APPLICATION NOTE 1007239

Test Procedures for Capacitance, ESR, Leakage Current and Self-Discharge Characterizations of Ultracapacitors

Maxwell Technologies, Inc.
June 2015

Maxwell Technologies, Inc.
Global Headquarters
3888 Calle Fortunada
San Diego, CA 92123
USA
Phone: +1 (85)8 503-3300
Fax: +1 (858) 503-3301

Maxwell Technologies SA
Route de Montena 65
CH-1728 Rossens
Switzerland
Phone: +41 (0)26 411 85 00
Fax: +41 (0)26 411 85 05

Maxwell Technologies GmbH
Leopoldstrasse 244
80807 München
Germany
Phone: +49 (0)89 4161403 0
Fax: +49 (0)89 4161403 99

Maxwell Technologies Korea Co., Ltd
Room 1524, D-Cube City
Office Tower, 15F #662
Gyeongin-Ro, Guro-Gu,
Seoul, South Korea, 152-706
Phone: +82 10 4518 9829

Maxwell Technologies
Shanghai Trading Co., Ltd
Unit A2BC, 12th Floor
Huarun Times Square
500 Zhangyang Road, Pudong
Shanghai 200122, P.R. China
Phone: +86 21 3852 4000
Fax: +86 21 3852 4099

Maxwell Technologies
Shanghai Representative Office
Unit B 12th Floor
Huarun Times Square
500 Zhangyang Road, Pudong
Shanghai 200122, P.R. China
Phone: +86 21 3852 4000
Fax: +86 21 3852 4099

1. Introduction

A capacitor is an electronic device which can store energy in the electrical field between two conductors ("plates"). Ultracapacitors, or electric double layer capacitors (EDLC), are electrochemical capacitors which have a very large energy density as compared to common capacitors. The large energy density is due to the enormous surface area created by the porous carbon electrodes and the small charge separation created by the dielectric separator.

An ideal capacitor is characterized by a single constant value, capacitance, which is the ratio of the electric charge on each conductor to the potential difference between them. In reality, we measure the integral average value,

$$C = \frac{\partial Q}{\partial U} \text{ or } C = \frac{I\Delta t}{\Delta U} \text{ (if the current is a constant value)} \quad (1)$$

The amount of energy stored in the capacitor is given by

$$E = \frac{CV^2}{2} \quad (2)$$

In practice, the dielectric between the plates passes a small amount of leakage current which will cause the voltage decay of a charged ultracapacitor over time. The conductors, leads and other factors introduce an equivalent series resistance (ESR). Capacitance, ESR and leakage/self-discharge are the three of the major parameters used to evaluate an ultracapacitors performance as an energy storage device; they characterize the capability to store the electrical charge (energy), the efficiency during charge/discharge, and the ability to hold the energy after charge.

2. Capacitance and ESR Characterization Test – Maxwell 6-Step Process

The measured capacitance and ESR values of an ultracapacitor depend on different test conditions, such as frequency, current, temperature, voltage, humidity, etc. The capacitance and ESR dependency on the frequency is tested by an impedance test. The test method discussed in this article is for a DC application only.

There are various methods to test, measure and calculate capacitance and ESR, but all methods are based on the same assumption: that the ultracapacitor can be represented by a simple RC equivalent circuit described in the following picture.

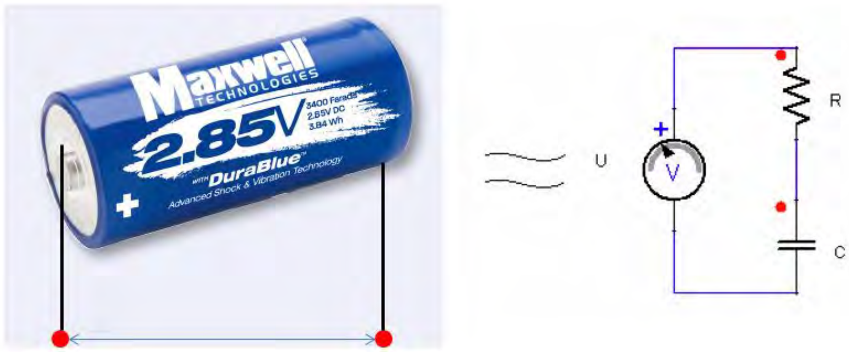

Figure 1. RC equivalent circuit of an ultracapacitor

Where the voltage measured between the two terminals of the ultracapacitor:

$$V = V_C + V_R \qquad (3)$$

Therefore, during constant current charge and discharge:

$$V = V_C + I * R \qquad (4)$$

$$R = \frac{V - V_C}{I} \qquad (5)$$

At open circuit, the measured ultracapacitor voltage:

$$V = V_C \qquad (6)$$

The capacitance value for certain constant current can be derived from equation (1):

$$C = \frac{I * \Delta t}{(V_{measure\_end} - V_{measure\_start})} \qquad (7)$$

The formulas listed above hold the principles of capacitance and ESR test and calculation.

There are four factors to be considered in the design of the test cycle for capacitance and ESR characterizations:

- How to charge and discharge the ultracapacitor?
- What to do between charge and discharge: hold (keep charging to the given voltage) or rest (open circuit) and for how long?
- At what voltage to start and end the charge/discharge?
- At which points to do the measurement?

We know from equation (2) that when the voltage of the ultracapacitor drops to one-half of the rated voltage there is only 25% of the energy stored remaining. For this reason the common operational voltage range for an ultracapacitor is from rated voltage to one-half rated voltage. During characterization testing the charge/discharge steps have to at least include the range from rated voltage to one-half rated voltage. Compared to open circuit, holding the charge of the ultracapacitor at the rated voltage before discharge provides higher capacitance value. At very slow charges, the ions can travel to the deeper pores inside the electrode which additionally contributes to the measured capacitance value. There are more applications which rest between charge and discharge than which hold the charge. In real applications, the purpose of holding the voltage is to compensate for the leakage of the ultracapacitor to maintain the voltage level, not to increase the capacitance to store more energy. Therefore the benefit of holding the voltage during the test to achieve a higher capacitance measurement value is insignificant.

Considering the above facts and principles, as well as the efficiency and cost involved in the production line, Maxwell Technologies uses a constant current test method for capacitance and ESR characterization for all ultracapacitor products, single cells and modules. We call this test method the 6-step process.

The following steps describe the 6-step process Maxwell Technologies uses for measuring the capacitance and ESR of ultracapacitors and modules:

Test Considerations:

- Short circuit the cell at least one hour before the test
- Rest cells for more than 4 hours between different tests
- If using a temperature-controlled chamber for tests, then the cell should stay in the chamber at the test temperature for a suitable soak period for thermal equalization (6 hours is recommended for the Maxwell cells).

Test Equipment:

- Bitrode Test System or any other test system which can be used to charge and discharge ultracapacitors with test cycle programming and data acquisition capabilities
- Temperature controlled chamber if testing at any environment other than room temperature

Test Temperature:

- Room temperature 23°C ± 2°C
- Tests carried out at other temperatures should be performed in a temperature controlled chamber

Test Current:

- One constant current value for charge and discharge, current rate at about 100mA/F, refer to Table 1. Maxwell Baseline Test Current
- Different current within the maximum limit specified by the test equipment manufacturer can be applied to the test.

Table1. Maxwell Baseline Test Current

Product	Nominal Capacity (F)	Rated Voltage (V)	Current (A)	Test Current
BCAP25	25	2.7	2.5	2.5
BCAP50	50	2.7	5.0	5
BCAP310	310	2.5	31.0	31
BCAP350	350	2.5	35.0	35
BCAP650	650	2.7	65.0	65
BCAP1200	1200	2.7	120.0	100*
BCAP1500	1500	2.7	150.0	100*
BCAP2000	2000	2.7	200.0	100*
BCAP3000	3000	2.7	300.0	100*
BCAP3400	3400	2.85	340.0	100*

*Limitation of the production test equipment

Test Process:

Step 1. Rest (Open Circuit)
- 10 seconds
- Record test time, test current and test article's voltage at end of the rest **(t1, I1, V1).**

Step 2. Charge
- Charge device to its rated voltage at specified current.
- Record test time, test current and test article's voltage at end of the rest **(t2, I2, V2).**

Step 3. Rest (Open Circuit)
- 5 seconds
- Record test time, test current and test article's voltage at end of the rest **(t3, I3, V3).**

Step 4. Rest (Open Circuit)
- 10 seconds
- Record test time, test current and test article's voltage at end of the rest **(t4, I4, V4).**

Step 5. Discharge
- Discharge device to one-half its rated voltage at its specified current.
- Record test time, test current and test article's voltage at end of the rest **(t5, I5, V5).**

Step 6. Rest (Open Circuit)
- 5 seconds
- Record test time, test current and test article's voltage at end of the rest **(t6, I6, V6).**

Step 7. Discharge module to a low safe voltage (<0.1V) and end test after the second cycle
- This step is not part of the measurement. It is for safety only.

The 6-step process is executed twice as described in the picture below:

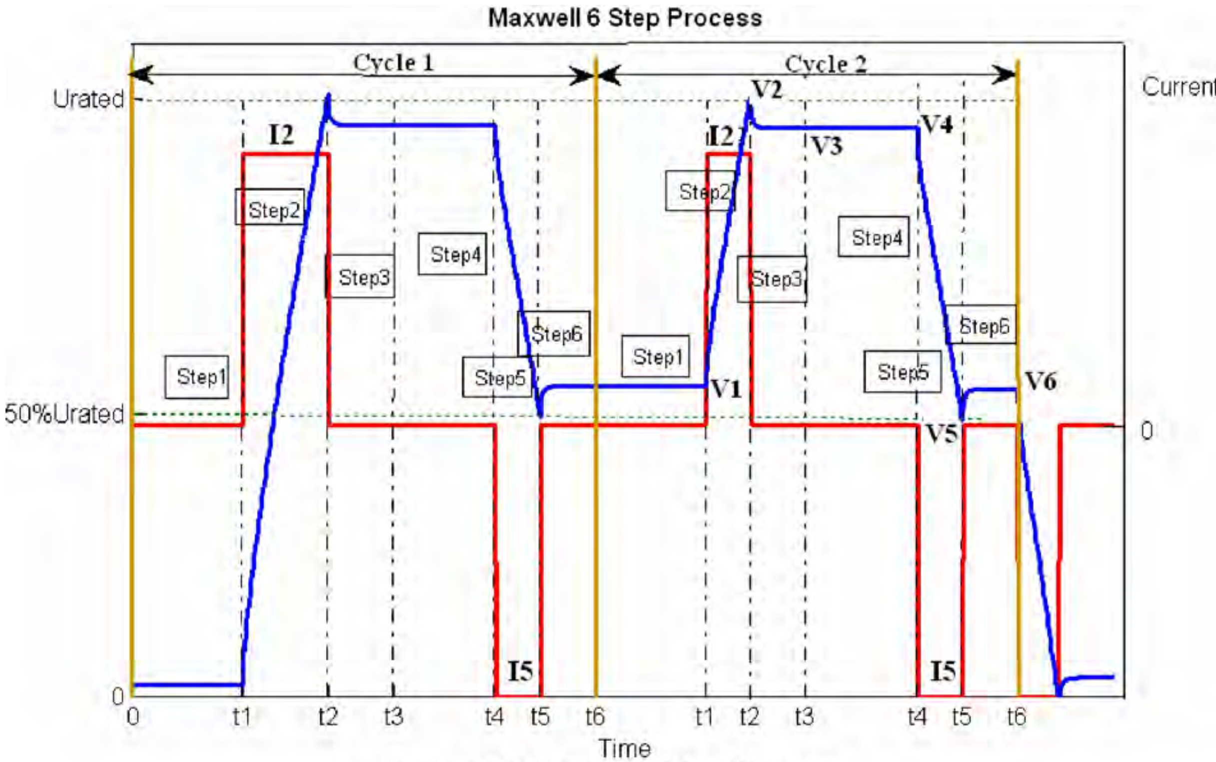

Figure 1: Maxwell 6 Step Process

Parameter Calculation:

The results of the second cycle are used to calculate the capacitance and ESR with the following formulas. The first cycle data are not used because the cell has not been activated and the measured capacitance and ESR values are different compared to the second cycle and the cycles after.

- $C_{ch} = \frac{I_2 * (t_2 - t_1)}{V_2 - V_1}$ (or $C_{ch} = \frac{I_2 * t_2}{V_2 - V_1}$ if t_2 is the step time of step 2)
- $R_{ch} = \frac{V_2 - V_3}{I_2}$
- $C_{dch} = \frac{I_5 * (t_5 - t_4)}{V_5 - V_4}$ (or $C_{dch} = \frac{I_5 * t_5}{V_5 - V_4}$) if t_5 is the step time of step 5)
- $R_{dch} = \frac{V_5 - V_6}{I_5}$
- The calculated C_{dch} and R_{dch} are used as the capacitance and ESR values by Maxwell Technologies.

3. Test Method for Leakage Current

The leakage current is the charging current required to maintain the ultracapacitor at the specified voltage value. The longer the ultracapacitor is held at voltage, the lower the leakage current of the ultracapacitor. The measured result will be influenced by the temperature, the voltage at which the device is charged, the test history of the device and the aging conditions. The leakage current reported in Maxwell Technologies datasheets is the value of the charging current required to maintain rated voltage after holding the ultracapacitor at rated voltage for 72 hours at room temperature. The measurement is taken immediately at the end of the 72-hour period.

The following steps describe the process Maxwell Technologies uses for measuring leakage current.

Test Temperature:

- Room temperature 23°C ± 2°C
- Tests carried out at other temperatures should be performed in a temperature controlled chamber

Test Equipment:

- Power supply equipment which can be used to charge ultracapacitors
- Data acquisition unit
- 1Ω, precision resistor R_{ext}

Test Setup:

- Connect R_{ext} in series with the ultracapacitor to be tested
- Connect the positive terminal of the Voltage Power Supply to the positive terminal of the cell
- Connect the negative terminal of the Voltage Power Supply to the negative terminal of the cell
- Connect the positive terminal of the Data Acquisition Unit to the positive side of R_{ext}
- Connect the negative terminal of the Data Acquisition Unit to the negative side of R_{ext}
- Install jumper across R_{ext} to expedite the charge cycle before the 72 hours' hold

Charge Current:

- The charge current should be within the maximum current limit of the ultracapacitor
- Suggested current, refer to Table 1 Maxwell Baseline test current

Test Procedure:

- Charge cell/module to the rated voltage
- Hold voltage for one hour
- Remove the jumper across R_{ext}
- Continue to hold voltage for 72 hours
- Measure and record the voltage of R_{ext}

Parameter Calculation:

- Leakage Current (A) = $\frac{V_{ext}}{R_{ext}}$

Table 2. Maxwell Production Cell Maximum Leakage Current

Product	Nominal Capacitance (F)	Leakage Current Maximum (mA)
BCAP25	25	0.045
BCAP50	50	0.075
BCAP310	310	0.45
BCAP350	350	0.3
BCAP650	650	1.5
BCAP1200	1200	2.7
BCAP1500	1500	3.0
BCAP2000	2000	4.2
BCAP3000	3000	5.2
BCAP3400	3400	15.0

4. Test Method for Self-Discharge

The self-discharge test is designed to see the natural decay of the ultracapacitor voltage over time after it is fully charged to a certain voltage. The measured result will be influenced by the temperature, the voltage at which the device is charged, the test history and the aging condition. The typical test setup is to measure the voltage over 72 hours open circuit at room temperature after charging the ultracapacitor to the rated voltage. To ensure the ultracapacitor is completely charged it is necessary to hold the rated voltage for one hour.

The following steps describe the process Maxwell Technologies uses for measuring self-discharge.

Test Temperature:

- Room temperature 23°C ± 2°C
- Tests carried out at other temperatures should be performed in a temperature controlled chamber

Test Equipment:

- Power supply equipment which can be used to charge ultracapacitors
- Data acquisition unit

Charge Current:

- The charge current should be within the maximum current limit of the ultracapacitor
- Suggested current, refer to Table 1 Maxwell Baseline test current

Test Procedure:

- Charge cell/module to the rated voltage
- Hold voltage for one hour
- Open circuit the cell/module 72 hours
- Measure and record the voltage of cell/module

Parameter Calculation:

- Self-discharge (Volts) = $abs(V - V_0)$ if reported as absolute charge
- Self-discharge (%) = $abs(100 \times \frac{V - V_0}{V_0})$ if reported as percent of voltage charge

5. Conclusions

The test methods for leakage current and self-discharge are consistent industry wide. However, there are various methods for capacitance and ESR characterization. Compared to other capacitance and ESR testing methods (such as IEC62391 and EUCAR), the Maxwell 6-step process has the following advantages:

- The Maxwell 6-step process requires less test time, which makes it more efficient for a production line environment. Other test methods use a holding period between charge and discharge, which makes the test time longer and inefficient in a production line environment.
- The Maxwell 6-step process requires that you record only the end of value of each step. The calculation is simple to manage as compared to other methods.
- The Maxwell 6-step process can measure capacitance and ESR from low to high current for small cells to large modules. Some of the other calculation methods cannot be used to compute ESR at low current.
- The Maxwell 6-step process determines both Capacitance and ESR values in one approach. Other methods use different approaches to measure capacitance and ESR.
- The Maxwell 6-step process provides capacitance and ESR values for both charge and discharge where other methods provide the values for discharge only.

The Maxwell 6-step process has been used for many years at Maxwell Technologies' test labs and production lines, and provides accurate and reliable results.