

Exam Summer Semester 2023

Student Group

| First Name | Surname | Matrikel Nr. |
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Exam Summer Semester 2023

Additional permitted Aids

- non-programmable calculator,
- formulary (2 DIN A4 pages)

Hits

- The duration of the exam is 60 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.

Tasks

Exercise E1 Resistivity and temperature dependent Resistance (written test, approx. 7 % of a 60-minute written test, SS2023)

The resistivity ρ of a dielectric material is described by the Arrhenius law in an exponential form as $\rho = \rho_0 \cdot \exp(\alpha/T + \beta/T^2)$ for T between 20°C and 100°C

Solution
The resistivity of the dielectric material is $\rho_{PP}(20^\circ\text{C}) = 10^{17} \Omega\text{m}$.

For the given material the temperature coefficients in the range 20°C and 55°C are given as $\alpha = -0.048 \text{ 1/K}$ and $\beta = +0.00057 \text{ 1/K}^2$.

$$\begin{aligned} R(55^\circ\text{C}) &= R(20^\circ\text{C}) \cdot (1 + \alpha \cdot \Delta T + \beta \cdot T^2 + \dots) \\ &= 80 \text{ G}\Omega \cdot (1 - 0.048 \text{ 1/K} \cdot (35 \text{ K}) + 0.00057 \text{ 1/K}^2 \cdot \Delta T^2) \end{aligned}$$

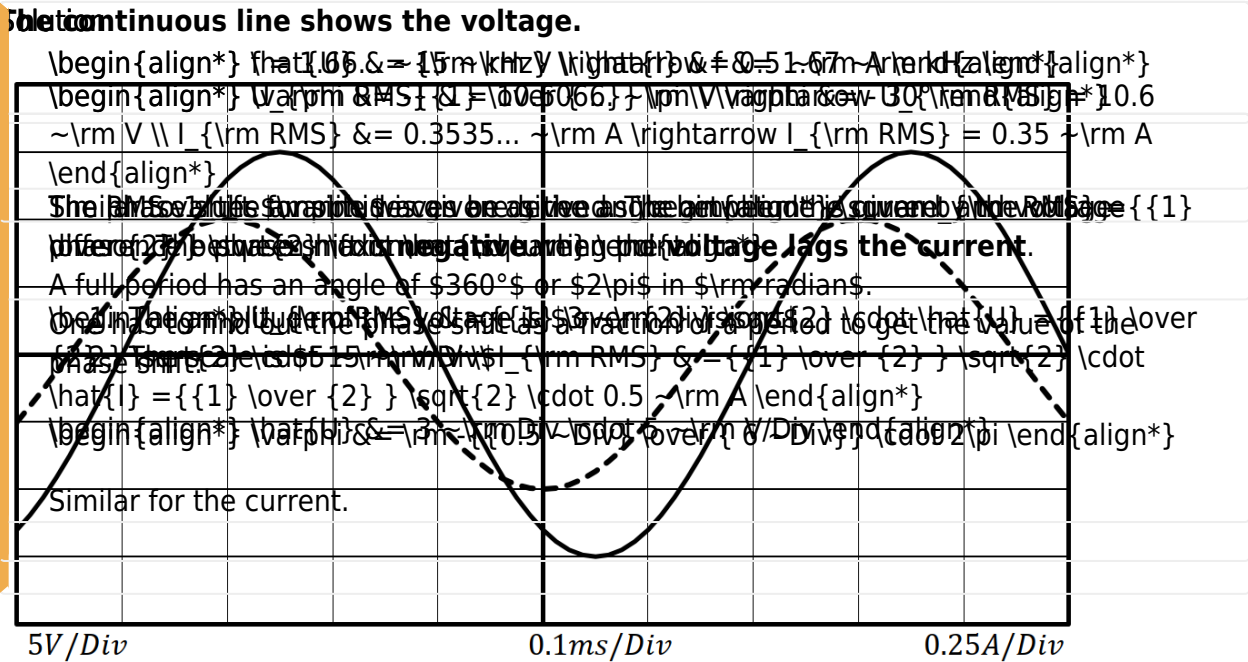
Calculate the resistance for the dielectric material for $20 \text{ }^\circ\text{C}$.

Solution

$$R(20 \text{ }^\circ\text{C}) = \rho \cdot \frac{d}{A} = 10^{17} \frac{\Omega \cdot \text{m}}{0.8 \cdot 10^{-6} \text{ m}} \cdot \frac{1 \text{ m}}{1 \text{ m}^2}$$

Exercise E2 Analyzing a Scope Plot
(written test, approx. 12 % of a 60-minute written test, SS2023)

0. What is the RMS value of a sine wave with a period of 10 ns and a peak-to-peak voltage of 1 V? (in mV and degree)?
 Result: The measured current curve shall be visible as a dashed line.



Use the correct symbols and units in your answers!

1. Calculate the frequency f of the periodic signals.

Solution

Frequency f is given by the period T . The period can be measured in the image of the scope.

1. The sine waves repeat after 6 divisions (e.g. from falling turning point to falling turning point of one curve)
2. The scale is 0.1 ms/Div

$$f = \frac{1}{T} \quad T = 6 \text{ Div} \cdot 0.1 \text{ ms/Div}$$

$$\rightarrow f = \frac{1}{6 \text{ Div} \cdot 0.1 \text{ ms/Div}}$$

Exercise E3 Complex voltage dividers
(written test, approx. 16 % of a 60-minute written test, SS2023)

Task: Calculate the complex impedance Z of the circuit below. The voltage U is 5 V . Choose an appropriate scaling factor and write it down.

- $R = 1.1 \text{ k}\Omega$

Solution $I = 3.5 \text{ mA}$

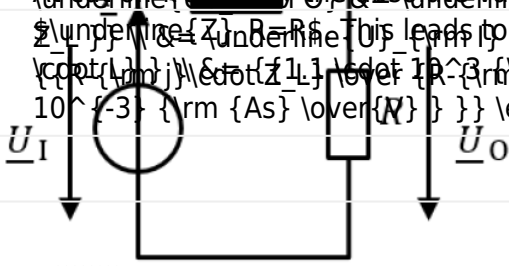
Solution:

$$U = 5 \text{ V}$$

$$I = 3.5 \text{ mA}$$

$$\underline{U}_O = 0.5 \cdot \underline{U}_I$$

The formula to start with is the (complex) voltage divider: $\underline{U}_O = \underline{U}_I \cdot \frac{Z_L}{Z_L + Z_1}$.
 And if we know the absolute values of impedances Z_L is equal to Z_1 then $\underline{U}_O = \underline{U}_I \cdot \frac{1}{2}$. This leads to $\underline{U}_O = \frac{1}{2} \cdot \underline{U}_I$.
 $\underline{U}_I = 10 \cdot 10^{-3} \cdot \frac{1}{\sqrt{2}}$ and $\underline{U}_O = 5 \cdot 10^{-3} \cdot \frac{1}{\sqrt{2}}$.



.. Calculate the impedance \underline{Z}_L .

Solution

$$\underline{Z}_L = j \cdot \omega \cdot L = j \cdot 2\pi \cdot 150 \cdot 3.5 \cdot 10^{-3}$$

Exercise E1 Pure Resistor Network Simplification (written test, approx. 12 % of a 60-minute written test, SS2023)

Calculate the voltage U_K when switch S is closed.

Result

The values in the circuit are

Solution

- $R_1 = 60 \Omega$
 - $R_2 = 40 \Omega$
 - $R_3 = 40 \Omega$
- The voltage divider for U_K has the same proportionality as the voltage divider for U_A . Therefore, the potential of K is the same as for A . There will be no current flow through R_3 . The resistance does not create a voltage drop and therefore does not interfere with the circuit.

1. Calculate the voltage at node K , when switch S is open. It might be beneficial to redraw the circuit first.

Solution

Rearranging the circuit one can get:

Once the switch S is opened, the upper part is a parallel circuit. Therefore, R_{eq} is given as:

$$R_{\text{eq}} = (R_1 + R_2) \parallel (R_1 + R_2) + R_4 = \frac{1}{2} \cdot (R_1 + R_2) + R_4 = \frac{1}{2} \cdot (60 \Omega + 40 \Omega) + 100 \Omega$$

Exercise E2 Pure Resistor Network Simplification I
(written test, approx. 14 % of a 60-minute written test, SS2023)

The circuit below should be given as $U_{\text{AB}} = 60 \text{ V}$. What is the value for I_{AB} the circuit?

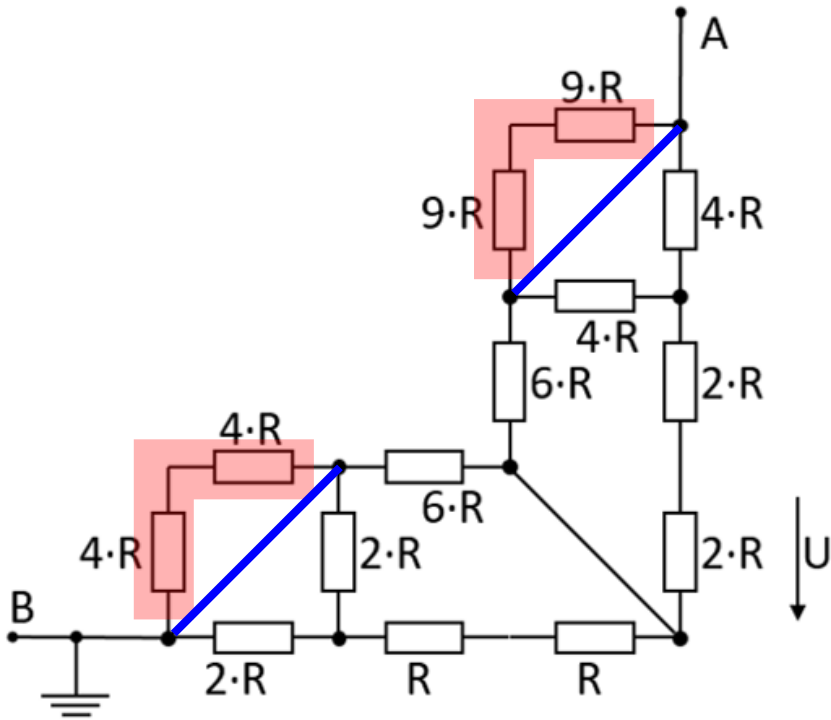
Solution

$$I_{\text{AB}} = \frac{U_{\text{AB}}}{R_{\text{eq}}} = \frac{60 \text{ V}}{100 \Omega}$$

The current through the circuit is given as $I_{\text{AB}} = \frac{U_{\text{AB}}}{R_{\text{eq}}}$.

This current has to flow in summary through parallel branches. The voltage U in question in the upper right branch given by $(4R \parallel 4R) + 2R + 2R$. Its resistance is just the same as the upper left branch $6R$.

Therefore, half of the current flows to the left half to the right side.



The circuit can then be rearranged for better interpretation:

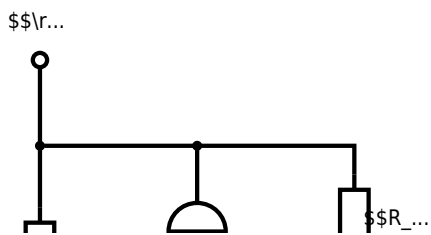
Therefore, R_{eq} is given as:
$$R_{\text{eq}} = (2R || 2R + R +$$

$$R_1 || 6R + 6R || (2R + 2R + 4R || 4R) || (R + R + R) || 6R + 6R || (2R + 2R + 2R) || 3R || 6R + 6R || 6R || \frac{3R \cdot 6R}{3R + 6R} + 3R$$

Exercise E1 Equivalent Linear Source
(written test, approx. 10 % of a 60-minute written test, SS2023)

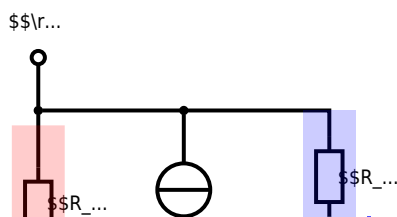
The circuit below has to be simplified. Use equivalent linear sources for simplification.
 Calculate the internal resistance R_{i} and the source voltage U_{s} of an equivalent linear voltage source.

- $R_1 = 5 \Omega$
- $U_1 = 10 \text{ V}$
- $R_2 = 5 \Omega$
- $I_3 = 0.5 \text{ A}$
- $R_4 = 10 \Omega$
- $U_5 = 4 \text{ V}$



Solution

The principle idea here is to find parts of the circuit which are already a linear (voltage or current) source. Then this can be transformed into the equivalent other source, as shown in the next picture.



In order to get the currents one has to calculate it by $I_x = \frac{U_x}{R_x}$

$$I_0 = \frac{U_0}{R_1} = \frac{10 \text{ V}}{5 \Omega} = 2 \text{ A}$$

$$I_5 = \frac{U_5}{R_4} = \frac{4 \text{ V}}{10 \Omega} = 0.4 \text{ A}$$

I_3 and I_0 can be combined to $I_{03} = I_0 - I_3$ facing upwards:

$$I_{03} = 1.5 \text{ A}$$

Then, the linear current source I_{03} with R_1 gets transformed into a linear voltage source with $U_{03} = R_1 \cdot I_{03}$ facing down.

$$U_{03} = 7.5 \text{ V}$$

Then, the resistors R_1 and R_2 can be combined to $R_{12} = R_1 + R_2$.

After this, the next step is to make a linear current source out of U_{03} and R_{12} . The current will be $I_{0123} = \frac{U_{03}}{R_{12}}$, facing up again.

$$I_{0123} = 0.6 \text{ A}$$

The second-last step is the sum up of the current sources I_{0123} and I_5 as $I_{01235} = I_{0123} - I_5$ and the resistors as $R_{124} = R_{12} || R_4$.

$$I_{01235} = 0.2 \text{ A} \quad R_{124} = 5.55 \Omega$$

The final step is the back-transformation to a linear voltage source, with $U_{\text{AB}} = R_{124} \cdot I_{01235}$.

The simplest and fastest (= for exams) is to work with interim results in the calculation.

Here, there there is also a full final formula given:

$$U_{\text{AB}} = U_{\text{AB}} = I_{01235} \cdot R_{124} = (I_{0123} - I_5) \cdot (R_{12} \parallel R_4) = \left(\frac{U_3}{R_{12}} - I_5 \right) \cdot (R_{12} \parallel R_4) = \left(\frac{R_1 \cdot I_3}{R_1 + R_2} - I_5 \right) \cdot (R_{12} \parallel R_4) = \frac{R_1 \cdot \left(\frac{U_0}{R_1} - I_3 \right)}{R_1 + R_2} - I_5 \cdot (R_{12} \parallel R_4)$$

Exercise E4 (Dis)Charging Capacities (written test, approx. 14 % of a 60-minute written test, SS2023)

The circuit below consists of a current source $I_0 = 0.2 \text{ mA}$, a voltage source $U_0 = 10 \text{ V}$, a capacitor $C = 200 \text{ nF}$, and resistors $R_1 = 8 \text{ k}\Omega$, $R_2 = 17 \text{ k}\Omega$, $R_3 = 10 \text{ k}\Omega$, and $R_4 = 50 \text{ k}\Omega$. The switch S_1 switches to the situation shown in the drawing. What is the new time constant?

- $C = 200 \text{ nF}$

Solution: $R = 8.0 \text{ k}\Omega$
 Solution: $\tau = 8.0 \text{ k}\Omega \cdot 200 \text{ nF} = 1.6 \text{ ms}$
 Solution: $U_C = 25 \text{ V}$

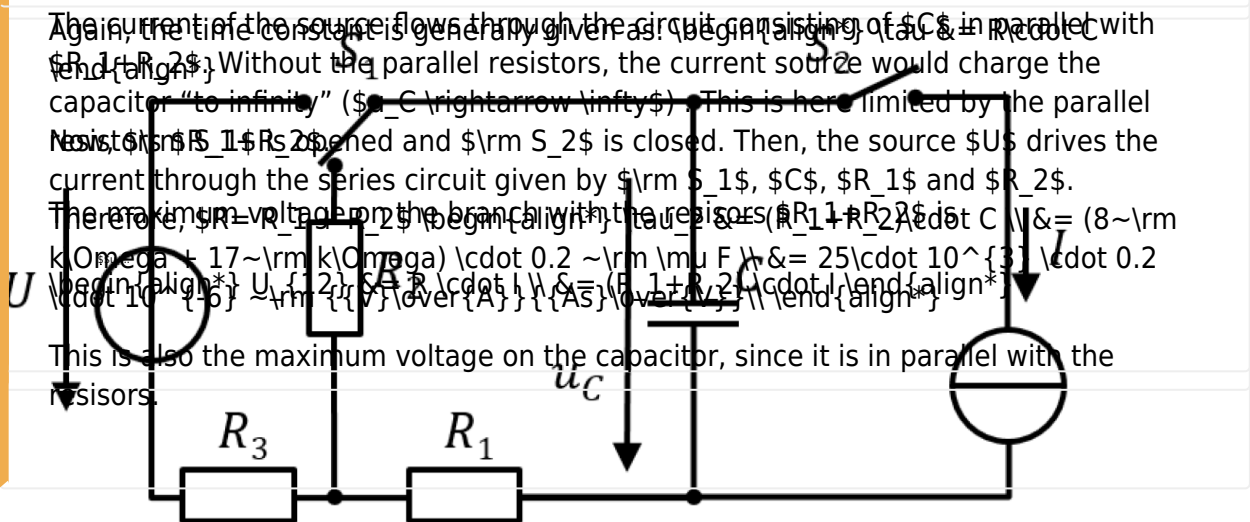
$$U_C = U_0 \cdot \left(1 - e^{-\frac{t}{\tau}} \right) \Rightarrow 25 = 10 \cdot \left(1 - e^{-\frac{t}{1.6 \text{ ms}}} \right) \Rightarrow e^{-\frac{t}{1.6 \text{ ms}}} = \frac{1}{4} \Rightarrow \frac{t}{1.6 \text{ ms}} = \ln(4) \Rightarrow t = 1.6 \text{ ms} \cdot \ln(4) \approx 2.2 \text{ ms}$$

Again, the current of the source flows through the circuit consisting of C in parallel with R_1 and R_2 . Without the parallel resistors, the current source would charge the capacitor "to infinity" ($C \rightarrow \infty$). This is here limited by the parallel resistors R_1 and R_2 . Then, the source U_0 drives the current through the series circuit given by I_0 , C , R_1 and R_2 .

The maximum voltage on the branch with the resistors $(R_1 \parallel R_2) \cdot C = (8 \text{ k}\Omega + 17 \text{ k}\Omega) \cdot 0.2 \text{ mA} = 25 \text{ V}$

$$U_C = U_0 \cdot \frac{R_1 \parallel R_2}{R_1 \parallel R_2 + C} = \frac{U_0 \cdot (R_1 \parallel R_2)}{R_1 \parallel R_2 + C} = \frac{10 \text{ V} \cdot (8 \text{ k}\Omega \parallel 17 \text{ k}\Omega)}{8 \text{ k}\Omega \parallel 17 \text{ k}\Omega + 200 \text{ nF}} \approx 25 \text{ V}$$

This is also the maximum voltage on the capacitor, since it is in parallel with the resistors.



Before t_0 all switches are switched as shown and the capacitor is fully discharged. At $t_0 = 0 \text{ s}$ the switch S_1 shall switch to the voltage source.

1. Calculate the time constant for charging the capacitor.

Solution

The time constant is generally given as: $\tau = R \cdot C$

Once S_1 is closed and S_2 is open at t_0 , the source U drives the current through the series circuit given by S_1 , C , R_1 and R_3 .

Therefore, $R = R_1 + R_3$

$$\tau_1 = (R_1 + R_3) \cdot C = (8 \text{ k}\Omega + 7 \text{ k}\Omega) \cdot 0.2 \text{ }\mu\text{F} = 15 \cdot 10^3 \cdot 0.2 \cdot 10^{-6} \text{ s} = 3 \text{ ms}$$

⚡⚡...

Solution

Both courses of the voltage for charging and discharging are described with an exponential function. However, the curve for charging increases first steep and flattens out for longer time scales ($\propto (1 - e^{-x})$).

Exercise E5 Impedances at Frequencies
(written test, approx. 14 % of a 60-minute written test, SS2023)

At a high frequency with $C_2 \rightarrow \infty$ (short circuit), the voltage across C_1 is $U_{C1} = U \cdot \frac{R_2}{R_1 + R_2}$. At a low frequency with $C_2 \rightarrow 0$ (open circuit), the voltage across C_1 is $U_{C1} = U \cdot \frac{R_2}{R_1 + R_2 + R_3}$.

Repeat the calculation with $\mu = 0.5$ and $L_1 = 15.9 \mu\text{H}$.

Solution

$$f_0 = 300000 \text{ Hz} \quad \omega = 2\pi f_0 = 600000 \text{ rad/s}$$

$$X_{C2} = \frac{1}{\omega C_2} = \frac{1}{600000 \cdot 10^{-8}} = 166.67 \Omega$$

$$X_{L1} = \omega L_1 = 600000 \cdot 15.9 \cdot 10^{-6} = 9.54 \Omega$$

$$X_{L2} = \omega L_2 = 600000 \cdot 10^{-6} = 0.6 \Omega$$

$$X_{C1} = \frac{1}{\omega C_1} = \frac{1}{600000 \cdot 10^{-8}} = 166.67 \Omega$$

$$Z_{\text{in}} = X_{C1} + X_{L1} + X_{L2} + X_{C2} = 166.67 + 9.54 + 0.6 + 166.67 = 343.48 \Omega$$

$$I = \frac{V_S}{Z_{\text{in}}} = \frac{3.5}{343.48} = 0.0102 \text{ A}$$

$$P_{\text{out}} = I^2 R = (0.0102)^2 \cdot 2 = 0.000208 \text{ W} = 0.208 \text{ mW}$$

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{0.000208}{0.000208} = 100\%$$

Exercise E1 Efficiency

(written test, approx. 14 % of a 60-minute written test, SS2023)

2. (100%) A battery with an internal resistance of $R_i = 2 \Omega$ and an open-circuit voltage of $V_S = 3.5 \text{ V}$ is connected to a load resistor $R_L = 30 \Omega$. The battery shall provide energy for a device with an internal resistance of $R_d = 2 \Omega$. The load resistor shall be chosen such that the efficiency is maximized. What is the maximum efficiency?

Solution: The device with an internal resistance of $R_d = 2 \Omega$ is connected in series with the load resistor R_L . The total resistance is $R_{\text{total}} = R_i + R_d + R_L = 2 \Omega + 2 \Omega + R_L = 4 \Omega + R_L$. The current flowing through the circuit is $I = \frac{V_S}{R_{\text{total}}} = \frac{3.5 \text{ V}}{4 \Omega + R_L}$. The power delivered to the load resistor is $P_L = I^2 R_L = \left(\frac{3.5}{4 + R_L}\right)^2 R_L$. The power delivered to the device is $P_d = I^2 R_d = \left(\frac{3.5}{4 + R_L}\right)^2 \cdot 2$. The efficiency is $\eta = \frac{P_d}{P_L + P_d} = \frac{2}{2 + R_L}$. The maximum efficiency is achieved when $R_L = 2 \Omega$, resulting in $\eta = \frac{2}{2 + 2} = 0.5 = 50\%$.

$$R_i = 2 \Omega \quad R_d = 2 \Omega \quad V_S = 3.5 \text{ V}$$

$$R_L = 30 \Omega \quad R_{\text{total}} = R_i + R_d + R_L = 4 \Omega + R_L$$

$$I = \frac{V_S}{R_{\text{total}}} = \frac{3.5}{4 + R_L}$$

Lowest efficiency from highest current is for $R_L = 2 \Omega$ in this case, the

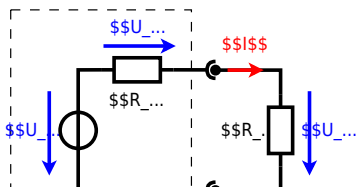
.. Efficiency of a circuit diagram with the internal resistance and an external load.

$$\eta = \frac{P_{\text{out}}}{P_{\text{in}}} = \frac{I^2 R_L}{I^2 (R_i + R_d + R_L)} = \frac{R_L}{R_i + R_d + R_L}$$

$$\eta = \frac{30}{2 + 2 + 30} = \frac{30}{34} = 0.882 = 88.2\%$$

$$\eta = 1 - \frac{R_i + R_d}{R_i + R_d + R_L} = 1 - \frac{4}{34} = 0.882 = 88.2\%$$

$$\eta = \frac{30}{34} = 0.882 = 88.2\%$$



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