

Exam Winter Semester 2022

Student Group

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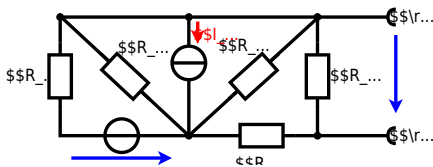
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~~StartTask~~

Exercise E1 Equivalent linear Source (written test, approx. 14 % of a 60-minute written test, WS2022)

The circuit in the following has to be simplified.
Result

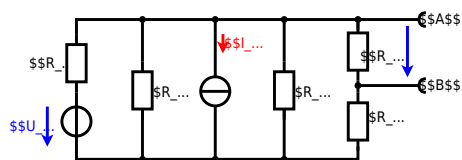
$$\begin{aligned} U_{\text{rs}} &= U_{\text{AB}} = 4.5 \text{ V} \\ R_{\text{i}} &= R_{\text{AB}} = 6 \Omega \end{aligned}$$



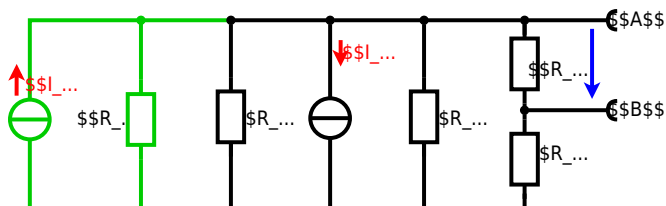
Calculated the internal resistance R_{i} and the source voltage U_{rs} of an equivalent linear voltage source on the connectors A and B .
$$\begin{aligned} R_1 &= 5.0 \Omega, \quad U_2 = 6.0 \text{ V}, \quad R_3 = 10 \Omega, \quad I_4 = 4.2 \text{ A}, \\ R_5 &= 10 \Omega, \quad R_6 = 7.5 \Omega, \quad R_7 = 15 \Omega \end{aligned}$$
 Use equivalent sources in order to simplify the circuit!

Solution

The best thing is to re-think the wiring like rubber bands and adjust them:



The linear voltage source of U_2 and R_1 can be transformed into a current source $I_2 = \frac{U_2}{R_1}$ and R_1 :



Now a lot of them can be combined. The resistors R_1 , R_3 , R_5 are in parallel, like also I_2 and I_4 :

$$R_{135} = R_1 || R_3 || R_5$$

$$I_{24} = I_2 - I_4 = \frac{U_{24}}{R_1} - I_4$$

The resulting circuit can again be transformed:



Here, the U_{24} is calculated by I_{24} as the following:

$$U_{24} = I_{24} \cdot R_{135}$$

$$I_{24} = \frac{U_{24}}{R_6 + R_7 + R_1 || R_3 || R_5} = \frac{(U_2 - I_4) \cdot R_1 || R_3 || R_5}{R_6 + R_7 + R_1 || R_3 || R_5}$$

On the right side of the last circuit, there is a voltage divider given by R_{135} , R_6 , and R_7 .

$$U_{AB} = U_{24} \cdot \frac{R_7}{R_6 + R_7 + R_1 || R_3 || R_5} = (U_2 - I_4) \cdot \frac{R_7 \cdot R_1 || R_3 || R_5}{R_6 + R_7 + R_1 || R_3 || R_5}$$

For the internal resistance R_i the ideal voltage source is substituted by its resistance ($=0\Omega$, so a short-circuit): $R_{AB} = R_7 || (R_6 + R_1 || R_3 || R_5)$

with $R_1 || R_3 || R_5 = 5\Omega || 10\Omega || 10\Omega = 5\Omega || 5\Omega = 2.5\Omega$:

$$U_{AB} = \frac{6.0V}{5.0\Omega} - 4.2\Omega \cdot \frac{15\Omega \cdot 2.5\Omega}{7.5\Omega + 15\Omega + 2.5\Omega} \quad R_{AB} = 15\Omega || (7.5\Omega + 2.5\Omega)$$

end~~~StartTask~~~

Exercise E1 Temperature-dependent Resistance (written test, approx. 6 % of a 60-minute written test, WS2022)

2. The given diagram shows a thermistor with a resistance of 10Ω at 25°C . The thermistor has a resistance of 10Ω at 25°C and a temperature coefficient of $\alpha = 0.01\text{K}^{-1}$ and $\beta = 71 \cdot 10^{-6}\text{K}^{-2}$. Calculate the resistance of the thermistor at -40°C .

Result: The temperature inside the refrigeration system can reach down to -40°C .

Calculate the resistance of the thermistor at -40°C .

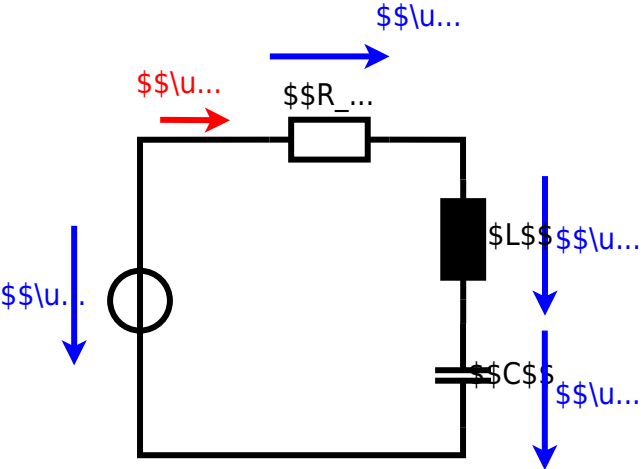
$$R = R_0 \cdot (1 + \alpha \cdot \Delta T + \beta \cdot \Delta T^2) \quad R = 10\Omega \cdot (1 + 0.01 \cdot (-40 - 25) + 71 \cdot 10^{-6} \cdot (-40 - 25)^2)$$

The power of the resistor $P = U^2 / R$ and $U = 2V$ is constant. Therefore, a solution is to increase the resistance of the thermistor.

Therefore, with constant U and increasing R the power decreases. Ten times more resistance decreases the heat flow to one-tenth.

$$R = R_0 \cdot (1 + \alpha \cdot \Delta T + \beta \cdot \Delta T^2) \quad R = 10\Omega \cdot (1 + 0.01 \cdot (-40 - 25) + 71 \cdot 10^{-6} \cdot (-40 - 25)^2)$$

[illegible]



end~~StartTask~~

Exercise E1 Impedances at different Frequencies (written test, approx. 18 % of a 60-minute written test, WS2022)

2. A series circuit consists of a resistor $R_1 = 1.00 \text{ k}\Omega$, a capacitor $C_1 = 40 \text{ nF}$, and an AC voltage source $U = 10 \text{ V}$ at $f = 4 \text{ MHz}$. The current I is 1.00 mA . The voltage U_R across the resistor R_1 shall have the same absolute value of the impedance as a capacitor C_2 at $f_2 = 4 \text{ MHz}$. Calculate the value of C_2 .

Solution

$$U_R = I \cdot R_1 = 1.00 \text{ V}$$

$$U_C = I \cdot X_C = 1.00 \text{ V}$$

A series circuit means that the current is constant on every component.

The equivalent impedance for R and L combined is given by

$$Z = R + jX_L = R + j\omega L$$

$$|Z|^2 = R^2 + X_L^2$$

Therefore the resulting current of the parallel circuit is given as:

$$I = \frac{U}{Z}$$

$$I^2 = \frac{U^2}{Z^2} = \frac{U^2}{R^2 + X_L^2}$$

$$R^2 + X_L^2 = \frac{U^2}{I^2}$$

$$R^2 + X_L^2 = \frac{U^2}{I^2}$$

end~~StartTask~~

Exercise E1 Resistance of a Wire by Resistivity (written test, approx. 6 % of a 60-minute written test, WS2022)

2. The heating element is used to heat the wire with a temperature of 180°C . The power dissipation (= heat flow) of $P = 40 \text{ W}$ is necessary.

Calculate the current I needed to operate the heating element.

The Nichrome wire has a resistivity of $1.10 \cdot 10^{-6} \text{ }\Omega\text{m}$.

The heating element is 3 m long and has a diameter of 3.57 mm .

Calculate the resistance R of the heating element.

Solution

$$\begin{aligned} P &= U \cdot I = R \cdot I^2 \quad \rightarrow \quad I = \sqrt{\frac{P}{R}} = \sqrt{\frac{40 \text{ W}}{0.33 \text{ } \Omega}} \end{aligned}$$

$$\begin{aligned} R &= \rho \cdot \frac{l}{A} \quad \& \quad A = r^2 \cdot \pi = \frac{1}{4} d^2 \cdot \pi \quad \& \quad R = \rho \cdot \frac{4 \cdot l}{d^2 \cdot \pi} \quad \& \quad R = 1.10 \cdot 10^{-6} \text{ } \Omega \cdot \frac{4 \cdot 3 \text{ m}}{(3.57 \cdot 10^{-3} \text{ m})^2 \cdot \pi} \end{aligned}$$

end~~StartTask~~

Exercise E1 Charging Capacitors

(written test, approx. 16 % of a 60-minute written test, WS2022)

The circuit (without the light bulb) also takes the form of an RC circuit. The voltage across the capacitor is again 0 V at the moment $t_0 = 0 \text{ s}$ when the switch S_1 is closed. Calculate the voltage $u_c(t_2)$ across the capacitor at $t_2 = 1 \text{ ms}$ after closing the switch.

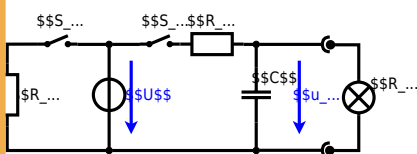
Solution

Hint: To solve this, first create an equivalent linear voltage source from U , R_1 , and R_2 .

$$\begin{aligned} \Delta U &= U - R_2 \cdot I = U - R_2 \cdot \frac{U}{R_1 + R_2} = U \cdot \frac{R_1}{R_1 + R_2} \end{aligned}$$

Solution **begin{align*}** $\Delta U = U \cdot \frac{R_1}{R_1 + R_2} = 12 \text{ V} \cdot \frac{20 \text{ } \Omega}{20 \text{ } \Omega + 10 \text{ } \Omega} = 8 \text{ V}$ **\end{align*}**

On an alternative view, one can try to create an equivalent linear voltage source again. Then, the internal resistance is given by substituting the ideal voltage source is again short-circuiting R_2 .



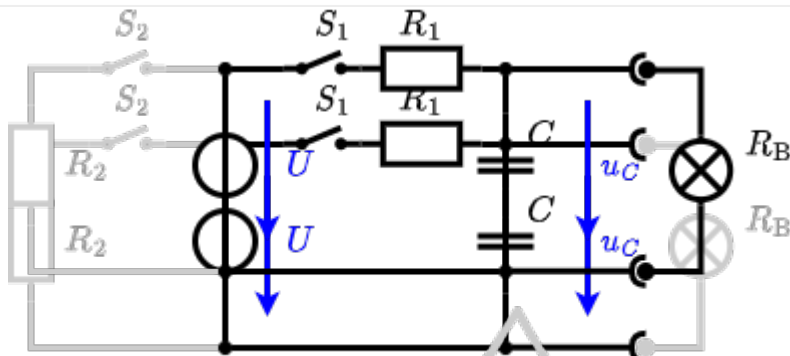
The circuit contains a voltage source $U = 12 \text{ V}$, a switch S_1 , a resistor of $R_1 = 20 \text{ } \Omega$ and a capacitor of $C = 100 \text{ } \mu\text{F}$.

The switch S_2 to an additional consumer R_2 will be considered to be open for the first tasks. At the moment $t_0 = 0 \text{ s}$ the switch S_1 is closed, the voltage across the capacitor is $u_c(t_0) = 0 \text{ V}$.

1. First do not consider the light bulb – it is not connected to the RC circuit.

Calculate the point of time t_1 when $u_c(t_1) = 0.5 \cdot U$.

Solution



So, here only R_1 and C gives the time constant: $\tau = R_1 \cdot C$

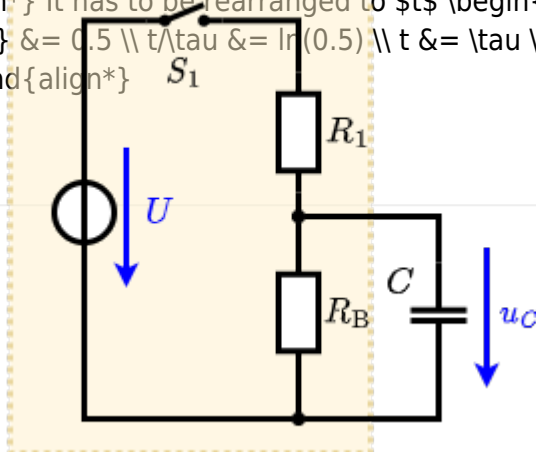
The following formula describes the time course of $u_c(t)$ which has to be $u_c(t_1) = 0.5 \cdot U$:

$$u_c(t) = U \cdot (1 - e^{-t/\tau}) = 0.5 \cdot U$$

It has to be rearranged to t :

$$(1 - e^{-t/\tau}) = 0.5 \implies e^{-t/\tau} = 0.5 \implies -t/\tau = \ln(0.5) \implies t = \tau \cdot \ln(0.5) = R_1 \cdot C \cdot \ln(0.5)$$

S_1



An equivalent linear voltage source can be given with U , R_1 , and R_{B} as seen in yellow.

Therefore, the voltage of the equivalent linear voltage source is: $U_s = U \cdot \frac{R_B}{R_1 + R_B} = 1/2 \cdot U$ The internal resistance is given by substituting the ideal voltage source with its resistance ($=0 \sim \Omega$, short-circuit).

$$R_i = R_1 \parallel R_B = 10 \sim \Omega$$

$$\begin{aligned} u_c(t_2) &= U_s \cdot (1 - e^{t_2/(R_i \cdot C)}) \parallel \&= \{1\over 2\} \\ &\cdot U \cdot (1 - e^{1 \sim \rm ms / (10 \sim \Omega \cdot 100 \sim \mu F)}) \end{aligned}$$

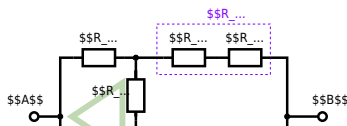
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end~~StartTask~~
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Exercise E1 Pure Resistor Network Simplification (written test, approx. 13 % of a 60-minute written test, WS2022)

The following shall in with \$B₁ use 200 at 0 rate, the \$R₂ a R₃ = 1.00 at 0 on \$a\$ and 0.5 between \$B₁ and \$B₂.

Solution

R_{eq} is given as:



Since $R_2 = R_3$ and based on the equations for the transformation, the transformed R_Y is given as:

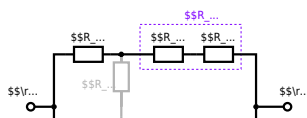
$$R_Y = \frac{R_2 \cdot R_2}{R_2 + R_2 + R_2} = \frac{(100 \, \Omega)^2}{3 \cdot 100 \, \Omega} = \frac{1}{3} \cdot 100 \, \Omega = 33.33 \, \Omega$$

The equivalent resistor is given by a parallel configuration of resistors in series:

$$R_{\text{eq}} = R_Y + (R_Y + R_1 + R_1) \parallel (R_Y + R_2) \parallel R_{\text{eq}} = 33.33 \, \Omega + (33.33 \, \Omega + 400 \, \Omega) \parallel (33.33 \, \Omega + 100 \, \Omega)$$

1. The switch shall now be open. Calculate the equivalent resistance R_{eq} between A and B.

Solution



The equivalent resistor is given by a parallel configuration of resistors in series:

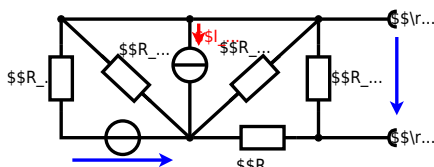
$$R_{\text{eq}} = (R_2 + R_1 || R_3) || R_4 = (100 \, \Omega + 200 \, \Omega || 200 \, \Omega) || (100 \, \Omega + 100 \, \Omega) = (500 \, \Omega) || (200 \, \Omega) = \frac{500 \, \Omega \cdot 200 \, \Omega}{500 \, \Omega + 200 \, \Omega}$$

end~~StartTask~~

Exercise E4 Equivalent linear Source (written test, approx. 14 % of a 60-minute written test, WS2022)

The circuit in the following has to be simplified.
Result

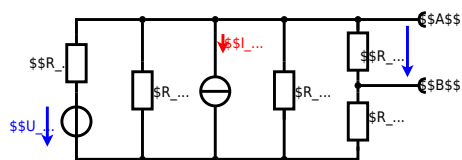
$$U_s = U_{AB} = 4.5 \, \text{V} \quad R_i = R_{AB} = 6 \, \Omega$$



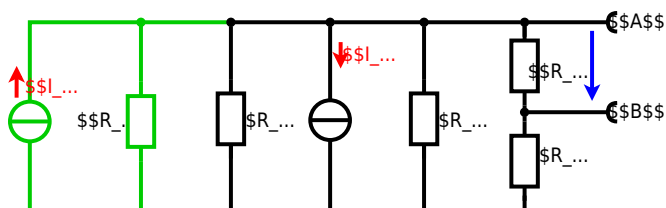
Calculate the internal resistance R_i and the source voltage U_s of an equivalent linear voltage source on the connectors A and B. $R_1=5.0 \, \Omega$, $U_2=6.0 \, \text{V}$, $R_3=10 \, \Omega$, $I_4=4.2 \, \text{A}$, $R_5=10 \, \Omega$, $R_6=7.5 \, \Omega$, $R_7=15 \, \Omega$ Use equivalent sources in order to simplify the circuit!

Solution

The best thing is to re-think the wiring like rubber bands and adjust them:



The linear voltage source of U_2 and R_1 can be transformed into a current source $I_2 = \frac{U_2}{R_1}$ and R_1 :



Now a lot of them can be combined. The resistors R_1 , R_3 , R_5 are in parallel, like also I_{12} and I_{14} :

$$R_{135} = R_1 || R_3 || R_5$$

$$I_{24} = I_{12} - I_{14} = \frac{U_{24}}{R_1} - I_{14}$$

The resulting circuit can again be transformed:



Here, the U_{24} is calculated by I_{24} as the following:

$$U_{24} = I_{24} \cdot R_{135}$$

$$\&= R_{135} \cdot I_{24} \quad \&= \left(\frac{U_2}{R_1} - I_4 \right) \cdot R_1 \parallel R_3 \parallel R_5$$

On the right side of the last circuit, there is a voltage divider given by R_{135} , R_6 , and R_7 .

Therefore the voltage between A and B is given as:

$$U_{AB} = U_{24} \cdot \frac{R_7}{R_6 + R_7 + R_1 \parallel R_3 \parallel R_5} = \left(\frac{U_2}{R_1} - I_4 \right) \cdot \frac{R_7 \cdot R_1 \parallel R_3 \parallel R_5}{R_6 + R_7 + R_1 \parallel R_3 \parallel R_5}$$

For the internal resistance R_i the ideal voltage source is substituted by its resistance ($=0\Omega$, so a short-circuit):

$$R_{AB} = R_7 \parallel (R_6 + R_1 \parallel R_3 \parallel R_5)$$

with $R_1 \parallel R_3 \parallel R_5 = 5\Omega \parallel 10\Omega \parallel 10\Omega = 5\Omega \parallel 5\Omega = 2.5\Omega$:

$$U_{AB} = \frac{6.0\text{V}}{5.0\Omega} - 4.2\Omega \cdot \frac{15\Omega \cdot 2.5\Omega}{7.5\Omega + 15\Omega + 2.5\Omega} \quad R_{AB} = 15\Omega \parallel (7.5\Omega + 2.5\Omega)$$

end~~~StartTask~~~

Exercise E2 Temperature-dependent Resistance (written test, approx. 6 % of a 60-minute written test, WS2022)

2. The given diagram shows a thermistor with a temperature coefficient of resistance $\alpha = 0.01\text{K}^{-1}$ and a reference resistance $R_0 = 10\text{k}\Omega$ at $T_0 = 25^\circ\text{C}$. The thermistor has a resistance of $10\text{k}\Omega$ at $T_0 = 25^\circ\text{C}$. Calculate the resistance R at $T = -40^\circ\text{C}$.

Its temperature coefficients are: $\alpha = 0.01\text{K}^{-1}$ and $\beta = 71 \cdot 10^{-6}\text{K}^2$.

Result The temperature inside the refrigeration system can reach down to -40°C .

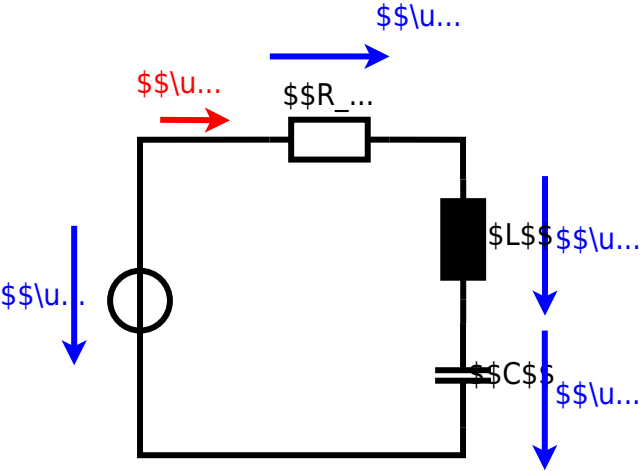
$$R = 10\text{k}\Omega \cdot \left(1 + \alpha \cdot \Delta T + \beta \cdot \Delta T^2 \right)$$

The power of the resistor $P = U^2/R$ decreases with increasing resistance R . Therefore, a solution is to use a higher resistance up the refrigeration system.

Therefore, with constant U and increasing R the power decreases. Ten times more resistance decreases the heat flow to one-tenth.

$$R = R_0 \cdot \left(1 + \alpha \cdot \Delta T + \beta \cdot \Delta T^2 \right) \quad \text{with } \Delta T = T_{\text{end}} - T_{\text{start}} \quad R = 10\text{k}\Omega \cdot \left(1 + 0.01\text{K}^{-1} \cdot (-40^\circ\text{C} - 25^\circ\text{C}) + 71 \cdot 10^{-6}\text{K}^2 \cdot (-40^\circ\text{C} - 25^\circ\text{C})^2 \right)$$

[illegible]



end~~StartTask~~

Exercise E7 Impedances at different Frequencies (written test, approx. 18 % of a 60-minute written test, WS2022)

2. A series circuit consists of a resistor with a resistance of $R_1 = 1.00 \text{ k}\Omega$, a capacitor with a capacitance of $C_1 = 40 \text{ nF}$, and an AC voltage source with a voltage of $U = 10 \text{ V}$ and a frequency of $f = 4 \text{ MHz}$. The current through the circuit is $I = 1.00 \text{ mA}$. Calculate the resistance R_2 of the resistor R_2 in parallel with the capacitor C_1 so that the current through the resistor R_1 is $I_1 = 1.00 \text{ mA}$.

Solution

$$R_1 = 1.00 \text{ k}\Omega$$

$$R_2 = 10.0 \text{ k}\Omega$$

A series circuit means that the current is constant on every component.

The equivalent impedance for R_1 and C_1 combined is given by

$$Z_{\text{eq}} = R_1 + \frac{1}{j\omega C_1} = R_1 - j\frac{1}{\omega C_1}$$

Since R_1 and C_1 are in series, the voltage across R_1 is $U_{R_1} = I \cdot R_1$ and the voltage across C_1 is $U_{C_1} = I \cdot \frac{1}{j\omega C_1}$. The total voltage is $U = U_{R_1} + U_{C_1}$.

Therefore, the resulting current of the parallel circuit is given as:

$$I = I_{R_1} + I_{C_1}$$

$$I = \frac{U}{Z_{\text{eq}}} = \frac{U}{R_1 + \frac{1}{j\omega C_1}} = \frac{U}{R_1 - j\frac{1}{\omega C_1}}$$

$$I = \frac{U}{R_1 + \frac{1}{j\omega C_1}} = \frac{U}{R_1 - j\frac{1}{\omega C_1}} = \frac{U}{R_1 + \frac{1}{j\omega C_1}}$$

$$I = \frac{U}{R_1 + \frac{1}{j\omega C_1}} = \frac{U}{R_1 - j\frac{1}{\omega C_1}} = \frac{U}{R_1 + \frac{1}{j\omega C_1}}$$

end~~StartTask~~

Exercise E1 Resistance of a Wire by Resistivity (written test, approx. 6 % of a 60-minute written test, WS2022)

2. The heating element is used to heat the wire with a temperature of $T = 1800 \text{ K}$. The power dissipation (= heat flow) of $P = 40 \text{ W}$ is necessary.

Calculate the current I in the heating element.

The Nichrome wire has a resistivity of $\rho = 1.10 \cdot 10^{-6} \text{ }\Omega \cdot \text{m}$.

The heating element is $l = 3 \text{ m}$ long and has a diameter of $d = 3.57 \text{ mm}$.

Calculate the resistance R of the heating element.

Solution

$$\begin{aligned} P &= U \cdot I = R \cdot I^2 \quad \rightarrow \quad I = \sqrt{\frac{P}{R}} = \sqrt{\frac{40 \text{ W}}{0.33 \text{ } \Omega}} \end{aligned}$$

$$\begin{aligned} R &= \rho \cdot \frac{l}{A} \quad \& \quad A = r^2 \cdot \pi = \frac{1}{4} d^2 \cdot \pi \quad \& \quad R = \rho \cdot \frac{4 \cdot l}{d^2 \cdot \pi} \quad \& \quad R = 1.10 \cdot 10^{-6} \text{ } \Omega \cdot \frac{4 \cdot 3 \text{ m}}{(3.57 \cdot 10^{-3} \text{ m})^2 \cdot \pi} \end{aligned}$$

end~~StartTask~~

Exercise E5 Charging Capacitors

(written test, approx. 16 % of a 60-minute written test, WS2022)

The circuit (without the light bulb) also takes the form of an RC circuit. The voltage across the capacitor is again 0 V at the moment $t_0 = 0 \text{ s}$ when the switch S_1 is closed. Calculate the voltage $u_c(t_2)$ across the capacitor at $t_2 = 1 \text{ ms}$ after closing the switch.

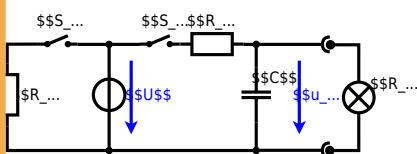
Solution

Hint: To solve this, first create an equivalent linear voltage source from U , R_1 , and R_2 .

$$\Delta U = U \cdot \frac{R_2}{R_1 + R_2}$$

Solution **Part 1:** The ideal voltage source U is in series with the voltage divider $\frac{R_2}{R_1 + R_2}$. The voltage across the capacitor is again 0 V at the moment $t_0 = 0 \text{ s}$ when the switch S_1 is closed.

On an alternative view, one can try to create an equivalent linear voltage source again. Then, the internal resistance is given by substituting the ideal voltage source is again short-circuiting R_2 .



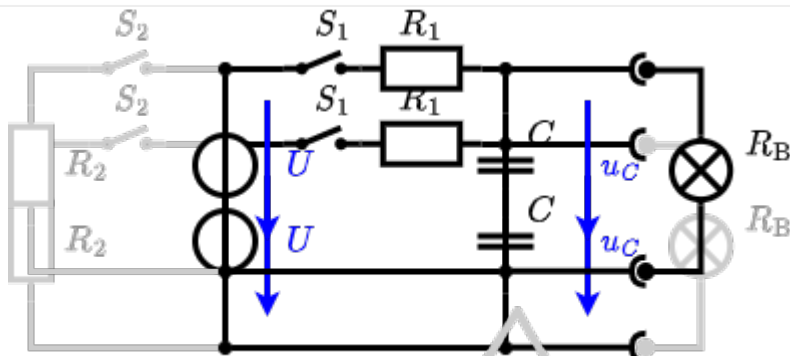
The circuit contains a voltage source $U = 12 \text{ V}$, a switch S_1 , a resistor of $R_1 = 20 \text{ } \Omega$ and a capacitor of $C = 100 \text{ } \mu\text{F}$.

The switch S_2 to an additional consumer R_2 will be considered to be open for the first tasks. At the moment $t_0 = 0 \text{ s}$ the switch S_1 is closed, the voltage across the capacitor is $u_c(t_0) = 0 \text{ V}$.

1. First do not consider the light bulb – it is not connected to the RC circuit.

Calculate the point of time t_1 when $u_c(t_1) = 0.5 \cdot U$.

Solution

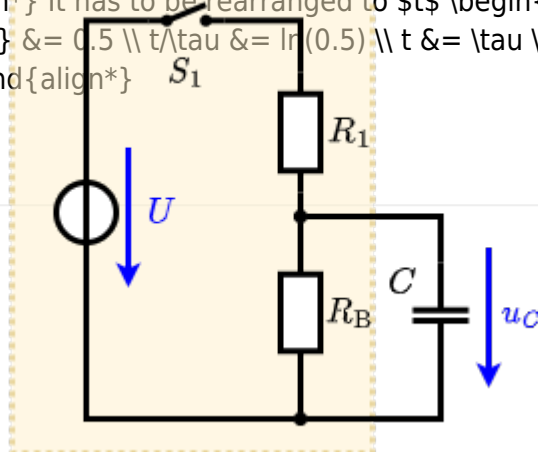


So, here only R_1 and C gives the time constant: $\tau = R_1 \cdot C$

The following formula describes the time course of $u_C(t)$ which has to be $u_C(t_1) = 0.5 \cdot U$:

$$u_C(t) = U \cdot (1 - e^{-t/\tau}) = 0.5 \cdot U$$

It has to be rearranged to $(1 - e^{-t/\tau}) = 0.5$

$$e^{-t/\tau} = 0.5 \quad \ln(0.5) = -t/\tau \quad t = \tau \cdot \ln(0.5) \quad t = R_1 \cdot C \cdot \ln(0.5)$$


An equivalent linear voltage source can be given with U , R_1 , and R_B as seen in yellow.

Therefore, the voltage of the equivalent linear voltage source is: $U_s = U \cdot \frac{R_B}{R_1 + R_B} = \frac{1}{2} \cdot U$ The internal resistance is given by substituting the ideal voltage source with its resistance ($= 0 \, \Omega$, short-circuit).

$$R_i = R_1 \parallel R_B = 10 \, \Omega$$

$$u_C(t_2) = U_s \cdot (1 - e^{-t_2/(R_i \cdot C)}) = \frac{1}{2} \cdot U \cdot (1 - e^{-1 \text{ ms} / (10 \, \Omega \cdot 100 \, \mu\text{F})})$$

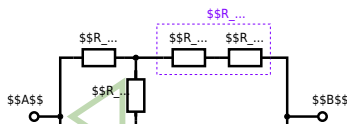
end~~StartTask~~

Exercise E3 Pure Resistor Network Simplification (written test, approx. 13 % of a 60-minute written test, WS2022)

The following shall be solved at 0 temperature, $R_1 = R_2 = 10 \, \Omega$, $R_3 = 10 \, \Omega$, $R_4 = 10 \, \Omega$, and the voltage source $U = 10 \, \text{V}$. Result given: R_B .

Solution

R_{eq} is given as:



Since $R_2 = R_3$ and based on the equations for the transformation, the transformed R_Y is given as:

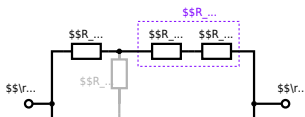
$$R_Y = \frac{R_2 \cdot R_2}{R_2 + R_2 + R_2} = \frac{(100 \, \Omega)^2}{3 \cdot 100 \, \Omega} = \frac{1}{3} \cdot 100 \, \Omega = 33.33 \, \Omega$$

The equivalent resistor is given by a parallel configuration of resistors in series:

$$R_{\text{eq}} = R_Y + (R_Y + R_1 + R_1) \parallel (R_Y + R_2) \parallel R_{\text{eq}} = 33.33 \, \Omega + (33.33 \, \Omega + 400 \, \Omega) \parallel (33.33 \, \Omega + 100 \, \Omega)$$

1. The switch shall now be open. Calculate the equivalent resistance R_{eq} between A and B.

Solution



The equivalent resistor is given by a parallel configuration of resistors in series:

$$\begin{aligned} R_{\text{eq}} &= (R_2 + R_1 + R_1) \parallel (R_2 + R_2) \parallel R_{\text{eq}} = (100 \\ &\sim \Omega + 200 \sim \Omega + 200 \sim \Omega) \parallel (100 \sim \Omega + 100 \sim \Omega) \parallel \\ R_{\text{eq}} &= (500 \sim \Omega) \parallel (200 \sim \Omega) \parallel R_{\text{eq}} = \{ \{ 500 \\ &\sim \Omega \cdot 200 \sim \Omega \} \over {500 \sim \Omega + 200 \sim \Omega} \} \parallel \\ \end{aligned}$$

end

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