Control strategy and lifetime optimization of Electrochemical Double-Layer Capacitors

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Abstract

Today, the most commonly used energy storage device in embedded systems is batteries. But unfortunately, batteries are associated with short lifetime. By introducing Electrochemical Double-Layer Capacitors (EDLCs) as an alternative power source, the lifetime of the backup energy source can be significantly increased.

The lifetime is dependent on two predominant factors; temperature and voltage. To evaluate the aging behavior of EDLCs, accelerated lifetime tests were performed. The measurements were carried out on capacitors from two different manufacturers (Cooper Industries and Maxwell Technologies). The results were then used for lifetime estimations.

To accomplish an increased lifetime, a control system is suggested which monitors the capacitance and controls the applied voltage i.e. optimizing the amount of stored energy. A complete power backup system with EDLCs as power source and an associated control system, was built and simulated in Simulink. It is found that the lifetime can be significantly increased when controlling the applied voltage, since the voltage can be held as low as possible at all time.

Keywords: Supercapacitor, Ultracapacitor, Electrochemical Double-Layer Capacitor, Energy Storage, Power Source, Simulink, Embedded Systems, Aging, Voltage Control

1. Introduction

Electrochemical Double-Layer Capacitors (EDLCs), also known as Supercapacitors (SCs) or Ultracapacitors (UCs) have experienced a rapid development and can today be used as a complement to batteries in a wide range of applications e.g. in hybrid vehicles or UPS-systems [1]. The main benefits of EDLCs, compared to batteries, are a higher power density and longer lifetime.

However, there are some properties to consider when using EDLCs as backup power source. The most dominate one is the aging process. This process is mostly related to ambient temperature and applied voltage. An increase in temperature and voltage will result in an acceleration of chemical reactions and thus decrease the capacitance and conductance [2].

To be able to optimize the lifetime, the behaviors and mechanisms of EDLCs are investigated. An equivalent circuit with its electrical properties is established. The equivalent circuit models the resistive and capacitive behavior of a typical EDLC.

The equivalent circuit is proposed as a model in Section 2. In Section 3 the aging factors are further explained. In Section 4 the control approach and energy optimization are discussed. In Section 5 experimental and simulation results are presented. It is observed that controlling the voltage can significantly increase the lifetime.

2. Modeling and parameter measurements

Compared to a traditional capacitor, the electrochemical behavior of an EDLC is highly complex due to its strong voltage and temperature dependency. In order to create a sufficient model of an EDLC that involves in-circuit voltage control and energy optimization, certain requirements need to be fulfilled: (i) the model should describe its relevant behavior, (ii) the model should be as simple as possible, (iii) the parameters should be possible to determine by measuring the EDLC’s terminals.

With the above mentioned requirements, a simple RC-circuit with parallel resistance over the capacitor is found to be sufficient, seen in Figure 1 [3].

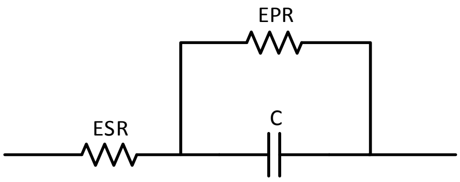

Figure 1. Simplified equivalent circuit of an EDLC. The model parameters are: an equivalent series resistance (ESR), equivalent parallel resistance (EPR) and a capacitor (C).

In Figure 1, the model parameters are [3][4]:

- Nonlinear capacitance (C).
- Equivalent Parallel Resistance (EPR) – models the losses due to current leakage.
- Equivalent Series Resistance (ESR) – models the resistive losses in current collectors and conductors during charge and discharge of an EDLC.

The parameters mentioned above can easily be obtained with standard laboratory equipment. Since the energy will be optimized by measuring the capacitance in-circuit and controlling the applied voltage, the parameter values have to be measured automatically in the electrical application.

To be able to measure a capacitance value there has to be a change in charge i.e. the EDLC has to be either charged or discharged. Traditional equations for capacitance measurements are only valid for a change in charge with constant current. Since a constant current cannot be guaranteed in the electrical application, a different approach for capacitance measurements will be presented.

Assuming that the capacitance is constant during a small voltage charge interval ΔV, the energy stored in the EDLC is expressed as [3]:

$$\Delta E = \frac{1}{2} \cdot C \cdot (V_2^2 - V_1^2) \qquad (1)$$

where C is the capacitance, V_1 is the initial voltage and V_2 is the final voltage. The energy can also be calculated with the integral of the instantaneous power seen in:

$$\Delta E = \int_{t_1}^{t_2} v(t) \cdot i(t) dt \qquad (2)$$

where i(t) and v(t) is the measured current and voltage. Combining Equation (1) and (2) gives a suitable method for calculating the capacitance:

$$C = \frac{2 \cdot \int_{t_1}^{t_2} v(t) \cdot i(t) dt}{(V_2^2 - V_1^2)} \qquad (3)$$

3. Aging

The aging of a typical EDLC is dependent on two dominating factors, temperature and voltage [2][5]. Both an increase in temperature and/or voltage will accelerate the aging process. The aging process can be described by a decrease in capacitance and an increase in the internal resistances (ESR, EPR).

The question is: how does the temperature and voltage affect the lifetime? One manufacturer, Cooper Industries, suggests two rules of thumb [5]:

- The lifetime is doubled if the temperature is decreased by 10°C.
- The lifetime is doubled if the voltage is decreased by 0.3V.

Where the first one can be derived either from experimental measurements or from the law of Arrhenius, and the second can be experimentally determined [5][6].

4. Voltage control and energy optimization

The main goal of this article is to optimize the energy level of EDLCs and increase their lifetime. Prior to today, the approach for maximizing the lifetime was to use EDLCs with a high capacitance value and apply a high constant voltage. The drawbacks of this approach are:

- More energy is stored than needed in the beginning, and the energy will decrease with decreasing capacitance.
- The aging process might be accelerated, since the aging is strongly dependent on the temperature and voltage.

To minimize the effects mentioned above, thus maximizing the lifetime, a control algorithm which monitors the capacitance value and controls the applied voltage is designed.

In embedded systems, where EDLCs can be used as backup power source, the energy stored in the EDLC is used for backing up important data when a blackout occurs. When a blackout occurs, the EDLCs may not be discharged to zero potential, due to a certain voltage level V_{limit}

that is required for the surrounding components/circuits to function. This means that the total energy stored in the EDLCs is expressed as:

$$E_{total} = E_{backup} + E_{limit} \tag{4}$$

where E_{backup} is the energy needed for backing up the data and E_{limit} is the needed energy to maintain a fixed voltage V_{limit}.

The stored energy in an EDLC can be expressed as [7]:

$$E = \frac{1}{2} \cdot C \cdot V^2 \tag{5}$$

where C is the capacitance and V is the applied voltage. Combining and rewriting Equation (4) and (5) gives:

$$E_{backup} = E_{total} - E_{limit}$$

$$= \frac{1}{2} \cdot C \cdot V^2 - \frac{1}{2} \cdot C \cdot V_{limit}^2 \tag{6}$$

where V is now the controlled voltage and V_{limit} is the minimum voltage level.

When the capacitance C, in Equation (6), decreases with time, the voltage V is increased to maintain a constant backup energy E_{backup}. In this article, this energy is set to 20J. Since ESR will affect the charge and discharge one should have these power losses in mind.

5. Experimental and simulation results

For various reasons the properties of an EDLC changes with time. These properties were studied during an accelerated lifetime test, where EDLCs from Cooperbussman (HB1625-2R5256-R) were stressed with a high temperature (70°C) and at predefined voltages. The experiment was divided into two parts:

1. Investigation of the exponential and linear degradation during 1000h and 2000h.
2. Investigation of the capacitance properties when the applied voltage is increased by 0.3V after 1000h.

The measurements (of capacitance and ESR) were made in room temperature with the following steps:

- Cool down the EDLCs to room temperature.
- Discharge them to zero potential
- Charge each EDLC from 0 to 2.5V and measure the ESR and capacitance.

The results from the first part of the accelerated lifetime test are seen in Figure 2 – 4.

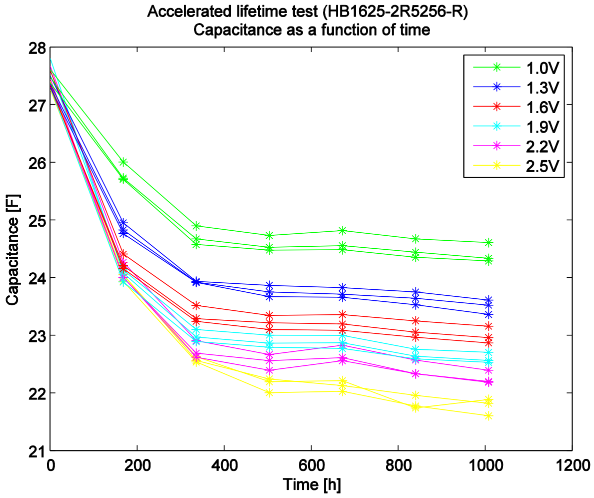

Figure 2. The capacitance as a function of time from the accelerated lifetime test on HB1625-2R5256-R stressed @ 70 °C and 1.0 - 2.5V during 1008h.

As seen from Figure 2, the curves indicate that capacitance was decreasing exponentially to a certain point and then decrease more linearly. One can also see that the capacitance drop is strongly dependent on the voltage i.e. the exponential drop is much smaller for lower voltages compared to higher voltages. Figure 3 and 4 displays the result when stressing the EDLCs at its rated temperature and voltage. This was done to verify the long term properties of EDLCs.

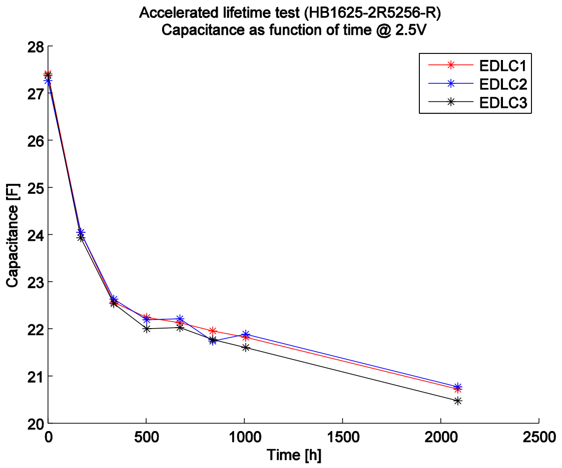

Figure 3. The capacitance as a function of time from the accelerated lifetime test on HB1625-2R5256-R stressed @ 70 °C and 2.5V during 2088h.

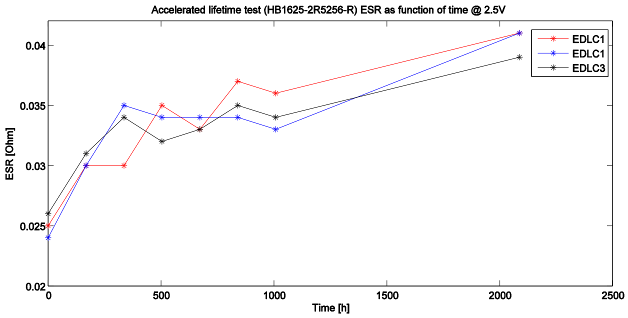

Figure 4. The ESR as a function of time from the accelerated lifetime test on HB1625-2R5256-R stressed @ 70 °C and 2.5V during 2088h.

Figure 3 and 4, indicate that the capacitance is decreasing and the ESR is increasing with time. These results have to be taken into account when designing a control algorithm for energy optimization. This means that the application has to be able to perform in-circuit capacitance and ESR measurements to be able to maintain a constant backup energy.

The reason for the second part of the accelerated lifetime test is based on the appearance of the generalized capacitance vs. time curve. This curve is based on a fix voltage level, but the question is: "if the voltage was to be increased from an initial voltage level to a higher one, will the capacitance decrease exponentially at first or will it continue linearly with a different slope?"

The result from the second part of the accelerated lifetime test is displayed in Figure 5.

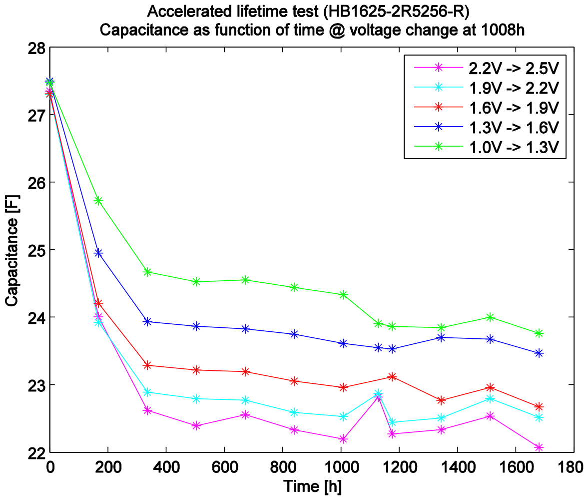

Figure 5. The capacitance as a function of time from the accelerated lifetime test on HB1625-2R5256-R during a change of voltage with 0.3V at 1008h.

The curves in Figure 5 do not seem to drop exponentially after a voltage increase, hence the capacitance drop is assumed linear when the voltage is increased.

The data obtained from the accelerated lifetime test is used to model the aging of the EDLC in Matlab Simulink. To counteract the degradation of the capacitance and still maintain a constant backup energy, the voltage should be increased. This procedure is handled in a control algorithm which increases the voltage as the capacitance decreases, seen in Figure 6.

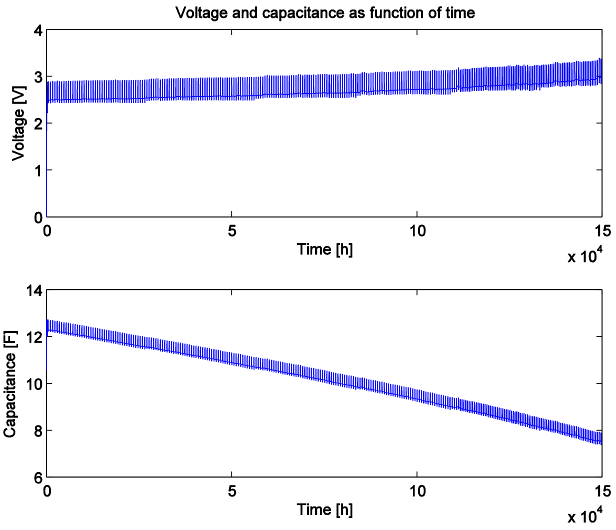

Figure 6. Voltage and capacitance as function of time when optimizing the energy in the EDLCs.

The small charges and discharges, described in Section 2, are visible in Figure 6. The in-circuit capacitance measurements are crucial for the control algorithm, since the new applied voltage is based on these measurements. Furthermore, the time for which the backup system can provide a constant power can be determined in Figure 7.

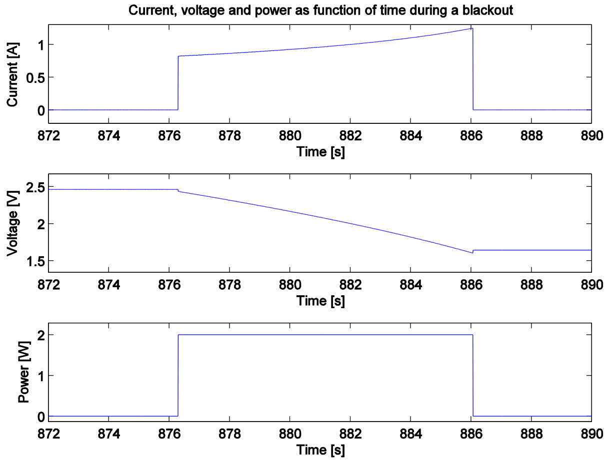

Figure 7. Top: Current as function of time during a blackout. Middle: Voltage as function of time. Bottom: Power as function of time.

From the result in Figure 7 (2W for 10s, 20J), one can clearly see that it is possible to maintain a desired energy level by monitoring the capacitance and controlling the applied voltage level accordingly.

In Table 1, the result (from controlling the voltage) can be compared with the results from keeping the voltage constant.

Table 1. Comparison in lifetime between Constant high voltage and Controlled voltage, at different temperatures.

Temperature [°C] \ Voltage [V]	1.7	1.9	2.1	Control
70	8.56yr	5.7yr	4.2yr	17.0yr
60	17.7yr	11.4yr	8.5yr	34.3yr
50	36.6yr	22.8yr	17.0yr	69.2yr

The result from Table 1 illustrate that it is very beneficial to minimize the voltage, since the lifetime is increased with approximately 200% when comparing with the reference value 1.9V (60°C) simulation.

6. Conclusions

Electrochemical Double-Layer Capacitors are promising components which can be used for different applications. In this article, the main topic was to study how the EDLC can be used as a backup power source. The work described in this article, illustrates that it is possible to develop a control system which monitors/measures the capacitance in-circuit and control the applied voltage, thus optimizing the stored energy and thereby also the lifetime of EDLCs.

Some of the most promising conclusions from the accelerated lifetime test are:

- The initial capacitance drop is voltage dependent i.e. by keeping a low initial voltage the capacitance degradation is reduced.
- If the voltage is increased during operation, the capacitance will not experience another exponential drop

These results are beneficial when trying to optimize the lifetime of EDLCs.

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