a module constructed from ultracapacitors, the bus-bar cross-section area should be chosen according to the application. Skeleton Technologies ultracapacitors are designed to be used with 3 mm thick bus-bars, which can be laser-welded to the capacitors. When choosing connecting bus-bars, one must keep in mind that additional resistance is added to series or parallel connections by every bus-bar. The additional resistance is usually not high, but it must be considered when calculating the overall parameters of the system.

When connecting ultracapacitor modules to an application, a sufficient cross-section area of wires or bus-bars must be selected to withstand the application's current and adhere to the allowable voltage drop.