Exam Summer Semester 2021

Student Group

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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.

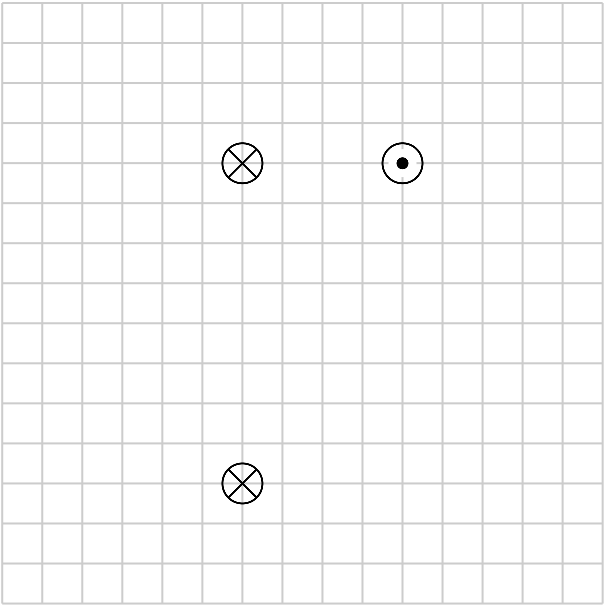
- Sub-tasks, which are independently solvable are marked with: (independent)
- Sub-tasks, which are hard are marked with: (hard)

Only EEE1-relevant Part

> # This part is only for about 65 minutes !

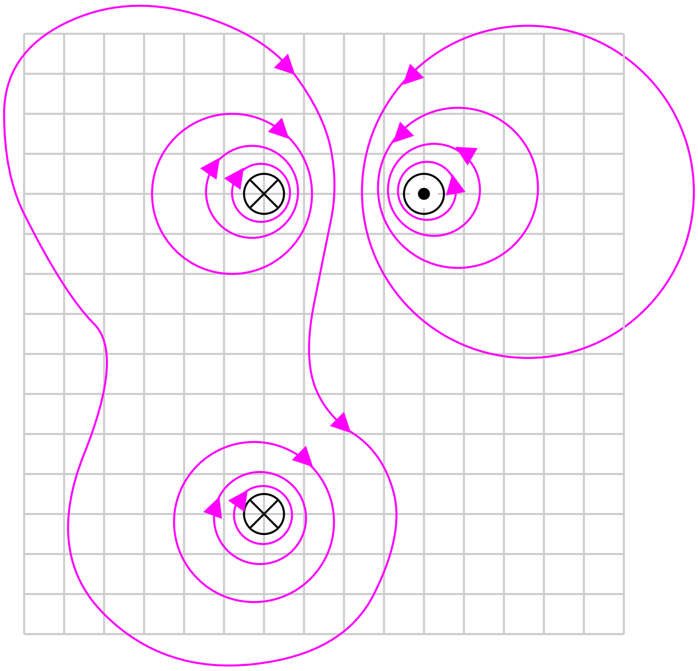
Exercise E2 Magnetic Field Lines
(written test, approx. 4 % of a 120-minute written test, SS2021)

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

An electric motor is operated for experiments in the laboratory. An alternating current with an amplitude of $\hat{I} = 100~\rm A$ is operated.
You stand next to it and think about whether you have any health problems to worry about.
The figure below shows the top view of the laboratory with the supply line between $\rm A$ and $\rm B$.

b) The limit value for the magnetic flux density at the frequency used is $B_0 = 100~\rm \mu T$.
At what distance around the conductor is this value exceeded? (3 points, independently of a))

Result

Path

$B = 0.2~\rm mT$

$r = 42~\rm mm$

$\mu_{0} = 4\pi\cdot 10^{-7} {{\rm Vs}\over{\rm Am}}$, $\mu_{r}=1$

The formula for the magnetic field strength can be rearranged: \begin{align*} H &= {{I}\over{2\pi \cdot r}} \\ r &= {{I}\over{2\pi \cdot H}} \\ \end{align*}

Again, the magnetic flux density B is given as: $B = \mu_0 \mu_r H$
Therefore: \begin{align*} r &= \mu_0 \mu_r {{ I }\over{2\pi \cdot B}} \\ &= 4\pi\cdot 10^{-7} {{\rm Vs}\over{\rm Am}} {{100 ~\rm A}\over{2\pi \cdot 100\cdot 10^{-6} {~\rm T}}} \\ \end{align*}

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:

$$\begin{align*} H &= {{I}\over{2\pi \cdot r}} \end{align*}$$

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

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

Therefore: $$\begin{align*} B &= 4\pi\cdot 10^{-7} {{\rm Vs}\over{\rm Am}} \cdot 1 \cdot {{100 ~\rm A}\over{2\pi \cdot 0.412... ~\rm m}} \end{align*}$$

Exercise E6 Toroidal Coil
(written test, approx. 5 % of a 120-minute written test, SS2021)

A magnetic field with a flux density of at least $50 ~\rm mT$ is to be achieved in a ring-shaped coil (toroidal coil).
The coil has 60 turns, wound around soft iron with $\mu_{\rm r} = 1200$.
The average field line length in the coil should be $l = 12 ~\rm cm$.

Result

$\mu_{0} = 4\pi\cdot 10^{-7} {{\rm Vs}\over{\rm Am}}$

$I = 66 ~\rm mA$

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{align*} H &= {{N \cdot I}\over{l}} \end{align*}

Based on the flux density the magnetic field strength can be derived by $B = \mu_0 \mu_{\rm r} \cdot H$.
By this, the formula can be rearranged:

\begin{align*} H &= {{N \cdot I}\over{l}} \\ {{B}\over{ \mu_0 \mu_{\rm r}}} &= {{N \cdot I}\over{l}} \\ I &= {{B \cdot l}\over{ \mu_0 \mu_{\rm r} \cdot N}} \end{align*}

Putting in the numbers: \begin{align*} I &= {{ 0.05 {~\rm T} \cdot 0.12{~\rm m} }\over{ 4\pi\cdot 10^{-7} {{\rm Vs}\over{\rm Am}} \cdot 1'200 \cdot 60}} \\ &= 0.6631... {{\rm T\cdot m}\over{ {{\rm Vs}\over{\rm Am}} }} &= 0.6631... {{\rm {{\rm Vs}\over{\rm m^2}} \cdot m}\over{ {{\rm Vs}\over{\rm Am}} }} &= 0.6631... ~\rm A \end{align*}

Exercise E8 Cylindrical Coil
(written test, approx. 6 % of a 120-minute written test, SS2021)

A cylindrical coil with the following information is given:

- Length $□ = 30 {~\rm cm}$,
- Winding diameter $□ = 390 {~\rm mm}$,
- Number of windings $□ = 240$,
- Current through the conductor $□ = 500 {~\rm mA}$,
- Material inside: Air
- $\mu_0 = 4\pi\cdot 10^{-7} {{\rm Vs}\over{\rm Am}}$

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

a) the magnetic field strength (2 points)

Path

\begin{align*} H &= {{N \cdot I}\over{l}} = {{w \cdot I}\over{l}} \end{align*}

Putting in the numbers: \begin{align*} H &= {{240 \cdot 0.5 {~\rm A}}\over{0.3 {~\rm m}}} \end{align*}

Result

$H = 400 ~\rm A/m$

b) the magnetic flux density (2 points)

Result

$B = 0.50 ~\rm mT$

Path

The magnetic flux density is given as $B = \mu_0 \mu_{\rm r} \cdot H$:

\begin{align*} B = \mu_0 \cdot H \end{align*}

Putting in the numbers: \begin{align*} B &= 4\pi\cdot 10^{-7} {{\rm Vs}\over{\rm Am}} \cdot 400 ~\rm {{A}\over{m}} \\ &= 0.0005026... {{\rm Vs}\over{\rm m^2}} \end{align*}

c) the magnetic flux (2 points)

Result

$\Phi = 0.060 ~\rm mWb$

Path

The magnetic flux is given as:

\begin{align*} \Phi &= B \cdot A \end{align*}

Since the coil is cylindrical, the cross-sectional area is given as:

\begin{align*} A = \pi r^2 = \pi \left({{d}\over{2}} \right)^2 \end{align*}

Therefore: \begin{align*} \Phi &= B \cdot \pi \left({{d}\over{2}} \right)^2 \end{align*}

Putting in the numbers: \begin{align*} \Phi &= 0.0005026... {{\rm Vs}\over{\rm m^2}} \cdot \pi \left({{0.39{\rm m}}\over{2}} \right)^2 \\ &= 0.00006004... {\rm Vs} \end{align*}

Exercise E11 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 $u_{\rm ind}(t)$ over time and draw it in a separate diagram.

Result

$$u...in$$\...

$$\...in$$\...

Path

Based on Faraday's Law of Induction the induced voltage is given by:
$$\begin{align*} u_{\rm ind} =& - {{ {\rm d} }\over{ {\rm d}t}} \Psi(t) \bigg\rvert_{n=1}\\ =& - {{ {\rm d} }\over{ {\rm d}t}} \Phi(t) \\ \end{align*}$$

For a linear function, the derivative can be substituted by Deltas ($\rm d \rightarrow \Delta$):
$$\begin{align*} u_{\rm ind} = - {{ \Delta \Phi(t)}\over{ \Delta t}} = - { { \Phi(t_{\rm n+1}) - \Phi(t_{\rm n}) } \over { t_{\rm n+1} - t_{\rm n} } } \\ \end{align*}$$

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 $\rm I$ to $\rm V$ from left to right:

$$\...in$$\...

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

$$\..in$$\...

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

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

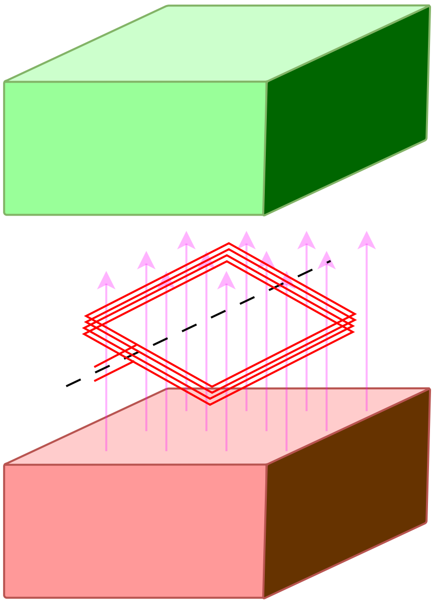
`$$\...in$$\...`

Exercise E12 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 $A = 600 ~\rm cm^2$ 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 $f = 80~\rm Hz$.
The maximum value of the magnetic flux density in the coil is $\hat{B} = 2 \cdot 10^{-6} ~\rm {{Vs}\over{cm^2}}$.

Result

$$\begin{aligned} u_{\rm ind} = - 181 {~\rm V} \cdot \cos(503 {{1}\over{\rm s}} \cdot t) \\ \end{aligned}$$



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

Path

The induced voltage $u_{\rm ind}$ is given by:

$$\begin{aligned} u_{\rm ind} &= - {{{\rm d}\Psi(t)}\over{{\rm d}t}} \\ &= - n{{{\rm d}\Phi(t)}\over{{\rm d}t}} \\ \end{aligned}$$

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:

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

This leads to: $$\begin{aligned} u_{\rm ind} &= - n{{{\rm d}}\over{{\rm d}t}}A \hat{B} \cdot \sin(2\pi f \cdot t + \varphi) \\ &= - n \cdot A \hat{B} \cdot 2\pi f \cdot \cos(2\pi \cdot f t + \varphi) \\ \end{aligned}$$

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

$$\begin{align*} \hat{U}_{\rm ind} &= n \cdot A \hat{B} \cdot 2\pi f \\ &= 300 \cdot 0.06{~\rm m^2} \cdot 2 \cdot 10^{-2} ~\rm {{Vs}\over{m^2}} \cdot 2\pi \cdot 80 {{1}\over{\rm s}} \\ &= 180.95... {~\rm m^2} \cdot {{\rm Vs}\over{\rm m^2}} \cdot {{1}\over{\rm s}} \\ &= 180.95... {~\rm V} \\ \end{align*}$$

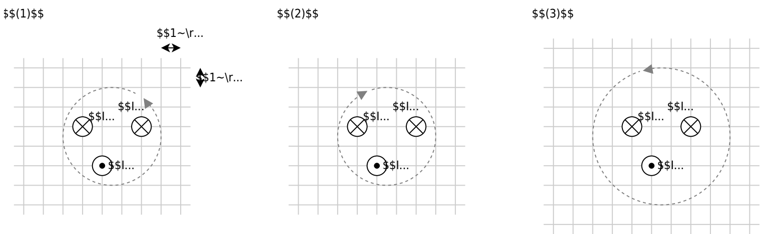
Exercise E13 Magnetic Voltage
(written test, approx. 6 % of a 120-minute written test, SS2021)

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:

- $I_1 = 5 {~\rm A}$
- $I_2 = 2 {~\rm A}$
- $I_3 = 1 {~\rm A}$
- $I_4 = 4 {~\rm A}$

Result

$$\begin{align*} \theta_{(1)} &= -4 {~\rm A} \\ \theta_{(2)} &= 0 {~\rm A} \\ \theta_{(3)} &= -5 {~\rm A} \\ \end{align*}$$



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

Exercise E16 Lorentz Force (hard!)
(written test, approx. 10 % of a 120-minute written test, SS2021)

A $300 ~\rm km$ long, straight high-voltage direct current transmission line shall be analyzed. A current of $I = 1'200 ~\rm A$ flows through it.

a) The picture below shows the top view again. In which of the directions shown does the horizontal component $F_{\rm h}$ of the resulting force act? (Independent)

A homogeneous geomagnetic field is assumed. The magnetic field strength has a vertical component of $B_{\rm v} = 40 ~\rm \mu T$ and a horizontal component of $B_{\rm h} = 20 ~\rm \mu T$.
The angle between the transmission line and the horizontal component of the field strength is $\alpha = 20 °$.
The picture on the right shows the line (black), the field strength components, and the angle in front and top view for illustration purposes.

Result

Only F_7 is perpendicular to $\vec{B}_{\rm v}$ and to $\vec{l}$ and points in the right direction by the right-hand rule.

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

Top View

Path

The force on the transmission line can be calculated via the Lorentz force $\vec{F}_\rm L$:

$$\begin{align*} \vec{F} = I \cdot (\vec{l} \times \vec{B}) \end{align*}$$

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 $B_{\rm v}$ generates a horizontal force $F_{\rm h}$ and vice versa.

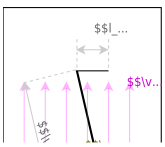
- The horizontal component $\vec{F}_{\rm h}$ of the force is based on the vertical component $\vec{B}_{\rm v}$ of the magnetic field.
- The vertical component $\vec{B}_{\rm v}$ of the magnetic field is not shown in the image but is pointing into the ground.
- It has to be perpendicular to $\vec{B}_{\rm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

The **horizontal component** is given by

\begin{align*} F_{\rm h} &= I \cdot (l \cdot B_{\rm v}) \\ &= 1′200 {~\rm A} \cdot 300 \cdot 10^3{~\rm m} \cdot 40 \cdot 10^{-6}{~\rm {{Vs}\over{m²}}} \\ &= 14'400 ~\rm {{VAs}\over{m}} = 14'400 ~\rm {{Ws}\over{m}} = 14'400 ~\rm N \end{align*}

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

Top View



\begin{align*} F_{\rm v} &= I \cdot l \cdot B_{\rm h} \cdot \sin\alpha \\ &= 1′200 {~\rm A} \cdot 300 \cdot 10^3{~\rm m} \cdot 40 \cdot 10^{-6}{~\rm {{Vs}\over{m²}}} \cdot \sin 20° \\ &= 2'462.545... ~\rm N \end{align*}

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

\begin{align*} F &= \sqrt{F_{\rm v}^2 +F_{\rm h}^2} \\ &= \sqrt{({14'400 ~\rm N})^2 +({2'462.545... ~\rm N})^2} \\ &= 14'609.04... ~\rm N \end{align*}

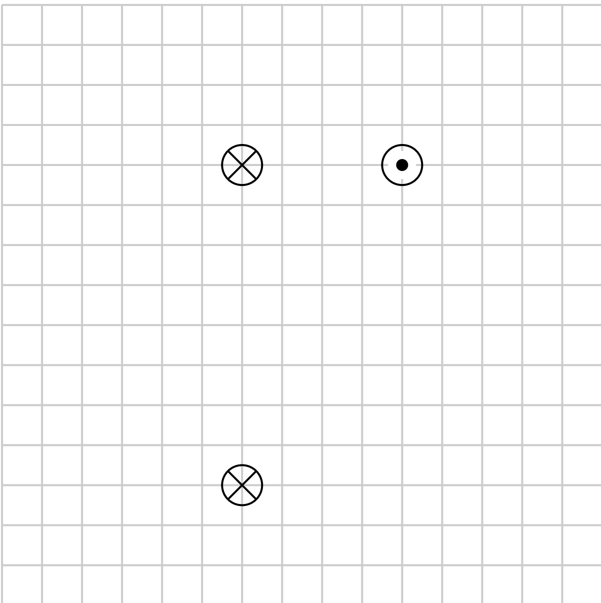
Full Exam

These is the full exam

Full exam

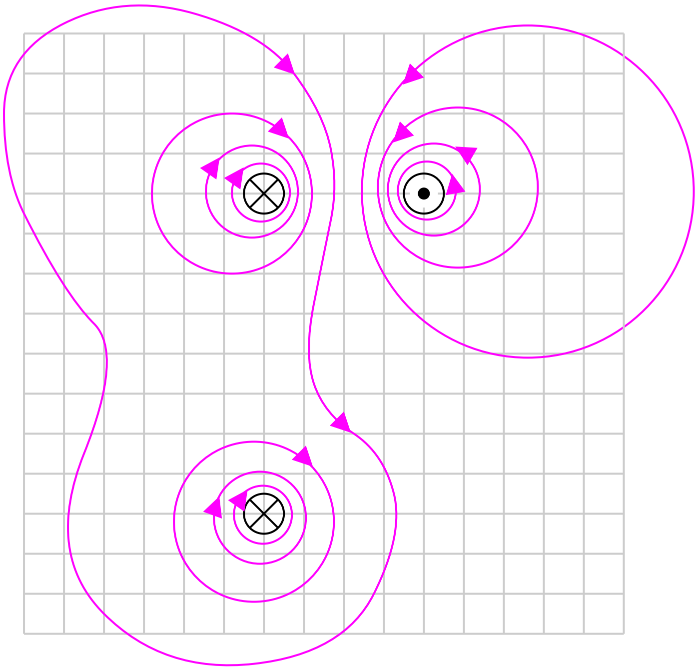
Exercise E2 Magnetic Field Lines
(written test, approx. 4 % of a 120-minute written test, SS2021)

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



electrical_engineering_and_electronics:task_76ksbc114ylxftfl_with_calculation
magnetostatic, field lines, exam ee2 ss2021

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

An electric motor is operated for experiments at the frequency. An alternating current with amplitude of $\hat{I} = 100~\rm A$ is operated. You stand next to it and think about whether you have any health problems to worry about. The figure below shows the top view of the laboratory with the supply line between $\rm A$ and $\rm B$.

A) The limit value for the magnetic flux density in the laboratory is $B_0 = 100~\rm \mu T$.
At what distance around the conductor is this value exceeded? (3 points, independent)

Result

Path

$B = 0.2 ~\rm m$ $r = 49 ~\rm mm$ μT

$\mu_{0} = 4\pi\cdot 10^{-7} {{\rm Vs}\over{\rm Am}}$, $\mu_{r}=1$

The formula for the magnetic field strength can be rearranged: \begin{align*} H &= {{I}\over{2\pi \cdot r}} \\ r &= {{I}\over{2\pi \cdot H}} \\ \end{align*}

Again, the magnetic flux density B is given as: $B = \mu_0 \mu_r H$ Therefore: \begin{align*} r &= \mu_0 \mu_r {{ I }\over{2\pi \cdot B}} \\ &= 4\pi\cdot 10^{-7} {{\rm Vs}\over{\rm Am}} {{100 ~\rm A}\over{2\pi \cdot 100\cdot 10^{-6} {~\rm T}}} \\ \end{align*}

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:

$$\begin{align*} H &= {{I}\over{2\pi \cdot r}} \end{align*}$$

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

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

Therefore: $$\begin{align*} B &= 4\pi\cdot 10^{-7} {{\rm Vs}\over{\rm Am}} \cdot 1 \cdot {{100 ~\rm A}\over{2\pi \cdot 0.412... ~\rm m}} \end{align*}$$

electrical_engineering_and_electronics:task_ti7loik6aurfewkb_with_calculation
magnetostatic, flux density, exam ee2 ss2021

Exercise E6 Toroidal Coil
(written test, approx. 5 % of a 120-minute written test, SS2021)

A magnetic field with a flux density of at least $50 ~\rm mT$ is to be achieved in a ring-shaped coil (toroidal coil).
The coil has 60 turns, wound around soft iron with $\mu_{\rm r} = 1200$.
The average field line length in the coil should be $l = 12 ~\rm cm$.

Result

$\mu_{0} = 4\pi\cdot 10^{-7} {{\rm Vs}\over{\rm Am}}$

$I = 66 ~\rm mA$

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{align*} H &= {{N \cdot I}\over{l}} \end{align*}

Based on the flux density the magnetic field strength can be derived by $B = \mu_0 \mu_{\rm r} \cdot H$.
By this, the formula can be rearranged:

\begin{align*} H &= {{N \cdot I}\over{l}} \\ {{B}\over{ \mu_0 \mu_{\rm r}}} &= {{N \cdot I}\over{l}} \\ I &= {{B \cdot l}\over{ \mu_0 \mu_{\rm r} \cdot N}} \end{align*}

Putting in the numbers: \begin{align*} I &= {{ 0.05 {~\rm T} \cdot 0.12{~\rm m} }\over{ 4\pi\cdot 10^{-7} {{\rm Vs}\over{\rm Am}} \cdot 1'200 \cdot 60}} \\ &= 0.6631... {{\rm T\cdot m}\over{ {{\rm Vs}\over{\rm Am}} }} &= 0.6631... {{\rm {{\rm Vs}\over{\rm m^2}} \cdot m}\over{ {{\rm Vs}\over{\rm Am}} }} &= 0.6631... ~\rm A \end{align*}

electrical_engineering_and_electronics:task_w3m7fo4hjahkzogw_with_calculation
magnetostatic, flux density, coil, toroid, exam ee2 ss2021

Exercise E8 Cylindrical Coil
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A cylindrical coil with the following information is given:

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- Winding diameter $□ = 390 {~\rm mm}$,
- Number of windings $□ = 240$,
- Current through the conductor $□ = 500 {~\rm mA}$,
- Material inside: Air
- $\mu_0 = 4\pi\cdot 10^{-7} {{\rm Vs}\over{\rm Am}}$

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

a) the magnetic field strength (2 points)

Path

b) the magnetic flux density (2 points)
Result

Path

The magnetic flux density is given as $B = \mu_0 \mu_{\rm r} \cdot H$:

\begin{align*} B &= \mu_0 \cdot H \end{align*}

Putting in the numbers: \begin{align*} B &= 4\pi\cdot 10^{-7} {{\rm Vs}\over{\rm Am}} \cdot 400 ~\rm {{A}\over{m}} \\ &= 0.0005026... {{\rm Vs}\over{\rm m^2}} \end{align*}

c) the magnetic flux (2 points)

The magnetic flux is given as

\begin{align*} \Phi &= B \cdot A \end{align*}

Since the coil is cylindrical, the cross-sectional area is given as

\begin{align*} A = \pi r^2 = \pi \left({{d}\over{2}} \right)^2 \end{align*}

Therefore: \begin{align*} \Phi &= B \cdot \pi \left({{d}\over{2}} \right)^2

\end{align*}

Putting in the numbers: \begin{align*} \Phi &= 0.0005026... {{\rm Vs}\over{\rm m^2}} \cdot \pi \left({{0.39{\rm m}}\over{2}} \right)^2 \\ &= 0.00006004... {\rm Vs} \end{align*}

\begin{align*} H &= {N \cdot I}\over{l}} = {{w \cdot I}\over{l}} \end{align*}

Putting in the numbers: \begin{align*} H &= {{240 \cdot 0.5 {~\rm A}}\over{0.3 {~\rm m}}} \end{align*}

electrical_engineering_and_electronics:task_0j7accfimmemytq9_with_calculation
magnetostatic, flux density, magnetic field strength, coil, flux, exam ee2 ss2021

Exercise E11 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 $u_{\rm ind}(t)$ over time and draw it in a separate diagram.

Result

$$u...in$$\...

$$\..in$$\...

Path

Based on Faraday's Law of Induction the induced voltage is given by:
\begin{align*} u_{\rm ind} =& - {{ {\rm d} }\over{ {\rm d}t}} \Psi(t) \bigg\rvert_{n=1}\\ =& - {{ {\rm d} }\over{ {\rm d}t}} \Phi(t) \\ \end{align*}

For a linear function, the derivative can be substituted by Deltas ($\rm d \rightarrow \Delta$):
\begin{align*} u_{\rm ind} = - {{ \Delta \Phi(t)}\over{ \Delta t}} = - { { \Phi(t_{\rm n+1}) - \Phi(t_{\rm n}) } \over { t_{\rm n+1} - t_{\rm n} } } \\ \end{align*}

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 $\rm I$ to $\rm V$ from left to right:

$$\..in$$\...

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

$$\..in$$\...

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

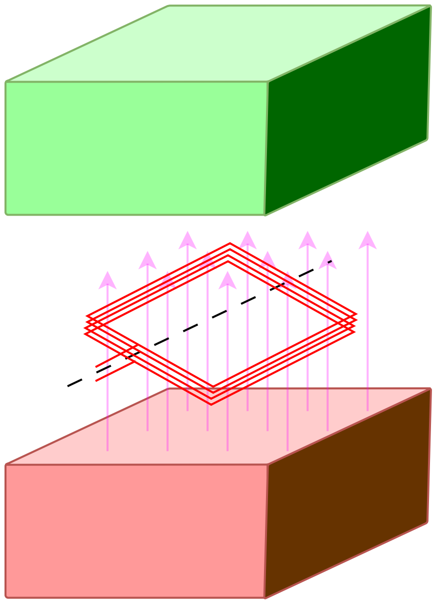
- For the interval $\rm IV$:
  - The change in the flux is: $ \Delta \Phi(t) = 0 \cdot 10^{-4} {~\rm Vs} - 1.5 \cdot 10^{-4} {~\rm Vs}= - 1.5 \cdot 10^{-4} {~\rm Vs}$
  - The time span is: $0.2 ~\rm s$
  - Conclusively, the induced voltage is: $u_{\rm ind}(t) = + {{1.5 \cdot 10^{-4} {~\rm Vs}} \over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

$$\...in$$\...

electrical_engineering_and_electronics:task_ludzwiuhjxitz85b_with_calculation
induction, flux, induced voltage, exam ee2 ss2021

Exercise E12 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 $A = 600 ~\rm cm^2$ 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 $f = 80~\rm Hz$.
The maximum value of the magnetic flux density in the coil is $\hat{B} = 2 \cdot 10^{-6} ~\rm {{Vs}\over{cm^2}}$.



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

Path

The induced voltage $u_{\rm ind}$ is given by:

$$\begin{align*} u_{\rm ind} &= - {{{\rm d}\Psi(t)}\over{{\rm d}t}} \\ &= - n{{{\rm d}\Phi(t)}\over{{\rm d}t}} \\ \end{align*}$$

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:

$$\begin{align*} B(t) &= \hat{B} \cdot \sin(\omega t + \varphi) \\ &= \hat{B} \cdot \sin(2\pi f \cdot t + \varphi) \\ \end{align*}$$

This leads to: \begin{align*} u_{\rm ind} &= - n{{{\rm d}}\over{{\rm d}t}}A \hat{B} \cdot \sin(2\pi f \cdot t + \varphi) \\ &= - n \cdot A \hat{B} \cdot 2\pi f

Result

$$\begin{align*} u_{\rm ind} = 181 {~\rm V} \cdot \cos(503 {{1}\over{\rm s}} \cdot t) \\ \end{align*}$$

\cdot \cos(2\pi \cdot f t + \varphi) \\ \end{align*}

The absolute value of the factor in front of the $\cos$ is the maximum induced voltage $\hat{U}_{\rm ind}$: \begin{align*} \hat{U}_{\rm ind} &= n \cdot A \hat{B} \cdot 2\pi f \\ &= 300 \cdot 0.06{~\rm m^2} \cdot 2 \cdot 10^{-2} ~\rm {{Vs}\over{m^2}} \cdot 2\pi \cdot 80 {{1}\over{\rm s}} \\ &= 180.95... {~\rm m^2} \cdot {{\rm Vs}\over{\rm m^2}} \cdot {{1}\over{\rm s}} \\ &= 180.95... {~\rm V} \\ \end{align*}

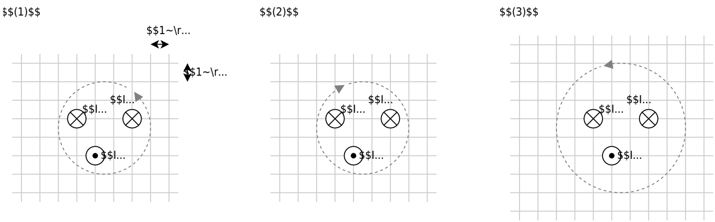
electrical_engineering_and_electronics:task_rdz03rspbwusy7wk_with_calculation
induction, coil, induced voltage, exam ee2 ss2021

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

The following images show cross-sections of electrical cables.
Result
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{align*} \theta_{(1)} &= -4 {~\rm A} \\ \theta_{(2)} &= 0 {~\rm A} \\ \theta_{(3)} &= -5 {~\rm A} \\ \end{align*}

- $I_1 = 5 {~\rm A}$
- $I_2 = 2 {~\rm A}$
- $I_3 = 1 {~\rm A}$
- $I_4 = 4 {~\rm A}$



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

electrical_engineering_and_electronics:task_jfzlmsucghsqvop5_with_calculation
magnetic voltage, exam ee2 ss2021

Exercise E16 Lorentz Force (hard!)
(written test, approx. 10 % of a 120-minute written test, SS2021)

A $300 ~\rm km$ long, straight high-voltage direct current transmission line shall be analyzed. A current of $I = 1'200 ~\rm A$ flows through it.
A homogeneous geomagnetic field is assumed. The magnetic field strength has a vertical component of $B_{\rm v} = 40 ~\rm \mu T$ and a horizontal component of $B_{\rm h} = 20 ~\rm \mu T$.
The angle between the transmission line and the horizontal component of the field strength is $\alpha = 20°$.
The picture on the right shows the line (black), the field strength components, and the angle in front and top view for illustration purposes.

a) The picture below shows the top view again. In which of the directions shown does the horizontal component of $\vec{F}_{\rm h}$ of the resulting force act? (Independent)

Result

Only option 7 is perpendicular to $\vec{B}_{\rm v}$ and to $\vec{l}$ and points in the right direction by the right-hand rule.

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

The force on the transmission line can be calculated via the Lorentz force $\vec{F}_\rm L$: \begin{align*} \vec{F} = I \cdot (\vec{l} \times \vec{B}) \end{align*}

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_{\rm

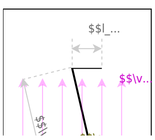
v}$ generates a horizontal force $F_{\rm h}$ and vice versa.

The **horizontal component** is given by

$$\begin{align*} F_{\rm h} &= I \cdot (l \cdot B_{\rm v}) \\ &= 1'200 {~\rm A} \cdot 300 \cdot 10^3{~\rm m} \cdot 40 \cdot 10^{-6}{~\rm {{Vs}\over{m^2}}} \\ &= 14'400 ~\rm {{VAs}\over{m}} = 14'400 ~\rm {{Ws}\over{m}} = 14'400 ~\rm N \end{align*}$$

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

Top View



$$\begin{align*} F_{\rm v} &= I \cdot l \cdot B_{\rm h} \cdot \sin\alpha \\ &= 1'200 {~\rm A} \cdot 300 \cdot 10^3{~\rm m} \cdot 40 \cdot 10^{-6}{~\rm {{Vs}\over{m^2}}} \cdot \sin 20° \\ &= 2'462.545... ~\rm N \end{align*}$$

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

$$\begin{align*} F &= \sqrt{F_{\rm v}^2 +F_{\rm h}^2} \\ &= \sqrt{({14'400 ~\rm N})^2 +({2'462.545... ~\rm N})^2} \\ &= 14'609.04... ~\rm N \end{align*}$$

electrical_engineering_and_electronics:task_elndbo3xwi2klxuu_with_calculation
lorentz force, exam ee2 ss2021

Exercise E18 Impedance Characteristics
(written test, approx. 6 % of a 120-minute written test, SS2021)

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

- $X_1 = 50 ~\rm \Omega$
- $X_2 = 121 ~\rm \Omega$
- $X_3 = 147 ~\rm \Omega$

Result

- $f_1 = 37.5~\rm kHz$
- $f_2 = 90.75~\rm kHz$
- $f_3 = 110.25~\rm kHz$

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.
This leads to: \begin{align*} {{X_n}\over{X_0}} &= {{f_n}\over{f_0}} \\ f_n &= {{X_n}\over{X_0}}\cdot f_0 = {{f_0}\over{X_0}}\cdot X_n \\ \end{align*}

Putting in the numbers: \begin{align*} f_n &= {{60 ~\rm kHz}\over{80~\rm \Omega}}\cdot X_n \\ &= 0.75 {{\rm \Omega}\over{\rm kHz}}\cdot X_n \\ \end{align*}

electrical_engineering_and_electronics:task_okznhljjycuqkbsh_with_calculation
impedance, inductor, exam ee2 ss2021

Exercise E20 Complex series circuit
(written test, approx. 8 % of a 120-minute written test, SS2021)

A series circuit of $C = 4.95~\rm nF$, $R = 200 ~\rm \Omega$ at $f = 40 ~\rm kHz$ shall be given.

b) Determine the absolute value of the resulting impedance of the series circuit using an impedance vector diagram. Pay attention to the correct dimensioning.

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

Result

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

Path

The complex impedance $\underline{Z}_C$ is given as \begin{align*} \underline{Z}_C &= {{1}\over{{\rm j} \cdot 2\pi \cdot f \cdot C }} \\ &= {{-{\rm j}}\over{2\pi \cdot 40 \cdot 10^3 ~\rm Hz \cdot 4.95 \cdot 10^{-9} ~\rm F }} \\ &= -{\rm j} \cdot 803.81... ~\rm \Omega \\ \end{align*}

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

electrical_engineering_and_electronics:task_9xy69axg3gi3nr26_with_calculation

complex voltage divider, exam ee2 ss2021

Exercise E22 Component Parameters
(written test, approx. 10 % of a 120-minute written test, SS2021)

The equivalent circuit diagram of a motor represents a resistive-inductive load. The values of the series resistance $R_{\rm M}$ and the inductance $L_{\rm M}$ are to be determined below. Both result in the impedance of the motor.

For the next exercises consider the following:

In two measurements, an AC voltage with a constant RMS value of $U = U_1 = U_2 = 50 ~\rm V$ but two different frequencies, f_1 and f_2 was applied.

This resulted in the recorded current of

- for $f_1 = 50~\rm Hz$: $I_1 = 8~\rm A$
- for $f_2 = 100~\rm Hz$: $I_2 = 5~\rm A$

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

Result

\begin{align*} Z = \sqrt{ (2\pi \cdot f \cdot L_{\rm M})^2 + R_{\rm M}^2 } \end{align*}

Path

The complex impedance $\underline{Z}$ for a resistive-inductive load (= R-L series circuit) is given as \begin{align*} \underline{Z} &= {\rm j} \cdot X_L + R_{\rm M} \\ &= {\rm j} \cdot 2\pi \cdot f \cdot L_{\rm M} + R_{\rm M} \\ \end{align*}

The Pythagorean theorem can derive the absolute value: \begin{align*} |\underline{Z}| &= \sqrt{ (2\pi \cdot f \cdot L_{\rm M})^2 + R_{\rm M}^2 } \end{align*}

b) Determine the absolute values of the impedances from the specified RMS values at f_1 and f_2 (independent).

Result

- $Z_1 = 6.25 ~\rm \Omega$
- $Z_2 = 10 ~\rm \Omega$

Path

The absolute value of the impedance is given as $Z = {{U}\over{I}}$.

This leads to:

- $Z_1 = {{U_1}\over{I_1}} = {{50 ~\rm V}\over{8~\rm A}}$
- $Z_2 = {{U_2}\over{I_2}} = {{50 ~\rm V}\over{5~\rm A}}$

c) Determine the component parameters $R_{\rm M}$ and $L_{\rm M}$ from a) and b)!

Result

- $R_{\rm M} = 4.33 ~\rm \Omega$
- $L_{\rm M} = 14.35 ~\rm mH$

Path

Since we have Z_1 and Z_2 from b) we can subtract two of the formulas from a).

This has the advantage that $R_{\rm M}$ will cancel out: \begin{align*} Z_2^2 - Z_1^2 &= (2\pi \cdot f_2 \cdot L_{\rm M})^2 + R_{\rm M}^2 - \left((2\pi \cdot f_1 \cdot L_{\rm M})^2 + R_{\rm M}^2 \right) \\ &= (2\pi \cdot f_2)^2 \cdot L_{\rm M}^2 - (2\pi \cdot f_1)^2 \cdot L_{\rm M}^2 \\ \end{align*}

Now we can rearrange to $L_{\rm M}^2$:

\begin{align*} Z_2^2 - Z_1^2 &= L_{\rm M}^2 \cdot \left((2\pi \cdot f_2)^2 - (2\pi \cdot f_1)^2 \right) \\ L_{\rm M}^2 &= {{Z_2^2 - Z_1^2} \over { (2\pi \cdot f_2)^2 - (2\pi \cdot f_1)^2 }} \\ L_{\rm M}^2 &= {{Z_2^2 - Z_1^2} \over { (2\pi)^2 \cdot (f_2^2 - f_1^2) }} \\ \end{align*}

And then to $L_{\rm M}$:

\begin{align*} L_{\rm M} &={{1}\over{2\pi}} \sqrt{{{Z_2^2 - Z_1^2} \over { f_2^2 - f_1^2 }} }\\ \end{align*}

With the values:

\begin{align*} L_{\rm M} &={{1}\over{2\pi}} \sqrt{{{(10~\Omega)^2 - (6.25~\Omega)^2} \over { (100 {{1}\over{s}})^2 - (50 {{1}\over{s}})^2 }} }\\ &=14.346... ~\rm mH\\ \end{align*}

The resistance value $R_{\rm M}$ can be derived from \begin{align*} Z_2^2 &= (2\pi \cdot f_2 \cdot L_{\rm M})^2 + R_{\rm M}^2 \\ R_{\rm M}^2 &= Z_2^2 - (2\pi \cdot f_2 \cdot L_{\rm M})^2 \\ R_{\rm M} &=\sqrt{ Z_2^2 - (2\pi \cdot f_2 \cdot L_{\rm M})^2}\\ \end{align*}

The values have to be inserted also for $R_{\rm M}$: \begin{align*} R_{\rm M} &=\sqrt{ (10~\rm \Omega)^2 - (2\pi \cdot 100 {{1}\over{s}} \cdot 0.014346... ~\rm H)^2}\\ &= 4.3301...~\Omega \end{align*}

electrical_engineering_and_electronics:task_wjttvmydrskzhcim_with_calculation
complex voltage divider, rms, inductor, exam ee2 ss2021

Exercise E23 Signal Analysis
(written test, approx. 6 % of a 120-minute written test, SS2021)

At an AC consumer, the following ... were measured:
The quantities are available in the consumer arrow system. (hard)

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

Result

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

Amplitude values:

- $f = 955 ~\rm Hz$
- $\hat{U} = 50{~\rm V}$
- $\hat{I} = 30{~\rm A}$

Path

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

\begin{align*} \omega &= 6000 {{1}\over{\rm s}} \\ 2\pi \cdot f &= 6000 {{1}\over{\rm s}} \\ f &= {{6000}\over{2\pi}} {{1}\over{\rm s}} \\ f &= 954.93... ~\rm Hz \\ \end{align*}

RMS values:

- $U = 35.4{~\rm V}$
- $I = 21.2{~\rm A}$
- $\varphi = +32.7°$

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

The phase shift is positive, therefore the element is resistive-inductive.

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

- $\varphi_i = 5$
- $\varphi_u = 4 + {{\pi}\over{2}}$

By this we get for φ \begin{align*} \varphi &= \varphi_u - \varphi_i \\ &= 4 + {{\pi}\over{2}} - 5 \\ &= 2.14159... \\ \end{align*}

Converted in degree: \begin{align*} \varphi &= 2.14159... \cdot

{{360°}\over{2\pi}} \\ &= 32.7042...° \\ \end{align*}

electrical_engineering_and_electronics:task_abh4vhlgczdbni37_with_calculation
signal analysis, rms, exam ee2 ss2021

Exercise E25 Resonant Circuit
(written test, approx. 4 % of a 120-minute written test, SS2021)

Given a resonant circuit, that is fed by a linear voltage source (circuit diagram on the right).
6) How large must R be, so that the voltage across the capacitor is $U_C = 4\cdot U_{\rm s}$? (independent)
Result
The inductance L and capacitance C are fixed. The resistance R can be varied.

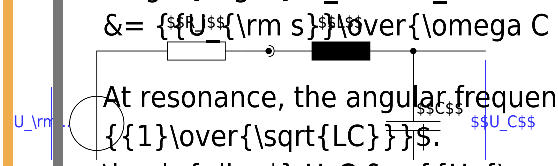
Path
- $u_{\rm s} = 12{~\rm V} \cdot \sin (2 \pi \cdot f_0 \cdot t) $
- $f_0 = 205.5 ~\rm Hz$
- $R_i = 0.25~\Omega$
- $R = 6.2055~\Omega$
- $L = 20~\rm mH$
- $C = 30~\rm \mu F$

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

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

When the gain factor is not known, one has to derive it:
The voltage I at resonance is only given by the total ohmic resistance R_Σ and the source voltage $U_{\rm s}$: \begin{align*} I = {{U_{\rm s}}\over{R_\Sigma}} \end{align*}

This current flow also through the impedance of the capacitor \begin{align*} U_C &= Z_C \cdot I \\ &= {{1}\over{\omega C}} \cdot I \\ &= {{U_{\rm s}}\over{\omega C R_\Sigma }} \\ \end{align*}



At resonance, the angular frequency ω is given by $\omega= {{1}\over{\sqrt{LC}}}$.
\begin{align*} U_C &= {{U_{\rm s}}\over{{{1}\over{\sqrt{LC}}} C R_\Sigma }} \\ &= {{U_{\rm s}}\over{\sqrt{{{C}\over{L}}} R_\Sigma }} \\ &= {{U_{\rm s}}\over{R_\Sigma }} \sqrt{{{L}\over{C}}} \\ \end{align*}

a) What is the resonance frequency f_0?

Path

In both cases, we end up with the same formula, where we have to insert the physical values: \begin{align*} R_\Sigma &= {{U_{\rm s}}\over{U_C}} \sqrt{ {{L}\over{C}} } \\ &= {{1}\over{4}} \sqrt{ {{20\cdot 10^{-3} ~\rm H}\over{30\cdot 10^{-6} ~\rm C}} } \\ &= 6.4549...~\Omega \\ \end{align*}

The resonant frequency f_0 is given as \begin{align*} f_0 = {{1}\over{ 2\pi \sqrt{LC} }} \end{align*}

With the values \begin{align*} ... \end{align*}

And so, the resistance is $R_{\rm Ω}$ ... 6.4549 ... 205.4681 ...

electrical_engineering_and_electronics:task_nyniewamxfshpuwt_with_calculation
resonance, resonant circuit, rms, exam ee2 ss2021

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

A symmetrical three-phase consumer is connected. Consider the following.

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

Through each of the windings, there is a current with an RMS value $I_{\rm RMS} = 5~\rm A$ and a phase shift of $\varphi = +25°$ compared to the voltage.

a) Draw the circuit diagram.

b) **Specify the RMS values of the phase current $I_\rm L$ and the string voltage $U_\rm S$.**

Path

Since the given current of $I_{\rm RMS} = 5~\rm A$ is running through each winding, this is also the string current $I_{\rm S}$. Since the voltage $U_{\rm RMS} = 110~\rm V$ is applied between the terminals of each winding, this is also the string voltage $U_\rm S$.

For the phase current $I_\rm L$, one has to consider that at each node the sum of the currents is zero (as shown in the example in the image below). One can see, that $I_\rm L= \sqrt{3} \cdot I_{\rm RMS} = \sqrt{3} \cdot 5~\rm A$

Result

- $U_{\rm S} = 110~\rm V$
- $I_{\rm L} = 8.66~\rm A$

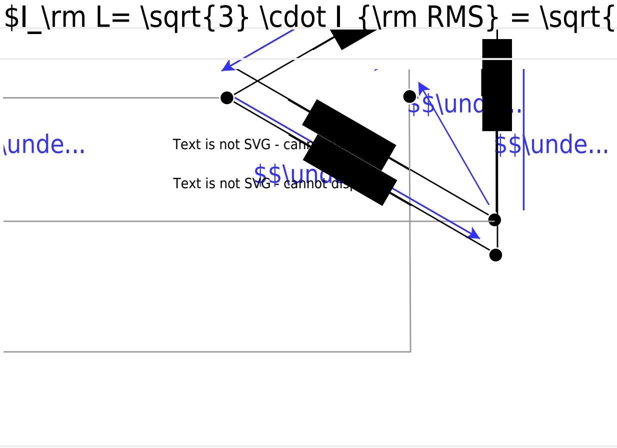
c) **Specify the active power.**

Path

The active power P is given by: $P = 3 \cdot U \cdot I \cdot \sin(\varphi)$
\begin{align*} P &= 3\cdot 110{~\rm V} \cdot 5{~\rm A} \cdot \sin(25°) \\ &= 1610.888...~\rm W \end{align*}

Result

$W = 1.61 ~\rm kW$



one single phase as an example

electrical_engineering_and_electronics:task_ezrkjzifcegttcpc_with_calculation
multiphase systems, rms, power, exam ee2 ss2021