

Block 13 - Capacitor Circuits and Energy

Student Group

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Learning objectives

After this 90-minute block, you can

- Recognize a series connection of capacitors and distinguish it from a parallel connection,
- Calculate the resulting total capacitance of a series or parallel circuit,
- Know how the total charge is distributed among the individual capacitors in a parallel circuit,
- Determine the voltage across a single capacitor in a series circuit.

Preparation at Home

Well, again

- read through the present chapter and write down anything you did not understand.
- Also here, there are some clips for more clarification under 'Embedded resources' (check the text above/below, sometimes only part of the clip is interesting).

For checking your understanding please do the following exercises:

- ...

90-minute plan

1. Warm-up (x min):
 1.
2. Core concepts & derivations (x min):
 1. ...
3. Practice (x min): ...
4. Wrap-up (x min): Summary box; common pitfalls checklist.

Conceptual overview

1. ...

Core content

Series Circuit of Capacitor

If capacitors are connected in series, the charging current I into the individual capacitors $C_1 \dots C_n$ is equal. Thus, the charges absorbed ΔQ are also equal:
$$\Delta Q = \Delta Q$$

$$Q_1 = \Delta Q_2 = \dots = \Delta Q_n$$

Furthermore, after charging, a voltage is formed across the series circuit, which corresponds to the source voltage U_q . This results from the addition of partial voltages across the individual capacitors.

$$U_q = U_1 + U_2 + \dots + U_n = \sum_{k=1}^n U_k$$

It holds for the voltage $U_k = \frac{Q_k}{C_k}$.

If all capacitors are initially discharged, then $U_k = \frac{\Delta Q}{C_k}$ holds. Thus

$$U_q = U_1 + U_2 + \dots + U_n = \sum_{k=1}^n U_k \quad U_q = \frac{\Delta Q}{C_1} + \frac{\Delta Q}{C_2} + \dots + \frac{\Delta Q}{C_3} = \sum_{k=1}^n \frac{1}{C_k} \Delta Q \quad \frac{1}{C_{\text{eq}}} \Delta Q = \sum_{k=1}^n \frac{1}{C_k} \Delta Q$$

Thus, for the series connection of capacitors $C_1 \dots C_n$:

$$\frac{1}{C_{\text{eq}}} = \sum_{k=1}^n \frac{1}{C_k} \quad \Delta Q_k = \text{const.}$$

For initially uncharged capacitors, (voltage divider for capacitors) holds:

$$Q = Q_k \quad U_{\text{eq}} \cdot C_{\text{eq}} = U_k \cdot C_k$$

In the simulation below, besides the parallel connected capacitors C_1 , C_2 , C_3 , an ideal voltage source U_q , a resistor R , a switch S , and a lamp are installed.

- The switch S allows the voltage source to charge the capacitors.
- The resistor R is necessary because the simulation cannot represent instantaneous charging. The resistor limits the charging current to a maximum value.
- The capacitors can be discharged again via the lamp.

Parallel Circuit of Capacitors

If capacitors are connected in parallel, the voltage U across the individual capacitors $C_1 \dots C_n$ is equal. It is therefore valid:

$$U_q = U_1 = U_2 = \dots = U_n$$

Furthermore, during charging, the total charge ΔQ from the source is distributed to the individual capacitors. This gives the following for the individual charges absorbed:

$$\Delta Q = \Delta Q_1 + \Delta Q_2 + \dots + \Delta Q_n = \sum_{k=1}^n \Delta Q_k$$

If all capacitors are initially discharged, then $Q_k = \Delta Q_k = C_k \cdot U$

Thus

$$\Delta Q = Q_1 + Q_2 + \dots + Q_n = \sum_{k=1}^n Q_k \quad \Delta Q = C_1 \cdot U + C_2 \cdot U + \dots + C_n \cdot U = \sum_{k=1}^n C_k \cdot U \quad C_{\text{eq}} \cdot U = \sum_{k=1}^n C_k \cdot U$$

Thus, for the parallel connection of capacitors $C_1 \dots C_n$:

$$C_{\text{eq}} = \sum_{k=1}^n C_k \quad U_k$$

$$= \{\mathrm{const.}\} \end{align*}$$

For initially uncharged capacitors, (charge divider for capacitors) holds:
$$\Delta Q = \sum_{k=1}^n Q_k$$

$$\boxed{\left\{ \frac{Q_k}{C_k} = \frac{\Delta Q}{C_{\mathrm{eq}}} \right\}}$$

In the simulation below, again, besides the parallel connected capacitors C_1 , C_2 , C_3 , an ideal voltage source U_q , a resistor R , a switch S , and a lamp are installed.

Energy in the electric Field

Now we want to see how much energy is stored in a capacitor during charging. When we want to charge a capacitor charges have to be separated (see [figure 1](#)). This gets more and more difficult as more charges are moved, since these already moved charges create an electric field.

Fig. 1: summary of electrostatics

We already had a first look onto the energy in the electric field in [block09](#).

There, we got:

$$\begin{aligned} \Delta W &= \int \vec{F} \cdot d\vec{r} \quad \&= q \int \vec{E} \cdot d\vec{r} \quad \&= q \cdot U \quad dW \\ &= dq \cdot U \end{aligned}$$

Now, For a capacitor we include the formula for the capacitor $C = \frac{q}{U}$, or better its rearranged version $U = \frac{q}{C}$:

$$\begin{aligned} dW &= dq \cdot \frac{q}{C} \quad \int dW = \int \frac{q}{C} dq \end{aligned}$$

Here we again see, that the needed energy portion dW to move a portion dq is also related to the already moved charges q .

To get the energy ΔW needed to move all of the charges $Q = \int dq$ we have to integrate from 0 to Q :

$$\begin{aligned} \Delta W &= \int_0^Q dW \quad \&= \int_0^Q \frac{q}{C} dq \quad \&= \\ \frac{1}{2} \frac{Q^2}{C} \quad \end{aligned} \quad \boxed{\Delta W = \frac{1}{2} \frac{Q^2}{C} = \frac{1}{2} Q U = \frac{1}{2} C Q^2}$$

Common pitfalls

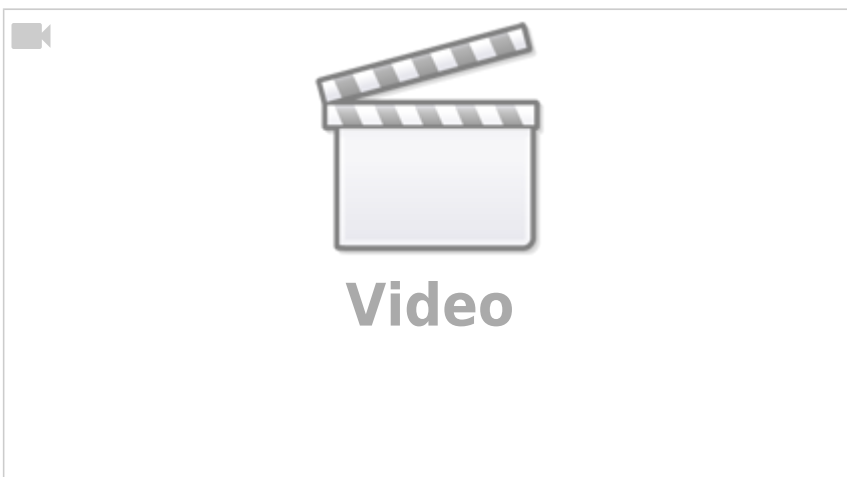
- ...

Exercises

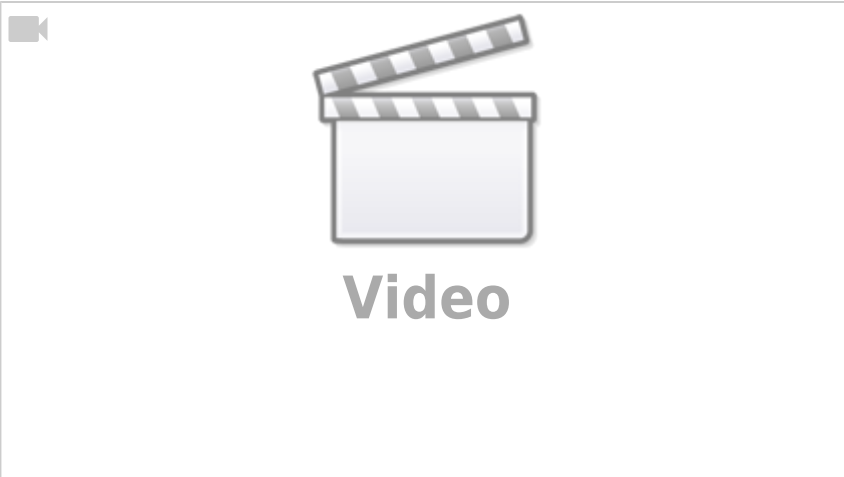
Task 5.8.1 Calculating a circuit of different capacitors

See <https://www.youtube.com/watch?v=vSeSHAmPd4Y>

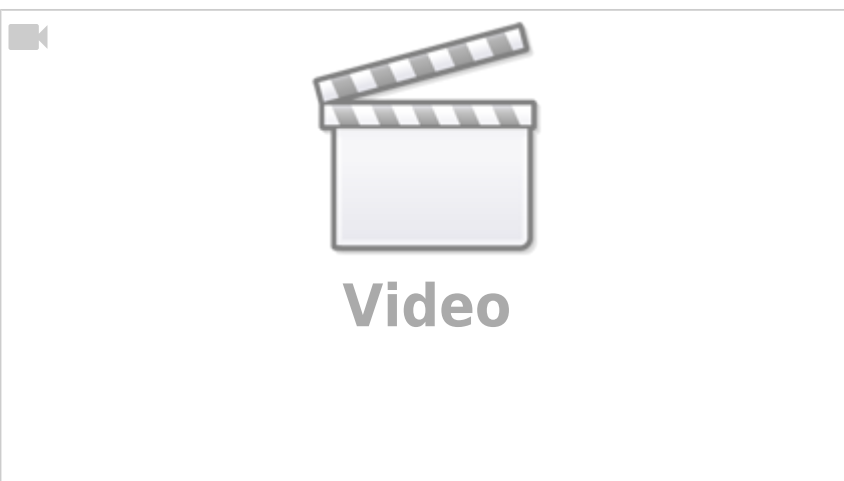
Task 5.9.1 Layered Capacitor Task



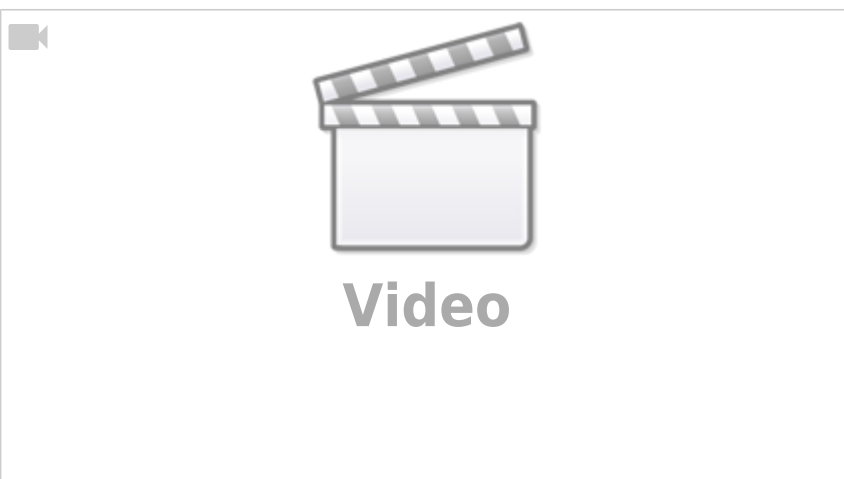
Exercise 5.9.2 Further capacitor charging/discharging practice Exercise



Exercise 5.9.3 Further practice charging the capacitor

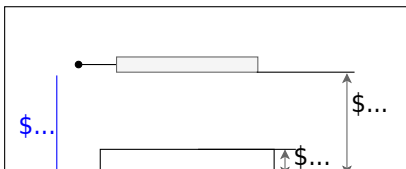


Exercise 5.9.4 Charge balance of two capacitors



Exercise 5.9.5 Capacitor with glass plate

Fig. 2: Structure of a capacitor with glass plate



Two parallel capacitor plates face each other with a distance $d_K = 10 \text{ mm}$. A voltage of $U = 3000 \text{ V}$ is applied to the capacitor. Parallel to the capacitor plates, there is a glass plate ($\epsilon_r = 8$) with a thickness $d_G = 3 \text{ mm}$ in the capacitor.

1. Calculate the partial voltages U_G in the glass and U_A in the air gap.
2. What is the maximum thickness of the glass pane if the electric field $E_{0,G} = 12 \text{ kV/cm}$ must not exceed?

Embedded resources

The equivalent capacitor for series of parallel configuration is well explained here



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