Instructions for Testing of Skeleton Technologies' Ultracapacitors

General testing considerations

Commonly, constant current testing is done within voltage range of 1.425V to 2.85V. Highest allowed current is 1 A/F, if not otherwise stated in the specifications. The maximum allowed application temperature is +65ºC as higher temperature may damage the ultracapacitors. Rated voltage (V_r = 2.85V) should not be exceeded and polarity must not be reversed.

Application temperature

The application temperature range for Skeleton ultracapacitors is -40ºC to +65ºC.

Capacitance

For capacitance estimation, constant current charge-discharge cycles are measured within voltage range of 2.85V to 1.425V at an applied current of 10mA/F (**Figure 1**). The testing temperature for rated capacitance estimation is 23ff12ºC. For other testing temperatures, climatic chamber should be used and temperature stabilization allowed for several hours.

Example: for 500F ultracapacitor the charge-discharge current is 0.010A/F × 500F = 5.0A.

The capacitance value is calculated from the discharge cycle according to equation:

$$C = \frac{I \times (t_2 - t_1)}{V_1 - V_2}$$

Capacitance measurement

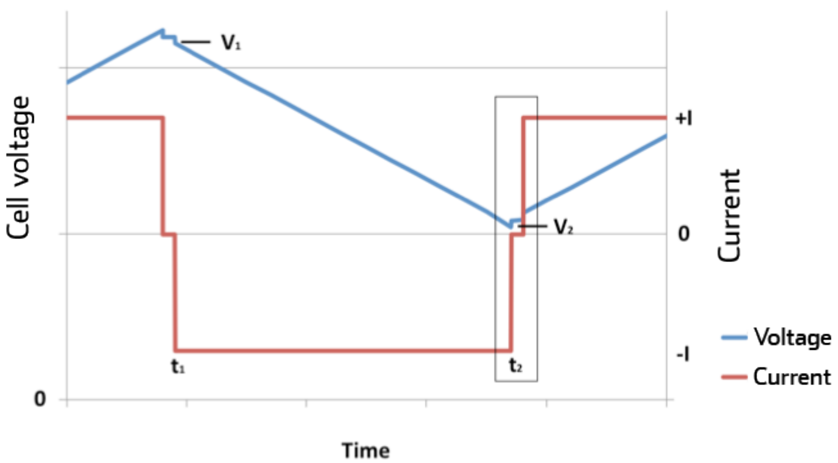

Figure 1. Constant current charge/discharge profiles for capacitance and ESR estimation.

Internal resistance (electrochemical series resistance, ESR)

Ultracapacitor ESR estimation is complicated by the fact that voltage is influenced by both the resistance and the capacitance of the device. Additionally charge redistribution effects occur due to the restricted electrolyte mobility inside the electrode porosity and the accompanying uneven surface charge regions. Both DC (direct current) and AC (alternating current) based electrochemical testing methods are widely applied for estimation of ESR. Different testing methods result in useful information from specific application point of view. International testing standards exist (e.g., IEC62391), indicating suggested testing methods according to applications. However, ultracapacitor producers often present ESR values obtained by adaptations of testing methods according to equipment limitations and preferred testing techniques.

DC methods for estimation of ESR

The ESR values for an ultracapacitor can be determined from the abovementioned constant current charge-discharge cycles measured at 10 mA/F. After discharge, the spontaneous rise in voltage is monitored during a current-cut period of 1 second (**Figure 2**).

The "DC 10ms ESR" and "DC 1s ESR" are determined according to equations:

$$ESR_{DC,10ms} = \frac{V_3 - V_2}{I}$$

$$ESR_{DC,1s} = \frac{V_4 - V_2}{I}$$

where V_2 is 1.425 V, V_3 is measured at t_3 = 0.01s after current-cut and V_4 is measured at t_4 = 1s after current-cut.

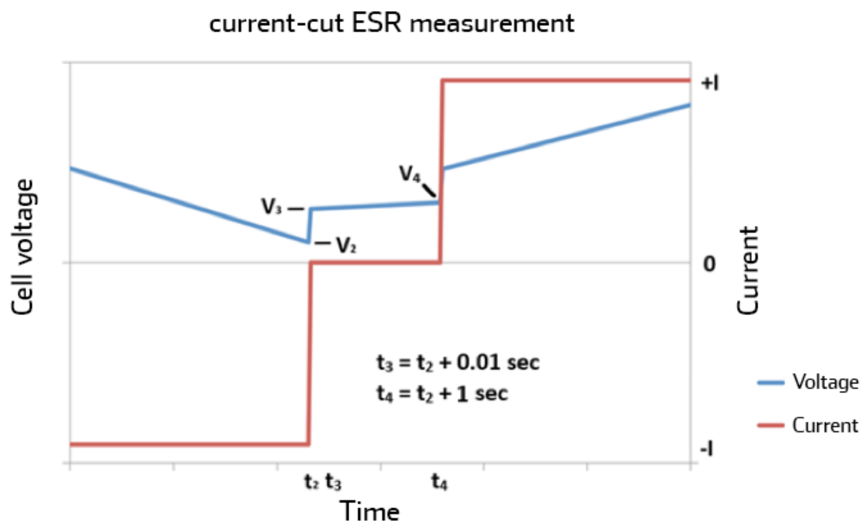

Figure 2. *Inset of constant current discharge profile section in Figure 1 for ESR estimation.*

Depending on the testing equipment limitations, another DC method can be used for estimating the "DC 10ms ESR", where 10 continuous DC current pulses of 10ms duration are generated and the voltage response is monitored (**Figure 3**). Typically 10mA/F pulse current value is applied*.

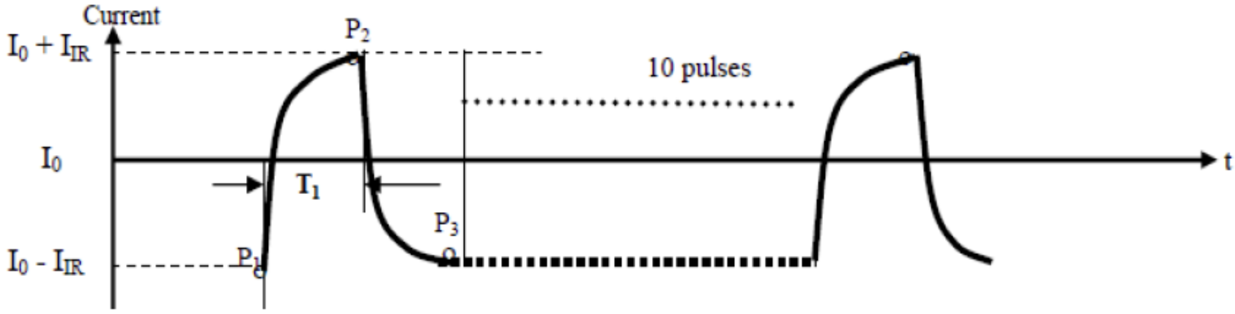

Figure 3. Current pulse measurement profile for nominal ESR estimation.

The "DC 10ms ESR" is calculated according to equation:

$$ESR_{DC,10ms} = \text{average}\left(\frac{\text{voltage at } P_2 - \text{voltage at } P_3}{2I}\right)$$

Detailed description of the current pulse method is available in Arbin instrument manual:

http://www.arbin.com/images/support/downloads/MITS4_3_Rev7_Manual.pdf

* If ultracapacitor has very low resistance, then up to 100 mA/F pulse current should be used. Different current pulses should be tested to evaluate the equipment accuracy for this test – same ESR value should be obtained from pulses of different current. If lower current pulse gives different value, then higher current should be selected.
Either of the "DC 10ms ESR" methods are acceptable for the performance testing.
Note: If pulse method is chosen for "DC 10ms ESR" estimation, the order of measurements is the opposite to current-cut measurements. Nominal ESR should be measured after measuring the "DC 1s ESR" (t_4 in **Figure 2**).

IEC62391 method for estimation of ESR

The IEC62391 standard based method for estimation of ultracapacitor ESR is described in the respective standard documentation:

https://webstore.iec.ch/publication/23581

Energy

The stored energy (E_{stored}) is calculated from the rated voltage (V_r) and the capacitance (C):

$$E_{stored} = \frac{\frac{1}{2} C V_r^2}{3,600}$$

Maximum specific energy (Wh/kg) and energy density (Wh/L) are determined by dividing the stored energy value by the ultracapacitor mass or volume.

Power

The power performance of the ultracapacitor is estimated from the rated voltage (V_r) and the internal resistance (ESR). The maximum power (P_{max}) is calculated according to equation:

$$P_{max} = \frac{V_r^2}{4 \times ESR}$$

Maximum specific power (kW/kg) and power density (kW/L) are determined by dividing the maximum power value by the ultracapacitor mass or volume.

Self-discharge

Self-discharge is spontaneous process of voltage loss during a specified period when a capacitor has been set to open-circuit condition after charging. Self-discharge is estimated by charging the capacitor with a 10 mA/F current to the rated voltage (2.85V), keeping this constant voltage during 2 hours, after which the current is interrupted and the cell is kept at ambient temperature. After 72 hours, the open circuit voltage is measured. The decay in voltage (V_r -V_{72h}) is the characteristic self-discharge.

Leakage current

Leakage current of ultracapacitor is specified as the current needed for maintaining the ultracapacitor at rated voltage (2.85V) at 23ffl2°C (if not specified otherwise). Leakage current is estimated by charging the ultracapacitor with a 10 mA/F current to the rated voltage (2.85V), or another fixed voltage, and by keeping this constant voltage over a period of 72h, during which the leakage current declines to a steady-state value. The measured value at 72h is the characteristic leakage current.

Thermal

Thermal resistance (R_{th}) is calculated according to equation:

$$R_{th} = \frac{\Delta T}{ESR \times I^2}$$

ΔT is the case-to-ambient temperature difference at applied current I. ESR is the total resistance at applied current I. ΔT should be measured at constant ambient temperature and with minimal air flow to avoid cooling by convection. The cell should be suspended in air from the cell's terminal ends to avoid cooling by conduction.

The maximum application current for a specified rise in temperature (ΔT) can then be calculated from the following equation:

$$I_{max} = \sqrt{\frac{\Delta T}{ESR \times R_{th}}}$$

Thermal capacitance (C_{th}) is determined from the ratio of energy emitted as heat during cooldown (I = 0A) from a stabilized temperature reached during cycling at I, and the cell's temperature difference before and after cooldown.