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**Test Bench for Characterization
of Supercapacitor Devices**

Master's Thesis

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1 Introduction

Supercapacitors are energy storage devices that have gained popularity due to their unique characteristics and potential applications.

An electric capacitor stores energy between two electrodes, separated by a non-conducting material. The conductors hold equal and opposite charges, and the non-conducting material creates an electric field. A supercapacitor stores the charge between an electrode and the electrolyte; therefore, the electrical energy is stored because of the generation of a double layer of electrolyte ions on the electrode surface [1].

Compared to conventional capacitors, supercapacitors can store much larger amounts of energy. Compared to batteries, they can charge and discharge at high current rates and have a great number of charge-discharge cycles. These qualities make them especially valuable in applications requiring high power density, a long cycle life, and fast charging capabilities.

One of the main applications of supercapacitors is using them as back-up power, with their high-power density and long lifetime, they have the ability to get a very fast powerful response after a power loss or shut down and maintain the energy until the power supply is restored. Another application is as a storage unit for renewable energy. Since these energies are very intermittent supercapacitors allow to provide a stable power output suitable for off-grid applications, which can operate in tough environmental conditions and have a very good charging/discharging cycling lifetime [2].

In electric vehicles, its use is becoming more popular since this market is growing very fast and requires innovative, efficient and environmentally friendly storage and power devices. First, they were introduced as power boosters and to recapture energy in trains and buses. Nowadays in electric vehicles they are being used as unique energy storage or combined with batteries, optimizing power output, lifetime and cost. An important asset for using supercapacitors instead of batteries is their thermal stability and the wide operating temperature range, since lithium-ion batteries have the risk of thermal runaway causing safety concerns. Although there are types of supercapacitors that do have lithium-ion technology, they are free of the metal oxides that cause thermal runaway. Another interesting application in electric vehicles is for regenerative braking. Because of the ability to store large amounts of energy and release it very quickly, they are great for capturing kinetic energy that would be dissipated as heat and converting it into electric power to recharge the battery [3].

2 Aim of the project

In order to put under test the capabilities and characteristics of supercapacitors, in this master's thesis a test bench and a test procedure will be proposed. The test bench must be able to charge and discharge the devices at different current rates in a safe way and it must be capable of measuring and recording the voltage. The data will be used to calculate the main characteristics that some of them are not provided by the manufacturers from the different devices.

A selection of different types of supercapacitors (operating voltage, capacity and technology) will be tested. As a result, their characteristics will be obtained, and then compared to the data provided by the manufacturer.

3 Types of supercapacitors

3.1 Electrostatic double layer capacitors

Electrostatic double layer capacitors differ from simple electrostatic capacitors in having much higher energy density. EDLCs are based in two electrodes made of porous carbon and electrolyte liquid with a separator between them. This type of supercapacitor is intended to have the biggest surface area possible in order to capture a bigger quantity of ions.

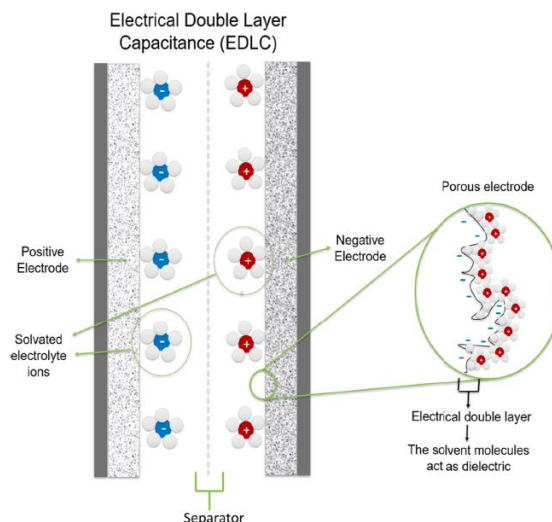


Figure 1. Schematic of a EDLC [4]

The thin separator layer between the two sides prevents the current from flowing between the double layers. However, the EDLC can endure low voltages only. In order to reach high voltage levels, EDLCs units must be made of matched series connected individuals, so they can have a higher voltage.

The electrodes are mostly made of biodegradable and derived from natural materials such as cellulose or from biomass waste, therefore they tend to be very porous so they can achieve a great capacity. Carbon materials such as activated carbon fibers are the most used, however, they have low conductivity. Aerogels and carbon nanomaterials are also utilized to form the porous structure that is normally used to build this type of capacitors and also to have a higher conductivity. The most promising material for building supercapacitors is graphene thanks to its properties, very high capacities can be achieved. Nowadays, there are big efforts to commercialize the process of producing it from cheap sources such as agricultural wastes [2].

3.2 Pseudocapacitors

Pseudocapacitors are a type of supercapacitors where the material of the electrodes allows the pseudocapacitance effect to be more relevant in the energy storage. The pseudocapacitance contributes to the total capacitance value of the cell, which depends on the surface area, the type of the material of electrodes and the electrolyte. The pseudo electrodes are mainly comprised of oxides of metals, carbon doped with metal and conductive polymers.

Pseudocapacitors show a behavior that is intermediate between batteries and EDLCs. The pseudocapacitance effect works in a similar way as in a battery, it is a faradic process, the charging and discharging is a redox chemical reaction that happens through the transfer

of charge between electrodes and electrolyte. This redox reaction is the intercalation or adsorption of cations such as Li^+ or Na^+ and the electrode material [5].

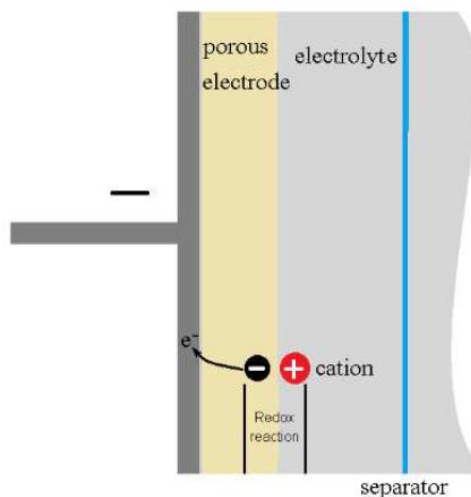


Figure 2. Schematic of a pseudocapacitor detail on redox reaction [2]

EDLCs in an ideal case have potential-independent capacitance and the constant current discharge of EDLC results in a linear potential versus time. On the other hand, batteries show nonlinearities associated with the chemical reactions involved in charge storage and discharging.

As EDLCs, batteries and pseudocapacitors have some overlapping in their characteristics; nevertheless, they can be distinguished by charge/discharge curve tests. Because of the faradic processes, pseudocapacitors can achieve higher capacities and energy densities than EDLCs, but they have a lack of power density and exhibit a shorter cycle lifetime. The first one happens due to a low electric conductivity of the materials and the second one because the repetitive cycling of the redox chemical reactions may damage the materials.

It has been stated that there are two electrode materials used to manufacture pseudocapacitors, metal oxides and conducting polymers.

In brief there is a correlation between pseudocapacitance and electrostatic capacitance and even pure carbon electrodes in EDLC have some pseudocapacitance. This effect can be increased by using doped electrodes and redox active electrolytes. The use of different materials such as doped activated carbon and metal oxide for one electrode and carbon to form the other electrode, will lead to the hybrid supercapacitor structure [2].

3.3 Hybrid supercapacitors

The hybrid supercapacitors were developed trying to take the best from the EDLCs and pseudocapacitors and minimizing their inconvenient to obtain the best results. The limited energy density of supercapacitors has two enhancement paths. The first one is to increase the capacitance through the electrode's material improvements and the second path is to expand the operating voltage of the supercapacitor cell.

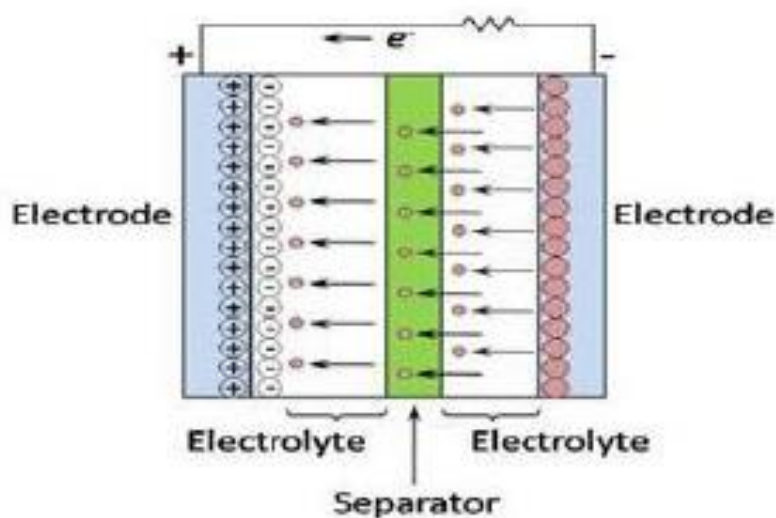


Figure 3. Schematic of a Hybrid supercapacitor [6]

Depending on the materials used and the storage mechanisms hybrid supercapacitors can be classified in three types: Composite, Asymmetric and Battery-Type [2].

Composite hybrid supercapacitors

Composite hybrid supercapacitors are an integration of carbon-based materials such as carbon nano tubes with either conducting polymer or metal oxide materials which are the same materials used to make pseudocapacitors.

This composite material incorporates both the physical and chemical charge storage mechanisms together in a single electrode. Carbon materials increase the capacitive charge and allow having big surface, whereas the pseudocapacitive materials through faradic reactions increase the capacitive of the composite electrode.

Asymmetric Hybrid supercapacitor

Asymmetric hybrid supercapacitors use carbon-based material as negative electrode and pseudocapacitive materials like metal oxide or a polymer as positive electrode. The pseudocapacitive electrodes, which use a faradic process, have higher capacitances and lower resistances than the carbon-based electrodes which utilise an electrostatic process.

This Asymmetric electrode couple are half EDLC and half pseudocapacitor, which has a cell capacity from two to four times bigger than a normal EDLC. On the other hand, since there are redox reactions, the cycle lifetime is reduced depending on the oxide, the electrolyte or the carbon used.

Battery-Type Hybrid supercapacitor

Battery-type hybrid supercapacitors are similar to asymmetric supercapacitors; however, battery-type hybrids use battery electrodes such as nickel hydroxide, lead dioxide, and lithium for the positive electrode and activated carbon for the negative one.

Hybrid supercapacitors have higher energy density and rated voltage, but lower power density, cycle lifetime and self-discharge, than the symmetrical EDLC's. As an inconvenient, they have minimum operating voltage and crossing this voltage limit would damage the supercapacitor.

All these properties make a battery-type hybrid supercapacitor similar to an actual lithium battery but with the benefit of the cycle lifetime and the fact that they are free of the metal oxides that cause thermal runaway, which could lead to catastrophic breakdown or explosions.

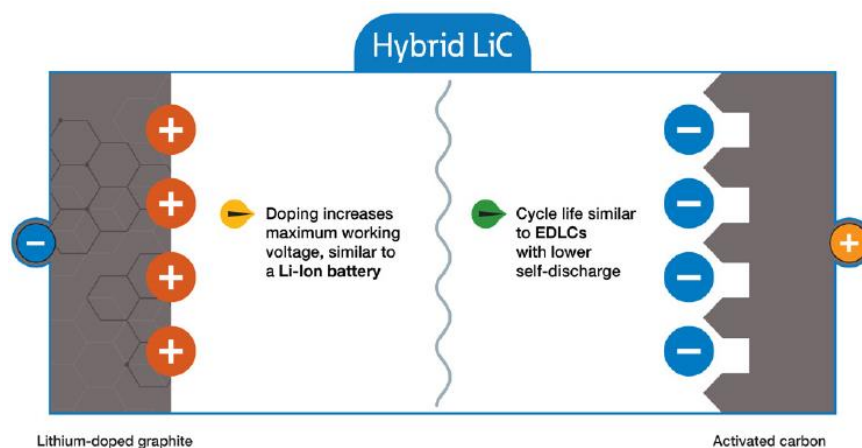


Figure 4. Schematic of Eaton's battery type hybrid supercapacitor [7]

3.4 Electrolyte

The electrolyte is the medium that allows the electrical connection between the electrodes and it is an important part of the supercapacitor performance. The ionic conductivity of the electrolyte is responsible for the internal resistance of the supercapacitor. Also, having an electrolyte with poor chemical stability at temperature or at high rates may increase the resistance and reduce the lifetime. A good chemical stability allows having larger voltage operational windows [1] pp 180-185.

It is important for the electrolyte to be safe for operation by having low volatility, low flammability and low corrosivity. When operating outside of the voltage window it may cause electrolyte decomposition.

Electrolytes are divided into three categories, each with various advantages and disadvantages [4]:

- Aqueous: Salt and acid based, they are the most common because of the low cost and their availability. They have high ionic conductivity, mobility and a low hazard level. As disadvantages they are corrosive and have a low voltage window.
- Organic: By using acetonitrile or propylene carbonate, they have a better voltage window than the aqueous, which provides also larger energy and power densities. As drawbacks, more internal resistance is present and there exist some safety concerns because of their toxicity.
- Ionic liquids: Typically composed by an asymmetric organic cation and an inorganic or an organic anion, they have a large potential window, but they are costly and have poor conductivity which translates into a high internal resistance.
- Solid State: Made of gel and solid polymer made, they try to combine the electrolyte with the separator as one component.

3.5 Supercapacitor characteristics

3.5.1 Capacitance

A supercapacitor is a storage device for electrical charge, and the capacitance is defined as the charge storage mechanism that a capacitor has for a certain voltage range.

During charging and discharging the operating voltage changes linearly. The following relation allows to calculate the capacitance of the device [8]:

$$C = \frac{\Delta Q}{\Delta V} = I \frac{\Delta t}{\Delta V} \quad (1)$$

The capacitance of supercapacitors depends on multiple factors, the most important one is the surface area. With a larger area more charge can be stored. The others depend on the materials of the device such as the electrolyte or the conductivity of the electrodes.

3.5.2 Voltage window

When charging a supercapacitor, the voltage limitations have to be taken into account. Supercapacitors have an operational voltage window, this means that they have upper and lower voltage limits. Operating outside this window provokes degradation and may cause electrolyte decomposition, leading to a short-circuit of the electrodes and damaging the device.

EDLC supercapacitors which have non-Faradic charge behaviour can be totally discharged to zero volts without degradation, and depending on the type of electrolyte they can have wider voltage window.

For hybrid supercapacitors which have Faradic charge behaviour there is a minimum operating voltage, so operating within the voltage window is very important to maintain the performance and to avoid reducing the lifetime of the device.

3.5.3 Internal resistance

Real supercapacitors have power losses during charge and discharge, which is caused by the resistance of the device materials, electrodes and electrolyte. For this reason, in EDLCs the resistance is lower than in hybrids and batteries. The internal resistance is defined as equivalent series resistance or ESR as it can be represented in series to the capacitor.

ESR can be determined during charge/discharge at constant current tests by the voltage drop which appears when starting the discharge [9]:

$$R_{ESR} = \frac{\Delta V}{I} \quad (2)$$

The power loss caused by the internal resistance is lost as heat and under extreme conditions like a large number of cycles and high current charge/discharge, can accumulate high temperature, reduce the performance of the device and cause damage [10].

$$P_{Loss} = I^2 \cdot R_{ESR} \quad (3)$$

3.5.4 Leakage resistance

Leakage resistance is another supercapacitor non-ideality. An ideal supercapacitor would maintain constant voltage without being connected to a power supply. In reality, supercapacitors require current (also called leakage current) to maintain the voltage constant. This phenomenon can also be called self-discharge [1] pp 67-68.

The leakage causes that the current needed to charge the supercapacitor is larger than expected and the current obtained from it is less than the expected.

Leakage resistance can be represented as a parallel resistance to the capacitor and in series to the internal resistance. Depending on the supercapacitor generally, parallel resistance is much bigger than the series resistance, making it not very relevant when charging or discharging the device, unless is done at a very small current rate.

EDLCs have small leakages resistances compared to hybrid, this causes them to be more affected by self-discharge.

Leakage current during self-discharging can be obtained by multiplying the voltage slope over time times the capacity [11].

$$I_{leak} = C \cdot \frac{dV}{dt} \quad (4)$$

3.5.5 Energy and power density

The energy stored in a capacitor is related to the necessary work for charging the capacitor and it can be expressed as:

$$E = \frac{1}{2} \cdot C \cdot V^2 (Wh) \quad (5)$$

This expression is equivalent to the maximum energy that can be stored in the supercapacitor, which is what the manufacturers provide, but in reality, only a part of the maximum energy is available because of the linear voltage drop during discharge, which affects the operation voltage range. With this in mind, we can express the effective energy as:

$$E_{eff} = \frac{1}{2} \cdot C \cdot (V_{max}^2 - V_{min}^2) (Wh) \quad (6)$$

Typically, the energy that can be stored in a supercapacitor can be represented as specific energy density (Wh/kg) which considers the mass, or as the volumetric energy density (Wh/l) which considers the volume.

From the previous expression the power can be defined on how fast the energy can be released to a load:

$$P_{eff} = \frac{E_{eff}}{t} (W) \quad (7)$$

Also, in electrical magnitudes the power can be expressed as the voltage multiplied by the current.

$$P = V \cdot I (W) \quad (8)$$

The maximum power (peak) available in a supercapacitor takes place when it is fully charged at the initial moment of the discharge, this is the value provided by the manufacturers. The complete process to obtain this expression can be found in [1] pp 82-83.

$$P_{max} = \frac{V^2}{4 \cdot R_{ESR}} (W) \quad (9)$$

The power available in a supercapacitor can be represented as specific power density (W/kg) which considers the mass, or as the volumetric power density (W/l) which considers the volume.

To compare the supercapacitors performance against other energy storage devices, the relation between energy and power densities can be represented using a Ragone plot:

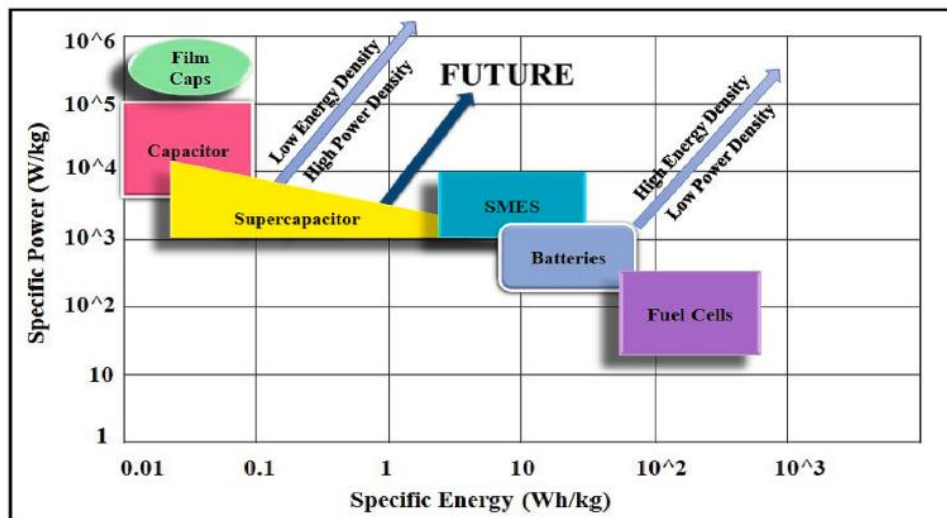


Figure 5. Energy storage devices Rangone plot [12]

As shown in the plot, supercapacitors can deliver higher power but less ability to storage energy compared for example with batteries. This is the major disadvantage of supercapacitors and the aim for future research.

3.5.6 Temperature range

The operating temperature range is another important characteristic to consider for all energy storage devices, and supercapacitors are not an exception.

In general, EDLC's have a great operating temperature, in the appendix of this master's thesis there are some supercapacitor datasheets which indicate a range of -40°C to $+85^{\circ}\text{C}$. This is caused by the low internal resistance, which minimizes the power losses that produce heat.

In case of the hybrids the temperature range is reduced, also in the appendix it is indicated a range from -25°C to $+70^{\circ}\text{C}$. Low temperatures slow the chemical reactions and since there is more internal resistance the upper temperature limit is reduced.

Compared to batteries whose temperatures ranges are normally from -20°C to $+40^{\circ}\text{C}$, supercapacitors perform better under different temperature conditions. Also, since there are fewer chemical reactions, the efficiency under low temperatures is better and under high temperatures there are no risks of self-accelerating reactions that can cause thermal runaway [7].

3.5.7 Lifetime

Since EDLC supercapacitors do not have faradic reactions, they should have a very long lifetime around 1 million cycles. In reality, as previously explained, there are multiple factors that reduce the lifetime of the device (voltage range, temperature). This is why the manufacturers recommendations from datasheets should be followed. The degradation can be monitored by checking the capacitance, the internal resistance and the leakage resistance.

In case of hybrid supercapacitors, the lifetime is less than EDLC's due to the faradic reactions from 500.000 to 250.000 cycles but still way better than batteries [2].

3.6 Characterization methods

3.6.1 Model

To represent the supercapacitor characteristics that were explained in previous sections of this master’s thesis, an equivalent circuit can be modelled. A supercapacitor can be very complex to represent since there is not a unique model. The most used the one described in IEC 62391-1, it consists of a capacitor with two resistances, one connected in series R_{ESR} which represents the internal resistance, and another one connected in parallel R_p which represents the self-discharging effect.

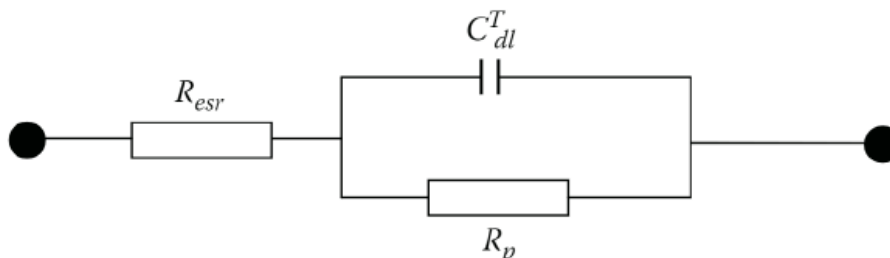


Figure 6. Supercapacitor model [1] pp 67

The previous circuit is just a simplified model for an ideal supercapacitor, in real life they have a non-ideal behaviour due to the porous materials of the electrodes. For this reason, supercapacitors have a more similar behaviour to transmission lines than actual capacitors. In the image below there is depicted a realistic and more accurate equivalent circuit for a supercapacitor. This model attempts to capture the distributed double-layer capacitance and the distributed electrolyte resistance that extends the depth of the pore.

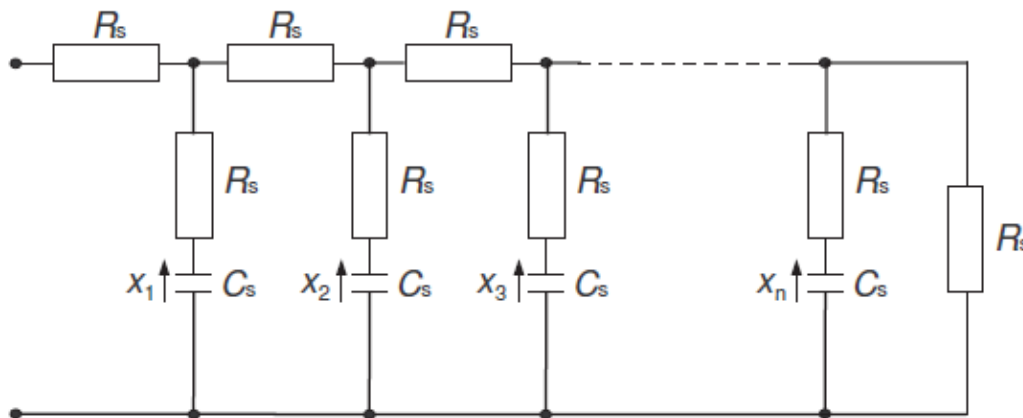


Figure 7. Supercapacitor RC Ladder network model [13]

There are lots of studies for modelling and creating equivalent circuits to obtain the closest model for supercapacitors such as in reference [14] which is based in the previous ladder model. For further information in references [15] and [16] more models are explored. To simplify and minimize errors, in this master’s thesis, the first model with the series and parallel resistances is used given that there are different supercapacitor types and from different manufacturers under study.

3.6.2 Charge/discharge at constant current

The charge and discharge test at constant current is one of the most used to determine the main characteristics of supercapacitors. It allows to estimate the capacity, the equivalent series resistance and the leakage resistance.

In the IEC 62391-1 standard is proposed a test method for charging/discharging at constant current.

First the supercapacitor is charged using constant current. from completely discharged (0 volts) to its rated voltage U_R . Then, the charging process continues with constant voltage during a determined time (standard proposes 30 minutes). After this time, the supercapacitor is discharged at constant current until 0 volts.

In the image below the supercapacitor terminal voltage profile is depicted while performing the test.

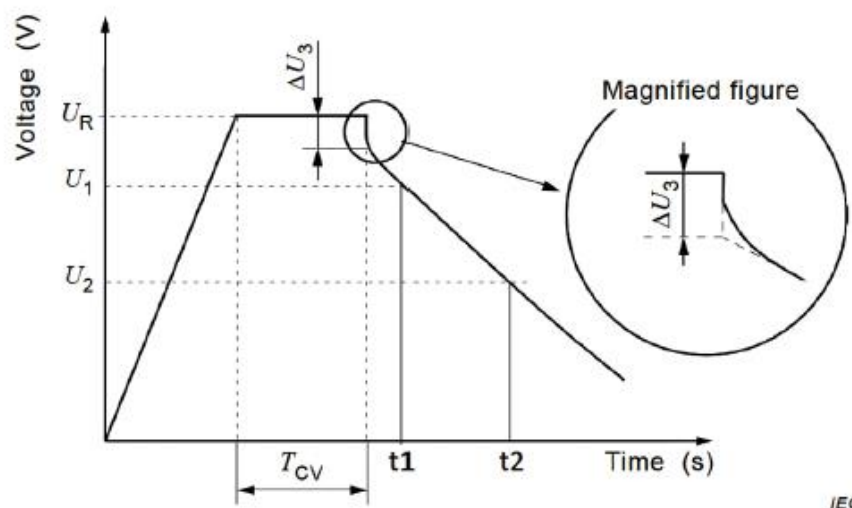


Figure 8. Charge/discharge voltage profile [17]

The capacity of the supercapacitor can now be calculated with the discharge slope data obtained using the following equation:

$$C = I \frac{\Delta t}{\Delta V} = I \frac{t_2 - t_1}{U_1 - U_2} \tag{10}$$

Where I is the discharge current, U_1 is the calculation start voltage which is the 80% of the rated voltage and U_2 is the calculation end voltage which is the 40% of the rated voltage. t_1 is the time at which the supercapacitor terminal voltage reaches U_1 from the start of the discharge process and t_2 the discharge time of the U_2 end voltage.

The standard recommends current and voltage values for performing the test depending on the class of the supercapacitor which also depends on its use. In the table below is shown the classification according to IEC 62391-1:

Table 1. Classification according to IEC 62391-1

Classification	Class 1	Class 2	Class 3	Class 4
Application	Memory backup	Energy storage	Power	Instantaneous power
Charge time	30 min	30 min	30 min	30 min
I (mA)	1 x C	0,4 x C U _R	4 x C U _R	40 x C U _R
U ₁	The value to be 80% of the charging voltage (0,8 x U _R)			
U ₂	The value to be 40% of the charging voltage (0,4 x U _R)			
Note: C is the rated capacitance in F (Farad) and U _R rated voltage in V (Volts)				

To evaluate the supercapacitor model when charging at constant current, the circuit below can be represented, and the equations of the model can be obtained [1] pp 70-73.

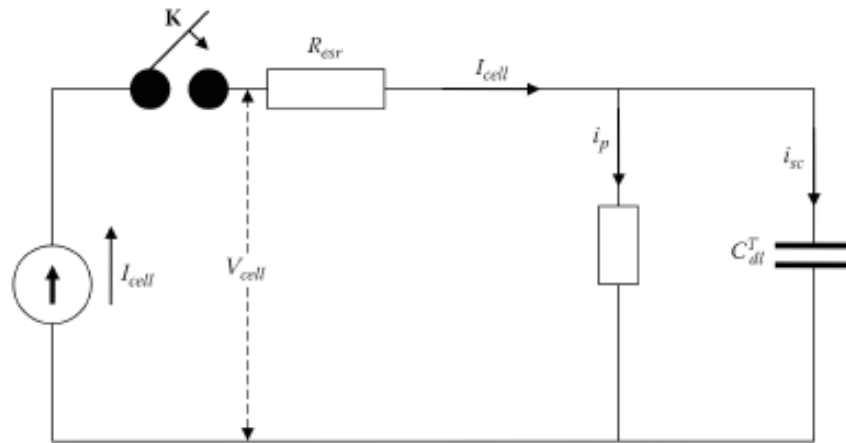


Figure 9. Supercapacitor model at constant current charge [1] pp 71

When charging a supercapacitor from zero charge at constant current, when $t > 0$ it can be expressed as the equation below:

$$V_{cell} = I_{cell}R_{esr} + I_{cell}R_p \left(1 - \exp\left(-\frac{t}{R_p C}\right) \right) \quad (11)$$

From this equation, the minimum voltage and the maximum voltage when the supercapacitor is fully charged can be obtained:

$$t = 0 \rightarrow V_{cell} = I_{cell}R_{esr} \quad (12)$$

$$t = \infty \rightarrow V_{cell} = I_{cell}R_{esr} + I_{cell}R_p \quad (13)$$

If the charging time is required for a targeted voltage:

$$V_{cell} = V_T \rightarrow t = -C \cdot R_p \cdot \ln \left(1 - \frac{V_T - I_{cell}R_{esr}}{I_{cell}R_p} \right) \quad (14)$$

Considering that there is no leakage current, the equation can be simplified:

$$R_p = \infty \rightarrow V_{cell} = I_{cell}R_{esr} + I_{cell} \frac{t}{C} \quad (15)$$

For the previous expression if the charging time is required for a targeted voltage:

$$V_{cell} = V_T \rightarrow t = C \left(\frac{V_T - I_{cell}R_{esr}}{I_{cell}} \right) \quad (16)$$

Considering no internal resistance:

$$R_{esr} = 0 \rightarrow V_{cell} = I_{cell}R_p \left(1 - \exp \left(-\frac{t}{R_p C} \right) \right) \quad (17)$$

Finally, if considering charging an ideal supercapacitor should not have internal resistance and no leakage current:

$$R_{esr} = 0 \ \& \ R_p = \infty \rightarrow V_{cell} = I_{cell} \frac{t}{C} \quad (18)$$

4 Description of the studied supercapacitors

Five different supercapacitors from two manufacturers have been studied in this master's thesis with different capacities, operational voltage ranges and sizes but all of them in a cylindrical format.

4.1 Cornell supercapacitors

From Cornell Dubliner manufacturer, two of their DSF series supercapacitors have been studied. These supercapacitors are EDLC type with an activated carbon anode and cathode, and organic electrolyte. Both have 3 V operational range and when it comes about their capacities, there is one with 350 F and a smaller one with 200 F, but according to the manufacturer both have similar energy densities.



Figure 10. Cornell supercapacitors 3 V 350 F (left), 3 V 200 F (right)

4.2 Eaton supercapacitors

From Eaton another two EDLC's type have been studied, also with carbon anode and cathode and organic electrolyte. One is from the XV series with an operational voltage of 2.7 V and 300 F capacity, the other one. in a smaller size from the TV series with 3 V and 100 F.

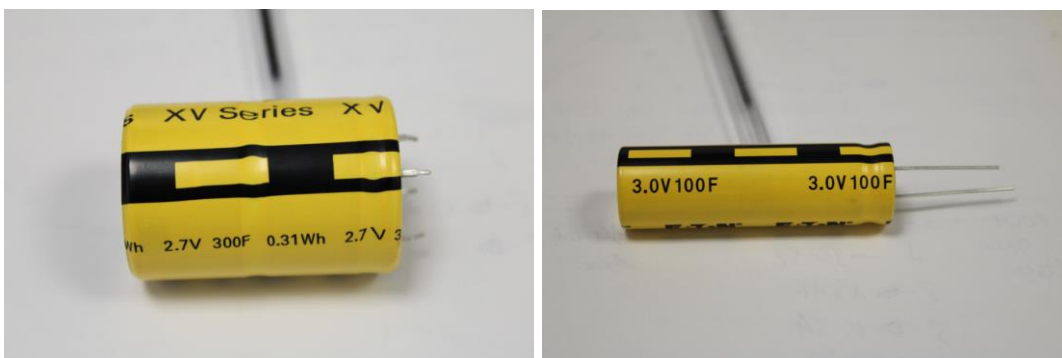


Figure 11. Eaton supercapacitors 2.7 V 300 F (left), 3 V 100 F (right)

Also from Eaton, a Hybrid Battery-Type supercapacitor, with a lithium-doped carbon and an activated carbon electrodes has been studied. This one has the highest operational voltage but because of hybrids nature, it cannot be totally discharged so it ends with an operational voltage window from 2.2 V to 3.8 V. Despite its size, it has a large capacity of 220 F. and a great energy stored but the manufacturer does not indicate the energy density, which should be higher than the other supercapacitors.



Figure 12. Eaton hybrid supercapacitor 3.8 V 220 F

4.3 Characteristics table

In the table below is shown a summary of the characteristics data extracted from the manufacturer's component datasheets. Notice that not all the characteristics provided, especially from Eaton manufacturer.

Table 2. Studied supercapacitors characteristics from manufacturer

Supercapacitors characteristics from manufacturer					
Device under test	A	B	C	D	E
Brand	Cornell	Cornell	Eaton	Eaton	Eaton
Type	EDLC	EDLC	EDLC	EDLC	Hybrid
Model	DSF	DSF	XV	TV	HS
Reference	DSF357Q3R0	DSF207Q3R0	XV3550-2R7307-R	TV1860-3R0107-R	HS1625-3R8227-R
Max Operating Voltage (V)	3	3	2.7	3	3.8
Capacitance (F)	350	200	300	100	220
Max current (A) (1s)	236	100	160	71	15.3
Max continuous current (A)	18.9	10	20	11.7	1.1
DC ESR (mOhms)	3.5	10	4.5	11	100
Max stored energy (mWh)	437.5	250	300	125	293
Leakage Current (mA)	1	0.7	0.6	0.225	0.012
Energy Density (Wh/kg)	6.73	6.94	N/A	N/A	N/A
Energy Volumetric Density (Wh/l)	7.58	7.07	N/A	N/A	N/A
Max Power (W)	N/A	N/A	410	205	36
Power Density (kW/kg)	4.75	3	N/A	N/A	N/A
Power Volumetric Density (kW/l)	5.4	3.1	N/A	N/A	N/A
Mass (g)	73	36	62	N/A	N/A
Diameter (mm)	35	30	35	18	16.5
Length (mm)	60	50	50	60	27
Volume (l)	0.0577	0.0353	0.0481	0.0153	0.0058

5 Test

5.1 Test proposed

For verifying the characteristics of the supercapacitors under study, a charge/discharge test at constant current is proposed.

To compare and check if there are any differences in levels of current, the following increment of current is tested:

- 1) 0.5 A
- 2) 1 A
- 3) 2 A
- 4) 5 A
- 5) 8 A

The test procedure is performed as follows:

- 1) Discharge the supercapacitor to a voltage below 0.1 V or to the minimum operating voltage.
- 2) Supply voltage and charge the supercapacitor to the rated voltage at the levels of constant current described above.
- 3) Maintain the supply voltage during 3 to 5 minutes to fully charge.
- 4) Discharge the supercapacitor at the same levels of constant current to at least 0.1 V or to the minimum operating voltage.
- 5) Monitor temperature and voltage during charge and discharge

To avoid damaging the hybrid supercapacitor only 0.5 A and 1 A currents were tested because, as indicated by the manufacturer, its maximum continuous current is 1.1 A. Also, the minimum discharge voltage was 2.2 V as it is the minimum operating voltage.

The objective is to obtain a similar curve as in figure 8 in section 3.6.2, with constant charging slopes and a voltage drop at the discharge start. In reality, since the perfect supercapacitor does not exist, the curves are not that sharp because of the internal and the leakage resistances of the supercapacitor

In addition, a self-discharge test is performed to determine the leakage current, the test has been performed as follows:

- 1) Discharge the supercapacitor to a voltage below 0.1 V or to the minimum operating voltage.
- 2) Supply voltage and charge the supercapacitor to the rated voltage at constant 5 A or to the maximum continuous current.
- 3) Maintain the supply voltage during 3 to 5 minutes to fully charge.
- 4) Disconnect the supply and let the supercapacitor self-discharge for at least 15 minutes.
- 5) Monitor temperature and voltage during charge and discharge

5.2 Charging time estimation

Before performing the test, an estimation of the charging time has been performed using the equations in section 3.6.2 and the supercapacitor data provided by the manufacturers shown in table 2, to compare it afterwards with the charging time of the test.

First, using equation (18), the charging time has been calculated, for an ideal capacitor that does not consider the internal resistances.

Table 3. Charging time for ideal supercapacitor

Estimated charging time at different constant current values					
Device under test	A	B	C	D	E
Capacitance (F)	350	200	300	100	220
Voltage supplied (V)	3	3	2.7	3	3.8
Charging Time at 0.5 A (s)	2100.0	1200.0	1620.0	600.0	704.0
Charging Time at 1 A (s)	1050.0	600.0	810.0	300.0	352.0
Charging Time at 2 A (s)	525.0	300.0	405.0	150.0	176.0
Charging Time at 5 A (s)	210.0	120.0	162.0	60.0	70.4
Charging Time at 8 A (s)	131.2	75.0	101.2	37.5	44.0

In addition, to obtain results closer to reality, the charging time taking into account the equivalent series resistance has been calculated by using equation (16).

Table 4. Charging time considering internal resistance

Estimated charging time at different constant current values					
Device under test	A	B	C	D	E
Capacitance (F)	350	200	300	100	220
Voltage supplied (V)	3	3	2.7	3	3.8
Charging Time at 0.5 A (s)	2098.8	1198.0	1618.6	598.9	682.0
Charging Time at 1 A (s)	1048.8	598.0	808.6	298.9	330.0
Charging Time at 2 A (s)	523.8	298.0	403.6	148.9	154.0
Charging Time at 5 A (s)	208.8	118.0	160.6	58.9	48.4
Charging Time at 8 A (s)	130.0	73.0	99.9	36.4	22.0

From the results above can be observed that there is little difference in considering the internal resistance because of the low resistance values provided by the manufacturer.

On the hybrid supercapacitor (E), the difference is noticeable because of the higher resistance value.

5.3 Test setup

In order to perform the test, the following test setup is prepared, it consists in a DC Power supply, a DC electronic charge, an acquisition system and a test board. In the image below a scheme of the setup is depicted:

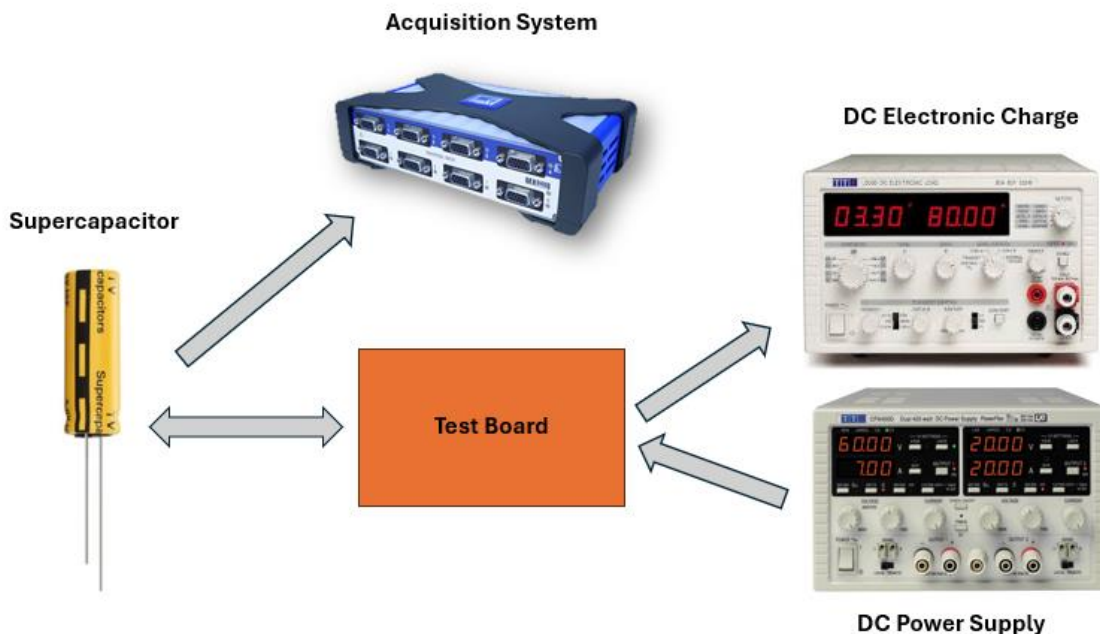


Figure 13. Test setup scheme

5.3.1 Test board

The test board is the interface between all the components of the test. Its main function is to switch from charge to discharge but also disconnect the supercapacitor. In addition, a safe discharge function was implemented by means of a resistor and a safety fuse as a supercapacitor protection. In the image below the board is shown with all the components numbered:

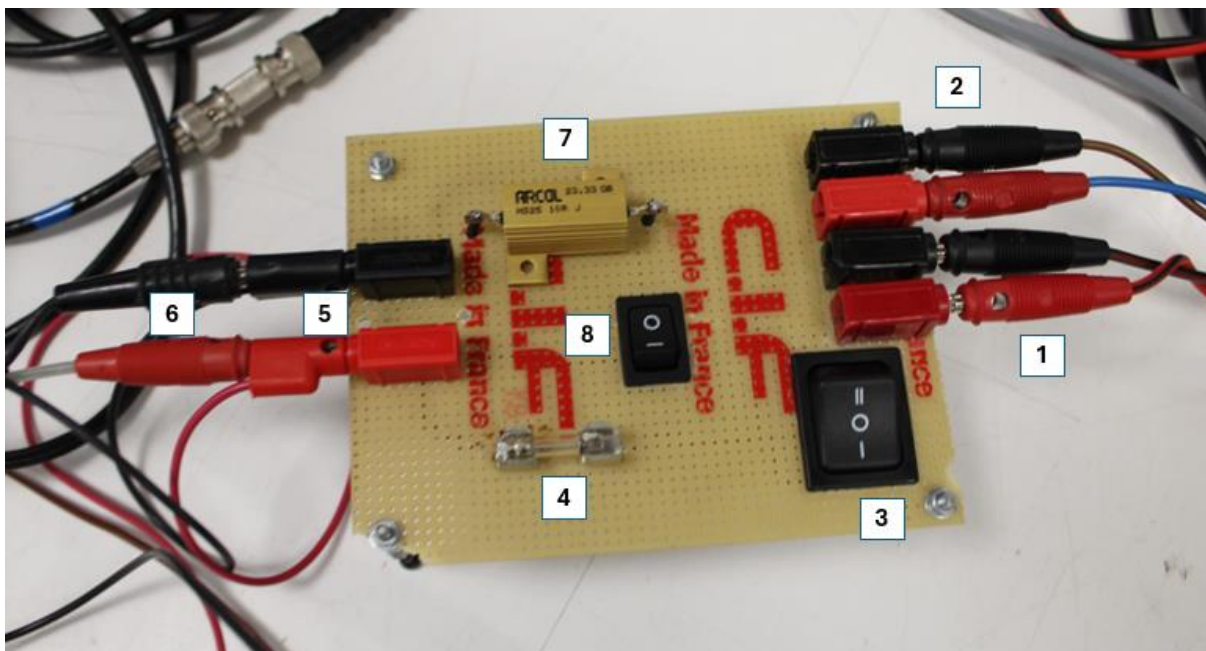


Figure 14. Test board

- 1) **DC power supply terminals:** Charging terminals.
- 2) **DC electronic charge terminals:** Discharging terminals.
- 3) **SPDT switch with off center position:** Switches form charge (I) to discharge (II) or off position (O) which disconnects the supercapacitor.
- 4) **10 A Fuse:** Protects the supercapacitor in case of overcurrent from the power supply or the electronic charge.
- 5) **Supercapacitor terminals:** Connects the supercapacitor to the board.
- 6) **Voltage readings terminals:** Connects the supercapacitor to the acquisition system.
- 7) **10 Ohm 25 W resistance:** To discharge the supercapacitor in a safe way avoiding shorting, before and after testing.
- 8) **SPST switch:** Enables the resistance for discharging.

5.3.2 DC Power Supply

Adjustable power supply to charge the supercapacitor at controlled constant current to rated voltage.

5.3.3 DC Electronic charge

Adjustable electronic charge to discharge the supercapacitor at controlled constant current to total discharge (0 V) and with the ability to stop the discharge at a minimum operating voltage if required.

5.3.4 Acquisition system

An acquisition system connected to a computer is used to record the test data. Voltage and temperature recordings have been performed at 5Hz rate during all tests.

Voltage readings were measured on the supercapacitor terminals as shown in figure 14. Temperature readings were measured by means of a thermocouple installed on top of the supercapacitor and stuck with tape to make contact with the surface, in figure 15 tape is not represented for visual purposes.

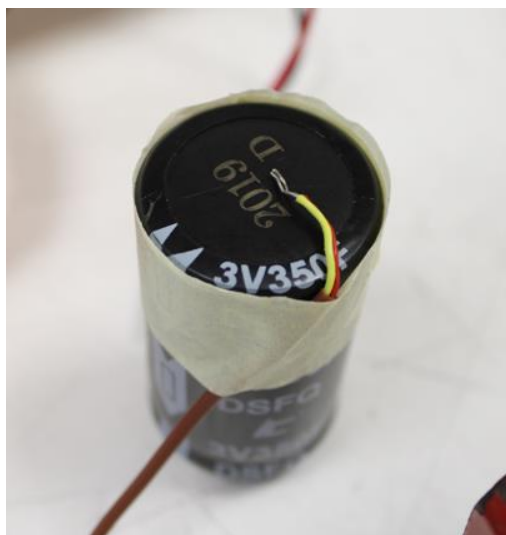


Figure 15. Thermocouple location on supercapacitor

6 Results

6.1 Voltage and temperature data from tests

For each of the supercapacitors, graphs with the voltage and temperature data recorded during the test are presented in this section. First, two graphs of the charge/discharge test at different constant currents, one with the voltage and another one with the temperature. Then a third one with the voltage recordings of the self-discharge test. With these data the characteristics of the supercapacitors can be calculated.

6.1.1 Device A – 3 V 350 F EDLC supercapacitor

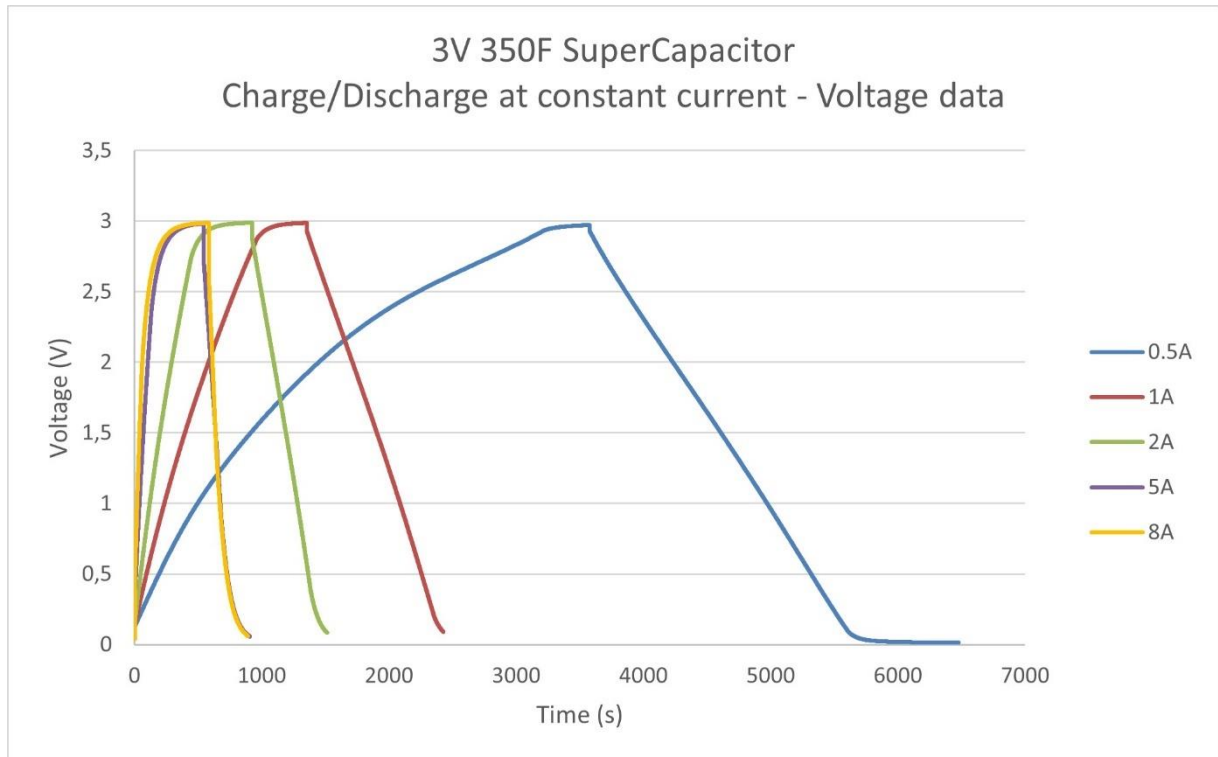


Figure 16. Device A – Charge/Discharge voltage profile

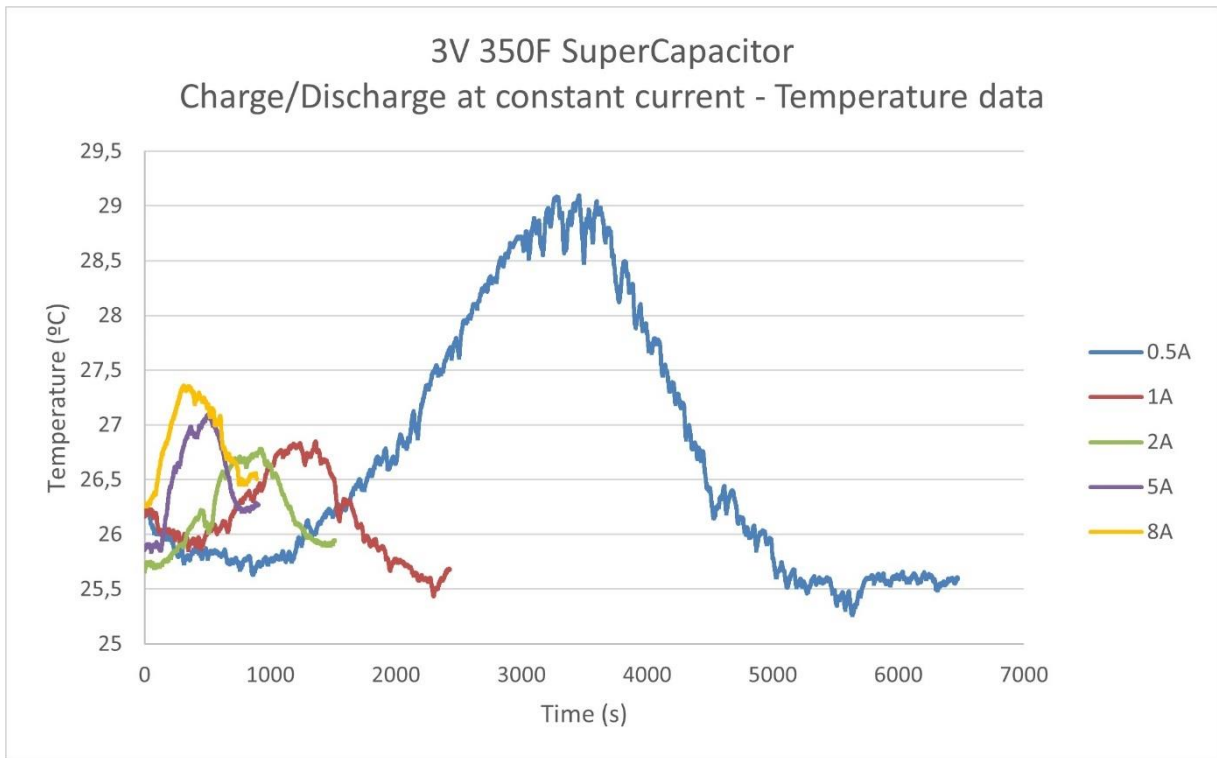


Figure 17. Device A – Charge/Discharge temperature profile

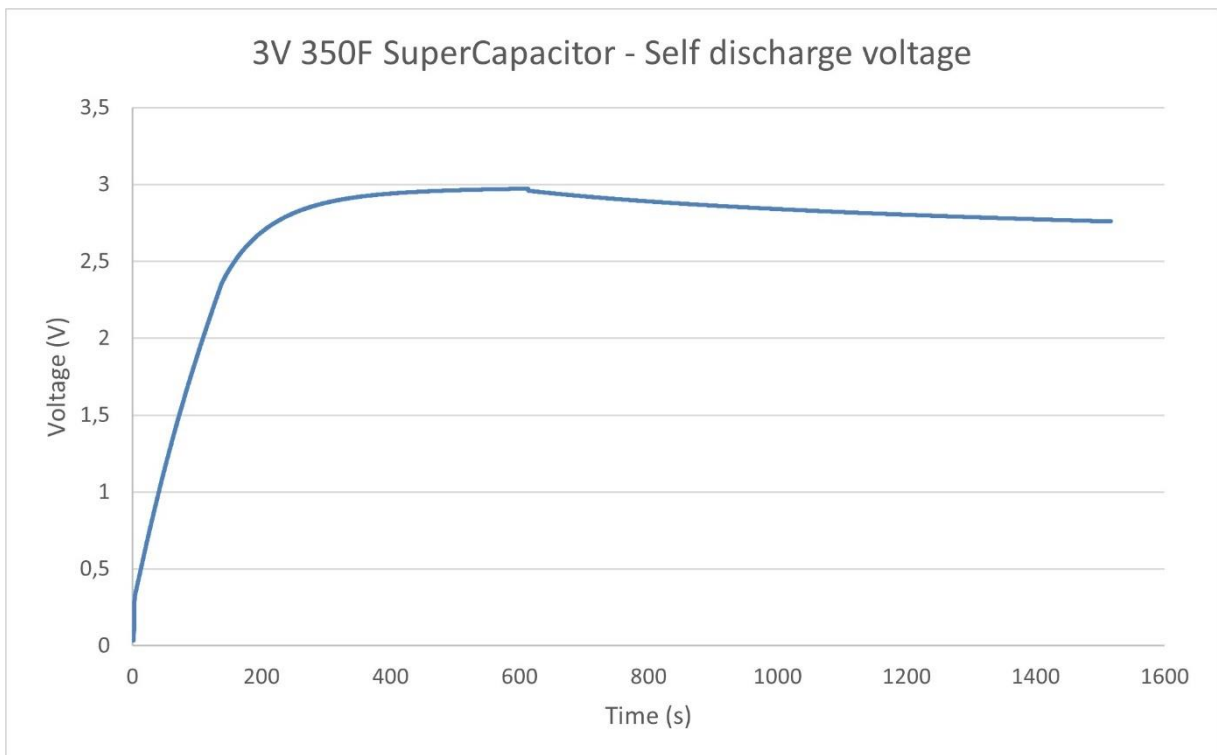


Figure 18. Device A – Self-discharge voltage profile

6.1.2 Device B – 3 V 200 F EDLC supercapacitor

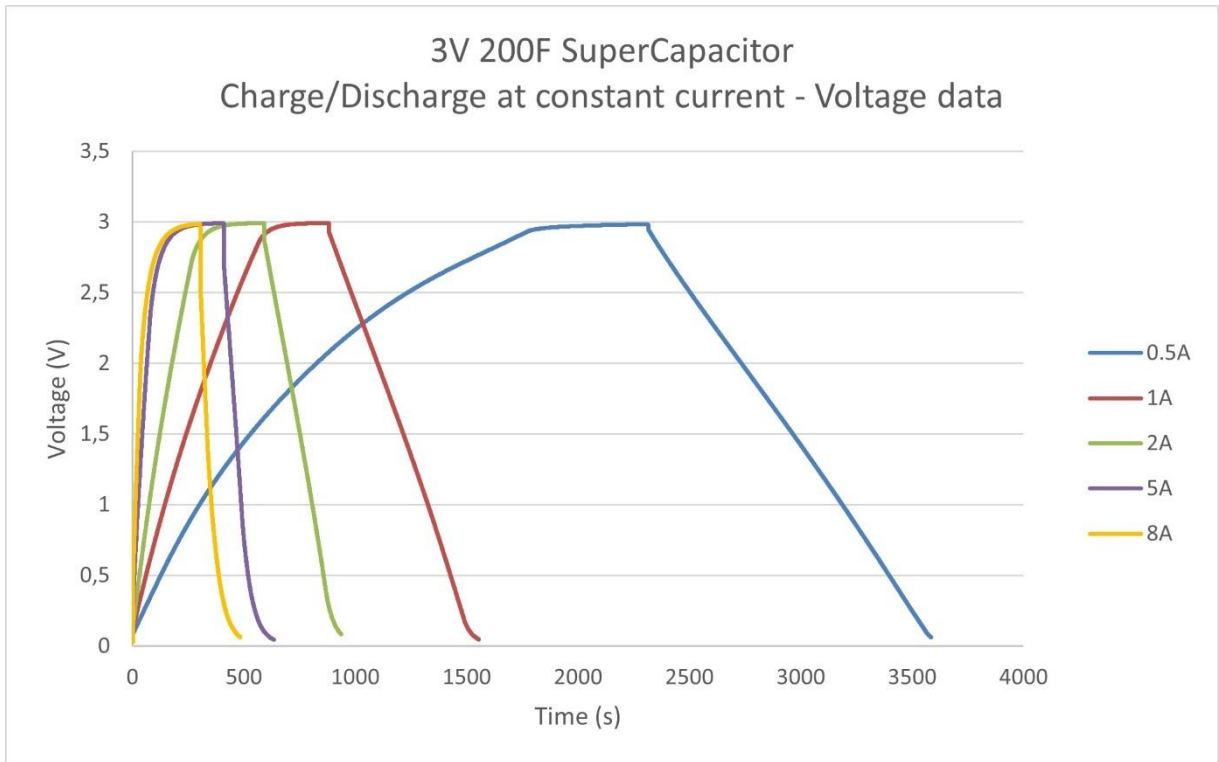


Figure 19. Device B – Charge/Discharge voltage profile

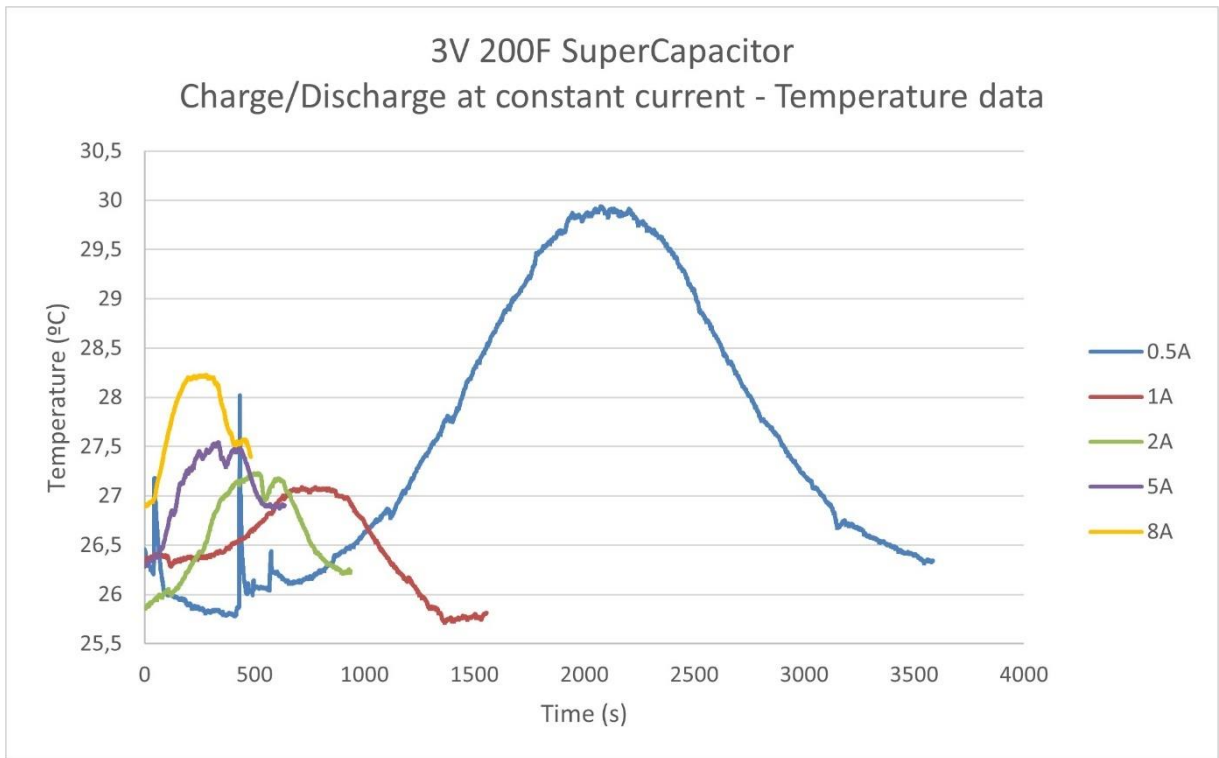


Figure 20. Device B – Charge/Discharge temperature profile

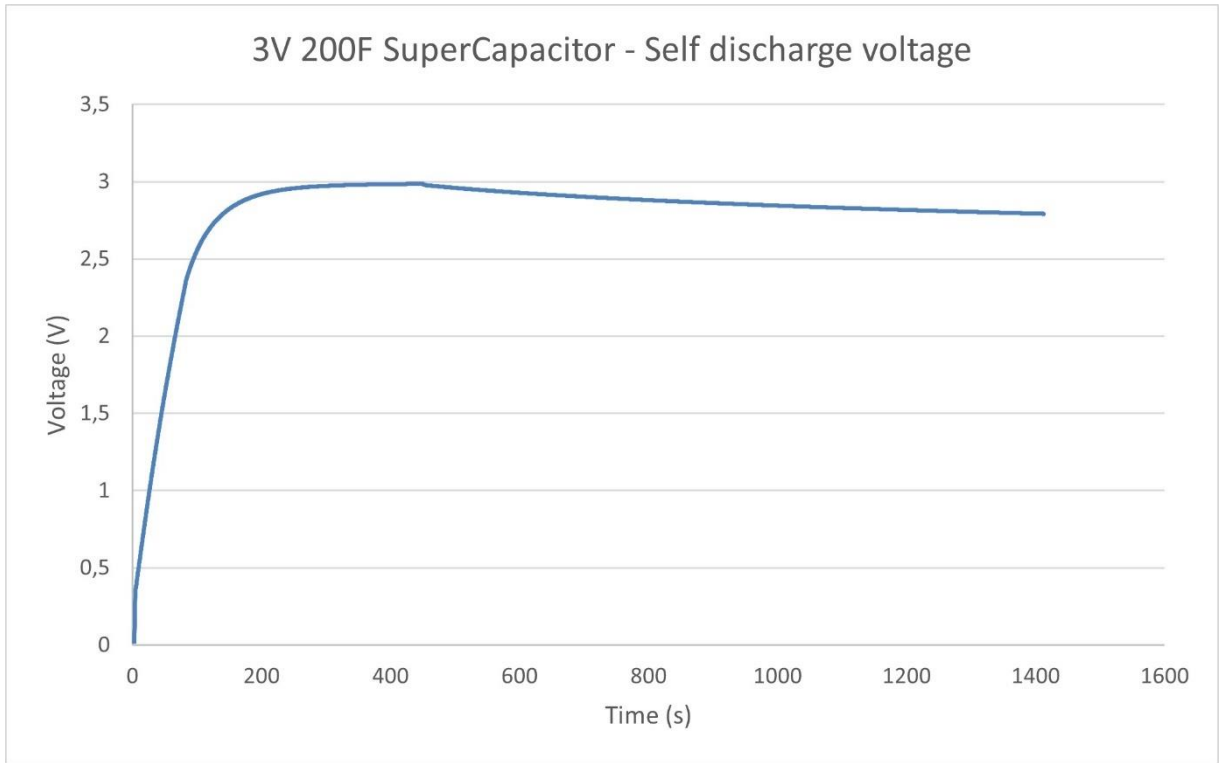


Figure 21. Device B – Self-discharge voltage profile

6.1.3 Device C - 2.7 V 300 F EDLC supercapacitor

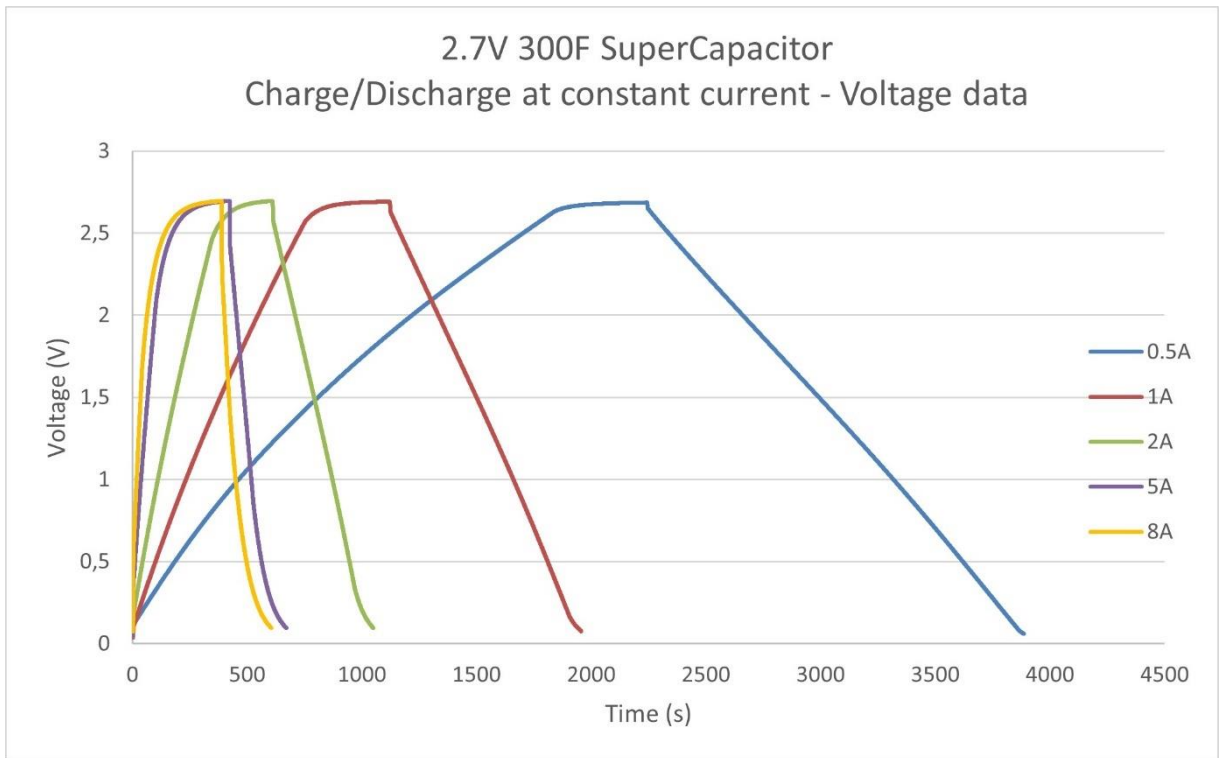


Figure 22. Device C – Charge/Discharge voltage profile

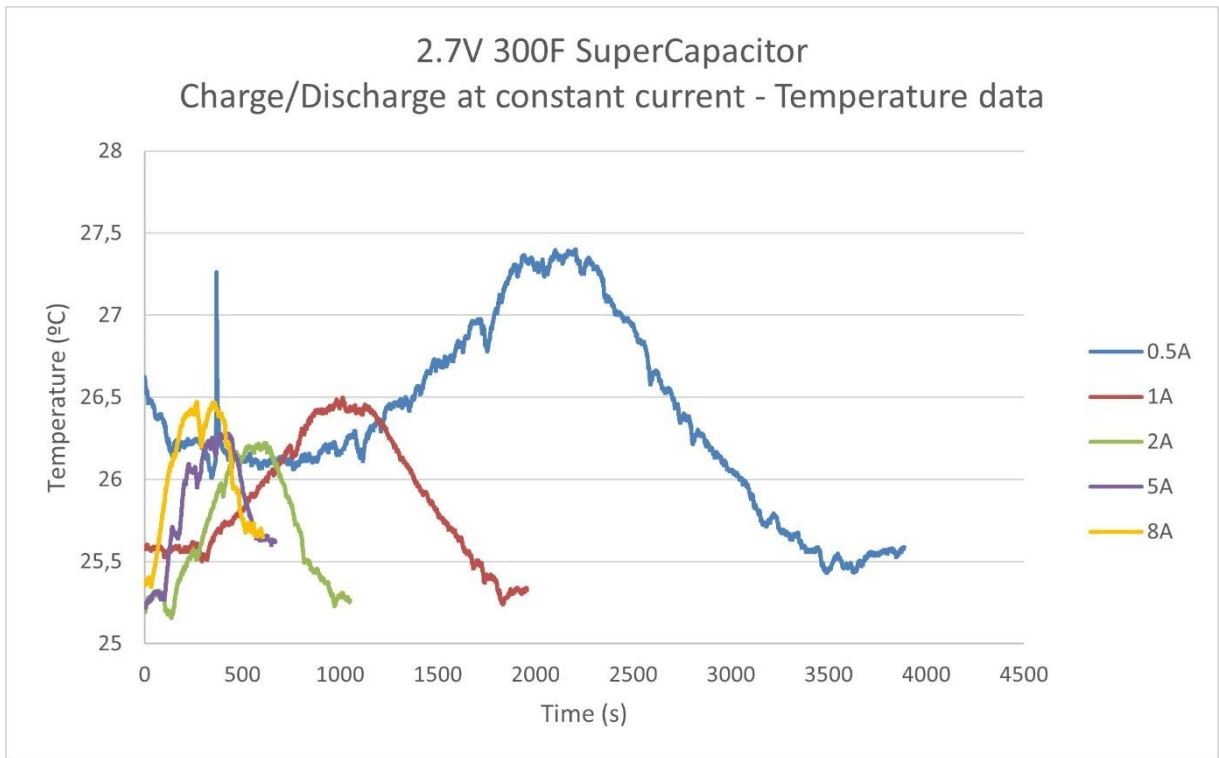


Figure 23. Device C – Charge/Discharge temperature profile

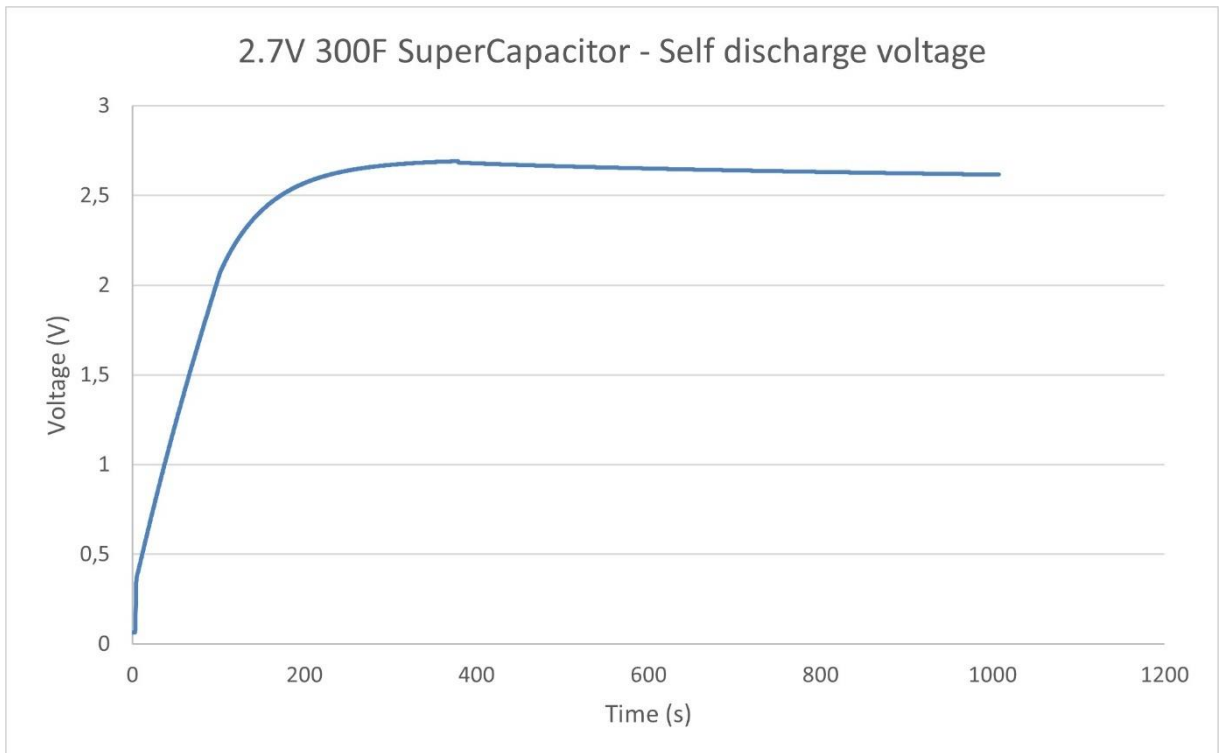


Figure 24. Device C – Self-discharge voltage profile

6.1.4 Device D – 3 V 100 F EDLC supercapacitor

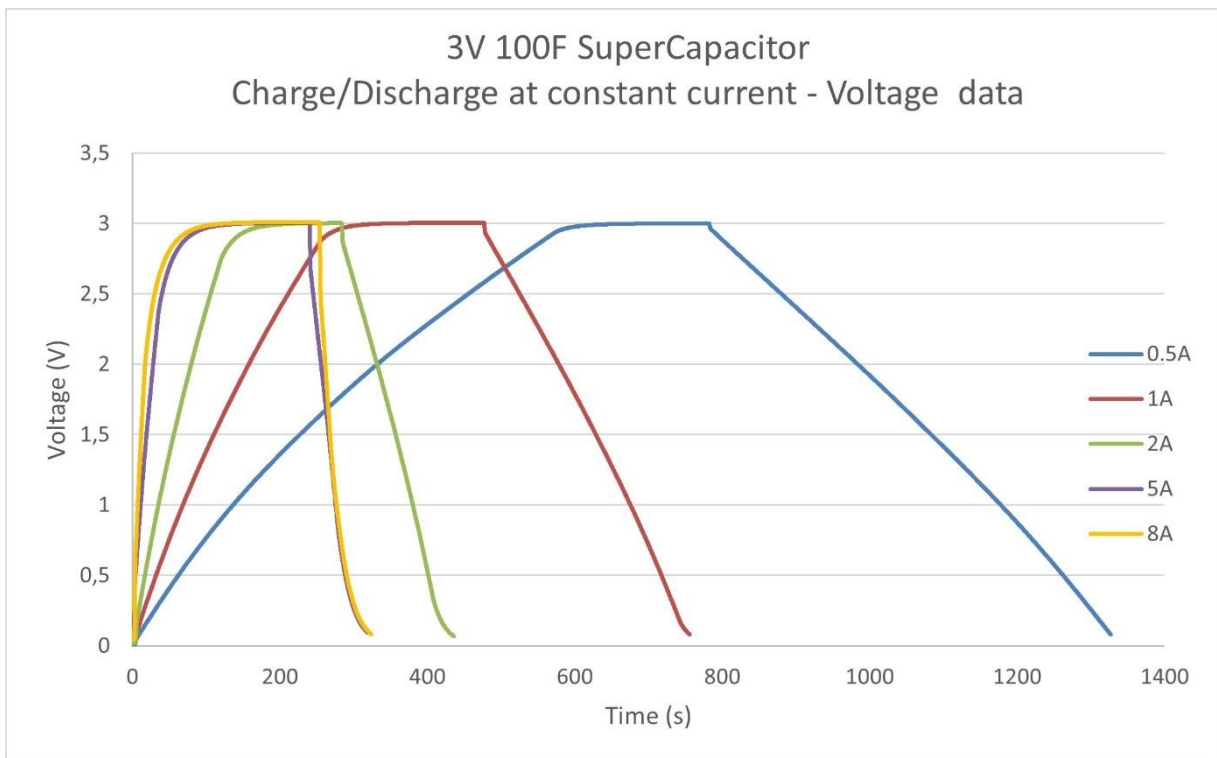


Figure 25. Device D – Charge/Discharge voltage profile

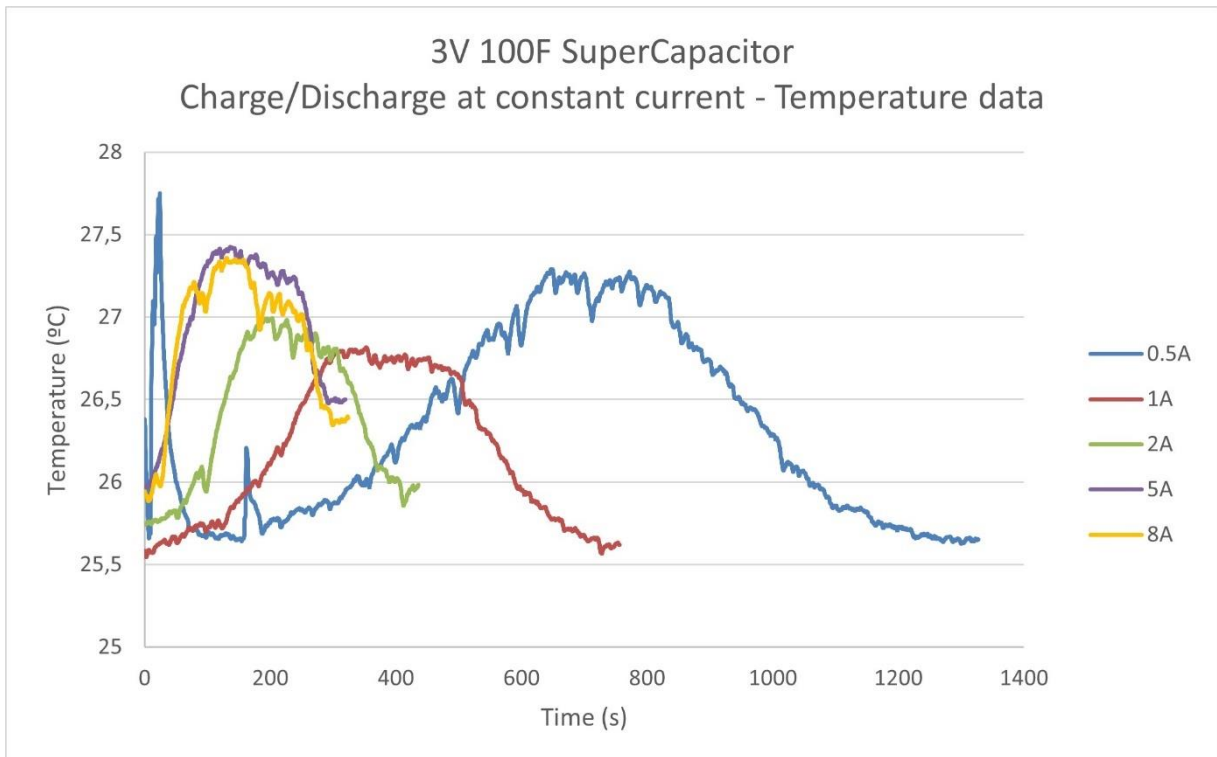


Figure 26. Device D – Charge/Discharge temperature profile

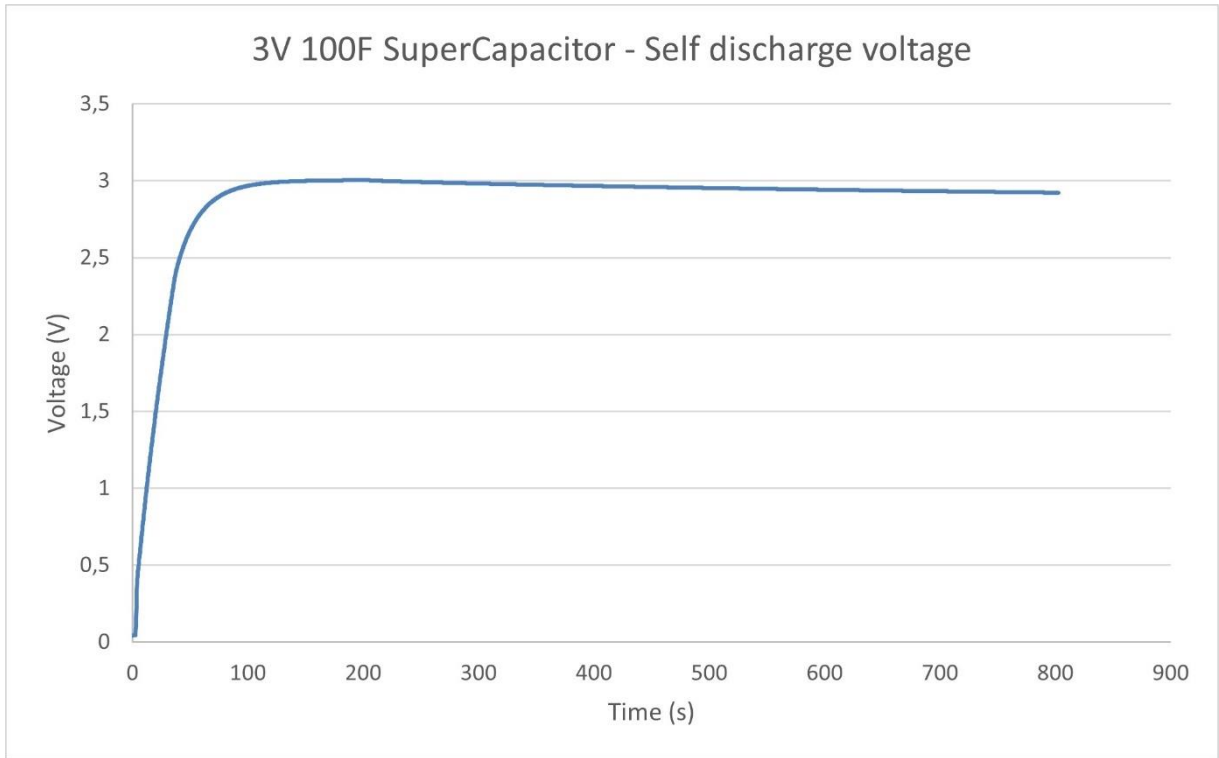


Figure 27. Device D – Self-discharge voltage profile

6.1.5 Device E - 3.8 V 220 F Hybrid supercapacitor

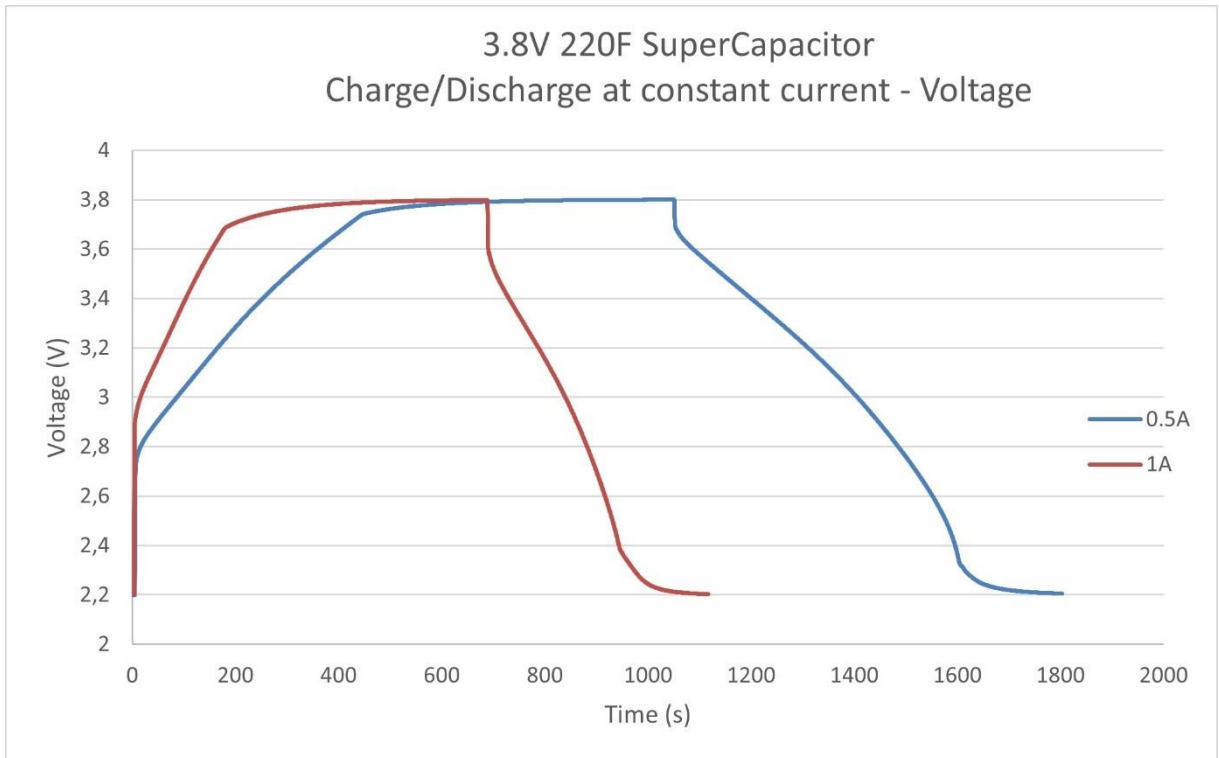


Figure 28. Device E – Charge/Discharge voltage profile

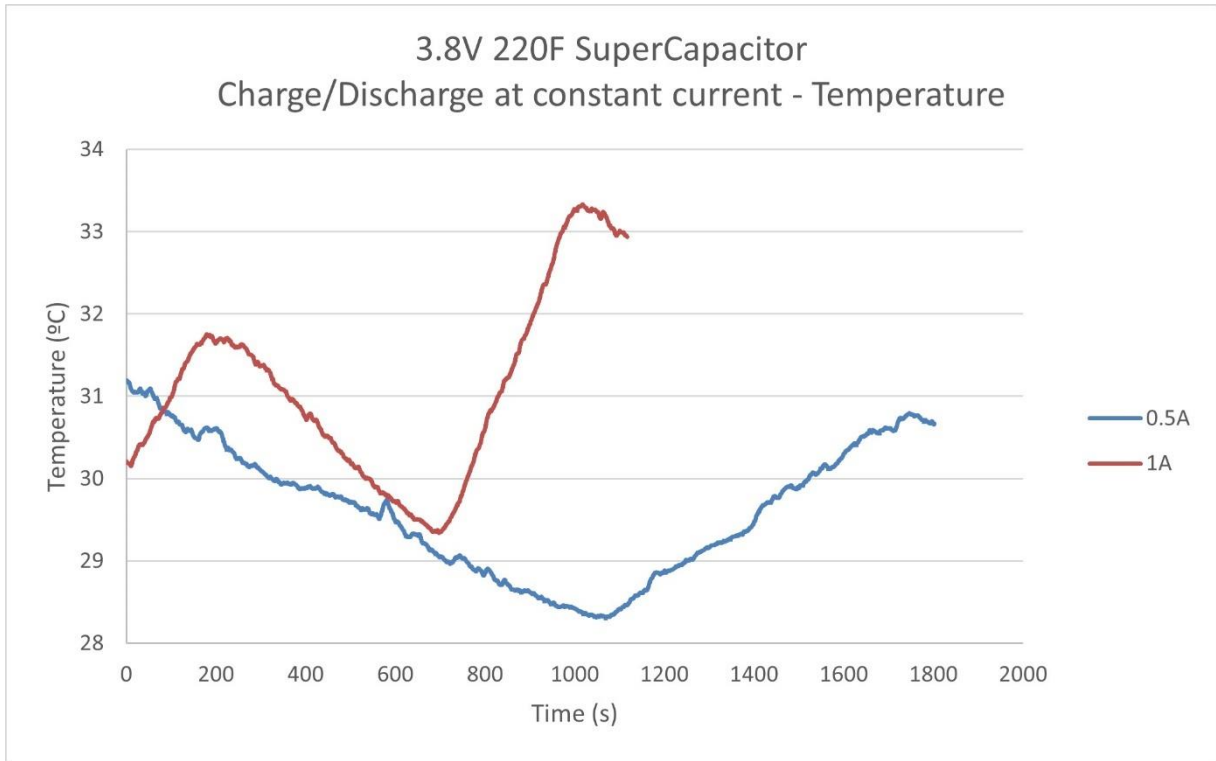


Figure 29. Device E – Charge/Discharge temperature profile

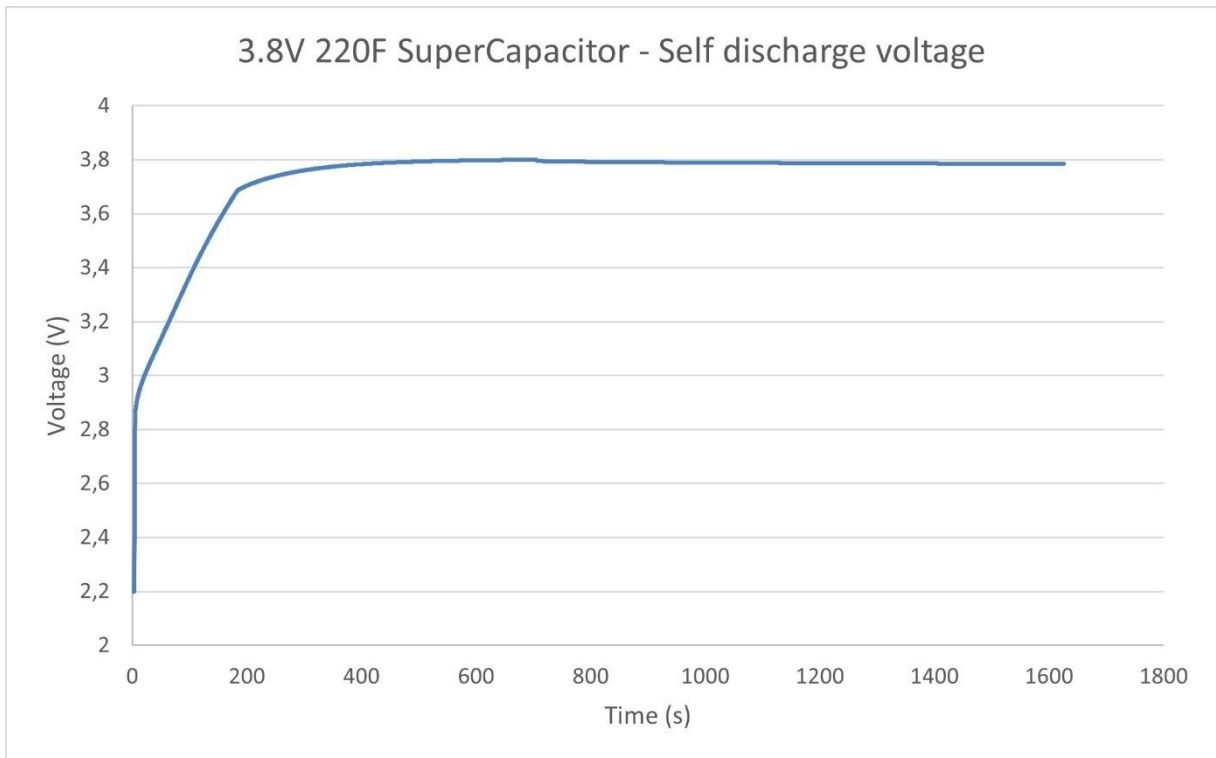


Figure 30. Device E – Self-discharge voltage profile

6.1.6 Results data analysis

Once the data has been analysed, as it was expected, the higher the current the steeper is the voltage slope, and less time is needed by the supercapacitor to fully charge or discharge. It has been observed at lower current rates that the voltage slope is not constant, and it bends over time. This is caused by the current leakage of the supercapacitor, and it is more noticeable at lower current rates and in the supercapacitors with higher leakage current value, for example in the device A.

Another phenomenon that has been observed is the sudden voltage increase at the beginning of the charge and at the voltage drop when starting the discharge, which is caused by the internal resistance. The higher this value and the higher the current, the bigger the step, as can be observed in the hybrid (E).

It is important to remark that while performing the tests, when approaching the target voltage value, the power supply in case of charging, and the electronic charge in case of discharging, start to reduce the constant current value to protect from over charge/discharge. This can be observed in the results as the voltage slope starts to bend when approaching to the target value, taking longer times to reach the target value.

About the temperature recordings some interesting results have been obtained. On EDLC's the results were similar. When charging the device, it starts to build temperature up to its maximum value. Then when the discharge starts, the temperature starts to drop and returns to a similar value as when it started. It has been observed that the longer it takes to charge (charging at a low current rate), more temperature is reached. Otherwise, it has been noted that increasing the current rate builds temperature faster, but it does not get as high as at the lowest current rate. Interestingly, in the smallest capacity device (D) the temperatures reached are similar and slightly smaller for the medium current rates (1 A and 2 A).

On hybrids a different trend has been noticed, since the device was discharged just before starting the test, the initial temperature is higher than the ambient one. When charging at 0.5 A the temperature constantly decreases even when the voltage stabilizes. Then, when discharging, the temperature increases, reaching a similar initial value. When charging at 1 A, first the temperature increases, but when the rated voltage is reached, the temperature starts to decrease and when the discharge starts, the temperature increases up to its maximum value.

Finally, for the self-discharge test results, when the supercapacitor is disconnected, the voltage slowly starts to decrease. As expected on the device with the highest leakage current (A), the decreasing voltage slope is steeper, then in the lowest leakage current device (E) the slope is flatter.

6.2 Charging time results

Due to the power supply protection that reduces the current when approaching the target voltage, the charging time is affected. In some cases, the voltage stabilizes and it does not reach the target value after several minutes.

In the table below is presented the charging time to reach 99% of the voltage supplied:

Table 5. Charging time results

Charging time at different constant current values					
Device under test	A	B	C	D	E
Capacitance (F)	350	200	300	100	220
Voltage supplied (V)	3	3	2.7	3	3.8
Charging Time at 0.5 A (s)	3510.8	1988.8	1953.4	591.4	668.0
Charging Time at 1 A (s)	1126.4	664.0	877.8	286.2	462.8
Charging Time at 2 A (s)	676.4	399.6	485.2	167.2	N/A
Charging Time at 5 A (s)	430.6	253.6	300.2	101.0	N/A
Charging Time at 8 A (s)	386.6	228.8	266.8	88.2	N/A

6.3 Capacity, internal resistance and leakage current results

In section 3.6.2 it has been determined that from the discharge data and using equation (10) the capacity of the supercapacitor can be obtained.

From section 3.5.3 the internal resistance or ESR can be obtained using equation (2) with the voltage drop represented in detail in figure 8.

From section 3.5.4 the leakage current can be determined by using equation (4) with the data from the self-discharge test and the calculated capacity.

Table 6. Device A results

Device A – 3 V 350 F EDLC supercapacitor					
Current (A)	0.5	1	2	5	8
Capacitance (F)	373.33	382.33	381.33	380.00	378.66
DC ESR (mOhms)	80	60	55	52	54
Leakage Current (mA)	83	85	84	84	84

Table 7. Device B results

Device B - 3 V 200 F EDLC supercapacitor					
Current (A)	0.5	1	2	5	8
Capacitance (F)	229.25	231.33	230.66	230.83	229.33
DC ESR (mOhms)	60	60	55	52	54
Leakage Current (mA)	43	44	43	43	43

Table 8. Device C results

Device C - 2.7 V 300 F EDLC supercapacitor					
Current (A)	0,5	1	2	5	8
Capacitance (F)	329.54	329.27	327.41	327.78	324.85
DC ESR (mOhms)	60	50	55	52	51
Leakage Current (mA)	34	34	34	34	33

Table 9. Device D results

Device D – 3 V 100 F EDLC supercapacitor					
Current (A)	0.5	1	2	5	8
Capacitance (F)	100.00	101.00	101.33	103.33	104.89
DC ESR (mOhms)	60	50	55	52	50
Leakage Current (mA)	13	13	13	14	14

Table 10. Device E results

Device E – 3.8 V 220 F Hybrid supercapacitor		
Current (A)	0.5	1
Capacitance (F)	246.87	257.19
DC ESR (mOhms)	280	250
Leakage Current (mA)	4	4

6.4 Weight and dimensions results

In order to obtain the supercapacitors densities, the mass and the dimensions have been obtained by means of a scale and a caliper.



Figure 31. Scale and caliper measurements

Table 11. Weight and dimensions results

Supercapacitors weight and dimensions					
Device under test	A	B	C	D	E
Mass (g)	66.20	40.82	61.72	21.08	9.30
Diameter (mm)	35.10	30.10	35.20	18.20	16.20
Length (mm)	61.80	51.99	52.20	59.40	25.70
Volume (l)	0.0598	0.0370	0.0508	0.0154	0.0053

6.5 Energy and power results

To calculate the energy and power results, equations (6) and (9) have been used, which are presented in section 3.5.5.

Table 12. Energy and power results

Supercapacitors energy and power					
Device under test	A	B	C	D	E
Max stored energy (mWh)	474	288	332	128	336
Energy Density (Wh/kg)	7.159	7.052	5.377	6.055	36.134
Energy Volumetric Density (Wh/l)	7.925	7.779	6.533	8.260	63.437
Max Power (W)	37.500	40.179	33.750	42.453	13.623
Power Density (kW/kg)	0.566	0.984	0.547	2.014	1.465
Power Volumetric Density (kW/l)	0.627	1.086	0.664	2.747	2.572

6.6 Results summary and comparison

In the table below a summary of the supercapacitor's characteristics data obtained from the tests.

Table 13. Studied supercapacitors characteristics results

Supercapacitors characteristics					
Device under test	A	B	C	D	E
Brand	Cornell	Cornell	Eaton	Eaton	Eaton
Type	EDLC	EDLC	EDLC	EDLC	Hybrid
Model	DSF	DSF	XV	TV	HS
Reference	DSF357Q3R0	DSF207Q3R0	XV3550-2R7307-R	TV1860-3R0107-R	HS1625-3R8227-R
Max Operating Voltage (V)	3	3	2.7	3	3.8
Capacitance (F)	379.13	230.28	327.76	102.11	252.03
DC ESR (mOhms)	60	56	54	53	265
Max stored energy (mWh)	474	288	332	128	336
Leakage Current (mA)	84	43	34	13	4
Energy Density (Wh/kg)	7.159	7.052	5.377	6.055	36.134
Energy Volumetric Density (Wh/l)	7.925	7.779	6.533	8.26	63.437
Max Power (W)	37.5	40.179	33.75	42.453	13.623
Power Density (kW/kg)	0.566	0.984	0.547	2.014	1.465
Power Volumetric Density (kW/l)	0.627	1.086	0.664	2.747	2.572
Mass (g)	66.2	40.82	61.72	21.08	9.3

Diameter (mm)	35.10	30.10	35.20	18.20	16.20
Length (mm)	61.80	51.99	52.20	59.40	25.70
Volume (l)	0.0598	0.0370	0.0508	0.0154	0.0053

Compared to the characteristics provided by the manufacturer in table 2, the capacitance measured is higher, which is caused due to the higher internal resistances measured, making the discharge to take longer times. In the smallest capacity device, since the internal resistance is not that high compared to the rest of the devices, the capacity measured is slightly higher but closer to the value indicated by the manufacturer.

Leakage current measured values show a big difference, which is occasioned by the testing method. In order to obtain low leakage current values, manufacturers measure the current 72 h after having disconnected the supercapacitor from the power supply. In this master's thesis, the leakage current has been measured during the first minutes after opening the circuit, by doing so, a more realistic value for practical use can be obtained.

Because of the higher capacity values, the energy, which has a direct relation is also high compared with the manufacturer values. In a different way, the measured power values are dramatically lower. Again, this is caused by the high internal resistance measured, which has an inverse relation with the power.

About the weight and the dimensions measurements, there are small differences, which involves changes in the energy and in the power densities.

7 Conclusions and further steps

According to this thesis regarding the creation of a test bench to characterize supercapacitors, several conclusions can be obtained:

Firstly, an introduction about the supercapacitors technology and their types is presented by exposing their benefits and inconveniences. Then, the main characteristics of supercapacitors are described (capacity, internal resistance, energy and power) and the equations to obtain them.

A model and a representative circuit to charge a supercapacitor at constant current is proposed together with the equations that relate the characteristics with the charging voltage and the current supplied over time.

From the available supercapacitors in the market, a selection of five (four EDLC's and one Hybrid type) is presented, and their characteristics are described showing that manufacturers do not provide all the necessary data. As the energy density or the power of the device, to properly choose for a certain application.

To determine the characteristics of the selected supercapacitors a test is proposed by charging and discharging at different constant current rates and a test bench is prepared to make the test possible, in a safe way and with the ability to record voltage and temperature data from the supercapacitor.

After performing the tests, it has been concluded that the characteristics of the supercapacitors can be obtained with the test and test bench proposed in this master's thesis. However, there are some differences between the data given by the manufacturer and the data obtained. Particularly, the internal resistances are much higher than the value provided, which leads to differences when calculating the rest of the characteristics of the devices.

As for the temperature results, it has been determined that for the tested current rates there are no concerns. When charging at low rates the supercapacitor builds more temperature over time, but when charging at higher current rates the temperature increases faster.

It is worth mentioning that the test bench with the power supply and the electronic charge that has been used has its limitation. For example, when approaching to the voltage target values, they reduce the constant current to have a smooth transition. This limitation extends the estimated time required for the test and induce into errors by not having constant current near to the rated voltage.

For further steps two options are proposed:

On the one hand, continuing with the charging/discharging test proposal, it would be important to implement a system for having continuous constant current over the whole charging and discharging processes, ideally with a current sensor for monitoring and recording data. In addition, a good improvement for the test bench would be the ability to automatize the test. This would help to standardize the testing times switching from charging to voltage maintenance and then to discharge. Also, it would help to have a faster response and to liberate the researcher while performing at low current rates, which may take a long time. Automatizing brings the opportunity to perform charge/discharge cycles for aging the device and evaluating its performance over time as in reference [18].

On the other hand, another approach could be to investigate and implement other testing methods to characterize supercapacitors to compare results and to evaluate the feasibility and the effectiveness. Other testing methods examples are constant power, cyclic voltammetry or impedance spectroscopy. More information is provided in reference [19].

8 References

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9 Appendix – Supercapacitors Technical Specifications

9.1 Devices A & B datasheet



FEATURES	High Voltage – Very Fast Charge/Discharge – High Power Density – Lower ESR RoHS Compliant
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APPLICATIONS	Battery Backup/Alternative – Pulse Power – Energy Harvesting – LED Displays – Mechanical Actuators – Audio Systems
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Operating Temperature Range	-40°C to +85°C	
Storage Temperature	-40°C to +70°C	
Capacitance Tolerance @ 20°C	-10% +30% (Q Tolerance) -20% +20% (M Tolerance)	
Voltage (Vdc) (+65°C/+85°C)	3.0V / 2.5V 6.0V / 5.0V 9.0V / 7.5V	
Life Time	1000 hours with rated voltage applied at rated temperature	
	Capacitance change	±30% of initially measured values
	ESR	<400% of initially specified values <200% of initially specified values (100F to 600F)
	Leakage current	≤100% specified maximum value
Shelf Life	1000 hours with no voltage applied at 65°C	
	Capacitance change	±30% of initially measured values
	ESR	<200% of initially specified values
Life Cycles (25°C) 1 cycle= Charge to WVDC for 20s, constant voltage charging for 10s, discharge to ½ WVDC for 20s, rest for 10s	500,000 cycles	
	Capacitance change	±30% of initially measured values
	ESR change	<200% of initially specified values

[RoHS Compliant](#)

810a Recognized

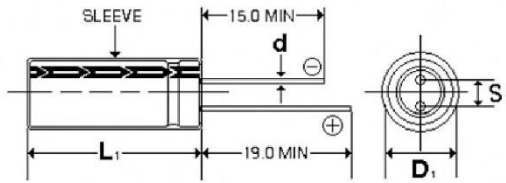


DSF

3 Volt Supercapacitor



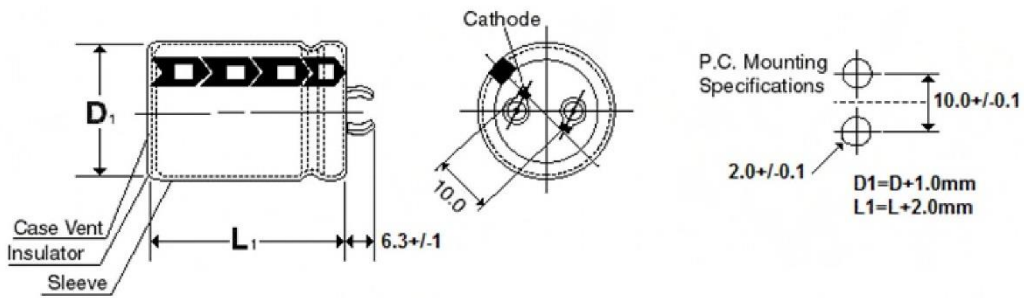
Diameter 6.3 mm to 18 mm



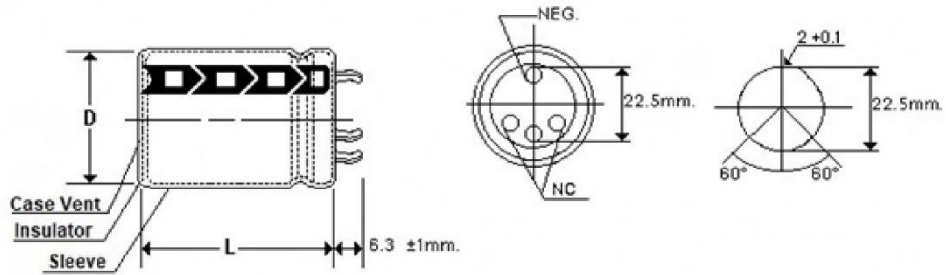
Lead spacing VS. Case diameter						
D	6.3	8	10	12.5	16	18
S	2.5	3.5	5.0	5.0	7.5	7.5
d	0.6	0.6	0.6	0.6	0.8	0.8
a	1.5	1.5	2.0	2.0	2.0	2.0

$L_1 = L + a$ mm
 $D_1 = D + 0.5$ mm
 $S_1 = S \pm 0.5$ mm
 $d = d \pm 0.05$ mm

Diameter > 18 mm to < 35 mm



Diameter 35 mm





WVDC	Capacitance (F)	IC PART NUMBER	MAX Current (A) (1 Sec.)	Maximum Continuous Current (A) (ΔT=15°C)	Short Circuit Current (A)	ESR AC 1 kHz (mΩ)	DC ESR (mΩ) 20°C	Max stored energy (mWh)	LC (mA), (72 hrs)	Energy Density (Wh/kg)	Energy Volumetric Density (Wh/l)	Power Density (kW/kg)	Power Volumetric Density (kW/l)
3	1.2	DSF125M3R0	0.98	0.11	4.29	350	700	1.5	0.01	1.88	3.21	1.93	3.3
3	1.5	DSF155M3R0	1.15	0.14	4.6	320	640	1.88	0.008	1.97	3.34	1.78	3.01
3	2.0	DSF205Q3R0	1.9	1.80	9.38	160	320	2.5	0.012	2.5	3.55	3.38	4.8
3	3.0	DSF305Q3R0	3.1	1.4	20	80	150	3.8	0.014	2.67	3.71	5.14	6.6
3	4.0	DSF405M3R0	3.66	0.38	18.75	80	160	5	0.012	3.57	4.97	4.82	6.71
3	5.0	DSF505Q3R0	4.5	2.2	23	70	130	6.3	0.02	2.97	3.98	3.95	5.3
3	7.0	DSF705Q3R0	6.7	2.4	38	55	80	8.8	0.03	3.8	4.46	5.86	6.9
3	10.0	DSF106Q3R0C	5.3	0.89	16.6	90	180	12.5	0.045	4.46	3.36	2.14	3.1
3	10.0	DSF106Q3R0	9.4	3.4	50	40	60	12.5	0.045	3.9	5.3	5.63	7.6
3	11.0	DSF116Q3R0	7.86	1.02	30	50	100	13.75	0.045	4.3	5.83	3.38	4.58
3	15.0	DSF156Q3R0B	10.98	1.40	42	35	70	18.75	0.055	4.57	1.12	3.76	0.9
3	15.0	DSF156Q3R0	10.98	1.40	42.86	35	70	18.75	0.055	3.99	5.09	3.283	4.191
3	25.0	DSF256Q3R0	20	4.4	86	25	35	31.3	0.1	4.46	6.21	4.4	6.1
3	35.0	DSF356Q3R0	19.09	3.13	60	25	50	43.75	0.1	4.97	6.91	2.45	3.41
3	50.0	DSF506Q3R0	35.7	7.10	136	15	22	62.5	0.15	4.88	6.14	3.83	4.8
3	70.0	DSF706Q3R0	27.3	5.9	75	20	40	87.5	0.45	5.18	8.7	1.6	2.7
3	100.0	DSF107Q3R0	68.2	8.3	250	8	12	125	0.3	5.95	7.31	4.3	5.3
3	110.0	DSF117Q3R0	59.8	6.3	188	18	36	137.5	0.21	6.25	9	3.07	4.4
3	200.0	DSF207Q3R0	100	10	300	6	10	250	0.7	6.94	7.07	3	3.1
3	350.0	DSF357Q3R0	236	18.9	857	3	3.5	437.5	1	6.73	7.58	4.75	5.4
3	400.0	DSF407Q3R0	250	18.9	857	3	3.5	500	1	7.35	8.66	4.96	5.9
3	470.0	DSF477Q3R0	267	18.9	857	3	3.5	587.5	1.3	8.05	10.18	4.23	5.4
3	600.0	DSF607Q3R0	290	20	587	3	3.5	750	1.5	9.15	11.1	4.12	5.4
6	1.5	DSF155Q6R0HAE	3.1	1.4	20	180	320	7.5	0.013	2.5	2.52	16.6	16.8
6	2.5	DSF255Q6R0JBE	4.05	2.2	23	160	280	12.5	0.018	3.1	2.51	14.1	11.3
6	3.5	DSF355Q6R0JBF	6.7	2.40	38	130	180	17.5	0.025	3.5	3	13.8	11.9
6	5.0	DSF505Q6R0JBG	9.4	3.4	50	100	140	25	0.04	3.57	3.62	12.9	13
9	0.33	DSF334Q9R0HDL	0.83	0.09	3.75	1200	2400	4	0.2	1.56	2.66	1.56	2.7
9	0.5	DSF504M9R0ZBN	1.14	0.14	4.68	980	1940	5.6	0.2	1.97	3.35	1.97	3.4
9	0.67	DSF674Q9R0HDL	1.82	0.19	9.18	500	980	7.5	0.25	2.5	3.56	2.48	3.6
9	1.0	DSF105Q9R0HDR	3.04	0.29	18.75	320	620	11.2	0.3	2.68	3.71	2.68	3.71
9	1.66	DSF165Q9R0JSE	4.1	0.47	18	260	500	18.7	0.4	2.98	3.98	2.97	4
9	3.3	DSF335Q9R0JSF	5.34	0.88	16.6	290	560	37	0.9	4.46	6.4	4.46	6.4
9	5.0	DSF505Q9R0KZT	10.98	1.4	42.9	125	230	56.2	1.1	3.99	5.1	3.98	5.1



WVDC	Capacitance (F)	IC PART NUMBER	Weight (grams)	Volume (mL)	Dims DxDL LxHxT (mm)	Lead Spacing S (mm)	Lead Diameter d (mm)
3	1.2	DSF125M3R0	0.8	0.47	6.3x15	2.5	0.5
3	1.5	DSF155M3R0	0.95	0.56	6.3x18	2.5	0.5
3	2.0	DSF205Q3R0	1	0.7	8x14	3.5	0.6
3	3.0	DSF305Q3R0	1.4	1.01	8x20	3.5	0.6
3	4.0	DSF405M3R0	1.4	1.01	8x20	3.5	0.6
3	5.0	DSF505Q3R0	2.2	1.57	10x20	5	0.6
3	7.0	DSF705Q3R0	2.3	1.96	10x25	5	0.6
3	10.0	DSF106Q3R0C	2.8	1.96	10x25	5	0.6
3	10.0	DSF106Q3R0	3.2	2.36	10x30	5	0.6
3	11.0	DSF116Q3R0	3.2	2.36	10x30	5	0.6
3	15.0	DSF156Q3R0B	4.1	3.07	12.5x25	5	0.6
3	15.0	DSF156Q3R0	4.7	3.68	12.5x30	5	0.6
3	25.0	DSF256Q3R0	7.4	5.03	16x25	7.5	0.8
3	35.0	DSF356Q3R0	8.8	6.33	16x31.5	7.5	0.8
3	50.0	DSF506Q3R0	13.8	10.18	18x40	7.5	0.8
3	70.0	DSF706Q3R0	16.9	10.05	16x50	7.5	0.8
3	100.0	DSF107Q3R0	20	17.11	22x45	10	1.2
3	110.0	DSF117Q3R0	22	15.27	18x60	7.5	0.8
3	200.0	DSF207Q3R0	36	35.3	30x50	10	1.2
3	350.0	DSF357Q3R0	73	57.73	35x60	22.5	1.2
3	400.0	DSF407Q3R0	73	57.73	35x60	22.5	1.2
3	470.0	DSF477Q3R0	73	57.73	35x60	22.5	1.2
3	600.0	DSF607Q3R0	90	67.35	35x70	22.5	1.2
6	1.5	DSF155Q6R0HAE	3	2.97	17x23x8.5	12	0.6
6	2.5	DSF255Q6R0JBE	5.2	4.97	21x22x11	15.5	0.6
6	3.5	DSF355Q6R0JBF	6	5.83	21x27x11	15.5	0.6
6	5.0	DSF505Q6R0JBG	8.3	6.91	21x32x11	15.5	0.6
9	0.33	DSF334Q9R0HDL	4	3.4	25x16x8.5	13.5	0.6
9	0.5	DSF504M9R0ZBN	5	2.73	21x20x6.5	11	0.6
9	0.67	DSF674Q9R0HDL	4	3.4	25x16x8.5	13.5	0.6
9	1.0	DSF105Q9R0HDR	5.5	4.67	25x22x8.5	13.5	0.6
9	1.66	DSF165Q9R0JSE	7.5	7.84	31x23x11	16	0.6
9	3.3	DSF335Q9R0JSF	11	9.21	31x27x11	16	0.6
9	5.0	DSF505Q9R0KZT	13	16.7	39x33x13	21	0.6

9.2 Device C datasheet

Technical Data 4424

Effective December 2017
Supersedes October 2014

XV Supercapacitor

Cylindrical snap-in



Features and benefits

- Over 10-year operating life at room temperature
- Ultra low ESR for high power density
- Large capacitance for high energy density
- Long cycle life
- UL Recognized

Applications

- Hybrid battery or fuel cell systems
- High pulse current applications
- UPS / hold up power

Description

Eaton supercapacitors are unique, ultra-high capacitance devices utilizing electrochemical double layer capacitor (EDLC) construction combined with new, high performance materials. This combination of advanced technologies allows Eaton to offer a wide variety of capacitor solutions tailored to specific applications that range from a few microamps for several days to several amps for milliseconds.



Technical Data 4424
Effective December 2017

XV Supercapacitor
Cylindrical snap-in

Specifications

Capacitance	300 F to 600 F
Working voltage	2.7 V
Surge voltage	2.85 V
Capacitance tolerance	-5% to +10%
Operating temperature range	-40 °C to +65 °C
Extended operating temperature range	-40 °C to +85 °C (with voltage derating to 2.3 V @ +85 °C)

Standard Product¹

Capacitance (F)	Part Number	Max. initial DC ESR (mΩ) (Equivalent Series Resistance)	Max continuous current ² (A)	Peak current ³ (A)	Max leakage current ⁴ (mA)	Max power ⁵ (W)	Stored energy ⁶ (Wh)	Typical mass (g)
300	XV3550-2R7307-R	4.5	20	160	0.60	410	0.30	62
400	XV3560-2R7407-R	3.2	26	220	0.85	570	0.41	72
600	XV3585-2R7607-R	2.6	33	320	1.30	790	0.60	108

1. Capacitance, ESR and Leakage current are all measured according to IEC 62391-1 at +20 °C
2. 15 °C Temperature Rise
3. Peak Current is for 1 second = 1/2 Working Voltage x Capacitance / (1 + DC ESR x Capacitance)
4. Leakage current measured after 72 hours, +20 °C
5. Max. Power = Working Voltage² / 4 / DC ESR
6. Stored energy = 1/2 Capacitance x Working Voltage² / 3600

Performance

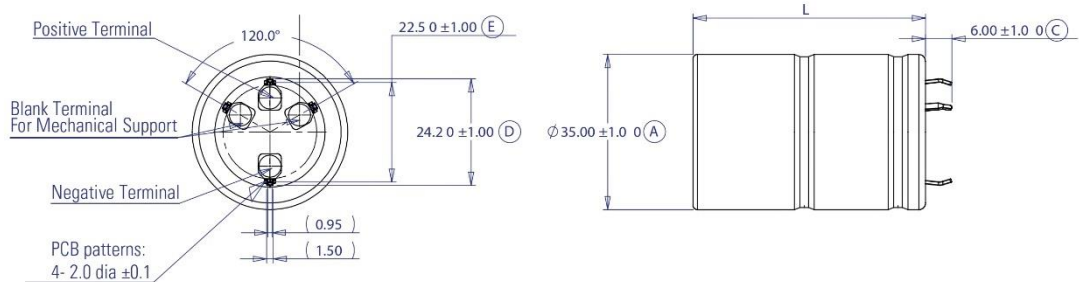
Parameter	Life	Capacitance Change (% of initial value)	ESR (% of max. initial value)
@ Max. operating voltage and temp)	1500 hours	≤ 20%	≤ 200%
Charge/discharge cycling ¹	500,000	≤ 20%	≤ 200%
Storage Life- uncharged			
-40 °C to +65 °C	1500 hours	≤ 20%	≤ 200%
≤ 30 °C	3 years	≤ 5%	≤ 10%

1. Cycling between max operating and 50% of max operating voltage at room temperature

**XV Supercapacitor
Cylindrical snap-in**

Technical Data **4424**
Effective December 2017r

Dimensions (mm)



Part Number	L ±1.0
XV3550-2R7307-R	53
XV3560-2R7407-R	63
XV3585-2R7607-R	87.5

Part Numbering System

xv		3560		-	2R7		40		7		-R	
Family Code	Size reference- mm		Voltage (V) R = Decimal	Capacitance (µF)		Standard product						
	Diameter	Length		Value	Multiplier							
XV = Family Code	35	60	2R7 = 2.7 V	Example: 407 = 40 x 10 ⁷ µF or 400 F								

Packaging Information

- Standard packaging: 20 pieces per box

Part Marking

- Manufacturer
- Capacitance (F)
- Max operating voltage (V)
- Series code (or part number)
- Polarity

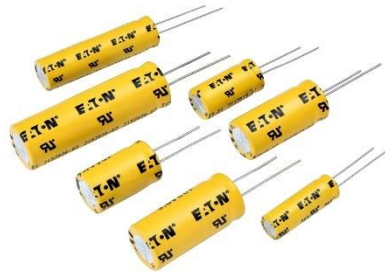
9.3 Device D datasheet

Technical Data 10554

Effective February 2024
Supersedes November 2023

TV Supercapacitors

Cylindrical cells



Description

Eaton supercapacitors are high reliability, high power, ultra-high capacitance energy storage devices utilizing electric double layer capacitor (EDLC) construction combined with proprietary materials and processes. This combination of advanced technologies allows Eaton to offer a wide variety of capacitor solutions tailored to applications for backup power, pulse power and hybrid power systems. They can be applied as the sole energy storage or in combination with batteries to optimize cost, life time and run time. System requirements can range from a few microwatts to megawatts. All products feature low ESR for high power density with environmentally friendly materials for a green power solution. Eaton supercapacitors are maintenance-free with design lifetimes up to 20 years* and operating temperatures down to -40 °C and up to +85 °C.

Features

- 3.0 V operating voltage for high power and high energy
- Ultra low ESR for high power density
- Large capacitance for high energy density
- UL recognized

Applications

- Electric, Gas, Water smart meters
- RF radio pulse power
- Storage server
- Industrial backup / ride through
- Pulse power
- Solar capture

Environmental compliance



Agency information



* Supercapacitor lifetimes vary based on charge voltage and temperature. See Eaton's application guidelines or contact your local Eaton sales representative for more information on lifetime estimates



Technical Data 10554
Effective February 2024

TV Supercapacitors
Cylindrical cells

Ratings

Capacitance	3.3 F to 100 F
Maximum working voltage	3.0 V
Surge voltage	3.3 V
Capacitance tolerance	-10% to +30% (+20 °C)
Operating temperature range	-40 °C to +65 °C
Extended temperature range	-40 °C to +85 °C (with linear voltage derating to 2.5 V @ +85 °C)

Specifications

Capacitance (F)	Part number	Maximum initial ESR ¹ (Ω)	Nominal leakage current ^{2,3} (μA)	Stored energy ³ (mWh)	Peak power ⁴ (W)	Pulse current ⁵ (A)	Continuous current ⁶ (A)	Typical thermal resistance ⁷ Rth (°C/W)	Short circuit current ⁸ (A)
3.3	TV0820-3R0335-R	0.075	15	3.75	30	3.7	1.6	76	40
6	TV1020-3R0605-R	0.035	13	7.5	64.3	7.4	2.4	73	86
10	TV1030-3R0106-R	0.026	25	12.5	86.5	12	3.7	40	115
15	TV1325-3R0156-R	0.024	35	18.8	94	17	3.4	53	125
25	TV1625-3R0256-R	0.018	60	31.3	125	26	4.2	47	167
30	TV1633-3R0306-R	0.017	70	37.5	132	30	4.5	43	176
34	TV1245-3R0346-R	0.016	75	42.5	141	33	6.5	22	188**
35	TV1635-3R0356-R	0.015	90	43.8	150	34	5.1	39	200**
60	TV1840-3R0606-R	0.013	135	75	173	51	6.7	26	231**
100	TV1860-3R0107-R	0.011	225	125	205	71	11.7	10	273**

** Repeated short circuit current will permanently damage the leads.

Performance

Parameter	Capacitance change (% of initial value)	ESR (% of maximum initial value)
Lifetime: (1000 hours at maximum temperature and voltage)	≤ 30%	≤ 200%
Charge/Discharge Cycles ⁹ : (500,000 at +20 °C)	≤ 30%	≤ 200%
Storage: (3 years, uncharged, <35 °C)	≤ 5%	≤ 10%

1. Capacitance, Equivalent Series Resistance (ESR) and Leakage current are measured according to IEC62391-1 with current in milliamps (mA) = $8 \times C \times V$.
2. Leakage current at +20 °C after 72 hour charge and hold.
3. Stored Energy (mWh) = $0.5 \times C \times V^2 \times 1000$
4. Peak Power (W) = $\frac{V^2}{4 \times ESR}$
5. Pulse current for 1 second from full rate voltage to half voltage (A) = $\frac{0.5 \times V \times C}{(1 + ESR \times C)}$
6. Continuous current with a 15 °C temperature rise. Continuous current (A) = $\sqrt{\frac{W}{ESR \times 0.015}}$
7. Thermal resistance (Rth) cell body temperature to ambient in open air in degrees C per Watt (°C/W).
8. Short circuit current is for safety information only. Do not use as operating current.
9. Cycling between rated voltage and half voltage, 3 second rest at +20 °C.
10. Testing and verification of product under end application conditions is recommended

Safety and certifications

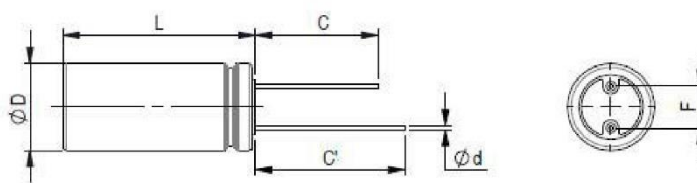
Regulatory	UL810a, RoHS, REACH
Shock and vibration	MIL-STD 202G
Warnings	Do not overvoltage, do not reverse polarity
Shipping	No restrictions, per UN3499 with all cells <0.3 watt-hours

TV Supercapacitors
Cylindrical cells

Technical Data 10554
Effective February 2024

Dimensions (mm) and mass (g)

Part number	ØD maximum	L maximum	F ±0.5	Ød ±0.02	C minimum	C' minimum	Mass (typical)
TV0820-3R0335-R	8.5	21	3.5	0.5	20	25	1.4
TV1020-3R0605-R	10.5	22.3	5	0.6	20	25	2.3
TV1030-3R0106-R	10.5	31.5	5	0.6	20	25	3.2
TV1325-3R0156-R	13.5	28.4	5	0.6	20	25	4.5
TV1625-3R0256-R	16.5	28.9	7.5	0.8	20	25	7.3
TV1633-3R0306-R	16.5	33	7.5	0.8	20	25	8.3
TV1245-3R0346-R	12.9	49	5	0.6	20	25	8
TV1635-3R0356-R	16.5	38	7.5	0.8	20	25	9.3
TV1840-3R0606-R	18.5	42	7.5	0.8	20	25	13



Longer lead is positive

Part numbering system

TV	1860	-3R0	60	6	-R
Family code	Size reference (mm)	Voltage (V) R = decimal	Capacitance (µF) value	Multiplier	Standard product
TV = Family code	Diameter = 18 Length = 60	3R0 = 3.0 V	Example 606= 60 x 10 ⁶ µF or 60 F		

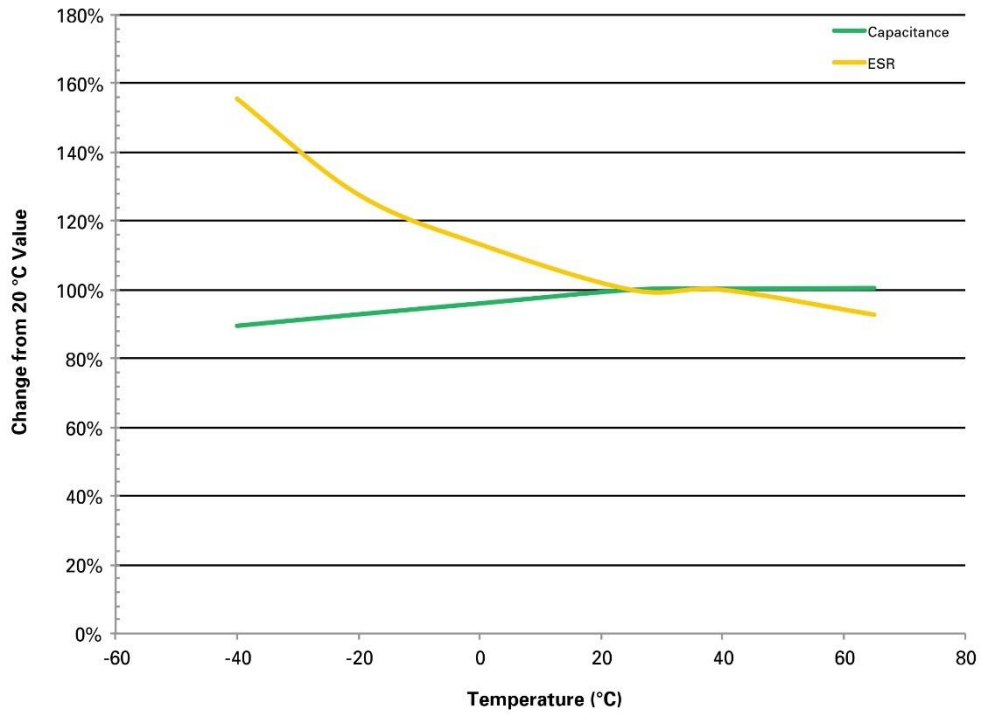
Packaging information

- Standard packaging: Bulk, 100 parts per bag (8 mm–13 mm diameter)
- 16 mm–18 mm diameter products: Bulk package quantity varies by size.

Part marking

- Eaton logo
- Capacitance value (F)
- Maximum operating voltage (V)
- TV Supercapacitors
- Polarity mark
- UL recognition Ru symbol
- date code ywwydd-nn
 y=year code for cell build (z=2016)
 ww=work week for cell build
 y=year code for electrode (z=2016)
 ddd=serial day of year for electrode build
 nn=number of lot in the day

Temperature vs. capacitance and ESR



9.4 Device E datasheet

Technical Data **11043**

Effective November 2021
Supersedes April 2020

HS/HSL Supercapacitors

Hybrid cylindrical cells



Description

Eaton hybrid supercapacitors are high reliability, high power, ultra-high capacitance energy storage devices utilizing proprietary materials and processes. This combination of advanced technologies allows Eaton to offer a wide variety of capacitor solutions tailored to applications for backup power, pulse power and hybrid power systems.

They can be applied as the sole energy storage or in combination with batteries to optimize cost, life time and run time. System requirements can range from a few microwatts to hundreds of watts.

All products feature low ESR for high power density with environmentally friendly materials for a green power solution. Eaton supercapacitors are maintenance-free with design lifetimes up to 20 years* and operating temperatures down to -25 °C (HSL) and up to +85 °C (HS)

Features and benefits

- 3.8 V operating voltage for high energy
- Low ESR for high power density
- Up to 8 times energy density compared to standard supercapacitors
- Low self discharge ideal for use with batteries
- UL recognized (10, 25, and 150 F pending)

Applications

- Industrial backup/ride through
- Backup for storage servers
- Water and gas smart meters
- IoT energy storage
- Medical backup power/alarm
- Commercial trucks/containers asset tracking

Environmental compliance



Agency information



*Supercapacitor lifetimes vary based on charge voltage and temperature. See Eaton's application guidelines or contact your local Eaton sales representative for more information on lifetime estimates



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HS/HSL Supercapacitors
Hybrid cylindrical cells

Ratings

Capacitance	10 F to 220 F
Working voltage	3.8 V
Minimum working voltage	2.2 V
Surge voltage	4.0 V
Capacitance tolerance	-20% to +20% (+20 °C)
Operating temperature range	HSL: -25 °C to +60 °C HS: -15 °C to +70 °C
Extended operating temperature range	HS: -15 °C to +85 °C (with linear voltage derating to 3.5 V @ +85 °C)

Specifications

Capacitance ¹ (F)	Part number	Maximum initial ESR ¹ (mΩ)	Continuous current ⁶ (A)	Peak current ⁶ (A)	Nominal leakage current ² (µA) HS/HSL	Peak power ⁴ (W)	Stored energy ³ (mWh)	Short circuit current ^{6,7} (A)
10	HS/HSL0814-3R8106-R	1500	0.075	1.0	2.0/3.0	2.4	13.3	2.5
25	HS/HSL0820-3R8256-R	650	0.125	2.3	2.5/3.3	5.5	33.3	5.8
30	HS/HSL1016-3R8306-R	550	0.15	2.7	3.0/4.0	6.6	40	7.0
50	HS/HSL1020-3R8506-R	450	0.25	3.4	4.0/5.0	8.0	67	9.0
70	HS/HSL1025-3R8706-R	250	0.35	6.1	5.0/8.0	14	93	15
120	HS/HSL1225-3R8127-R	200	0.6	7.7	7.0/12	18	160	19
150	HS/HSL1040-3R8157-R	140	0.75	10.9	9.0/16	26	200	27
220	HS/HSL1625-3R8227-R	100	1.1	15.3	12/25	36	293	38

** Repeated short circuit current will permanently damage the leads.

Performance

Parameter	Capacitance change (% of initial value)	ESR (% of maximum initial value)
Lifetime: (1000 hours, rated voltage, maximum operating temperature)	≤ 30%	≤ 200%
Charge/discharge cycles ⁸ : HS: (500,000 at +20 °C), HSL: (250,000 at +20 °C)	≤ 30%	≤ 200%
Storage: (3 years, uncharged, <+35 °C)	≤ 5%	≤ 10%

1. Capacitance, Equivalent series resistance (ESR) and Leakage current are measured according to IEC62391-1
2. Leakage current at +20 °C after 72 hour charge and hold.
3. Stored energy (mWh) = $0.5 \times (V_{max}^2 - V_{min}^2) \times C \times 1000$
3600
4. Peak power (W) = $\frac{V^2}{4 \times ESR}$
5. Pulse current for 1 second from full rate voltage to minimum rated voltage (A) = $\frac{(V_{rated} - V_{min}) \times C}{(1 + ESR \times C)}$
6. Continuous current with a 15 °C temperature rise.
7. Short circuit current is for safety information only. Do not use as operating current.
8. Cycling between rated voltage and 2.5 V, 3 second rest at +20 °C.

Note: Do not discharge supercapacitors below minimum working voltage.

Safety and certifications

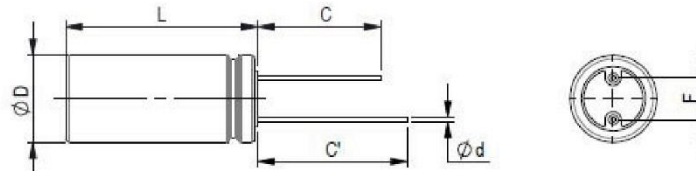
Agency information	UL810a
Shock and vibration	MIL-STD 202G
Environmental compliance	RoHS, REACH, lead free, halogen free
Warnings	Do not overvoltage, do not reverse polarity
Shipping	No restrictions, per UN 3508 with all cells <0.3 watt-hours

HS/HSL Supercapacitors
Hybrid cylindrical cells

Technical Data 11043
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Dimensions (mm)

Part number	ØD maximum	L maximum	F ±0.5	Ød ±0.05	C minimum	C' minimum
HS/HSL0814-3R8106-R	8.5	15.5	3.5	0.6	19	22
HS/HSL0820-3R8256-R	8.5	22	3.5	0.6	19	22
HS/HSL1016-3R8306-R	10.5	18	5	0.6	22	27
HS/HSL1020-3R8506-R	10.5	22	5	0.6	22	27
HS/HSL1025-3R8706-R	10.5	27	5	0.6	22	27
HS/HSL1225-3R8127-R	12.9	27	5	0.6	22	27
HS/HSL1040-3R8157-R	10.5	42	5	0.6	19	22
HS/HSL1625-3R8227-R	16.5	27	7.5	0.8	22	27



Longer lead is positive

Part numbering system

HS	1020	-3R8	50	6	-R	
Family code	Size reference (mm)		Voltage (V) R = decimal	Capacitance (µF) Value	Multiplier	Standard product
HS/HSL = Hybrid supercapacitor	Diameter = 10	Length = 20	3R8 = 3.8 V	Example 506= 50 x 10 ⁶ µF or 50 F		

Part marking

Packaging information

- Bulk

- Manufacturer
- Capacitance value (F)
- Max working voltage (V)
- Family code or part number
- Polarity

Manual solder only (Wave and reflow soldering not recommended)

+350 °C (4-5 seconds by soldering iron)

Cleaning/Washing

No clean soldering recommended. Do not wash the supercapacitors..

Life Support Policy: Eaton does not authorize the use of any of its products for use in life support devices or systems without the express written approval of an officer of the Company. Life support systems are devices which support or sustain life, and whose failure to perform, when properly used in accordance with instructions for use provided in the labeling, can be reasonably expected to result in significant injury to the user.

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