SUPPORT NOTE

SN009 | How to Use Supercapacitors? A Brief Guide to the Design-In Process

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01. EDLC – SUPERCAPACITOR

Compared to other capacitor technologies, EDLCs (Electric Double Layer Capacitor) are outstanding for their very high charge storage capacity and very low equivalent series resistance (ESR). Their high cycle life, low charging time and their large power output make them the ideal choice for many electric power applications.

Possible applications are:

(Intermediate) storage devices

- To provide an application with power during battery change or power-offline periods
- To provide power in emergency cases as uninterruptible power supplies (UPS)

Hybrid application with battery

- To relieve batteries during high power peak
- To buffer energy fluctuations in order to increase battery life time

The most important parameters for the design-in process are capacitance, discharging and charging time as well as the corresponding voltages. Below we present a summary of the most important formulas and provide examples of calculations. [1][2][3]

Charging Unit
- Constant Current
- Constant Voltage

Supercapacitor (EDLC)
- Main Device Parameters, governing its performance:
  - Rated voltage U_R
  - Capacitance C
- EDLCs are low voltage devices
- No constant voltage source: Voltage is decreasing as it delivers power

Discharging Unit
- Constant Resistance
- Constant Current
- Constant Power

Figure 1: General concept of charging/discharging infrastructure.

02. GENERAL PROCEDURE OF DESIGN-IN

1st Identify the mode of operation for the discharge process:

- Constant Resistance
- Constant Current
- Constant Power

2nd Calculate*) the necessary capacitance depending on desired operation parameter such as operation time, output power and output current.

**)For the sake of simplicity we may neglect the losses due to ESR, leads and connections.*

3rd Identify the suitable charging process:

- Constant Current
- Constant Voltage

4nd Calculate the charging time depending on the charging current. If necessary calculate the protective resistor.

Figure 2: Radial through-hole EDLC series WCAP-STSC

Some important formulas for the design-in process are summarized in the following sections.

03. PARAMETER AND PERFORMANCE

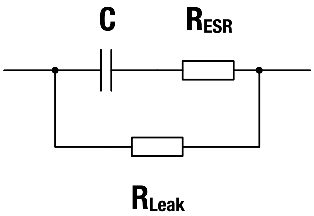

Figure 3: Equivalent Circuit of EDLC

Basic Parameters:

V_R rated voltage
- Non-Aqueous Electrolyte (typ.) ≈ 2 V – 3 V
- given in the datasheet

C capacitance (given in the datasheet and directly on the capacitors marking)

R_{ESR} equivalent series resistance (ESR) (given in the datasheet)

R_{Leak} equivalent parallel resistance, leakage resistance
- corresponding parameter is leakage current I_{Leak}, given in the datasheet
- relation: $R_{Leak} = \frac{U_R}{I_{Leak}}$
- influence on charge storing capabilities
  $R_{Leak} \approx 10\ k\Omega$ - $1\ M\Omega$

P power output, i.e. power consumption of application

Performance Parameters:

V_1 charging voltage, usually $V_R = V_1$

V_2 lower cut-off voltage

energy storage capacity:

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

$$E = \int P(t)\,dt = P \cdot t \qquad \text{(if } P(t) = \text{const.)}$$

maximum power output:

$$P_{max} = \frac{V_R^2}{4 \cdot R_{ESR}}$$

3.1 Example

An application needs to be driven with a constant power of P = 0.4 W for t = 360 s. The lower cutoff voltage is V_2 = 1 V. How large is the total amount of energy E and how large is the required capacitance C?

Calculation:

P = 0.4 W for t = 360 s; $V_1 = V_R$ = 2.7 V; V_2 = 1 V

$$E = P \cdot t = 0.4\ W \cdot 360\ s = 144\ J = 0.04\ Wh$$

The required energy is E = 144 J

$$C = 2 \cdot \frac{E}{V_1^2 - V_2^2} = 2 \cdot \frac{144\ J}{(2.7\ V)^2 - (1\ V)^2} \approx 46\ F$$

The required capacitance is C = 46 F, thus a capacitor with a capacitance of 50 F is recommended.

04. CONSTANT VOLTAGE CHARGING

For constant voltage charging it is recommended to use a protective resistor in series with the EDLC. It may be necessary to restrict the current with a protective resistor R_P to a specific value I_{max}. For a given I_{max} the resistance is calculated by:

$$R_P = \frac{V_1}{I_{max}} - R_{ESR}$$

The charge characteristic is calculated by ($t_0 = 0$):

$$V = V_1 \cdot \left(1 - e^{-\frac{t}{(R_{ESR} + R_p) \cdot C}}\right)$$

$$I = \frac{U_1}{R_{ESR} + R_p} \cdot e^{-\frac{t}{(R_{ESR} + R_p) \cdot C}}$$

The corresponding charging time is calculated by:

$$t = \ln\left(\frac{V_1}{V_1 - V}\right) \cdot (R_{ESR} + R_P) \cdot C$$

$$t = \ln\left(\frac{100\ \%}{100\ \% - p}\right) \cdot (R_{ESR} + R_P) \cdot C$$

Charging to 99.9%:

$$t \approx 7 \cdot (R_{ESR} + R_P) \cdot C$$

C	capacitance
V_1	charging voltage
I_0	current at t_0
I_{max}	max. allowable current
V_R	rated voltage
V	voltage at t
t	charging time
t_0	start time
R_P	protective resistance
R_{ESR}	equivalent series resistance

4.1 Example Protective Resistance

A capacitor with capacitance C = 50 F and an equivalent series resistance R_{ESR} = 0.02 Ω shall be charged with a unprotected power source at $V_1 = V_R$ = 2.7 V. The power source has a maximal allowable current of I_{max} = 5 A. How large should the protective resistance be, to prevent overcurrent?

Calculation:

I_{max} = 5 A; $V_R = V_1$ = 2.7 V; R_{ESR} = 0.02 Ω

$$R_P = \frac{V_1}{I_{max}} - R_{ESR}$$

$$R_P = \frac{2.7\ V}{5\ A} - 0.02\ \Omega = 0.52\ \Omega$$

In order to prevent over current at the power source, a protective resistor with $R_P \geq 0.52\ \Omega$ should be used.

4.2 Example Charging Time

A capacitor with capacitance C = 50 F is charged to V = 2.16 V (80 % of V_R) at constant voltage V_R = 2.7 V with a protective resistor R_P = 0.5 Ω and an equivalent series resistance R_{ESR} = 0.02 Ω. How long is the charging process?

Calculation:

C = 50 F; V = 2.16 V; $V_1 = V_R$ = 2.7 V; R_P = 0.5 Ω; R_{ESR} = 0.02 Ω

$$t = \ln\left(\frac{V_1}{V_1 - V}\right) \cdot (R_{ESR} + R_P) \cdot C$$

$$t = \ln\left(\frac{2.7\ V}{2.7\ V - 2.16\ V}\right) \cdot (0.02\ \ + 0.5\ \ ) \cdot 50\ F \approx 42\ s$$

The charging time is ≈ 42 s.

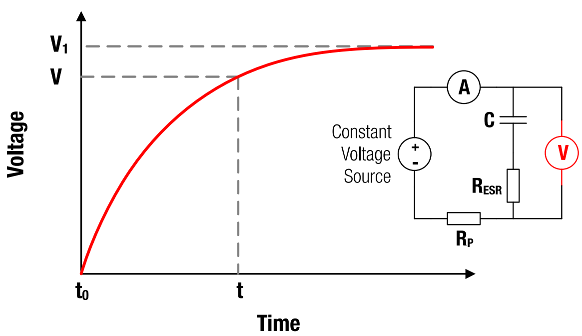

Figure 4: V-t characteristics for constant voltage charging

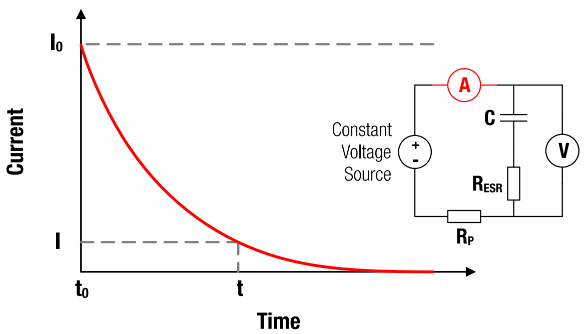

Figure 5: I-t characteristics for constant voltage charging

05. CONSTANT RESISTANCE DISCHARGING

The discharging characteristics of a capacitor with capacitance C over given load resistance R_L is calculated by (t_0=0):

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

$$|I| = \frac{V_0}{R_{ESR} + R_L} \cdot e^{-\frac{t}{(R_{ESR} + R_L) \cdot C}}$$

The corresponding discharging time is calculated by:

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

The necessary capacitance is calculated with:

$$C = \frac{t}{\ln\left(\frac{V_1}{V}\right) \cdot (R_{ESR} + R_L)}$$

C	capacitance
V_0	charging voltage at t_0
I_0	current at t_0
V_R	rated voltage
V	voltage at t
t	discharging time
t_0	start time
R_L	load resistance
R_{ESR}	equivalent series resistance

5.1 Example Discharging Time

A capacitor with capacitance C = 50 F is discharged from its rated voltage V_R = 2.7 V to V = 0.3 V with a load of R_L = 1 Ω. How long is the discharging process?

Calculation:

R_{ESR} = 0.02 Ω; R_L = 1 Ω; C = 50 F; V_0 = V_R = 2.7 V; V = 0.3 V

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

$$t = \ln\left(\frac{2.7\,V}{0.3\,V}\right) \cdot (0.02 \quad + 1 \quad) \cdot 50\,F \approx 112\,s$$

The discharge time is approximately 112 seconds.

5.2 Example Voltage Drop

A capacitor with a capacitance C = 50 F is discharged from its rated voltage V_R = 2.7 V with a load of R_L = 2 Ω for a period of time t = 280 s. What is the remaining voltage?

Calculation:

R_{ESR} = 0.02 Ω; R_L = 2 Ω; C = 50 F; V_0 = V_R = 2.7 V; t = 280 s

$$V = V_0 \cdot e^{-\frac{t}{(R_{ESR} + R_L) \cdot C}} = 2.7\,V \cdot e^{-\frac{280\,sec}{(0.02 \quad + 2 \quad) \cdot 50\,F}} = 0.17\,V$$

The remaining voltage is V = 0.17 V.

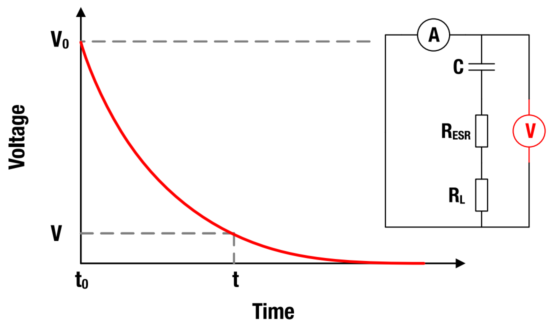

Figure 6: V-t characteristics for constant resistance discharging

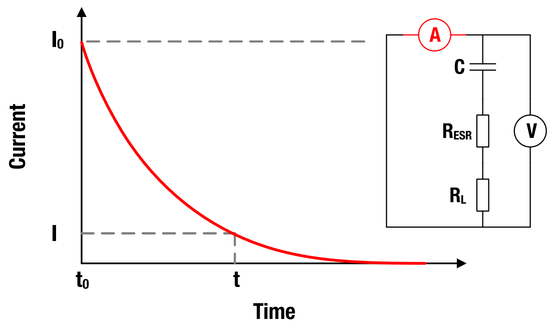

Figure 7: I-t characteristics for constant resistance discharging

06. CONSTANT CURRENT CHARGING/DISCHARGING

If a constant current is used, the voltage V at the terminals for time t (t = 0) is calculated by:

$$V - V_0 = \frac{I_C}{C} \cdot t$$

The corresponding discharge time (t_0 = 0) is calculated by:

$$t = (V_0 - V) \cdot \frac{C}{I_D}$$

The corresponding charging time (t_0 = 0) is calculated by:

$$t = (V - V_0) \cdot \frac{C}{I_C}$$

The necessary capacitance is calculated with:

$$C = \frac{t \cdot I_D}{(V_0 - V)}$$

$I_{C,D}$	constant charge / discharge current
C	capacitance
V_R	rated voltage
V, I	voltage, current at t
V_0	voltage at t_0 (charging)
$\lvert t - t_0 \rvert$	(dis)charge time
t_0	start time
R_{ESR}	equivalent series resistance

6.1 Example Charging Time

A capacitor with capacitance C = 50 F is charged from V_0 = 0.3 V to its rated voltage V_R = 2.7 V with a constant current I_C = 2 A. How long is the charging process?

Calculation:

I_C = 2 A; C = 50 F; V = V_R = 2.7 V; V_0 = 0.3 V

$$t = (V - V_0) \cdot \frac{C}{I_C} = (2.7\ V - 0.3\ V) \cdot \frac{50\ F}{2\ A} = 60\ s$$

The charge time is 60 seconds.

6.2 Example Voltage Increase

A capacitor with capacitance C = 50 F and an initial voltage V_0 = 0.3 V is charged with a constant current I_C = 2 A for t = 5 s. How large is the capacitor voltage?

Calculation:

I_C = 2 A; C = 50 F; V_0 = 0.3 V; t = 5 s

$$V = V_0 + \frac{I_C}{C} \cdot t = 0.3\ V + \frac{2\ A}{50\ F} \cdot 5\ s = 0.5\ V$$

The capacitor voltage is V = 0.5 V.

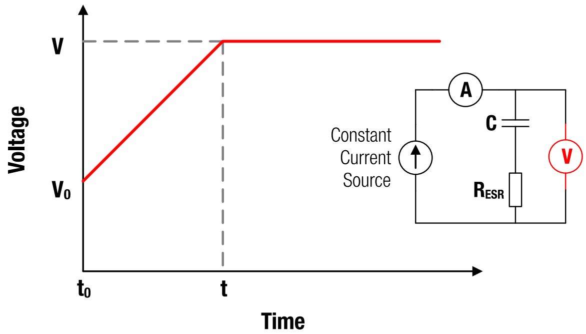

Figure 8: V-t characteristics for constant current charging.

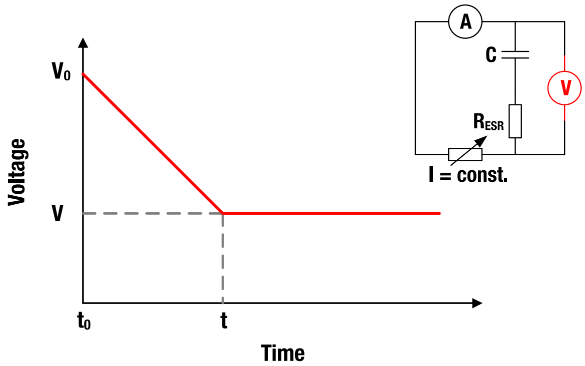

Figure 9: V-t characteristics for constant current discharging.

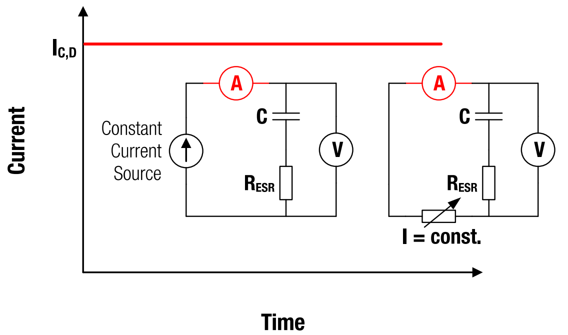

Figure 10: I-t characteristics for constant current charging and discharging.

07. CONSTANT POWER DISCHARGING

If the capacitor is discharged at a constant power P_C, the voltage and current characteristic are calculated by ($t_0 = 0$):

$$V_0^2 - V^2 = \frac{2 \cdot P_C}{C} \cdot t$$

$$|I| = \left(\frac{V_0^2}{P_C^2} - \frac{2}{C \cdot P_C} \cdot t\right)^{-\frac{1}{2}}$$

The corresponding discharge time ($t_0 = 0$) is calculated by:

$$t = \left(V_0^2 - V^2\right) \frac{C}{2 \cdot P_C}$$

The necessary capacitance is calculated with:

$$C = \frac{2 \cdot t \cdot P_C}{V_0^2 - V^2}$$

P_C	constant power output
C	capacitance
V_R	rated voltage
V, I	voltage, current at t
I_0	current at t_0
V_0	voltage at t_0 (charging)
$t - t_0$	discharge time
t_0	start time

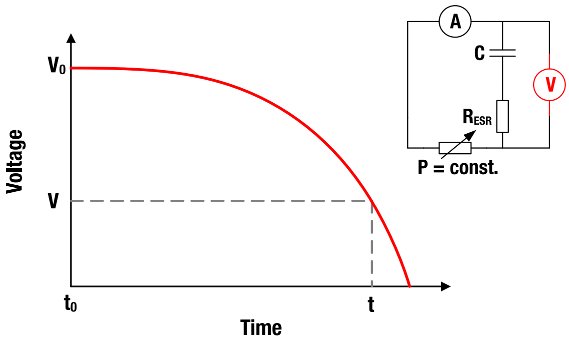

Figure 11: V-t characteristics for constant power discharging

7.1 Example Discharge Time

A capacitor with capacitance C = 50 F and rated voltage $V_R = 2.7$ V is discharged at constant power $P_C = 0.2$ W. The cut-off voltage is V = 0.7 V. How long can the capacitor be operated under this condition?

Calculation:

$P_C = 0.2$ W; C = 50 F; $V_0 = V_R = 2.7$ V; V = 0.7 V

$$t = \left(V_0^2 - V^2\right) \frac{C}{2 \cdot P_C}$$

$$t = \left((2.7\text{ V})^2 - (0.7\text{ V})^2\right) \cdot \frac{50\text{ F}}{2 \cdot 0.2\text{ W}} = 850\text{ s}$$

It can be operated for t = 850 s.

7.2 Example Voltage Drop

A fully charged capacitor with capacitance C = 50 F and rated voltage $V_R = 2.7$ V has been operated for t = 180 s at constant power output of $P_C = 0.7$ W. How large is the remaining voltage?

Calculation:

$P_C = 0.7$ W; C = 50 F; $V_0 = V_R = 2.7$ V; t = 180 s; $t_0 = 0$ s

$$V = \sqrt{V_0^2 - \frac{2 \cdot P_C}{C} \cdot t}$$

$$V = \sqrt{(2.7\text{ V})^2 - \frac{2 \cdot 0.7\text{ W}}{50\text{ F}} \cdot 180\text{ s}} = 1.5\text{ V}$$

The remaining voltage is V = 1.5 V

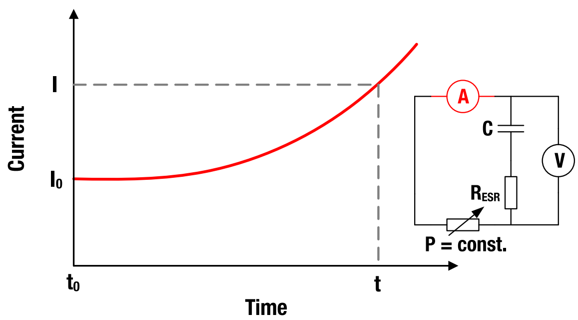

Figure 12: I-t characteristics for constant power discharging

A Appendix

A.1 Design-In of Supercapacitors in 4 Steps

Supercapacitors (SC) are often used as energy storage devices. In those cases, the early conceptual phase of the design-in process can be subdivided 4 steps.

1. Determine the number of serial connected supercapacitors. Some applications require higher voltage than the rated voltage of an individual SC.
2. Determine the capacitance of the stack, based on the required power.
3. Determine the requirements of the charging unit. Determine the charging time.
4. Determine the lifetime, based on the operational conditions.

Once the concept is developed, the electrical engineer can make qualified decision about the circuit design and choose the appropriate electronic components.

Please, answer the following questions. With the given information we are able to provide the parameters of the SC application.

TO CALCULATE THE SIZE OF THE STACK

Larger operating voltages require the serial connection (cascades) of supercapacitors.

Please, specify the required charging voltage V_c of the supercapacitor unit and its cut off voltage V_{cut} an.

V_c = [____]

V_{cut} = [____]

Please fill in the relevant magnitude and corresponding unit.

TO CALCULATE THE REQUIRED CAPACITANCE

Identify the mode of operation for the discharge process. Please mark the appropriate box with an "x".

Constant Current ☐

Please, specify the required current I.

I = [____]

Constant Power ☐

Please, specify the required power P.

P = [____]

Constant Resistance ☐

Please, specify the resistance R of the load.

R = [____]

How long is the discharge time *t* for the above chosen process?

t = [____]

TO CALCULATE THE CHARGING TIME OR CHARGING CURRENT OR PROTECTIVE RESISTOR

What type of power source is used to charge the capacitor unit?

Please, identify the relevant charging process. Please, mark the appropriate box with an "X".

Constant Current ☐

To calculate the charging time t_c please state current output I_c of the constant current source, used for charging the SC unit.

I_c = [____]

OR

To calculate the required charging current please, state the desired charging time t_c

t_c = [____]

Constant Voltage ☐

To calculate the protective resistor for your charging voltage source, please, state the maximum allowable current I_{cm} of your source. Please fill in the relevant magnitude and corresponding unit.

I_{cm} = [____]

TO ESTIMATE THE LIFETIME

We may also estimate the degradation of capacitance for user defined operational profiles. The user may define a "typical working day" (24 h), such as given in Table 1. Based on this operational profile the remaining relative capacitance vs. time can be calculated, as given in Figure A1.

You may choose between two load schemes:

1. DC-voltage load and
2. Low current load (i.e. cycle life test conditions).

Load Scheme	Low current load	Low current load	Low current load	Low current load
Op. Time [h]	_____	_____	_____	_____
Op. Temp. [°C]	_____	_____	_____	_____
Applied Voltage [V]	_____	_____	_____	_____

Load Scheme	DC-voltage load	Low current load	Low current load	Low current load
Op. Time [h]	3	4	12	5
Op. Temp. [°C]	65	50	40	22
Applied Voltage [V]	/	2.0	2.7	0

Table 1: Example of high temperature operational profile for 24 h.

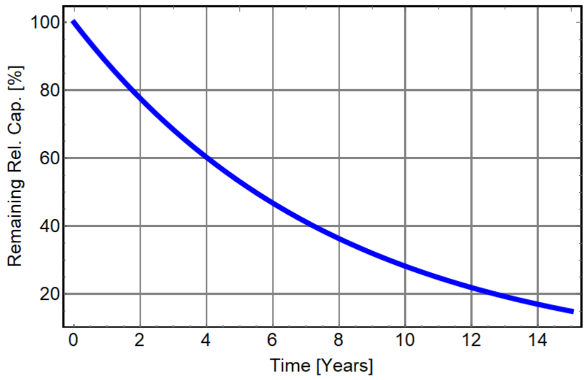

Figure A1: Example. Relative capacitance vs. time for operational profile, given in Table 1

A.2 References

[1] N. Kularatna (2015). Energy Storage Devices for Electronic Systems – Rechargeable Batteries and Supercapacitors. Elsevier Academic Press (Print Book)

[2] F. Beguin, E. Frackowiak, G. Q. M. Lu (eds.) (2013). Supercapacitors - Materials, Systems, and Applications. Wiley-VCH (Print Book)

[3] B. E. Conwa (1999). Electrochemical Supercapacitors – Scientific Fundamentals and Technological Applications. Kluwer Academics / Plenum Publishers, New York (Print book)

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