Study of Supercapacitor in the Application of Power Electronics

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Abstract: - The purpose of this paper is to carry out a comprehensive study of supercapacitor in the application of power electronics. According to the practical demand and feasibility of power electronics, the modelling, voltage management and topology of supercapacitor-based power system have been discussed. Further more, in order to study the terminal behaviour of supercapacitor and voltage balancing strategy for the application of power electronics, a test bench based on HP-VEE has been built. The measurements on supercapacitor's capacitance, ESR (Equivalent serial resistance) and the consistency of a group of serial supercapacitors, concerning practical application have been suggested. As an example, Maxwell's BCAP0120 supercapacitors have been selected for a 1.5kW hybrid supercapacitor- fuel cell power system. Tests have been carried out and the results show that the ESR is higher and the capacitance is lower compared with the values supplied by manufacturers; and the consistency of them is good, thus the voltage initialization strategy can be used for voltage balancing.

Key-Words: - Supercapacitor, Power Electronics, Voltage-balancing, Capacitance, ESR

1 Introduction

Supercapacitor is a kind of electrical energy storage device. The advantages of supercapacitor are high power density, high efficiency, fast charging and discharging speed, long cycle life, wide operating temperature range and environment friendly. It has become an ideal option for high-power applications, such as hybrid power systems, regenerative energy systems and instantaneous back-up power source [1-2].

When designing a supercapacitor-based power system, building a proper model for supercapacitor, taking the appropriate methodology of voltage management, choosing a right topology of power system, and knowing the dynamic terminal behaviour are very important factors for the performance of power system. Power electronics device, such as DC/DC converter, is an indispensable part for the power system.

In power electronics applications, we concern more about the dynamic parameters of supercapacitors for they are often used for high duty cycle applications. Regarding that parameters on data sheet supplied by manufacturers are the static value. Hence, a supercapacitor testing method is needed in order to test the dynamic characteristic parameters.

Due to the low cell voltage of supercapacitor (0.9~3.3V), a series connection of supercapacitor cells is necessary to obtain higher voltage. However, the unequal distribution of cell voltage will affect the performance and lifetime of the cell. Reference [3] has recommended 37several voltage balancing strategies. Another way to overcome the problem is so-called Voltage initialization described by Okamura [4]. It has yet to be decided that the consistency of supercapacitors in order to choose a proper voltage balancing strategy.

The paper has carried out a comprehensive study of supercapacitor from the view of power electronics. Methodologies on modelling, voltage management and topology of supercapacitor-based power system have been discussed. A test bench based on HP-VEE has been built. Experiments on deciding the dynamic behaviour of supercapacitor and studying the consistency of supercapacitors for power electronics application have been carried out.

2 Supercapacitor Description

2.1 Principle of EDLC

Below the decomposition voltage, while the current does not flow, an electric double layer occurs at the boundary of electrode and electrolyte. The electrons are charged across the double layer and form a capacitor. Energy is stored in the double-layer capacitor as charge separation in the double-layer formed at the interface between the solid electrode material surface and the liquid electrolyte in the micro pores of the electrodes. Figure 1 shows the structure of electric double layer capacitor.

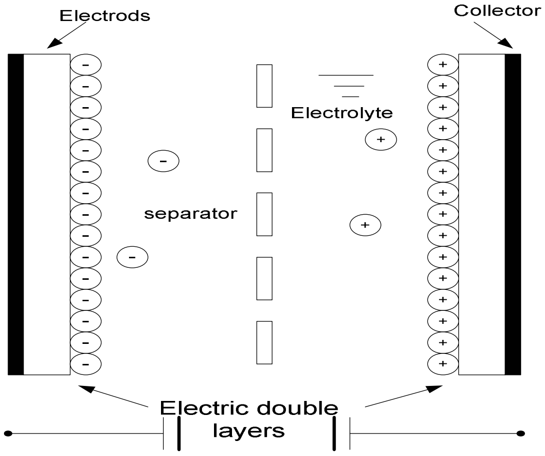

Fig. 1 Principle of a double layers capacitor

The electrodes are fabricated by high surface area, porous material having pores of diameter in the nanometre range. Charge is stored in the micro pores at or near the interface between the solid electrode material and the electrolyte. Double-layer capacitor electrodes have been fabricated using carbon black and carbon aero gel and carbon cloth.

There are two kinds of electrolyte: aqueous and organic electrolyte. Aqueous electrolyte, such as potassium hydroxide or sulfuric acid, has a much smaller resistance and thus a larger power density is easy to be obtained; Organic electrolyte based on propylene carbonate or acetonitrile whose ions are bigger, usually has higher resistance and smaller power density (but higher energy density due to the voltage used). Up to now, capacitor rated voltage with an aqueous electrolyte is about 0.9V per cell and with organic electrolyte is 2.3 to 3.3 V for each cell. When developing supercapacitors, the electrode material and electrolyte characteristics should be considered jointly and not separately.

The capacitance is dependent primarily on the characteristics of the electrode material (surface area and pore size distribution). The resistance of the supercapacitor cell is strongly dependent on the resistivity of the electrolyte used and size of the ions from the electrolyte that diffuse into and out of the pores of the micro porous electrode particles [5].

2.2 Recent development of supercapacitor

In terms of energy density, existing commercial electric double-layer capacitors range from around 0.5 to 10Wh/kg. Especially, the Okamura lab has developed the Nanogate capacitor[6] which is characterized by making pores in the carbon with the ions in the electrolyte solution which has an energy density of 20~60Wh/kg, while EEStor claims their examples will offer capacities on the order of 200 to 300Wh/kg. For comparison, a conventional lead-acid battery is typically 30~40Wh/kg, modern lithium-ion batteries are about 150~200Wh/kg.

The power density of supercapacitors in commercial use is around 4~7kW/kg, which is much higher than other energy-storage devices, for example 1.8kW/kg for lithium-ion batteries. High power density combined with long life cycle makes supercapacitors ideal devices for peak power application.

Maxwell (USA), NESSCap (koren), Panasonic (Japan), Epcos (Germany), ECOND (Russia), and NEC (Japan), Ao-wei (China), Shuangdeng (China) are main manufactures of supercapacitor. Saft (France), Batscap (France) Superfarad (Sweden), Okamura lab (Japan) have been doing research on supercapacitors.

Manufacturers, such as Maxwell, NessCap, Epcos, Econd, offer to sell supercapacitor module, which is a package of a group of supercapacitors in series and contains supercapacitor management equipment, giving much more feasibility in application.

3 Equivalent model for power electronics application

In the application of power electronics, an equivalent model which reflects the terminal behaviour of supercapacitors is desired in simulation with the purpose of further studying the characteristics of supercapacitor based power system.

3.1 RC serial model

The simplest equivalent model for EDLC is the RC serial model as shown in Figure 2 [7]. This method assumes ideal behaviour of supercapacitor and it neither reflects physical aspects, nor the influence of voltage or temperature on supercapacitors. However, this model can be applied in the low required precision.

Fig.2 RC Equivalent model

3.2 Three branch model

Another model shown as Figure 3 which is based on the physical aspects and the desire of practical engineering is proposed by reference [8].

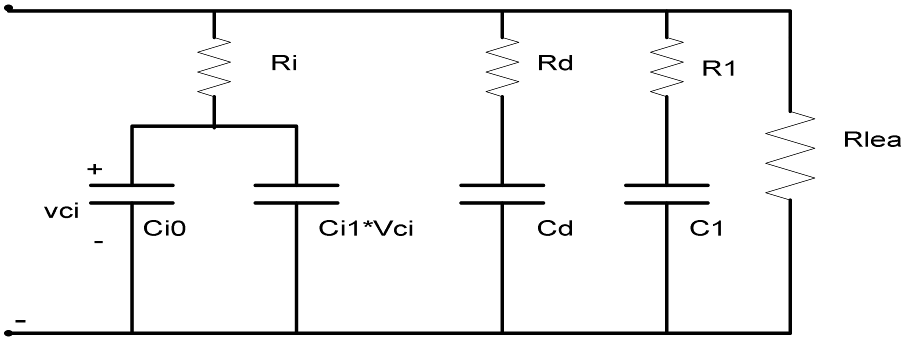

Fig.3 Three branch model

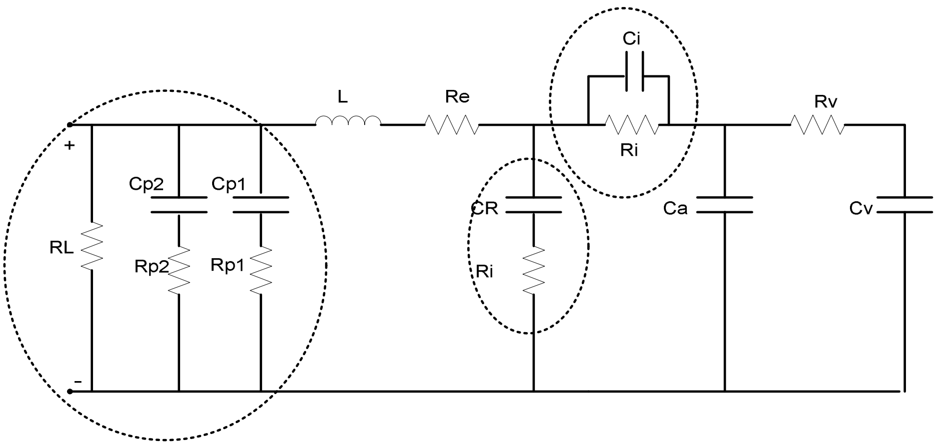

Fig.4 Time domain model

The model has three well distinct RC time constants covering the desired time range. Each of the three branches has a distinct time constant differing from the others in more than an order of magnitude which will result in an easily measurable model.

The first branch, with the elements R_i,C_{i0}, and the voltage-dependent capacitor C_{i1}(in F/V), dominates the immediate behaviour of the DLC in the time range of seconds in response to a charge action. The second branch, with parameters R_d and C_d, dominates the terminal behaviour in the range of minutes. Finally, the third branch, with parameters Rl and Cl, determines the behaviour for times longer than 10 minutes.

The equivalent circuit model reflects the physics of the double-layer charge distribution. First, the resistive element represents the resistivity of carbon particles. The capacitive element represents the capacitance between carbon and electrolyte. Second, the capacitance of the double-layer charge distribution depends on the potential difference across the material, and according to measurements, in the practical voltage range of the device, the DLC capacitance varies linearly with the capacitor terminal voltage. Third, double layer charge distribution shows self-discharge. It is possible to determine the parameters of the model using measurements at the DLC terminals which is very practical for engineering.

This model shows good agreement with experimental data and is possible for gaining the parameters. Reference [9] has added temperature influences to this model and making it an efficient way to study its application in power electronic circuits and automotive applications.

3.3 Time domain model

A model shown as Figure 4 which takes into account frequency, voltage and temperature dependencies of capacitance, series resistance, redistribution of electrical charges on the electrode surface and leakage current is proposed by [10]. It is also on the base of second model.

"Circuit 1" takes into account the electrolyte ionic resistance temperature dependence in the low frequency range. The parallel capacitance C_i has been used to cancel the contribution of $R_i(T)$ in high frequency range. For low frequency, the circuit 1 behavior is close to that of resistance $R_i(T)$. The relationship between R_i and the temperature can be established from experimental results by using EIS. "Circuit 2"is introduced to increase the value of capacitance of the average frequencies. Their behaviour is the one of a phase shifter.

"Circuit 3" describes the leakage current and the internal charge redistribution. The self discharge behaviour of supercapacitors is an important factor because it determines the duration time of stored energy on open circuit. The supercapacitor self-discharge is also a function of temperature. It is necessary to use two different time constant circuits RC by elements $R_{p1}C_{p1}$, $R_{p2}C_{p2}$ which depend on the voltage and on the operating temperature. It also includes a parallel R_L resistance, which gives the long time leakage current contribution.

It depends on the practical application to decide a proper model which meets the requirement. Generally speaking, the RC serial model can be used in a system with low precision; the three branch model is fit for the application which has requirement on dynamic characteristics; while the time domain model is often used for precise study. It is suggested that the three branch model is the most appropriate choice for power electronics applications.

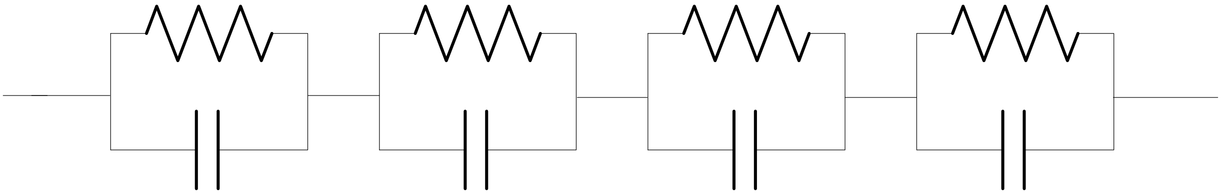

Fig.5 Passive Balancing

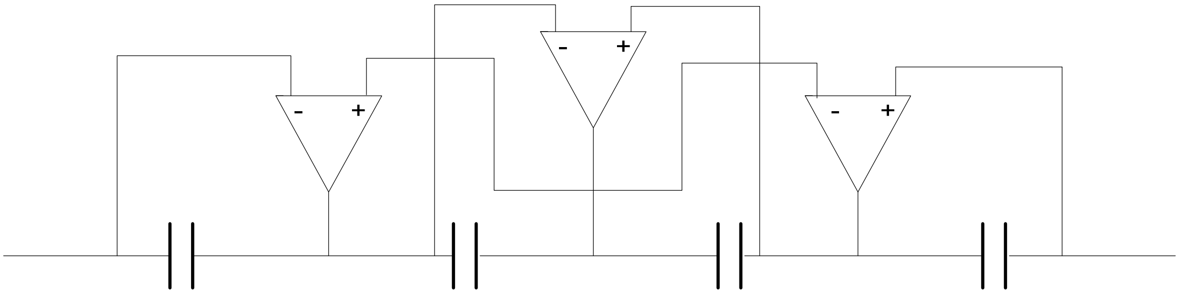

Fig.6 Active Balancing

4 Management of supercapacitor power systems

When connecting many capacitors in series, the issue of voltage balancing inevitably comes into play [11]. Basically there are two reasons for an imbalance of voltages in a serial string of supercapacitors: (i) deviations from the nominal capacitance of the capacitors and (ii) deviations in self discharge performance. While the first topic is mainly important during dynamic performance of the capacitor string, the latter topic dominates for static capacitor performance during constant voltage phases. A cell management circuit maximizes the performance and life of supercapacitors installed in series [12-14].

Generally speaking, there are two ways in voltage balancing, one is passive balancing, and the other is active balancing. Another way to overcome the problem caused by unbalance of voltage is so-called voltage initialization described by Okamura[4].

4.1 Passive balancing

A passive balancing system is designed to overwhelm the inherent variations in leakage current by installing a resistor in parallel with each other. The resistor is typically sized at 10 times the average leakage current of the cell. The benefits to this balancing method are simplicity and low cost. The drawback of this technique is slow response due to the linearity of leakage current with voltage and high parasitic losses due to the 10-time additional leakage current. Passive balancing is mainly used in low-duty cycle applications such as in backup power systems. Fig 5 shows a simple balancing network with resistors.

4.2 Active balancing

In contrast to passive solutions, an active balancing circuit behaves nonlinearly and works to force the cells to have an equal voltage, resulting in the most effective use of the supercapacitor string. Fig.6 shows a simplified diagram of an active balancing circuit incorporating a comparator. In this configuration, each circuit stretches across two cells, comparing their voltage and moving charge to equalize the two cells. A number of schemes are used to achieve active balancing and many are patented. Active balancing circuit is required in high duty-cycle applications and where low parasitic losses are necessary.

4.3 Voltage Initialization

The principle of voltage initialization is that all capacitors are balanced at the upper voltage limit of the capacitor module. As a consequence, when the module is discharged, the individual capacitors will adopt different voltages on a lower level. When recharged to the upper voltage, all the capacitors will be balanced again. Provided that the capacitances of individual capacitors change slowly with time, an occasional initialization of the module will keep the capacitors balanced at the upper working voltage. This is shown by Figure7.

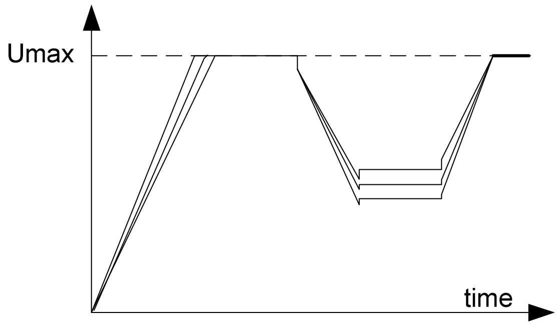

Fig.7 Principle of voltage initialization

This method is much more feasible and less expensive. Reference [15] has implemented it with an occasional initialization of all capacitors, which has achieved a nice result. However, it demands sound consistency and high quality of supercapacitor.

5 Topology of supercapacitor energy storage system

The terminal voltage of supercapacitor changes significantly when being charged or discharged. For this reason, a power electronics device —DC/DC converter is necessary to form a supercapacitor power system [16-18]. The non-isolated Buck-Boost bidirectional DC/DC converter shown as Figure 8 is the first choice for that. The advantage of this topology is high efficiency, high reliability, low power loss, less expensive and small in size.

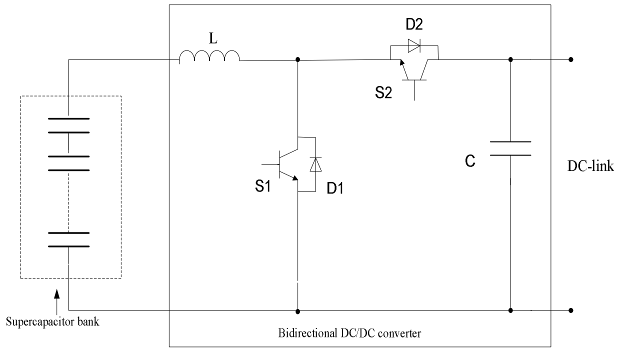

Fig.8 Supercapacitor energy storage system topology

This bidirectional Buck-Boost DC/DC converter allows the power transfer in both directions. This feature enables the process of charging and discharging through one unit. The current from the supercapacitor is fully controlled by bidirectional DC/DC converter, and the voltage of DC link is dependent on the control result of it. When charging the supercapacitor bank, the DC/DC converter works in Buck mode, and supplies a constant charge current. The power flows from DC-link to supercapacitor bank. When discharging, the DC/DC converter works in Boost mode, and keeps the voltage of DC-link constant. The power flows from supercapacitor bank to DC-link.

6 Supercapacitor measurement

Regarding that parameters on data sheet supplied by manufacturers are the static value. In power electronics applications, we concern more about the dynamic parameters of supercapacitors for they are often used for high duty cycle applications. Hence, a supercapacitor testing method is needed in order to test the dynamic characteristic parameters.

In this section, a test bench based on HP-VEE has been built firstly. Then, methods on testing supercapacitor’s capacitance, ESR (Equivalent serial resistance) and the consistency of a group of serial supercapacitors, concerning practical application have been suggested. As an example, Maxwell’s BCAP0120 supercapacitors have been tested for a project which was to build up a hybrid supercapacitor-fuel cell power system of 1.5kW.

6.1Review of testing methods for supercapacitors

Currently, electrochemical impedance spectroscopy (EIS) and constant current charge and discharge are two main ways in research of supercapacitors. EIS is used to characterize electrode material for supercapacitors in frequency domain, and professional electrochemical equipment is required for doing this test [19-21]. However, for power electronics applications, we concern more about the terminal behaviour. Hence, constant current charge and discharge is used for this study.

6.2 Test bench based on HP-VEE

The test bench is based on HP-VEE, which is a graphical programming language optimized for designing test and measurement applications, and programs with operator interfaces. Through HP-VEE, we can design a test procedure; communicate with test equipment over a general purpose interface bus (GPIB), and record data of measurements. Table 1 shows the main equipment for building this test bench.

Table 1: Equipment for building the test bench.

Equipment	Parameters
Programmable DC electronic Load: Chroma 6310	Current 0~40A, voltage 0~80V, resolution 1mA/10mV
Programmable Power Source : ITech 6121	Current 0~40A, voltage 0~80V, resolution 1mA/10mV
Agilent34970A	Data Acquisition Unit, 61/2-digit multimeter accuracy

Measurements have been done on a Maxwell Technologies BCAP0120 supercapacitor, with a nominal capacitance of 120F, ESR of 5mhom, and a rated voltage of 2.5V. Figure 9 shows the test bench.

Fig9. Test bench for terminal behavior

6.3 Terminal behavior tests

6.3.1 Scheme design for measuring Capacitance and ESR

The capacitance of supercapacitor is voltage-depended, and it is also affected by discharging current when the initial voltage is the same. Generally speaking, the step of measurement is to keep the supercapacitor at rated voltage for 30~60 minutes, and then discharge it by a constant current I, and the value of capacitance and ESR is calculated by the following formulas:

$$C = I \cdot \Delta t / \Delta U \tag{1}$$

$$ESR = \Delta U / I \tag{2}$$

Among which,

C— the capacitance at rated voltage；

I—the constant discharge current；

ΔU—the absolute value of voltage variation during Δt；

ΔV—the voltage leap occurred at the instant when a discharge current is applied or taken out.

According to technique guide of manufacturers, Necsscap chooses a $\Delta U=(0.7\sim0.3)U_{rated}$ with discharge current at 1mA/F[21]; EUCAR—an European association of vehicle manufactures—choose a $\Delta U=(0.6\sim0.4)\ U_{rated}$ with discharge current at 5mA/F[22]; Maxwell choose a $\Delta U=(1\sim0.5)\ U_{rated}$ with discharge current at 1mA/F[23].

The above scheme of measurement is to test the static characteristics of supercapacitor. The procedure of keeping voltage constant and discharging by a small current has given enough time for the ions from the electrolyte to diffuse into and out of the pores of the micro porous. However, in practical power electronics applications, supercapacitors are often used for supplying high power, which means a very large current, often hundreds of ampere , will pass though it. Thus, there is not enough time for ions' diffusing, which will lead to a smaller dynamic capacitance. This dynamic capacitance will affect the performance of the power system.

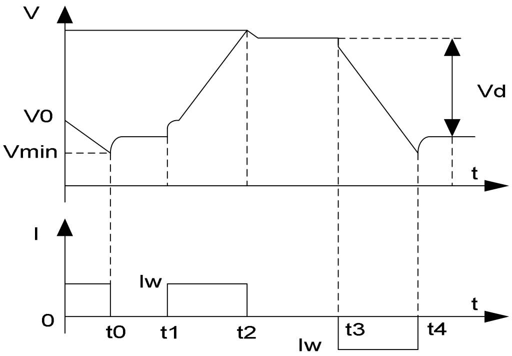

Fig10. Procedure of Measurement for Capacitance and ESR

From the above discussion, the scheme of measurement for supercapacitor considering practical operation situation such as duty cycle, and charging current is suggested by the author. A testing procedure, which is shown by figure 10, is proposed as follows:

1st. From 0 to t_0, discharge supercap to V_{min} with current I_w.

2nd. From t_0 to t_1, set I=0;

3rd. From t_1 to t_2, charge supercap to V_{max} at I_w;

4th. From t_2 to t_3, set I=0 for a period, record the voltage at t_3;

5th. From t_3 to t_4, discharge supercap to V_{min} at constant current I_w;

6th. From t_4 to t_5, set I =0 for a period, record the voltage at t_5;

7th. Repeat this cycle for 10 times and calculate the average value.

Calculation

$$C = I_w \cdot (t_4 - t_3) / V_d \qquad (3)$$

$$ESR_{DC} = (V_{t5} - V_{t4}) / I_w \qquad (4)$$

V_d is the V_{t3} minus V_{t5}.

I_w is the rated current of supercapacitor in practical application. V_{max} is the rated voltage of supercapacitor in practical application. The cycle of charging and discharging is the rated duty cycle in practical application.

6.3.2 Consistency Test for a group of supercapacitors

The purpose for this test is to check the consistency of the selected supercapacitors in order to choose a proper voltage-balancing strategy.

Cycling test was carried out to test the consistency of supercapacitors. Three BCAP0120 supercapacitors in serial connection were tested. This test is to check the voltage change of each cell after voltage initialization in long term cycle. The test consists of two parts:

Test I: balance each cell at 2.45V, charge the capacitor group with I_{charge} that equals 2A, discharge them with $I_{discharge}$ that equals 4A, and last for 7 hours.

Test II: change the current, with I_{charge} that equals 4A, $I_{discharg}$ that equals 10A, and last for 7 hours.

6.4 Test Results and Analysis

Based on this test bench, measurements were carried out for a project which was to build up a hybrid supercapacitor-fuel cell power system of 1.5kW. Supercapacitor BCAP120 of Maxwell was chosen. The following is the test result.

6.4.1 Capacitance and ESR

The application of the power system requires a rated current I_w of 20A, and rated voltage of 2.3 V for a single cell. According to former principle, three supercapacitors were carried out. Table 2 shows the test result. From the above result that the capacitance is lower and the ESR is larger than that of the value on the datasheet.

Table 2. Test result of capaciatance and ESR

BCAP0120/num	1	2	3
Capacitance/F	110	115	113
ESR/mohm	5.2	5.3	5.5

6.4.2 Cycling test result