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https://doi.org/10.5109/7151736

出版情報：Evergreen. 10 (3), pp.1862-1867, 2023-09. 九州大学グリーンテクノロジー研究教育センター
バージョン：

EVERGREEN Joint Journal of Novel Carbon Resource Sciences & Green Asia Strategy, Vol. 10, Issue 03, pp1862-1867, September 2023

Characterization of Supercapacitors for Electric Vehicles Applications

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(Received April 29, 2023; Revised June 30, 2023; accepted September 17, 2023).

Abstract: In this paper, the characterization of the supercapacitor is carried out, especially for applications in electric vehicles regenerative braking. Supercapacitors (SC) are explored in terms of self-discharge, and different charge-discharge currents. Supercapacitor testing has been carried out for charging, discharging, and self-discharge testing using the BCAP3000 P270 supercapacitor with a voltage of 2.7 V and a rated capacitance of 3250 F. The experiments were conducted using either a single supercapacitor or a pack of supercapacitors. On the basis of the estimated charge-discharge time, the results of the charge-discharge test will be compared. According to the findings of the SC charging and discharging tests, there are variances in the computation of the charging and discharging time ranging from 5.33% to 32.19%. The self-discharge test shows that for 40 days, the supercapacitor cell voltage drops from 2.7 V to 1.819 V.

Keywords: electric vehicle; charge-discharge; regenerative braking; supercapacitor

1. Introduction

Electric mobility is at the center of attention, especially in the transportation sector which, is one of the highest-polluting sectors in the world[1,2]. An important component of mobility is the use of Electric Vehicles (EV). An electric vehicle is a type of vehicle whose power source is an electric motor that receives its energy from a rechargeable energy storage device. This electric motor also produces electrical energy[3]. Electric vehicles receive electrical energy by connecting it to a network which is in the form of an inverter and electric motor, while the storage of electrical energy is contained in a battery pack[4]. The use of electric vehicles is seen as important for reducing pollution from internal combustion engine vehicles (ICEV)[5].

The battery functions as an energy storage device with a high energy density but a low power density. The battery also has several other drawbacks, including a heavy load, relatively slow charging, and a limited life cycle. The battery life is determined by the battery depth of discharge (DoD), and high current and operating temperature[6].

In electric vehicles, using batteries as the only form of energy storage is currently not cost-effective. Energy density, cost, life cycle, and driving range are very important in the electric vehicle market. This has opened up opportunities for regenerative braking, in which the vehicle's kinetic energy is converted and stored into electrical energy during braking and is recycled to increase the range of electric vehicles. Although significant progress has been achieved in recent years to further enhance battery performance, the main issue arises during peak load changes. Even in small electronic gadgets like laptops and cell phones, a sudden breakdown occurs in energy use. This issue also arises with electric vehicles as a result of a number of variables, including driving technique and road conditions, which cause abrupt variations in power demand. The battery may not work properly if it is discharged suddenly.

It is known that supercapacitors (SC) have an excellent power density and are able to absorb the power generated during braking as well as have a very good life cycle[7]. The quick charge/discharge cycles, extremely high power density, and long life cycle of the SC have increased interest in a variety of applications, including transportation. In contrast to fuel cells and batteries, they continue to have a low energy density. SC is especially appropriate for use in power assistant applications in hybrid powertrain systems since they may be fully charged or discharged in seconds without destroying the cell. There is no need for a phase change at the electrode during the highly reversible charging and discharge operation. High coulometric efficiency is the result, and the life cycle is improved. However, the losses of SC during self-discharge are larger than those of batteries, restricting their usage as the exclusive source of energy in fully electric vehicles.

Batteries, especially lithium batteries, are one of the best energy storage in electric and hybrid vehicles[8]. Presently, lithium ion batteries are one of the most popular options; however, because of their low cost, sodium ion batteries are seen as the next generation of energy storage that could replace lithium ion batteries[9]. In electric vehicles, when the vehicle requires sudden use of power during an increase in speed, the battery cannot discharge in a short time to meet the demand[10,11]. The same applies to storing regenerative current in the battery during EV braking. Temporary high-power charging that can occur during braking can cause problems for the battery and can affect performance, cause significant degradation and reduce life. The battery may suffer damage if there are significant changes in the flow of electric current to and from it. Battery life may be shortened by frequent acceleration and braking, such as during city driving. The battery can be complemented by the employment of additional high power density energy storage systems (ESS), also referred to as secondary energy storage, particularly in regenerative braking and vehicle start/acceleration. SC has the ability to provide the power required for vehicle acceleration and to absorb energy during regenerative braking. This combination will extend the battery life and enhance EV dynamic performances[12].

The addition of SC may provide a remedy for the lack of batteries, which are a class of high power density sources. SC can help batteries to lessen deterioration brought on by peak currents[13]. There have been numerous attempts in recent years to use SC in electric vehicles to make up for the lack of batteries. Electric Double Layer Capacitors (EDLC) are supercapacitors that have high capacitance, high power density, fast charging and discharging capability, high efficiency, wide operating temperature range, and long cycle life[6,14]. Although seeing that SC offers advantages that batteries do not have, SC still cannot be the sole energy storage system in electric vehicles. The main problem is the relatively low energy density of SC[15]. A hybrid energy storage system (HESS), which is characterized by the combination of two or more energy storage technologies, can make use of the features that batteries and SC possess in order to achieve the desired performance. HESSs are solutions that combine the features of various technologies in order to achieve the desired performance.

In terms of supercapacitor modeling and estimation, many previous studies have been carried out such as a simplified electrical circuit model based on the voltage-current equation[16], a simplified model and a universal adaptive stabilization, optimization (UAS+O) based parameter identification[17], and self-discharge model based on a kinetic model with a distribution of time-independent rate constants[18]. For supercapacitor estimation, several studies have also been carried out such as supercapacitor charge capacity bounds estimation considering charge redistribution[19], and discharge time prediction using Peukert's Law[20].

SC testing is needed to determine the performance of the SC that will be used. In the previous papers, SC tests were carried out for charge-discharge, self-discharge, and life cycle tests. In[21], SC life cycle tests were carried out up to 11 million cycles to determine the life time of SC. SC tests were also carried out as in[22], where charge-discharge and self-discharge tests were carried out on SC with a capacitance of 63 F and voltage of 125 V. Testing the effect of the charging method on the self-discharge of SCs was carried out at[23] with capacitances of 3.3 F and 4.7 F. In[24,25] the test was carried out on SC with a capacitance of 3000 F with a large current test (≥30 A). Compared to the previous papers, in this paper, SC with a capacitance of 3250 F are tested for electric vehicles' regenerative braking applications, where the maximum charging current of regenerative braking is limited to 20 A.

2. Supercapacitors Testing

Testing the charging and discharging of supercapacitors is needed to determine their performance, even though theoretically the variable we want to measure can be calculated from the known supercapacitor parameters. The voltage V at the terminals for time t (t = 0) during the charging process using a constant current approach is determined by Equation (1). Equation (2) is used to compute the discharge characteristics of a capacitor with capacitance (C) over a given load resistance (R_L), and Equation (3) is used to get the associated discharging time.

$$V - V_0 = \frac{I_C}{C}.t \quad (1)$$

$$V = V_0.e^{-\frac{t}{(R_{ESR}+R_L).C}} \quad (2)$$

$$t = \ln\left(\frac{V_0}{V}\right).(R_{ESR} + R_L).C \quad (3)$$

where:

V : voltage at time t

V_0: voltage at time t_0

I_C: charge current

C : capacitance

t : charge time

R_{ESR}: equivalent series resistance

R_L: load resistance

The supercapacitors (SC) under test are applied to capture the regenerative braking energy of electric vehicles with a system voltage of 96 V. From testing electric vehicles on the road, the amount of current generated from the vehicle's regenerative braking reaches 20 A. The SC examined in this study is based on a Maxwell Technologies Inc. 2.7 V cell with a 3250 F capacity. Table 1 provides general technical information from the manufacturer[26].

Testing for charge-discharge will be done on SC cells and SC packs made up of 41 SC cells stacked in series. A constant current-constant voltage (CC-CV) method was used to conduct the SC charging test. In the SC cell test, currents of 3, 5, and 9 amperes were used, while for the SC pack test, charging currents of 5, 10, and 15 amperes were used. In the discharge test, a resistive load of 0.222 ohms, 0.148 ohms, and 0.0878 ohms was used to discharge the SC cell, while a resistive load of 10.25 ohms, 3.38 ohms, 2.54 ohms, and 1.26 ohms was used to discharge the SC pack. Finally, the SC will be charged until it reaches 2.7 V then left and the voltage is measured to determine the self-discharge of the SC.

Table 1. Supercapacitor technical data

Parameters	Value
Product name	BCAP
Rated voltage (Vr)	2.7 V
Rated capacitance (Cr)	3250 F
Stored energy	3.3 Wh
ESR (R_{ESR})	0.15 mΩ
Rated continuous current (ΔT=15°C)	170 A
Leakage current	2.8 mA

3. Experimental Results

This experiment tests the BCAP3000 P270 supercapacitor, which has a rated capacitance of 3250 F and a voltage of 2.7 V. In the experimental test, the beginning and final voltages are 0.75 V and 2.67 V for the SC cell, and 30.75 V and 109.5 V for the SC pack, respectively.

3.1 Charging Test Results

In the SC charging test, the constant current and constant voltage (CC-CV) method is used with a maximum charging current of 20 A. This charging current is the maximum current resulting from the regenerative braking of an electric vehicle when tested on the road. Due to the equipment's restrictions, SC charging is only tested up to a maximum current of 15 A. Three different current values, 3, 5, and 9 A for the SC cell and 5, 10, and 15 A for the SC pack, were chosen for the SC charging test. The time required to charge SC cells with a 3A current is 1565 seconds. It takes 1147 seconds to charge at a rate of 5 A, while 731 seconds are needed to charge at a rate of 9 A. The SC pack needs 1090 seconds to completely charge at 5A current. A charging current of 10 A takes 565 seconds, while a charging current of 15 A takes 385 seconds. Details of the SC pack voltage for various charging currents are exhibited in Figure 1.

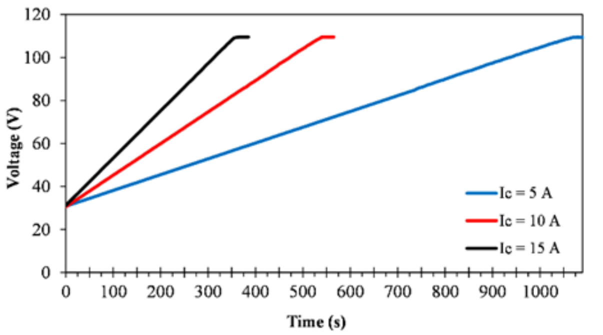

Fig. 1: SC pack charging test results

The SC charging test results have been performed, and they deviate from the estimated charging time. The complete results are summarized in Tables 2 and 3.

Table 2. SC cell charging times

Charging current	Calculation	Testing
3 A	2080 s	1565 s
5 A	1248 s	1147 s
9 A	694 s	731 s

Table 3. SC pack charging times

Charging current	Calculation	Testing
5 A	1249 s	1090 s
10 A	625 s	565 s
15 A	417 s	385 s

3.2 Discharging Test Results

In the SC discharge test, a load bank with a resistive load is used. This means that there will be a decrease in the discharge current along with a decrease in the SC voltage. When the SC voltage reaches 0.75 V, the discharge operation will end and the SC voltage will return to its initial value of 2.67 V. The SC cell discharge test is carried out with load resistance of 0.222 ohms, 0.148 ohms, and 0.0878 ohms. The load resistance used for the SC pack discharge test is 10.25 ohms, 3.38 ohms, 2.54 ohms, and 1.26 ohms. A 0.222 ohms load resistance requires 790 seconds to discharge SC cells. A discharge with a 0.148 ohms load resistance requires 415 seconds, while a discharge with a 0.0878 ohms load resistance requires 315 seconds. With a 10.25 ohms load resistance, the SC pack needs 875 seconds to discharge fully. A load resistance of 3.38 ohms requires 285 seconds to complete, while a load resistance of 2.54 ohms requires 215 seconds. Finally, a 1.26 ohms load resistance requires

109 seconds to discharge. Figure 2 displays the SC pack voltage for various load resistances.

The results of the SC discharging test have been completed, and they differ from the discharging time calculation. Tables 4 and 5 provide a summary of all the findings.

Table 4. SC cell discharging times

Load Resistance	Calculation	Testing
0.222 ohm	917 s	790 s
0.148 ohm	612 s	415 s
0.0878 ohm	363 s	315 s

Table 5. SC pack discharging times

Load Resistance	Calculation	Testing
10.25 ohm	1049 s	875 s
3.38 ohm	347 s	285 s
2.54 ohm	261 s	215 s
1.26 ohm	130 s	109 s

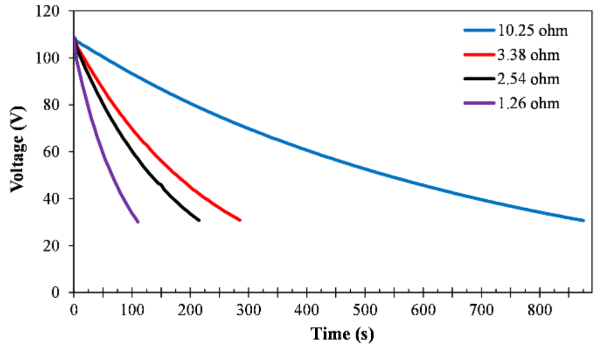

Fig. 2: SC pack discharging test results

3.3 Self-Discharging Test Results

The voltage measurement in the self-discharge process was taken from 5 samples of the BCAP3000 P270 supercapacitor. Self-discharge measurements were taken for 40 days. Prior to becoming linear with a slope of a few mV per week, the SC voltage drop is rather significant at the beginning of the measurement. Over a period of two weeks, voltage losses between 5 and 20 percent happen. In the first ten days, the value of the voltage on the SC is pretty much wasted in the self-discharging process. The value of wasted voltage in the first ten days was 0.571 V. The wasted voltage amount for the following ten days was 0.147 V. The wasted voltage value for the third and fourth ten-day periods was 0.048 V and 0.041 V, respectively. From six SC samples that have been discharged for 40 days, the average residual voltage is about 1.819 V. Figure 3 shows the results of the self-discharge test for the five samples of SC.

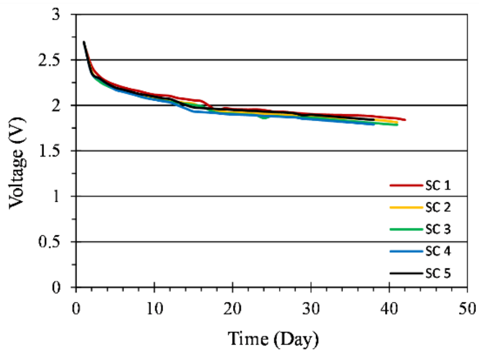

Fig. 3: Supercapacitor self-discharging test results

4. Conclusion

Supercapacitor (SC) testing has been carried out on the BCAP3000 P270 with a voltage of 2.7 V and a capacitance of 3250 F. For charging, discharging, and self-discharging tests, SC testing has been done on both SC cells and SC packs. According to the findings of the SC charging and discharging tests, there are variances in the computation of the charging and discharging time ranging from 5.33% to 32.19%. The self-discharge test shows that for 40 days, the SC cell voltage drops from 2.7 V to 1.819 V.

Acknowledgments

This research was funded by the Research Organization of Electronics and Informatics (OREI), BRIN – EV technology grant. Amin is the main contributor to this manuscript. There is no conflict of interest to declare.

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