# University of Jordan
# School of Engineering
# Electrical Engineering Department


# EE 219
# Electrical Circuits Lab

# EXPERIMENT 4
# TRANSIENT ANALYSIS


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# EXPERIMENT 4
# TRANSIENT ANALYSIS

## OBJECTIVE

When you complete this experiment, you will have learnt how to read the values of capacitors and inductors from their number or color codes. You will also have tested the transient behavior when charging and discharging a capacitor, and the transient behavior when energizing and de-energizing an inductor. In addition, you will have learnt how to use an oscilloscope to display and measure various waveforms.

## DISCUSSION

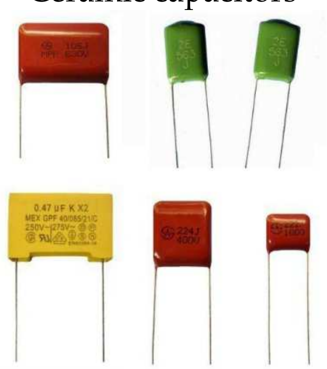
### Capacitors

A *capacitor* (also known as a *condenser*) is a passive electrical component that can store energy as an electric field. The forms in which practical capacitors are built vary widely, but all contain at least two electrical conductors (plates) separated by a dielectric (i.e. insulator). The following are some of the most common capacitors used in practice:

Ceramic capacitors

Electrolytic capacitors


Tantalum capacitors

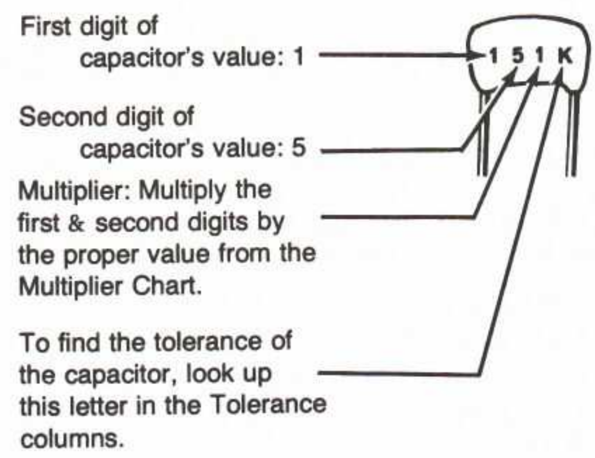

Polyester film capacitors


Variable capacitors (trimmer)


SMT (surface mount technology)

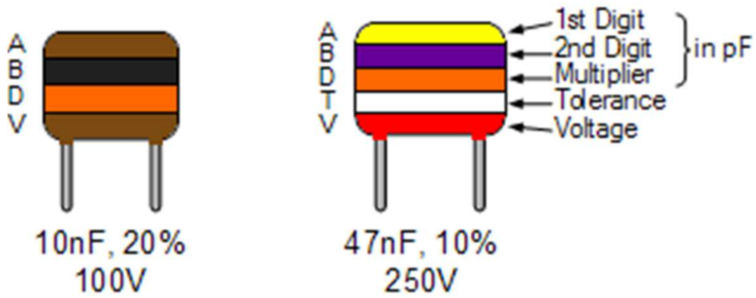
Unlike a resistor, an ideal capacitor does not dissipate energy. Instead, a capacitor stores energy in the form of an electrostatic field between its plates. The capacitance SI unit is the farad (F), which is equal to one coulomb per volt. Typical capacitance values range from about 1 pF ($10^{-12}$ F) to about 1 mF ($10^{-3}$ F). Capacitance values are usually encoded using numbers and letters on the face of the capacitor, but sometimes colors are also used (similar to resistors).

The following shows how to read the capacitance values from both the number/letter code and the color code. Three examples are provided: 150pF, 10 nF and 47 nF. In practice, the dielectric between the plates passes a small amount of leakage current and also has an electric field strength limit, known as the breakdown voltage, which you can also read from the capacitor code.




| For number: | Multiply by: | Letter | Tolerance ≤10pF | Tolerance >10pF |
|---|---|---|---|---|
| 0 | 1 | B | ±0.1pF | |
| 1 | 10 | C | ±0.25pF | |
| 2 | 100 | D | ±0.5pF | |
| 3 | 1000 | F | ±1.0pF | ±1% |
| 4 | 10,000 | G | ±2.0pF | ±2% |
| 5 | 100,000 | H | | ±3% |
| | | J | | ±5% |
| 8 | 0.01 | K | | ±10% |
| 9 | 0.1 | M | | ±20% |

Values are in pico farad (pF)
Example: **151K** means 150 pF ±10%

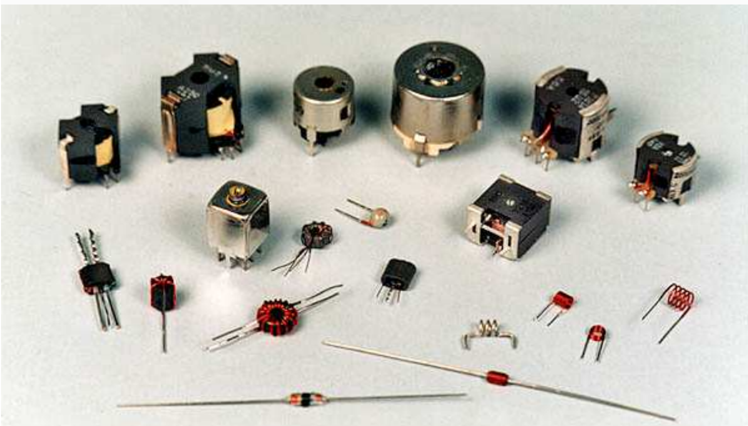



| Color | | A (1st digit) | B (2nd digit) | D (multiplier) | Tolerance ≤10pF | Tolerance >10pF | V (voltage) |
|---|---|---|---|---|---|---|---|
| Black | | 0 | 0 | 1 | ±2pF | ±20% | |
| Brown | | 1 | 1 | 10 | ±0.1pF | ±1% | 100V |
| Red | | 2 | 2 | 100 | ±0.25pF | ±2% | 250V |
| Orange | | 3 | 3 | 1000 | | ±3% | |
| Yellow | | 4 | 4 | 10,000 | | ±4% | 400V |
| Green | | 5 | 5 | 100,000 | ±0.5pF | ±5% | |
| Blue | | 6 | 6 | 1,000,000 | | | 600V |
| Violet | | 7 | 7 | | | | |
| Grey | | 8 | 8 | 0.01 | | +80%,-20% | |
| White | | 9 | 9 | 0.1 | ±1pF | ±10% | |
| Gold | | | | 0.1 | | ±5% | |
| Silver | | | | 0.01 | | ±10% | |

**Inductors**

An inductor (also known as *coil* or *choke*) is a passive electrical component that resists *changes* in electric current passing through it. It consists of a wire wound into a coil. When a current flows through it, energy is stored temporarily as a magnetic field in the coil. When the current flowing through an inductor changes, the time-varying magnetic field induces a voltage in the conductor, according to Faraday's law of electromagnetic induction, which opposes the change in current that created it.

The unit for inductance is the Henry (H). Inductors have values that typically range from 1 μH ($10^{-6}$H) to 1 H. Many inductors have a magnetic core made of iron or ferrite inside the coil, which serves to increase the magnetic field and thus the inductance. The following are some of the most common forms of practical inductors:

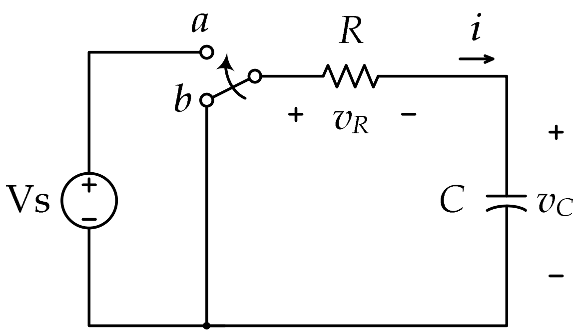



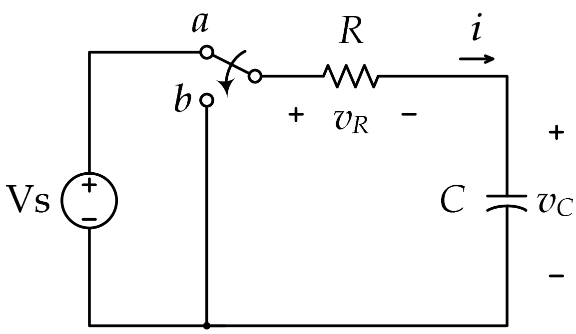
Inductance values are usually encoded using numbers and letters on the casing of the inductor, and sometimes using colors. To read this code, follow the same rules for the capacitor, except that you read the inductance value in μH (instead of pF for the capacitor). It is also important to remember that a practical inductor has a small internal resistance, so you have to be careful in experimenting with inductors as you sometimes need to represent an inductor as a series combination of an ideal $L$ element (the inductance) in series with $R_{DC}$ (the internal resistance of the inductor). More discussion on the discrete component model of a practical inductor is presented later.

Measurement of capacitance and inductance in the laboratory can be performed using an RLC meter. Simply set the test frequency of the RLC meter, its function (L or C), and then connect it in parallel with the component you want to measure.

**Transient Behavior and Pulse Response**

Remember that capacitors cannot change their voltage in zero time. Hence, when connecting a power supply to an uncharged capacitor by moving the switch in the circuit below to position $a$, the capacitor voltage $v_C$ builds up gradually in an increasing exponential form until it reaches the steady state value of $V_S$ after approximately $5\tau$, where $\tau = RC$ seconds is known as the time constant of the first-order RC circuit.




Solving the differential equation for the above circuit gives the shape of the capacitor voltage, which is given by,

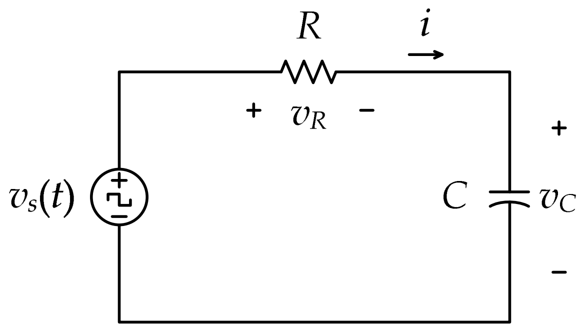
$$v_C(t) = V_S - V_S\, e^{-t/\tau}, \qquad t \geq 0$$

Similarly, if the switch in the above circuit is moved to position $b$, the capacitor starts discharging gradually (in a decaying exponential fashion) until it reaches the steady state value of 0 V. The capacitor voltage in this case is given by,

$$v_C(t) = V_0\, e^{-t/\tau} = V_S\, e^{-t/\tau}, \qquad t \geq 0$$

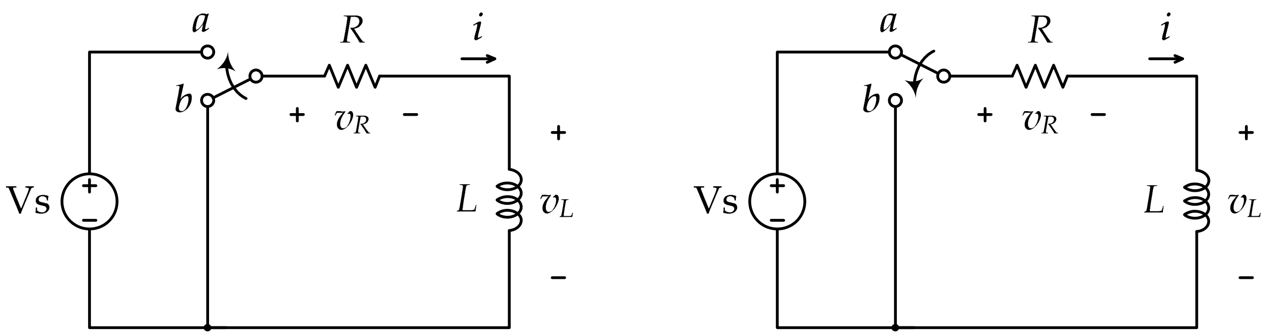
where $V_0$ is the initial voltage across the capacitor due to its stored energy at the time of closing the switch.

Since the Oscilloscope cannot measure signals other than periodic ones, we will perform a trick to see the transient behavior for charging and discharging a capacitor on the oscilloscope. The trick is to replace the DC source and the two-position switch with a function generator that generates a square wave signal (see the circuit below). We will set the square wave signal to go to 6 Volt for half the time, which is similar to connecting a 6 V supply to charge the capacitor, followed by the square wave going to 0 Volt for the remainder of the time, which is similar to the capacitor discharging through the resistor $R$. As the function generator repeats the process, the oscilloscope can capture the signal and display it on its screen.



Please note that (strictly speaking) periodic signals are not transient signals, but what we do here is a neat trick to capture the same behavior seen in transients due to switching. This will work as long as we maintain a square wave half-period that is longer than $5\tau$ of the RC circuit.

On the other side of the coin, inductors cannot change their current in zero time. Hence, when connecting a power supply to an un-energized inductor, by moving the switch in the circuit below to position $a$, the inductor current $i$ builds gradually in an increasing exponential form until it reaches the steady state value of $V_S/R$ after approximately $5\tau$, where $\tau = L/R$ seconds is the time constant of the first-order RL circuit.




Solving the differential equation for the above circuit gives the shape of the inductor current, which is given by,

$$i(t) = \frac{V_S}{R} - \frac{V_S}{R}\, e^{-t/\tau}, \qquad t \geq 0$$

Similarly, if the switch in the above circuit is moved to position $b$, the inductor starts de-energizing gradually (in a decaying exponential fashion) until it reaches the steady state value of 0 A. The inductor current in this case is given by,

$$i(t) = I_0\, e^{-t/\tau} = \frac{V_S}{R}\, e^{-t/\tau}, \qquad t \geq 0$$

where $I_0$ is the initial current through the inductor due to its stored magnetic energy at the time of closing the switch.

**PROCEDURE A – CAPACITORS AND INDUCTORS**

1. You will be provided with three capacitors $C_1$, $C_2$, and $C_3$ in the Lab. Use their color or number/letter coding to read their nominal values, tolerances and break down voltage. Record that information in Table 1. Also note the type of the capacitor: ceramic, electrolytic, etc in the table.

**Table 1**

| | $C_1$ | $C_2$ | $C_3$ |
|---|---|---|---|
| **Code or color on the capacitor** | | | |
| **Nominal Value** | | | |
| **Tolerance (%)** | | | |
| **Breakdown voltage** | | | |
| **Capacitor type** | | | |
| **Measured @ $f_1$** | | | |
| **Deviation (%)** | | | |
| **Measured @ $f_2$** | | | |
| **Deviation (%)** | | | |

2. Use the RLC meter to measure the actual value for each of the three capacitors. Use the two available frequencies in the RLC meter. Record the results in Table 1. Also record the deviation between the nominal value and the measured value as a percentage, calculated as:

$$Deviation = \frac{Measured - Nominal}{Nominal} \times 100\%$$

3. What are the two frequencies $f_1$ and $f_2$ that the RLC meter uses for its measurements?

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4. You will also be provided with two inductors $L_1$ and $L_2$ in the Lab. Use their color or number/letter coding to read their nominal values and tolerances. State the code, nominal value and tolerance in Table 2.

5. Use the RLC meter to measure the actual value for the inductor, and then evaluate the deviation from nominal value. Use both available frequencies. Record the measured values and deviations in Table 2.

**Table 2**

| | $L_1$ | | $L_2$ | |
|---|---|---|---|---|
| **Code or color on the inductor** | | | | |
| **Nominal Value** | | | | |
| **Tolerance (%)** | | | | |
| **Measured @ $f_1$** | | | | |
| **Deviation (%)** | | | | |
| **Measured @ $f_2$** | | | | |
| **Deviation (%)** | | | | |
| **Internal series resistance $R_{DC}$** | @$f_1$ | @$f_2$ | @$f_1$ | @$f_2$ |
| **Internal parallel resistance $R_P$** | @$f_1$ | @$f_2$ | @$f_1$ | @$f_2$ |

6. Use the RLC meter to measure the internal *series* resistance of each inductor (also known as the inductor DC resistance $R_{DC}$), which is a property of practical inductors due to the internal resistance of the long wire wound to make up the inductor? Record this resistance value at the two test frequencies in Table 2.

7. Why do you think the resistance values measured by the two test frequencies are different? Which one should be more accurate and why?

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8. Finally, use the RLC meter to measure the internal *parallel* resistance of each inductor $R_P$ (which is due to frequency-dependent low power core losses)? Record this resistance value at the two test frequencies in Table 2.

9. At what frequencies (low or high) should we consider the internal series resistance $R_{DC}$ of the inductor in our calculations? and *Why*?

. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .

10. At what frequencies (low or high) should we consider the internal parallel resistance $R_P$ of the inductor in our calculations? and *Why*?

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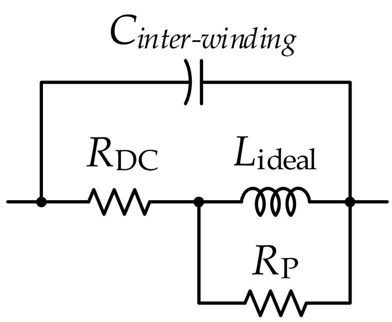
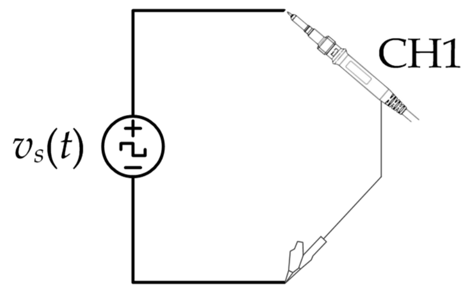
11. Practical inductors also have an extra parallel capacitance due to the proximity of the coil inter-windings. The equivalent circuit typically used to model a practical inductor is shown below. More sophisticated models also exist, which include more physical phenomena, such as the skin effect in the conductor wire, limited impedance at resonance, etc. However, in several occasions we just accept approximate answers by modeling a practical inductor using only an ideal inductor model.



**PROCEDURE B – OSCILLOSCOPE**

1. Turn the **oscilloscope** ON. Set channel 1 of the oscilloscope to 0.5 V/DIV and set the sweep to 0.25 ms/DIV. Set the coupling of Channel 1 to DC, and set the Trigger Source to CH1.

2. With the help of the breadboard, connect the output of the **function generator** to channel 1 probe of the **oscilloscope** (as shown below). Turn the function generator ON.




3. Set the output frequency of the function generator to 1 kHz and its output voltage to 6 $V_{p\text{-}p}$, and the signal type to **square wave**.

4. If the vertical position or horizontal position on the oscilloscope is not set in the middle, perform the necessary adjustments. How many cycles of the square wave do you see on the oscilloscope screen?

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5. Increase the frequency of the signal using the function generator controls. What do you see on the oscilloscope screen?

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6. Decrease the frequency of the signal using the function generator controls. What do you see on the oscilloscope screen?

. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .

7. How do you increase the voltage level coming out of the function generator?

. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .

8. Now increase the voltage level from the function generator. What do you see on the oscilloscope screen?

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9. If you increased the signal voltage level from the function generator until it exceeds the screen limits of the oscilloscope, what should you do to see the signal again on the oscilloscope screen?

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10. What other signal shapes (other than square wave) can the function generator produce? See them on the oscilloscope screen.

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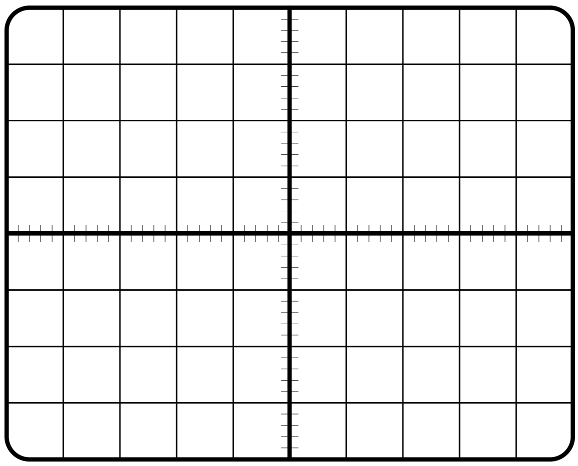
11. Now make sure the vertical position of the oscilloscope is set to zero. You can do that by noticing the movement of the small triangle to the left of the oscilloscope screen as you adjust the vertical position knob. Make sure it points exactly to the middle of the screen.

12. Bring the function generator signal back to 1 kHz frequency square wave.

13. Set the function generator to produce a DC offset so that the output voltage ranges between a minimum of 0 V and a maximum of 6 V. Draw what you see on the oscilloscope screen below. Make sure you have channel 1 of the oscilloscope set to 0.5 V/DIV and the sweep set to 0.25 ms/DIV.



14. What is the period (one cycle) of the above square wave signal in units of horizontal screen divisions and also in units of milliseconds?

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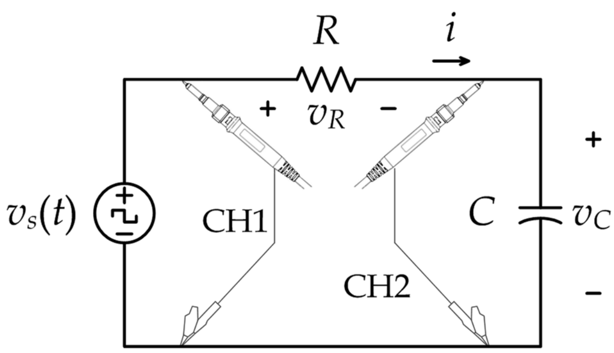
**PROCEDURE C – TRANSIENT RESPONSE OF RC CIRCUITS**

1. Construct the circuit shown below. Assume that $R$ = 1000 Ω, $C$ = 0.1 μF.



3. What is time constant $\tau$ for this first-order RC circuit? Show both the equation and the value.

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4. Set the function generator to produce a 700 Hz frequency square wave with output voltage ranging between a minimum of 0 V and a maximum of 6 V.

5. Use theoretical analysis (increasing and decaying exponential) to determine the voltages and currents in the circuit: $v_S(t)$, $v_C(t)$, $v_R(t)$, $i(t)$ at the time instances shown in Table 3. Record these values in the table? Also show below the mathematical expressions of $v_C(t)$, $v_R(t)$, $i(t)$.

. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .

6. Use the oscilloscope screen to measure the voltages: $v_S(t)$ (on channel 1 of the oscilloscope) and $v_C(t)$ (on channel 2 of the oscilloscope). Record these values in Table 3 for all required time instants. Remember that you can change the oscilloscope horizontal sweep setting to get more accurate readings. Are the measured values close to the theory-based answers?

. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .

7. Now evaluate the *measured* values of $v_R(t)$ and $i(t)$ and record them in Table 3. Remember that you can measure $v_R(t)$ by subtracting the *measured* values of $v_S(t)$ and $v_C(t)$, and you can measure the current $i(t)$ by applying Ohm's law on the resistor using the measured value of $v_R(t)$ (i.e., $i(t) = v_R(t)/R$).

**Table 3**

| **Time since switch (ms)** | $v_S(t)$ | | $v_C(t)$ | | $v_R(t) = v_S(t) - v_C(t)$ | | $i(t) = v_R(t)/R$ | |
|---|---|---|---|---|---|---|---|---|
| | **Theory** | **Meas.** | **Theory** | **Meas.** | **Theory** | **Meas.** | **Theory** | **Meas.** |
| 0 | 6 V | | | | | | | |
| **0.05** [= 0.5$\tau$] | 6 V | | | | | | | |
| **0.1** [= $\tau$] | 6 V | | | | | | | |
| **0.2** [= 2$\tau$] | 6 V | | | | | | | |
| **0.3** [= 3$\tau$] | 6 V | | | | | | | |
| **0.4** [= 4$\tau$] | 6 V | | | | | | | |
| **0.5** [= 5$\tau$] | 6 V | | | | | | | |
| 0 | 0 V | | | | | | | |
| **0.05** [= 0.5$\tau$] | 0 V | | | | | | | |
| **0.1** [= $\tau$] | 0 V | | | | | | | |
| **0.2** [= 2$\tau$] | 0 V | | | | | | | |
| **0.3** [= 3$\tau$] | 0 V | | | | | | | |
| **0.4** [= 4$\tau$] | 0 V | | | | | | | |
| **0.5** [= 5$\tau$] | 0 V | | | | | | | |

8. Notice that you cannot measure $v_R(t)$ by attaching the channel 2 probe to it while still measuring $v_S(t)$ at the same time, since the grounds of channel 1 and channel 2 of the oscilloscope are attached to each other inside the oscilloscope, which means you will short circuit the capacitor. However, there is a trick to measure $v_R(t)$, which is to swap the locations of the resistor and capacitor in the circuit while keeping the oscilloscope connections unchanged. This way, channel 2 of the oscilloscope will show $v_R(t)$ rather than $v_C(t)$. Use this technique to measure $v_R(t)$ without calculations and record the results in Table 4. To speed up your work you can use the cursor feature of the oscilloscope as explained below. Are the results for $v_R(t)$ in Table 3 and Table 4 close or not?

. . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . . .

9. Finally, remember that an oscilloscope can only measure voltages (like a voltmeter) but not currents (like ammeters do).

**Table 4**

| **Time since switch (ms)** | $v_S(t)$ | | $v_R(t)$ by swapping | |
|---|---|---|---|---|
| | **Theory** | **Meas.** | **Theory** | **Meas.** |
| 0 | 6 V | | | |
| **0.05** [= $0.5\tau$] | 6 V | | | |
| **0.1** [= $\tau$] | 6 V | | | |
| **0.2** [= $2\tau$] | 6 V | | | |
| **0.3** [= $3\tau$] | 6 V | | | |
| **0.4** [= $4\tau$] | 6 V | | | |
| **0.5** [= $5\tau$] | 6 V | | | |
| 0 | 0 V | | | |
| **0.05** [= $0.5\tau$] | 0 V | | | |
| **0.1** [= $\tau$] | 0 V | | | |
| **0.2** [= $2\tau$] | 0 V | | | |
| **0.3** [= $3\tau$] | 0 V | | | |
| **0.4** [= $4\tau$] | 0 V | | | |
| **0.5** [= $5\tau$] | 0 V | | | |

**USING THE OSCILLOSCOPE CURSOR**

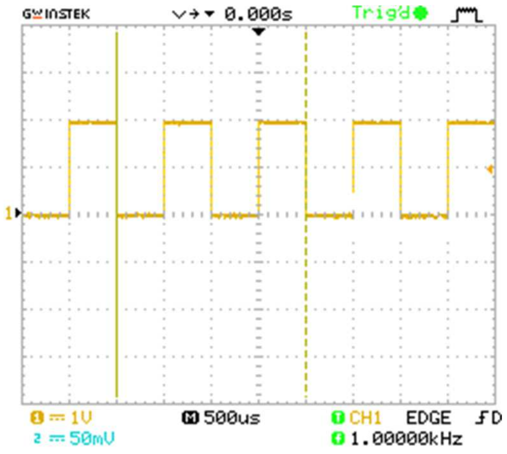
Newer digital oscilloscopes have extra features that can make the life of an engineer easier. For example, if you want to skip the process of converting vertical and horizontal divisions into voltages and seconds, respectively, you can use the cursor feature in the oscilloscope.

For the rest of this experiment try the following steps to measure the time difference between two points on the oscilloscope screen.

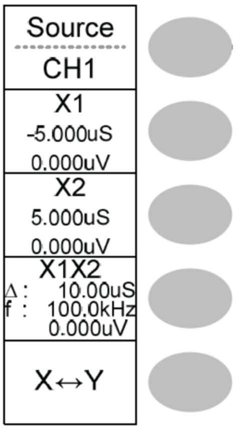
**CAUTION**: You still need to know how to work with the oscilloscope's vertical and horizontal divisions since this is a skill that will be tested in the exam.

a. On the oscilloscope turn the cursors feature ON by pressing the "Cursor" key.

b. Two vertical cursors will show up on the oscilloscope screen.




c. The function keys next to the oscilloscope screen allow you to control the cursors and will automatically calculate the time difference between such cursor positions.




d. The first function key selects the channel you want to measure. In this case it is CH1 of the oscilloscope.

e. Pressing the second function key allows you to move the X1 cursor by adjusting the VARIABLE knob clockwise and counter-clockwise. The voltage value at the cursor is also displayed.

f. Pressing the third function key allows you to move the X2 cursor by adjusting the VARIABLE knob. The voltage value at the cursor is also displayed.

g. The time difference between X1 and X2 cursors is continuously calculated and displayed next to the fourth function key. This key moves both cursors simultaneously.

h. If you need to measure voltage difference instead of time difference, the fifth function key switches to horizontal cursors instead of vertical ones.

10. Using the measured values in Table 3, plot (**by hand**) the following two figures using the graph paper attached at the end of the report: (1) $v_S(t)$ and $v_C(t)$ on the same plot versus time; (2) $v_S(t)$ and $i(t)$ on the same plot versus time. Make sure you include both cases of $v_S(t)$ suddenly jumping to 6 V and $v_S(t)$ suddenly dropping to 0 V. For the second plot ($v_S(t)$ and $i(t)$) please use two vertical axes, one to the left for voltage, and one to the right for current. You can use different scales on these vertical axes so that the plot looks intelligible. How much voltage does the capacitor lose as it is discharging after exactly one time constant $\tau$?

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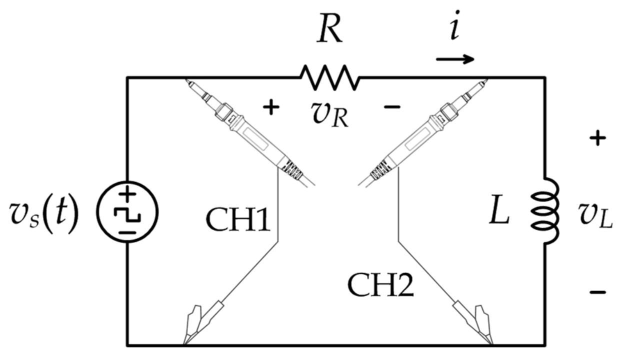
## PROCEDURE D – TRANSIENT RESPONSE OF RL CIRCUITS

1. Construct the circuit shown below. Assume that $R$ = 3300 Ω, $L$ = 100 mH. **Remember** to use the correct resistor value here.




2. What is time constant $\tau$ for this first-order RL circuit? Show both the equation and the value.

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3. Set the function generator to produce a 3 kHz frequency square wave with output voltage ranging between a minimum of 0 V and a maximum of 6 V.

4. Use theoretical analysis (increasing and decaying exponential) to determine the voltages and currents in the circuit: $v_S(t)$, $v_L(t)$, $v_R(t)$, $i(t)$ at the time instances shown in Table 5. Record these values in the table? Also show below the mathematical expressions of $v_L(t)$, $v_R(t)$, $i(t)$.

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5. Use the oscilloscope screen to measure the voltages: $v_S(t)$ (on channel 1 of the oscilloscope) and $v_L(t)$ (on channel 2 of the oscilloscope). Record these values in Table 5 for all required time instants. Remember that you can change the oscilloscope horizontal sweep setting to get more accurate readings. Are the measured values close to the theory-based answers?

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6. Now evaluate the *measured* values of $v_R(t)$ and $i(t)$ and record them in Table 5. Remember that you can measure $v_R(t)$ by subtracting the *measured* values of $v_S(t)$ and $v_L(t)$, and you can measure the current $i(t)$ by applying Ohm's law on the resistor using the measured value of $v_R(t)$ (i.e., $i(t) = v_R(t)/R$).

7. Using the measured values in Table 5, plot (**by hand**) the following two figures using the graph paper attached at the end of the report: (1) $v_S(t)$ and $v_L(t)$ on the same plot versus time; (2) $v_S(t)$ and $i(t)$ on the same plot versus time. Make sure you include both cases of $v_S(t)$ suddenly jumping to 6 V and $v_S(t)$ suddenly dropping to 0 V. For the second plot ($v_S(t)$ and $i(t)$) please use two vertical axes, one to the left for voltage, and one to the right for current. You can use different scales on these vertical axes so that the plot looks intelligible. How much current does the inductor gain as it is being energized after exactly one time constant $\tau$?

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**Table 5**

| **Time since switch (ms)** | $v_S(t)$ | | $v_L(t)$ | | $v_R(t) = v_S(t) - v_L(t)$ | | $i(t) = v_R(t)/R$ | |
|---|---|---|---|---|---|---|---|---|
| | **Theory** | **Meas.** | **Theory** | **Meas.** | **Theory** | **Meas.** | **Theory** | **Meas.** |
| 0 | 6 V | | | | | | | |
| **0.0152** [= $0.5\tau$] | 6 V | | | | | | | |
| **0.0303** [= $\tau$] | 6 V | | | | | | | |
| **0.0606** [= $2\tau$] | 6 V | | | | | | | |
| **0.0909** [= $3\tau$] | 6 V | | | | | | | |
| **0.1212** [= $4\tau$] | 6 V | | | | | | | |
| **0.1515** [= $5\tau$] | 6 V | | | | | | | |
| 0 | 0 V | | | | | | | |
| **0.0152** [= $0.5\tau$] | 0 V | | | | | | | |
| **0.0303** [= $\tau$] | 0 V | | | | | | | |
| **0.0606** [= $2\tau$] | 0 V | | | | | | | |
| **0.0909** [= $3\tau$] | 0 V | | | | | | | |
| **0.1212** [= $4\tau$] | 0 V | | | | | | | |
| **0.1515** [= $5\tau$] | 0 V | | | | | | | |

8. If you did not know the value of $L$ before you did the experiment, can you measure its value from the above plots? Explain how in detail.

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9. Assume that we increased the frequency of the source voltage $v_S(t)$ to three times its value (from 3 kHz to 9 kHz), sketch (**by hand**) using the graph paper attached at the end of the report an approximate plot showing $v_S(t)$ and $i(t)$. Your plot does not have to be exact, but should show the expected effect. Make sure you include both cases of $v_S(t)$ suddenly jumping to 6 V and $v_S(t)$ suddenly dropping to 0 V.

**** End ****