Support Note

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

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1 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:

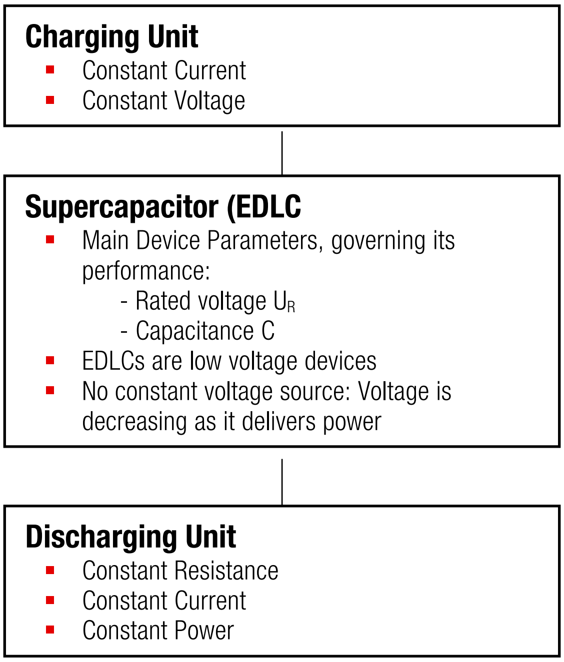
(Intermediate) storage devices

- 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.

2 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

4th 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.

3 Parameter and Performance

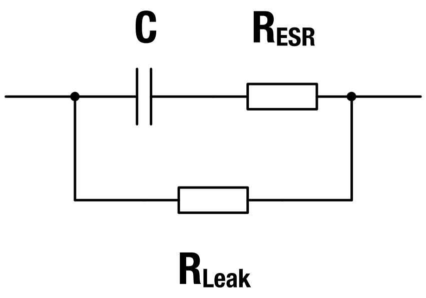


Figure 3: Equivalent Circuit of EDLC

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 ILeak, given in the datasheet
- relation: RLeak = $\frac{U_R}{I_{Leak}}$
- 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.

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4 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
p	charging level in %

4.1 Example Protective Resistance

A capacitor with capacitance C = 50 F and an equivalent series resistance $R_{ESR} = 0.02\ \Omega$ 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; $R_{ESR} = 0.02\ \Omega$

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

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

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 $R_P = 0.5\ \Omega$ and an equivalent series resistance $R_{ESR} = 0.02\ \Omega$. How long is the charging process?

Calculation:

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

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

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

The charging time is ≈ 42 s.

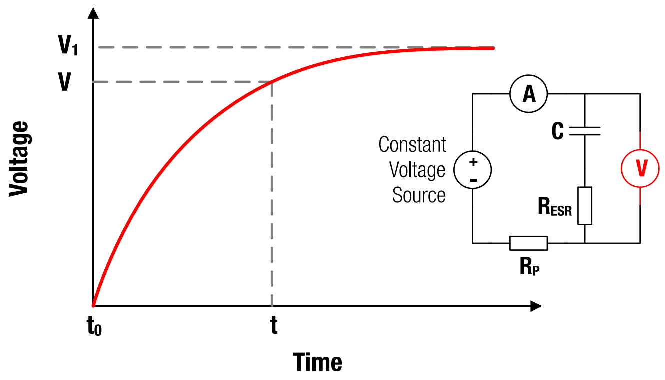

Figure 4: V-t characteristics for constant voltage charging

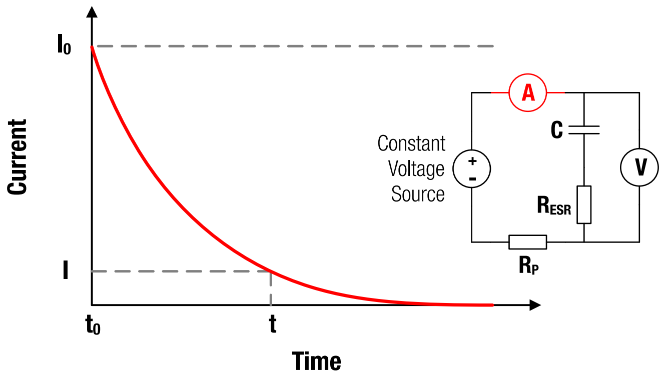

Figure 5: I-t characteristics for constant voltage charging

5 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:

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

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

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

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:

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

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

The remaining voltage is V = 0.17 V.

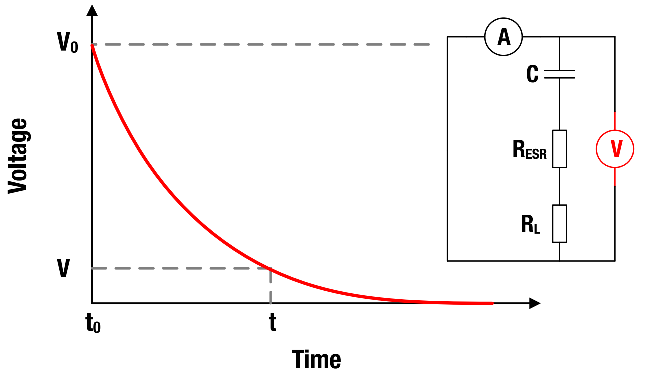

Figure 6: V-t characteristics for constant resistance discharging

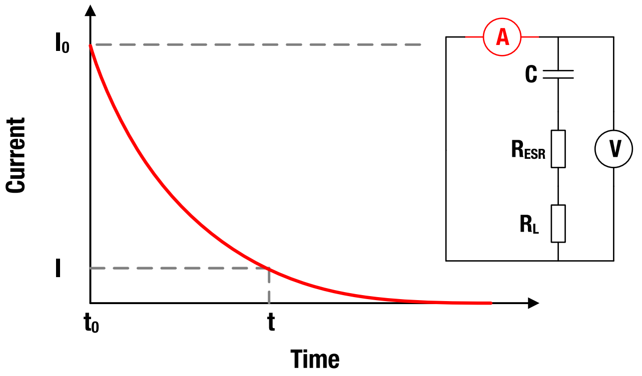

Figure 7: I-t characteristics for constant resistance discharging

6 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

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

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

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

The capacitor voltage is V = 0.5 V.

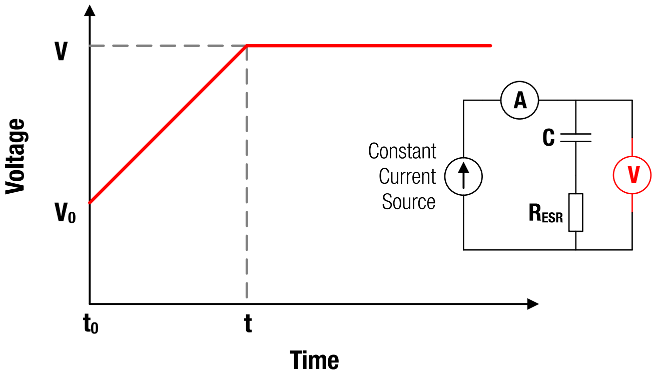

Figure 8: V-t characteristics for constant current charging.

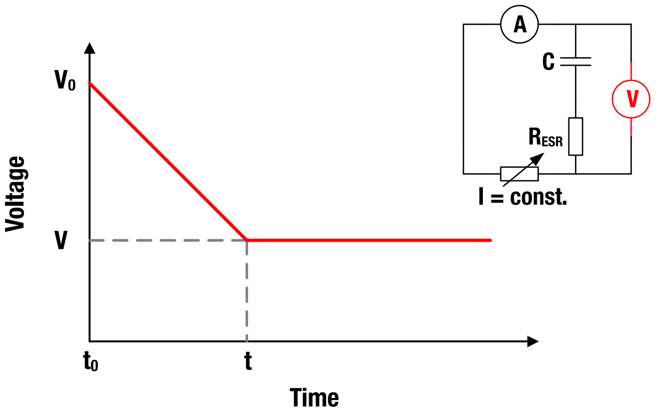

Figure 9: V-t characteristics for constant current discharging.

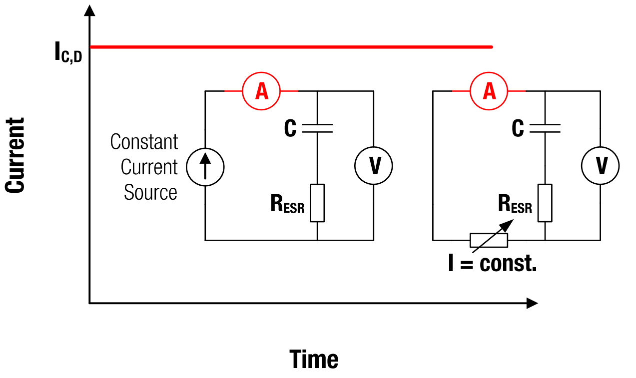

Figure 10: I-t characteristics for constant current charging and discharging.

7 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

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

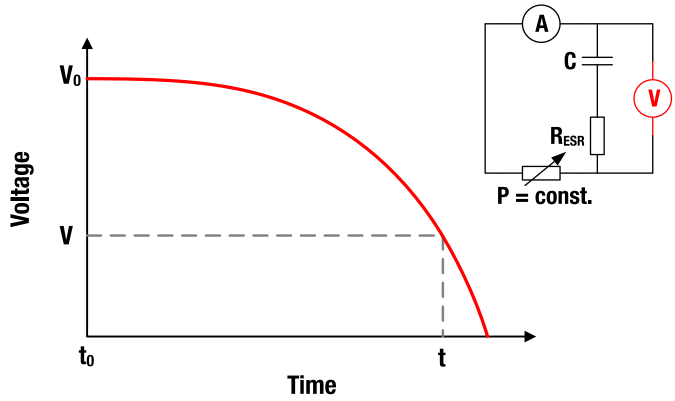

Figure 11: V-t characteristics for constant power discharging

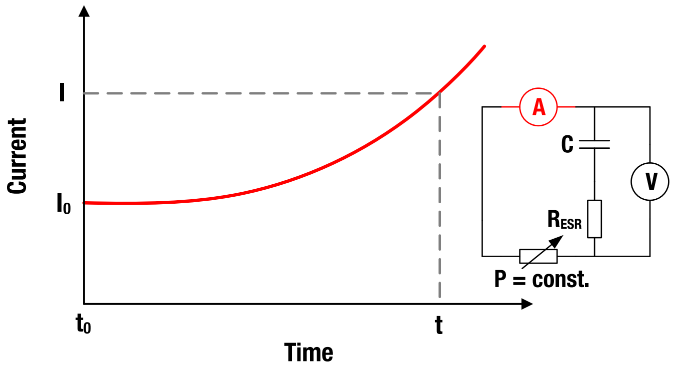

Figure 12: I-t characteristics for constant power discharging

A. Appendix

A.1. References

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

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