

# dummy

## Student Group

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capacitors, rc circuit, transient response, energy storage, industrial safety, chapter1 1

### Exercise E1 Machine-Vision Strobe Unit: Charging and Safe Discharge of a Flash Capacitor

A machine-vision inspection system on a production line uses a short high-voltage flash pulse. For this purpose, an energy-storage capacitor is charged from a DC source and must be safely discharged before maintenance.

Data:  $C = 1 \mu\text{F}$   $W_e = 0.1 \text{ J}$   $I_{\text{max}} = 100 \text{ mA}$   $R_i = 10 \text{ M}\Omega$

1. What voltage must the capacitor have so that it stores the required energy?

SolutionResult

$$\begin{aligned} W_e &= \frac{1}{2} C U^2 \\ U &= \sqrt{\frac{2W_e}{C}} \\ &= \sqrt{\frac{2 \cdot 0.1 \text{ J}}{1 \cdot 10^{-6} \text{ F}}} \\ &= \sqrt{200000} \text{ V} \approx 447.2 \text{ V} \end{aligned}$$

$$U = 447.2 \text{ V}$$

2. The charging current must not exceed  $100 \text{ mA}$  at the start of charging. What charging resistor is required?

SolutionResult

At the beginning of charging, the capacitor behaves like a short circuit, so  $i_{C(\text{max})} = i_C(t=0) = \frac{U}{R}$ . Thus,  $R \geq \frac{U}{I_{\text{max}}} = \frac{447.2 \text{ V}}{0.1 \text{ A}} \approx 4472 \Omega = 4.47 \text{ k}\Omega$

$$R \geq 4.47 \text{ k}\Omega$$

3. How long does the charging process take until the capacitor is practically fully charged?

#### SolutionResult

The time constant is 
$$T = RC = 4.47 \text{ k}\Omega \cdot 1 \text{ }\mu\text{F} = 4.47 \text{ ms}$$
 In engineering practice, a capacitor is considered practically fully charged after about  $5T$ : 
$$t \approx 5T = 5 \cdot 4.47 \text{ ms} = 22.35 \text{ ms}$$

$$t \approx 22.35 \text{ ms}$$

4. Give the time-dependent capacitor voltage and the voltage across the charging resistor.

#### SolutionResult

For the charging process:  

$$u_C(t) = U \left(1 - e^{-t/T}\right)$$

$$u_R(t) = U e^{-t/T}$$
 with 
$$U = 447.2 \text{ V}$$

$$T = 4.47 \text{ ms}$$
 So the capacitor voltage rises exponentially from  $0$  to  $447.2 \text{ V}$ , while the resistor voltage falls exponentially from  $447.2 \text{ V}$  to  $0$ .

$$u_C(t) = 447.2 \left(1 - e^{-t/4.47 \text{ ms}}\right) \text{ V}$$

$$u_R(t) = 447.2 e^{-t/4.47 \text{ ms}} \text{ V}$$

5. After charging, the capacitor is disconnected from the source. Its leakage can be modeled

by an internal resistance of  $10\text{ M}\Omega$ . After what time has the stored energy dropped to one half, and what is the capacitor voltage then?

### SolutionResult

Half the energy means  $W_e' = 0.5W_e$  Since  $W_e = \frac{1}{2}CU^2$  the voltage at half energy is  $U' = \frac{U}{\sqrt{2}} = \frac{447.2\text{ V}}{\sqrt{2}} = 316.2\text{ V}$  For the discharge through the internal resistance:  $u_C(t) = Ue^{-t/T_2}$  with  $T_2 = R_iC = 10\text{ M}\Omega \cdot 1\text{ }\mu\text{F} = 10\text{ s}$  Set  $u_C(t) = U'$ :  $Ue^{-t/T_2} = U' \Leftrightarrow t = T_2 \ln\left(\frac{U}{U'}\right) = 10\text{ s} \cdot \ln\left(\frac{447.2}{316.2}\right) \approx 3.47\text{ s}$

$$U' = 316.2\text{ V} \\ t = 3.47\text{ s}$$

6. The fully charged capacitor is discharged through the charging resistor before maintenance. How long does the discharge take, and how much energy is converted into heat in the resistor?

### SolutionResult

The discharge time constant through the same resistor is again  $T = RC = 4.47\text{ ms}$  Thus the practical

$$t \approx 22.35\text{ ms} \\ W_R = 0.1\text{ Ws}$$

discharge time is  $t \approx 5T = 22.35 \text{ ms}$   
 The complete stored capacitor energy is converted into heat in the resistor:  $W_R = W_e = 0.1 \text{ Ws}$

[rc circuit](#), [thevenin equivalent](#), [transient response](#), [sensor interface](#), [industrial electronics](#), [chapter1](#) 1

### Exercise E2 Sensor Input Buffer: Source, T-Network and Capacitor

A 12 V industrial sensor electronics unit feeds a buffered measurement node through a resistor T-network. A capacitor smooths the node voltage. At first, the load is disconnected. After the capacitor is fully charged, a measurement load is connected by a switch.

Data:  $U = 12 \text{ V}$   $R_1 = 2 \text{ k}\Omega$   $R_2 = 10 \text{ k}\Omega$   $R_3 = 3.33 \text{ k}\Omega$   $C = 2 \text{ }\mu\text{F}$   $R_L = 5 \text{ k}\Omega$

Initially, the capacitor is uncharged and the switch is open.

1. What is the capacitor voltage after it is fully charged?

#### SolutionResult

Using the equivalent voltage source of the network on the left-hand side, the open-circuit voltage is  $U_{0e} = \frac{R_2}{R_1 + R_2} U = \frac{10 \text{ k}\Omega}{2 \text{ k}\Omega + 10 \text{ k}\Omega} \cdot 12 \text{ V} = 10 \text{ V}$   
 After full charging, the capacitor voltage equals this voltage.

$$U_C = U_{0e} = 10 \text{ V}$$

## 2. How long does the charging process take?

## SolutionResult

The internal resistance seen by the capacitor is 
$$R_{ie} = R_3 + (R_1 \parallel R_2) = 3.33 \text{ k}\Omega + \frac{2 \text{ k}\Omega}{2} = 3.33 \text{ k}\Omega + 1.67 \text{ k}\Omega = 5.00 \text{ k}\Omega$$
 So the time constant is 
$$T = R_{ie}C = 5.00 \text{ k}\Omega \cdot 2 \text{ }\mu\text{F} = 10 \text{ ms}$$
 Practical charging time: 
$$t \approx 5T = 50 \text{ ms}$$

$$R_{ie} = 5.00 \text{ k}\Omega \quad t \approx 50 \text{ ms}$$

## 3. Give the time-dependent capacitor voltage.

## SolutionResult

The charging law is 
$$u_C(t) = U_{0e} \left(1 - e^{-t/T}\right) = 10 \left(1 - e^{-t/10 \text{ ms}}\right) \text{ V}$$
 So the capacitor voltage rises exponentially from  $0 \text{ V}$  to  $10 \text{ V}$ .

$$u_C(t) = 10 \left(1 - e^{-t/10 \text{ ms}}\right) \text{ V}$$

4. After the capacitor is fully charged, the switch is closed and the load resistor is connected. What is the stationary load voltage?

### SolutionResult

Now use a second equivalent voltage-source step. The Thevenin source seen by the load has 
$$U_{0e} = 10 \text{ V} \quad R_{ie} = 5.00 \text{ k}\Omega$$
 Thus, the stationary load voltage is 
$$U_{C'} = U_{0e}' = \frac{R_L}{R_{ie} + R_L} U_{0e} = \frac{5 \text{ k}\Omega}{5 \text{ k}\Omega + 5 \text{ k}\Omega} \cdot 10 \text{ V} = 5 \text{ V}$$

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

5. How long does it take until this new stationary state is practically reached?

### SolutionResult

The new internal resistance is 
$$R_{ie}' = R_{ie} \parallel R_L = 5.00 \text{ k}\Omega \parallel 5.00 \text{ k}\Omega = 2.50 \text{ k}\Omega$$
 Hence the new time constant is 
$$T' = R_{ie}' C = 2.50 \text{ k}\Omega \cdot 2 \text{ }\mu\text{F} = 5 \text{ ms}$$
 Practical settling time: 
$$t \approx 5T' = 25 \text{ ms}$$

$$R_{ie}' = 2.50 \text{ k}\Omega \quad t \approx 25 \text{ ms}$$

6. Give the time-dependent load voltage after the switch is closed.

### SolutionResult

At the switching instant, the capacitor voltage cannot jump. Therefore:

$$u_L(0^+) = 10 \text{ V} \quad u_L(\infty) = 5 \text{ V}$$

The voltage therefore decays exponentially toward the new final value:

$$u_L(t) = u_L(\infty) + (u_L(0^+) - u_L(\infty))e^{-t/T'} = 5 + 5e^{-t/5 \text{ ms}} \text{ V}$$

$$u_L(t) = 5 + 5e^{-t/5 \text{ ms}} \text{ V}$$

[inductors](#), [air core coil](#), [magnetic field](#), [hall sensor](#), [transient response](#), [current density](#), [chapter1 1](#)

### Exercise E3 Hall-Sensor Calibration Coil: Short Air-Core Coil

A Hall-sensor calibration bench uses a short air-core coil to create a defined magnetic field. An air-core coil is chosen because it avoids hysteresis and remanence effects. The coil is wound as a short cylindrical coil.

Data:  $l = 22 \text{ mm}$   $d = 20 \text{ mm}$   $d_{\text{Cu}} = 0.8 \text{ mm}$   $N = 25$   $\rho_{\text{Cu}, 20^\circ\text{C}} = 0.0178 \text{ m}\Omega/\text{mm}^2/\text{m}$

A DC current of  $1 \text{ A}$  shall flow through the coil.

1. Calculate the coil resistance  $R$  at room temperature.

### SolutionResult

The wire cross section is

$$R = 55.6 \text{ m}\Omega$$

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\begin{align*} A_{\text{Cu}} &= \pi \left( \frac{d_{\text{Cu}}}{2} \right)^2 = \pi (0.4 \text{ mm})^2 \approx 0.503 \text{ mm}^2 \\ \end{align*} \text{The total wire length is approximated by the number of turns times the circumference:} \\
\begin{align*} l_{\text{Cu}} &= N \pi d \approx 25 \pi \cdot 20 \text{ mm} \approx 1570.8 \text{ mm} = 1.571 \text{ m} \\ \end{align*} \text{Thus, } \begin{align*} R_{\text{Cu}} &= \rho_{\text{Cu}} \frac{l_{\text{Cu}}}{A_{\text{Cu}}} \approx 0.0178 \frac{\Omega \cdot \text{m}}{\text{m}} \cdot \frac{1.571 \text{ m}}{0.503 \text{ mm}^2} \approx 0.0556 \Omega \\ \end{align*}

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2. Calculate the coil inductance \$L\$.

### SolutionResult

For this short air-core coil, use

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\begin{align*} L &= N^2 \cdot \frac{\mu_0}{4\pi} \cdot \frac{1}{1 + \frac{d}{2l}} \\ \end{align*} \text{with } \begin{align*} A &= \pi \left( \frac{d}{2} \right)^2 = \pi (10 \text{ mm})^2 = 314.16 \text{ mm}^2 = 3.1416 \cdot 10^{-4} \text{ m}^2 \\ \mu_0 &= 4\pi \cdot 10^{-7} \text{ Vs/(Am)} \\ \end{align*} \text{Therefore,} \\
\begin{align*} L &= 25^2 \cdot \frac{4\pi \cdot 10^{-7}}{4\pi} \cdot \frac{1}{1 + \frac{20}{2 \cdot 22}} \cdot 3.1416 \cdot 10^{-4} \cdot 10^{-3} \\ &\approx 7.71 \cdot 10^{-6} \text{ H} \\ \end{align*}

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\begin{align*} L &= 7.71 \mu\text{H} \\ \end{align*}

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3. Which DC voltage must be applied so that the stationary current becomes  $I=1\text{~}\text{A}$ ? How large is the current density  $j$  in the copper wire?

#### SolutionResult

In the stationary DC state, the coil behaves like its ohmic resistance:

$$\begin{aligned} U &= RI \\ &= 55.6\text{~}\text{m}\Omega \cdot 1\text{~}\text{A} \\ &= 55.6\text{~}\text{mV} \end{aligned}$$

The current density is

$$\begin{aligned} j &= \frac{I}{A_{\text{Cu}}} \\ &= \frac{1\text{~}\text{A}}{0.503\text{~}\text{mm}^2} \\ &\approx 1.99\text{~}\text{A/mm}^2 \end{aligned}$$

$$\begin{aligned} U &= 55.6\text{~}\text{mV} \\ j &= 1.99\text{~}\text{A/mm}^2 \end{aligned}$$

4. How much magnetic energy is stored in the coil in the stationary state?

#### SolutionResult

$$\begin{aligned} W_m &= \frac{1}{2}LI^2 \\ &= \frac{1}{2} \cdot 7.71 \cdot 10^{-6}\text{~}\text{H} \cdot (1\text{~}\text{A})^2 \\ &= 3.86 \cdot 10^{-6}\text{~}\text{Ws} \end{aligned}$$

$$W_m = 3.86 \cdot 10^{-6}\text{~}\text{Ws}$$

5. Give the time-dependent coil current  $i(t)$  when the coil is switched on.

## SolutionResult

A coil current cannot jump instantly. It starts at  $0$  and approaches the final value  $I=1\text{~}\text{A}$  exponentially:

$$i(t) = I \left(1 - e^{-t/T}\right)$$
 So the sketch starts at  $0\text{~}\text{A}$ , rises quickly, and then slowly approaches  $1\text{~}\text{A}$ .

$$i(t) = I \left(1 - e^{-t/T}\right)$$

6. How long does it take until the current has practically reached its stationary value?

## SolutionResult

The time constant is  $T = \frac{L}{R} = \frac{7.71\text{~}\text{mH}}{55.6\text{~}\text{m}\Omega} \approx 138.9\text{~}\mu\text{s}$

A practical final value is reached after about  $5T$ :

$$t \approx 5T = 5 \cdot 138.9\text{~}\mu\text{s} \approx 695\text{~}\mu\text{s}$$

$$t \approx 695\text{~}\mu\text{s}$$

7. How much energy is dissipated as heat in the coil resistance during the current build-up?

## SolutionResult

Using the current from task 5,

$$i(t) = I \left(1 - e^{-t/T}\right)$$

$$W_R \approx 27.05 \cdot 10^{-6}\text{~}\text{Ws}$$

$t/T$  the heat dissipated in the winding resistance up to the practical final time  $5T$  is
 
$$W_R = \int_0^{5T} R i^2(t) dt = R \int_0^{5T} I^2 \left(1 - e^{-t/T}\right)^2 dt$$
 For this interval, the integral is approximately
 
$$\int_0^{5T} \left(1 - e^{-t/T}\right)^2 dt \approx \frac{7}{2} T$$
 Thus,
 
$$W_R \approx R I^2 \cdot \frac{7}{2} T = 0.0556 \cdot \Omega \cdot (1 \sim A)^2 \cdot \frac{7}{2} \cdot 138.9 \sim \mu s \approx 27.05 \cdot 10^{-6} \sim Ws$$

$\end{align*}$

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Last update: **2026/03/27 02:19**

