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 where 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 back up system with EDLCs as power source and an associated control system, was built and simulated in Simulink. Furthermore, an electrical hardware prototype was implemented to create a proof-of-concept. 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, MATLAB, Simulink, Embedded Systems, Aging, Lifetime Estimation, Voltage Control, Control System.

Acknowledgments

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The personal benefits from this experience are not only the practical and theoretical knowledge we gained, more importantly we have learned to work better as a group and as a part of a development team. The time spent at Schneider Electric has been a great learning experience and therefore we want to thank some people: first we want to thank our supervisors Fredrik Göth, Thomas Nordwall and Goran Stojcevski for their advice, guidance and support, we also want to give our thanks to Mats Karlsson, Oskar Nilsson, Mattias Grundelius and Sven Björck for taking their time to answer our questions. We also want to express our gratitude to Bonde Börjesson, who made the project happen. We also want to express our gratitude to our supervisor Josefin Berner and examiner Bo Bernhardsson, from the Department of Automatic Control at LTH, for their helpful advice and support.

We hope that our control solution will be included in Schneider Electric's future products.

List of Symbols

ε_0	Vacuum Permittivity	[As/Vm]
ε_r	Relative Permittivity	[%]
τ	Time constant	[s]
A	Area	[m^2]
C	Capacitance	[F]
C_d	Delayed branch capacitance	[F]
C_{di}	Diffuse double layer capacitance	[F]
C_{diff}	Differential Capacitance	[F]
C_{eq}	Equivalent Capacitance	[F]
C_{i0}	Immediate branch constant capacitance	[F]
C_m	Helmholtz layer capacitance	[F]
C_0	Initial capacitance	[F]
d	Distance	[m]
e	Controller error	[V]
e_s	Difference between two control signals	[V]
E	Energy	[Wh]
E_{Stored}	Stored Energy	[J]
E_a	Activation energy	[eV]
EPR	Equivalent Parallel Resistance	[Ω]
ESR	Equivalent Series Resistance	[Ω]
h	Step length	[s]
i	Current	[A]
i_C	Current through a Capacitor	[A]
i_{ESR}	Current through a ESR	[A]
I	Current	[A]
I_c	Charging current of the EDLCs	[A]
I_d	Discharging current of the EDLCs	[A]
k	Boltzmann constant	[eV/K]
k	initial value compensation	[%]
k_{GCa}	Coefficient from Gouy-Chappman model	–

k_{GCb}	Coefficient from Gouy-Chappman model	–
k_s	Slope or constant value	–
K	Proportional gain	–
K_i	Integral gain	–
K_p	Proportional gain	–
K_s	Back-calculation gain	–
L	Estimated life	[h]
L_B	Expected service life at rated voltage	[h]
P	Power	[W]
Q	Electric Charge	[As]
R	Resistance	[Ω]
R_d	Delayed branch resistance	[Ω]
R_i	Immediate branch resistance	[Ω]
R_l	Long-term branch resistance	[Ω]
R_{lea}	Leakage resistance	[Ω]
t	Time	[s,h]
T_C	Actual core temperature	[K]
T_i	Integral time/reset time	[s]
t_k	Sampling instant	[s]
T_M	Rated temperature	[K]
T_r	Back calculation time constant	[s]
u	Controller output signal/control signal	[V]
V	Voltage	[V]
v_{di}	Applied voltage on C_{di}	[V]
V_C	Voltage drop over a capacitor	[V]
V_{cap}	Voltage over the EDLCs	[V]
V_{charge}	Charge voltage	[V]
$V_{discharge}$	Discharge voltage	[V]
V_{fb}	DC/DC converter feedback voltage	[V]
V_R	Voltage drop over a resistance	[V]
V_{Rated}	Rated voltage	[V]
V_{ref}	Reference voltage	[V]
V_{out}	DC/DC converter output voltage	[V]
V_O	Initial voltage	[V]
y	Process output	[V]
y_{sp}	set point/reference value	[V]

Glossary

AN	Acetonitrile
A/D	Analog to Digital converter
C(t)	Capacitance as function of time
C(T)	Capacitance as function of Temperature
C(V)	Capacitance as function of Voltage
DC	Direct Current
DC/DC	Direct Current to Direct Current converter
D/A	Digital to Analog converter
EDLC	Electrochemical Double Layer Capacitor
EIS	Electrochemical Impedance Spectroscopy
EOL	End of Life
EPR	Equivalent Parallel Resistance
ESR	Equivalent Series Resistance
GUI	Graphical User Interface
KCL	Kirchoffs Current Law
KVL	Kirchoffs Voltage Law
LP	Low Pass
LTSpice	Linear Technology Simulation Program with Integrated Circuit Emphasis
Opamp	Operational amplifier
PC	Propylene Carbonate
PI	Proportional-Integral
PMOS	P-channel MOSFET
RC	Resistor-Capacitor
ROT	Rule Of Thumb
SC	Supercapacitor
SOC	State of Charge
SOL	State of Life
SW	Switch
UC	Ultracapacitor
UPS	Uninterruptible power supply

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Introduction

Electrochemical Double-Layer Capacitors (EDLCs), also known as Supercapacitors (SC) or Ultracapacitors (UC), are used today in some electrical applications as energy storage device. Some examples of the field of use are intermediate energy storage in cars or as a backup power source in embedded systems.

Two commonly used backup power sources in embedded systems are batteries and EDLCs. The main differences between batteries and EDLCs lie in their power density and lifetime. Power density is defined as the maximum amount of power that can be supplied per volume unit i.e. a higher power density can supply a larger amount of power in respect to its volume. The EDLCs have an advantage since their power density is much larger than batteries. The second advantage EDLCs has is that they suppress most battery technologies in term of lifetime. The aging of an EDLC is influenced particularly by the ambient temperature and the applied voltage. An increase in temperature and voltage will result in accelerated chemical reactions and thus decrease the capacitance and conductance. Optimizing the amount of stored energy, with respect to the temperature and voltage, can increase the lifetime.

It is critical to develop an accurate method for controlling and estimating the lifetime, since it directly impacts the duration of the system. Since the EDLC is still a rather new component, the development of new models that represent the components mechanism and aging behavior are still a subject of research.

1.1 Previous work

Because of the complex physics of the EDLC, there have been many studies on this topic. The authors from these studies have tried to understand its behavior with different experimental tests and modeling approaches [12][14][15]. Several accelerated lifetime tests on various type of EDLCs from different manufacturers have been studied before e.g. accelerated lifetime tests with charge and discharge cycles and accelerated lifetime tests with high temperatures and voltages [21]. Since the cycle tests are often used for high power applications, these are omitted in this thesis.

This thesis is divided into two parts: voltage control of the applied voltage and lifetime estimation. The most interesting and used articles, on the lifetime subject, in this thesis are: " Ageing behaviour of electrochemical double layer capacitors Part I. Experimental study and aging model " (Oliver Bohlen, Julia Kowal & Dirk Uwe Sauer 2007) and " Deriving Life Multipliers for Electrolytic Capacitors " (Sam G. Parler, Jr. 2004). Previous work on energy optimization in EDLCs are very limited, therefore a method in this subject will be presented.

1.2 Purpose and Method

The current approach of using EDLCs, as power backup in embedded systems, is to apply a high initial capacitance value and charge the EDLC to a high constant voltage level. The energy level in the capacitor will initially be high using this solution, but as the capacitance drops with time the energy will decrease as well. At a certain point, the energy will be too low to fulfill its purpose. The scope of this project is to improve the use of EDLCs as backup power source and thereby develop a more efficient and reliable solution.

The main goal of this master thesis was therefore to develop a control algorithm, that is able to maintain a desired energy level in EDLCs. As previously stated, the purpose of such work was to be able to replace backup batteries with EDLCs. To accomplish such solution, the work was divided into two parts. The first part was to examine the energy storage ability and other relevant properties of EDLCs. This was done to learn more about EDLCs in general and to get a better understanding of their behavior. To obtain the appropriate data, a literature study was carried out together with relevant measurements on the EDLC. The second part of this work was to evaluate how the energy level in a EDLC can be controlled. This was done by deriving a simulation model of the EDLC, using the collected data from the literature study and the measurements. Further on, a control system was implemented in a simulation model in order to control the energy level.

The second goal of this master thesis was to further improve the developed algorithm. This was done in order to maximize the lifetime, but also to provide a solution for lifetime estimation for the EDLC when used as backup power. By Schneider Electric, this has been stated as a highly desired feature. The developed solution will be implemented on a prototyp with associated limitations as a proof of concept.

We hope that this master thesis work will result in a solution that can be used as an alternative for batteries when a backup power source for embedded systems is needed.

1.3 Limitations

The inputs to the control system and lifetime estimations are based on the accelerated time experiments and measurements on EDLCs. The detailed physics and chemical reactions in EDLCs will not be studied in this master thesis project. Since the aim of this thesis is to design a control system for the EDLCs, there are also some limitations on the hardware of the products. This narrows down the measurements that can automatically be performed in the hardware.

1.4 Outline of the thesis

Chapter 2 - Introduces the main theoretical fundamentals used during the master thesis project e.g. background on the EDLCs, control design etc.

Chapter 3 - Describes the various measurements that are conducted on EDLCs, in order to give a better understanding of the components properties. These measurements are the basis for the control algorithm and the lifetime estimations.

Chapter 4 - Contains the modeling of an entire backup system, where the control system, the controller and the EDLCs are key parts. The modeling of the characteristic behavior of EDLCs e.g. voltage dependency and aging, is explained. A flowchart displaying the control system states with notes about each transition is included.

Chapter 5 - Displays the acquired results from the various measurements and from the simulations of the entire backup system. Since the amount of measurements and simulation results is large, only the most interesting ones are displayed. In this chapter the result from a complete long-term simulation with and without the control system is presented.

Chapter 6 - Covers the electrical hardware design where a simplified electrical circuit and its mechanisms are described.

Chapter 7 - Presents our conclusions from the results.

Chapter 8 - Contains our suggestions on further work that can be done on this topic and what Schneider Electric can do to evaluate our solution further.

2

Background

As this thesis report covers a wide range of technical areas, this chapter is dedicated to explain the fundamental principles of these areas. The purpose of this is to help the reader understand the fundamental principles, but also to evince and explain assumptions that are used in the embodiment.

2.1 Backup power, in embedded systems

An embedded system is a computer system, normally within a larger system, that uses a combination of customized hardware and software to perform a specific function. These functions are often performed with real-time computing constraints.

The simplest form of such systems runs without operating system. An advantage with these types of systems is that there is no need of reliable backup power. This is true since it is easy to prevent the processor from overwriting essential data when there is a power fail.

In many cases, when operating systems are used, the embedded system demands a reliable power source in order not to lose important data in case of a power blackout. A traditional solution to this problem, if there are only low power demands, is to use a UPS. UPS stands for “Uninterruptible power supply” and is a unit that provides backup power during a blackout. The system can therefore run as normal even if there is a blackout.

If the system demands a higher amount of power, a UPS will not be able to provide enough electricity. Blackout generators can then be used instead of an UPS, such generators are often found in hospitals and other facilities where electricity is essential at all time. Since both UPS and backup-generators can be quite expensive, built in backup batteries can be used as an alternative in many applications. If a blackout occurs, data in the processor and the ram-memory is then saved to a flash-memory and the system can be shutdown properly. When the electricity returns, the system can reboot and continue at normal operation [1].

Using batteries as a secondary power supply is the traditional way to provide the necessary backup power in systems where a controlled shutdown is accepted at a blackout. Batteries have some good properties but also some less favorable. In products with demands on great lifetime, batteries are often a weak point since their lifetimes are greatly limited. Even if rechargeable batteries are used, the lifetime cannot match the lifetime of the product.

The main reason why rechargeable batteries have limited lifetime is its limitation in recovering all the energy stored in the battery when it is discharged. This means that some of the energy converted in the chemical reaction, when the battery is charged, is non-reversible. Each time the battery is charged and discharged a small amount of its energy storage ability is lost.

If batteries are used in products that need to have a high reliability, the battery has to be replaced often. If the product contains a lot of batteries, or if a lot of product units are used, the workload of just changing batteries can be quite heavy. An energy storage unit that does not have this limitation is therefore desired [2].

Electrochemical Double Layer Capacitors also have limited lifetime, but only during some circumstances. A big advantage with EDLC is that if one takes certain characteristics into account, the lifetime can be maximized and practically unlimited, since it will outlive other components when used in a system. Compared to batteries, Electrochemical Double Layer Capacitors do not have any limitations in the number of charges and discharges they can perform [4]

In Figure 2.1, a comparison between power and energy density for different energy sources are displayed. As shown, EDLCs have a significantly higher power density than batteries, but do not provide the same amount of energy density. This makes EDLCs an ideal energy source if a lot of power is demanded during a short period of time e.g. in a backup scheme for embedded systems [2].

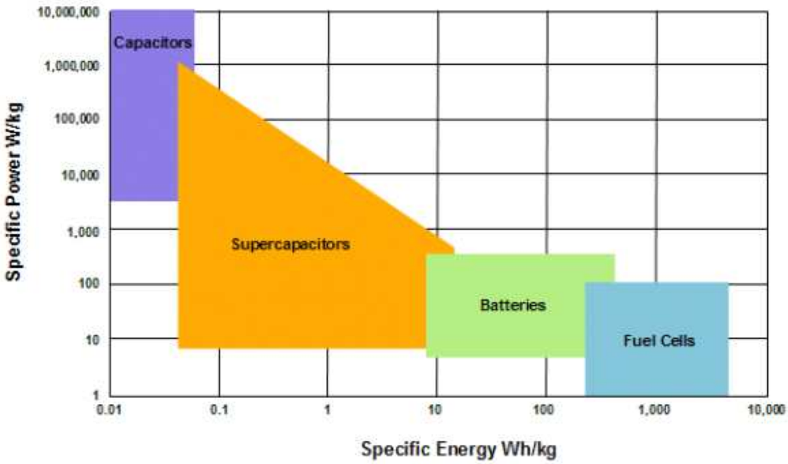

Figure 2.1 Plot showing power density and energy density for different energy sources. As seen in the figure, Supercapacitors have a higher power density than batter batteries, but a lower energy density [3] "© 2014 CAP-XX (Australia) Pty Ltd. Reproduced with Permission".

2.2 The fundamentals of traditional capacitors

The principles behind a traditional electrostatic capacitor and an Electrochemical Double Layer Capacitor are the same. Therefore, a number of fundamental properties will be described in more detail.

A capacitor is a passive electronic component that can be used to electrostatically store energy in an electrical field. The capacitor is characterized by its ability to store electrical charge. This ability is measured in Farad and is called capacitance. Equation 2.1 shows the relationship between the capacitance C, the voltage V and the electrical charge Q.

$$C = \frac{Q}{V} \tag{2.1}$$

For a conventional capacitor the capacitance is constant, independent of Q and V. This means that there is a relationship that connects the charge and the voltage, making the ratio constant.

The capacitor with the simplest design is the Parallel Plate Capacitor. This capacitor is made from two conductive plates with a dielectric material in between. The dielectric material can be made of paper, plastic, glass, etc. The capacitance of a Parallel Plate Capacitor is calculated with Equation 2.2 [5].

$$C = \frac{\varepsilon_o \cdot \varepsilon_r \cdot A}{d} \tag{2.2}$$

Where ε_0 is the vacuum permittivity, ε_r the relative permittivity of the dielectric material, A the area of the plates and d the thickness of the dielectric material. This shows that the smaller the distance between the conductors is, and the larger the conductors are made, the larger the capacitance get.

When there is a difference in potential between the conductors, it results in an electrical field over the dielectric material, causing positive charge to accumulate at one conductor and negative to the other. The difference in electrical charge gives the energy stored in the capacitor, Equation 2.3 [5].

$$E_{stored} = \frac{1}{2} \cdot C \cdot V \tag{2.3}$$

The current I(t) through electrical components is expressed as the charge passing through per time unit. In a capacitor, no current flows through, but the charge movement in the component creates a current, see Equation 2.4 [5][6][7].

$$I = \frac{dQ}{dt} = C \cdot \frac{dV}{dt} \tag{2.4}$$

2.3 RC Circuit

A primitive way to model charging and discharging of a capacitor is to use a Thevenin equivalent circuit, made from a resistance R in series with a capacitor, C, to represent the capacitor, Figure 2.2.

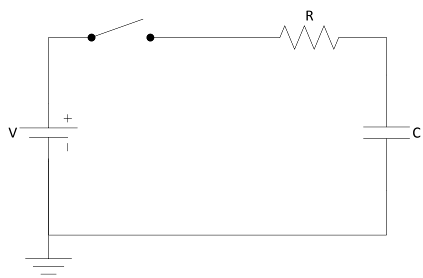

Figure 2.2 A power source connected in series with a resistor (R) and a capacitor (C) i.e. a RC circuit

The Kirchhoff Voltage Law (KVL) gives that the sum of the voltage drop over the resistance and the capacitance equals the voltage V, Equation 2.5.

$$V = V_R + V_C = R \cdot i(t) + \frac{q(t)}{C} = R \cdot \frac{dq(t)}{dt} + \frac{q(t)}{C} \tag{2.5}$$

By solving the differential Equation for V = V_{charge} and V = 0, equations for charging and discharging are obtained, see Equation 2.6 charging and 2.7 discharging. The corresponding charge and discharge currents are obtained by applying Ohm's law [8].

$$V_{charge}(t) = V_0 \cdot \left(1 - e^{-\frac{t}{RC}}\right) \tag{2.6}$$

$$V_{discharge}(t) = V_0 \cdot e^{-\frac{t}{RC}} \tag{2.7}$$

2.4 Parallel and series connected capacitors

When capacitors are being connected to each other, they can be attached either in series, in parallel or in a combination of both. Equation 2.8 shows how two capacitors in series can be converted into an equivalent capacitor called C_{eq}. Two capacitors in series can be seen in Figure 2.3.

$$\frac{1}{C_{eq}} = \frac{1}{C_1} + \frac{1}{C_2} \tag{2.8}$$

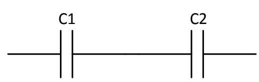

Figure 2.3 Two capacitors connected in series.

When the capacitors are connected in parallel, the equivalent capacitor can be calculated with Equation 2.9, two capacitors in parallel can be seen in Figure 2.4 [9].

$$C_{eq} = C_1 + C_2 \tag{2.9}$$

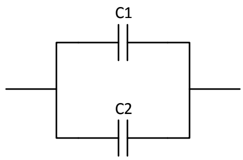

Figure 2.4 Two capacitors connected in parallel.

2.5 Electrochemical Double Layer Capacitor

As stated in Chapter 2.2, the EDLC is derived from the same fundamentals as the traditional electrostatic capacitor but constructed in a totally different way. As a result of this, it has many properties that the traditional capacitance does not have.

Instead of having a solid dielectric material separating the two conductor plates the EDLC is using a liquid. The liquid is an electrolyte mixed with positive and negative ions. When a current is applied over the EDLC, the ions accumulate at different sides. This means that a charge Q, with different polarities, builds up at the different sides of the EDLC, as it does in an electrostatic capacitor, but using a different technique.

By constructing the anode and the cathode from an extremely porous material, the surface area of both the conductors can be made significantly bigger than in the traditional capacitors. This gives the EDLC a much higher capacitance value compared to an electrostatic capacitor.

The design of an EDLC makes it strongly voltage and temperature dependent, meaning that the capacitance of an EDLC is not constant. If the voltage over an EDLC increases the capacitance value will also increase.

The opposite effect will take place if an EDLC is exposed to high voltage and/or high temperature during a longer period of time. A rule of thumb is that an EDLC exposed to rated voltage and temperature will lose half its capacitance after 10.000 hours, approximately little more than a year. The EDLC is also affected by frequency, charge and discharge current.

Even if the EDLC stores energy without chemical reactions, in contrast, there occur chemical reactions if the voltage and/or temperature is high. This is the reason why the capacitance value decreases with time i.e. if it is exposed to these two conditions [2].

2.5.1 Structure

Figure 2.5 demonstrates the different components of an EDLC, and how they are fitted together. Two important components are the conductors i.e. the anode and the cathode. Both the anode and cathode are composed of a metal collector covered with activated carbon. The anode and cathode are placed in an electrolytic liquid that is mixed with positive and negative ions. Between the anode and cathode lies a thin non-conducting separator, which main task is to lower the risk of short circuit. The thin separator has integrated holes, which allows positive and negative ions to pass through it. This mechanism is illustrated in Figure 2.5.

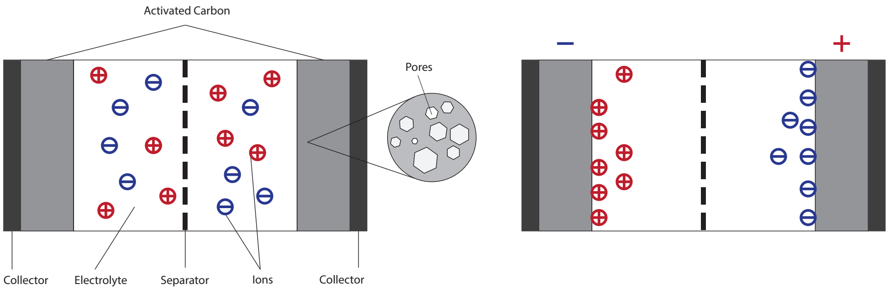

Figure 2.5 An intersecting picture of an EDLC, where the different parts are displayed. The different parts are: Activated Carbon, Collectors, Electrolyte, Separator and Ions. How these parts behave during a charge is seen on the right.

By using activated carbon, the surface area of the two conductors can be made remarkably large. This is due to the high porosity of the activated carbon material, which allows ions fold against a much wider area. The pores are hexagonally shaped, and their structure is seen in Figure 2.6.

Figure 2.6 The structure of the pores in activated carbon. The surface in which the ions can fold on is much wider than in a traditional capacitor.

As previously stated, the capacitance is proportional to the surface area of the conductors, see Equation 2.2. Due to the high porosity, the activated carbon is an ideal material for capacitor manufacturing when high capacitance values are desired.

The difference between an EDLC and a battery is that during charge and discharge a chemical reaction is taking place in batteries. In an EDLC, there is theoretically no chemical reaction taking place, instead there is the accumulation of the ions that stores the energy in the component [10].

2.5.2 EDLC models

Before considering the usage of EDLCs in applications, it is necessary to develop a sufficiently good component model. This model has to be able to predict electrical and energetic behavior with high accuracy. The electric behavior of an EDLC is more complex than of a conventional capacitor, due to its frequency, voltage and temperature dependency [11]. In this paper, only time domain models are discussed and this section will illustrate some of the modeling methods that represent the electrical behavior of the EDLC.

Equivalent RC model The EDLC can be modeled as a simple RC circuit with a parallel resistance over the capacitor. Since the simplified model is used in the practical parts of this thesis, a more detailed explanation is presented. As mentioned earlier the electric behavior of an EDLC is more complex than of a conventional capacitor. The ideal conventional capacitor can store and convert energy without losses, while an EDLC has losses due to internal resistance and leakage currents [12]. To model this behavior a simple equivalent circuit is suggested in Figure 2.7.

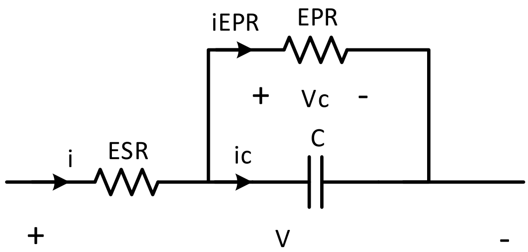

Figure 2.7 Simplified equivalent circuit of an EDLC. The model is constructed with an equivalent series resistor (ESR), equivalent parallel resistor (EPR) and a capacitor (C).

The equivalent parallel resistance (EPR) has a large resistance value ($k\Omega$ range) and models the losses due to current leakage, which has an influence on the long-term energy storage in the capacitor. The equivalent series resistance (ESR) has a smaller resistance value ($m\Omega$ range) and models the resistive losses in the current collectors and conductors, which is important during charge and discharge. It is also known that the power density of an EDLC is a function of the ESR i.e. a lower

ESR means a smaller time constant and thus more energy delivered per time unit. By using Figure 2.7 as a reference the charging current (i) can be expressed with the current through EPR and the capacitor (KCL). The expression can be seen in Equation 2.10.

$$i = i_{EPR} + i_C \tag{2.10}$$

By rewriting the expression in Equation 2.10 we get Equation 2.11.

$$\frac{V_C - V}{ESR} + \frac{V_C}{EPR} + C \cdot \frac{dV_C}{dt} = 0 \tag{2.11}$$

Equation 2.12 shows that the Equation can be seen as the derivative of a time dependent product. The expression is solved by using the integrating factor presented as α in Equation 2.13.

$$\left(\frac{1}{ESR} + \frac{1}{EPR}\right) \cdot \frac{1}{C} \cdot V_C - \frac{V}{ESR} \cdot \frac{1}{C} + \frac{dV_C}{dt} = 0 \tag{2.12}$$

$$\alpha = e^{\left(\frac{1}{ESR} + \frac{1}{EPR}\right) \cdot \frac{1}{C} \cdot t} \tag{2.13}$$

$$V_C(t) = V \cdot \frac{EPR}{ESR + EPR} \cdot \left(1 - e^{-\left(\frac{1}{ESR} + \frac{1}{EPR}\right) \cdot \frac{1}{C} \cdot t}\right) \tag{2.14}$$

Equation 2.14 gives that if the time (t) gets large, the stationary error between applied voltage and voltage over the capacitor is obtained by Equation 2.15.

$$V_C = V \cdot \frac{EPR}{ESR + EPR} \tag{2.15}$$

By knowing the values of ESR and EPR, their influence on the voltage can be established. Since normally EPR $\gg$ ESR, the difference between V and V_c is insignificant. Furthermore, the term one divided by EPR gets insignificant small and can be neglected. This means that during charge and discharge the EDLC can be seen as an RC-circuit, with properties like the one presented in Chapter 2.3, with a time constant obtained from Equation 2.16.

$$\tau = C \cdot ESR \tag{2.16}$$

Detailed equivalent circuit A common equivalent circuit, which captures the physical mechanisms in the EDLC, is called the transmission line network model [13]. This model can be represented with a complex network of nonlinear capacitors connected with resistances. The resistances in the model are e.g. resistance in the electrode material and resistance from the membrane that the mobile ions experience. An equivalent circuit is seen in Figure 2.8.

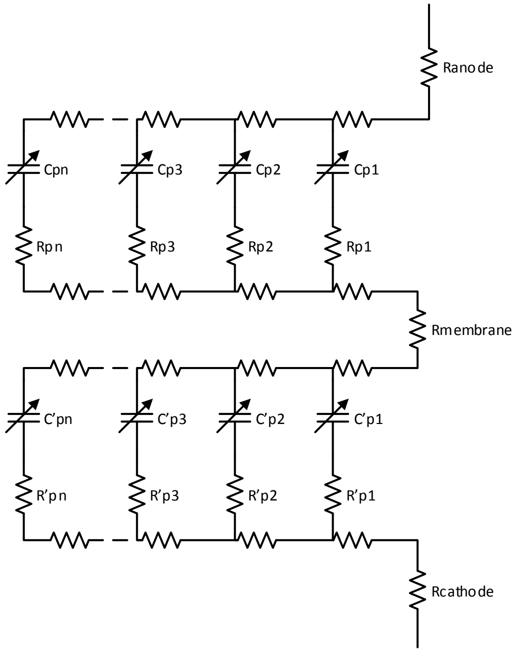

Figure 2.8 Detailed equivalent model of an EDLC: The transmission network line model is represented with a complex network of nonlinear capacitors connected with resistances.

The different resistances, seen in the transmission network line model, depends on various parameters e.g. resistivity of the electrolyte, resistivity of the electrode material, pore size, membrane porosity and how everything is packed together.

A more simplified version of the transmission line network model is called the ladder model. The ladder model is based on the Porous Electrode Theory developed by de Levie. Using this theory the ladder model can be derived according to Figure 2.9 [14].

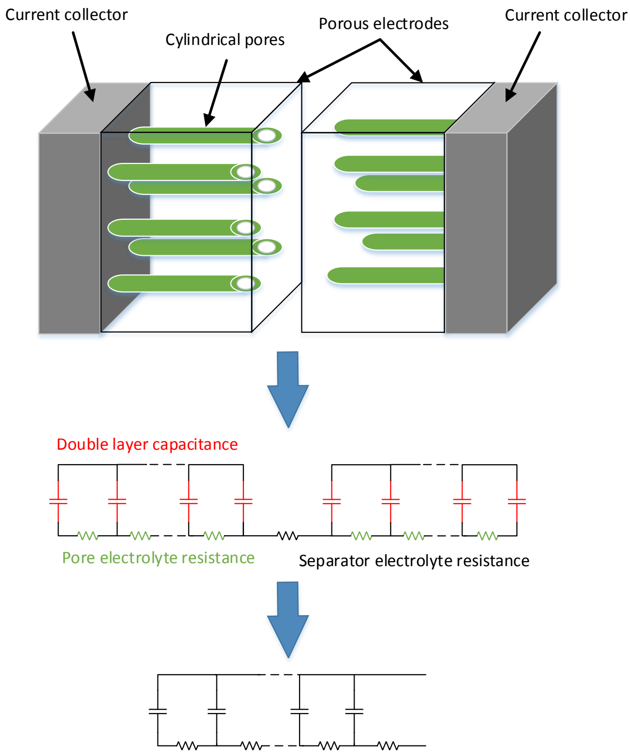

Figure 2.9 Detailed equivalent model of an EDLC: The ladder model. The pores are assumed to be cylindrical and each pore is modeled by an electrolyte resistance and a double-layer capacitance.

As seen in Figure 2.9, the pores in the electrodes are assumed to be cylindrical and filled with homogeneous electrolyte solution. Each single cylindrical pore is modeled by an equivalent pore electrolyte resistance and a double-layer capacitance. If these cylindrical pores on each electrode are identical and grouped together, the EDLC can be represented as a ladder network with potentially many RC elements. However, there are some inconveniences when using these complex models. It is very difficult to measure and calculate a fix value for each component. In e.g. back up applications, one is limited to the measurements that can be done automatically without proper lab equipment. Thereby, a more simplified equivalent model is needed.

Three branches model There are various models describing the electrical behavior of the EDLC e.g. the simplified model in Figure 2.7. This simplified model becomes insufficient when compared to experimentally collected data.

An extended model, which mimics the experimentally collected data better, is called the three branches model and is presented by Zubieta and Bonert in [15]. The model consists of three branches, where each branch has its own time constant. Each time constant differs from the other more than one order of magnitude, which makes the measurements of the parameters fairly easy. The branches are called immediate, delayed and long term branch, where the first one is represented by the parameters R_i, C_{i0} and $C_{i1} * V_{ci}$, which determines the behavior in the time range of seconds, the second is represented by R_d and C_d, which determines the terminal behavior in the range of minutes, the last and third one is represented by R_1 and C_1, which determines the behavior for times longer than ten minutes.The suggested equivalent circuit is seen in Figure 2.10.

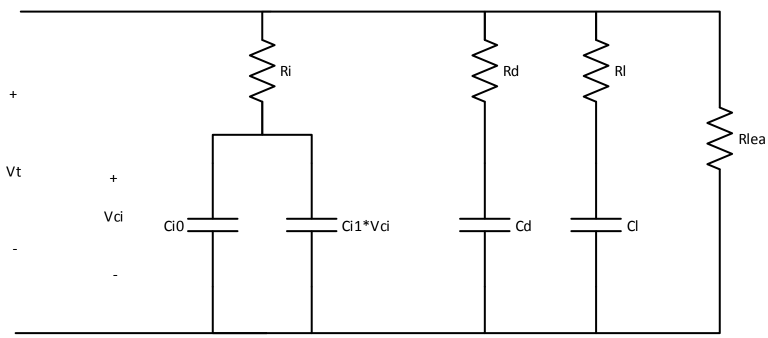

Figure 2.10 An equivalent model of an EDLC: The three branch model. Mimics the experimental behavior better than the simplified model.

As mentioned in previous sections, the capacitance of an EDLC is voltage dependent. To represent the voltage dependence of the capacitance, the immediate branch contains a differential capacitor which consists of a voltage dependent capacitor $C_{i1} * V_{ci}$ and a constant capacitance C_{i0}. The parallel resistance R_{lea} models the current leakage of the EDLC. In [15], Zubieta demonstrates that the circuit parameters, in Figure 2.10, can be determined with experimental measurements on the EDLCs terminals.

2.5.3 Charge and discharge characteristics

EDLCs can be charged and discharged with constant or non-constant current. In Figure 2.11, an EDLC is charged with constant current. Since some of the equations, mentioned in this report, are only valid at a constant current, this method of charging is preferred by the authors. To be able to discharge an EDLC with constant current an active load is required.

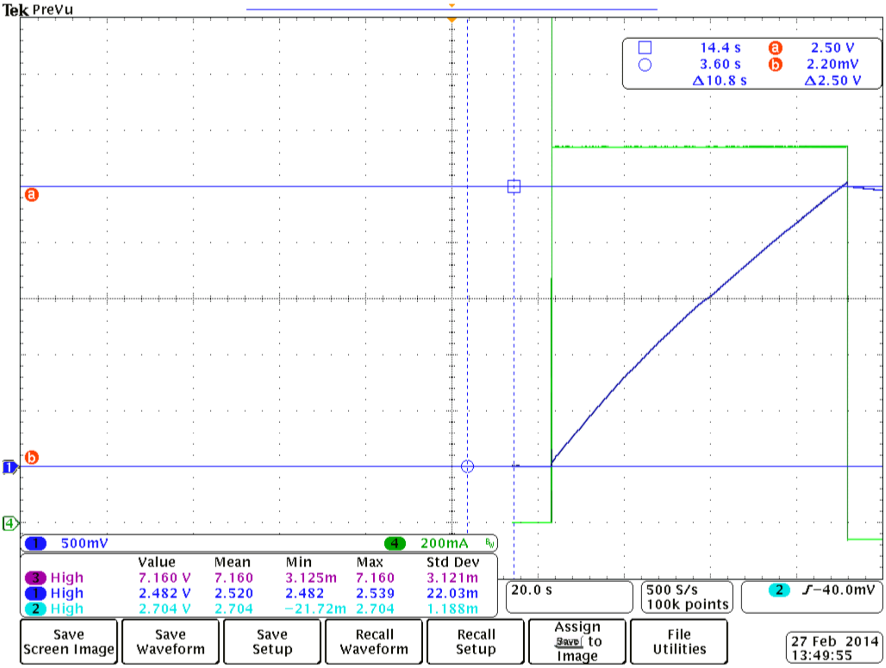

Figure 2.11 Charge of an EDLC during a constant current, where the green curve is the current and the blue is the voltage as function of time. The characteristic behavior is the initial voltage drop in the beginning, the nonlinear voltage dependence and voltage drop due to internal leakage current.

As mentioned above, capacitors can also be charged and discharged with a non-constant current. A discharge with non-constant current is displayed in Figure 2.12. A discharge of a capacitor through a resistive load is a typical case when the current is non constant.

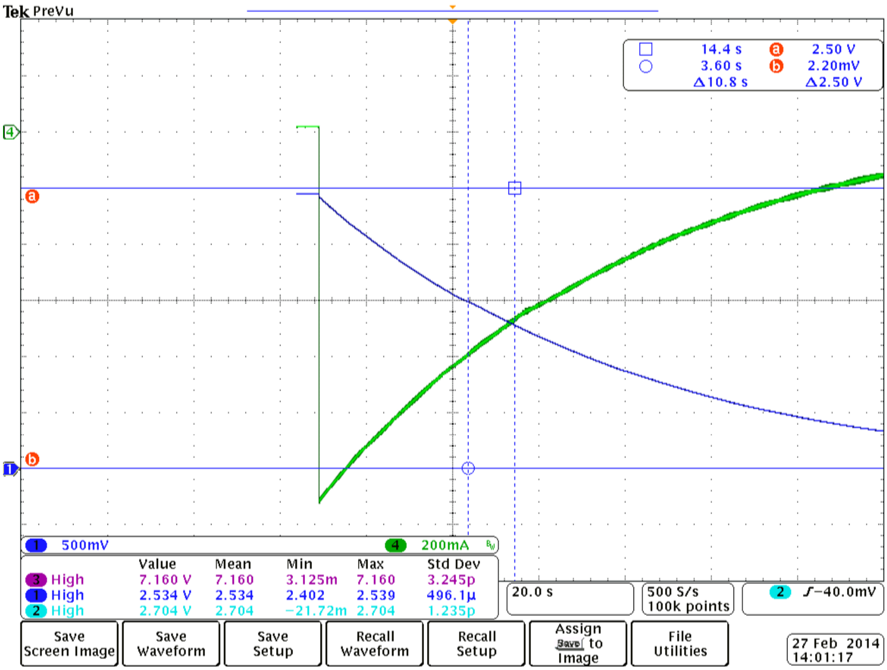

Figure 2.12 Discharge of an EDLC trough a resistance to ground, where green curve is the current and blue curve is the voltage as function of time. The voltage (blue) is decreasing over the EDLC and the current (green) shows the current delivered from the EDLC.

2.5.4 Voltage dependence

Unlike a conventional capacitor, the capacitance of an EDLC varies with the applied voltage. This physical phenomenon has its origin from the EDLCs complex physical structure. A typical relationship between capacitance and voltage is shown in Figure 2.13. [16]

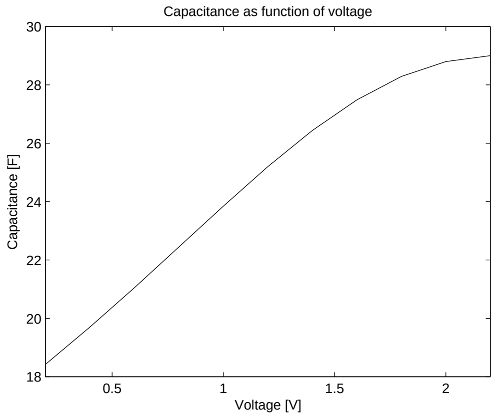

Figure 2.13 Capacitance as function of the voltage. At each given voltage level the EDLC has a certain capacitance value i.e. a high voltage gives a high capacitance value. This voltage dependent property is important to consider when studying the stored energy in an EDLC.

In [16], Rafik tries to explain the cause of this phenomenon. One possibility is that the dielectric constant of the electrolyte increases when the voltage increases, or that the distance, which separates the charges between the electrolyte and electrode, is reduced. Another possible explanation lies in the complex structure of the capacitance. The capacitance is represented as a compound of series connected capacitances of each electrode. These series connected capacitances have different contribution:

- The capacitance due to the applied voltage extends into the carbon electrode causing a space change .
- The Helmholtz layer capacitance C_m.
- The diffuse capacitance C_{di}.

The Helmholtz double layer capacitance is represented by a fixed electrostatic capacitance C_m [17]. Since the capacitance is fixed i.e. it does not change with the voltage, the Helmholtz capacitance cannot alone explain the behavior of the voltage dependency of the capacitance. The C-V characteristics can be explained by the diffused capacitance C_{di}. The capacitance can be expressed as a function of the applied voltage on the diffused double layer, see Equation 2.17.

$$C_{di}(v_{di}) = k_{GCa} \cdot cosh(k_{GCb} \cdot v_{di}) \tag{2.17}$$

Where v_{di} is the applied voltage on the diffused double layer and k_{GCa} and k_{GCb} are coefficients that originate from the Gouy - Chappman model. The capacitance described by the Gouy - Chappman model becomes insufficient when trying to explain the measured results. The equation that expresses the capacitance does not take into account the limitations on the capacitance at a completely discharged condition i.e. v_{di} equal to zero. Stern suggests that the deficiencies of the Helmholtz and Gouy - Chappman models can be limited by connecting them in series according to Equation 2.18.

$$\frac{1}{C(v)} = \frac{1}{C_m} + \frac{1}{C_{di}(v_{di})} \tag{2.18}$$

Other authors [11][13][15] model the voltage dependent capacitance through the so-called differential capacitor C_{diff} , seen in Equation 2.19.

$$C_{diff}(V) = \frac{dQ}{dV} \tag{2.19}$$

The differential capacitance is then rewritten as a constant and a voltage dependent capacitance in parallel i.e. it has the form: $C_{diff}(V) = C_0 + k_s \cdot V$, where C_0 is the capacitance close to zero voltage, V is the applied voltage and k_s is a constant value or a slope.

2.5.5 Temperature dependence

EDLCs are used in many applications where they experience different external conditions and temperatures. Therefore it is important to characterize the behavior of an EDLC at different temperatures. The temperature dependency at low frequencies is illustrated in Figure 2.14.

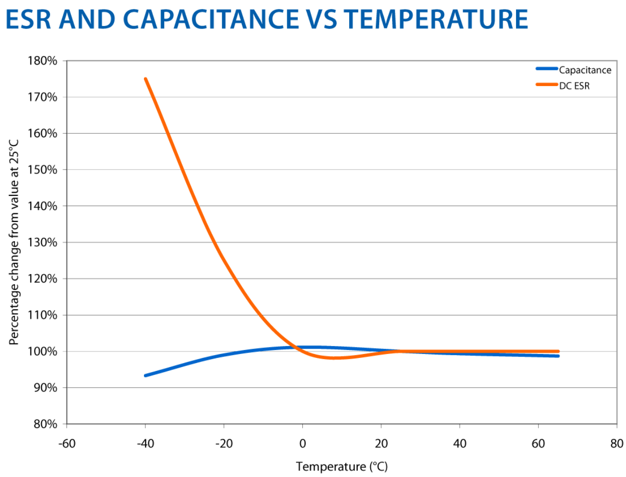

Figure 2.14 Temperature dependency of the capacitance (blue) and ESR (red) of an EDLC measured at low frequencies (DC) [18]. Compared to the rated values, the measured capacitance will be lower and the ESR will be higher for temperatures below 0 °C.

Temperatures below 0 °C have significant affect on an EDLC, the ESR decreases and the capacitance increases as the temperatures rises. It is mainly the ESR that is influenced by temperatures below 0 °C, since the resistivity of carbon and electrolytes, which the ESR characterizes, generally exhibits negative temperature coefficients [17].

Furthermore, the self-discharge rate of the EDLC is dependent on the temperature [19]. This is due to the acceleration of the ionic transport process when the temperature increases. The accelerated process will cause an excess concentration of ions near the electrodes of the EDLC, hence the diffusion will increase and thereby result in a higher self-discharge rate i.e. a higher value on the leakage resistance.

2.5.6 EDLC parameter measurements for equivalent RC model

The parameters that characterize the simplified model can easily be obtained with simple experiments with standard laboratory equipment i.e. oscilloscope, power supply etc. These three measurable parameters, the capacitance, ESR and EPR, can then be used to develop a first order approximation from the model in Figure 2.7.

Capacitance Contrary to a traditional capacitor, the capacitance value of an EDLC is not constant. The varying capacitance value is thereby more complicated to measure. To obtain the capacitance value the capacitor must either be charged or discharge and since the capacitance varies with the voltage, the voltage dependence must be taken into account. If one does not reflect on this the measurements will be inconsistent with the real capacitance value.

There are some different methods used for measuring the capacitance of an EDLC. The main method used in this thesis project is using the stored energy principle [12]. The change in energy, when charging or discharging the EDLC is expressed in Equation 2.20 and 2.21. As stated in Chapter 2.5.4 the EDLC is voltage dependent, which means that $C_1 \neq C_2$

$$\Delta E = \frac{1}{2} \cdot \left(C_2 \cdot V_2^2 - C_1 \cdot V_1^2\right) \tag{2.20}$$

Where the change in energy is derived from the difference in energy at the initial voltage and the final voltage. The change in energy is also calculated with the integral of the instantaneous power, Equation 2.21.

$$\Delta E = \int_{t_1}^{t_2} v(t) \cdot i(t)\, dt \tag{2.21}$$

By combining these two equations and making the assumption that V_1 is zero or that the capacitance C is constant during a voltage interval, the capacitance is calculated according to Equation 2.22.

$$C = \frac{2 \cdot \int_{t_1}^{t_2} v(t) \cdot i(t)\, dt}{\left(V_2^2 - V_1^2\right)} \tag{2.22}$$

The assumption that the capacitance is constant i.e. $C_1 = C_2$, is true if the voltage interval between V_1 to V_2 is made sufficiently small. If this is not true, the capacitance value obtained from Equation 2.22 cannot represent the actual capacitance value at a certain voltage V_2. The calculated capacitance will instead show a mean value in the interval V_1 to V_2. The same reasoning is applied if $V_1 = 0$.

Alternative method for capacitance measurements In this section, an alternative method for capacitance measurements is explained. This method is the most common used for measuring capacitance by manufacturers. A leading manufacturer of capacitors is Illinois Capacitor Inc [20]. As in the previous method, they use the same approach of charging or discharging the EDLC. Contrary to the method using the energy principle, they use a different expression and workflow to calculate the capacitance. For the capacitance measurements, Illinois Capacitor Inc suggests the circuit seen in Figure 2.15.

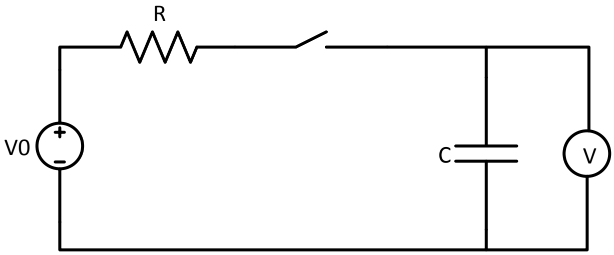

Figure 2.15 A suggested RC circuit setup for capacitance measurements of an EDLC. The EDLC is charged to its rated voltage and then discharged through a constant current load. During the discharge the capacitance can be calculated.

The capacitance value is then determined according following steps:

1. Charge the capacitor to the rated voltage.

2. Charge the capacitor at its rated voltage for a significant time (30min).

3. Discharge the capacitor through a constant current load.

4. Measure the time for the capacitor to discharge $V_1 = 0.7 \cdot V_{Rated}$ to $V_2 = 0.3 \cdot V_{rated}$.

5. Measure the voltages V_1 and V_2 and times t_1 and t_2.

6. Calculate the capacitance according to Equation 2.23 and Figure 2.16.

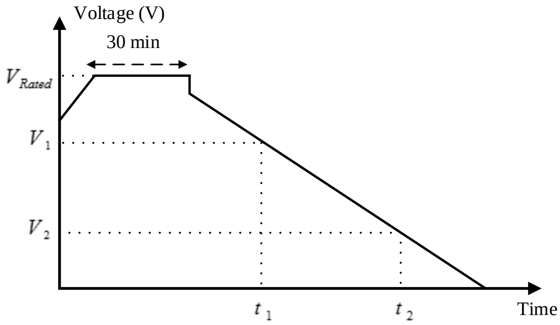

Figure 2.16 Charge and discharge curve for capacitance measurements recommended by Illinois Capacitor Inc.

Measuring the mentioned parameters above, the capacitance is calculated according to Equation 2.23.

$$C = I \cdot \frac{\Delta t}{\Delta V} = I \cdot \frac{t_2 - t_1}{V_1 - V_2} \tag{2.23}$$

Since the expressions accuracy is dependent on the current, it is mandatory to hold the current constant. If the current is varying, the accuracy of this capacitance calculations is not reliable.

ESR The simplest approach for determining the ESR is to measure the instantaneous response to constant current charge or discharge, with the assumption of zero stored energy as initial condition or fully charged capacitor [12]. The charge and discharge of an EDLC is illustrated in Figure 2.17.

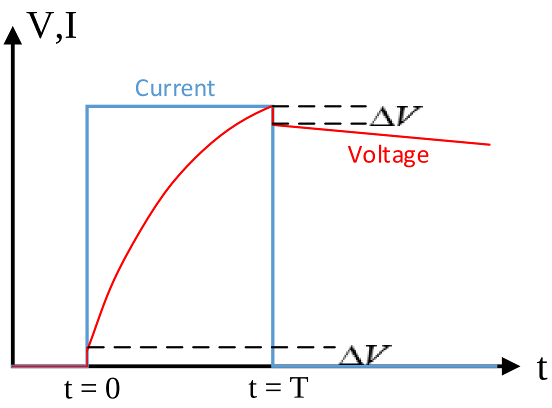

Figure 2.17 Charging of an EDLC with constant current plot, where the initial voltage step or the voltage step after the charge is used for the ESR calculations.

At time t = 0, there is an instantaneous voltage increase according to Figure 2.17. The change in voltage is related to ESR. By measuring the voltage drop and the current, ESR can by calculated with Equation 2.24.

$$ESR = \frac{\Delta V}{I} \tag{2.24}$$

EPR The EPR models the leakage or self-discharge which influences the long term energy storage and thus changes the terminal voltage over a long period [12]. Since this effect is generally small over long periods the capacitance can be assumed as the rated value. To calculate the EPR the following steps can be done:

- Slowly charge the capacitor to its rated voltage.
- Turn off the charger.
- Put EDLC in open circuit.
- Wait a significant amount of time to pass.
- Measure the capacitor's terminal voltage.

Since the voltage is exponentially decreasing with the time constant $\tau = EPR \cdot C$, the EPR can be calculated according to Equation 2.25.

$$V_2 = V_1 \cdot e^{\frac{-t}{EPR \cdot C}} \Leftrightarrow EPR = \frac{-t}{ln\left(\frac{V_2}{V_1}\right) \cdot C} \tag{2.25}$$

where V_1 is the initial voltage, V_2 the final voltage, t the time between initial and final voltage and C the rated capacitance. According to Spyker and Nelms [12] the time constant of EPR and C is usually quite large and if the transient capacitor discharge is shorter than a few minutes then the EPR can be ignored.

2.5.7 Aging

When using EDLCs with direct current (DC), a RC-circuit may be a sufficient model of the EDLC. This means that the EDLC has an inner resistant (ESR) in series with a capacitor. Both the capacitance and the inner resistance are affected by the two most predominated aging factors, temperature and voltage [21]. In practice, this means that the capacitance will decrease and the ESR will increase with time. If both the voltage and temperature are held low, the degradation may be insignificantly small. By performing an accelerated lifetime test, the rate that the EDLC is degrading with can be established.

The decrease of the capacitance The capacitance in an EDLC is decreasing with time, temperature and voltage. The results from an accelerated lifetime test and the data provided by the suppliers are the basis for modeling the decrease in capacitance of an EDLC. According to Cooperbussmann [22], the capacitance drop over time can be divided into four sections. Two of the sections have exponential behavior (1) (3) and the other two have a linear behavior (2) (4), seen in Figure 2.18.

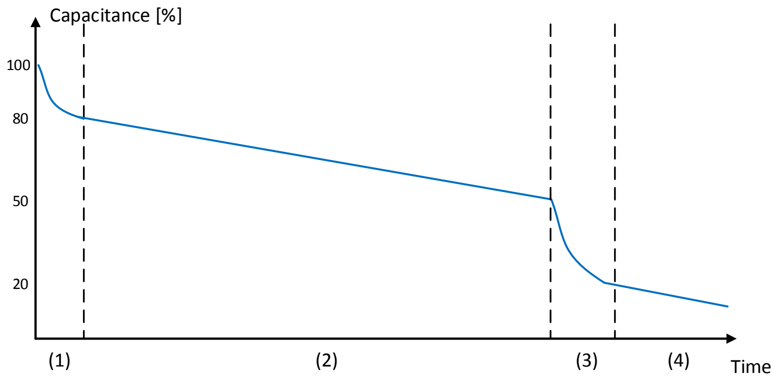

Figure 2.18 A generalized curve of the capacitance as function of time for an EDLC. The capacitance degradation consists of exponential and linear sections. In this thesis only the initial exponential and the following linear decrease is studied.

Seen in Figure 2.18, at first the EDLC experiences an exponential drop to approximately 80% of its initial value, and then the capacitance is slowly decreasing with a constant slope. When the capacitance has dropped to approximately 50% of its initial value, there is again an exponential drop to about $15-20\%$. In the last section the capacitance is decreasing linearly. When the capacitance has decreased to 50% of its initial value, this point is defined as the End of Life (EOL). The sections (3) and (4) will not be studied in this thesis.

Lifetime calculations Automation applications require robust design and long lifetime. Therefore lifetime estimations of electrical components are important. If EDLCs are used as backup power source, they are required to have a lifetime above 10 years. Since 10 years is a long time, the need of an adequate lifetime estimation method is desired. This section describes the fundamental expressions when trying to estimate the lifetime of an EDLC. A general equation used for the lifetime estimation is expressed in Equation 2.26 [23]

$$L = L_B \cdot f_1\left(T_M - T_C\right) \cdot f_2\left(V\right) \tag{2.26}$$

where the L is the estimated life, L_B is expected service life at rated voltage and temperature, T_M is the rated temperature, T_C is the actual core temperature, $f_1(T_M - T_C)$ describes the effect of temperature and $f_2(V)$ describes the effect of voltage on an EDLC. The function f_1, which describes the effect of the temperature, is expressed with the Law of Arrhenius, seen in Equation 2.27.

$$f_1 = e^{\frac{E_a}{k}\cdot\left(\frac{1}{T_C}-\frac{1}{T_M}\right)} = e^{\frac{E_a}{k}\cdot\left(\frac{T_M-T_C}{T_C\cdot T_M}\right)} \tag{2.27}$$

The Law of Arrhenius or the Arrhenius equation is a very simple formula which describes the temperature dependence of chemical reaction rates. The new parameters from Equation 2.27 are the activation energy E_a and Boltzmann constant k, where k is equal to $1.38065 \cdot 10^{-23}\frac{J}{K}$ or $8.617 \cdot 10^{-5}\frac{eV}{K}$. In the EDLC industry there are two common expressions or rules of thumb: the lifetime doubles for every $10\,°\text{C}$ drop in temperature and a decrease in 0.3V in voltage doubles the lifetime. The first mentioned rule of thumb is derived when rearranging the Arrhenius equation from Equation 2.27. By using that the activation energy for anodic alumina is $E_a = 0.94eV$ and that the highest usage electrolytic temperature is $125\,°\text{C}$ or 398K. The Arrhenius equation is rewritten as Equation 2.28.

$$f_1 = e^{\frac{0.94}{8.617\cdot 10^{-5}}\cdot\frac{(T_M-T_C)}{398^2}} = e^{ln(2)\cdot\frac{(T_M-T_C)}{10}} = 2^{\frac{(T_M-T_C)}{10}} \tag{2.28}$$

The function f_2, which describes the effect of the voltage, is stated by the second rule of thumb i.e. a decrease in 0.3V in voltage doubles the lifetime. The expression is seen in Equation 2.29 [24][22].

$$f_2\left(V\right) = 2^{\frac{V_{Rated}-V}{0.3}} \tag{2.29}$$

where V is the operating voltage and V_{Rated} is the rated or reference voltage.

2.6 Simulation Tools

2.6.1 Simulink Matlab

Simulink is a powerful simulation tool that can simulate, model and analyze dynamic systems. The developer uses a graphical interface when building the models. The models are from modules from component libraries that can represent real parts, e.g. a resistor or a voltage source.

Since real processes have different time constants it can be difficult to study them in reality, this can be the case if the system is very fast or extremely slow. By creating a sufficiently good model the system can be simulated and it is therefore possible to study events that for instance will happen in a distant future. [26].

Solving differential equations in Simulink In Chapter 2.3 the differential equation for a RC circuit (Figure 2.2) was solved using an integrating factor. By creating a graphical model in Simulink from the same differential equation:

$$V = V_R + V_C = i \cdot R + V_C = R \cdot C \cdot \frac{dV_C}{dt} + V_C \tag{2.30}$$

If Equation 2.30 is rewritten with the voltage V set to zero Equation 2.31 is obtained. By using Equation 2.31 as a reference, the model in Figure 2.19 can be created.

$$V_C = \int -\frac{1}{R \cdot C} \cdot V_R dt \tag{2.31}$$

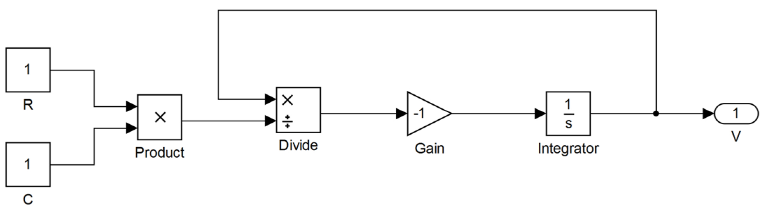

Figure 2.19 Equation 2.31 implemented using blocks from the Simulink library.

2.6.2 LTSpice

SPICE stands for "Simulation Program with Integrated Circuit Emphasis" and was initially developed under a different name, "Computer Analysis of Nonlinear Circuits", as a project at University of California in the 1960s. During the years, a lot of different commercial Spice tools have been developed. Linear Technology is distributing their own version of SPICE, called LTSpice. LTSpice is a freeware and according to Linear Technology, "a high performance SPICE simulator, schematic capture and waveform viewer with enhancements and models for easing the simulation of switching regulators. Our enhancements to SPICE have made simulating switching regulators extremely fast compared to normal SPICE simulators, allowing the user to view waveforms for most switching regulators in just a few minutes" (Linear Technology). LTSpice is today a commonly used tool for designing analog circuits both commercially and educationally [27].

2.7 Balancing circuits

Power storage applications often consist of several cells connected in series and/or in parallel. Due to inconsistencies in the manufacturing process, the individual cells differ in parameter values. This means that if e.g. two cells are connected in series, the voltage over each cell will not be equal during operation. To ensure that the voltage over the cells is divided equally between each other, balancing is required. The balancing is achieved through active or passive balancing circuits.

2.7.1 Passive balancing

The simplest solution for balancing series connected cells is to connect a passive resistor across each capacitor cell [25]. These resistors are balancing the cell-voltage by dissipating the energy, created by over-voltage, as thermal effect. The advantage of this passive method is due its simplicity and low cost. The drawback of this method is; the high power losses that occur in the passive resistors across the cells. If the charge current is high the balancing resistors must have low resistance in order for the balancing to be effective. Therefore, passive balancing is mostly used in applications with low duty cycles e.g. backup power systems [24]. A simple balancing circuit with passive resistors is seen in Figure 2.20.

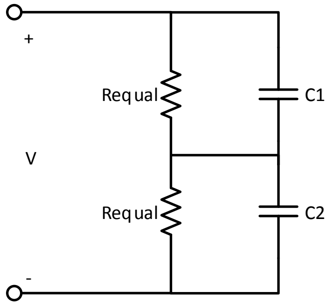

Figure 2.20 Passive voltage balancing of two in series connected EDLC's.

2.7.2 Active balancing

Active balancing is used in applications where high duty cycle and low parasitic losses are not allowed [24]. An active balancing circuit is nonlinear and works by forcing the voltage at the nodes of series connected EDLCs to be fixed to the same voltage reference. There are a number of electrical designs to achieve active balancing and many are patented. The simplest solution for active balancing is to integrate comparators with a fix reference value to the series connected EDLCs, seen in Figure 2.21.

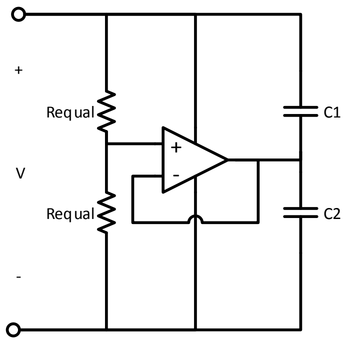

Figure 2.21 Active voltage balancing of two in series connected EDLCs.

2.8 Control theory

The term automatic control is becoming a more common element in our daily live. This is due to the fast development of sophisticated computers, which enables us to build more advanced control and monitoring systems. Furthermore, various types of control designs can today be implemented in various types of products and facilities e.g. consumer electronics, process industry, energy industry etc. A simple control system is seen in Figure 2.22.

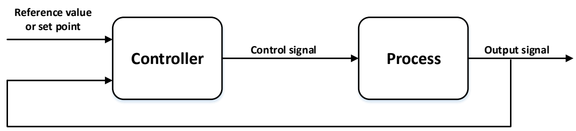

Figure 2.22 A simple control system with a controller and a process with its in- and outputs.

The simple control system consists of two major parts, the controller and the process [30][31]. The controller and the process are usually connected with a feedback loop i.e. they are a closed system. The process input signal, or control signal, affects the process behavior. The process output, or the measured signal, gives the information of the actual behavior of the process. The controller has two inputs: a reference value or set point and the process output. The controller error is the difference between the reference value and the process. The controller adjusts this error to make it as small as possible and then sends this information to the process input. Since the relation between the process in- and output act as a dynamical system i.e. if the process input (the control signal) changes its value, the change will then not be instantaneous on the process output. The control system can either be described as a continuous- or discrete-time system. The main focus will lie in the practical aspects of the controller design and its implementation.

2.8.1 PI controller

PI control is a name generally given to the two term control. The initials PI refer to the first names of the individual term of the controller, where the P stands for the proportional term and I for the Integral term. This two term controller is probably the most commonly encountered controller in the industry. The PI controller produces an output signal (the control signal) that is the sum of two terms [30]. The first term (P) is proportional to the current value of the controller error i.e. the difference between the reference value (the set point) and the process output. The second term (I) is based on the controller error history. The equation of a typical continuous-time PI controller has the from seen in Equation 2.32 and 2.33

$$u(t) = K \cdot \left(e(t) + \frac{1}{T_i} \int_0^t e(\tau)\, d\tau \right) \tag{2.32}$$

$$U(s) = K \cdot \left(E(s) + \frac{1}{s \cdot T_i} \cdot E(s) \right) = P + I \tag{2.33}$$

where K is the gain or proportional gain and T_i is the integration time or reset time. The Signal framework of inputs and outputs which are discussed in this section, are seen in Figure 2.23.

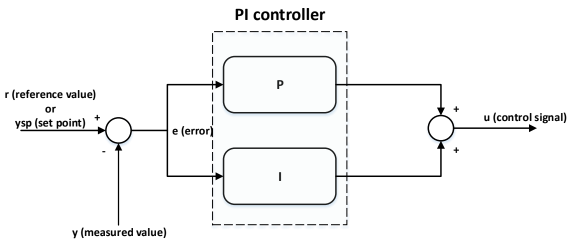

Figure 2.23 A basic structure of the PI controllers in- and outputs.

PI controllers were originally implemented using analog technology e.g. relays, analog electronics etc. Today almost all PI controllers are implemented digitally i.e. a discretization of the continuous-time PI controller is made. The discretization is further explained later in this section.

Proportional term The control signal from a typical proportional controller (P controller) is expressed in Equation 2.34 [30].

$$u = K \cdot (y_{sp} - y) + u_b = K \cdot e + u_b \tag{2.34}$$

where e is the controller error, K is the proportional gain and u_b is the bias or reset term. The reset term is adjustable and used to give a desired steady state value. Since the output of a P controller is always limited, the Equation 2.34 can only be used in a limited range. The input output relationship of a P controller is represented in Figure 2.24 [31].

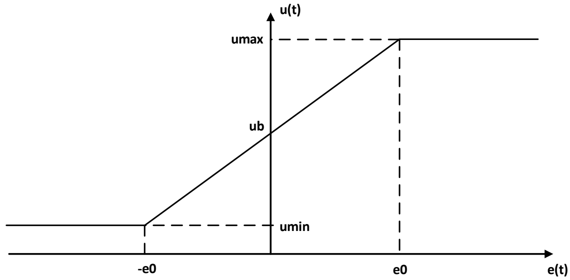

Figure 2.24 The input/output relation of a P controller.

When using a P controller one should be aware of the problem that the steady state error might not be zero. The non-zero steady state error can be described by rewriting Equation 2.34 to Equation 2.35.

$$e = \frac{u - u_b}{K} \tag{2.35}$$

In steady state, the controller error e can only become zero if one of the following two conditions are fulfilled [30]:

1. K = ∞ (infinity)

2. u = u_b

The first condition is practically impossible and will result in an oscillating system. As mentioned above u_b can be adjustable and this parameter should be chosen, close to u, to minimize the error.

Integral term The steady state error is eliminated by adjusting the reset term u_b close to the control signal u [31]. In the early controllers the reset parameter was manually adjusted. This became a tedious adjustment and a more automated solution was desired. By allowing the reset term to automatically adjust itself to reach u = u_b, the steady state error was eliminated [30]. The approach to find the reset term was to add a low pass filter and filter the control signal through it, then the output signal from the filter was added to the control signal, seen Figure 2.25.

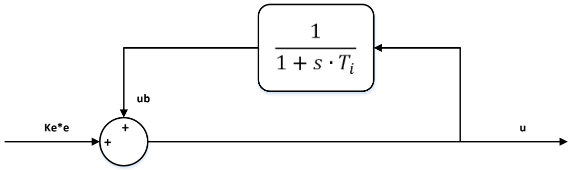

Figure 2.25 Automatically adjusted rest term in a controller.

This resulted in the input output relation of a PI controller seen in Equation 2.36.

$$u(t) = K_e \cdot \left(e(t) + \frac{1}{T_i} \int_0^t e(\tau)\, d\tau \right) = P + I \tag{2.36}$$

where the reset term u_b is replaced with an integral. However, when introducing an integral term one should be aware of the negative effect on the speed of the response and the stability of the system i.e. overshoots and oscillations.

2.8.2 Integrator windup

In a process, there are some limitations in the output of any actuator e.g. the speed of a motor. The speed of a motor is limited to a maximum speed i.e. the speed of a motor cannot be increased further although if the PI controller would demand it. When the control signal reaches the actuator limits the feedback loop is broken and the system will run in an open loop. Thus, there will be an insufficient control signal to eliminate the controlling error. As the main function of the integral term is to make sure that the error disappears, the integral term will increase which leads to an increase in the control signal. There will now be a difference between the desired control signal and the actual signal to the actuator [30][31]. Figure 2.26 illustrates the effect of the desired and actual control signal on the actuator.

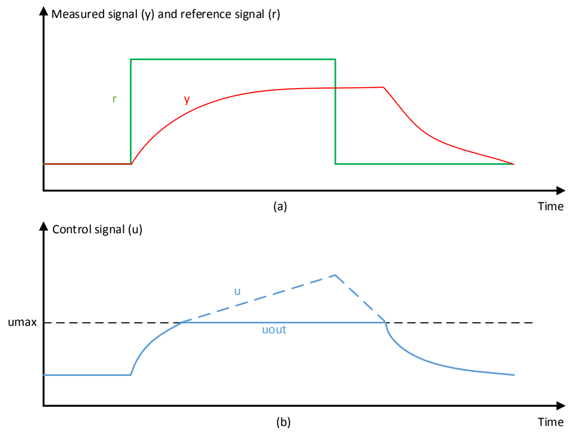

Figure 2.26 Integrator windup at saturating actuator.

When the reference value to the controller is decreased to a level where the controller can reduce the error, the error will change signs and the control signal will decrease. The control signal of the actuator will not leave the saturation until the negative error reduces the integrator term sufficient. This phenomenon with a combination of a saturating actuator and an increasing integrator term in the controller is called an integrator windup.

This phenomenon can be counteracted with different types of anti windup methods. The method used in this thesis project is called back-calculation or tracking and will be further explained. It works as following: when the controller output saturates, the back-calculation method recalculates the integral and gives a new value on the output. The integral action is not reset instantaneously but rather dynamically with a time constant K_s. A PI controller and an anti-windup based on back calculation are illustrated in Figure 2.27.

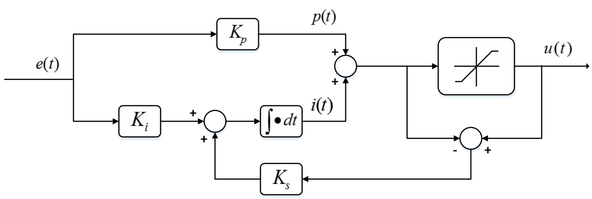

Figure 2.27 PI controller with an anti-windup based back-calculation.

2.8.3 Implementation

PI controllers were originally implemented using analog technology e.g. relays, analog electronics etc. Today almost all PI controllers are implemented digitally i.e. using a microprocessor [30]. The microprocessor or computer operates periodically, with sampling analog signal, conversion from A/D converters, control signal computation and then conversion to analog signal to the actuators. As mentioned before the PI controller is a continuous-time system. To be able to implement the continuous-time system, by a computer, the PI controller has to be approximated by a discrete-time system.

Discretization The P term, in continuous-time, consists of the proportional gain K multiplied with the error $e = y_{sp} - y$ i.e. the control signal is proportional to the error [30]. To avoid severe overshoots, an attenuation constant can be multiplied with the reference value . This method is called setpoint weighting. The continuous-time P term is now expressed in Equation 2.37.

$$P = K \cdot (b \cdot y_{sp} - y) \tag{2.37}$$

The discretization of the P term is very simple, Equation 2.32 variables are only replaced with its sampled version seen in Equation 2.38.

$$P(t_k) = K \cdot (b \cdot y_{sp}(t_k) - y(t_k)) \tag{2.38}$$

where t_k is the times when the computer reads the analog input i.e. the sampling instant.

The I term, in continuous-time, consists of the integral gain multiplied by the integral of the error, seen in Equation 2.39 [30].

$$I = \frac{K}{T_i} \int_0^t e(s)\, ds \Leftrightarrow \frac{dI}{dt} = \frac{K}{T_i} \cdot e \tag{2.39}$$

where K is the proportional gain and T_i is the reset time.

There are several approaches to discretize 2.39 using e.g. backward difference, forward difference or Tustin's approximation. Since the method used in this master thesis project was forward difference, thus the forward difference will be further explained. Replacing the variables with its sampled version gives the expression seen in Equation 2.40.

$$\frac{dI(t_k)}{dt_k} = \frac{K}{T_i} \cdot e(t_k) \tag{2.40}$$

Using the forward difference approximation gives the expression seen in Equation 2.41.

$$\frac{I(t_{k+1}) - I(t_k)}{h} = \frac{K}{T_i} \cdot e(t_k) \Leftrightarrow I(t_{k+1}) = I(t_k) + \frac{K \cdot h}{T_i} e(t_k) \tag{2.41}$$

Implementation of anti-windup with back-calculation Back-calculation is an anti-windup method which prevents the integral to increase too much, which causes undesired behavior on the control signal. This anti-windup system is implemented according to Equation 2.42 and 2.43 [30].

$$I\left(t_{k+1}\right) = I\left(t_k\right) + \frac{K \cdot h}{T_i} e\left(t_k\right) + \frac{h}{T_r} e_s\left(t_k\right) \tag{2.42}$$

and

$$e_s\left(t_k\right) = u\left(t_k\right) - v\left(t_k\right) \tag{2.43}$$

where $u(t_k)$ is the previous control signal and $v(t_k)$ is the new updated control signal.

3

Experimental setups and measurements

In this chapter, different experimental setups and measurements are explained. The different measurements are done in order to get at better understanding of the EDLC and its properties. The most important properties in this thesis are related to voltage and temperature dependency. All the explained experiments are therefore related to how voltage and temperature affects an EDLC. The results from this chapter are presented in Chapter 5.

3.1 Laboratory equipment

Since the EDLCs have a complex behavior, measurements have to be done in order to better understand and model its behavior. The measurements on the EDLC were carried out at Schneider Electrics laboratory in Malmö. The equipment used was:

- Temperature chamber Binder MK53 06-98130
- Power supply TTi OPX1200 60V 50A PSU Power Flex
- Power supply ES 030-5
- Tektronix DPO 4034 Digital Phosphor Oscilloscope (350Mhz)
- Tektronix TCP0030 120MHz (Current probe)
- Tektronix P6139A voltage probe (500MHz, 8.0pF, 10MΩ)
- FLUKE 87 TRUE RMS MULTIMETER
- FLUKE 45 DUAL DISPLAY MULTIMETER
- Maxwell BCAP0025 P270 T01

- Cooperbussmann HB1625-2R5256-R
- Electrical components e.g. resistors, operational amplifier, capacitors etc.

3.2 EDLC specifications

The EDLCs studied in this thesis are BCAP0025 (Maxwell Technologies) and HB1625-2R5256-R (Cooper Industries), seen in Figure 3.1. The corresponding product specifications are seen in Table 3.1 and 3.2.

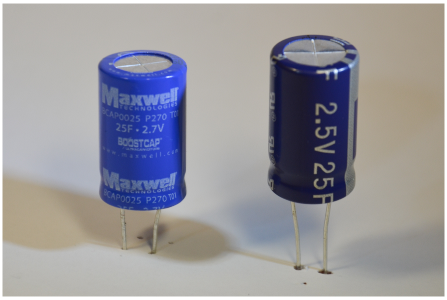

Figure 3.1 Two different kinds of EDLCs. To the left: BCAP0025 (Maxwell Technologies), and to the right: HB1625-2R5256-R (Cooper Industries).

Table 3.1 Product specification of BCAP0025 [17].

Rated Capacitance	25F
Minimum capacitance initial	25F
Rated Voltage (65 °C / 85 °C)	2.7 / 2.3V
Maximum ESR (65 °C / 85 °C)	42mΩ
Leakage current max	0.045mA
Short circuit current (65 °C / 85 °C)	64 / 55A
Operating temperature range	-40 °C to (65 °C / 85 °C)
Mass module	7.5g
Power density (max) (65 °C / 85 °C)	2800 / 2000W/kg
Energy density (max) (65 °C / 85 °C)	3.4 / 2.4Wh/kg
Life at rated voltage and maximum operating temperature.	1000h, 30% decrease in capacitance, 100% increase in ESR
Life at rated voltage and 25 °C.	10 year, 30% decrease in capacitance, 100% increase in ESR

Table 3.2 Product specification of HB1625-2R5256-R [32].

Rated Capacitance	25F
Minimum capacitance initial	-10% to +30% (20°C)
Rated Voltage (70°C / +85°C)	2.5 / 2.1V
Maximum ESR at 100Hz	40mΩ
Nominal Leakage current after 72h at (20°C)	0.028mA
Operating temperature range	-25°C to +70°C at 2.5V -25°C to +85°C at 2.1V
Mass module	8.2g
Life at 70°C and 2.5V	1000h, 30% decrease in capacitance, 200% increase in ESR

The EDLCs named above are capable of operating from zero voltage to its rated voltage. The main difference between BCAP0025 and HB1625-2R5256-R is the electrolytes. The capacitors from Maxwell Technologies contains the organic electrolyte called Acetonitrile (AN), while Cooper Industries uses Propylene Carbonate (PC) [32][33]. The organic electrolyte AN enables higher operating voltages and utilization in a wider range of temperature compared to PC [34]. The EDLCs should not be operating beyond their specified rated voltages. An operating voltage above the rated will result in a significant shorter lifetime. Another important remark is that if the operating voltage is above the rated, the electrolyte might evolve cyanide gas in small portions. In order to ensure optimal performance the EDLC should be utilized between half rated and rated voltage [32].

3.3 Charge and discharge

The goal of the test was to study the charge and discharge behavior of EDLCs. The EDLC was connected in parallel with a constant current source and two switches. One switch controlled the charging (1) and the other removed current spikes from the power box (2). To measure the current and voltage, a current and voltage probe were connected to an oscilloscope seen Figure 3.2.

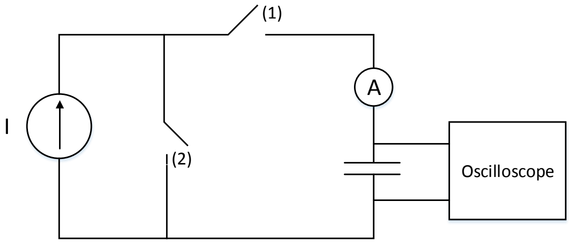

Figure 3.2 The circuit from the test set up. Initially (2) is closed. When charging (1) should be closed and (2) open.

The capacitor was charged to approximately its rated voltage with a constant current. From this data the capacitance and ESR were calculated according to Equation 2.22 and 2.24. Furthermore, to determine the EPR the capacitor was put in open circuit for a significant amount of time and EPR was calculated according to Equation 2.25. The correspond results are presented in Chapter 5.1.1.

3.4 In-circuit capacitance measurement

The input to a typical PI controller is the controller error i.e. the reference value subtracted with the measured value of the process output. Since the calculations of the reference values are based on the capacitance, a method for in-circuit capacitance measurements is explained. Based on the theory, the capacitance can only be measured if the capacitor is either charged or discharged. The question is: how small charges or discharges can be made and still give a fairly accurate capacitance value?

To be able to verify a high accuracy of the in-circuit capacitance measurements, capacitance reference values had to be obtained. The reference values were calculated using obtained data from charging an EDLC with constant current. The voltage was increased from zero to rated voltage. The result was presented in a C-V plot, showing the relationship between applied voltage and capacitance value.

The in-circuit capacitance measurements were carried out by performing a small voltage increase, approximately 0.1V per capacitor. The voltage was then decreased with the same amount to its initial voltage value. A calculated capacitance value was obtained both from the charge and the discharge. Since the voltage change is kept as small as possible, we assume the capacitance to be constant during this interval, see Equation 2.22. These value were then compared with the C-V plot.

Both the voltage and the current values were collected and thus the capacitance value was calculated according to the energy principle Equation 2.22. The results are provided in Chapter 5.1.2.

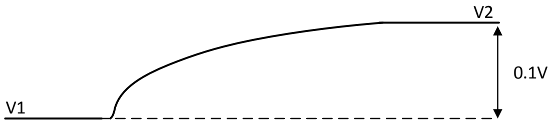

Figure 3.3 Small charges to determine the accuracy of capacitance measurements. The voltage is charged to steady state (V1) and then a small charge is made to a new voltage level (V2).

3.5 Accelerated lifetime test

For various reasons the properties of Electrochemical Double-Layer Capacitors change with time. The aim of this section is to study these changes during an accelerated lifetime test. The result of an accelerated lifetime test is crucial for understanding the long term effects. The results from the tests will be a key part for the simulations of the complete backup system. The accelerated lifetime test is based on stressing EDLCs with high temperature (approximately 70 °C) at predefined voltage levels. The main purpose of the test is to investigate the exponential and linear capacitance drop for different voltages when stressed at high temperature. The test was performed in a temperature chamber (Binder) seen in Figure 3.4.

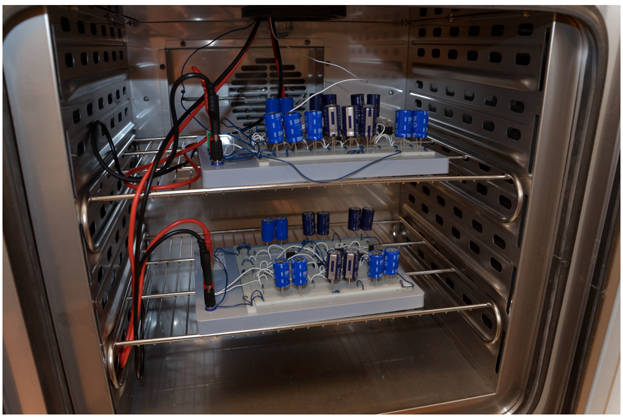

Figure 3.4 The temperature chamber used during the accelerated lifetime tests, where the temperature was held at 70 °C.

In the accelerated lifetime test, 36 EDLCs from two different suppliers were tested. The EDLCs tested were BCAP0025 (Maxwell Technologies) and HB1625-2R5256-R (Cooperbussmann). Their product specifications are shown in Table 3.1

and 3.2 (see previous section). The 36 EDLCs were divided into six groups consisting of six EDLCs in each group (three capacitors from each supplier). Each group was stressed at a predefined voltage level from 1.0 – 2.5V with steps of 0.3V i.e. the first group of EDLCs were stressed at 1.0V, the second at 1.3V etc. To be able to apply the mentioned voltages and guarantee that each EDLC is independent of the other, an electrical circuit was designed (see Appendix A for detailed circuit description).

The circuit was built with suitable electrical components on two breadboards. One of these breadboards, with its electrical circuit, is seen in Figure 3.5.

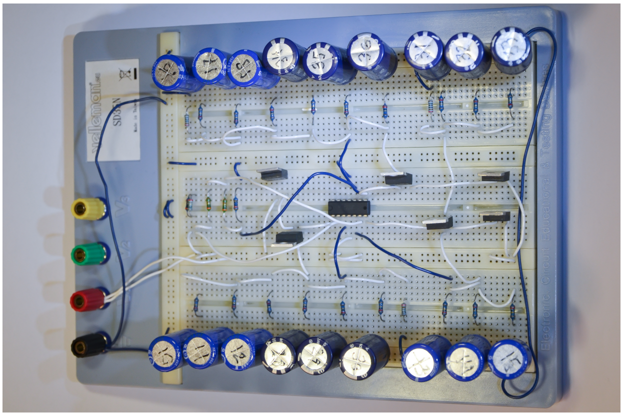

Figure 3.5 Breadboard with the electrical circuit used for the accelerated lifetime test.

By exposing different capacitors to different voltages, the changing properties of the capacitor were studied. The experiment was divided into two parts:

1. The experiment lasted for about 1000h and every 168th hour the capacitance and ESR value on each capacitor were measured.

2. After 1000h the voltage was increased with 0.3V on the capacitors that were initially stressed with voltages 1.0 – 2.2V. The voltage level for capacitors stressed at 2.5V was maintained. The experiment lasted another 1000h.

The measurements were made in room temperature with the following steps:

- The capacitors were cooled down to room temperature.
- The capacitors were discharged to zero potential over its terminals.
- Each capacitor was charged from zero to 2.5V.

- The capacitance and ESR were calculated. The capacitance was calculated using the energy principle from Equation 2.22.
- The C-V curve for each capacitance was plotted.

Given the measured capacitance and ESR values, a suitable curve fit was used. The curve fit was then evaluated, this was done in order to predict when the EDLCs would reach their end of life i.e. 50% of its initial capacitance value. For this purpose nonlinear least square methods were used to find a suitable extrapolating function. In order to know if the extrapolating function gave proper values, the functions were compared to the manufacturer specifications, Figure 3.6.

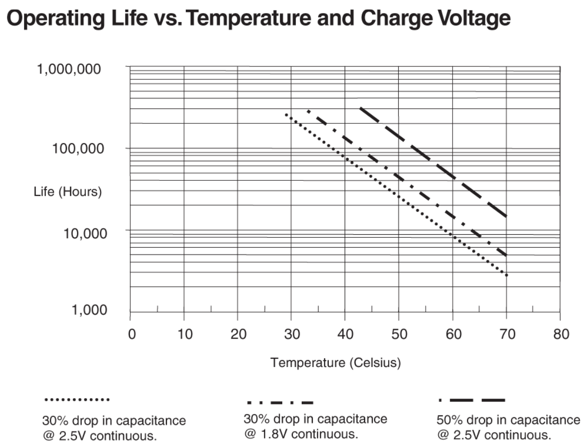

Figure 3.6 Application guidelines for Cooper Industries [24].

Other guidelines from the manufacturer were the rule of thumbs for decrease in temperature and voltage. The rules of thumbs are:

- A decrease with 0.3V in voltage will increase the lifetime with the double.
- A decrease with 10 °C in temperature will increase the lifetime with the double.

With these guidelines and the Curve Fitting toolbox in Matlab the end of lifetime was predicted. The results from the accelerated lifetime tests can be seen in Chapter 5.1.3.

3.6 Instantaneous temperature dependence

The products, which use EDLCs as backup power source, can be exposed to a wide range of temperatures. As mentioned in the theoretical parts, the EDLCs are temperature dependent i.e. their behavior changes when they are stressed with different temperatures. The goal of this experiment was to investigate, if and how, the instantaneous temperature changes affect the capacitance and ESR. To perform the instantaneous temperature tests, one EDLC from each supplier was selected. Each EDLC was discharged to zero potential and stressed at five different temperatures i.e. -20, 0, +30, +50 and +70°C. The EDLCs were stressed at each temperature level during 40 minutes. At each 40th minute mark, the capacitance and ESR were measured during a charge from 0 to 2.5V. After the measurement was completed the EDLCs were discharged and the temperature was increased to a new level. This procedure was then repeated every 40 minutes. The test setup, with the used laboratory equipment, is seen in Figure 3.7. A more detailed sketch is seen in Figure 3.8. The results from this experiment can be seen in Chapter 5.1.4.

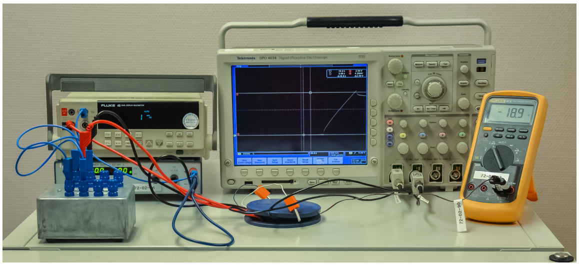

Figure 3.7 The test setup and equipment used for the instantaneous temperature dependence measurements.

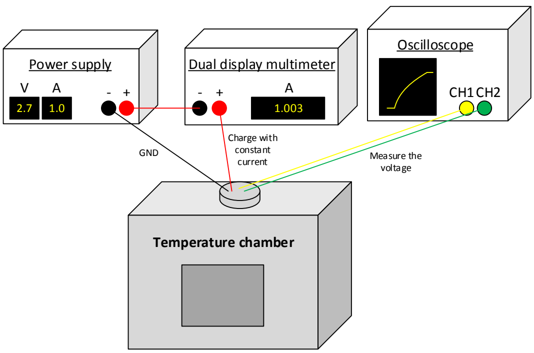

Figure 3.8 A sketch of the test setup for the instantaneous temperature dependence measurements.

4

Modeling and Simulation

To be able to provide a complete backup power source, using EDLCs, a great deal of properties and relationships needs to be studied toughly. A foreseeable way to do this study, is to model and simulate different solutions before implementing them on a physical prototype. The models and algorithms presented in this chapter are developed from the background information, provided in Chapter 2, and from results obtained from the measurements in Chapter 3. The results from the explained experiments in Chapter 3, can be seen in Chapter 5.

In this chapter, two EDLCs connected in series are modeled and simulated. This is done in order to be able to provide sufficiently high voltages. As a result of this, the rated capacitance and voltage will be equal to 12.5F and 5.0V respectively.

4.1 Energy optimization

Energy optimization in this thesis report is referred to as an optimization of the usable energy stored in an EDLC, stated as E_{backup}. As can be seen in Equation 4.1, the total amount of stored energy consists of usable energy and the energy needed to charge the EDLC to a specific minimal voltage level. In theory this voltage level is 0V, but in practice it is not. The reason is that boost-converters, and some other electrical components, will stop working properly at a specified voltage level. The minimum voltage level to which an EDLC can provide a system with backup power is therefore higher than 0V, making the energy E_{limit} greater then zero.

$$E_{tot} = E_{backup} + E_{limit} \tag{4.1}$$

Because of ageing affects the capacitance (decreasing capacitance), the stored energy will decrease with capacitance. By controlling the voltage, the backup energy can be kept constant. By rewriting Equation 4.1, an expression for the backup energy can be obtained, seen in Equation 4.2.

$$E_{backup} = E_{tot} - E_{limit} = \frac{1}{2} \cdot C \cdot V^2 - \frac{1}{2} \cdot C \cdot V_{limit}^2 \tag{4.2}$$

Where C is the capacitance, V is the controlled voltage and V_{limit} is the minimum voltage level. When the capacitance (C) decreases, the voltage (V) will be increased i.e. keeping E_{backup} constant. The term E_{limit} will decrease, since C is decreasing and V_{limit} is constant. This also leads to a decrease in total energy stored in the EDLC.

As an example, a given system requires a backup power source that can provide a constant power of 2W for 10 seconds. The system needs this power in order to ensure a proper shut down if a blackout occur. This means that the EDLC needs to contain no less than 20J of backup energy (E_{backup}) at any given time. By rewriting Equation 4.2, knowing the voltage limit (V_{limit}) and the capacitance value (C), the optimal voltage level can be calculated.

4.2 State of life calculation

Traditional State of life (SOL) calculations for capacitors is defined as the ratio between the initial capacitance value ($C_{initial}$) and the current capacitance value ($C_{current}$), Equation 4.3. The state of life can be a good parameter to look at when evaluating the condition of a capacitor. Since the capacitance of an EDLC change with voltage, a more suitable solution has to be developed for systems with variable voltage.

$$SOL_1 = \frac{C_{current}}{C_{initial}} \tag{4.3}$$

By establishing the voltage dependent capacitance, a different method can be developed. This method calculates the SOL by dividing the measured capacitance value ($C_{measured}$) at a given voltage with the corresponding reference value ($C_{reference}$) for the same voltage (V). The calculated ratio describes how the current capacitance value differs from the value it had, at the specific voltage, when it was new.

In order to avoid the need of deriving the unique voltage dependent capacitance reference for each EDLC, a more general equation is desired. By introducing an initial value compensation, called k, a more efficient method is suggested with Equation 4.4. Since there can be an offset in capacitance value between units, the efficiency lies in that the initial value compensation is calculated when the EDLC is new. The value will adjust the ratio between $C_{measured}$ and $C_{reference}$, so that the SOL value will be 100% when the EDLC is new regardless the offset.

$$SOL_2 = \frac{C_{measured}(V)}{C_{reference}(V) \cdot k} \tag{4.4}$$

4.3 Lifetime estimation

The EDLC is a type of capacitor that has a variety of complex properties. One of the most prominent once is its aging behavior. The aging of an EDLC is, as stated previously, mostly linked to voltage and temperature. The relationship can be described as following: the aging process will increase, or that the lifetime will decrease, if the voltage and/or temperature increases.

When the EDLC is to be used as a backup power source it is preferred that the degradation of the capacitance is kept as low as possible. This is due to the fact that a constant energy level is desired and a lifetime as long as possible is preferred. The relationship between capacitance and energy can be seen in Equation 2.3 and shows that if the capacitance decreases the energy will decrease as well.

Since it is impossible to eliminate the aging behavior, it would be of great use if the aging could be estimated. Therefore some different estimation methods of lifetime are explained below.

4.3.1 Prior art

Take a point at any given time t_1 and calculate the slope of the capacitance between it and a prior point in time, t_0, see Figure 4.1. If we then assume that the capacitance will decrease with the same speed as it has done in the past, an estimated lifetime at time t_1 is calculated. The estimated lifetime is the time from t_1 to a point when the capacitance value has decreased to a certain end of life value. This method is represented with the dotted green line in Figure 4.1.

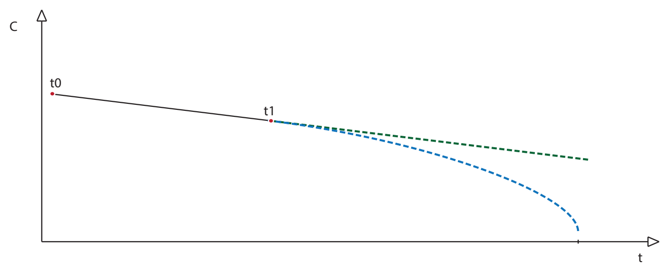

Figure 4.1 The result of two methods for lifetime estimation presented in a capacitance as function of time graph. Prior art (green dots) is based on a capacitance derivative during constant voltage and temperature, while innovation (blue dots) is based on an iterative method that compensates for changes in voltage and temperature.

4.3.2 Innovation

When the EDLC is used as a backup power source, the backup energy is desired to be constant. The method used in prior art will not be sufficient, since the voltage has to be increased when the capacitance decreases. An increased voltage will lead to an increased aging. Unlike prior art, the innovation will take this into account when calculating the estimated lifetime. The one thing that makes this method a bit more complex than prior art, is that the relationship between temperature, voltage and aging has to be established.

The first steps in this solution are the same as in prior art, the derivative at a given point in time t_1 is calculated. The estimated lifetime is then calculated using an iterative method where the increased voltage will be taken into account, unlike prior art. In Figure 4.2, a flowchart is displayed. Together with Table 4.1 a method for calculating the estimated lifetime is explained. To make the method easier to understand the temperature T is assumed to be constant.

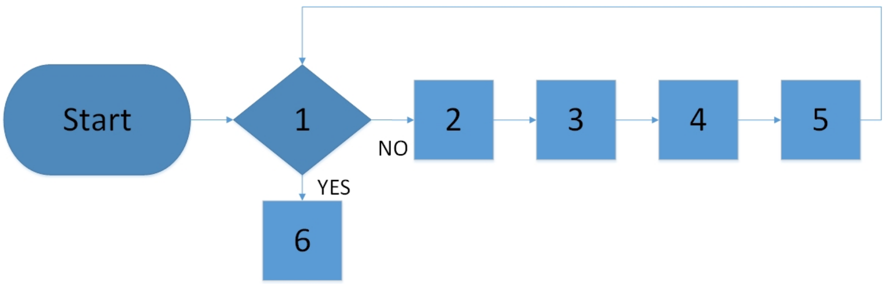

Figure 4.2 Flowchart illustrating the iterative solution for lifetime estimation of EDLCs. The different steps are described in Table 4.1.

Table 4.1 Workflow for lifetime estimation.

State	Description
Start	Set $\hat{C}(0)$ to the measured capacitance value at t_1 and define the time as t = 0. Also calculate the derivative of the capacitance in t_1 and set $V_{initial}$ to the voltage value at t_1.
1	Is the capacitance $\hat{C}(t)$ smaller then the end of life value?
2	Calculate the new voltage V_{new} , by using Equation 4.5.
3	Calculate the lifetime factor α with the new voltage value using Equation 4.6.
4	Calculate the decreas of capacitance by using Equation 4.7 and a suitable step length h.
5	Calculate the new capacitance value by using Equation 4.8 and calculate the new time with Equation 4.9.
6	The estimated lifetime is now equal to t.

$$V_{new} = \sqrt{\frac{2 \cdot E}{C}} \tag{4.5}$$

$$\alpha(V,T) = 2^{\frac{V_{new}-V_{initial}}{0.3}} \cdot 2^{\frac{T_{new}-T_{initial}}{10}} \tag{4.6}$$

$$\Delta C = \frac{dC}{dt} \cdot \alpha \cdot h \tag{4.7}$$

$$\hat{C}(t+h) = C(t) - \Delta C \tag{4.8}$$

$$t = t + h \tag{4.9}$$

4.4 Time delay between voltage adjustments

To optimize the stored energy, the voltage is increased as the capacitance decreases. The rate, of which the capacitance decreases, is increased with increasing voltage. This means that the voltage adjustments has to be performed more aggressive, if the voltage is high. It is therefore desirable to be able to predict how long time the system can wait before it has to increase the voltage again.

We present an algorithm that enables a dynamic time delay between voltage adjustments. The algorithm is initiated with calculating the needed voltage, using Equation 4.10.

$$V_{new} = \sqrt{\frac{2 \cdot E}{C}} \tag{4.10}$$

This voltage together with the current capacitance value will give the desired energy level. But since the capacitance in an EDLC is constantly decreasing, the energy will immediately be too small. To solve this problem a ΔV must be added to the calculated voltage, making the energy slightly higher, Equation 4.11.

$$E = \frac{1}{2} \cdot C \cdot (V + \Delta V)^2 \tag{4.11}$$

The amount of extra energy in the capacitor can be calculated using Equation 4.12.

$$\Delta E = \frac{1}{2} \cdot C \cdot \left((V + \Delta V)^2 - V^2\right) \tag{4.12}$$

The energy decreases with capacitance and the capacitance will decrease linearly if the voltage is constant. The decrease in energy is shown with Equation 4.13.

$$E = k \cdot t + E_0 = k \cdot t + \Delta E \tag{4.13}$$

By setting the energy E to zero, the time it takes the capacitance to decreases to the point were the energy equals the desired level, can be calculated with Equation 4.14.

$$t = \frac{\Delta E}{k} = \frac{\Delta E}{\frac{dE}{dt}} = \frac{2 \cdot \Delta E}{V^2 \cdot \frac{dC}{dt}} \tag{4.14}$$

The only unknown parameter in Equation 4.14 is the derivative of the capacitance. Since the derivative of the capacitance can be calculated in the time prior to the voltage change, a new derivative of the capacitance can be calculated using Equation 4.15.

$$\left(\frac{dC}{dt}\right)_{new} = \left(\frac{dC}{dt}\right)_{previous} \cdot \alpha\,(V,T) \tag{4.15}$$

The new capacitance derivative, in Equation 4.15, is calculated by multiplying the previous derivative with an aging factor α. α is approximating how a change in voltage and/or temperature will effect the derivative of the capacitance. As can be seen in Equation 4.15, the derivative will be doubled with either a 0.3V increase in voltage or a 10°C increase in temperature. The term $V_{previous}$ and $T_{previous}$ refers to the voltage and temperature values when $\left(\frac{dC}{dt}\right)_{previous}$ was calculated.

$$\alpha\,(V,T) = 2^{\frac{V_{new} - V_{previous}}{0.3}} \cdot 2^{\frac{T_{new} - T_{previous}}{10}} \tag{4.16}$$

In Figure 4.3, the method of how the voltage is increased at two different points in time is displayed. The picture also tries to present how the calculated time delay (t) is related to the energy.

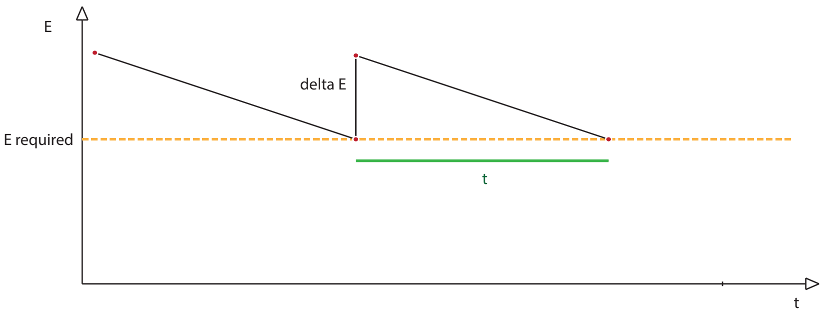

Figure 4.3 Energy as function of time illustrating the time between the measurements approach. The energy in an EDLC changes with time and when the energy has reached $Erequire$ the system is performing a new capacitance measurement.

4.5 Modeling of capacitance as a function of time

The capacitance degradation over time is very difficult to predict due to several key factors e.g. varying temperature and/or voltage. A generalized curve of the capacitance as function of time was seen in Figure 2.18. The aim of this section is to model, with the result from the accelerated lifetime test in Chapter 5.1.3, the initial exponential and linear behavior of the capacitance. Since the accelerated test is based on constant voltages, this chapter aims to describe the exponential and linear behaviors at fixed voltage levels. The approach of modeling the capacitance decrease as the voltage increases is described in Chapter 4.6.

4.5.1 Exponential decrease

The results in Chapter 5.1.3 Figure 5.8, indicates that the initial exponential decrease is voltage dependent i.e. applying a lower constant voltage minimizes the exponential decrease. This is a favorable property, since keeping the voltage level low enables a longer lifetime.

This initial exponential voltage dependent capacitance decrease is modeled by interpolating the measured data with a non-linear least square fit method. The used curve fit, is a second order exponential curve seen in Equation 4.17.

$$C(t) = a \cdot e^{b \cdot t} + c \cdot e^{d \cdot t} \tag{4.17}$$

Where C is the capacitance, a, b, c and d are the coefficients from the non-linear least square fit and t is the time.

The exponential part of the curves (at each applied voltage level) in Figure 5.8 is modeled by using the curve fit equation suggested in 4.17. When extracting each of the coefficients values and mapping them to its applied voltage level gives a graph where the coefficient values are a function of the voltage. With the relationship between their coefficient values and the stressed voltage, Equation 4.17 is rewritten to Equation 4.18.

$$C(t,V) = a(V) \cdot e^{b(V) \cdot t} + c(V) \cdot e^{d(V) \cdot t} \tag{4.18}$$

Where the coefficients are dependent on the voltage. To illustrate the voltage dependency of the coefficients (a,b,c,d), six capacitors are selected from each applied voltage level in Figure 5.8. The non-linear least square fit, with Equation 4.17, is used and the coefficients as a function of their applied voltage are plotted in Figure 4.4, 4.5, 4.6 and 4.7.

To establish the voltage dependence of the coefficients in the figures, a third order polynomial is used. These new coefficient values are used in Equation 4.18. The simplified workflow can be further developed with better fitting curves for the coefficients, but to prove a point the illustration is good enough.

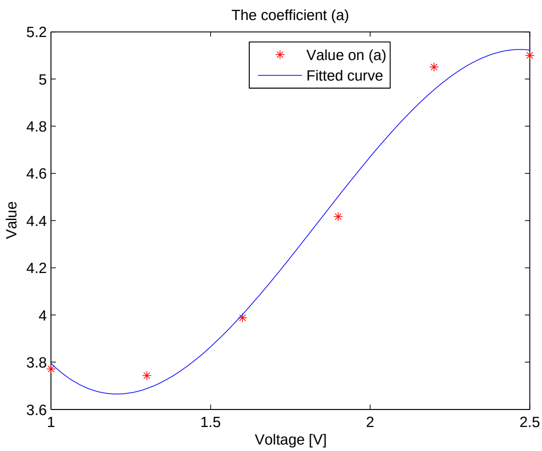

Figure 4.4 The (a) coefficient as a function of the stressed voltage level, from the second order exponential fit. The blue curve is an approach to interpolate the coefficient values (red dots).

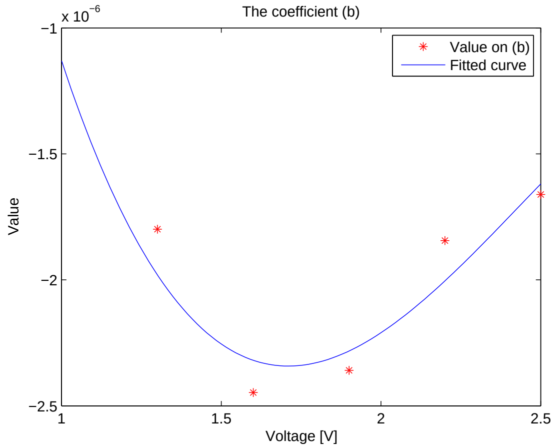

Figure 4.5 The (b) coefficient as a function of the stressed voltage level, from the second order exponential fit. The blue curve is an approach to interpolate the coefficient values (red dots).

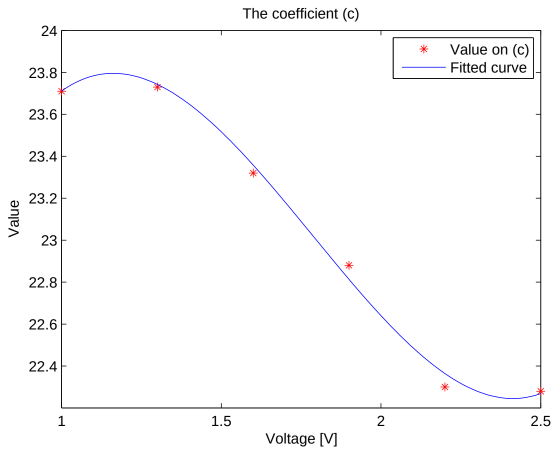

Figure 4.6 The (c) coefficient as a function of the stressed voltage level, from the second order exponential fit. The blue curve is an approach to interpolate the coefficient values (red dots).

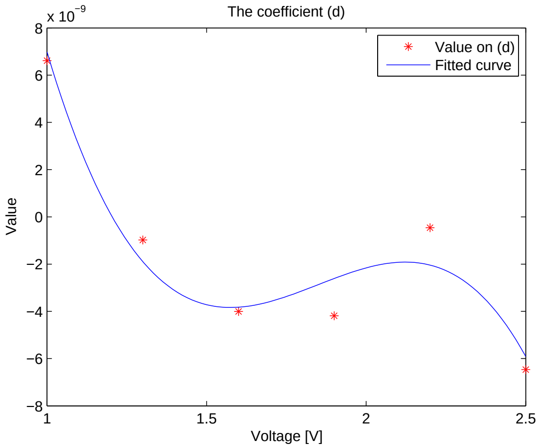

Figure 4.7 The (d) coefficient as a function of the stressed voltage level, from the second order exponential fit. The blue curve is an approach to interpolate the coefficient values (red dots).

4.5.2 Linear decrease

When the capacitance has decreased to a certain point, the decrease is no longer exponential. There will be a transition from an exponentially to a linearly decreasing capacitance. This slope (for each applied voltage level) can be modeled with a linear least square method seen in Equation 4.19.

$$Capacitance(t) = a \cdot t + b \tag{4.19}$$

Where a and b are coefficient from the linear least square method and t is the time. From the results of the accelerated lifetime test in Chapter 5.1.3, one can see that the linear decrease in capacitance is increasing with increased voltage. This results in a much shorter lifetime, or faster decrease in capacitance with time, if the applied voltage is high. Taking the voltage dependency into account, the linearly decreasing Equation 4.19 can be rewritten to Equation 4.20.

$$Capacitance(t,V) = a(V) \cdot t + b(V) \tag{4.20}$$

where the coefficients are dependent on the applied voltage.

4.6 Modeling in Simulink

To be able to properly evaluate the performance of a control system, an EDLC was implemented in a simulation model. The EDLC was realized as an "Equivalent RC model", explained in Chapter 2.5.2, with a non-linear capacitor. The different properties of the non-linear capacitor was derived from the measurements carried out in Chapter 3. The results obtained from the experiments in Chapter 3 are presented in Chapter 5. The different parts of the model can be seen in Figure 4.8.

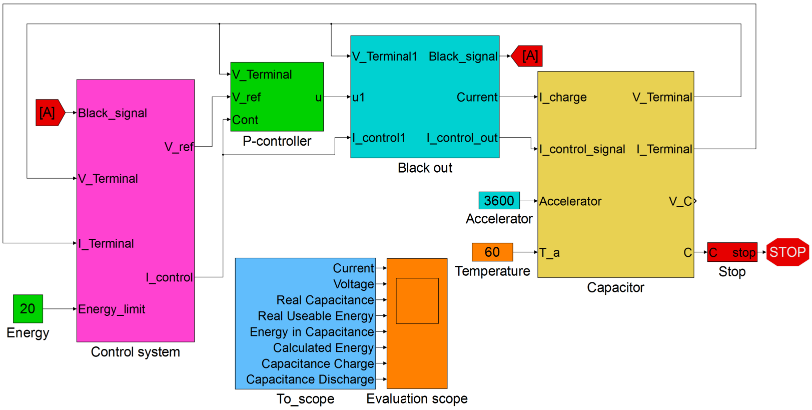

Figure 4.8 Simulink model of an entire blackout system with EDLCs used as power back up source. The systems consists of four main bricks: control system (magenta), controller (green), black out (turquoise) and capacitor (yellow). The brick to scope is used to gather and evaluate the appropriate data.

4.6.1 Capacitor brick

As can be seen in Figure 4.9, the "Equivalent RC model" in Chapter 2.5.2 is implemented as a representation of the EDLC. The model is found sufficient since it models the most important properties (series and parallel resistance, capacitance) of the EDLC, and since the parameters are easy to measure on a real EDLC. A known drawback with the model is however its poor ability to model the changing dynamics at charge and discharge. But, since these properties will be of less importance in this thesis, this drawback is found insignificant. In Figure 4.9, it can also be seen that an applied current (I_Charge) will generate a change in voltage over the terminals (V_terminal). This voltage is the sum of the voltage drop over ESR (I_Charge·ESR) and the voltage over the equivalent capacitance (V_C).

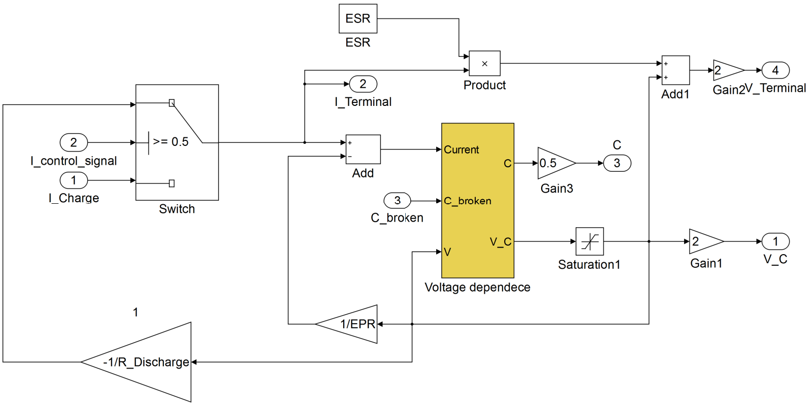

Figure 4.9 Implementation of the equivalent RC model in Simulink. Additional to the RC model the capacitance is modeled as a voltage dependent capacitance in the voltage dependent brick (yellow). In this subsystem the discharge mechanism is also implemented with a Switch and a resistance R Discharge.

The yellow brick in Figure 4.9, called "Voltage dependence", is where the capacitance value at different voltages is calculated. The implementation of this subsystem can be seen in Figure 4.10. The brick also calculates the voltage over the capacitor using Equation 4.21.

$$V_C = \int \frac{1}{C} \cdot I dt \tag{4.21}$$

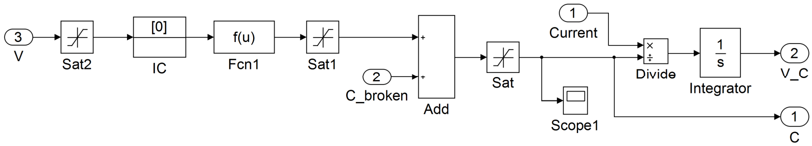

Figure 4.10 Implementation of the voltage dependent capacitance values in Simulink. The voltage dependency is modeled in Fcn1.

Implementation of the decreasing capacitance in Simulink In Chapter 4.5 we discussed how to model the exponential and linear decrease of the capacitance if the voltage was held constant. Since the voltage will not be held constant, the aging process must be implemented accordingly.

From the accelerated lifetime test results presented in Chapter 5.1.3, the relationship between the voltage and the derivative of the capacitance was established. By integrating the time derivative of the capacitance, the degradation of capacitance could be calculated. The implementation can be seen in Figure 4.11, where the time derivative of the capacitance is calculated in the brick called "MATLAB Function" as a function of voltage and temperature.

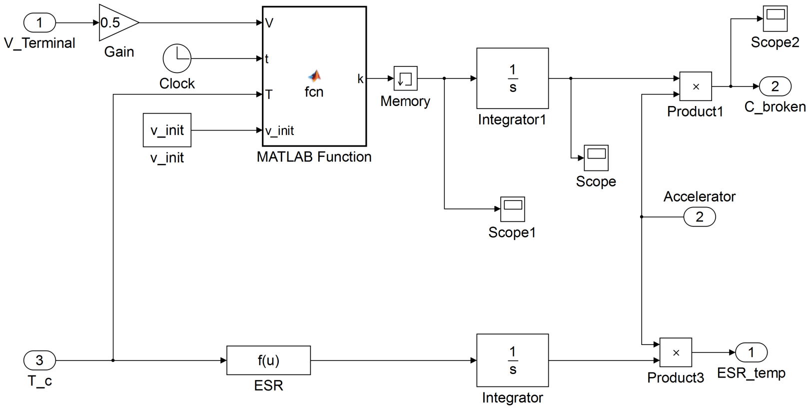

Figure 4.11 Implementation of the aging of an EDLC. The aging process affects the capacitance value and the ESR, where the process depends mostly on the two most predominating factors temperature and voltage. The aging of and EDLC is characterized by an increase in ESR and decrease in capacitance.

4.6.2 Blackout brick

This brick is used to implement blackouts in the simulation. Practically this means that the brick sets a variety of system parameters to the same values as they had been if a real blackout had occurred. This brick is therefore only necessary in the simulation model and will not be needed in the real implementation. The blackouts can be triggered either automatically or manually.

4.6.3 P-controller

This is a discretized P-controller that will control the voltage over the capacitor. The controller calculates the error between voltage over the capacitor and the reference voltage, set by the control system. It then delivers a corresponding current to the capacitor. Since the regulator cannot consume current the control signal can only be positive i.e. can only increase the voltage. The controller is therefore tuned so that there will be no, or very small, overshoots. If the voltage has to be decreased, a resistance is connected between the terminals of the EDLC with a switch.

4.6.4 Control system

The control system is the brain of the system. It is in this brick where all the measurements and calculations are implemented. It is also this part that will be realized on the microcontroller in the final product. Since the control system is the most essential part of this model a deeper explanation is given in Chapter 4.7.

4.7 Control system

The key task for the control system is to maintain a desired energy level in the EDLC and estimate how long it will be able to provide the required amount of energy. As mentioned numerous of times, the capacitance will decrease with time. Since the energy is capacitance dependent, the energy will also decrease if the voltage is kept fixed, according to Equation 4.22. Since the voltage can be increased when the capacitance drops, the energy level can be maintained.

$$E = \frac{1}{2} \cdot C \cdot V^2 \tag{4.22}$$

To know how much to increase the voltage, the capacitance has to be measured with high precision. As stated in Chapter 3.4, capacitance cannot be measured statically. Capacitance can only be measured with a change in electrical charge Q.

In the model, such a change is done by making a small charge and an equivalent discharge. Capacitance is calculated by measuring the energy between two points in time, at a charge or a discharge according to Equation 4.23.

$$C = \frac{2 \cdot \int_{t_1}^{t_2} v(t) \cdot i(t)\, dt}{\left(V_2^2 - V_1^2\right)} \tag{4.23}$$

In Figure 5.27, an image of a capacitance measurement from the simulation is displayed. As can be seen the voltage will increase to a certain value, and then decrease by the same amount. After the discharge, the control system calculates the required voltage and sets reference. The increased voltage after a measurement can also be seen in Figure 5.27.

In reality, the new voltage reference value has to be greater than the calculated one. The reason is that the voltage is calculated for the current capacitance value, and since this value will decrease right away, the voltage has to be increased so that the energy will not be too small.

By using the method described in Chapter 4.6.1, the time until next capacitance measurement is calculated. The lifetime estimation that is presented in Chapter 4.3 is also calculated.

4.7.1 State chart

The steps that have to be performed in order to maintain a constant energy level are few and quite trivial. The implementation is a bit trickier, and the different steps

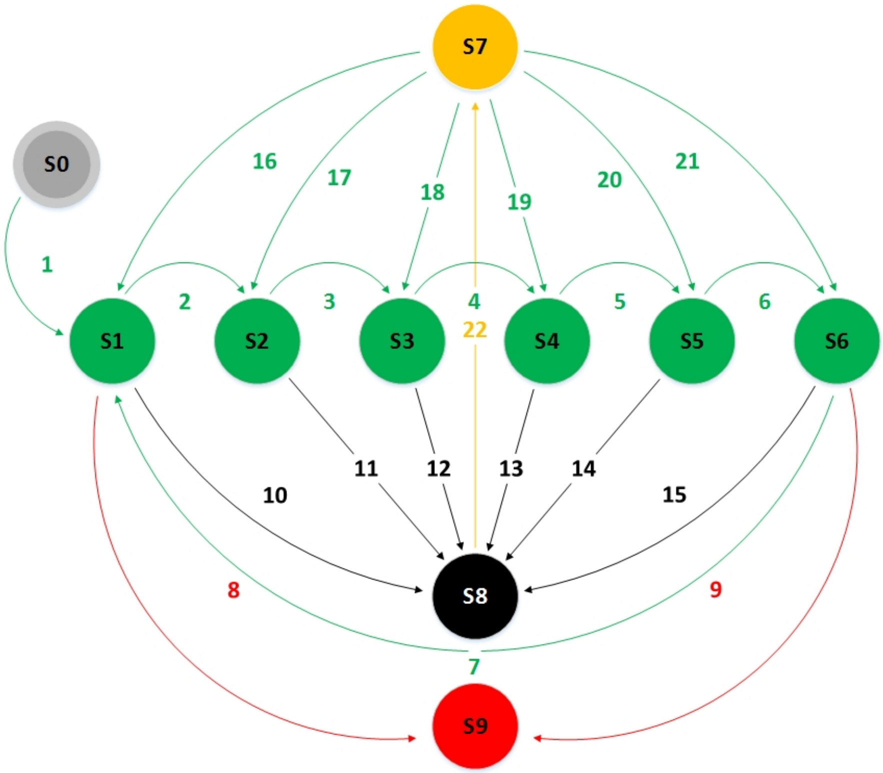

Figure 4.12 State chart illustrating the main mechanisms of the control system i.e. initiation of the system, small charge and discharges, computations of the reference value, blackout handling and recovery etc. The different states are seen in Table 4.2 and 4.3.

have to be divided into smaller parts. To be able to know where and when these different parts are to be executed, a state chart was developed. The state chart shows all the states and transitions that are implemented in the control system. The state chart can be seen in Figure 4.12. Corresponding tables of all the states and transitions can be seen in Table 4.2 and 4.3.

Table 4.2 Implemented states in the control system.

State	Description
S0	Initiation
S1	Wait
S2	Charge
S3	Wait
S4	Discharge
S5	Calculation
S6	Update
S7	Recovery
S8	Blackout
S9	End of Life

Table 4.3 Transition conditions for the control system.

Transition	Condition
1	If the voltage over the EDLC has reached the initial reference voltage.
2	If the present time is greater than the one set for the next charge.
3	If the voltage over the EDLC is equal or greater than the reference voltage for the charge.
4	If the voltage reference and the discharge signal is changed.
5	If the voltage is equal or lower than the reference voltage for the discharge.
6	If all the calculations are performed.
7	If the voltage over the EDLC is equal or greater than the reference voltage for the charge.
8	If the voltage reference plus the change in voltage during a small charge is greater than the maximal allowed voltage.
9	If the new voltage reference is greater than the maximal allowed voltage.
10-15	If a blackout occurs.
16-21	If the voltage is equal to the one it was when the system entered the state were the blackout occurred.
22	If the blackout ends.

5

Results

In this chapter, the results from the measurements and simulations in Chapter 3 and 4 are presented. Since the amount of results is large, only the most interesting ones are displayed and discussed.

5.1 Experimental

5.1.1 Charge and discharge

Both BCAP0025 and HB1625-2R5256-R were charged with a constant current of 1.4A and the parameters of an equivalent RC model were calculated. The results are seen in Figure 5.1 – 5.3.

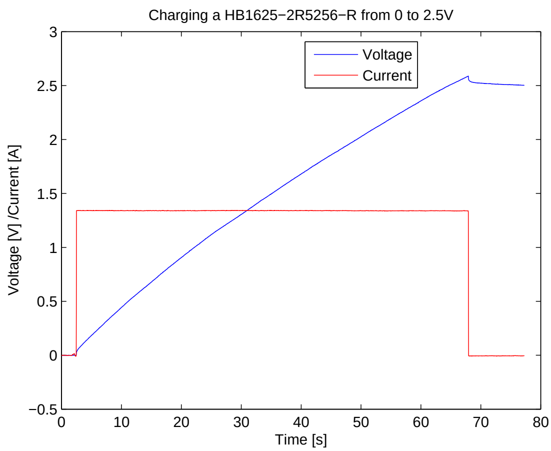

Figure 5.1 Charging a HB1625-2R5256-R from 0 to 2.5V with a constant current.

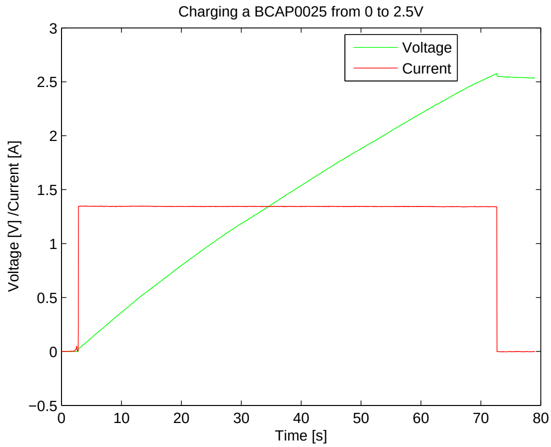

Figure 5.2 Charging a BCAP0025 from 0 to 2.5V with constant current.

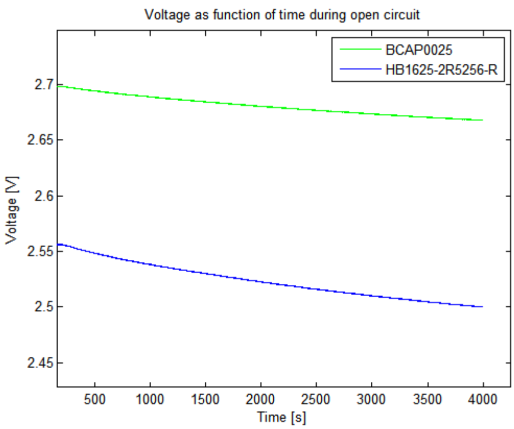

Figure 5.3 Voltage as a function of time during open circuit. The leakage current lowers the voltage on the EDLCs with time.

The parameters in the equivalent RC model are calculated with Equation 2.22, 2.24 and 2.25, the results are displayed in Table 5.1.

Table 5.1 Experimentally measured parameter values i.e. capacitance, ESR and EPR at room temperature.

EDLC	Capacitance [F]	ESR [Ω]	EPR [Ω]
HB1625-2R5256-R	30.6	0.018	6.26k
BCAP0025	27.4	0.022	11.11k

Discussion The aim of this part was to study the properties of EDLCs during a charge and discharge. If we look in Figure 5.1 or 5.2, we see that there is a fast change in voltage both in the beginning and the end of a charge. This change is caused by a resistive load. This means that an equivalent model of an EDLC has a resistance in series with a capacitor. On the other hand, if the EDLC is charged to a certain voltage and then left open circuit, the voltage across the terminals will gradually decrease according to Figure 5.3. The voltage decrease is caused by a internal leakage current and can be modeled with a capacitor in parallel with a resistance. Having these properties in mind we find us confident that the RC-model described in Chapter is 2.5.2 sufficient for our purposes.

The measured values on the capacitance and ESR from Table 5.1 is consistent with the manufacturers specifications from Table 3.1 and 3.2. Before commenting on the EPR measurements we need to calculate the leakage current. If we assume a reference voltage at 2.5 - 2.7V and using Ohm's law the leakage current can be calculated according to Equation 5.1:

$$i = \frac{V}{EPR} \tag{5.1}$$

The leakage current for BCAP0025 (2.7V) and HB1625-2R5256-R (2.5V) is 0.24mA and 0.4mA respectively. Comparing these values with the specifications in Table 3.1 and 3.2, the calculated leakage currents are well over the specified values. The difference by a factor of almost 10 is surprising. We believe that the "wait time" has an affect on the EPR value. One explanation is that the time we used is insufficient. To further improve these measurements we suggest to study the decrease for a longer time period than the one we used (4000s).

5.1.2 Evaluation of in-circuit capacitance measurements

The idea of measuring the capacitance value in-circuit is a fundamental part of the presented solution. Therefore, the accuracy of this method had to be verified.

By charging an EDLC from 0 to 2.5V, with constant current, necessary measurement data was obtained. The measurement data was together with Equation 5.2 used to determine reference values for the voltage dependent capacitance. The reference values are presented as the black line in Figure 5.4.

$$C_2 = 2 \cdot \frac{\int_{t_1}^{t_2} i(t) \cdot v(t)\, dt + C_1 \cdot V_1^2}{V_2^2} \tag{5.2}$$

By assuming the capacitance value to be constant during a small voltage interval, Equation 5.2 can be rewritten as Equation 5.3. When preforming in-circuit capacitance measurement, the goal is to make the change in charge as small as possible, the capacitance can therefore be assumed constant and Equation 5.3 will be valid. If the voltage was for example changed from 1.0 to 1.2V, the equivalent capacitance value for 1.1V could be calculated with Equation 5.3. This method was used to determine the capacitance value at different voltage level when measured in-circuit. The results from these measurements are presented in Figure 5.4 as red dots.

$$C = \frac{2 \cdot \int_{t_1}^{t_2} v(t) \cdot i(t)\, dt}{\left(V_2^2 - V_1^2\right)} \tag{5.3}$$

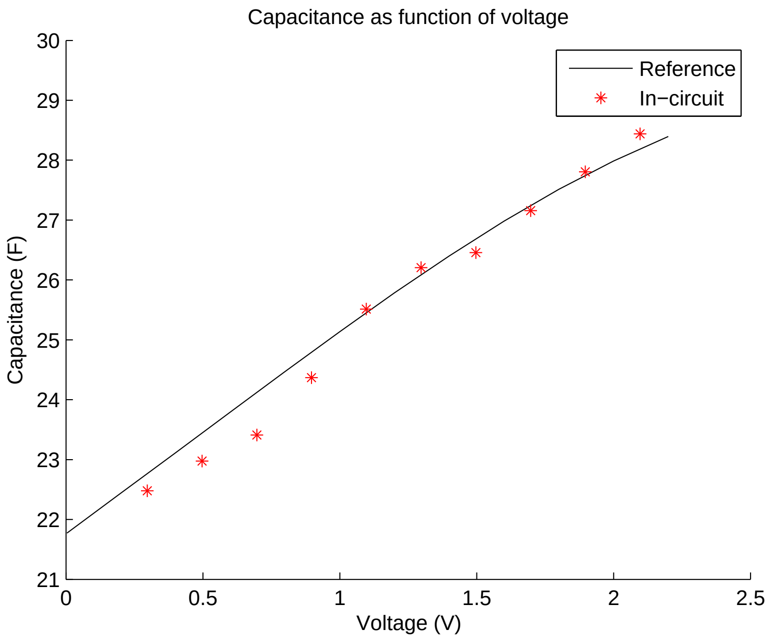

Figure 5.4 Evaluation of the accuracy of in-circuit capacitance measurements (red stars) in relation to a reference curve (blue).

Discussion Since capacitance can not be measured statically and the EDLC has a strong voltage dependency, there is no trivial method to measure capacitance. In this chapter, the results from evaluating the accuracy of the in-circuit capacitance measurements was presented.

The results from the evaluation showed that it was possible to make a small change in voltage, at any initial voltage, and still obtain a fairly accurate capacitance value. Since we want to be able to measure the capacitance regardless of the current, the method was also verified for non-constant current.

5.1.3 Accelerated lifetime test

The results from the accelerated lifetime test are illustrated with photographic images and various types of graphs. The first images (Figure 5.5 – 5.7) show how the cylindrical capsules have been affected by high temperature and voltage. Since the HB1625-2R5256-R is rated at 2.5V, the voltage has proven to be a big issue for the ones which were held at 2.5V. Looking at the physics of HB1625-2R5256-R, the capsule has swollen and some of the electrolyte might have leaked. On the other hand, the physics of a BCAP0025 has only some minor changes i.e. they have proven to endure a high temperature and voltage better than HB1625-2R5256-R.

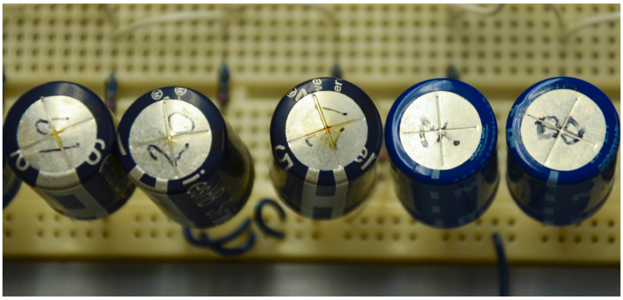

Figure 5.5 The shape of capacitors 19, 20, 21 (HB1625-2R5256-R) after the accelerated lifetime test. A yellow/brown liquid (Electrolyte) has leaked.

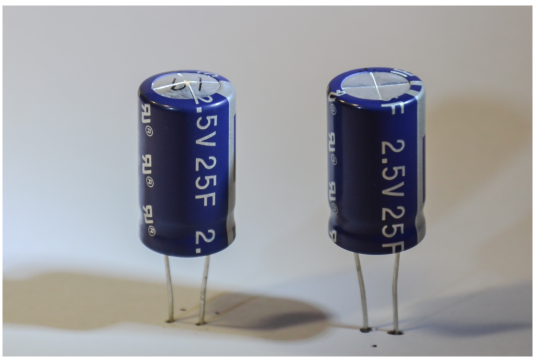

Figure 5.6 Comparison between a new capacitor (right) and a capacitor from the accelerated lifetime test (left) (HB1625-2R5256-R).

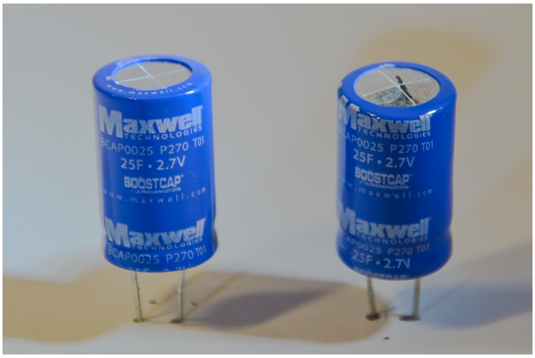

Figure 5.7 Comparison between a new capacitor (left) and a capacitor from the accelerated lifetime test (right) (BCAP0025).

Capacitance and ESR as function of time The results from the first part of the accelerated lifetime test are displayed in Figure 5.8 and 5.9. These plots show the capacitance as a function of time during 1008h for HB1625-2R5256-R and BCAP0025. As one can see, the decrease in capacitance is voltage and time dependent. The results indicate that the degradation curve consists of two parts: (1) an exponential part in the beginning where the capacitance decreases up to 80-90% of its initial value and (2) a linear part from approximately 80-90% of its initial value.

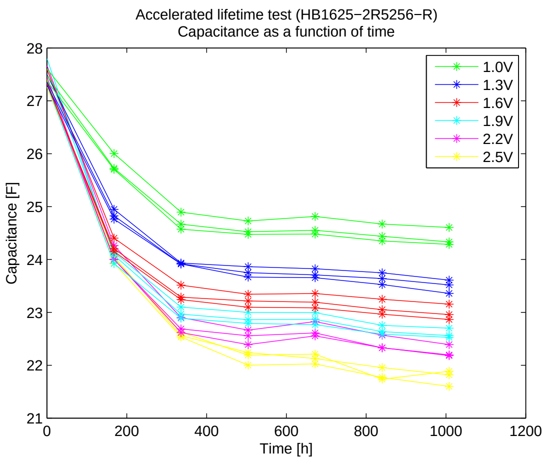

Figure 5.8 The capacitance as function of time from the accelerated lifetime test on HB1625-2R5256-R stressed @ 70 °C and 1.0 - 2.5V during 1008h.

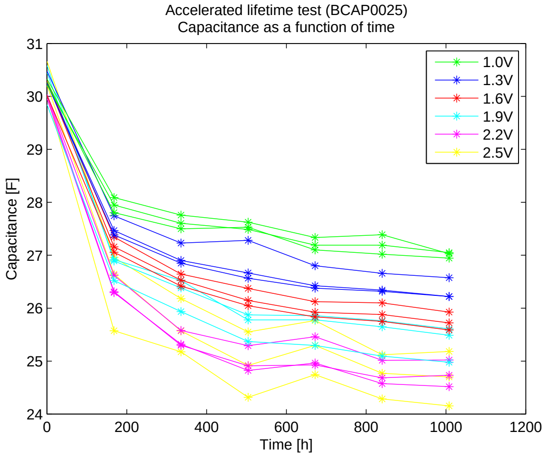

Figure 5.9 The capacitance as function of time from the accelerated lifetime test on BCAP0025 stressed @ 70°C and 1.0 - 2.5V during 1008h.

The results from the second part of the accelerated lifetime test are displayed in Figure 5.10 – 5.15. Figure 5.10 – 5.13 show the capacitance and ESR as function of time during 2088h, when stressed with 2.5V and 70°C. One can clearly see the exponential and linear part of the capacitance degradation. Furthermore, also the ESR seems to eventually increase linearly.

The second two plots (Figure 5.14 – 5.15) show the capacitance as function of time also during 2088h but at 1008h the voltage was increased for capacitors at 1.0-2.2V.

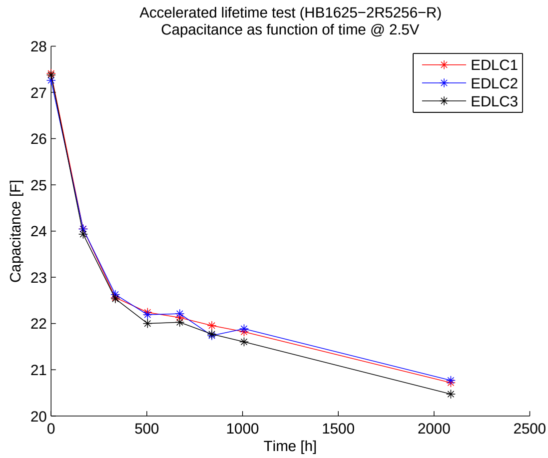

Figure 5.10 The capacitance as function of time from the accelerated lifetime test on HB1625-2R5256-R stressed @ 70 °C and 2.5V during 2088h.

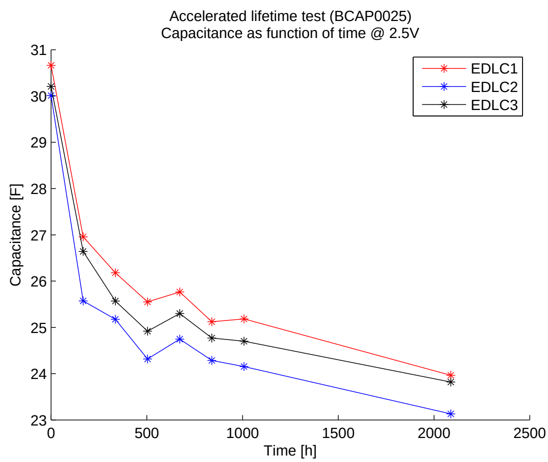

Figure 5.11 The capacitance as function of time from the accelerated lifetime test on BCAP0025 stressed @ 70 °C and 2.5V during 2088h.

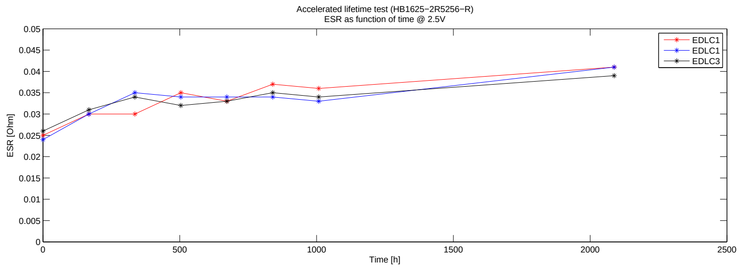

Figure 5.12 The ESR as function of time from the accelerated lifetime test on HB1625-2R5256-R stressed @ 70 °C and 2.5V during 2088h.

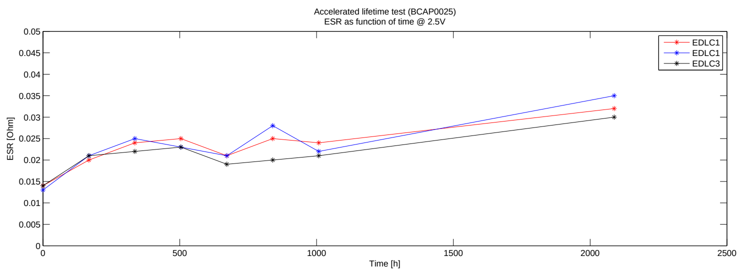

Figure 5.13 The ESR as function of time from the accelerated lifetime test on BCAP0025 stressed @ 70 °C and 2.5V during 2088h.

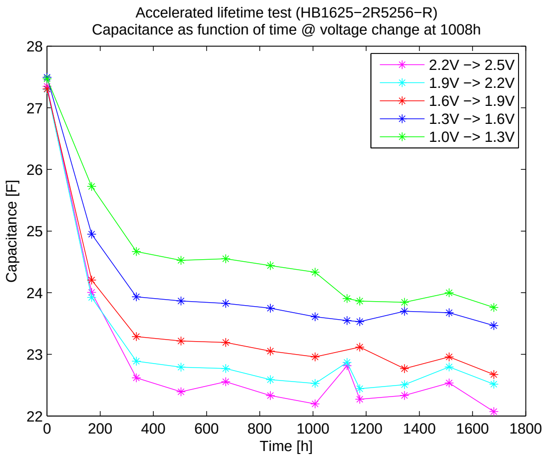

Figure 5.14 The capacitance as function of time from the accelerated lifetime test on HB1625-2R5256-R during a change of voltage with 0.3V at 1008h.

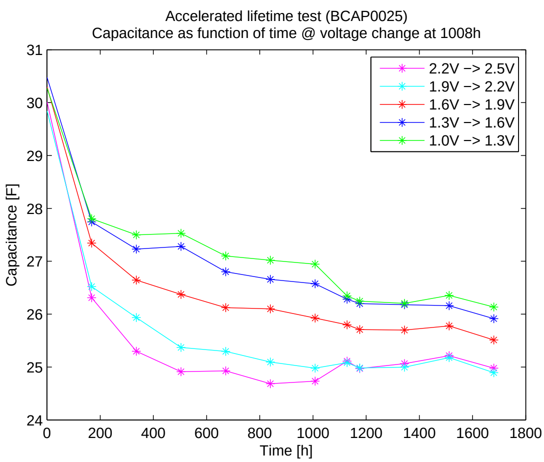

Figure 5.15 The capacitance as function of time from the accelerated lifetime test on BCAP0025 during a change of voltage with 0.3V at 1008h.

Discussion As can be seen in the Figure 5.5 - 5.7, two different types of EDLCs was evaluated. The accelerated lifetime test was carried out during 2000h in a heat chamber, where the EDLCs were stressed at high voltage and temperature. After two to three weeks in the heat chamber, we could observe performance changes related to capacitance value on both types. The change in capacitance, during the first 1000h, can be seen in Figure 5.8 and 5.9. As expected, the capacitance decreases exponential at first and than linearly. One can also see that the rate of which the capacitance decreases is strongly voltage dependent. These results where used in the simulation model, in order to implement the aging properties of the EDLC.

As mentioned in Chapter 3.5, the accelerated lifetime test was divided into two parts. After the first 1000h the voltage was changed on the EDLCs with 0.3V, except on the ones with an applied voltage of 2.5V. This was done in order to determine if the capacitance would decrease exponentially or linearly after a voltage change. The results showed no proof of an exponential decrease if the voltage level was increased. The results were however a bit inconclusive, since the measurements showed some strange capacitance values. The underlying cause may be different ambient temperature in the lab room or that the EDLC was not rested enough. With these results in mind we have in our work assumed that the capacitance will decrease linearly with a different slope if the voltage is increased. The measurements of capacitance, both before and after the voltage change, can be seen in Figure 5.14 - 5.15. The obtained results from the EDLCs, which were exposed too 2.5V during all of the 2000h, can be seen in Figure 5.10 - 5.11.

How ESR is affected by aging is also of great interest. In Figure 5.12 - 5.13, the change in ESR can be seen. As expected, the ESR value increases with time. There is however some unexpected behavior between 500 and 1000h for BCAP0025, this is probably also related to temperature.

When the tests were finished we could see some negative impacts, seen in Figure 5.5 – 5.7. The EDLCs, with label HB1625-2R5256-R, which were stressed at 2.5V had swollen and it seemed as if some electrolyte had leaked on one of them. Since these EDLC were stressed at its rated limit the swelling did not come as surprise. However, we believe that the manufacturer should have specified that there can be some swellings if the EDLCs are stressed at its limit i.e. 2.5V and 70 °C.

Capacitance as function of voltage This section displays the results from the first part of the accelerated lifetime test measurements. To be more precise, the pictures show the EDLCs instantaneous voltage dependence at different measuring occasions. The results are seen in Figure 5.16 – 5.21, where we have chosen to display capacitors stressed at three different voltage levels (1.0V, 1.9V and 2.5V). The graphs indicate that the shape of the curve and capacitance vs. voltage characteristics are changing with time.

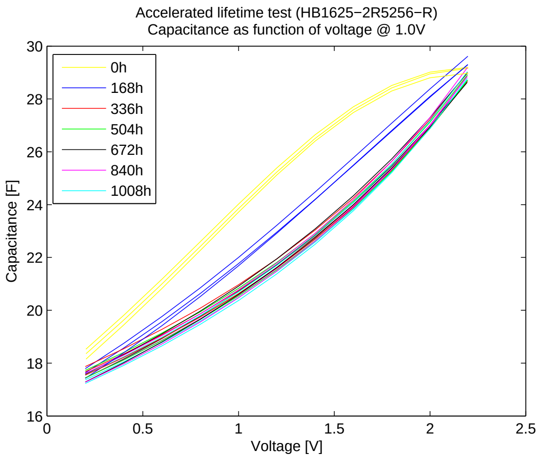

Figure 5.16 Capacitance as function of voltage from accelerated lifetime test on HB1625-2R5256-R stressed @ 70 °C and 1.0V.

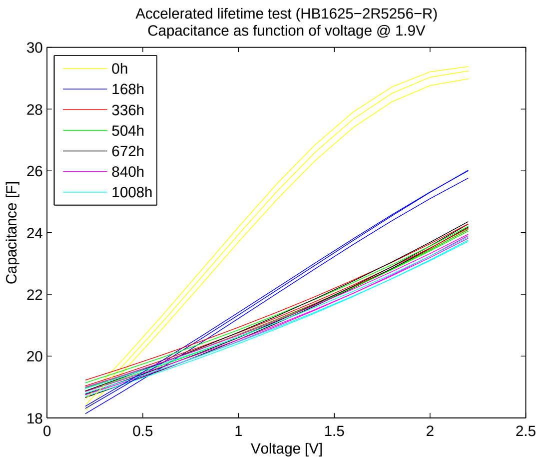

Figure 5.17 Capacitance as function of voltage from accelerated lifetime test on HB1625-2R5256-R stressed @ 70 °C and 1.9V.

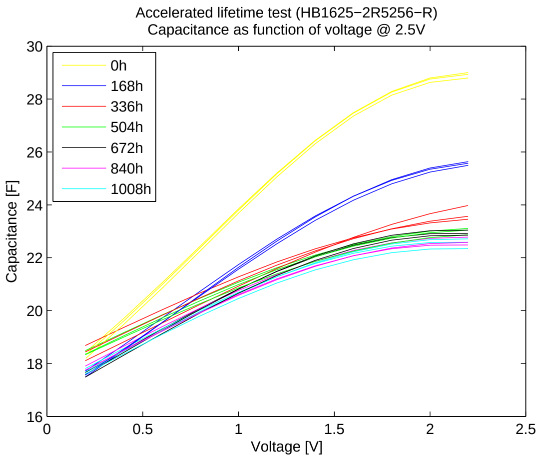

Figure 5.18 Capacitance as function of voltage from accelerated lifetime test on HB1625-2R5256-R stressed @ 70 °C and 2.5V.

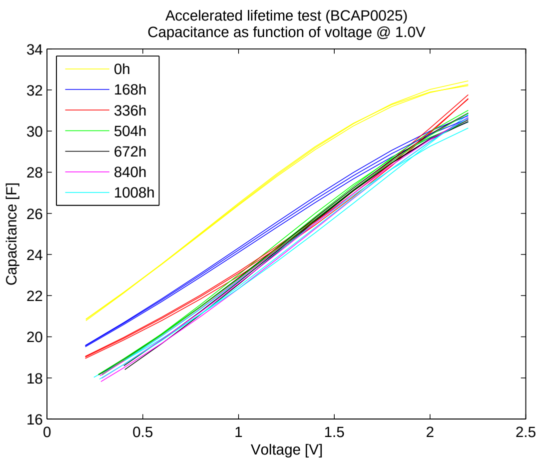

Figure 5.19 Capacitance as function of voltage from accelerated lifetime test on BCAP0025 stressed @ 70 °C and 1.0V.

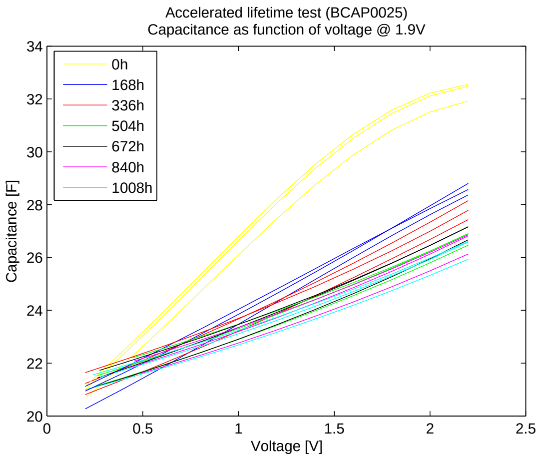

Figure 5.20 Capacitance as function of voltage from accelerated lifetime test on BCAP0025 stressed @ 70°C and 1.9V.

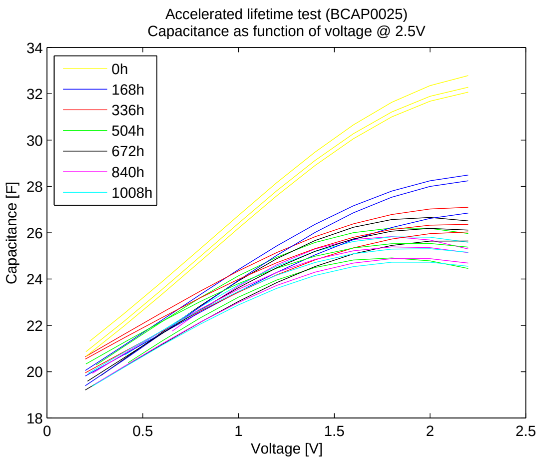

Figure 5.21 Capacitance as function of voltage from accelerated lifetime test on BCAP0025 stressed @ 70°C and 2.5V.

Discussion In Figure 2.13, we show that there is a strong voltage dependency on the capacitance values. The voltage dependency also changes with time, as can be seen in Figure 5.16 - 5.21. We have not been able to make a good explanation of the relationship between age and voltage dependency. The only conclusion we have been able to make is that the voltage dependency decreases with time.

5.1.4 Instantaneous temperature behavior

The results of the instantaneous temperature dependence test are seen in Figure 5.22 and 5.23. In Figure 5.22, the capacitance as a function of temperature is plotted, where the capacitance is increasing with an increasing temperature.

The results from the ESR measurements as a function of the temperatures, seen in Figure 5.23, differ when comparing the curves from HB1625-2R5256-R and BCAP0025. It seems that lower temperatures effects the BCAP0025 capacitors more than HB1625-2R5256-R capacitors i.e. the ESR is increasing with lower temperatures for BCAP0025.

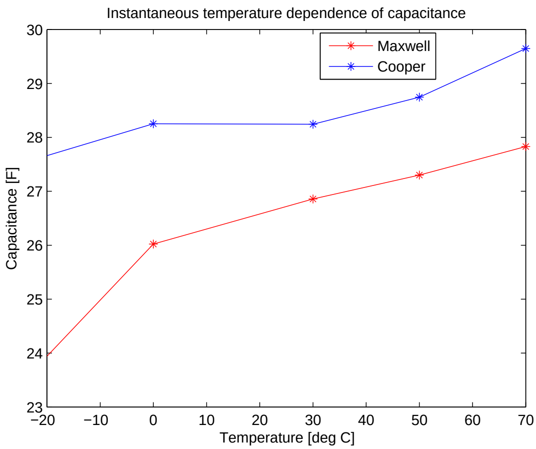

Figure 5.22 Instantaneous temperature dependence of the capacitance, measurements performed on Cooper (HB1625-2R5256-R) and Maxwell (BCAP0025).

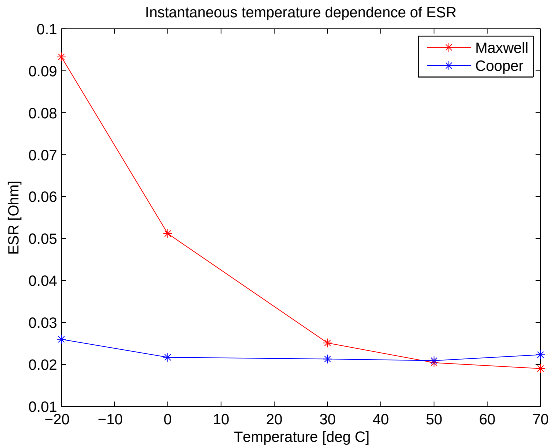

Figure 5.23 Instantaneous temperature dependence of the ESR, measurements performed on Cooper (HB1625-2R5256-R) and Maxwell (BCAP0025).

Discussion These measurements were performed to prove the datasheets and theory right. Figure 5.22 illustrates the capacitance values at different temperatures. These results are inconclusive, since according to the datasheets and the theory the capacitance value should be fairly constant for temperatures above 0 °C. Some research has been done, but no good explanation has been found. On the other hand, the ESR values in Figure 5.23 behaved as expected.

The difference in temperature dependency between the two models lies in the usage of different types of electrolyte. Since the electrolyte AC, used in BCAP0025, is more sensitive for temperatures, the ESR value will not be constant. On the other hand, the electrolyte PC, used in HB1625-2R5256-R, can operate at higher temperatures. According to spokesmen from Cooperbussmann, the electrolyte AC starts to boil at 85 °C, while the electrolyte PC has a boiling temperature of 240 °C.

5.2 Simulations

The simulation model was developed in order to evaluate a lot of different aspects of the proposed backup system. The most important aspect was the systems ability to maintain a constant backup energy as the capacitance decreases. This ability is presented in Figure 5.24. In Figure 5.25, it can be seen how the capacitance drops with time.

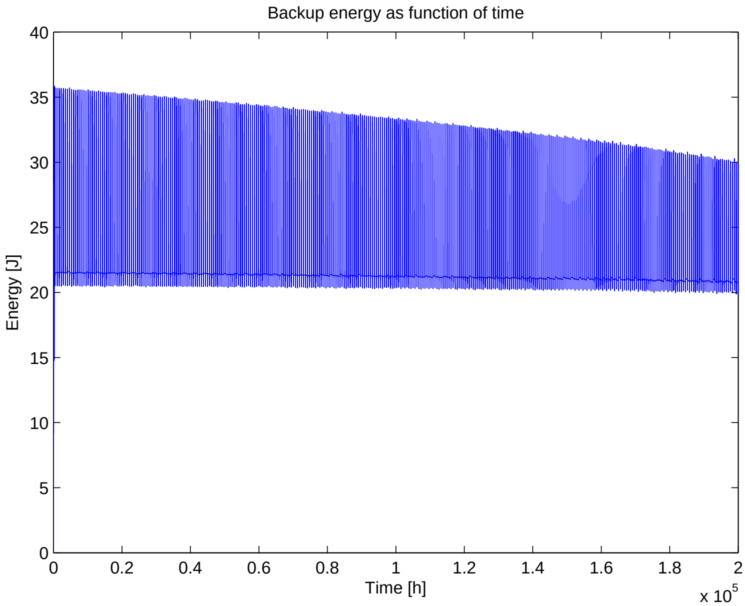

Figure 5.24 The backup energy as a function of time. If one disregards the changes in energy when the capacitance is measured, due to change in voltage, the backup energy is held constant.

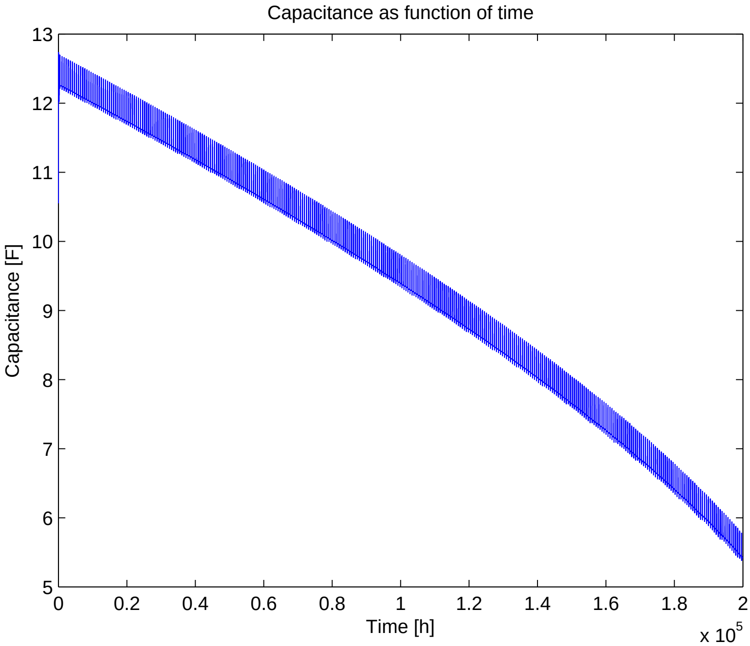

Figure 5.25 Capacitance as function of time, in an EDLC, when the voltage is increased. The non-linear curve is caused by an increased voltage which increases the capacitance degradation.

In Figure 5.26, the voltage reference (blue) and the applied voltage (magenta) are presented. Figure 5.27 shows how a small charge and discharge, in Figure 5.26, looks like up close.

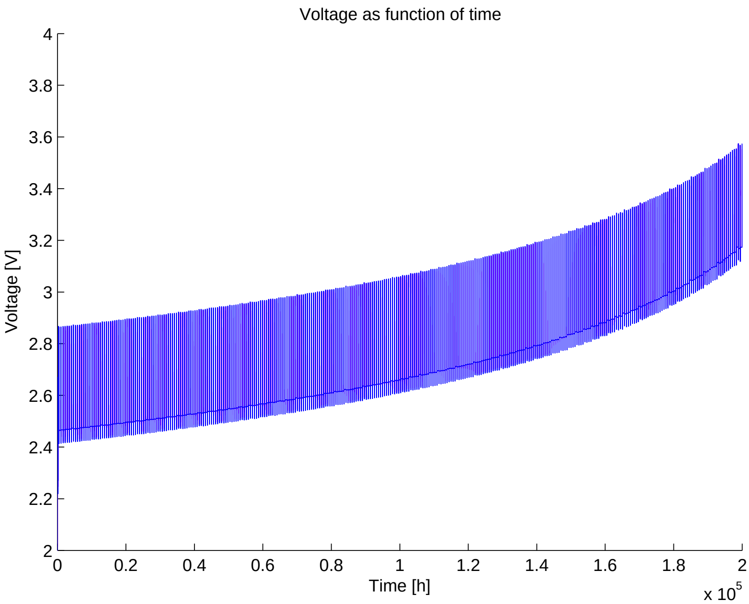

Figure 5.26 Voltage as function of time over the EDLCs. The voltage is increased to maintain a constant energy.

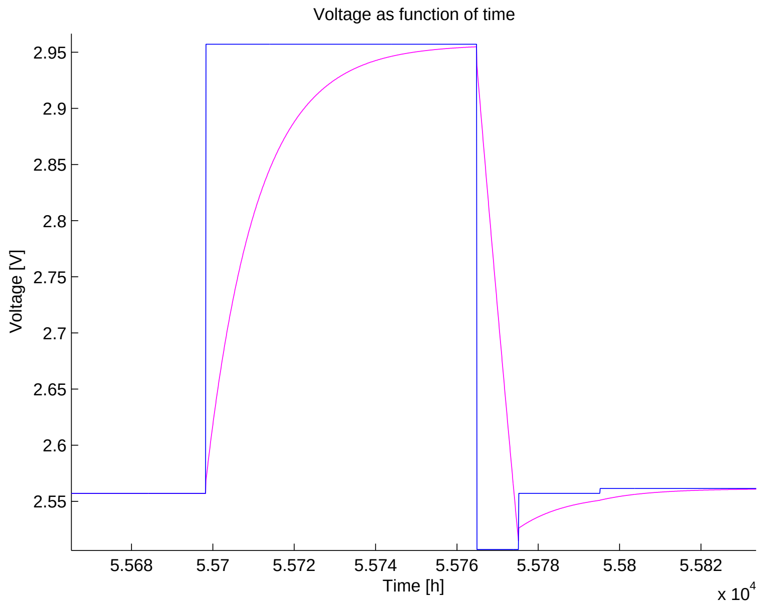

Figure 5.27 Small charge and discharge for a capacitance measurement. Blue curve is the reference voltage and the magenta is the actual voltage over the EDLCs.

Another important issue, is how well the system preforms during blackouts. Figure 5.28 presents how the extracted current (I), voltage (V) and corresponding power (P), change during a blackout.

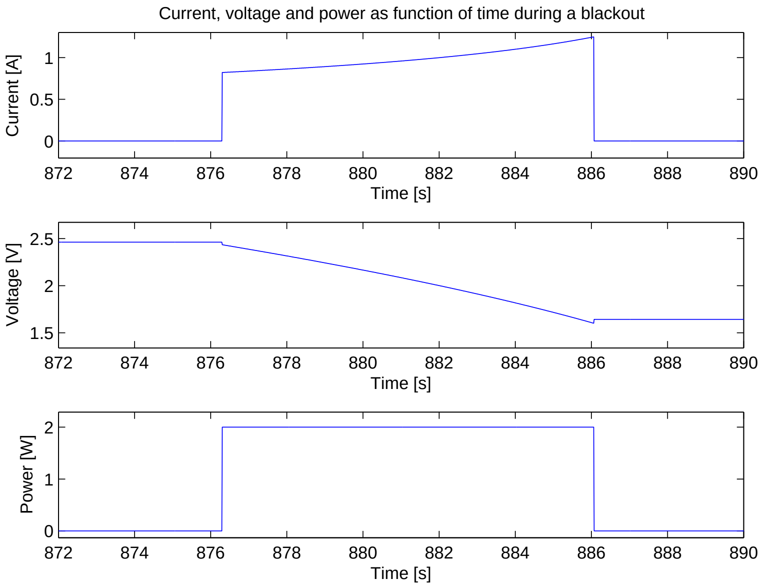

Figure 5.28 Top: Current as function of time during a blackout. Middle: Voltage as function of time. Bottom: Power as function of time.

To simplify the running of the simulation model a Graphical User interface (GUI) was created. By running the GUI, all the essential parameters for two different simulations models are set respectively. The user is also able to enable blackouts from the GUI, set ambient temperature (°C) and enter the desired energy (J) level in the EDLCs.

Discussion According to Figure 5.24, the backup energy is not constant. If one have in mind that the voltage is changed in order for the system to measure the capacitance, the energy will not be constant. If the change in energy related to the capacitance measurement is disregarded, the energy is actually constant.

As can be seen in Figure 5.25, the capacitance is decreasing with time. The rate of the decrease is however not constant and is due to the increasing voltage. The fast changing dynamics of the capacitance value is also related to voltage, and can be related to the capacitance measurements.

Figure 5.26 shows how the voltage is changed when capacitance measurements are performed and how it is increased to compensate for the decrease in capacitance. Both changes looks like expected.

As can be seen in Figure 5.28, the backup system can provide a constant power of 2W for approximately 10 seconds during a blackout. This means that there is 20J of usable backup energy stored in the EDLC previous to the blackout. The amount of extracted energy from the EDLC is the same amount that was desired, the system is therefore preforming as expected.

5.2.1 Simulation comparison between constant voltage and controlled voltage

As stated, the voltage over the EDLCs can either be changed gradually or it can be held at a fixed value. The coresponding capacitance values, from these two cases, are seen in Figure 5.29 and 5.30.

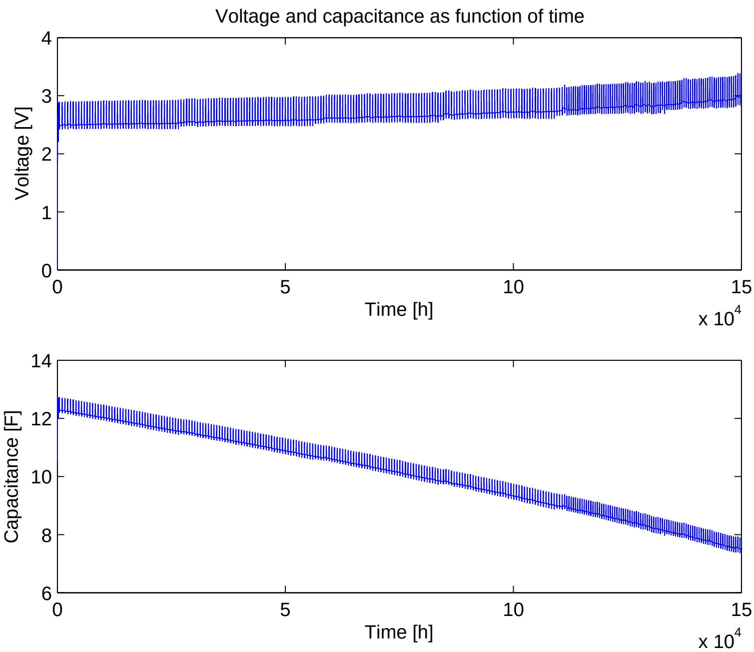

Figure 5.29 Voltage and capacitance as function of time when optimizing the energy in the EDLCs.

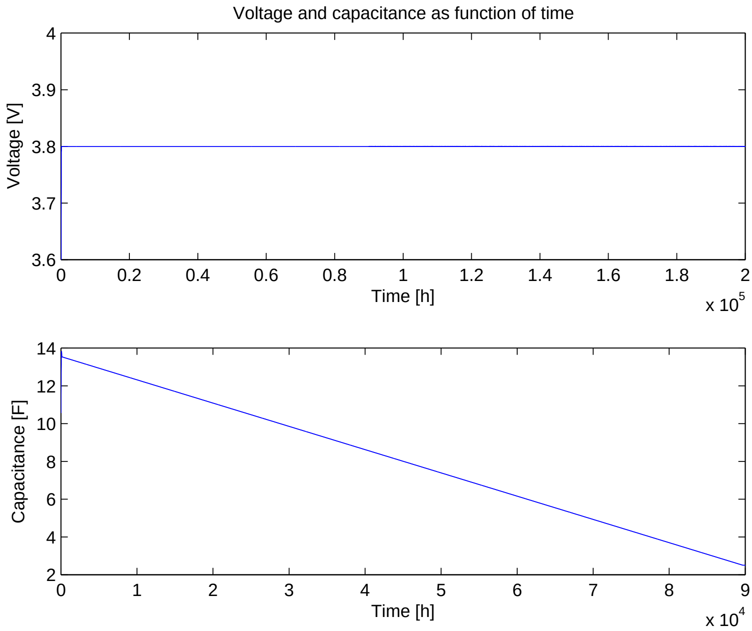

Figure 5.30 Voltage and capacitance as function of time without energy optimization. The voltage is held constant at 3.8V.

Assuming the end of life is at 50% of its initial capacitance value, the lifetime of the EDLCs at different voltages and temperature is displayed in Table 5.2.

Table 5.2 Comparison in lifetime between constant high voltage and controlled voltage, at different temperatures.

Temperature [°C]\ Voltage [V]	1.7	1.9	2.1	Controlled
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

Discussion In Table 5.3, it can be seen that the lifetime will be reduced with half if the temperature is increased with 10°C. This indicates that the model preform as expected in relation to temperature changes. The rule of thumb for voltage state that a increase with 0.3V will reduce the lifetime be half. As can be seen in Table 5.4, this is not the case. The reason for this lies in the implementation of the initial exponential drop in capacitance and that we not actually use 0.3V in the model. We have instead used another value, obtained from measurements.

Table 5.3 Comparison in lifetime between constant high voltage and controlled voltage, at different temperatures, presented as change in percent from the reference value 60 °C (ref).

Temperature [°C]\ Voltage [V]	1.7	1.9	2.1	Controlled
70	52%	50%	51%	50%
60	ref	ref	ref	ref
50	107%	100%	100%	102%

Table 5.4 Comparison in lifetime between constant high voltage and controlled voltage, at different temperatures, presented as change in percent from the reference value 1.9V (ref).

Temperature [°C]\ Voltage [V]	1.7	1.9	2.1	Controlled
70	50%	ref	-26%	198%
60	55%	ref	-25%	201%
50	61%	ref	-25%	203%

The conclusions we have made is that our model mimics the performance of an EDLC in a realistic way and that our control system performs as we had hoped. Compared to holding the voltage constant at 3.8V, the lifetime is increased with approximately 200%.

6

Hardware implementation

This is a suggestion on how to integrate our solution on an already existing Schneider Electric prototype. The hardware requires just some small modifications: two pins are added to measure the voltage over a shunt resistor R_{lim}. By measuring the two terminals of the shunt resistance R_{lim}, both the voltage over and current through the EDLCs can be measured. These two signals can both be fed to the STM32 processor via a low pass filter (LP filter), A/D- converters and finally to the STM32. A brief survey of the main electrical parts of the system is illustrated in Figure 6.1.

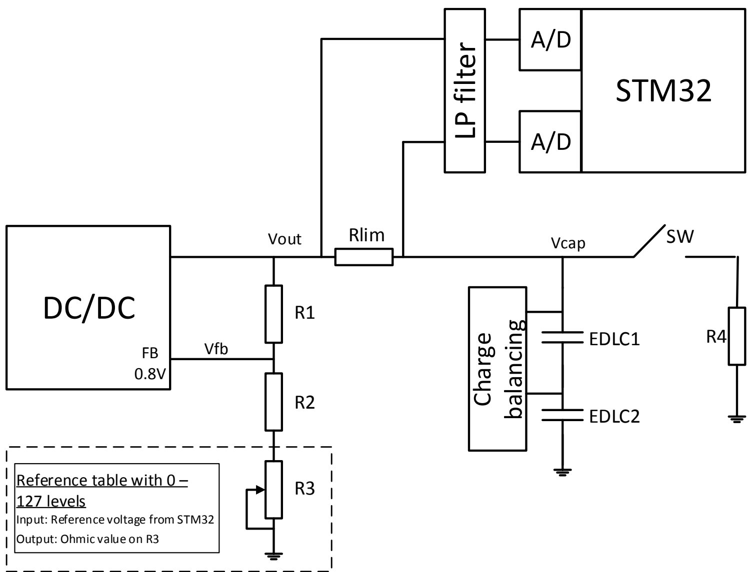

Figure 6.1 A survey of the hardware of the system during operation.

The software part will be a bit more complex to implement. The control system and the mechanism around it needs to be modified and integrated with our solution. The control system is programmed as a state machine and its function was explained in Chapter 4.7.1. To help the reader understand the electrical construction in Figure 6.1 and control system better, a brief explanation is given:

When the control system wants to charge the EDLCs i.e. a new set point is calculated or capacitance measurements with small charges are demanded, a new reference voltage is set. The DC/DC converter and the switch (SW) are both controlled by the STM32. When the new reference value is set the DC/DC converter is enabled and the switch is open. The reference voltage is then processed through a lookup table and mapped into an ohmic value on the resistance R_3. Using voltage division, the output voltage V_{out} is expressed according to Equation 6.1.

$$V_{out} = \frac{R_1 + R_2 + R_3}{R_2 + R_3} \cdot V_{fb} \tag{6.1}$$

If the voltage over the EDLCs V_{cap} is not equal to V_{out}, there will be a current flowing through the resistor R_{lim}. The current through the resistor R_{lim} is given by the Ohms law in Equation 6.2.

$$I_c = \frac{V_{out} - V_{cap}}{R_{lim}} \tag{6.2}$$

This current will then charge the EDLCs i.e. V_{cap} will increase. Since V_{out} is a fix value (if there is no changes in the reference voltage) the charging current will decrease when the voltage over the EDLCs increases i.e. the current will not be constant. When V_{cap} has reached the same voltage potential as V_{out}, the charging current will be zero. Because of the resistive mechanisms in the EDLCs i.e. leakage currents, there will be a small current (approx 1 – 5 mA) charging the capacitors to compensate for this resistive behavior.

Furthermore, the capacitance values of the EDLCs are determined during a charge or a discharge. After the charging with a predefined voltage, follows a discharge to its initial potential before the charging. When the control system demands a discharge, the DC/DC converter is disabled i.e. its output impedance is set high, and the switch is closed. Since the resistances $R_1 - R_3$ is high compared to R_4, most of the current from the EDLCs will flow through the resistance R_4 to ground i.e. the EDLCs will be discharged. This discharge current I_d, through R_4, is given by Equation 6.3.

$$I_d = \frac{V_{cap}}{R_4} \tag{6.3}$$

The capacitance calculations are based on the ability to measure the current and voltage. From the inputs V_{out} and V_{cap}, the charge and discharge currents can be calculated. The parameter values of V_{cap}, I_c, and I_d are then used as inputs for calculations of the capacitance values.

A common STM32F0 discovery development kit is seen in Figure 6.2.

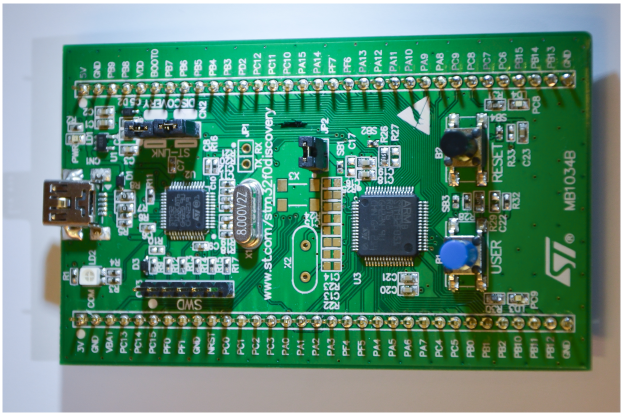

Figure 6.2 STM32F0 discovery development kit from STMicroelectronics.

7 Conclusion

EDLCs are promising components which can be used for many different applications. In this thesis, the main topic has been to study how EDLCs can be used in embedded systems as power back up source. The current solution in these systems is based on using batteries, or having an EDLC with a higher initial capacitance value and a higher constant applied voltage than needed for a certain energy level. The simulations explained in this paper indicate that a better solution can be used, leading to a significant increases in lifetime. Instead of applying a constant voltage, the voltage is controlled to optimize the energy stored in the EDLCs. The benefits by controlling the voltage are:

- The lifetime of the existing EDLCs can be increased by approximately 200% i.e. a new and increased worst case lifetime can be specified/guaranteed.
- If the increased lifetime is higher than needed, the EDLCs can be made smaller (smaller size gives smaller capacitance value) to save money and space on the hardware.
- The ambient temperature can be increased (max 70 °C), without taking any penalty on guaranteed lifetime.
- The lifetime estimations can be used for self-diagnostic purposes i.e. one can plan future maintenance on the system etc.

The control system and the simulations are based on the result from the accelerated lifetime measurements. These measurements illustrated that if the applied voltage is kept as low as possible, the exponential drop of capacitance in the beginning will be smaller. Another important conclusion is that if the voltage is increased during an accelerated test there will not be another exponential drop, instead the capacitance is decreasing with a different linear slope.

8

Further improvements and suggestions

8.1 Prototype test

By the scope of our work and the amount of labor we have put in to this thesis, we are quite optimistic that we have designed a simple and robust solution. Having that said, we know that Murphy's Law is one of the most important lessons ever learned, "Anything that can go wrong — will go wrong". We will therefore present some different ways on how we believe that the solution can be tested and verified in a controlled environment. We have also rated the different alternatives, in difficulty, risk and reliability. This rating is not produced scientifically, but reflects our opinion on which alternative to use.

> Implement the solution on an existing prototype and test its ability to calculate the correct capacitance value and its capability to maintain the desired energy level in the EDLCs.
> Difficulty: Easy
> Risk: Low
> Reliability: Moderate
>
> Implement the solution on an existing prototype and place it in a heat chamber together with a non modified prototype at high temperature. Compare the performance between the two prototypes.
> Difficulty: Easy
> Risk: Low
> Reliability: High
>
> Use the solution in a finished product, and let it save data that can be evaluated after a period of time.
> Difficulty: Moderate
> Risk: High
> Reliability: Low

Combining different alternative, for example alternative 1 and 2.
Difficulty: Low
Risk: Low
Reliability: High

8.2 Self-diagnostics

Today there are no self diagnostic tools available for measuring the EDLCs status. To be able to perform a satisfactory self diagnostic on EDLCs, a method for measuring in-circuit capacitance value and a dynamic lifetime estimation method is necessary. Since there are no adequate methods that accomplish these measurements and thereby no Self diagnostic tool available for EDLCs. We are presenting a fairly accurate method for measuring in-circuit capacitance values and a method for lifetime estimation in this report; thereby illustrating that self diagnostic is actually possible on EDLCs when used as power source. The idea of a self diagnostic tool has not been discussed in this project, but the potential is promising. We believe that the self diagnostic tool can be used to improve the following:

- The operator can easily detect when the EDLCs are approaching their end of life and then plan the maintenance accordingly, see Figure 8.1.
- When the energy is below the needed energy for backing up the data, the backup time can be recalculated and only the necessary data can be saved. Change the energy parameter to save more data during a longer time.
- An end of life indicator can be implemented in the software, which illustrates the current status of the EDLCs.

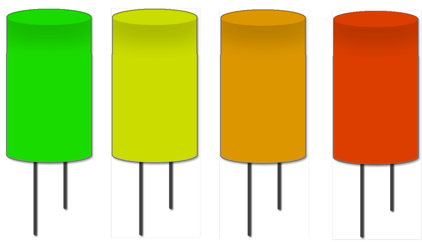

Figure 8.1 A suggestion on how a self-diagnostic symbol can look like for an EDLC.

8.3 Standardized electrical energy source for low power demands, using EDLC

By using the presented solution, we believe that a standardized electrical energy source for low power demands, using EDLC, can be made. If so, the solution would consist of a microprocessor, voltage regulator, connections for EDLCs, connection for charger and a power output. Using this solution, the user only has to connect suitable EDLCs, a suitable charger (i.e. solar panel) and the load in question. The lifetime of such a system would be much greater than a similar solution using batteries. This is true both since the EDLCs can be charged and discharged more times, and since the control system will keep the voltage over the EDLCs as low as possible. The solution could be of great use, especially in times like these when there is an increasing demand in using and storing renewable energy.

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9

Appendix

9.1 Appendix A

When stressed with high temperature most electrical components change their expected behavior for the worse or they simply break. In some applications several EDLC's are used in parallel connections. If one of them breaks i.e. becomes a short or an open circuit, the rest should not be affected. Using the design in Figure 9.1 ensures that the circuit works properly despite a broken EDLC.

In Figure 9.1, a voltage source is connected in parallel with two resistors. These two resistors divide the voltage between each other and this voltage is the reference value for the operational amplifier (opamp) LT1001. Whenever the voltage to be compared (Vin+) is under the reference value (Vin-), the output of the opamp has its positive saturation value (Vcc) and vice versa. The output of the opamp is connected to the gate of the P channel MOSFET (PMOS). When the output voltage of the opamp is 0 V, the PMOS will act as a short circuit. This leads to a current flow through the 1Ω resistor, PMOS and then to the EDLC's. The opamp is continuously comparing the voltage of the source leg of the PMOS with the reference voltage i.e. Vin+ and Vin-. If an EDLC breaks and creates a short circuit, the 10Ω resistor compensates for the short circuit if the impedance of the resistor is larger than the impedance of the output of the opamp. Without this solution, there will be a direct short circuit to ground and all the current will flow through it. The function of the 100Ω resistors is to provide a discharge path for the EDLC's, if they are charged over the reference voltage.

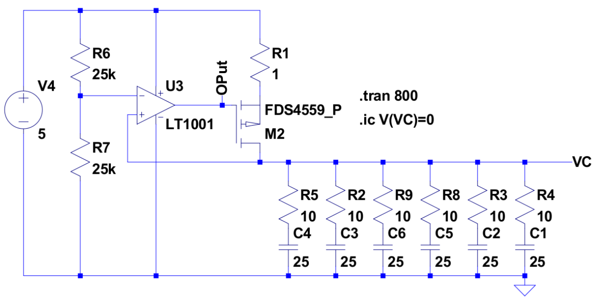

Figure 9.1 A more detailed picture of the circuit used in the temperature chamber.

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Control strategy and lifetime optimization of Electrochemical Double-Layer Capacitors

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 where 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 back up system with EDLCs as power source and an associated control system, was built and simulated in Simulink. Furthermore, an electrical hardware prototype was implemented to create a proof-of-concept. 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, MATLAB, Simulink, Embedded Systems, Aging, Lifetime Estimation, Voltage Control, Control System.

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