Investigation of Supercapacitor Terminal Behavior for Power Electronics Applications

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Abstract: - The paper treats an experimental study of supercapacitors for power electronics applications. When designing a supercapacitor-based power system, the terminal behavior of supercapacitor and voltage balancing strategy are two important factors to be considered. In order to study this, a test bench based on HP-VEE has been built firstly. Then, 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.

Keywords: - 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/discharging,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, two important factors should be concerned. One is the dynamic characteristic parameters and the other is the voltage-balancing strategy for a group of serial connected supercapacitors.

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.

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 several 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.

In this paper, a test bench based on HP-VEE has been built. Experiments on deciding the dynamic behavior of supercapacitor and studying the consistency of supercapacitors for power electronics application have been carried out.

2 Building of Test bench

2.1 Review 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 [5-6]. However, for power electronics applications, we concern more about the terminal behavior. Hence, constant current charge and discharge is used for this study.

2.2 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 I shows the main equipment for building this test bench.

Table I: Equipment for building this 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/Switch 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. Fig1 shows the test bench.

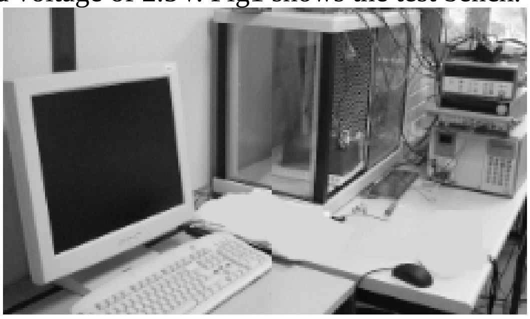

Fig1. Test bench for terminal behavior

3. Terminal behavior tests

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:

$$C = I \cdot \Delta t / \Delta U \qquad (1)$$

$$ESR = \Delta U / I \qquad (2)$$

Among which,

C— the capacitance at rated voltage;

I—the constant discharge current;

⊿U—the absolute value of voltage variation during ⊿t;

⊿V—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 ⊿U=(0.7~0.3)U_{rated} with discharge current at 1mA/F[7]; EUCAR—an European association of vehicle manufactures—choose a ⊿U=(0.6~0.4) U_{rated} with discharge current at 5mA/F[8]; Maxwell choose a ⊿U=(1~0.5) U_{rated} with discharge current at 1mA/F[10].

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.

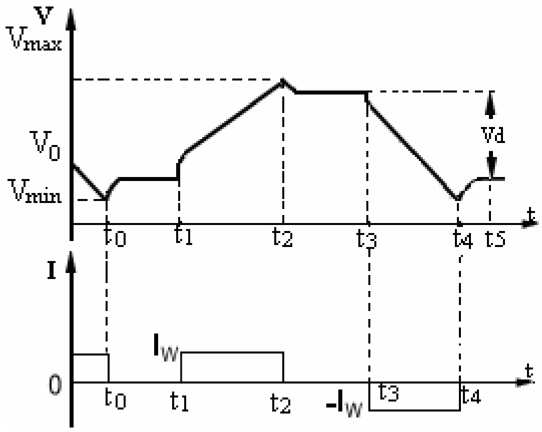

Fig3. Procedure of Measurement for Capacitance and ESR

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 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

$$C = I_w \cdot (t_4 - t_3) / V_d \tag{3}$$

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

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.

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. Reference [3] has an analysis and evaluation on the charge-balancing circuits. However, these circuits are either efficiency-lacking, or costly and of less reliability.

Another way to overcome the problem caused by unbalance of voltage is so-called Voltage Initialization described by Okamura [4]. According to the principle, 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 Fig4.

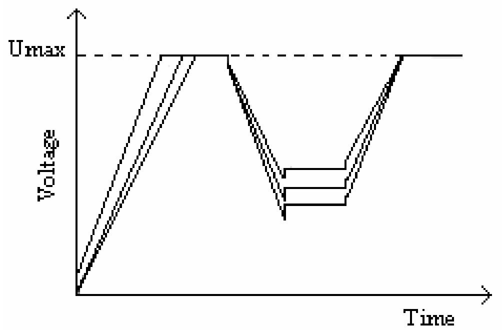

Fig.4 Principle of voltage initialization

This method is much more feasible and less expensive. Reference [9] 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.

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.

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.

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 II 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 II. Test result of capaciatance and ESR

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

4.2 Cycling test result

Fig.5 shows the voltage variation of the cell in test I (V1, V2, V3 is the terminal voltage of supercapacitor). During the whole cycle, the voltage deviation of each cell is less than 0.1V, and doesn't change with time. The largest voltage variation is between V1and V3 caused by the difference of ESR. Fig.6 is the enlarged view of V1, V3 and (V1-V3). We can see that, voltage variation is bigger when charging and discharging, and it is smaller when cell voltage reaches the initialized value.

Fig.7 shows the voltage deviation of the cell in test II, and the maximum voltage deviation is less than 0.2V, which is also a constant with time. The largest voltage variation is between V1and V3. Fig.8 is the enlarged view of V1, V3 and (V1-V3).

The voltage variation is bigger when charging and discharging, and smaller when cell voltage reaches the initialized value. However, voltage deviation of test II is larger than that of test I, resulted of higher discharging current.

From the result, we can conclude that the voltage variation among cells after voltage initialization has relationship with charge and discharge current and the initialized voltage. There is no apparently voltage change in long time cycle, which means the BCAP0120 supercapacitors show good consistency during cycling. Hence, an occasional voltage initialization of all capacitors can be adopted for voltage management.

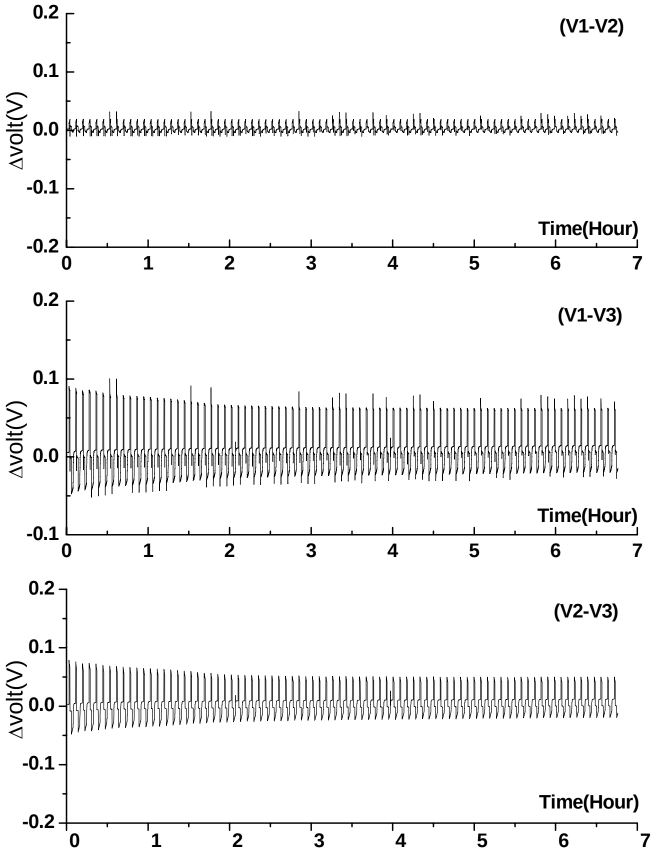

Fig.5 Voltage deviation among cells in Test I

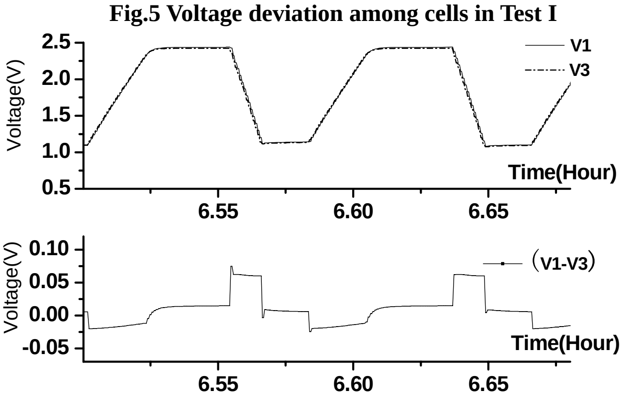

Fig.6 Enlarged view of V1, V3 and (V1-V3) in Test I

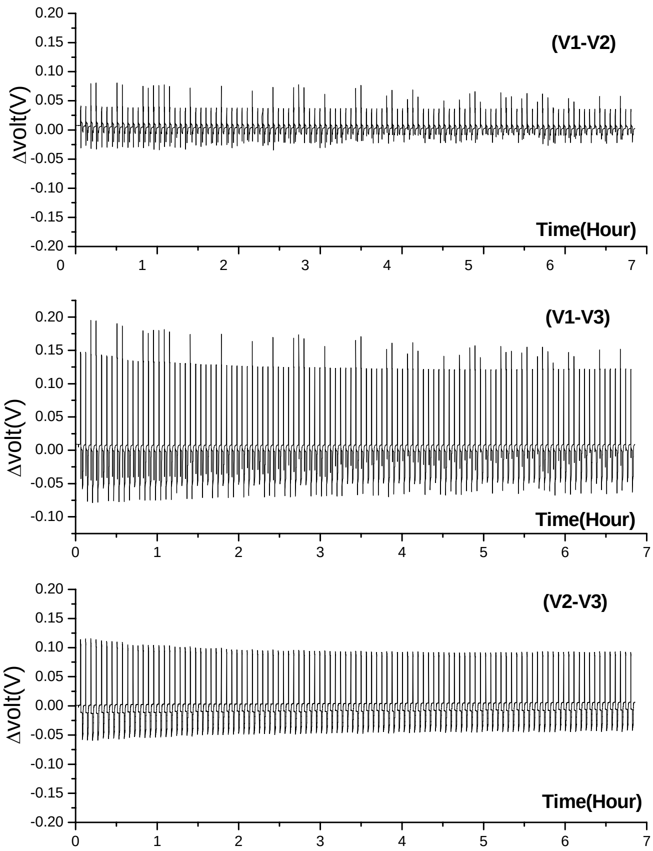

Fig.7 Voltage deviation among cells in Test II

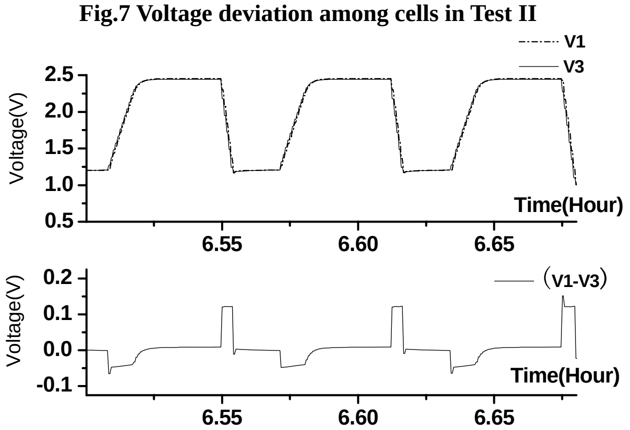

Fig.8 Enlarged view of V1, V3 and (V1-V3) in Test II

5. Conclusion

The paper focuses on the study of supercapacitors for power electronics applications. A test bench has been built, and the scheme of measurement for supercapacitor's characteristic parameters considering practical operation situation such as duty cycle, and discharging current is proposed. Cycling test for studying the consistency of supercapacitor has also been carried out. According to the test result, Maxwell BCAP0120 supercapacitor has shown good consistency, thus voltage initialization strategy can be applied in its management.

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