

Exam Summer Semester 2021

Student Group

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Exam Summer Semester 2021

Additional permitted Aids

- non-programmable calculator,
- formulary (4 one-sided DIN A4 pages)

Hits

- The duration of the exam is 120 min.
- Attempts to cheat will lead to exclusion and failure of the exam.
- Withdrawal is no longer possible after these exam has been handed out.
- Please write down intermediate calculations and results on the assignment sheet. (when more space is needed also on the reverse side. In this case: Mark it clearly).
- Always use units in the calculation.
- Use a document-proof, non-red pen.

- Sub-tasks, which are independently solvable are marked with: (independent)
- Sub-tasks, which are hard are marked with: (hard)

Tasks

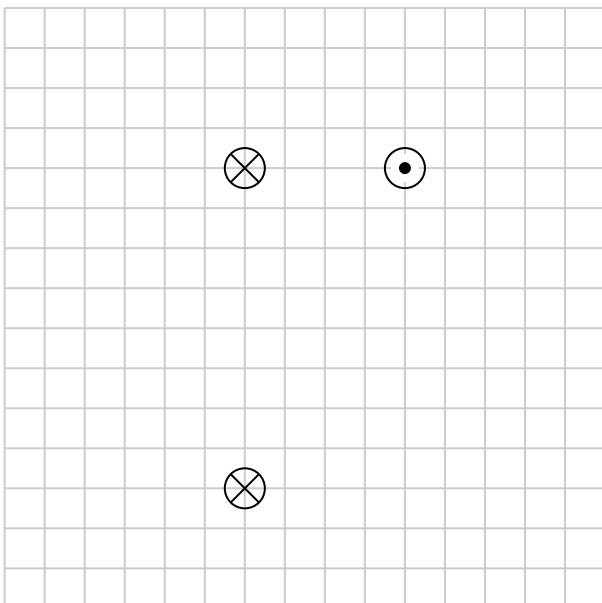
Exercise E1 Magnetic Field Lines

(written test, approx. 4 % of a 120-minute written test, SS2021)

Several parallel conductors are projecting out of the plane.

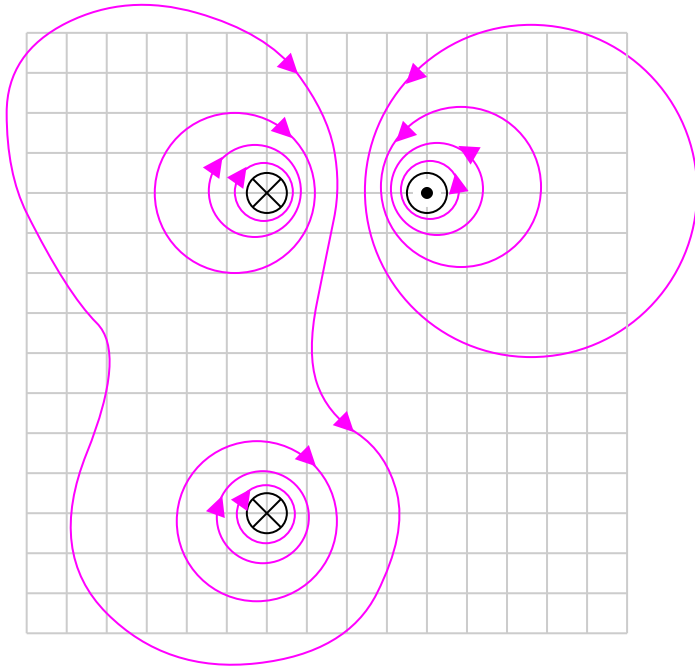
The same current I flows through all the conductors in different directions (see image below).

Sketch at least 10 field lines of the magnetic field strength \vec{H} in such a way that the different properties of the field lines (e.g. direction and density) can be seen.



Result

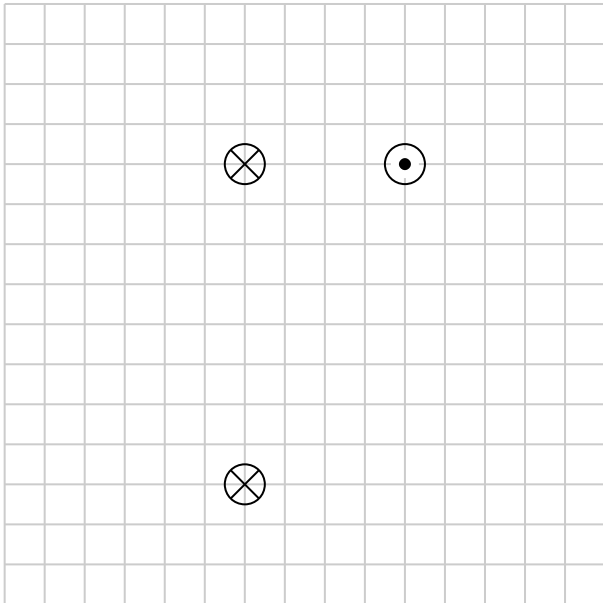
- high density of field lines near the conductors
- direction of the field lines given by the right-hand rule
- magnetic field has closed field lines
- resulting field given by superposition of field lines



Exercise E2 Magnetic Field Lines (written test, approx. 4 % of a 120-minute written test, SS2021)

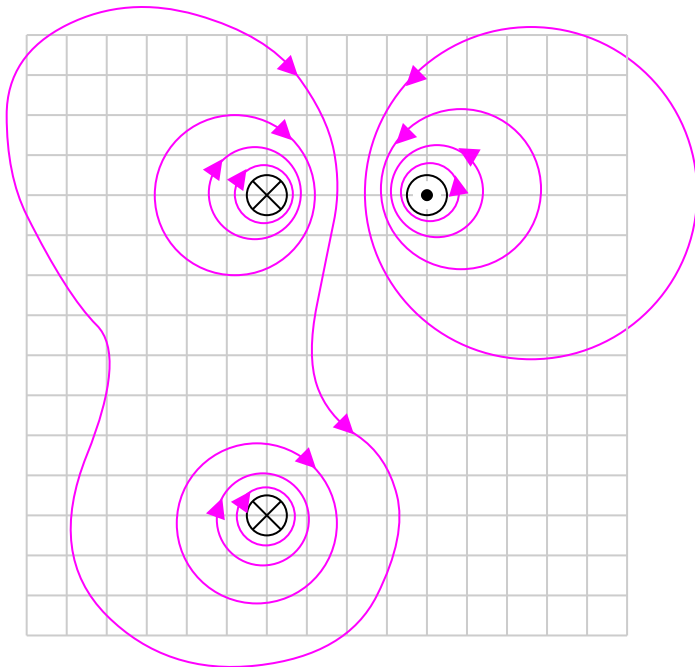
Several parallel conductors are projecting out of the plane. The same current I flows through all the conductors in different directions (see image below).

Sketch at least 10 field lines of the magnetic field strength \vec{H} in such a way that the different properties of the field lines (e.g. direction and density) can be seen.



Result

- high density of field lines near the conductors
- direction of the field lines given by the right-hand rule
- magnetic field has closed field lines
- resulting field given by superposition of field lines



Exercise E3 Magnetic Flux Density (written test, approx. 6 % of a 120-minute written test, SS2021)

A) The circuit is operated for experiments in the laboratory. A source $\hat{I} = 100 \text{ A}$ with an amplitude of $\hat{I} = 100 \text{ A}$ is operated.

How is the distance to the cable and the current in your body? (3 points, independent)

The figure below shows the top view of the laboratory with the supply line between A and B .

Path $B = 0.2 \text{ m}$
 $\mu_0 = 4\pi \cdot 10^{-7} \frac{\text{Vs}}{\text{Am}}$, $\mu_r = 1$

The formula for the magnetic field strength can be rearranged:
$$H = \frac{I}{2\pi \cdot r} \quad r = \frac{I}{2\pi \cdot H}$$

Again, the magnetic flux density B is given as: $B = \mu_0 \mu_r H$

Therefore:
$$r = \frac{\mu_0 \mu_r I}{2\pi B} = \frac{4\pi \cdot 10^{-7} \frac{\text{Vs}}{\text{Am}} \cdot \{100 \text{ A}\}}{2\pi \cdot 100 \cdot 10^{-6} \text{ T}}$$

a) What is the highest magnetic flux density through the line in your body? (3 points)

Path

The magnetic field strength for a conducting wire is given as:

$$H = \frac{I}{2\pi \cdot r}$$

The magnetic flux density B is given as: $B = \mu_0 \mu_r H$

Here, the maximum current is $\hat{I} = 100 \text{ A}$ and the distance to the cable is $r = \sqrt{(0.1 \text{ m})^2 + (0.4 \text{ m})^2} = 0.412... \text{ m}$.

$$B = 4\pi \cdot 10^{-7} \frac{\text{Vs}}{\text{Am}} \cdot 1 \cdot \frac{100 \text{ A}}{2\pi \cdot 0.412... \text{ m}}$$

Exercise E4 Magnetic Flux Density (written test, approx. 6 % of a 120-minute written test, SS2021)

A) The electric motor is operated for an experiment in the laboratory. A rotor with a diameter of $\hat{I} = 100 \text{ A}$ is operated.

Now stand next to it and think about what its value means. (3 points, independent)
The figure below shows the top view of the laboratory with the supply line between A and B .

$$\mu_0 = 4\pi \cdot 10^{-7} \frac{\text{Vs}}{\text{Am}}, \mu_r = 1$$

The formula for the magnetic field strength can be rearranged: $H = \frac{I}{2\pi \cdot r} \implies r = \frac{I}{2\pi \cdot H}$

Again, the magnetic flux density B is given as: $B = \mu_0 \mu_r H$
Therefore: $r = \frac{\mu_0 \mu_r \cdot I}{2\pi \cdot B} \implies = \frac{4\pi \cdot 10^{-7} \frac{\text{Vs}}{\text{Am}} \cdot 100 \text{ A}}{2\pi \cdot 100 \cdot 10^{-6} \text{ T}}$

a) What is the highest magnetic flux density through the line in your body? (3 points)

Path

The magnetic field strength for a conducting wire is given as:

$$\begin{aligned} H &= \frac{I}{2\pi \cdot r} \end{aligned}$$

The magnetic flux density B is given as: $B = \mu_0 \mu_r H$

Here, the maximum current is $\hat{I} = 100 \text{ A}$ and the distance to the cable is $r = \sqrt{(0.1 \text{ m})^2 + (0.4 \text{ m})^2} = 0.412... \text{ m}$.

$$\begin{aligned} B &= 4\pi \cdot 10^{-7} \frac{\text{Vs}}{\text{Am}} \cdot 1 \\ &\cdot \frac{100 \text{ A}}{2\pi \cdot 0.412... \text{ m}} \end{aligned}$$

Exercise E1 Toroidal Coil
(written test, approx. 5 % of a 120-minute written test, SS2021)

A magnetic field with a flux density of at least 50 mT is to be achieved in a ring-shaped coil (toroidal coil).

The coil has 60 turns, wound around soft iron with $\mu_r = 1200$.

The average field line length in the coil should be $l = 12 \text{ cm}$.

$I_{\text{min}} = 4 \cdot 10^{-7} \frac{\text{Vs}}{\text{Am}}$



What is the minimum current that must flow through a single winding?

Path

The magnetic field strength of a toroidal coil is given as:

$$H = \frac{N \cdot I}{l}$$

Based on the flux density the magnetic field strength can be derived by $B = \mu_0 \mu_{\text{r}} \cdot H$.

By this, the formula can be rearranged:

$$H = \frac{N \cdot I}{l} \quad || \quad \frac{B}{\mu_0 \mu_{\text{r}}} = \frac{N \cdot I}{l} \quad || \quad I = \frac{B \cdot l}{\mu_0 \mu_{\text{r}} \cdot N}$$

Putting in the numbers: $I = \frac{0.05 \text{ T} \cdot 0.12 \text{ m}}{4\pi \cdot 10^{-7} \frac{\text{Vs}}{\text{Am}} \cdot 1200 \cdot 60} = 0.6631... \frac{\text{T} \cdot \text{m}}{\frac{\text{Vs}}{\text{Am}}} = 0.6631... \frac{\text{Vs}}{\text{m}^2} \cdot \text{m} \cdot \frac{\text{Vs}}{\text{Am}}} = 0.6631... \text{ A}$

Exercise E5 Toroidal Coil

(written test, approx. 5 % of a 120-minute written test, SS2021)

A magnetic field with a flux density of at least 50 mT is to be achieved in a ring-shaped coil (toroidal coil).

The coil has 60 turns, wound around soft iron with $\mu_{\text{r}} = 1200$.

The average field line length in the coil should be $l = 12 \text{ cm}$.

$$I = \frac{B \cdot l}{\mu_0 \mu_{\text{r}} \cdot N} = \frac{0.05 \text{ T} \cdot 0.12 \text{ m}}{4\pi \cdot 10^{-7} \frac{\text{Vs}}{\text{Am}} \cdot 1200 \cdot 60}$$



What is the minimum current that must flow through a single winding?

Path

The magnetic field strength of a toroidal coil is given as:

$$\begin{aligned} H &= \frac{N \cdot I}{l} \end{aligned}$$

Based on the flux density the magnetic field strength can be derived by $B = \mu_0 \mu_{\text{r}} \cdot H$.

By this, the formula can be rearranged:

$$\begin{aligned} H &= \left\{ \frac{N \cdot I}{l} \right\} \parallel \left\{ \frac{B}{\mu_0 \mu_r} \right\} \\ &= \left\{ \frac{N \cdot I}{l} \right\} \parallel \left\{ \frac{B \cdot l}{\mu_0 \mu_r \cdot N} \right\} \end{aligned}$$

Putting in the numbers:

$$I = \frac{0.05 \text{ T} \cdot 0.12 \text{ m}}{4\pi \cdot 10^{-7} \frac{\text{Vs}}{\text{Am}} \cdot 1'200 \cdot 60} \parallel = 0.6631... \frac{\text{T} \cdot \text{m}}{\frac{\text{Vs}}{\text{Am}}}$$

$$= 0.6631... \frac{\text{Vs}}{\text{m}^2} \cdot \text{m} \parallel = 0.6631... \text{ A}$$

Exercise E6 Cylindrical Coil
(written test, approx. 6 % of a 120-minute written test, SS2021)

A) the magnetic flux (2 points) information is given:

Result

- Length $l = 30 \text{ cm}$,

Path Winding diameter $d = 390 \text{ mm}$,

- Number of windings $N = 240$,
- Current through the conductor $I = 500 \text{ mA}$,
- Material inside: Air

$$\mu_0 = 4\pi \cdot 10^{-7} \frac{\text{Vs}}{\text{Am}}$$

The magnetic field strength is $B = \mu_0 \mu_r \cdot H$:

The proportion of the magnetic voltage outside the coil can be neglected. Determine the following for the inside of the coil:

$$\begin{aligned} \Phi &= B \cdot A \\ A &= \pi \cdot \left(\frac{d}{2} \right)^2 \end{aligned}$$

a) Determine the magnetic field strength H (2 points)

$$A = \pi r^2 = \pi \left(\frac{d}{2} \right)^2$$

Path

Therefore: $\Phi = B \cdot \pi \left(\frac{d}{2} \right)^2$

Putting in the numbers:

$$H = \frac{\Phi}{\mu_0 \mu_r \cdot l} = \frac{0.0005026 \text{ Vs} \cdot \pi \left(\frac{0.39 \text{ m}}{2} \right)^2}{4\pi \cdot 10^{-7} \cdot 30 \text{ m}} = 0.0006004 \frac{\text{Vs}}{\text{m}}$$

Putting in the numbers:

$$H = \frac{240 \cdot 0.5 \text{ A}}{0.3 \text{ m}}$$

Exercise E7 Cylindrical Coil
(written test, approx. 6 % of a 120-minute written test, SS2021)

A) the magnetic flux (2 points) information is given:

Result Length $\varnothing = 30 \text{ cm}$,

- Winding diameter $\varnothing = 390 \text{ mm}$,
- Number of windings $N = 240$,
- Current through the conductor $I = 500 \text{ mA}$,

EMF $\Phi = 0.000604 \text{ Wb}$

The magnetic field strength is $B = \mu_0 \cdot n \cdot I = 0.0005026 \text{ Vs/m}$

The proportion of the magnetic flux outside the coil can be neglected. Determine the following for the inside of the coil:

But the coil is cylindrical $B = \mu_0 \cdot n \cdot I = 0.0005026 \text{ Vs/m}$

a) the magnetic field strength (2 points)

$$A = \pi r^2 = \pi \left(\frac{d}{2} \right)^2$$

Therefore: $\Phi = B \cdot \pi \left(\frac{d}{2} \right)^2$

Putting in the numbers: $\Phi = 0.0005026 \text{ Vs/m} \cdot \pi \left(\frac{0.39 \text{ m}}{2} \right)^2 = 0.0006004 \text{ Vs}$

Therefore: $H = \frac{N \cdot I}{l} = \frac{240 \cdot 0.5 \text{ A}}{0.3 \text{ m}}$

Putting in the numbers: $H = \frac{240 \cdot 0.5 \text{ A}}{0.3 \text{ m}}$

Exercise E8 effect of induction (written test, approx. 5 % of a 120-minute written test, SS2021)

A single conductor loop is penetrated by a changing magnetic flux.

The following figure shows the variation of the flux $\Phi(t)$ over time.

Calculate the variation of the induced voltage $u_{\text{ind}}(t)$ over time and draw it in a separate diagram.

SSu...inSSL...

ss\..ins\..

Path

Based on Faraday's Law of Induction the induced voltage is given by:
$$u_{\text{ind}} = - \frac{d}{dt} \Psi(t) = - \frac{d}{dt} \Phi(t)$$

For a linear function, the derivative can be substituted by Deltas ($d \rightarrow \Delta$):

$$u_{\text{ind}} = - \frac{\Delta \Phi(t)}{\Delta t} = - \frac{\Phi(t_{n+1}) - \Phi(t_n)}{t_{n+1} - t_n}$$

For a piece-wise linear function, the induced voltage can be calculated for each interval.

Here, there are 5 different intervals - in the following called I to V from left to right:

...

- For the intervals I , III , and V , the flux $\Phi(t)$ is constant. Therefore, $\Delta \Phi(t) = 0$ and $u_{\text{ind}}(t) = 0$.

- \$\$\dots\$\$...
- For the interval Δt :
 - The change in the flux is: $\Delta \Phi(t) = 1.5 \cdot 10^{-4} \text{ Vs} - 4.5 \cdot 10^{-4} \text{ Vs} = -3.0 \cdot 10^{-4} \text{ Vs}$
 - The time span is: 0.2 s
 - Conclusively, the induced voltage is: $u_{\text{ind}}(t) = + \frac{3.0 \cdot 10^{-4} \text{ Vs}}{0.2 \text{ s}} = 1.5 \text{ mV}$

- For the interval IV :
 - The change in the flux is: $\Delta \Phi(t) = 0 \cdot 10^{-4} \text{ Vs} - 1.5 \cdot 10^{-4} \text{ Vs} = -1.5 \cdot 10^{-4} \text{ Vs}$
 - The time span is: 0.2 s
 - Conclusively, the induced voltage is: $u_{\text{ind}}(t) = + \frac{1.5 \cdot 10^{-4} \text{ Vs}}{0.2 \text{ s}} = 0.75 \text{ mV}$

\$\$\dots\$\$

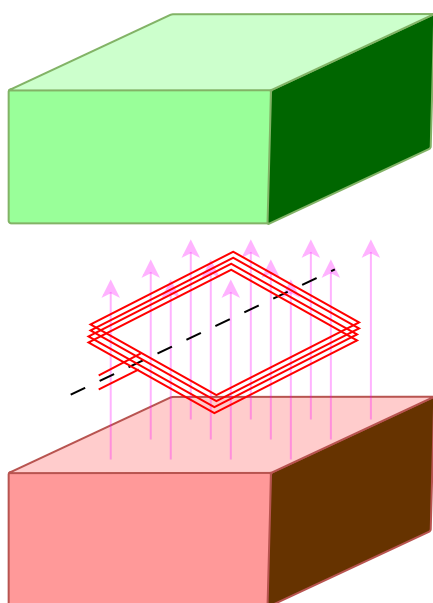
Exercise E9 Coil in a magnetic Field
(written test, approx. 4 % of a 120-minute written test, SS2021)

A coil with $n = 300$ turns and a cross-sectional area $A = 600 \text{ cm}^2$ is located in a homogeneous magnetic field.

The rotation of the coil causes a sinusoidal change in the magnetic field in the coil with the frequency $f = 80 \text{ Hz}$.

The maximum value of the magnetic flux density in the coil is $\hat{B} = 2 \cdot 10^{-6} \text{ Vs/cm}^2$.

$$B(t) = -181 \text{ V} \cdot \cos(503 \text{ s}^{-1} \cdot t)$$



Derive the formula for the voltage induced in the coil and calculate the voltage amplitude.

Path

The induced voltage u_{ind} is given by:

$$u_{\text{ind}} = - \frac{d\Psi(t)}{dt} = - n \frac{d\Phi(t)}{dt}$$

With $\Phi(t) = B(t) \cdot A$, where A is the constant area of a single winding and $B(t)$ is the changing field through this winding.

Due to the rotation, the field changes as:

$$B(t) = \hat{B} \cdot \sin(\omega t + \varphi) = \hat{B} \cdot \sin(2\pi f \cdot t + \varphi)$$

$$u_{\text{ind}} = - \frac{d}{dt} (n \cdot A \cdot \hat{B} \cdot \sin(2\pi f \cdot t + \varphi)) = - n \cdot A \cdot \hat{B} \cdot 2\pi f \cdot \cos(2\pi f \cdot t + \varphi)$$

The absolute value of the factor in front of the \cos is the maximum induced voltage \hat{U}_{ind} :

$$\hat{U}_{\text{ind}} = n \cdot A \cdot \hat{B} \cdot 2\pi f = 300 \cdot 0.06 \text{ m}^2 \cdot 2 \cdot 10^{-2} \text{ T} \cdot 2\pi \cdot 80 \text{ s}^{-1} = 180.95 \text{ V}$$

Exercise E10 effect of induction (written test, approx. 5 % of a 120-minute written test, SS2021)

A single conductor loop is penetrated by a changing magnetic flux. The following figure shows the variation of the flux $\Phi(t)$ over time.

Calculate the variation of the induced voltage $u_{\text{ind}}(t)$ over time and draw it in a separate diagram.

Path

Based on Faraday's Law of Induction the induced voltage is given by:

$$u_{\text{ind}} = - \frac{d}{dt} \Psi(t) = - \frac{d}{dt} \Phi(t)$$

For a linear function, the derivative can be substituted by Deltas (Δ):

$$u_{\text{ind}} = - \frac{\Delta \Phi(t)}{\Delta t} = - \frac{\Phi(t_{n+1}) - \Phi(t_n)}{t_{n+1} - t_n}$$

For a piece-wise linear function, the induced voltage can be calculated for each interval.

Here, there are 5 different intervals - in the following called I to V from left to right:

...

- For the intervals I , III , and V , the flux $\Phi(t)$ is constant. Therefore, $\Delta \Phi(t) = 0$ and $u_{\text{ind}}(t) = 0$

\$\$\dots\$\$

- For the interval Δt :
 - The change in the flux is: $\Delta \Phi(t) = 1.5 \cdot 10^{-4} \text{ Vs} - 4.5 \cdot 10^{-4} \text{ Vs} = -3.0 \cdot 10^{-4} \text{ Vs}$
 - The time span is: 0.2 s
 - Conclusively, the induced voltage is: $u_{\text{ind}}(t) = + \frac{3.0 \cdot 10^{-4} \text{ Vs}}{0.2 \text{ s}} = 1.5 \text{ mV}$

- For the interval IV :
 - The change in the flux is: $\Delta \Phi(t) = 0 \cdot 10^{-4} \text{ Vs} - 1.5 \cdot 10^{-4} \text{ Vs} = -1.5 \cdot 10^{-4} \text{ Vs}$
 - The time span is: 0.2 s
 - Conclusively, the induced voltage is: $u_{\text{ind}}(t) = + \frac{1.5 \cdot 10^{-4} \text{ Vs}}{0.2 \text{ s}} = 0.75 \text{ mV}$

\$\$\dots\$\$

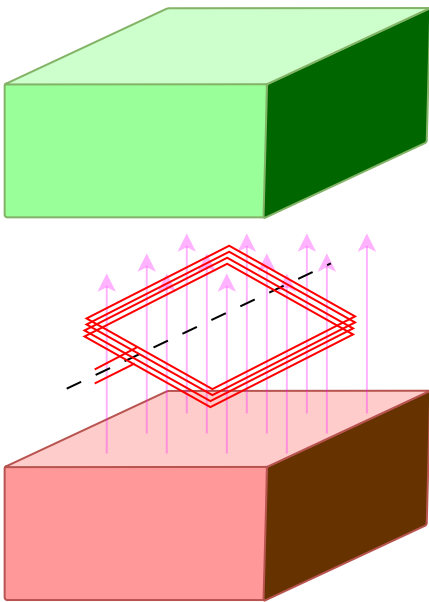
Exercise E11 Coil in a magnetic Field (written test, approx. 4 % of a 120-minute written test, SS2021)

A coil with $n = 300$ turns and a cross-sectional area $A = 600 \text{ cm}^2$ is located in a homogeneous magnetic field.

The rotation of the coil causes a sinusoidal change in the magnetic field in the coil with the frequency $f = 80 \text{ Hz}$.

The maximum value of the magnetic flux density in the coil is $\hat{B} = 2 \cdot 10^{-6} \text{ Vs/cm}^2$.

$$B(t) = -181 \text{ V} \cdot \cos(503 \text{ s}^{-1} t)$$



Derive the formula for the voltage induced in the coil and calculate the voltage amplitude.

Path

The induced voltage u_{ind} is given by:

$$u_{\text{ind}} = - \frac{d\Psi(t)}{dt} = - n \frac{d\Phi(t)}{dt}$$

With $\Phi(t) = B(t) \cdot A$, where A is the constant area of a single winding and $B(t)$ is the changing field through this winding.

Due to the rotation, the field changes as:

$$B(t) = \hat{B} \cdot \sin(\omega t + \varphi) = \hat{B} \cdot \sin(2\pi f \cdot t + \varphi)$$

$$u_{\text{ind}} = - n \frac{d}{dt} A \hat{B} \sin(2\pi f \cdot t + \varphi) = - n \cdot A \hat{B} \cdot 2\pi f \cdot \cos(2\pi f \cdot t + \varphi)$$

The absolute value of the factor in front of the \cos is the maximum induced voltage \hat{U}_{ind} :

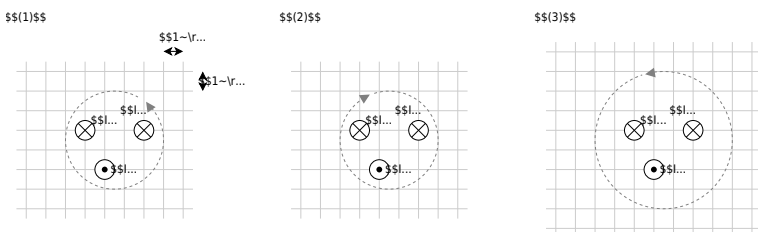
$$\hat{U}_{\text{ind}} = n \cdot A \cdot \hat{B} \cdot 2\pi f = 300 \cdot 0.06 \text{ m}^2 \cdot 2 \cdot 10^{-2} \text{ T} \cdot 2\pi \cdot 80 \text{ s}^{-1} = 180.95... \text{ V}$$

Exercise E12 Magnetic Voltage
(written test, approx. 6 % of a 120-minute written test, SS2021)

The following images show cross-sections of electrical cables.
 Resulted path is shown as a dashed line. The magnetic voltage θ on these paths shall be analyzed.

The following values are given for the currents:

- $\theta_1 = 5 \text{ A}$
- $\theta_2 = 2 \text{ A}$
- $\theta_3 = 1 \text{ A}$
- $\theta_4 = 4 \text{ A}$



Specify which magnetic voltages $\theta_{(1)}$, $\theta_{(2)}$, and $\theta_{(3)}$ result. Note the direction of the path in each case!

Path

For the resulting current the direction of the path has to be considered with the right-hand rule:

- $I_{(1)} = +I_2 - I_1 - I_3 \quad \rightarrow \quad \theta_{(1)} = 2 \text{ A} - 5 \text{ A} - 1 \text{ A}$
- $I_{(2)} = +I_3 + I_4 - I_1 \quad \rightarrow \quad \theta_{(2)} = 1 \text{ A} + 4 \text{ A} - 5 \text{ A}$
- $I_{(3)} = +I_3 - I_4 - I_2 \quad \rightarrow \quad \theta_{(3)} = 1 \text{ A} - 4 \text{ A} - 2 \text{ A}$

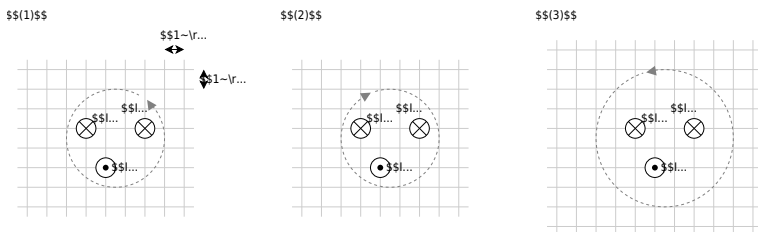
Exercise E13 Magnetic Voltage (written test, approx. 6 % of a 120-minute written test, SS2021)

The following images show cross-sections of electrical cables.

A closed path is shown as a dashed line. The magnetic voltage θ on these paths shall be analyzed.

The following values are given for the currents:

- $\begin{aligned} \theta_{(1)} &= -4 \text{ A} \\ \theta_{(2)} &= 0 \text{ A} \\ \theta_{(3)} &= 5 \text{ A} \end{aligned}$
- $I_3 = 1 \text{ A}$
 - $I_4 = 4 \text{ A}$



Specify which magnetic voltages $\theta_{(1)}$, $\theta_{(2)}$, and $\theta_{(3)}$ result. Note the direction of the path in each case!

Path

For the resulting current the direction of the path has to be considered with the right-hand rule:

- $I_{(1)} = +I_2 - I_1 - I_3 \quad \rightarrow \quad \theta_{(1)} = 2 \text{ A} - 5 \text{ A} - 1 \text{ A}$
- $I_{(2)} = +I_3 + I_4 - I_1 \quad \rightarrow \quad \theta_{(2)} = 1 \text{ A} + 4 \text{ A} - 5 \text{ A}$
- $I_{(3)} = +I_3 - I_4 - I_2 \quad \rightarrow \quad \theta_{(3)} = 1 \text{ A} - 4 \text{ A} - 2 \text{ A}$

Exercise E14 Lorentz Force (hard!)

(written test, approx. 10 % of a 120-minute written test, SS2021)

A) The picture below shows a straight high voltage direct current transmission line with a current of $I = 2000 \text{ A}$. The resulting force is? (Independent)

A homogeneous geomagnetic field is assumed. The magnetic field strength has a vertical component of $B_{\text{v}} = 40 \text{ } \mu\text{T}$ and a horizontal component of $B_{\text{h}} = 20 \text{ } \mu\text{T}$.

The angle between the transmission line and the horizontal component of the field strength is $\alpha = 20^\circ$.

The picture on the right shows the line (black), the field strength components, and the angle in front and top view for illustration purposes.

Top View

Path

a) Calculate the force that results from the current flow on the entire conductor. First, calculate the vertical and horizontal components and combine them accordingly.

Path

- The horizontal component \vec{F}_{h} of the force is based on the vertical component \vec{B}_{v} of the magnetic field.
- The vertical component \vec{B}_{v} of the magnetic field is not shown in the image but is pointing into the ground.

The force on the transmission line can be calculated via the Lorentz force hand rule, has to be applied.

$$\vec{F} = I \cdot (\vec{l} \times \vec{B})$$

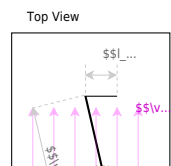
Here, we have two components for the current - and therefore for the force - to evaluate.

Considering the right-hand rule (and the cross product), the vertical field B_{v} generates a horizontal force F_{h} and vice versa.

The **horizontal component** is given by

$$\begin{align*}
 F_{\text{h}} &= l \cdot (l \cdot B_{\text{v}}) = 1'200 \text{ m} \cdot 300 \text{ m} \cdot 40 \cdot 10^{-6} \frac{\text{Vs}}{\text{m}^2} = 14'400 \text{ N} \\
 F_{\text{As}} &= 14'400 \text{ N} \\
 F_{\text{Ws}} &= 14'400 \text{ N}
 \end{align*}$$

For the **vertical component** the angle α has to be considered.
 For the maximum F_{v} the angle α has to be 90° , therefore the \sin has to be used.



$$F_{\text{v}} = l \cdot l \cdot B_{\text{h}} \cdot \sin \alpha = 1'200 \text{ m} \cdot 300 \text{ m} \cdot 40 \cdot 10^{-6} \frac{\text{Vs}}{\text{m}^2} \cdot \sin 20^\circ = 2'462.545... \text{ N}$$

For the **overall force** F the Pythagorean theorem has to be used:

$$F = \sqrt{F_{\text{v}}^2 + F_{\text{h}}^2} = \sqrt{(14'400 \text{ N})^2 + (2'462.545... \text{ N})^2} = 14'609.04... \text{ N}$$

**Exercise E15 Lorentz Force (hard!)
(written test, approx. 10 % of a 120-minute written test, SS2021)**

A) ~~300 picture below shows a straight high voltage direct current transmission line with a~~
 Result: A component of $F = (1/200) \cdot I$ results in force fact? (Independent)

A homogeneous geomagnetic field is assumed. The magnetic field strength has a vertical component of $B_{\text{v}} = 40 \mu\text{T}$ and a horizontal component of $B_{\text{h}} = 20 \mu\text{T}$.

Only $1000 \cdot 7 \text{ A}$ is perpendicular to \vec{B}_{v} and to \vec{I} and points in the right direction by the right-hand rule.

The angle between the transmission line and the horizontal component of the field strength is $\alpha = 20^\circ$.
 The picture on the right shows the line (black), the field strength components, and the angle in front and top view for illustration purposes.

Top View

Path

a) Calculate the force that results from the current flow on the entire conductor.
 First, calculate the vertical and horizontal components and combine them accordingly.

Path

- The horizontal component \vec{F}_{h} of the force is based on the vertical component \vec{B}_{v} of the magnetic field.
- The vertical component \vec{B}_{v} of the magnetic field is not shown in the image but is pointing into the ground.
- It has to be perpendicular to \vec{B}_{v} and to \vec{I} . The right-

The force on the transmission line can be calculated via the Lorentz force

$$\vec{F} = I \cdot (\vec{l} \times \vec{B})$$

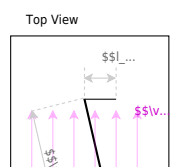
Here, we have two components for the current - and therefore for the force - to evaluate.

Considering the right-hand rule (and the cross product), the vertical field B_{v} generates a horizontal force F_{h} and vice versa.

The **horizontal component** is given by

$$\begin{align*}
 F_{\text{h}} &= l \cdot (l \cdot B_{\text{v}}) = 1'200 \text{ m} \cdot 300 \text{ m} \cdot 10^3 \text{ m} \cdot 40 \cdot 10^{-6} \frac{\text{Vs}}{\text{m}^2} = 14'400 \text{ N} \\
 F_{\text{As}} &= 14'400 \text{ N} \quad F_{\text{Ws}} = 14'400 \text{ N}
 \end{align*}$$

For the **vertical component** the angle α has to be considered.
 For the maximum F_{v} the angle α has to be 90° , therefore the \sin has to be used.



$$F_{\text{v}} = l \cdot l \cdot B_{\text{h}} \cdot \sin \alpha = 1'200 \text{ m} \cdot 300 \text{ m} \cdot 10^3 \text{ m} \cdot 40 \cdot 10^{-6} \frac{\text{Vs}}{\text{m}^2} \cdot \sin 20^\circ = 2'462.545... \text{ N}$$

For the **overall force** F the Pythagorean theorem has to be used:

$$F = \sqrt{F_{\text{v}}^2 + F_{\text{h}}^2} = \sqrt{(14'400 \text{ N})^2 + (2'462.545... \text{ N})^2} = 14'609.04... \text{ N}$$

Exercise E16 Impedance Characteristics
(written test, approx. 6 % of a 120-minute written test, SS2021)

A coil has an inductive reactance of $X_0 = X(f_0) = 80 \text{ } \Omega$ at a frequency $f_0 = 60 \text{ kHz}$.
 Calculate the frequencies f_1 , f_2 , f_3 at which the following reactances are measured:

- $X_1 = 50 \text{ } \Omega$
- $f_1 = 37.5 \text{ kHz}$
- $X_2 = 121 \text{ } \Omega$
- $f_2 = 90.75 \text{ kHz}$
- $X_3 = 147 \text{ } \Omega$
- $f_3 = 110.25 \text{ kHz}$

Path

There are multiple ways to solve this question.
 One way would be, to calculate the inductance L first by rearranging $X(f) = 2\pi \cdot f \cdot L$.

Another way uses ratios (or "rule of three"), since $X(f) = f \cdot k$ with a constant k .

Therefore one can set up two formulas $X_n = f_n \cdot k$, $X_0 = f_0 \cdot k$, and divide the formulae by each other.

$$\begin{aligned} \frac{X_n}{X_0} &= \frac{f_n}{f_0} \quad \parallel \quad f_n = \frac{X_n}{X_0} \cdot f_0 \end{aligned}$$

$$\begin{aligned} f_n &= \frac{60 \text{ kHz}}{80 \text{ } \Omega} \cdot X_n \quad \parallel \quad = 0.75 \frac{\text{ } \Omega}{\text{kHz}} \cdot X_n \end{aligned}$$

Exercise E17 Impedance Characteristics
(written test, approx. 6 % of a 120-minute written test, SS2021)

A coil has an inductive reactance of $X_0 = X(f_0) = 80 \text{ } \Omega$ at a frequency $f_0 = 60 \text{ kHz}$.
 Calculate the frequencies f_1 , f_2 , f_3 at which the following reactances are measured:

- $X_1 = 50 \text{ ~}\Omega$
- $X_2 = 121 \text{ ~}\Omega$
- $X_3 = 177 \text{ ~}\Omega$
 - $f_1 = 37.5 \text{ ~kHz}$
 - $f_2 = 90.75 \text{ ~kHz}$
 - $f_3 = 110.25 \text{ ~kHz}$

Path

There are multiple ways to solve this question.

One way would be, to calculate the inductance L first by rearranging $X(f) = 2\pi \cdot f \cdot L$.

Another way uses ratios (or “rule of three”), since $X(f) = f \cdot k$ with a constant k .

Therefore one can set up two formulas $X_n = f_n \cdot k$, $X_0 = f_0 \cdot k$, and divide the formulae by each other.

$$\begin{aligned} \frac{X_n}{X_0} &= \frac{f_n}{f_0} \quad \parallel \quad f_n = \frac{X_n}{X_0} \cdot f_0 \\ &= \frac{f_0}{X_0} \cdot X_n \end{aligned}$$

$$\begin{aligned} f_n &= \frac{60 \text{ ~}\Omega}{80 \text{ ~}\Omega} \cdot X_n \\ &= 0.75 \cdot \frac{\Omega}{\text{kHz}} \cdot X_n \end{aligned}$$

Exercise E18 Complex series circuit (written test, approx. 8 % of a 120-minute written test, SS2021)

A) Determine the absolute value of Z_C , $|Z_C| = 200 \text{ ~}\Omega$ in the series circuit using a phasor diagram. Pay attention to the correct dimensioning.

a) Determine the complex impedance \underline{Z}_C .

Result

$$\underline{Z}_C = -j \cdot 804 \text{ ~}\Omega$$

Path

The complex impedance \underline{Z}_C is given as
$$\underline{Z}_C = \frac{-j}{2\pi \cdot 40 \cdot 10^3 \text{ ~Hz} \cdot 4.95 \cdot 10^{-9} \text{ ~F}} = -j \cdot 803.81... \text{ ~}\Omega$$

Based on the diagram: $|\underline{Z}| = 828 \Omega$

Exercise E19 Complex series circuit
(written test, approx. 8 % of a 120-minute written test, SS2021)

A) Determine the absolute value of the result I_{eff} in the circuit using a phasor diagram. Pay attention to the correct dimensioning.

a) Determine the complex impedance \underline{Z}_C .

Result

$$\underline{Z}_C = -j \cdot 804 \Omega$$

Path

The complex impedance \underline{Z}_C is given as
$$\underline{Z}_C = \frac{1}{j \cdot 2\pi \cdot f \cdot C} = \frac{-j}{2\pi \cdot 40 \cdot 10^3 \cdot 4.95 \cdot 10^{-9}} = -j \cdot 803.81... \Omega$$

Based on the diagram: $|\underline{Z}| = 828 \Omega$

Exercise E20 Component Parameters
(written test, approx. 10 % of a 120-minute written test, SS2021)

Determine the circuit parameters of an AC motor presents a resistive inductive load! The values of the series resistance R_M and the inductance L_M are to be determined below. Both result in the impedance of the motor.

This resulted in the recorded current of

Derive in general the equation for the absolute value of the impedance of the motor.

$$|Z| = \sqrt{(2\pi \cdot f \cdot L_M)^2 + R_M^2}$$

$$R_M = 1.48 \Omega$$

$$L_M = 110 \text{ mH}$$

b) Since we have the absolute values of the impedances from the specified values at f_1 and f_2 has the advantage that R_M will cancel out:

$$Z_2^2 - Z_1^2 = (2\pi \cdot f_2 \cdot L_M)^2 + R_M^2 - ((2\pi \cdot f_1 \cdot L_M)^2 + R_M^2)$$

$$\underline{Z} = R_M + j \cdot 2\pi \cdot f \cdot L_M$$

The complex impedance \underline{Z} for a resistive inductive load is given as
$$\underline{Z} = R_M + j \cdot 2\pi \cdot f \cdot L_M + R_M$$

The Pythagorean theorem can be used to derive the absolute value:
$$|Z|^2 = Z_1^2 - Z_2^2 = L^2 \cdot \left((2\pi f_2)^2 - (2\pi f_1)^2 \right) \implies L = \frac{\sqrt{Z_1^2 - Z_2^2}}{2\pi \sqrt{f_2^2 - f_1^2}}$$

And then to L :

$$L = \frac{1}{2\pi} \sqrt{\frac{Z_1^2 - Z_2^2}{f_2^2 - f_1^2}}$$

With the values:

$$L = \frac{1}{2\pi} \sqrt{\frac{(10\Omega)^2 - (6.25\Omega)^2}{(100\text{ Hz})^2 - (50\text{ Hz})^2}} \approx 14.346\text{ mH}$$

The resistance value R can be derived from $Z^2 = (2\pi f L)^2 + R^2 \implies R^2 = Z^2 - (2\pi f L)^2 \implies R = \sqrt{Z^2 - (2\pi f L)^2}$

The values have to be inserted also for R : $R = \sqrt{(10\Omega)^2 - (2\pi \cdot 100\text{ Hz} \cdot 0.014346\text{ mH})^2} \approx 4.3301\Omega$

Exercise E21 Component Parameters (written test, approx. 10 % of a 120-minute written test, SS2021)

Determine the component parameters of an electric motor. The next exercises consider the following results: The measured series resistance with a constant current of $I = 50\text{ mA}$ determined at two different frequencies, the impedance was applied.

This resulted in the recorded current of

Derive in general the equation for the absolute value of the impedance of the motor.

$$|Z| = \sqrt{(2\pi f L)^2 + R^2}$$

- $R = 10\Omega$
- $f_1 = 100\text{ Hz}$
- $I_1 = 5\text{ mA}$
- $f_2 = 110\text{ Hz}$
- $I_2 = 4\text{ mA}$

Since we have Z_1 and Z_2 from b) we can subtract two of the formulas from a). This has the advantage that R will cancel out:

$$Z_1^2 - Z_2^2 = (2\pi f_2 L)^2 + R^2 - \left((2\pi f_1 L)^2 + R^2 \right) \implies Z_1^2 - Z_2^2 = (2\pi L)^2 (f_2^2 - f_1^2)$$

Now we can rearrange to L :

$$L = \frac{\sqrt{Z_1^2 - Z_2^2}}{2\pi \sqrt{f_2^2 - f_1^2}}$$

$$L_{\text{M}} = \frac{Z_2^2 - Z_1^2}{f_2^2 - f_1^2}$$

- $Z_1 = \frac{U_1}{I_1} = \frac{50 \text{ V}}{8 \text{ A}}$
- And then to $Z_2 = \frac{U_2}{I_2} = \frac{50 \text{ V}}{5 \text{ A}}$

$$L_{\text{M}} = \frac{1}{2\pi} \sqrt{\frac{Z_2^2 - Z_1^2}{f_2^2 - f_1^2}}$$

With the values:

$$L_{\text{M}} = \frac{1}{2\pi} \sqrt{\frac{(10 - \Omega)^2 - (6.25 - \Omega)^2}{(100 \frac{1}{s})^2 - (50 \frac{1}{s})^2}} = 14.346... \text{ mH}$$

The resistance value R_{M} can be derived from $Z_2^2 = (2\pi \cdot f_2 \cdot L_{\text{M}})^2 + R_{\text{M}}^2$ $R_{\text{M}} = \sqrt{Z_2^2 - (2\pi \cdot f_2 \cdot L_{\text{M}})^2}$

The values have to be inserted also for R_{M} : $R_{\text{M}} = \sqrt{(10 - \Omega)^2 - (2\pi \cdot 100 \frac{1}{s} \cdot 0.014346... \text{ mH})^2} = 4.3301... \Omega$

Exercise E22 Signal Analysis
(written test, approx. 6 % of a 120-minute written test, SS2021)

A) Determine the frequency of the signal and the phase angle between $u(t)$ and $i(t)$. The quantities are available in the consumer arrow system. (hard)

- $u(t) = 50 \text{ V} \cdot \cos(6000 \frac{1}{s} \cdot t + 4)$
- $i(t) = 30 \text{ A} \cdot \sin(6000 \frac{1}{s} \cdot t + 5)$

Result

a) Determine the amplitude values \hat{u} , \hat{i} and the RMS values U , I

- $f = 955 \text{ Hz}$

The frequency can be derived by the term in the sine function: $\omega = 6000 \frac{1}{s}$
 $f = \frac{\omega}{2\pi} = \frac{6000}{2\pi} \frac{1}{s} = 954.93... \text{ Hz}$
 RMS values:

For the phase φ , we have to subtract φ_i from φ_u .
 But to get these values, both the $u(t)$ and $i(t)$ need to have the same sinusoidal function. Therefore:

- $\hat{u} = 35.4 \text{ V}$
- For the RMS values of sinusoidal functions the amplitudes have to be multiplied with $\frac{1}{\sqrt{2}}$
- $\hat{u} = 4 + \frac{\varphi}{2}$

By this we get for φ $\varphi = \varphi_u - \varphi_i = 4 - 5 = -1$ $\varphi = 2.14159... \text{ rad}$

Converted in degree: $\varphi = 2.14159... \cdot \frac{360^\circ}{2\pi}$

$$\varphi = 32.7042...^\circ$$

Exercise E23 Signal Analysis

(written test, approx. 6 % of a 120-minute written test, SS2021)

A) Determine the phase difference φ between the voltage $u(t)$ and the current $i(t)$.

Result: Quantities are available in the consumer arrow system. (hard)

- $u(t) = 50 \sqrt{2} \cos(6000 t + 4)$

Path: $i(t) = 30 \sqrt{2} \sin(6000 t + 5)$

Result

a) Determine the amplitude values \hat{U} , \hat{I} and the RMS values U , I

- $f = 955 \text{ Hz}$

- $\hat{U} = 50 \sqrt{2} \text{ V}$

The frequency can be derived by the term in the sine function: $\omega = 6000 \text{ rad/s}$

Path: $\hat{I} = 30 \sqrt{2} \text{ A}$

$$f = \frac{6000}{2\pi} = 954.93... \text{ Hz}$$

RMS values:

For the phase φ , we have to subtract φ_i from φ_u .

But to get these values, both the $u(t)$ and $i(t)$ need to have the same sinusoidal function! Therefore:

- $U = 35.41 \text{ V}$
- The amplitude values \hat{U} , \hat{I} are given directly by the coefficient of the cosine and sine functions

- For the RMS values of sinusoidal functions the amplitudes have to be multiplied with $\frac{1}{\sqrt{2}}$

- $\varphi = 4 + \frac{\pi}{2} - 5 = 2.14159... \text{ rad}$

$$\varphi = 2.14159... \text{ rad} = 2.14159... \cdot \frac{360^\circ}{2\pi} = 32.7042...^\circ$$

$$\varphi = 2.14159... \cdot \frac{360^\circ}{2\pi} = 32.7042...^\circ$$

Exercise E24 Resonant Circuit

(written test, approx. 4 % of a 120-minute written test, SS2021)

b) Determine the resonance frequency f_0 of the circuit.

Result: Inductance L and capacitance C are fixed. The resistance R can be varied.

- $u(t) = 12 \sqrt{2} \sin(2\pi f_0 t)$

Path: $R_i = 200 \text{ m}\Omega$

- $R = 6.2055 \text{ m}\Omega$

- $C = 30 \text{ nF}$

For the following calculation, the internal resistance R_i and the resistance R have to be combined: $R_{\Sigma} = R_i + R$

Here, either one knows that the gain factor Q stands for $Q = \frac{U_C}{U_{\text{rms}}}$ and therefore can directly use the following formula:
$$Q = \frac{U_C}{U_{\text{rms}}} = \frac{1}{R_{\Sigma}} \sqrt{\frac{L}{C}} \parallel R_{\Sigma} = \frac{U_{\text{rms}}}{U_C} \sqrt{\frac{L}{C}} \parallel \end{align*}$$

When the gain factor is not known, one has to derive it:

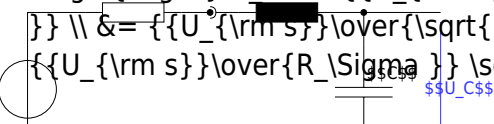
The voltage U at resonance is only given by the total ohmic resistance R_{Σ} and the source voltage U_{rms} :
$$I = \frac{U_{\text{rms}}}{R_{\Sigma}} \end{align*}$$

This current flow also through the impedance of the capacitor
$$U_C = Z_C \cdot I \parallel = \frac{1}{\omega C} \cdot I \parallel = \frac{U_{\text{rms}}}{\omega C R_{\Sigma}} \parallel \end{align*}$$

At resonance, the angular frequency ω is given by $\omega = \frac{1}{\sqrt{LC}}$.

$$U_C = \frac{U_{\text{rms}}}{\frac{1}{\sqrt{LC}} C R_{\Sigma}} \parallel = \frac{U_{\text{rms}}}{\sqrt{\frac{C}{L}} R_{\Sigma}} \parallel = \frac{U_{\text{rms}}}{R_{\Sigma}} \sqrt{\frac{L}{C}} \parallel \end{align*}$$

U_{rms}



a) What is the resonance frequency f_0 ?

In both cases, we end up with the same formula, where we have to insert the physical values:
$$R_{\Sigma} = \frac{U_{\text{rms}}}{U_C} \sqrt{\frac{L}{C}} \parallel = \frac{1}{4} \sqrt{\frac{20 \cdot 10^{-3} \text{ H}}{30 \cdot 10^{-6} \text{ F}}} \parallel = 6.4549... \Omega \end{align*}$$

path

And so, the resistance R_{Σ} is:
$$R_{\Sigma} = R_{\Sigma} - R_i \parallel =$$

$$6.4549... \Omega - 0.2 \Omega \parallel = 6.2549... \Omega \end{align*}$$

With the values:
$$f_0 = \frac{1}{2\pi \sqrt{20 \cdot 10^{-3} \text{ H} \cdot 30 \cdot 10^{-6} \text{ F}}} \parallel = 205.4681... \text{ Hz} \end{align*}$$

Exercise E25 Resonant Circuit

(written test, approx. 4 % of a 120-minute written test, SS2021)

b) The voltage U_{rms} and the capacitance C are fixed. The resistance R_{Σ} can be varied.

• $U_{\text{rms}} = 12 \text{ V} \cdot \sin(2\pi \cdot f_0 \cdot t)$

path

• $R_i = 200 \text{ m}\Omega$

• $R_{\Sigma} = 205.4681 \text{ }\Omega$

• $C = 30 \text{ }\mu\text{F}$

For the following calculation, the internal resistance R_i and the resistance R have to be combined: $R_{\Sigma} = R_i + R$

Here, either one knows that the gain factor Q stands for $Q = \frac{U_C}{U_{\text{rms}}}$ and therefore can directly use the following formula: $Q = \frac{U_C}{U_{\text{rms}}} = \frac{1}{R_{\Sigma}} \sqrt{\frac{L}{C}}$
 $R_{\Sigma} = \frac{U_{\text{rms}}}{U_C} \sqrt{\frac{L}{C}}$

When the gain factor is not known, one has to derive it:

The voltage U_C at resonance is only given by the total ohmic resistance R_{Σ} and the source voltage U_{rms} : $I = \frac{U_{\text{rms}}}{R_{\Sigma}}$

This current flow also through the impedance of the capacitor $U_C = Z_C \cdot I = \frac{1}{\omega C} \cdot I = \frac{U_{\text{rms}}}{\omega C R_{\Sigma}}$

At resonance, the angular frequency ω is given by $\omega = \frac{1}{\sqrt{LC}}$

$U_C = \frac{U_{\text{rms}}}{\frac{1}{\sqrt{LC}} C R_{\Sigma}} = \frac{U_{\text{rms}} \sqrt{LC}}{R_{\Sigma}}$
 a) What is the resonant frequency f_0 ? $f_0 = \frac{1}{2\pi \sqrt{LC}} = \frac{1}{2\pi \sqrt{20 \cdot 10^{-3} \cdot 30 \cdot 10^{-6}}} = 6.499 \dots \text{ kHz}$

In both cases, we end up with the same formula, where we have to insert the physical values: $R_{\Sigma} = \frac{U_{\text{rms}}}{U_C} \sqrt{\frac{L}{C}} = \frac{110 \text{ V}}{161 \text{ V}} \sqrt{\frac{20 \cdot 10^{-3}}{30 \cdot 10^{-6}}} = 6.299 \dots \text{ }\Omega$
 The resonant frequency f_0 is given as $f_0 = \frac{1}{2\pi \sqrt{LC}} = \frac{1}{2\pi \sqrt{20 \cdot 10^{-3} \cdot 30 \cdot 10^{-6}}} = 6.499 \dots \text{ kHz}$

And so, the resistance R_{Σ} is: $R_{\Sigma} = \frac{110 \text{ V}}{161 \text{ V}} \sqrt{\frac{20 \cdot 10^{-3}}{30 \cdot 10^{-6}}} = 6.299 \dots \text{ }\Omega$
 $f_0 = \frac{1}{2\pi \sqrt{20 \cdot 10^{-3} \cdot 30 \cdot 10^{-6}}} = 6.499 \dots \text{ kHz}$

Exercise E26 Multiphase systems (written test, approx. 4 % of a 120-minute written test, SS2021)

a) Specify the RMS value of the phase voltage U_{rms} and the line voltage U_{rms} .
 Result: $U_{\text{rms}} = 110 \text{ V}$, $U_{\text{rms}} = 190 \text{ V}$

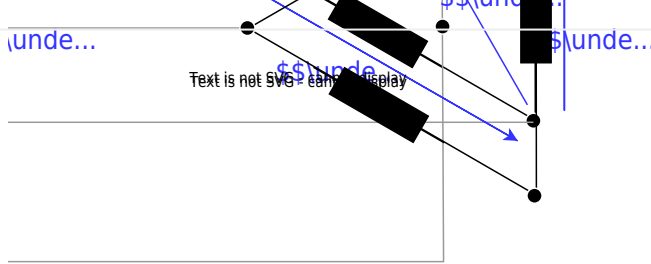
A voltage with the RMS value $U_{\text{rms}} = 110 \text{ V}$ is applied between the terminals of each winding.

Through each of the windings, there is a current with an RMS value $I_{\text{rms}} = 5 \text{ A}$ and the phase shift $\varphi = +25^\circ$ compared to the voltage.
 $P = U_{\text{rms}} \cdot I_{\text{rms}} \cdot \cos(\varphi) = 110 \text{ V} \cdot 5 \text{ A} \cdot \cos(25^\circ) = 490 \text{ W}$

b) Since the given $U_{\text{rms}} = 110 \text{ V}$ is supplied to each winding, draw the circuit diagram.

The real power P is given by $P = U_{\text{eff}} I_{\text{eff}} \cos \varphi$. The string voltage U_{eff} is $U_{\text{eff}} = U_{\text{eff}} \sqrt{3}$. For that to be true, the phase angle φ must be zero. $\varphi = 0$.

By this (and showing in the example in the image below), One can see, that $I_{\text{eff}} = \sqrt{3} \cdot I_{\text{RMS}} = \sqrt{3} \cdot 5 \text{ A}$



one single phase as an example



Exercise E27 Multiphase systems
 (written test, approx. 4 % of a 120-minute written test, SS2021)

1) Specify the RMS value of the phase voltage U_{eff} and the string voltage U_{eff} .
 Result:

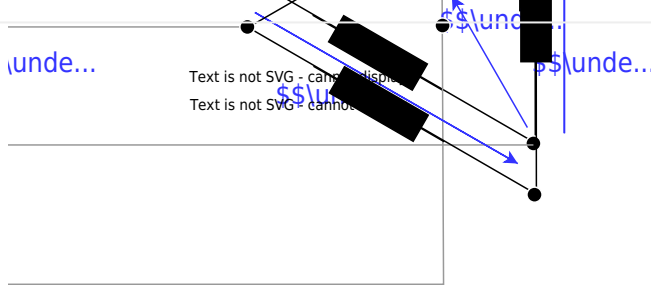
A voltage with the RMS value $U_{\text{eff}} = 110 \text{ V}$ is applied between the terminals of each winding.

Through each of the windings, there is a current with an RMS value $I_{\text{eff}} = 5 \text{ A}$ and a phase shift $\varphi = +25^\circ$ compared to the voltage.
 • $U_{\text{eff}} = 110 \text{ V}$
 • $I_{\text{eff}} = 5 \text{ A}$

a) Draw the circuit diagram of a 3-phase system.

Since the given voltage of $U_{\text{RMS}} = 5110 \text{ V}$ is applied between the winding, the active power P is given by $P = 3 \cdot U_{\text{RMS}} \cdot I_{\text{RMS}} \cdot \cos(\varphi)$. For a balanced system, the total active power P_{total} is the sum of all the powers. $P_{\text{total}} = 3 \cdot U_{\text{RMS}} \cdot I_{\text{RMS}} \cdot \cos(\varphi)$.

By this (and showing in the example in the image below), One can see, that $I_{\text{L}} = \sqrt{3} \cdot I_{\text{RMS}} = \sqrt{3} \cdot 5 \text{ A}$



one single phase as an example



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