**Effects of Aging and Temperature on Supercapacitor Charge Capacity**

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**Abstract**—This paper examines the effects of aging condition and operating temperature on supercapacitor charge capacity. Both the utilized and total charge capacities are studied: the former refers to the amount of charge delivered during a constant current discharge process and the latter measures the total available charge stored in the supercapacitor. Experimental results show that aging leads to degradation of supercapacitor capacitance and therefore a drop in charge capacity. Supercapacitor charge capacity also drops when the operating temperature decreases. Depending on the specific aging condition and operating temperature, the effects of these two mechanisms on supercapacitor charge capacity may be enhanced or reduced. Comparisons of the upper and lower bounds of the utilized and total charge capacities show that the differences between the bounds are significant for all samples under different aging conditions and at different operating temperatures.

**Index Terms**—Supercapacitor, charge capacity, aging, temperature, constant current discharge.

I. INTRODUCTION

Energy storage is becoming an increasingly critical asset in electric power systems [1]–[3]. According to the DOE Global Energy Storage Database [4], 1579 operational or announced projects totaling a rated power of 187.79 GW have been reported as of July 2019. The significant growth of the global energy storage installation is due to the huge technical and economic benefits introduced by a variety of applications and use cases of these systems. In fact, 17 energy storage applications grouped into five categories [5] have been identified and analyzed.

Among various energy storage technologies, supercapacitors feature high power density and long cycle life. Therefore, supercapacitor-based energy storage systems have been employed to enhance the grid efficiency, reliability, and resilience [6]. To exploit the supercapacitor technology, a comprehensive and in-depth understanding of its characteristics at the device level is crucial. In particular, the supercapacitor terminal voltage behavior [7], [8], applicability of Peukert’s law to supercapacitors with constant current [9]–[12] or power [13] loads, supercapacitor energy delivery capability [14], [15], supercapacitor capacitance characterization methods [16], and supercapacitor cell balancing circuits [17], [18] have been extensively studied.

Recently, the effects of energy storage device degradation on the design, operation, and management of energy storage systems are of great interest. While most existing works focus on batteries [19]–[22], this paper studies the effects of aging and temperature on supercapacitor charge capacity based on the methodology established in [23]–[25]. Specifically, a framework is developed in [23] to investigate the utilized charge capacity (i.e., the amount of charge delivered by the supercapacitor during a constant current discharge process) and the total charge capacity (i.e., the total charge stored in the supercapacitor). The impact of various aspects of the supercapacitor physics on its charge capacity is analyzed in [24]. The effects of aging and temperature on the upper bound of the utilized charge capacity are examined in [25] to study the supercapacitor Peukert constant dependence. This paper develops [23]–[25] and examines both the upper and lower bounds of the utilized and total charge capacities under various aging conditions and at different operating temperatures.

The remainder of this paper is organized as follows. Sections II and III examine the effects of aging condition and operating temperature on supercapacitor charge capacity, respectively. Section IV compares the bounds of the utilized and total charge capacities. Section V concludes this paper.

II. EFFECTS OF AGING CONDITION

A. Experiments

The effects of aging on supercapacitor charge capacity are examined using the methodology established in [23]–[25]. The three supercapacitor samples with different rated capacitances from different manufacturers listed in Table I are tested using an automated Maccor Model 4304 tester at room temperature.

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Model</th>
<th>Capacitance (F)</th>
<th>Voltage (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Eaton</td>
<td>HV1030-2R7106-R</td>
<td>10</td>
<td>2.7</td>
</tr>
<tr>
<td>AVX</td>
<td>SCCV60B107MRB</td>
<td>100</td>
<td>2.7</td>
</tr>
<tr>
<td>Maxwell</td>
<td>BCAP0350</td>
<td>350</td>
<td>2.7</td>
</tr>
</tbody>
</table>

As in [23]–[25], a set of constant current discharge experiments is performed for each sample to study the effects of aging on supercapacitor charge capacity. To illustrate the experiment design, Fig. 1 shows two examples for sample 2: Fig. 1(a) is designed to investigate the upper bound of
the charge capacity and Fig. 1(b) is for the lower bound. Specifically, the upper bound is measured by discharging a fully charged supercapacitor after a long time constant voltage charge process. Fig. 1(a) shows the measured supercapacitor terminal voltage during a 10 A experiment when the initial voltage of the discharge process is 2.7 V. During this experiment, the supercapacitor is first conditioned by ten charging-redistribution-discharging cycles to minimize the effect of residual charge. It is then charged by a constant voltage source of 2.7 V for 3 hours, which is designed to fully charge the supercapacitor. After that, a 10 A constant discharge current is applied and the supercapacitor is discharged to 0.01 V. The discharge termination voltage is set as 0.01 V instead of 0 V for safety considerations. Taking 2.7 V as the initial voltage and 0.01 V as the cutoff voltage, the charge delivered during this constant current discharge process is calculated as

$$Q = It,$$  \hspace{1cm} (1)

where $I$ is the discharge current and $t$ is the discharge time. For this experiment, the delivered charge is 252.4 C, which is referred to as the utilized charge capacity. In this paper, “delivered charge” means “utilized charge capacity” by default and these two terms are used interchangeably. The experiment continues to estimate the total charge capacity. After the supercapacitor voltage reaches the discharge termination condition of 0.01 V, the discharge current is disconnected and the supercapacitor experiences charge redistribution, which results in an increase in the terminal voltage. Once the terminal voltage increase rate is less than 0.01 V per 5 minutes, the charge redistribution process is considered complete and the discharge current is applied again. This discharging-redistribution cycle is repeated ten times to extract the charge stored in the supercapacitor to the maximum extent possible. For this experiment, the sum of the charge delivered during the ten discharging-redistribution cycles is 293.7 C, which is referred to as the total charge capacity.

On the other hand, the lower bound of the charge capacity is achieved when the supercapacitor is only partially charged to the desired voltage using the largest possible current specified in the supercapacitor datasheet. Fig. 1(b) shows a 10 A experiment when the initial voltage of the constant current discharge process is 2.7 V. Similar to the experiment shown in Fig. 1(a) for the upper bound case, the experiment in Fig. 1(b) also includes three phases: the first and third phases use the same settings as those in the upper bound experiment while the second phase is modified. The supercapacitor is first discharged by a constant voltage source of 0.01 V for 3 hours to approximate the ideal condition that the supercapacitor is completely discharged before the charging phase is initiated. It is then charged by a constant current source of 10 A to 2.7 V. After that, a 10 A discharge current is applied and the third phase of the experiment begins. Taking 2.7 V as the initial voltage and 0.01 V as the cutoff voltage, the delivered charge is 231.1 C. The total charge capacity estimated using the ten discharging-redistribution cycles and the constant current charge phase is 242.9 and 250.8 C, respectively.

**B. Results**

Following the examples above, constant current discharge experiments are performed for all samples at room temperature: 20-25 °C, which is denoted as 23 °C in this paper. The initial voltage of the discharge process is fixed at the rated voltage of 2.7 V for all samples. The discharge current values are selected based on the supercapacitor sample specifications and the supercapacitor tester capabilities. For instance, nine currents are swept for sample 2: 10, 5, 1, 0.5, 0.1, 0.05, 0.01, 0.005, and 0.0025 A. Fig. 2 shows the relationship between the delivered charge and the discharge current for both the upper and lower bound cases. For each case, three aging conditions are examined, which are denoted as three datasets: S1, S2, and S3. The aging condition is characterized by the “hours of use” since the device is used for the first time. Sample 2 was purchased in November 2016 and first used in May 2017. The S1 dataset was obtained in July 2017. Prior to that, it was used (i.e., charge and discharge processes in current, voltage, and power modes and minutes-long rests between charge/discharge processes) for approximately 700 hours. The S2 dataset was obtained in April 2018 and sample 2 was used for approximately 3000 more hours since S1. Finally, after another 400 hours of use, the S3 dataset was obtained in May 2018. For all datasets, the upper bound experiments were first conducted and then the lower bound experiments. For samples 1 and 3, the delivered charge results are similar.
Table II lists the results for the total charge capacity estimated using the procedure established in [23], [24]. The upper bound is denoted as \( Q_{\text{max}} \). The lower bound estimated using the ten discharging-redistribution cycles and the constant current charge process is denoted as \( Q_{\text{min}} \) and \( Q_{\text{min}}^* \), respectively. Note that the lower bound estimates for sample 3 are unavailable for S1 and denoted as “—”. This is because the charge current in the constant current charge phase establishing the lower bound of the charge capacity was different in the three datasets: 14 A for S1 and 10 A for S2/S3. Fig. 2 and Table II show that the supercapacitor charge capacity decreases when it is more heavily aged from S1 to S2 and finally to S3.

## III. EFFECTS OF OPERATING TEMPERATURE

### A. Experiments

To investigate the effects of temperature on supercapacitor charge capacity, a set of temperatures is swept. The supercapacitor tester is used together with a Maccor Model MTC-020 chamber that generates temperatures between -20 and 100 °C. The typical operating temperature range of the three supercapacitor samples is between -40 and 65 °C. Considering the temperature chamber capabilities, four temperatures were swept in January through April 2018 in the descending order: 60, 40, 0, and -18 °C. The temperature, the upper bound experiments were first performed and then the lower bound experiments. It should be noted that although the intention of this study was to investigate the effects of temperature on supercapacitor charge capacity, the effects of aging also need to be taken into account considering the extensive experiment durations. For instance, sample 2 was used for approximately 270 hours during a complete set of upper and lower bound experiments, which means that it was more heavily aged during a succeeding set of experiments compared to a preceding set (e.g., more heavily aged at 40 °C compared to 60 °C).

### B. Results

Fig. 3 plots the results for the utilized charge capacity for sample 2 and Table III lists the results for the total charge capacity for all samples. The utilized charge capacity results for samples 1 and 3 are similar to those for sample 2.

First, consider the four temperatures swept in the descending order: 60, 40, 0, and -18 °C. For both the utilized charge capacity shown in Fig. 3 and the total charge capacity listed in Table III, the charge drops when the temperature decreases. This is due to the combined effects of temperature and aging: from 60 down to -18 °C, the temperature decreases and the supercapacitor samples are more heavily aged in the meantime.

Next, consider the -18 and 23 °C: S2 datasets, which can be used to more clearly demonstrate the effects of temperature.
the 23 °C: S2 set. Therefore, the supercapacitor samples were more heavily aged at 23 °C: S2, which could result in a drop in the charge. In the meantime, the temperature was higher and the charge could increase. The actual change in the charge was determined by the relative significance of these two competing mechanisms. If the effects of temperature dominated, the charge would increase, which was the case for samples 1 and 2 as well as the upper bound of sample 3 ($Q_{\text{max}}$ in Table III). If the effects of aging were more significant, the charge would decrease, which can be observed for the lower bound of sample 3 ($Q_{\text{min}}$ and $Q_{\text{min}}^*$ in Table III).

IV. COMPARISONS OF SUPERCAPACITOR CHARGE CAPACITY BOUNDS

As in [24], the difference between the upper and lower bounds of the utilized charge capacity is quantified as follows:

$$\delta_U = \frac{U_{\text{max}} - U_{\text{min}}}{Q_{\text{rated}}} \times 100\%,$$

where $U_{\text{max}}$ is the upper bound, $U_{\text{min}}$ is the lower bound, and $Q_{\text{rated}}$ is the rated charge capacity determined using the rated voltage and the rated capacitance. The difference is normalized with respect to the rated charge capacity to compare the results for the three supercapacitor samples with different rated capacitances. The results are plotted in Fig. 4.

Similarly, for the total charge capacity, the difference between the upper and lower bounds is quantified as follows:

$$\delta_Q = \frac{Q_{\text{max}} - Q_{\text{min}}}{Q_{\text{rated}}} \times 100\%,$$

$$\delta_Q^* = \frac{Q_{\text{max}} - Q_{\text{min}}^*}{Q_{\text{rated}}} \times 100\%,$$

where $Q_{\text{max}}$ is the upper bound, $Q_{\text{min}}$ is the lower bound estimated using the ten discharging-redistribution cycles, $Q_{\text{min}}^*$ is the lower bound estimated using the constant current charge phase, and $Q_{\text{rated}}$ is the rated charge capacity determined using the rated voltage and the rated capacitance. The results are listed in Table IV.

For all samples, the difference between the upper and lower bounds is significant for both the utilized and total charge capacities regardless of the aging condition and operating temperature. When the utilized charge capacity is considered, the difference depends on the discharge current: the difference peaks at a particular discharge current and decreases when the discharge current deviates from this value, which is similar to the delivered charge pattern.

V. CONCLUSION

This paper studies the effects of aging and temperature on supercapacitor charge capacity by conducting extensive constant current discharge experiments. Both the utilized and total charge capacities are examined. Moreover, this paper studies both the upper and lower bounds of these two types of charge capacity. Experimental results show that the charge capacity of a more heavily aged supercapacitor is lower because aging results in degradation of capacitance. A lower operating temperature leads to a smaller capacitance and therefore a drop in the charge capacity. Although the effects of aging and temperature are examined separately in this paper, the effects of these two mechanisms on charge capacity may be coupled: the overall impact (i.e., enhanced or reduced) depends on the specific aging condition and operating temperature. Finally, comparisons of the upper and lower bounds of the utilized

### Table II: Effects of Aging on Supercapacitor Total Charge Capacity

<table>
<thead>
<tr>
<th>$T$ (°C)</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Q_{\text{max}}$ (C)</td>
<td>$Q_{\text{min}}$ (C)</td>
<td>$Q_{\text{max}}^*$ (C)</td>
</tr>
<tr>
<td>23 (S1)</td>
<td>31.72</td>
<td>24.89</td>
<td>25.03</td>
</tr>
<tr>
<td>23 (S2)</td>
<td>29.05</td>
<td>22.21</td>
<td>22.40</td>
</tr>
<tr>
<td>23 (S3)</td>
<td>28.87</td>
<td>22.05</td>
<td>22.24</td>
</tr>
</tbody>
</table>

### Table III: Effects of Temperature on Supercapacitor Total Charge Capacity

<table>
<thead>
<tr>
<th>$T$ (°C)</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$Q_{\text{max}}$ (C)</td>
<td>$Q_{\text{min}}$ (C)</td>
<td>$Q_{\text{max}}^*$ (C)</td>
</tr>
<tr>
<td>60</td>
<td>34.12</td>
<td>23.61</td>
<td>23.58</td>
</tr>
<tr>
<td>40</td>
<td>29.86</td>
<td>22.79</td>
<td>22.95</td>
</tr>
<tr>
<td>0</td>
<td>29.12</td>
<td>21.86</td>
<td>22.05</td>
</tr>
<tr>
<td>-18</td>
<td>28.74</td>
<td>21.43</td>
<td>21.62</td>
</tr>
<tr>
<td>23 (S2)</td>
<td>29.05</td>
<td>22.21</td>
<td>22.40</td>
</tr>
</tbody>
</table>

### Table IV: Normalized Difference Between Upper and Lower Bounds of Total Charge Capacity

<table>
<thead>
<tr>
<th>$T$ (°C)</th>
<th>Sample 1</th>
<th>Sample 2</th>
<th>Sample 3</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$\delta_Q$ (%)</td>
<td>$\delta_Q^*$ (%)</td>
<td>$\delta_Q$ (%)</td>
</tr>
<tr>
<td>23 (S1)</td>
<td>25.3</td>
<td>24.8</td>
<td>19.4</td>
</tr>
<tr>
<td>23 (S2)</td>
<td>25.3</td>
<td>24.6</td>
<td>25.9</td>
</tr>
<tr>
<td>23 (S3)</td>
<td>25.3</td>
<td>24.6</td>
<td>25.2</td>
</tr>
<tr>
<td>60</td>
<td>28.9</td>
<td>29.0</td>
<td>30.5</td>
</tr>
<tr>
<td>40</td>
<td>26.2</td>
<td>25.6</td>
<td>27.2</td>
</tr>
<tr>
<td>0</td>
<td>26.9</td>
<td>26.2</td>
<td>26.7</td>
</tr>
<tr>
<td>-18</td>
<td>27.1</td>
<td>26.4</td>
<td>29.2</td>
</tr>
</tbody>
</table>
and total charge capacitances show that the differences between the bounds are significant for all samples under different aging conditions and at different operating temperatures.

**REFERENCES**


Fig. 4. Normalized difference between upper and lower bounds of utilized charge capacity. (a) Sample 1. (b) Sample 2. (c) Sample 3.