Supercapacitors
Webinar about Technology and Applications

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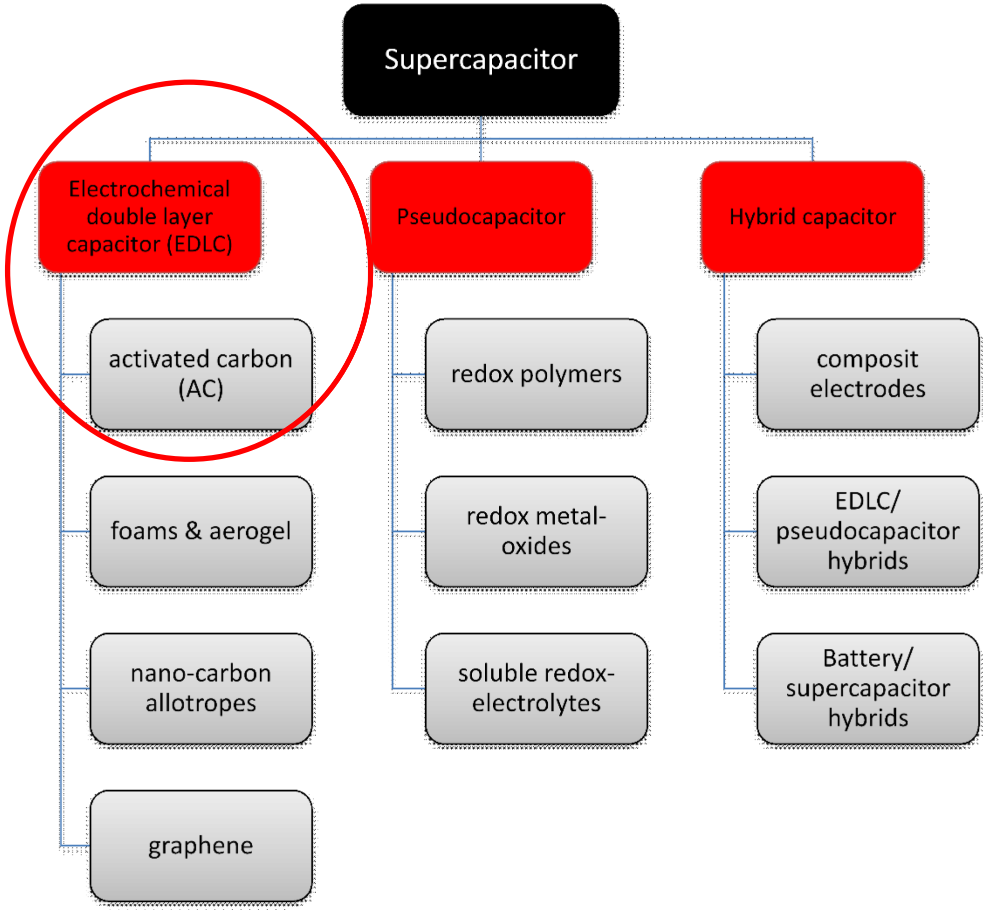
Agenda Technology

- **Classification of Capacitors**
- **Physical Processes**
- **Model Parameters and Performance**
- **Charge, Discharge frequency behavior**
- **Physical limitations of Capacitance**

Classification of Capacitors



Types of Supercapacitors, based on design of electrodes:

- **Double-layer capacitors**
  - **Electrodes: carbon or carbon derivatives**
- **Pseudocapacitors**
  - **Electrodes: oxides or conducting polymers (high faradaic pseudocapacitance)**
- **Hybrid capacitors**
  - **Electrodes: special electrodes with significant double-layer capacitance and pseudocapacitance, such as lithium-ion**

Classification of Capacitors

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- **Tradename / Synonyms:**

  - **PowerCap,**
  - **BestCap,**
  - **BoostCap,**
  - **CAP-XX,**
  - **EVerCAP,**
  - **DynaCap,**
  - **Goldcap,**
  - **HY-CAP,**
  - **SuperCap,**
  - **PAS Capacitor,**
  - **PowerStor,**
  - **PseudoCap,**
  - **Ultracapacitor,**
  - **Ultracap,**
  - **ENYCAP,**
  - **…**

Classification of Capacitors

- Supercapacitors vs. Batteries and Caps

Supercaps

- fast charging and discharging (min – sec)
- high life cycle (≈ 500,000 cycles)
- high power output
  - ≈ 10 times higher than Li-ion battery
- low energy capacity
  - ≈ 30 times lower than Li-ion battery
- linear voltage dependence

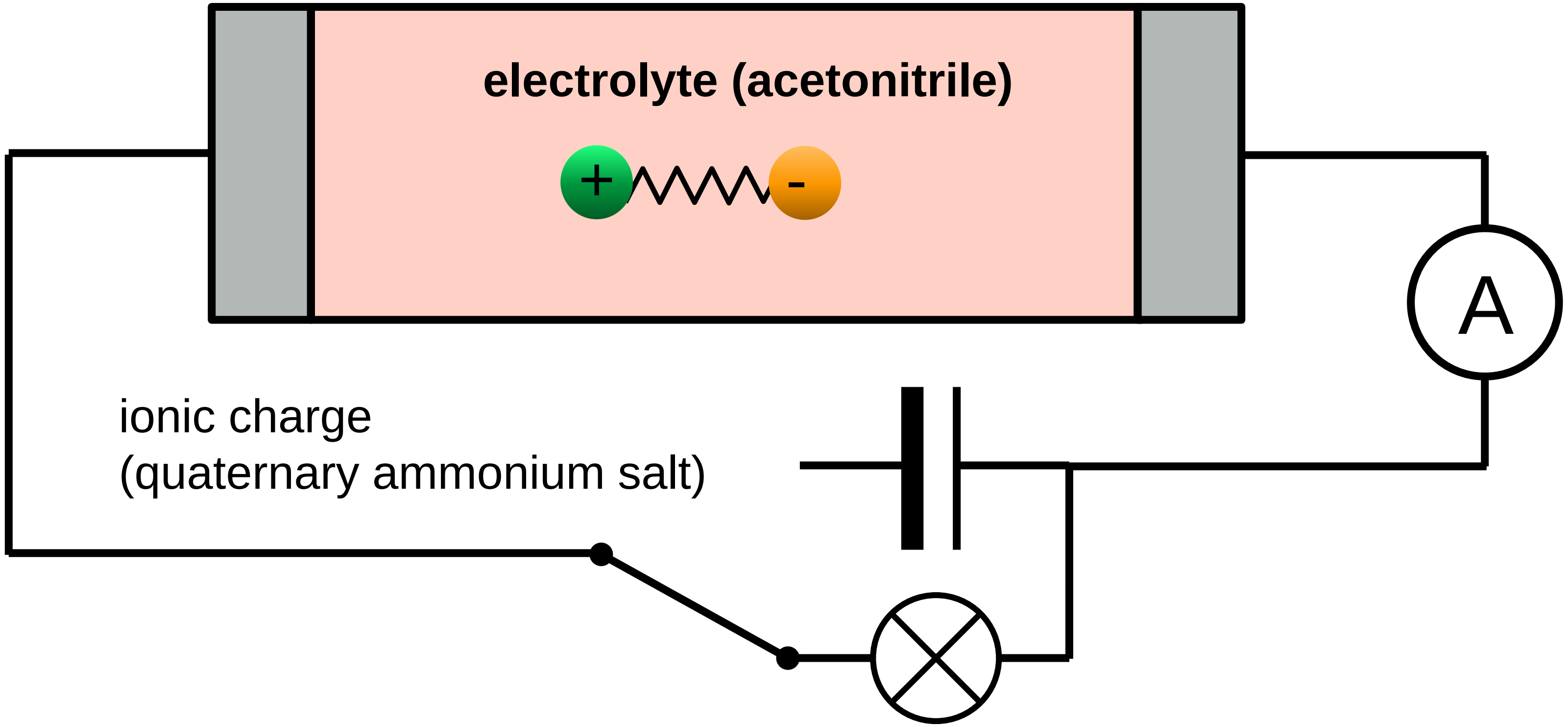
Capacitors

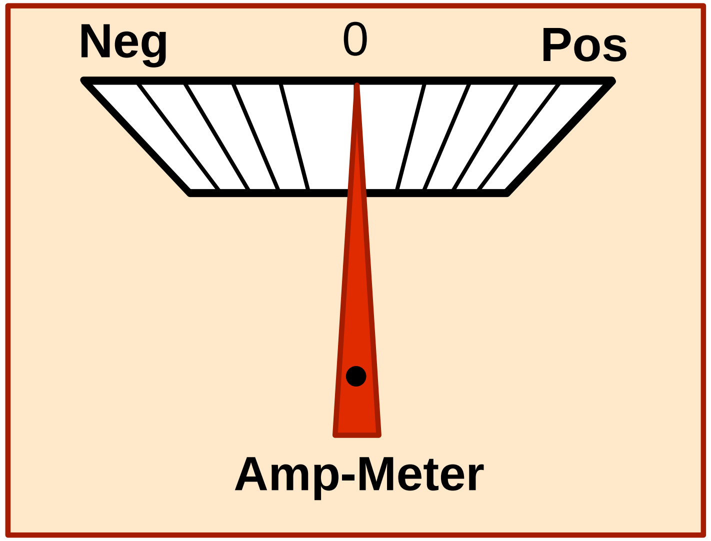
- fast charging and discharging (≪ sec)
- high life time
- high operating voltages
- high power output
- low energy capacity

Batteries

- high energy capacity
- constant voltage dependence
- low power output
- low life expectancy (≈ 1000 cycles)
- long charging time (hours)

Energy Storage - Charge Separation

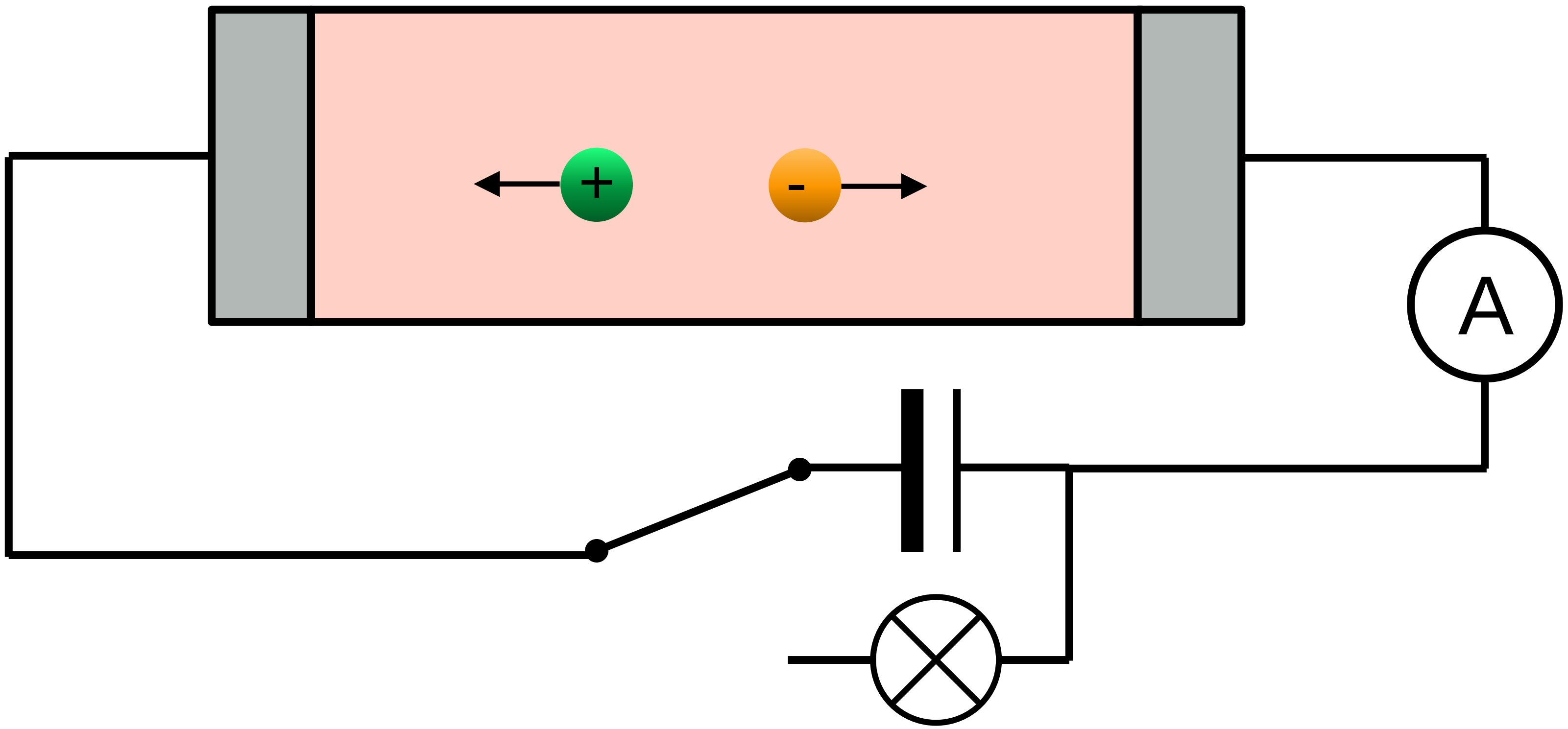


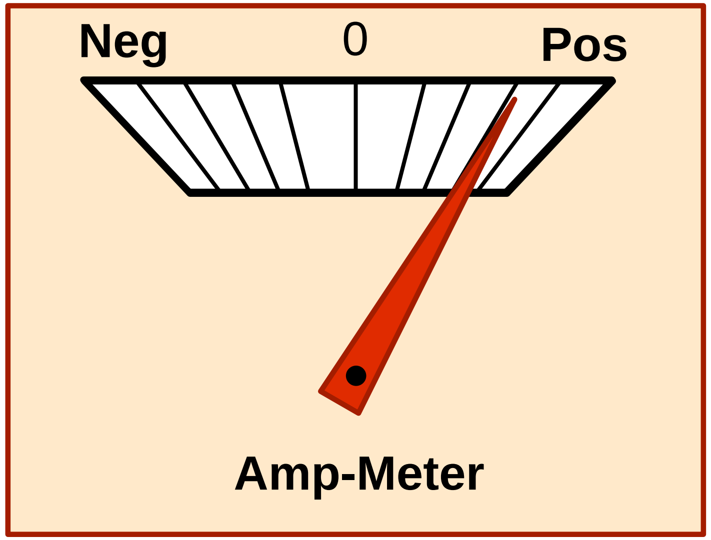


Discharged State:

1) **no voltage is applied to electrodes**
2) **anions and cations are in close vicinity to each other**
3) **Movement of anions and cations governed by electrostatic interaction and diffusion processes**

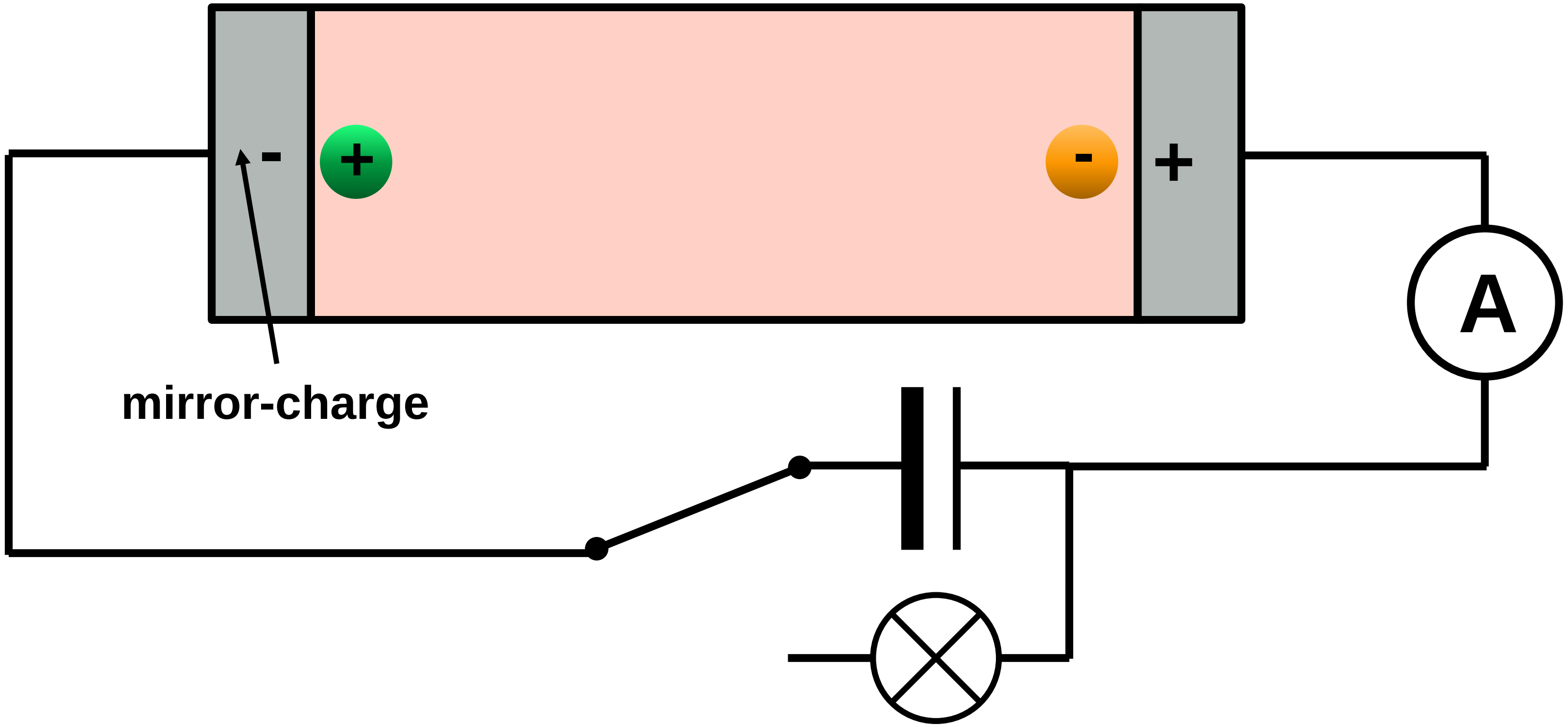
Energy Storage - Charge Separation

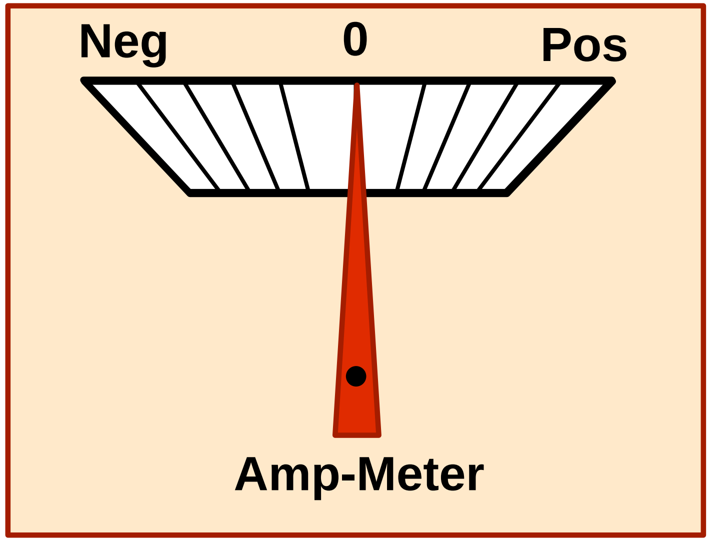




Charging:
1) voltage between plates (i.e. electric field) is applied
2) electric field “tears” charges apart
3) movement of the charges causes a current, provided by the voltage source

Energy Storage - Charge Separation

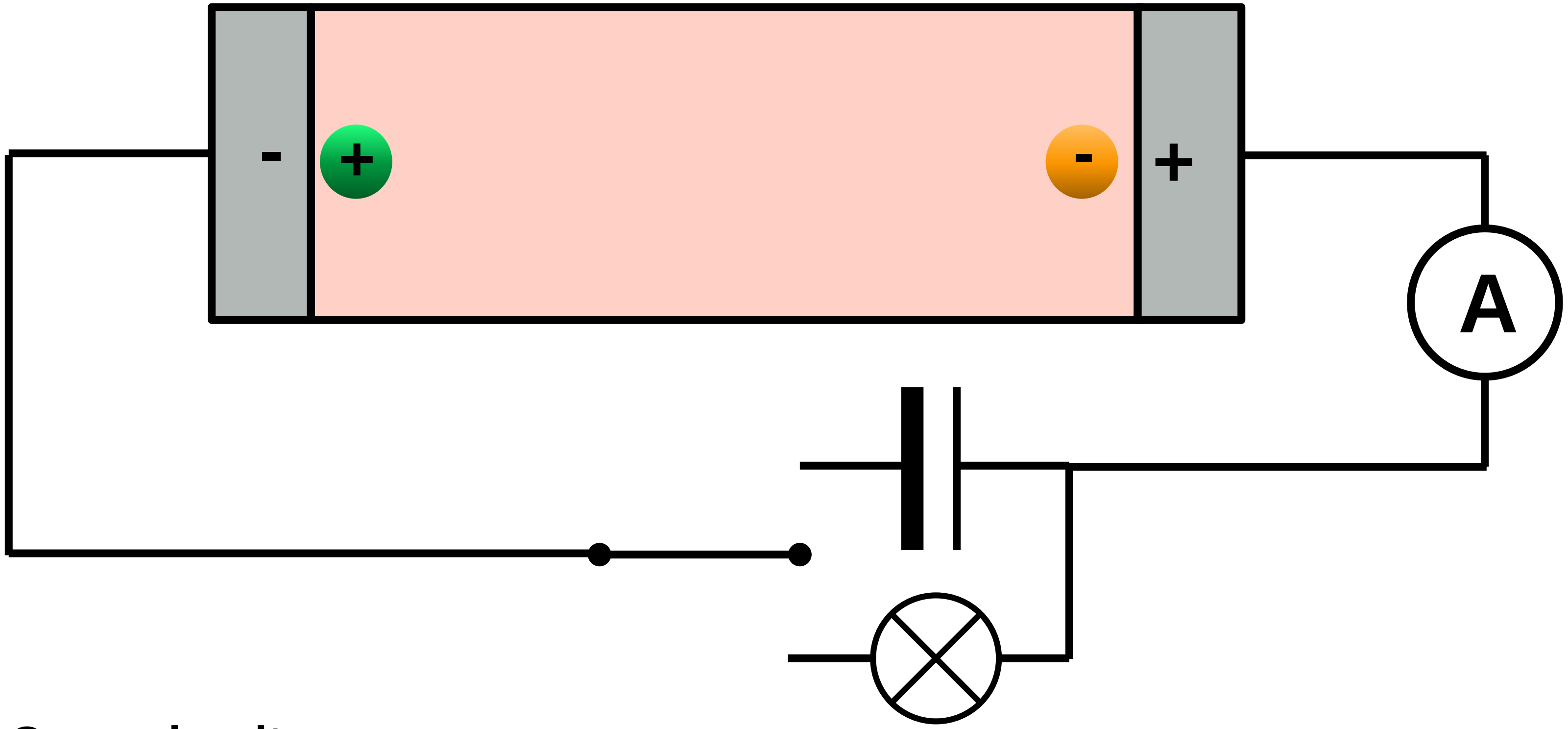


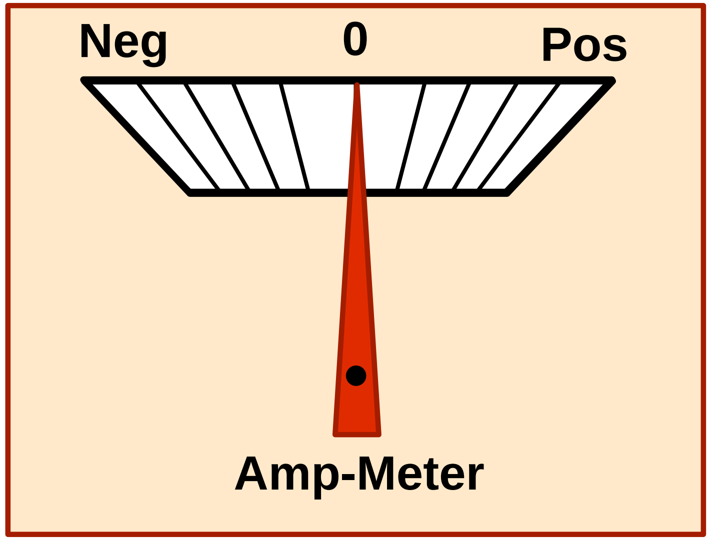


Fully charged:

1) anions and cations reach interface/electrode
2) Reorientation of charges comes to hold
3) Each anion/cation is mirrored by a opposing positive/negative charge at the electrode

Energy Storage - Charge Separation

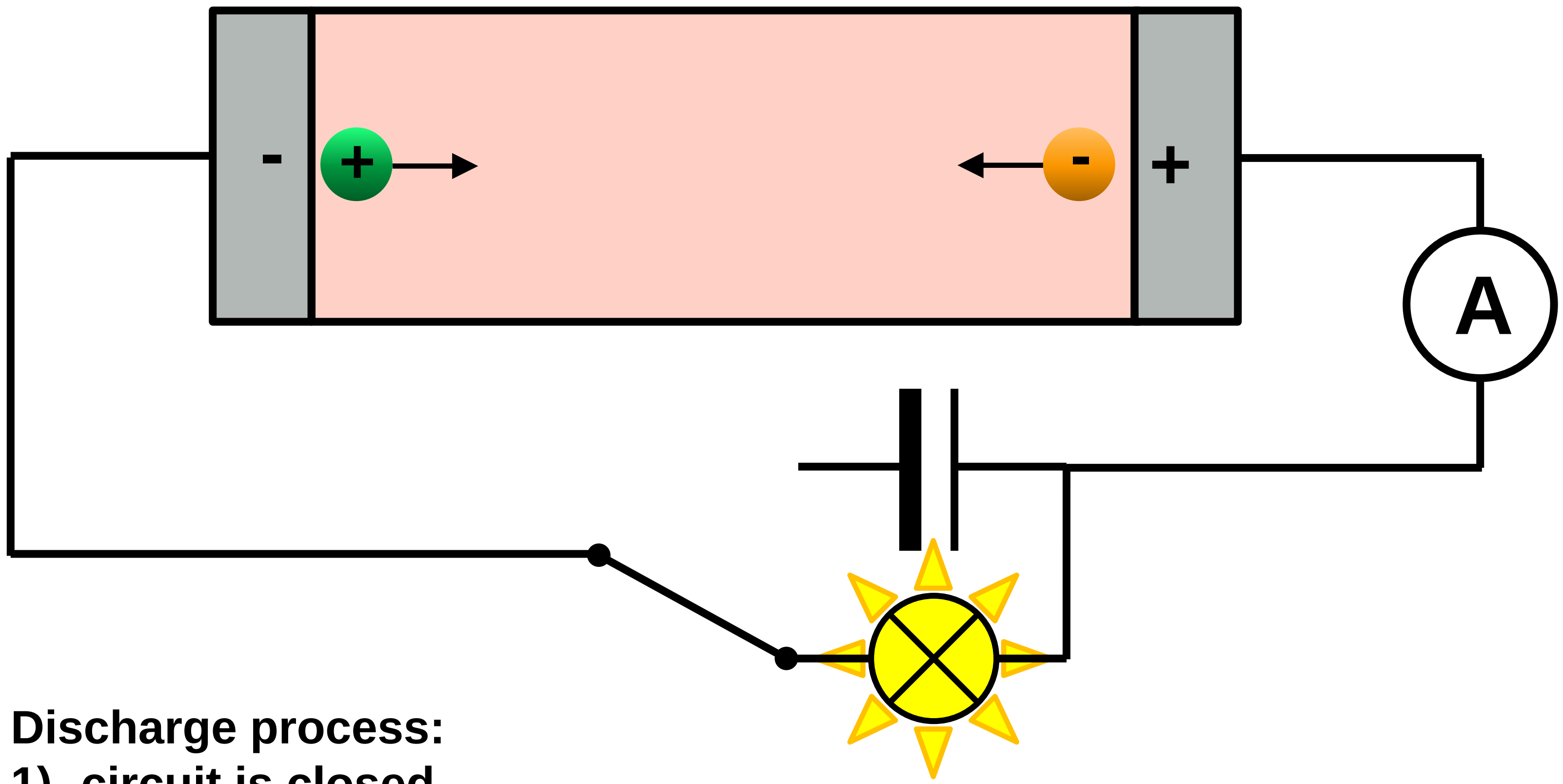


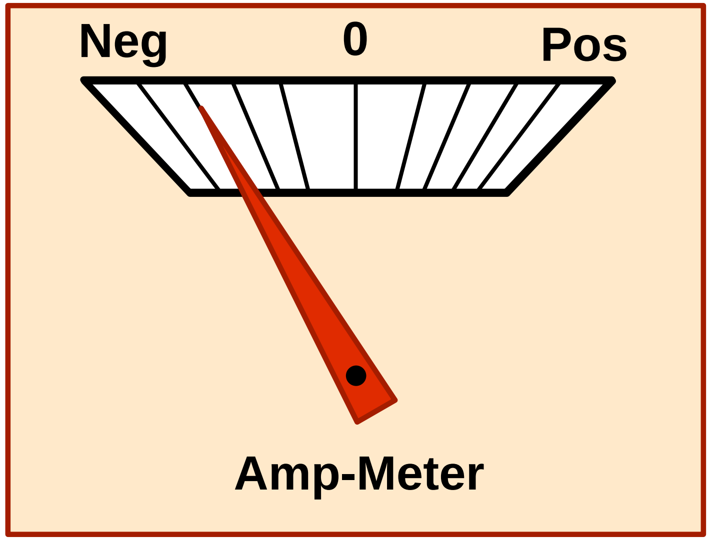


Open circuit:

1) **Each anion/cation is balanced by an equal amount of mirror charge at the interface**
2) **Anions and cations reside a the interface**
3) **Charges can be stored at interface for a long time**

Energy Storage - Charge Separation

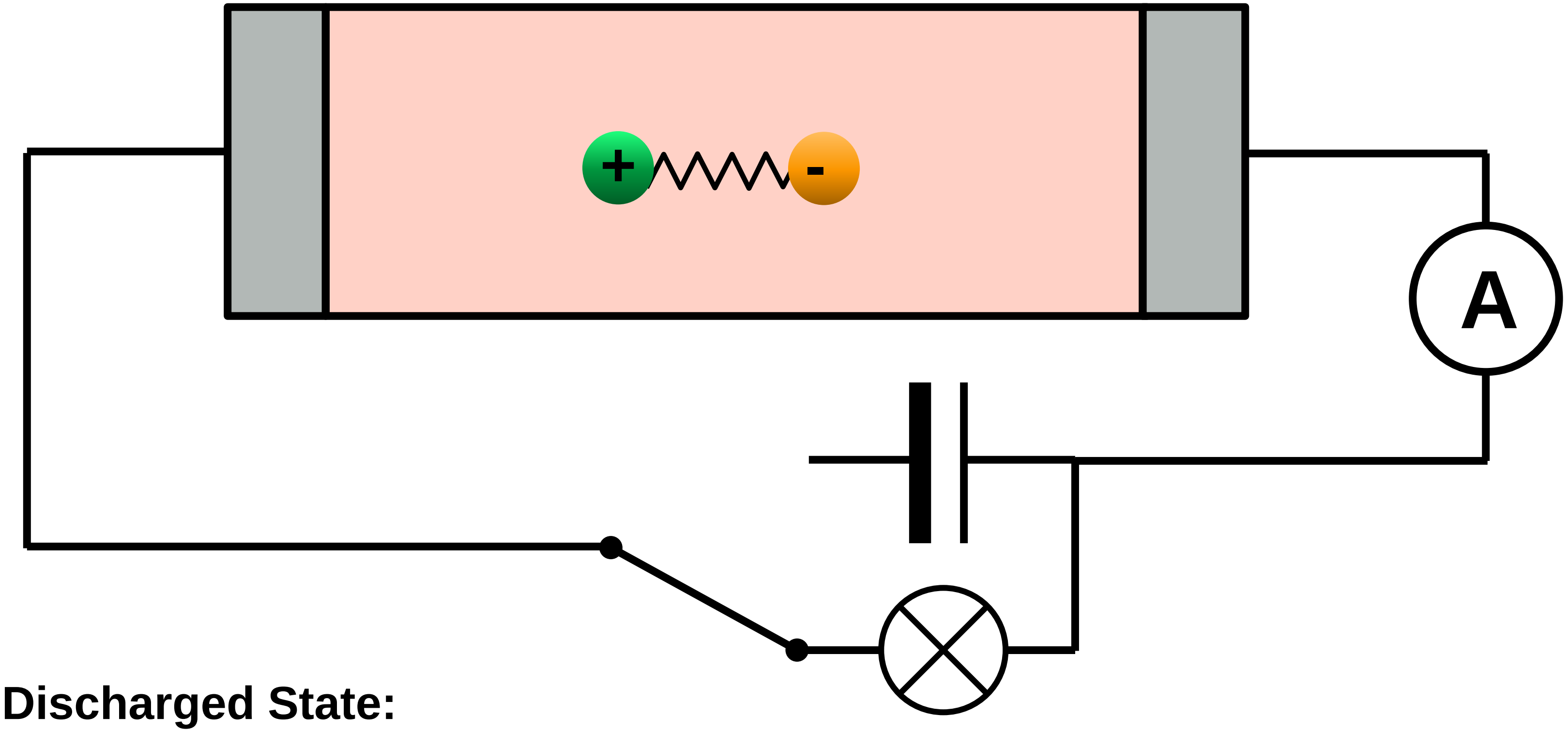


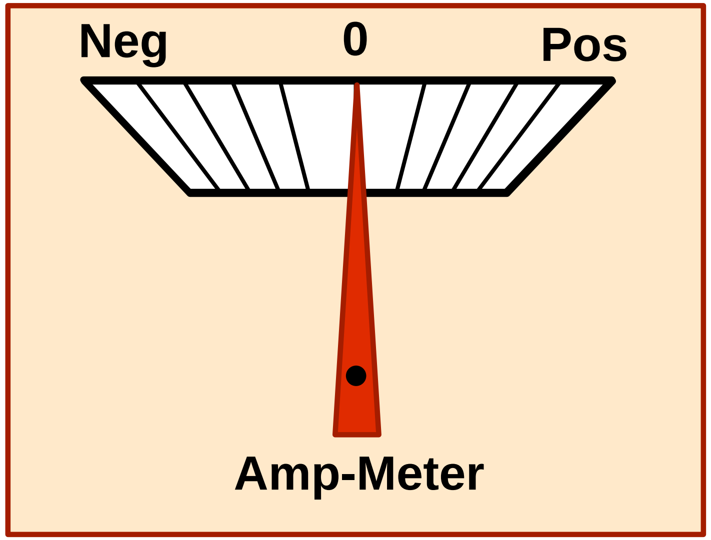


Discharge process:

1) circuit is closed
2) potential difference between the plates, causes electrical current at a certain voltage
3) Anion/cations “loose” their mirror charge, leading to charge movement
4) The quicker the anions/cations can be released, the larger the current

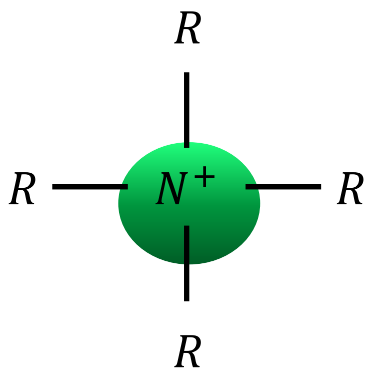
Energy Storage - Charge Separation

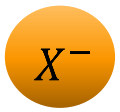




Discharged State:
1) no voltage is applied to electrodes
2) anions and cations are again in close vicinity to each other
3) movement of anions and cations governed by electrostatic interaction and diffusion processes

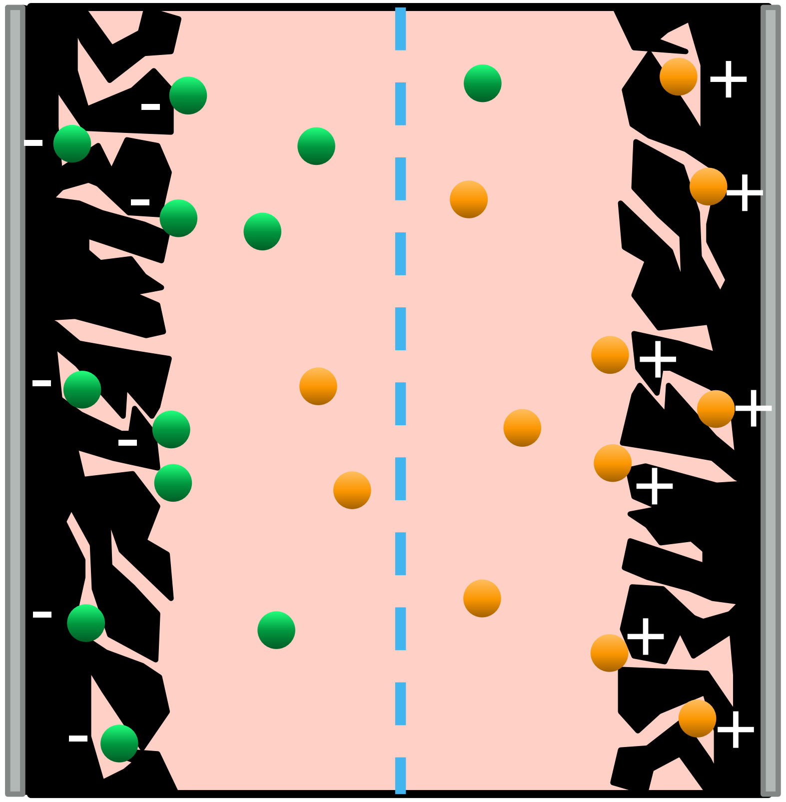
Structure of EDLC

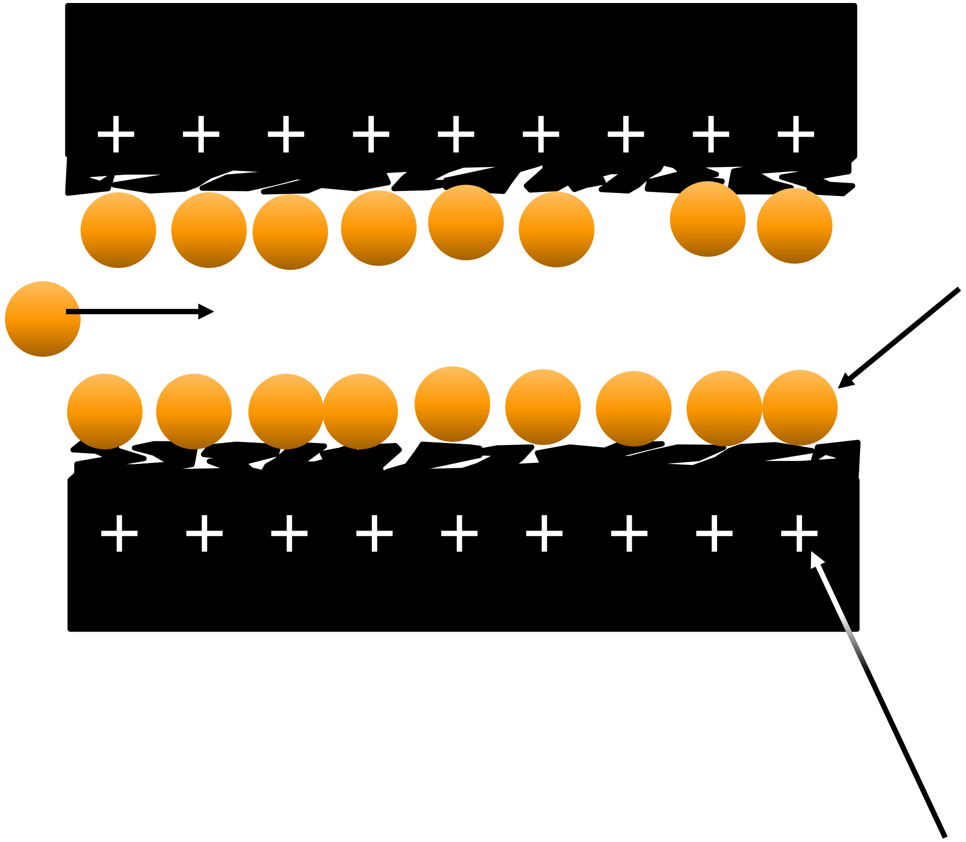




Acetonitrile

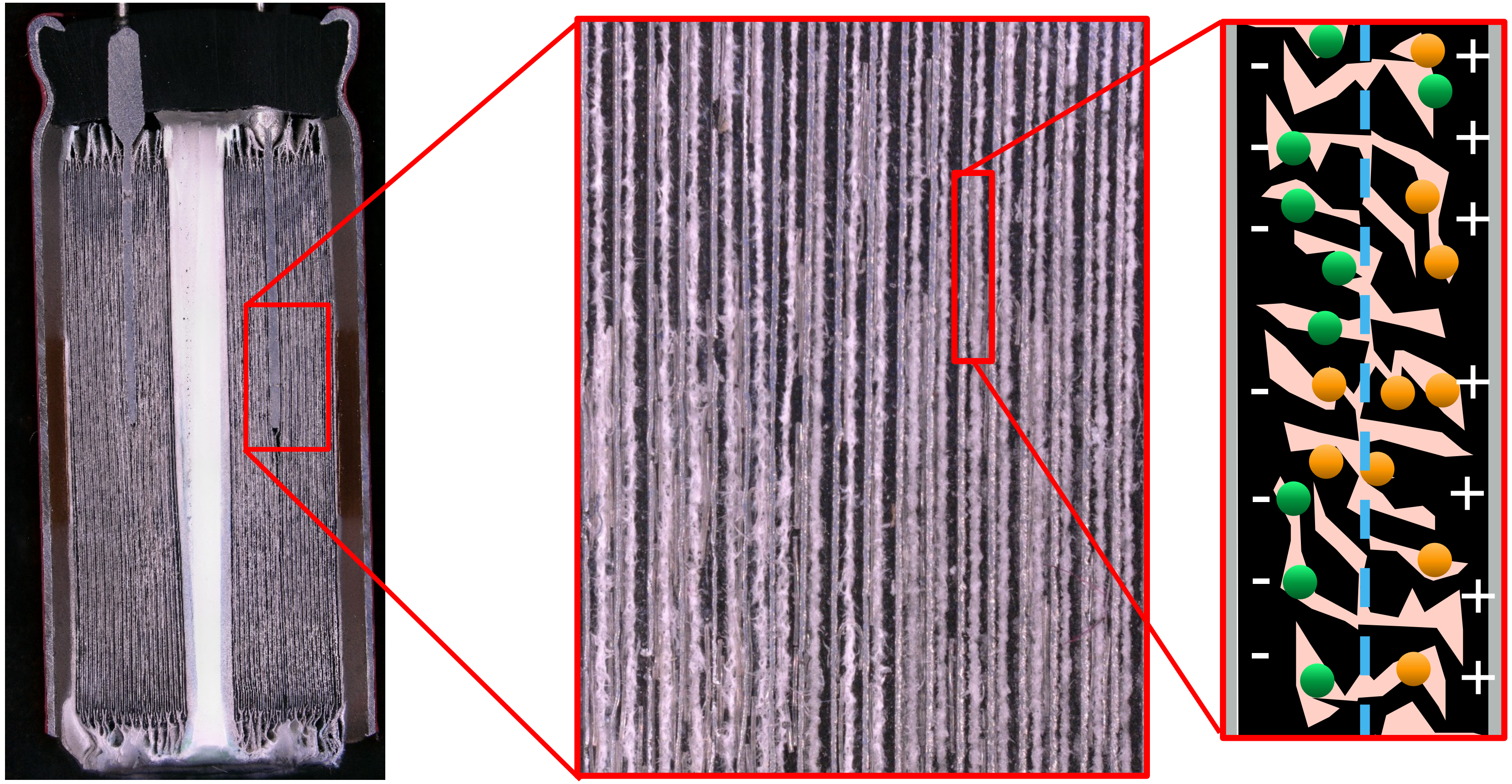
$H_3C-C\equiv N$



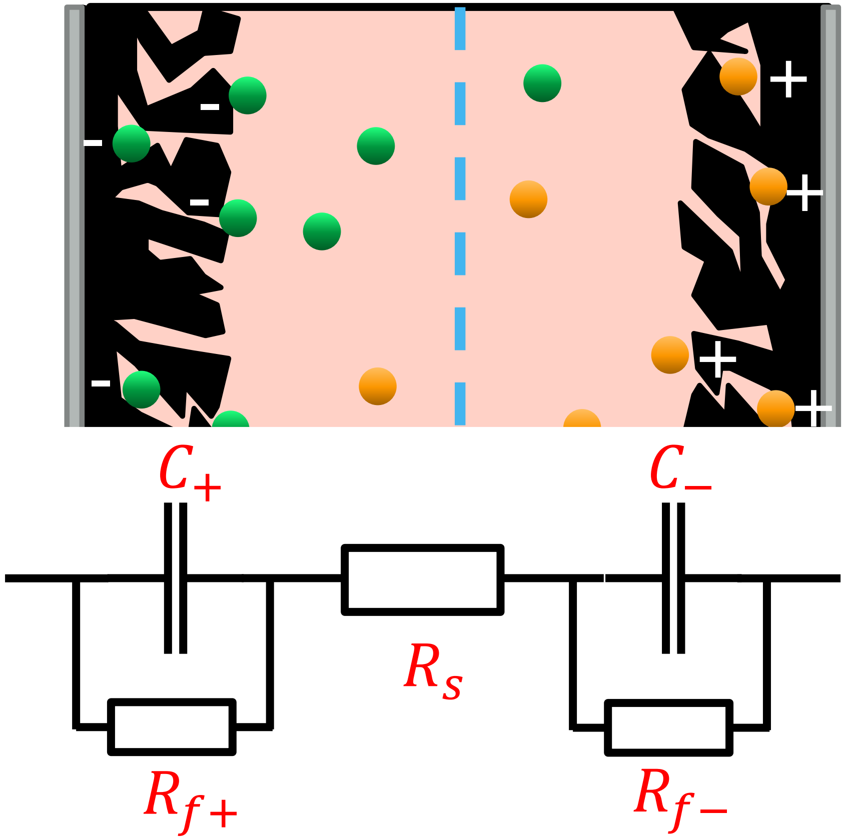


Helmholtz (double) layer:
Ionic charge is balanced by mirror-charge

Structure of EDLCs



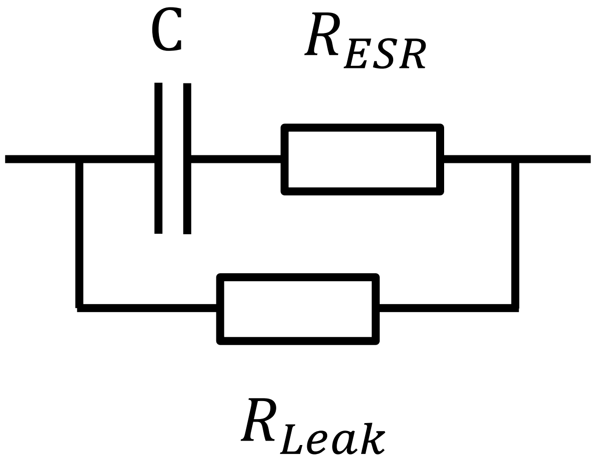
Physical Processes and Parameters



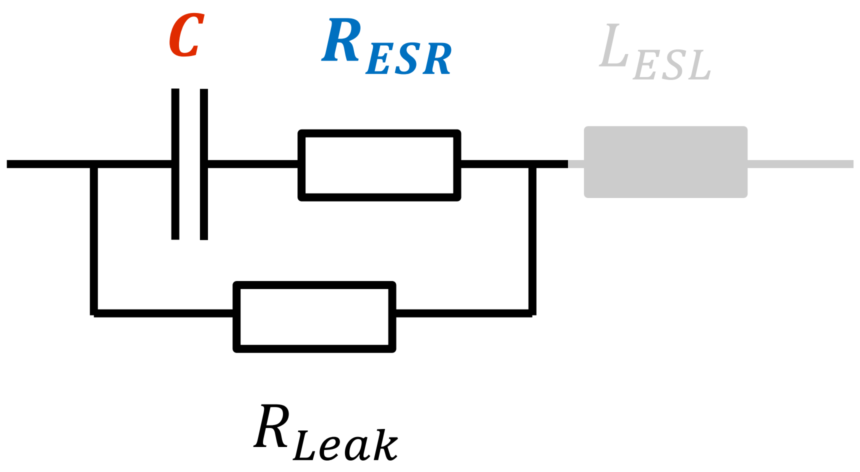
$$\frac{1}{C_+} + \frac{1}{C_-} = \frac{1}{C}$$

$$R_s \sim R_{ESR}$$

$$R_s + R_{f+} + R_{f-} \sim R_{Leak}$$



Parameter and Performance



$$E = \frac{1}{2} \times C \times U_r^2$$

$$P_{max} = \frac{U_r^2}{4\, R_{ESR}}$$

$$\tau = R_{ESR} \times C$$

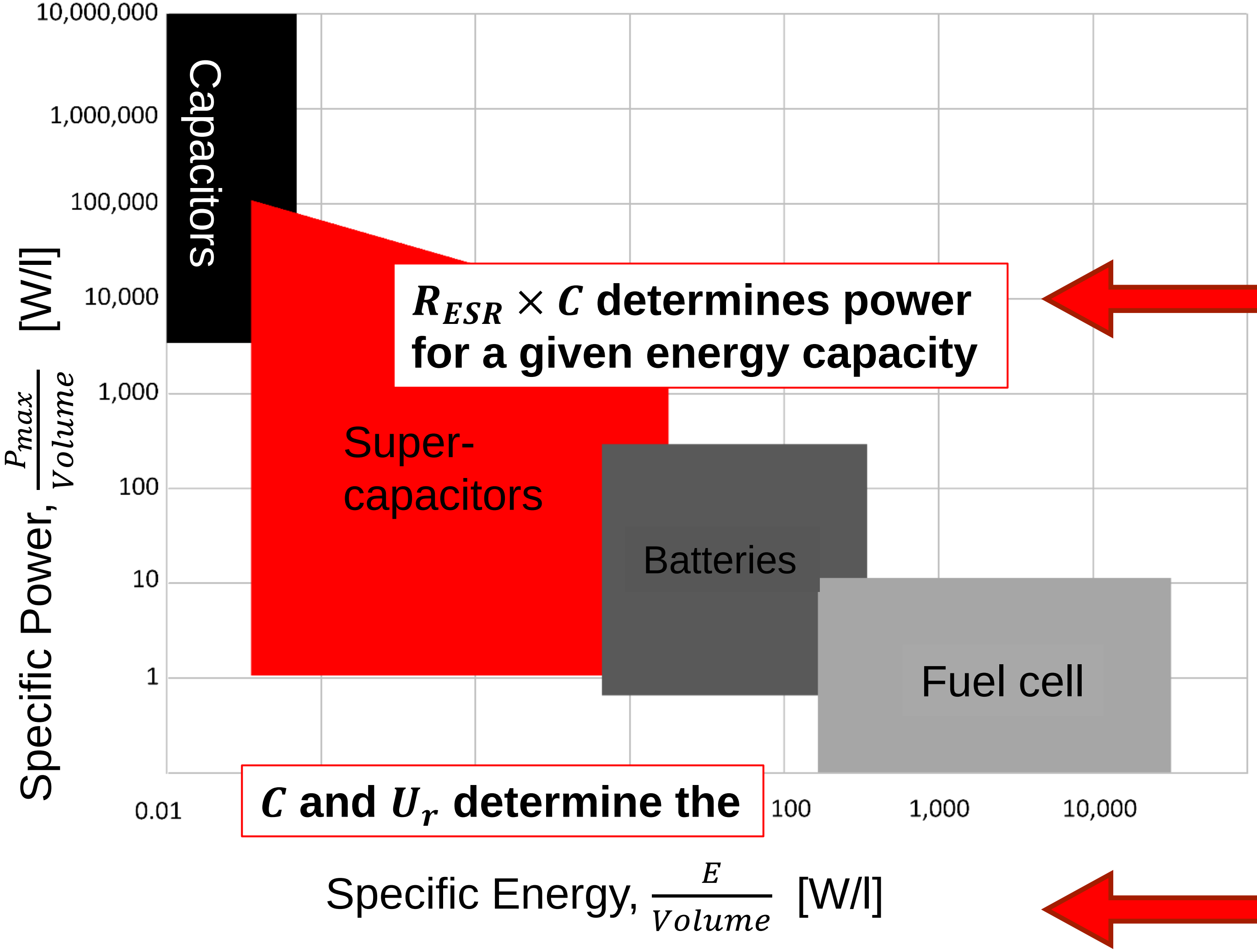
$$P(E) = \frac{2}{R_{ESR} \times C} E$$

- Rated Voltage: U_r
  - Strongly influences power output and energy storage capacity
- Capacitance: C
  - Influence on energy storage capacity
- ESR: R_{ESR}
  - Influence on power output
- Leakage: R_{Leak}
  - Influence on charge storing capabilities ($R_{Leak} \approx 10\ \mathrm{k\Omega} \ldots 1\ \mathrm{M\Omega}$)

$\mathrm{U_r}$ is not determined by the equivalent circuit but by electrochemistry (Decomposition Voltage)

- Non-Aqueous Electrolyte (typ.): $\approx 2\ V \ \ldots\ 3V$
- Aqueous Electrolyte (typ.): $\approx 1.5\ V$

Parameter and Performance



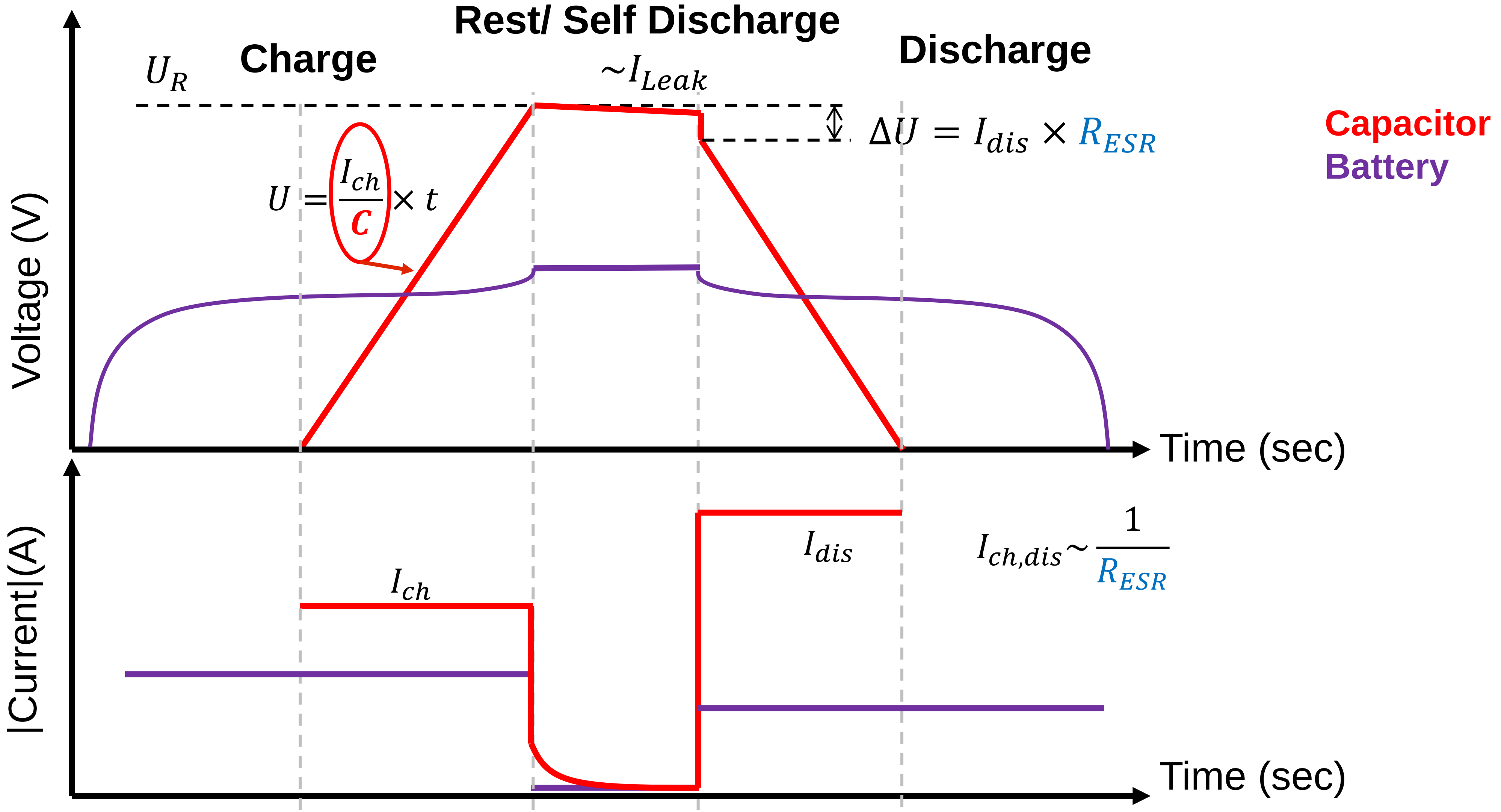
$R_{ESR} \times C$ determines power for a given energy capacity

$$P(E) = \frac{2}{R_{ESR} \times C} E$$

C and U_r determine the

$$E = \frac{1}{2} \times C \times U_r^2 \ ,$$

Charge and Discharge Behavior



Impedance Spectra

- **Electrical model is equal to that for MLCC, ELKOs, …**
- **Inductive reactance (neglectable)**

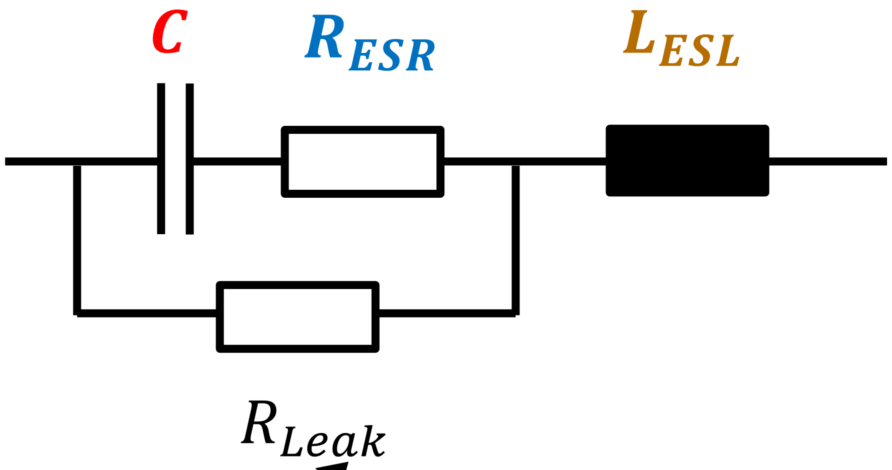
$$X_L = \omega \times L_{ESL}$$

- **Capacitive reactance**

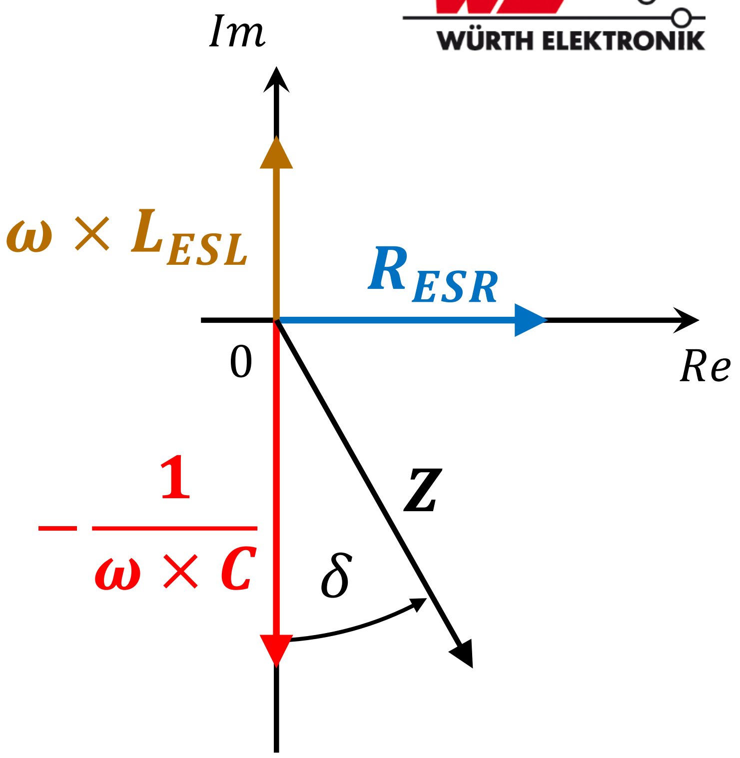
$$X_C = -\frac{1}{\omega \times C}$$

- **Impedance**

$$Z = R_{ESR} + jX_L + jX_C$$



no influence on frequency dependence

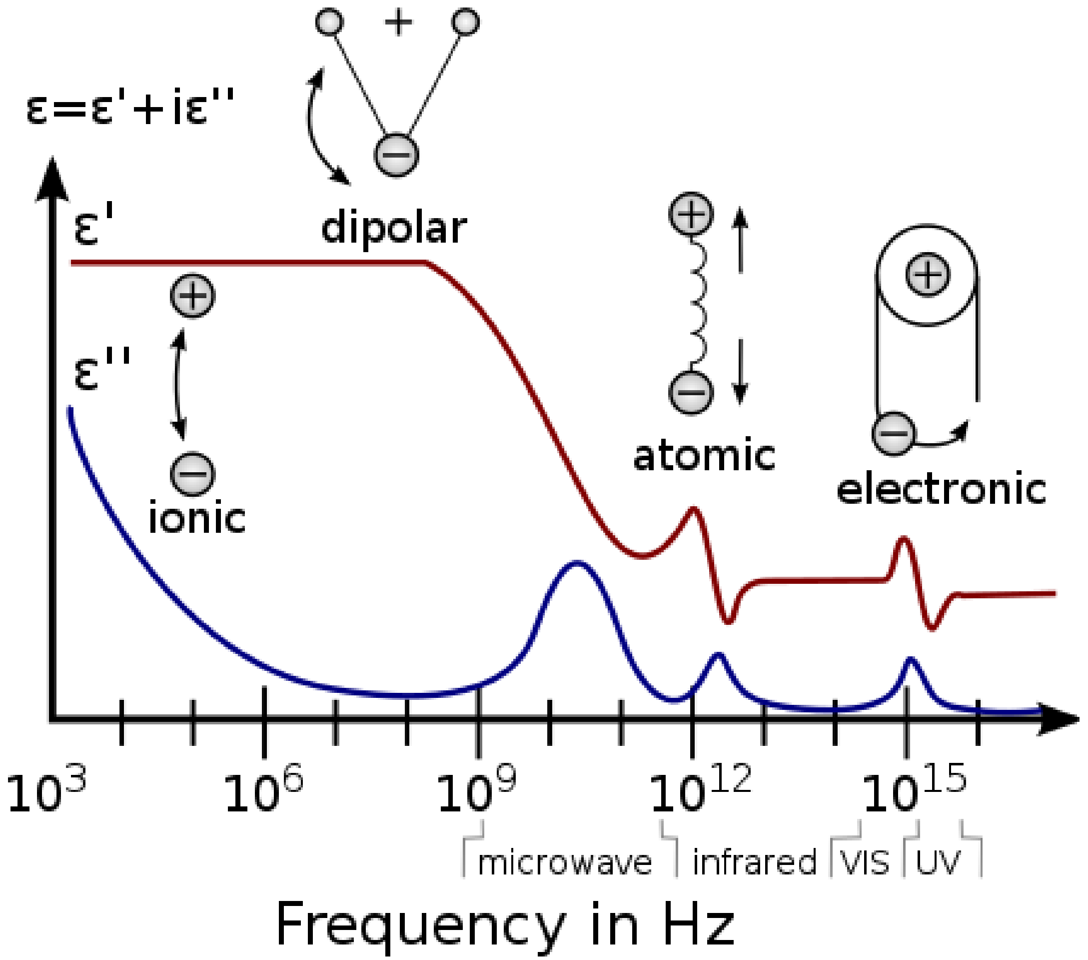


$$DF = \tan(\delta)$$

Impedance Spectra

Dielectric (impedance) spectroscopy:

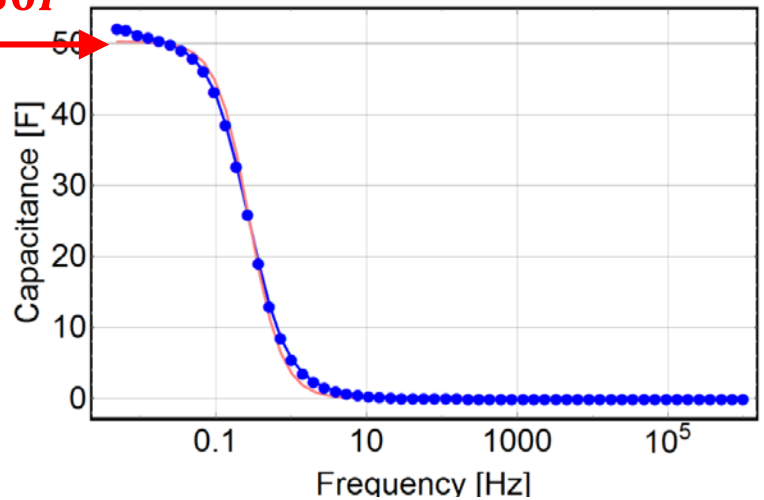
- **“measures” polarizability of a medium as a function of frequency**

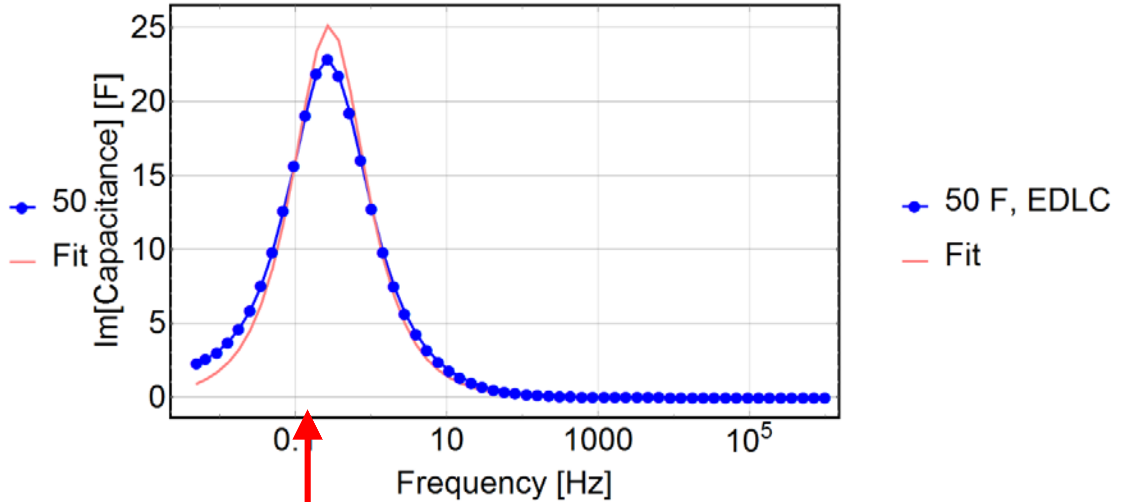


Source: *Wikipedia: “https://en.wikipedia.org/wiki/Dielectric_spectroscopy”*

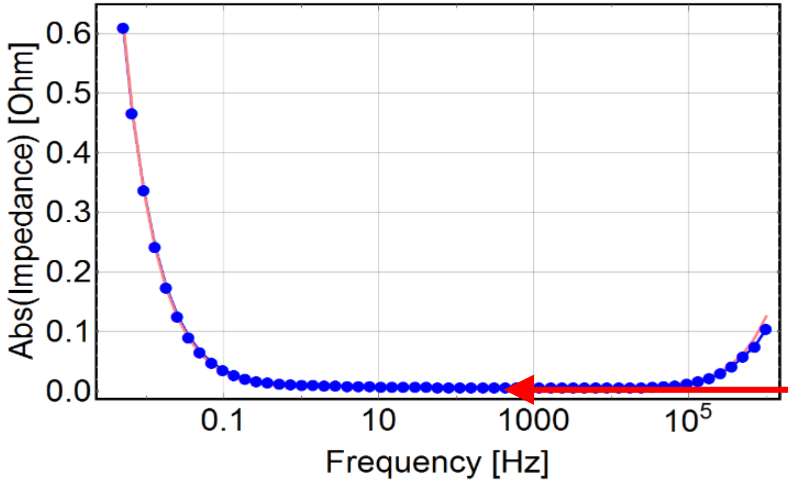
Impedance Spectra

$C \approx 50F$





$$\frac{1}{2\pi\, R_{ESR} C} \approx 0.29Hz$$



$R_{ESR} \approx 0.01\ \Omega$

Fitresults:

$R_{ESR} = 0.011\ \Omega$,

$C = 50.3\ \mathrm{F}$

Physical Limitations of Capacitance

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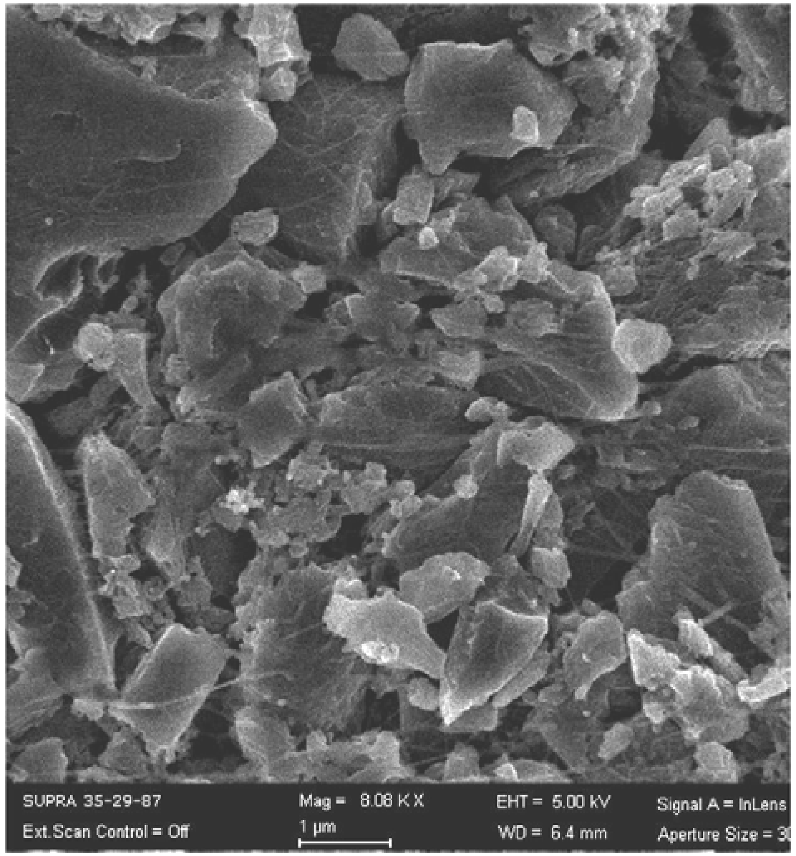


Specific surface area of a. c.:

$$\boldsymbol{A^* = \frac{A}{m} \quad \left[\frac{\mathrm{m}^2}{\mathrm{g}}\right]}$$

Specific capacitance of a. c.:

$$\boldsymbol{C^* = \frac{C}{m} \quad \left[\frac{\mathrm{F}}{\mathrm{g}}\right]}$$

Example of calulation: 50F EDLC contains ≈ 2.2 g a. c.

	m [g]	$A^* \left[\frac{\mathrm{m}^2}{\mathrm{g}}\right]$	A $[\mathrm{m}^2]$	$C^* \left[\frac{\mathrm{F}}{\mathrm{g}}\right]$	C [F]
Comm.		500	**1120**	24	**54**
Micro.	2.2	935	**2095**	142	**318**
Micro.		2312	**5179**	113	**253**

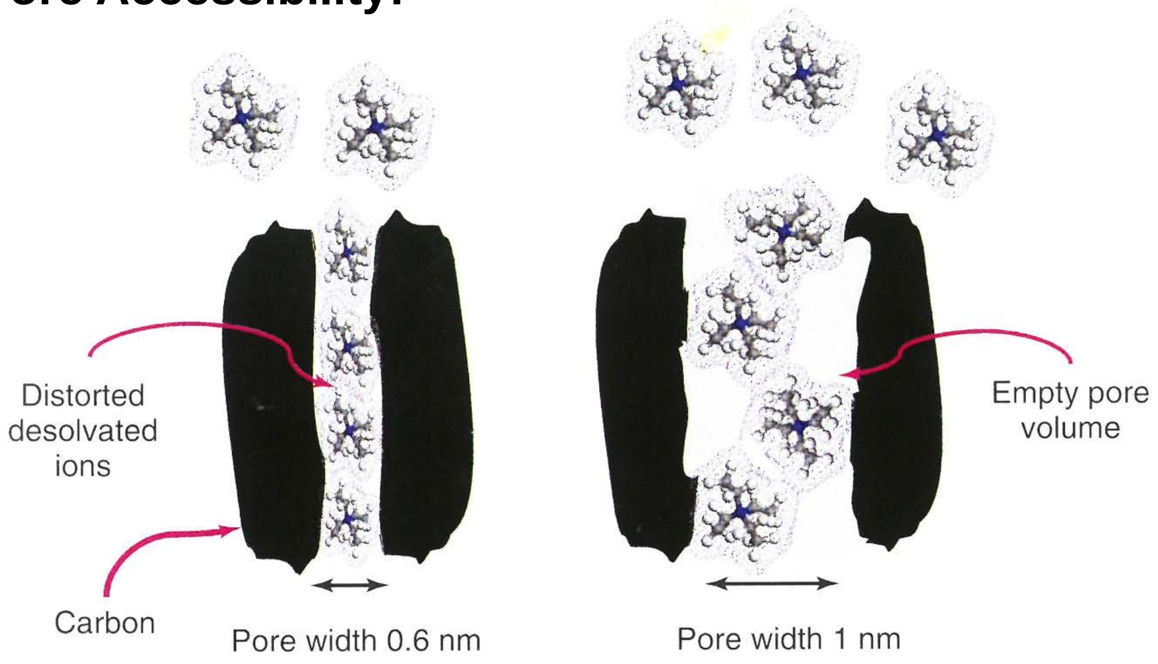
$$\frac{C}{m} \sim \frac{A}{m}$$

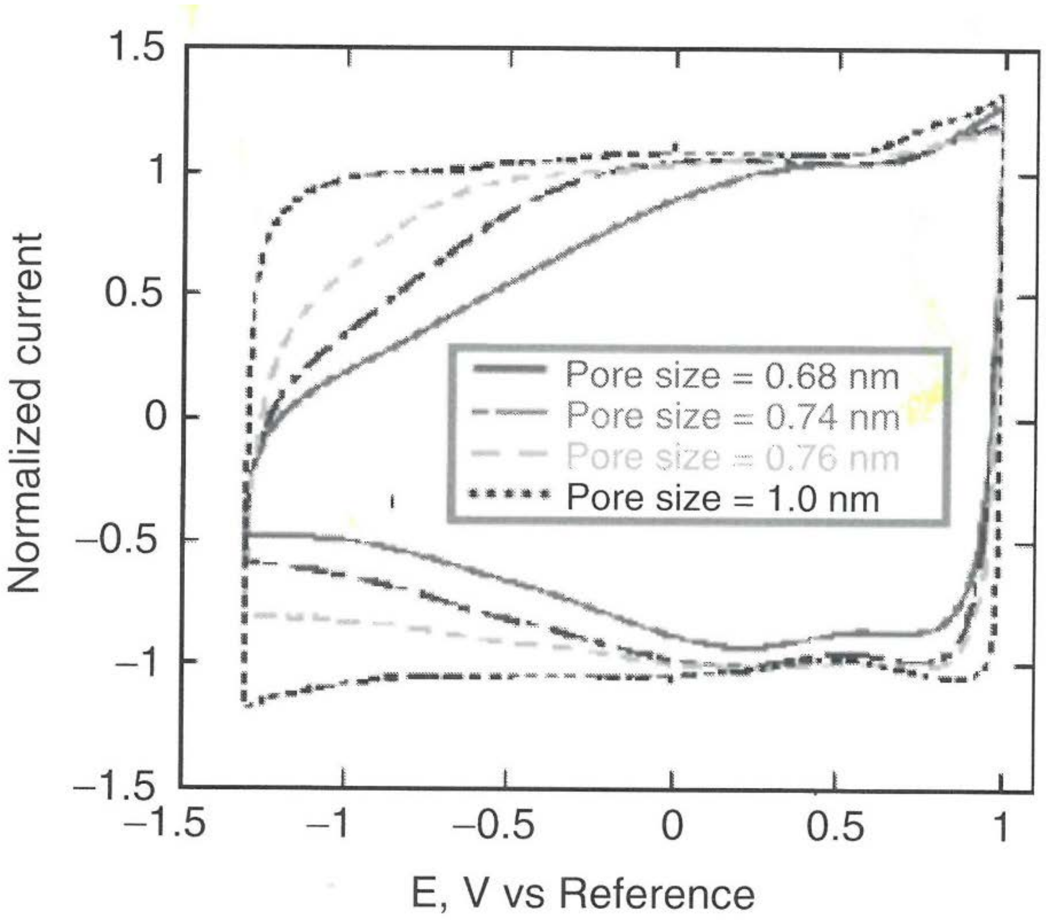
C: capacitance
m: mass of a.c.
A: specific area of a.c.

<u>Source:</u> Activated carbon based electrodes in commercial supercapacitors and their performance, *V. Obreja et al., International Review of Electrical Engineering (2010)*

Physical Limitations of Capacitance

Pore Accessibility:





Source: ***Supercapacitors Materials, Systems and Applications***, *ed. F. Beguin et al., WILEY-VCH (2013)*

Parameters – Device Properties

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$\tau = R_{ESR} \times C$	$\leftrightarrow$	fast charging and discharging (min – sec)
only physical processes involved	$\leftrightarrow$	high life cycle ($\approx$ 500,000 cycles)
low R_{ESR}	$\leftrightarrow$	high power output • $\approx$ 10 times higher than Li-ion battery
charges are only stored at the interface	$\leftrightarrow$	low energy capacity • $\approx$ 30 times lower than Li-ion battery
ELDC are capacitors	$\leftrightarrow$	linear voltage dependence
$U_r <$ Decomposition Voltage	$\leftrightarrow$	low operating voltage

Agenda Application

- **Usage in Low to High Power and eMobility**
- **Why Balancing is Important**
- **Further Applications - You didn’t had in mind?!**

Supercapacitor – What makes the Difference?

- **EDLC's**
  - **don't have an insulating dielectric layer.**
  - **store energy by charge separation.**
  - **have high effective surface area.**
  - **are not for filtering applications but energy storage.**

Supercaps

Advantage:
- **fast charging and discharging (min – sec)**
- **high life cycle (≈ 500,000 cycles)**
- **high power output**
  - **≈ 10 times higher than Li-ion Battery**

Disadvantage:
- **low energy capacity**
  - **≈ 30 times lower than Li-ion Battery**
- **linear voltage dependence**

Batteries

Advantage:
- **High energy capacity**
- **Constant voltage dependence**

Disadvantage:
- **low power output**
- **low life expectancy (≈ 1000 cycles)**
- **long charging time (hours)**

Supercapacitor – What makes the Difference?

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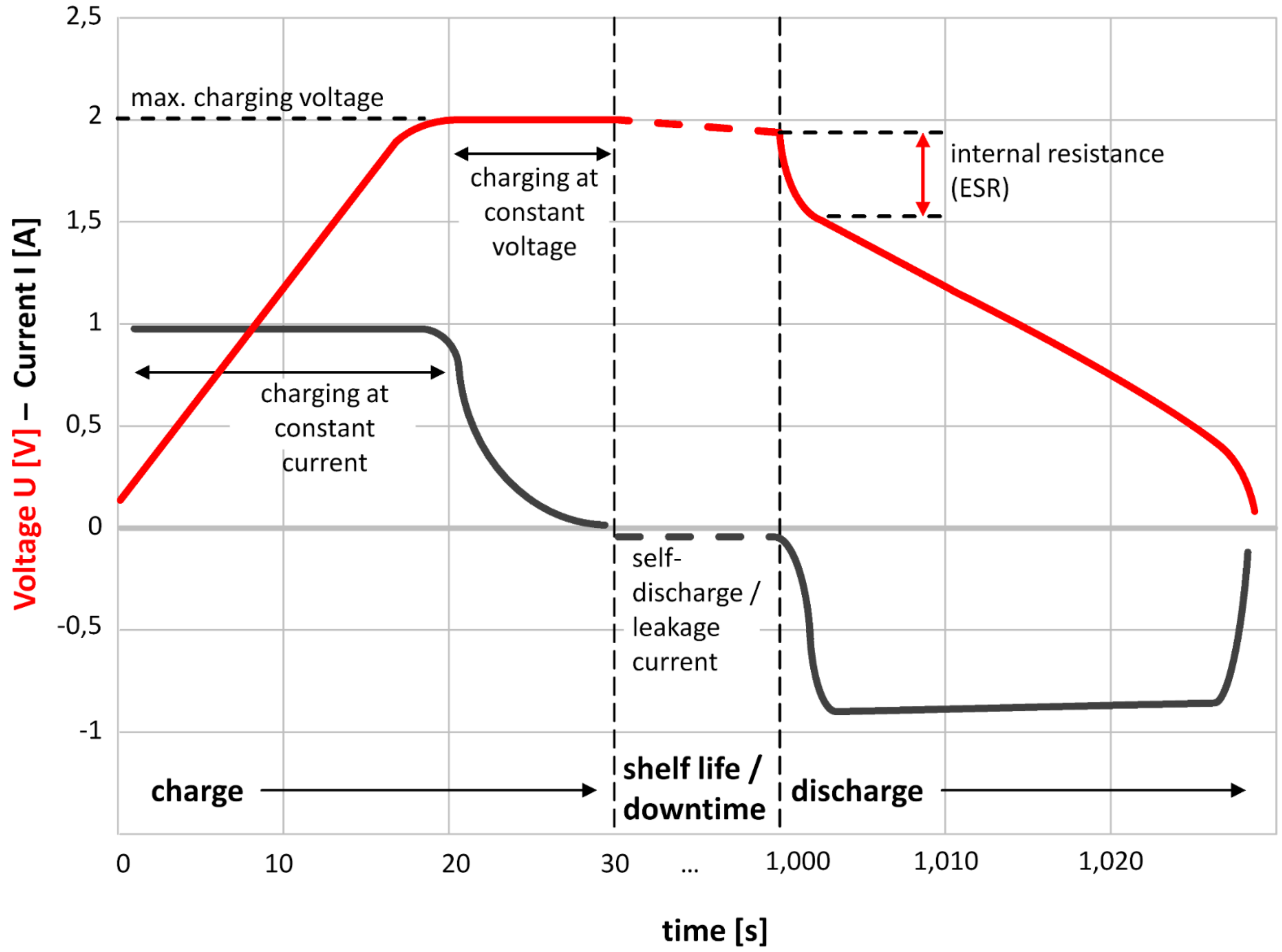

Supercapacitor – Typical Applications

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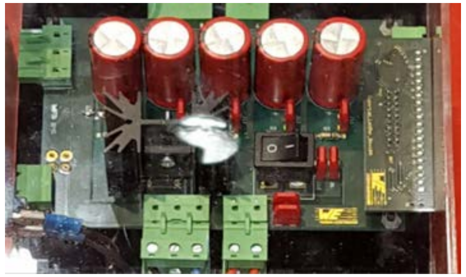
- Backup battery for RAM memory
- Replacement for rechargeable battery during short-ter
- Smart meter
- UPS
- Kinetic Energy Recovery System (KERS)
- Defibrillators
- RFID locking systems



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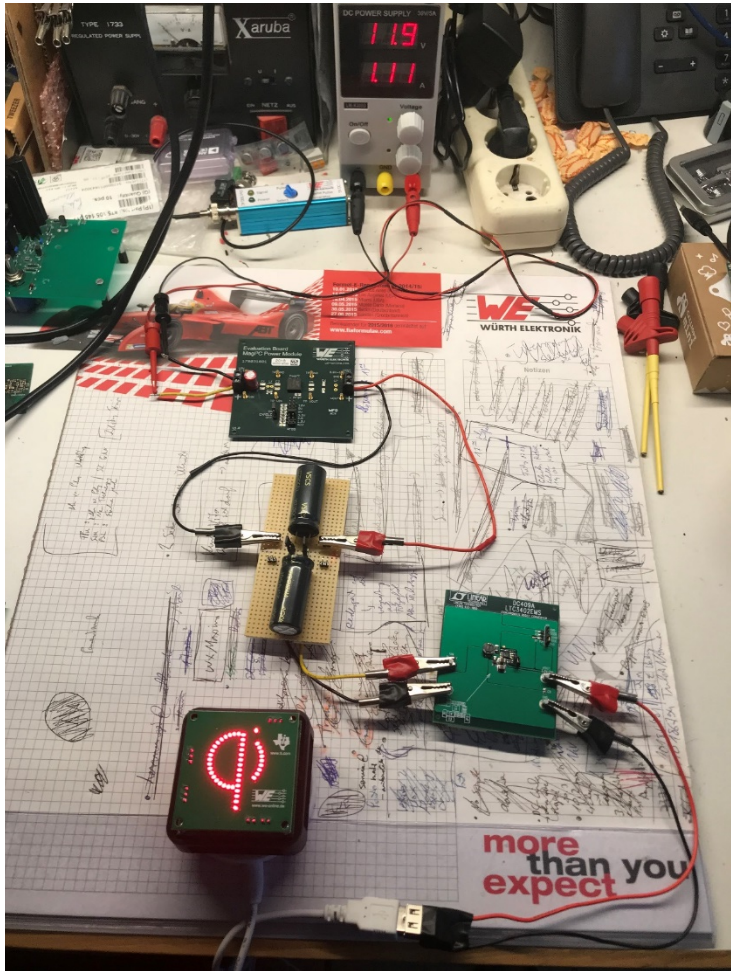
Usage in Low to High Power and eMobility

Supercapacitor in low power application

- **Input voltage: 12 V**
- **Input current: 3 A**
  - Constant current source
  - End-of-charge voltage: 2.7V

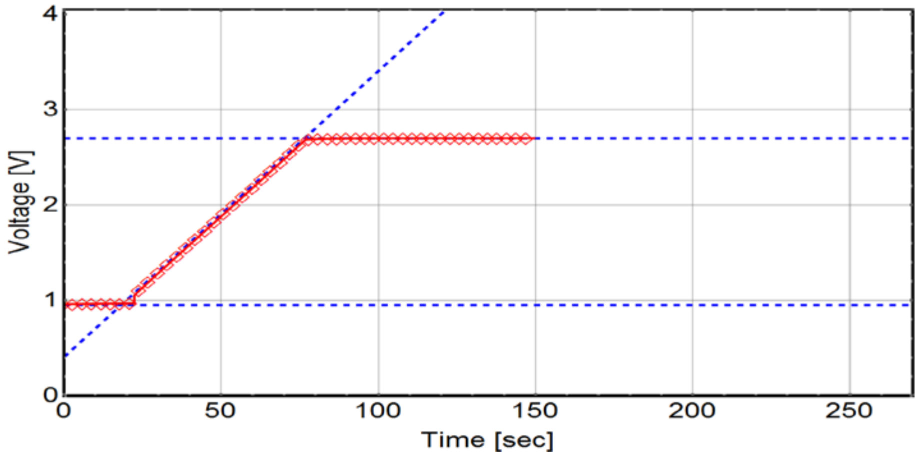
- **Two 50F / 2.7V Supercapacitor in parallel connection**
- **Output voltage: 5V@1A => due to a Boost Converter**

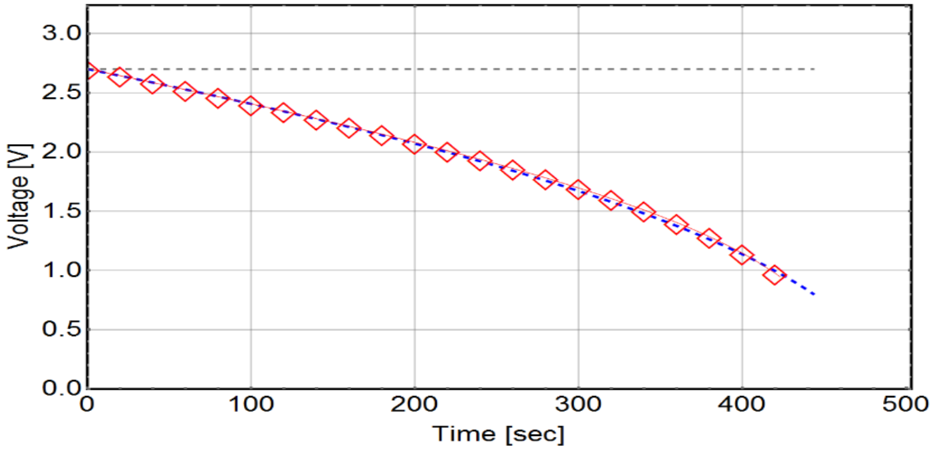
- **Stored energy: 135J**
- **Charging time: 60sec**
- **Discharging time @ constant power: 400sec**
  - Cut off voltage: 1V

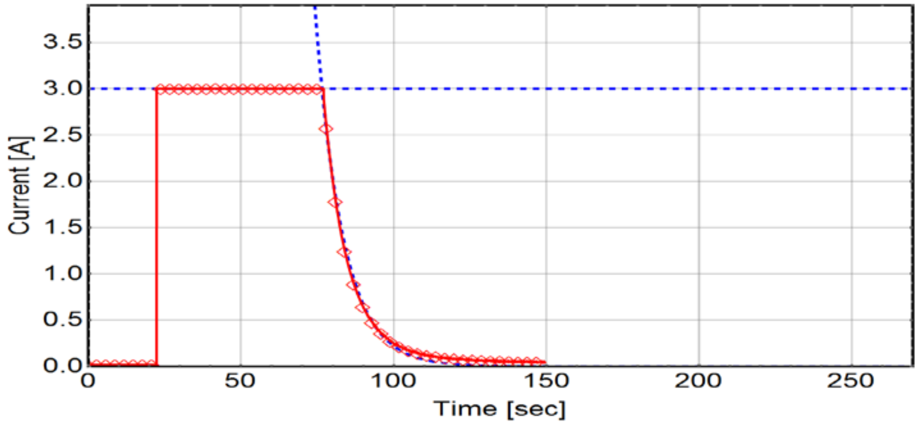


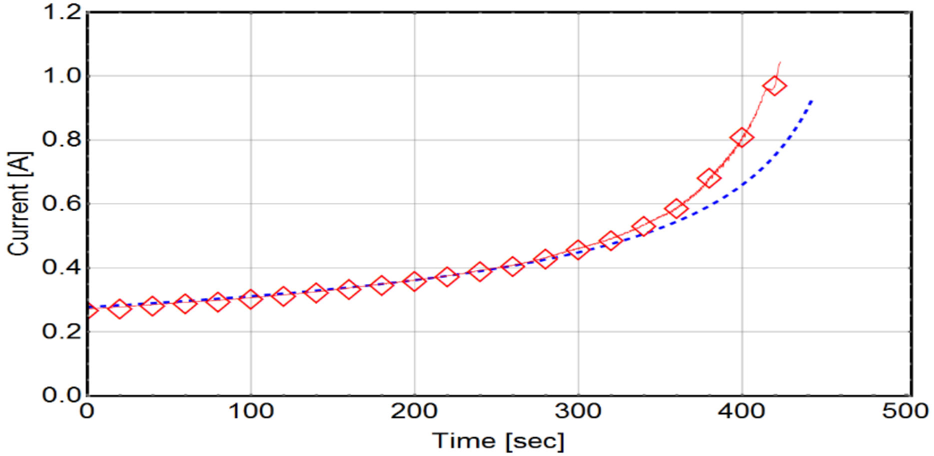
Usage in Low to High Power and eMobility

Supercapacitor in low power application









Usage in Low to High Power and eMobility

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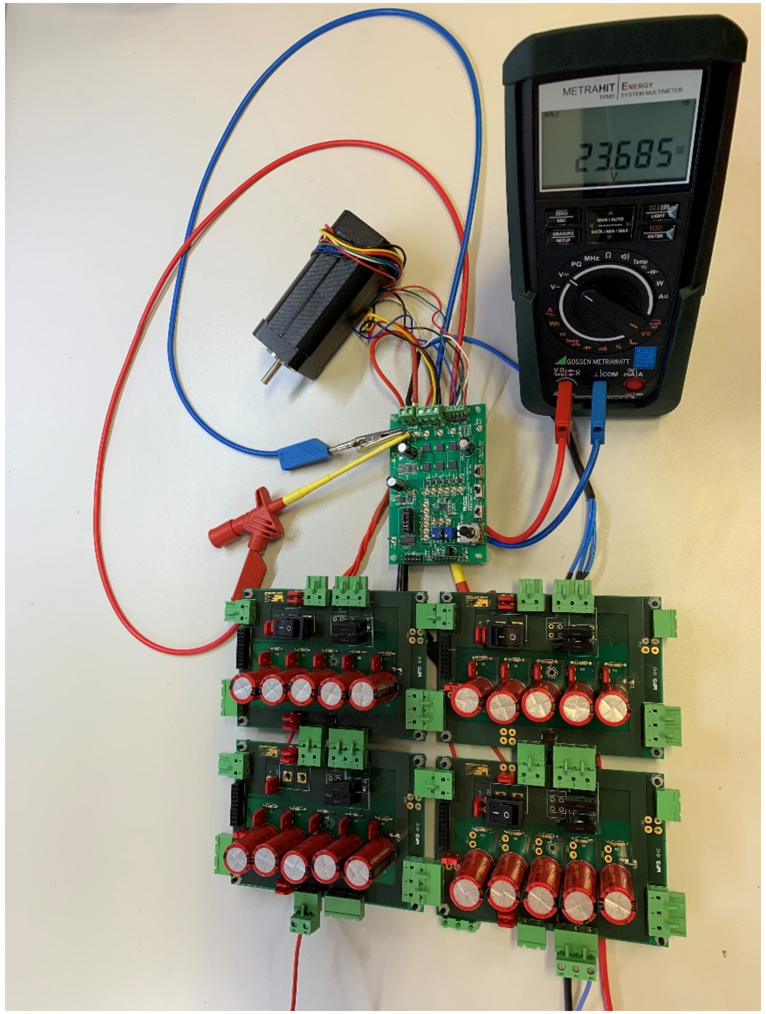
Supercapacitor in mid power application

- **Input voltage: 24 V**
- **Input current: 10 A**
- **In total 20 Supercapacitor 50 F / 2.7 V**
  - 10 in parallel / 10 in series
  - Passive balancing
- **Motor control provides 24 V @ 6 A => 150 W**

- **Stored Energy: 2880 J**
- **Charging time: 25 sec.**
- **Discharging time @ constant power: 18 sec.**
  - Motor delivers 150 W
  - Cut off voltage: 5 V



Usage in Low to High Power and eMobility

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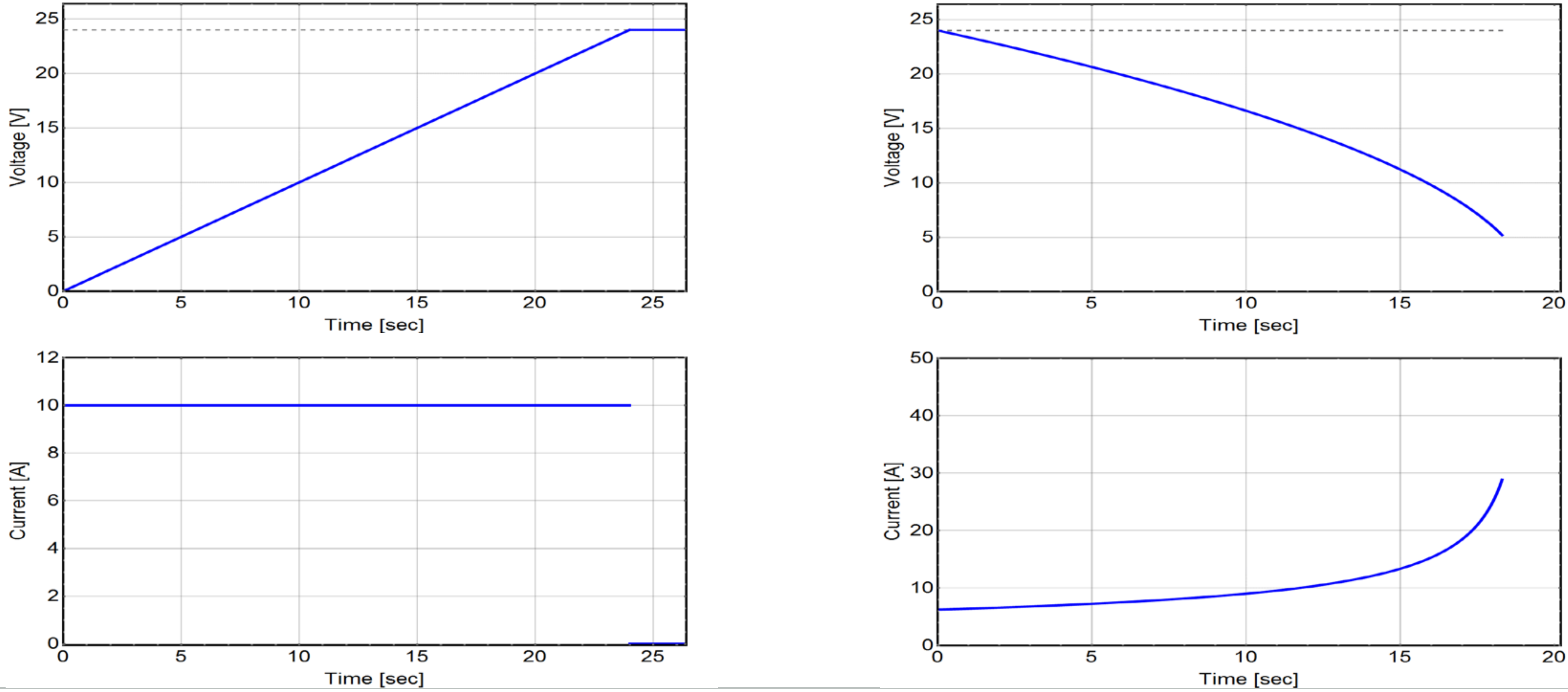
Supercapacitor in mid power application



Usage in Low to High Power and eMobility

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Supercapacitor in high power application (UPS, Windmill)

- **UPS @ 1 kW**
- **Input voltage: 230 Vac**
- **Charge current: 10 A**
- **Output: 24 Vdc @ 40 A**
- **Supply time @ 1 kW for 60 sec.**
- **Needed capacitance: 9 x 3000 F**
  - **Parallel / series combination**
  - **Active / passive balancing**

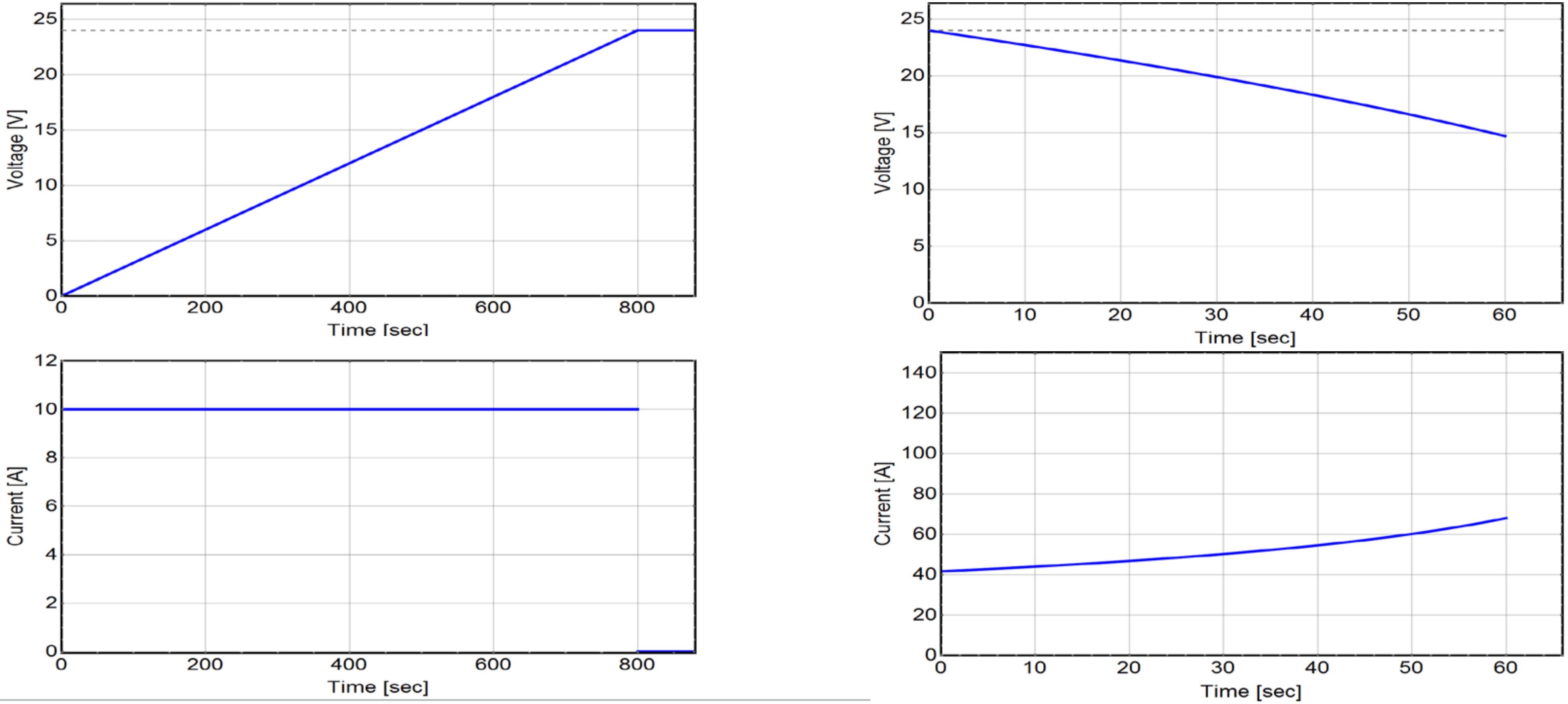
- **Stored Energy = 27 Wh**
- **Charging time @ 10 A: 800 sec.**
- **Discharging time @ 1 kW: 60 sec.**
  - **Cut of voltage: 12 V**

- **Windmill provides 690 V @ 150 kW**
- **Change pitch electronic**
  - **2 degree per sec**
- **Assuming 1 kVA for 10 min**
- **Motor 230 Vac @ 1 kVA**
  - **Motor current ~4 A**

- **Energy needed = 22 Wh**
- **Needed capacitance: 9 x 2500 F**

Usage in Low to High Power and eMobility

Supercapacitor in high power application



Usage in Low to High Power and eMobility

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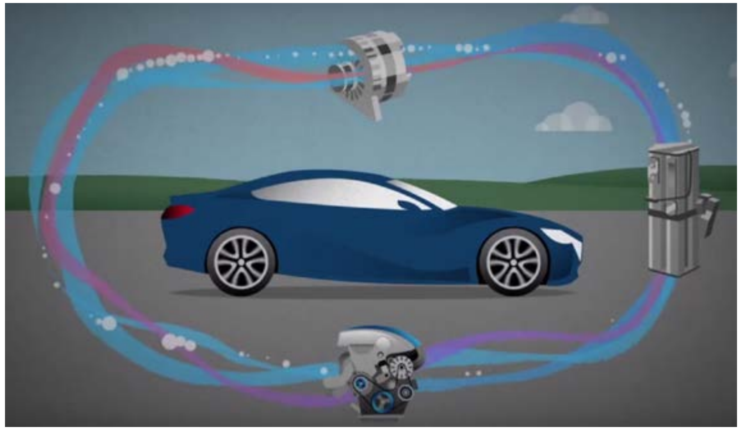
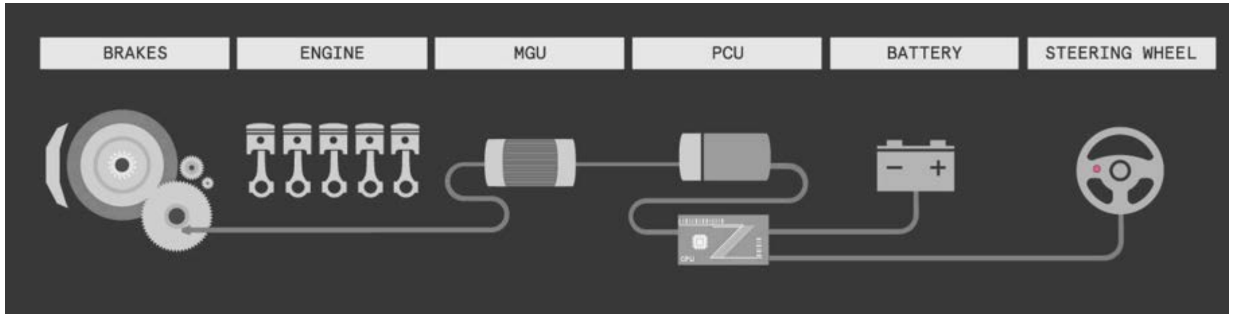
- **Mazda I-ELOOP (Intelligent Energy Loop)**
  - Recuperation during braking
  - Energy stored in a Supercapacitor (EDLC)
  - Generator -> Supercapacitor -> DC/DC converter
  - 7 seconds to full charge when stop acceleration from 60km/h



I-ELOOP Mazda Video Screenshot => https://www.youtube.com/watch?v=BJHAr4wA2fc

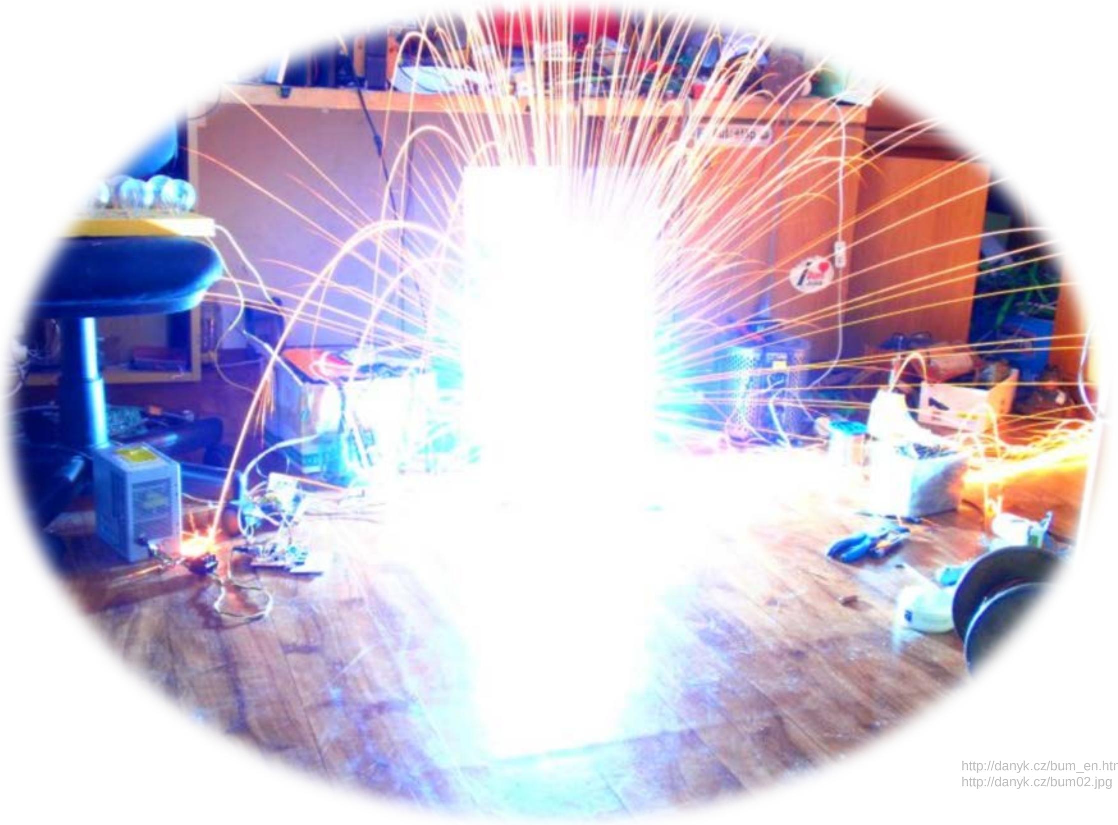
- **KERS (Kinetic Energy Recovery System)**
  - Recuperation during braking
  - Releasing power on command
  - Flywheel or high voltage battery



Usage in Low to High Power and eMobility

- **Transportation and logistics → Recuperation during braking**

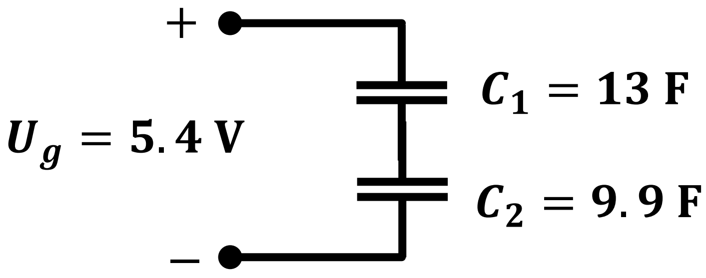
Why Balancing is Important?



http://danyk.cz/bum_en.html
http://danyk.cz/bum02.jpg

Balancing

- **Two in series connected capacitors:**
  - U_r = 2.7 V
  - C_{total} = 10 F (tol.: -10%, +30%)
  - Charged at 5.4 V



- **Worst case:** $C_2 = 9.9\ (-10\%)F, C_1 = 13\ F\ (+30\%)$
- **Following equation are need for the calculations:**
  - $U_g = U_1 + U_2$
  - $U_2 = \frac{q}{C_2}$ and $U_1 = \frac{q}{C_1}$

$$\rightarrow U_1 = \frac{5.4\ \mathrm{V}}{(0.762+1)} = 3.07\ V \text{ (Caution, Overvoltage!)}$$

$$\rightarrow U_2 = \frac{5.4\ \mathrm{V}}{\left(\frac{1}{0.762}+1\right)} = 2.34\ V$$

Balancing

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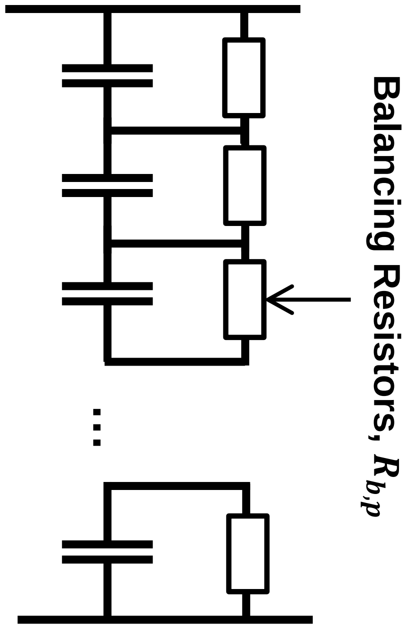
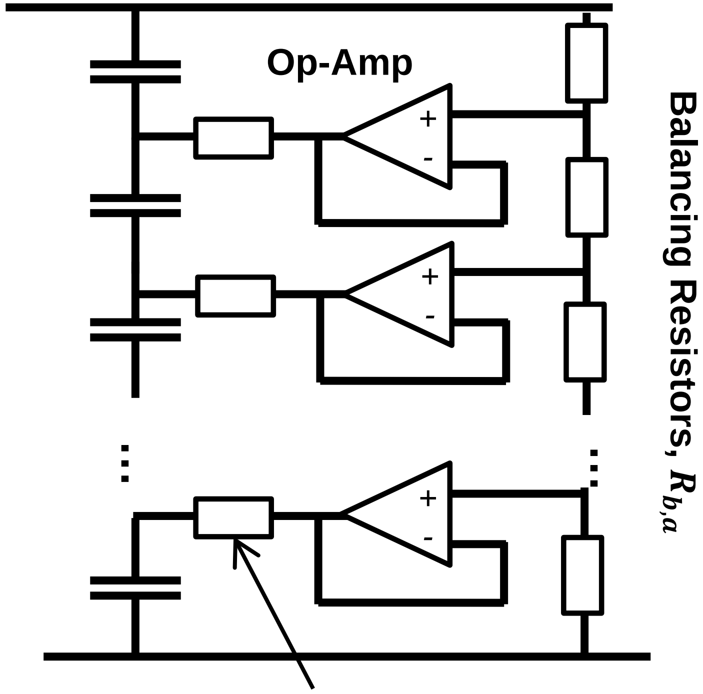
▪ Passive Balancing:

- If operated primarily under DC conditions
- Low cost
- Slow balancing
- High losses
- Balance Resistor: $R_{b,p} \approx \frac{1}{10} \times \frac{U_r}{I_{Leak}}$
- Typically $R_{b,a} \approx 1k\Omega \ldots 100k\Omega$



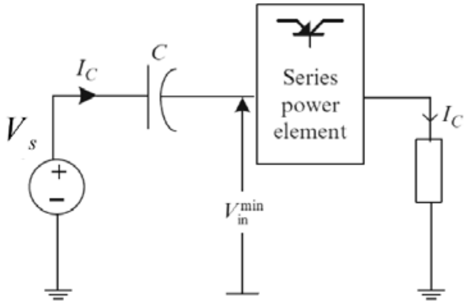
▪ Active Balancing:

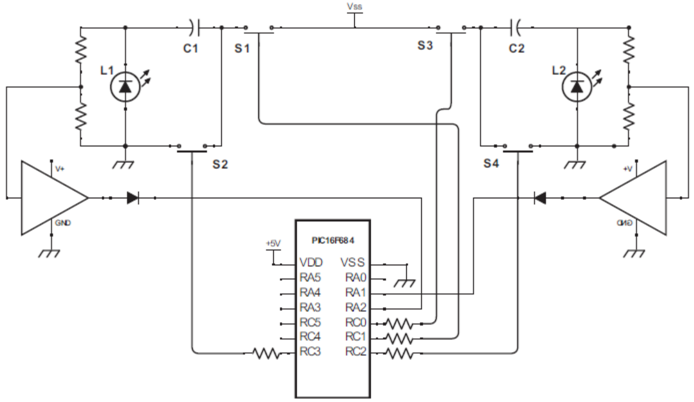
- Often charged and discharged
- High cost
- Fast balancing
- Low losses
- Balance Resistor: $R_{b,a} > R_{b,p}$
- Typically $R_{b,a} \approx 1M\Omega \ldots 10M\Omega$



Further Applications – You didn’t had in mind?!

- **SCA Application (Super Capacitor Assisted)**
  - SCALDO
  - SCALED
  - Surge Absorber Technique
  - Water heating





by Nihal Kularatna
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- **Construction machinery and port terminals**
  - Recover energy when lowering loads in gantry cranes or excavators

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