Measuring the current in a coil when switching DC on and off

Experiment Objectives

- Investigation of a coil's current when switching DC voltage on and off.
- Determination of the half-life for different resistances and inductances ($T_{\frac{1}{2}} = \ln 2 \cdot \frac{L}{R}$).

Basic Information

A coil functions as a simple ohmic resistor in a DC circuit. Only during a modification of the amperage is an additional drop produced at the coil from self-induction. So the induction L causes a delay in the amperage change compared to the voltage change, i.e. switching the voltage on makes the amperage slowly rise through the coil up to the value limited by the ohmic resistor in the circuit, and switching the voltage off makes the amperage decline correspondingly to zero. The progression of the amperage in each case can be described by an exponential function.

For the shutdown cycle's amperage:

$$I(t) = I_0 \cdot e^{-\frac{t}{\tau}} \qquad \text{(I)}$$

where τ is the time constant

The time constant or decay time τ is the time it takes the voltage to fall to the value $\frac{1}{e} \cdot I_0$. It is determined by the resistance R and the inductance L:

$$\tau = \frac{L}{R}$$

During the half-life $T_{\frac{1}{2}}$ the amperage is reduced by half. From (I) we have:

$$I(T_{\frac{1}{2}}) = \frac{1}{2} \cdot I_0 = I_0 \cdot e^{-\frac{T_{\frac{1}{2}}}{\tau}}$$

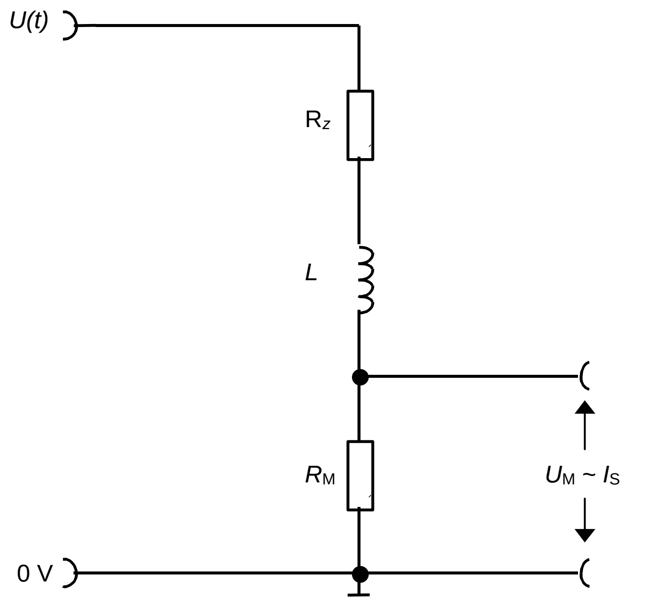
And therefore: $T_{\frac{1}{2}} = \tau \cdot \ln 2$ or $T_{\frac{1}{2}} = \ln 2 \cdot \frac{L}{R}$ (II)

The progression of the amperage for the start-up process can correspondingly be considered:

$$I(t) = I_0 \cdot (1 - e^{-\frac{t}{\tau}})$$

In the experiment, the start-up and shutdown cycle is implemented by a function generator's square-wave voltage $U(t)$. The progression of the amperage I_S through the coil is represented as a voltage curve U_M with the oscilloscope at an ohmic measuring resistor R_M (see the illustration). The half-life $T_{\frac{1}{2}}$ is determined by the sweep.

To verify equation (II), the dependence of the half-life $T_{\frac{1}{2}}$ is studied, first on the total resistance R ($T_{\frac{1}{2}} \sim \frac{1}{R}$ applies), and then on the ratio of inductance L over resistance R ($T_{\frac{1}{2}} \sim \frac{L}{R}$ applies).



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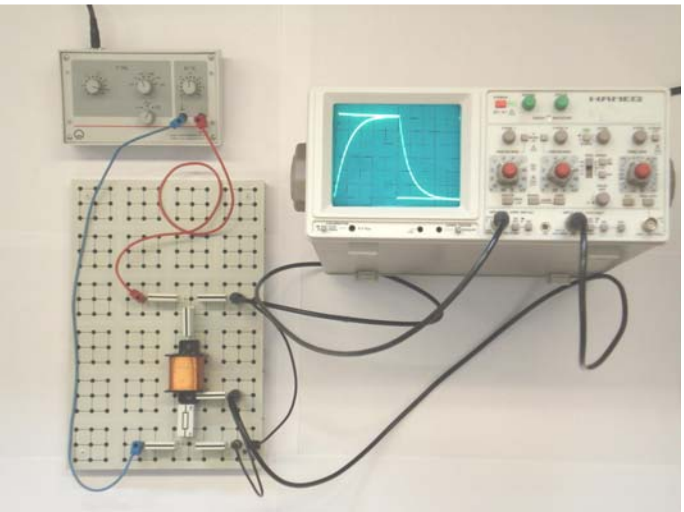
Apparatus

1 Plug-in board, DIN A4 .... 576 74
1 Set of 10 bridging plugs 501 48
1 STE Resistor 1 Ω 577 19
1 STE Resistor 10 Ω 577 20
1 STE Resistor 22 Ω 577 24
1 STE Resistor 47 Ω 577 28
2 Coils with 1000 turns 590 84
1 Function generator S 12 .... 522 621
1 Two-channel oscilloscope 575 211
2 Screened cables BNC/4 mm 575 24
1 Pair of cables, 1 m, red and blue 501 46

Setup



- Setup according to the illustration.
- Measure the function generator's square-wave voltage with Channel I and the drop at the measuring resistor 1 Ω with Channel II.
- Display both curves simultaneously on the oscilloscope (DUAL). Set coupling and trigger to DC. Calibrate the sweep for a good readout of the time *t* (CAL. position).

Procedure

a) Investigation of the coil's start-up and shutdown cycle

- Initially, do not add any resistance (bridging plugs, R_Z = 0 Ω) into the setup and only use one coil.
- Choose a square-wave voltage with a frequency of $f \approx 100$ Hz on the function generator, and set the voltage $U(t)$ to about 3 V.
- Using the oscilloscope's adjustable amplification, display the curve progression U_M at the measuring resistor so that an even number (e.g. 8) of fields is covered on the screen.
- For the shutdown cycle, measure the times *t* for the voltage's decline from the maximum to its half and from a half to a quarter of the maximum (e.g. from the 8th field to the 4th and from the 4th field to the 2nd, Table 1).
- Similarly, for the start-up cycle measure the times *t* for the voltage's rise (Table 1).

b) Dependence of the half-life on the resistance

- Connect one more resistor in series to the coil and use different resistances successively.
- In each case determine the time $t = T_{\frac{1}{2}}$ it takes the voltage U_M at the measuring resistor to decline from the maximum to its half, or to rise from zero to a half. If necessary for a more precise readout, increase the oscilloscope's sweep (Table 2).

c) Dependence of the half-life on the inductance

- Successively implement different inductances *L* with parallel or series connections of the two coils and use the additional resistance according to Table 3.
- In each case determine the time $t = T_{\frac{1}{2}}$.

Measurement Examples

a) Investigation of the coil's starting and breaking current

Table 1:

Voltage change	Max. → 1/2	1/2 → 1/4	0 → 1/2	1/2 → 3/4
$\frac{t}{\text{ms}}$	0.58	0.58	0.58	0.58

b) Dependence of the half-life on the resistance

The total resistance *R* results from the sum of the measuring resistor R_M = 1 Ω, the coil's ohmic resistor R_S = 18 Ω and the additional resistor R_Z:

$$R = R_M + R_S + R_Z = 1\,\Omega + 18\,\Omega + R_Z$$

Table 2:

$\frac{R_Z}{\Omega}$	0	10	22	47
$\frac{R}{\Omega}$	19	29	41	66
$\frac{T_{\frac{1}{2}}}{\mu\text{s}}$	580	400	290	188

c) Dependence of the half-life on the ratio of inductance and resistance

If the coils have a parallel connection then: $\frac{1}{L} = \frac{1}{L_1} + \frac{1}{L_2}$,

and if they have a series connection then: $L = L_1 + L_2$

For the coils with 1000 turns, $L_1 = L_2 \approx 18\,\text{mH}$, the ohmic resistance amounts to about 18 Ω each.

Table 3:

	Coils in parallel connection	Single coil	Coils in series connection
$\frac{L}{\text{mH}}$	9	18	36
$\frac{R_S}{\Omega}$	9	18	36
$\frac{R_Z}{\Omega}$	47	22	10
$\frac{R}{\Omega}$	57	41	47
$\frac{T_{\frac{1}{2}}}{\mu\text{s}}$	104	295	490

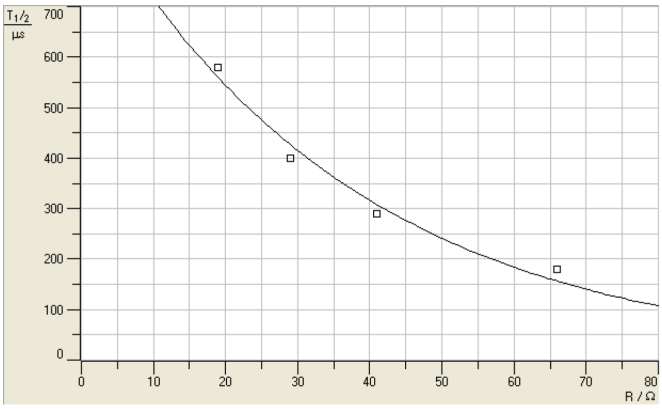
Analysis and Results

a) Investigation of the coil's start-up and shutdown cycle

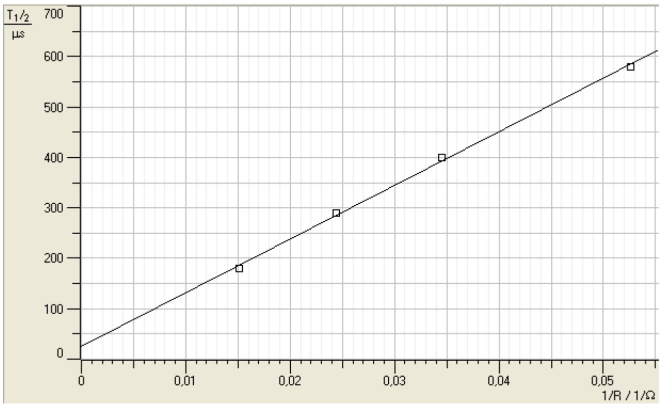
- The time the amperage takes to decline to half is always the same. Hence this time is designated as the half-life $T_{\frac{1}{2}}$.
- The half-life for the amperage's decline and the half-life for its rise are the same.

b) Dependence of the half-life on the resistance

Carry the values from Table 2 into a diagram:



and in the representation $T_{\frac{1}{2}} = f\left(\frac{1}{R}\right)$:



So: $T_{\frac{1}{2}} \sim \frac{1}{R}$

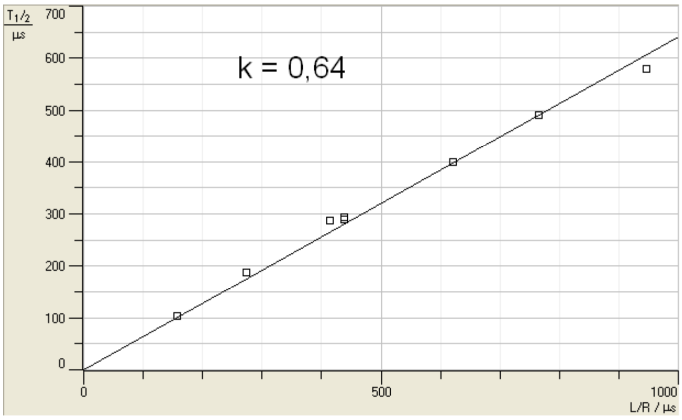
c) Dependence of the half-life on the ratio $\frac{L}{R}$

Carry the values from Table 3 and Table 2 into Table 4, by computing the values from Table 2 with the inductance of a coil *L* = 18 mH:

Table 4:

$\frac{L}{\text{mH}}$	18	36	18	18	18	18	9
$\frac{R}{\Omega}$	19	47	29	41	41	66	57
$\frac{L/R}{\mu\text{s}}$	947	766	621	439	439	273	158
$\frac{T_{\frac{1}{2}}}{\mu\text{s}}$	580	490	400	290	295	188	104

Carry the values from Table 4 into a diagram:



So: $T_{\frac{1}{2}} \sim \frac{L}{R}$

d) Determination of the proportionality constant

If $T_{\frac{1}{2}} \sim \frac{L}{R}$, then: $T_{\frac{1}{2}} = k \cdot \frac{L}{R}$

From the diagram, we have: *k* = 0.64

Theoretical value: $k = \ln 2 = 0.69$

Besides the tolerances of inductances and the resistors, the oscilloscope's imprecise readout is primarily responsible for the discrepancy.