Electronics and Electromagnetism

Lab 9: RC and RL circuit
(Capacitors & Inductors)

Purpose

In this Lab, we will discuss the electrical transient responses, seen in **RC** and **RL** circuits. We will start by constructing charging and discharging circuits and analyze the rise and decay of voltage and current along with finding the time constants associated with each circuit. In cases where a large enough time constant is not possible to obtain, we will turn to our function generator and oscilloscope and look at the response of these circuits to a rectangular input pulse.

The R-C Circuit

You have previously studied the charging and discharging response of R-C circuits in class. Many devices incorporate circuits in which a capacitor is alternately charged and discharged. These include flashing traffic lights, automobile turn signals, and electronic flash units. Understanding what happens in such circuits is thus of great practical importance. In the first part of this lab, we will focus on building these circuits and studying their time varying **(transient)** response.

R-C Charging Circuit

An **R-C** circuit is simply made of a **DC** battery source **(emf ε)** that is connected in series fashion with a resistor R and a capacitor C. A switch S is used here to study the transient response of the circuit after time t=0, the moment when the switch is closed. We are aware that the voltage across a capacitor cannot change instantaneously because $I = C(dv/dt)$ and an instantaneous change in voltage would mean an infinite current through the capacitor. The voltage will however increase gradually until it is fully charged to the potential (emf) of the battery. The charging relation is given as

$$V_c = \varepsilon\left(1 - e^{\frac{-t}{RC}}\right)$$

where, V_c is the voltage across the capacitor. The quantity **RC** that appears in the exponent is called the **time-constant τ** of the circuit. **1τ** is defined as the time taken to charge the capacitor to **63 % of the battery's emf ε**. Typically, it takes about **3- or 4-time constants** for a capacitor to become fully charged as is evident for the charging curve shown below.

On the contrary, the **current through the capacitor decreases with time.** As soon as the switch S is closed, the initial current flowing through the circuit is determined solely by the resistance R. As the capacitor charges, the rate of change of voltage (dv/dt) decreases and the current decays and eventually ceases to flow. The capacitor then behaves like an open circuit element. The variation of the capacitor current is obtained from $I = C\ (dv/dt)$ and is given as

$$I = \frac{\varepsilon}{R} e^{\frac{-t}{RC}}$$

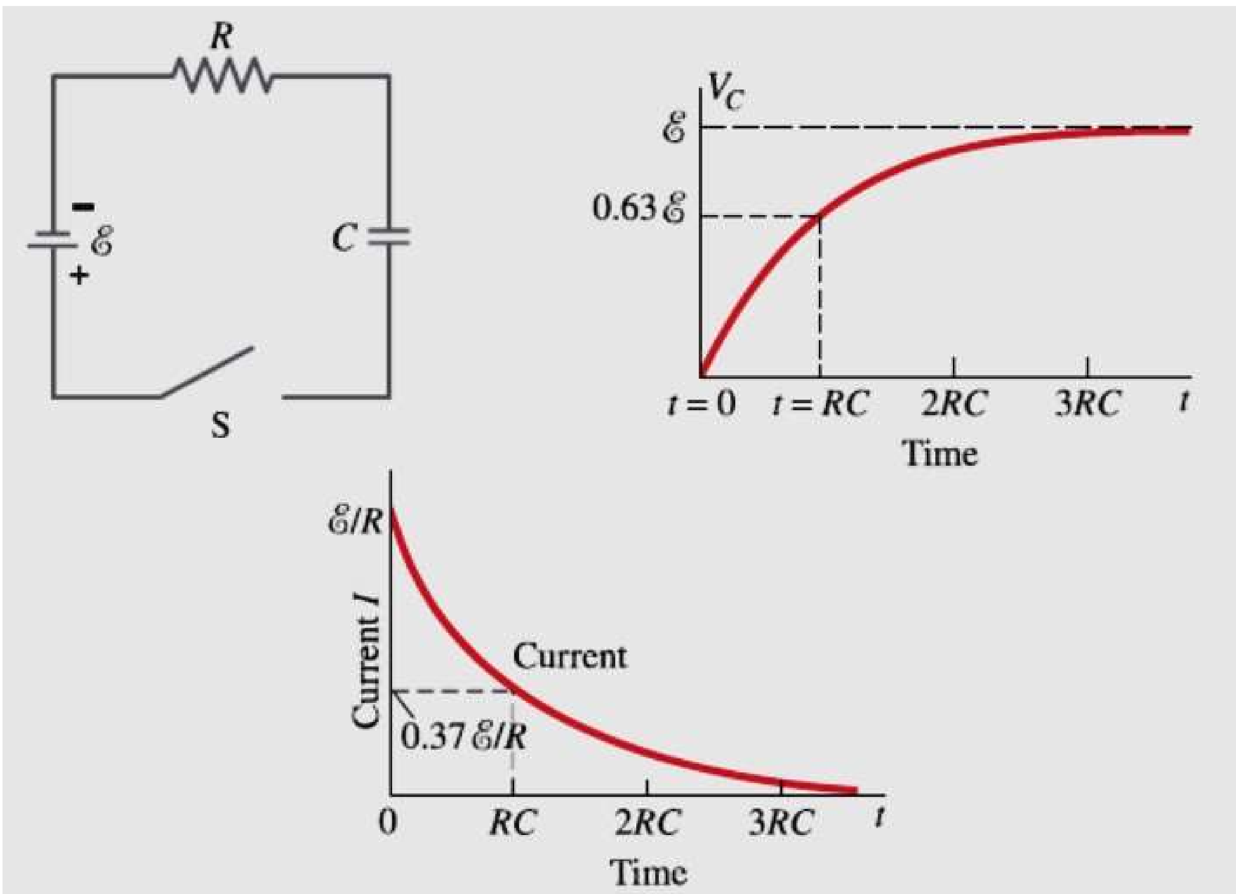


Figure 1: R-C charging circuit and the transient response of the capacitor voltage and current after time t=0

R-C Discharging Circuit

Once the capacitor has been fully (or partially) charged, it can be discharged by removing the source of EMF in the circuit. Once the switch is closed, the capacitor starts to lose all of its previously stored energy (in the electric field) by discharging through the resistor present in the circuit. The decaying voltage and current associated with the capacitor are then given as

$$V_C = V_0 e^{\frac{-t}{RC}} \;;\; I = I_0 e^{\frac{-t}{RC}}$$

Where V_0 and I_0 are the initial voltage and current respectively

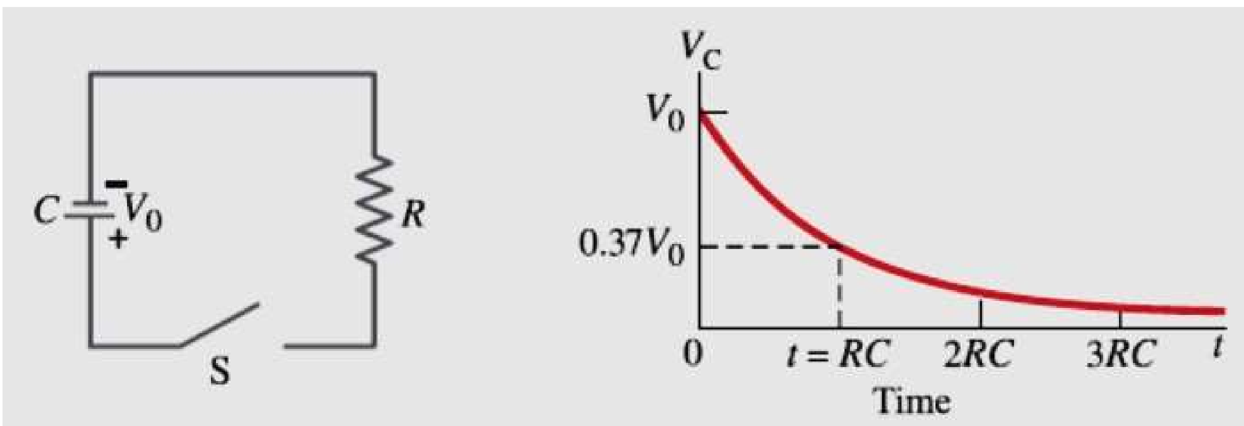


Figure 2: R-C discharging circuit and the transient response of the capacitor voltage

The R-L Circuit

In class you have studied the response of R-L circuits. We have also seen some applications based on this as well. For instance, we have seen how an inductor acts as a surge protector for sensitive electronic equipment. In this part of your lab, you will build a simple inductor circuit and study its responses. An R-L circuit is simply made of a DC battery source (emf ε) that is connected in series fashion with a resistor R and an inductor L. A switch S is used here to study the transient response of the circuit after time t=0, the moment when the switch is closed.

R-L Charging Circuit

We know that the current across an inductor cannot change instantaneously$\left(V = L\frac{dI}{dt}\right)$. As soon as the switch is closed and current starts to flow, there is also a voltage drop of magnitude IR across the resistor R. Hence the voltage across the inductor is reduced and the current increases less rapidly. The current then rises gradually and approaches the steady state value (or the maximum value). When steady state is reached, the rate of change of current is zero and the voltage across the inductor also drops to zero. In other words, the inductor behaves like a short, circuited element and all the voltage is now dropped across the resistance alone. The gradual rise in current through the inductor is expressed as

$$\boldsymbol{I = \frac{\varepsilon}{R}\left(1 - e^{\frac{-tR}{L}}\right)}$$

where, I is the current flowing through the inductor. The quantity $\boldsymbol{L/R}$ appears in the exponent is called the time-constant τ of the circuit. 1τ is defined as the time taken for the current in the inductor to reach 63% of the maximum current $I_{max} = \boldsymbol{V_0/R}$. Typically, it takes about 3- or 4-time constants for an inductor to allow the maximum current to flow through it. The corresponding voltage variation across the inductor is obtained from $\boldsymbol{V = L\frac{dI}{dt}}$

$$\boldsymbol{V_L = \varepsilon e^{\frac{-tR}{L}}}$$

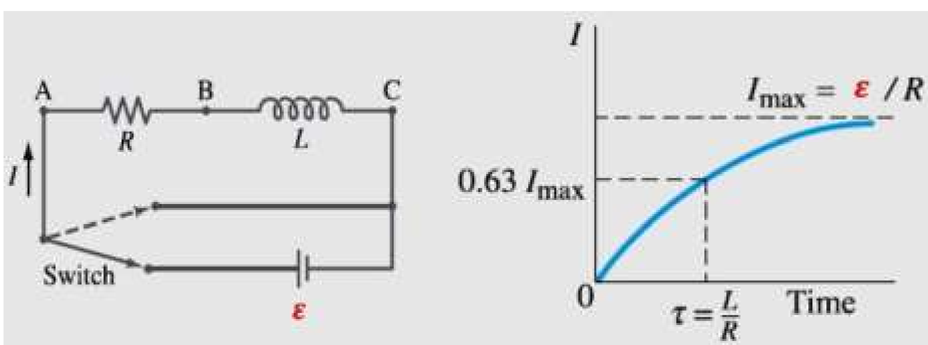


Figure 3: R-L charging circuit and the transient response of the inductor current

R-L Discharging Circuit

When the switch S is flipped to the other position, we end up taking the battery out of the circuit. The current and the voltage in the inductor is then seen to decay following the relation

$$I = I_0 e^{\frac{-tR}{L}}\ ;\quad V = V_0 e^{\frac{-tR}{L}}$$

Here, I_0 and V_0 are the initial current and voltage, respectively. The energy stored in the inductor is said to have dissipated through the resistor in the circuit.

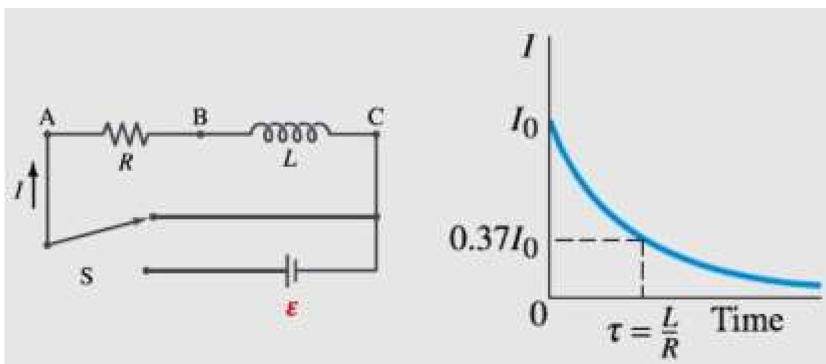


Figure 4: R-L discharging circuit and the transient response of the inductor current

Name	ID	Group ID

TASK 1 (10 points)

For this task, we will consider a situation where the time constants of RC circuits are much smaller. Let us say that we want to design an RC circuit with $\boldsymbol{\tau = 10\ \mu s}$. Since it is evident that the human eye will not be able to track or discern changes at this time scale, we will need to call upon our signal generators and oscilloscopes for help.

In this exercise, we will use a function generator. The generator shall be set to output a **rectangular waveform** at a certain **frequency that we need to figure out**. The switch will no longer be used; the rising and falling edges of the rectangular pulse will serve as the "switches" in this case. A rectangular pulse output from your signal generator is shown below. Keep in mind that the rectangular pulse shown below is bi-directional (similar to an AC signal) and therefore the capacitor goes through charging and discharging cycles in both directions. At a particular rising or falling edge, we are therefore seeing combined effects of charging and discharging. This will end up giving us a time constant value that may not perfectly match expectations.

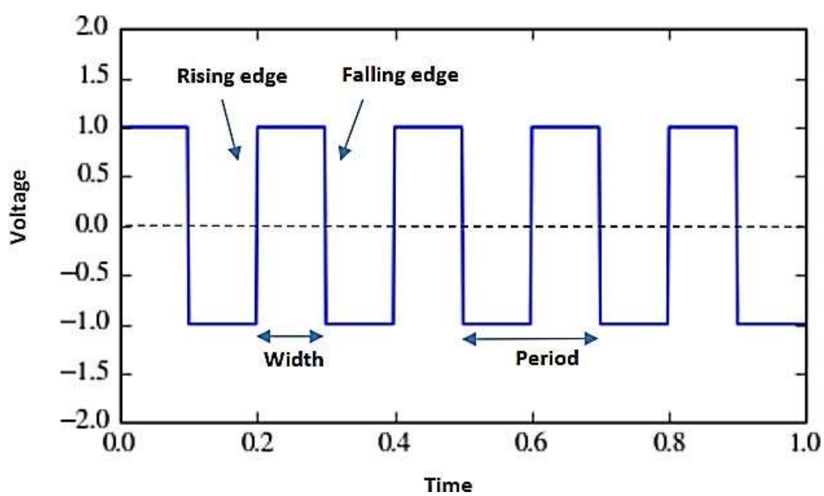


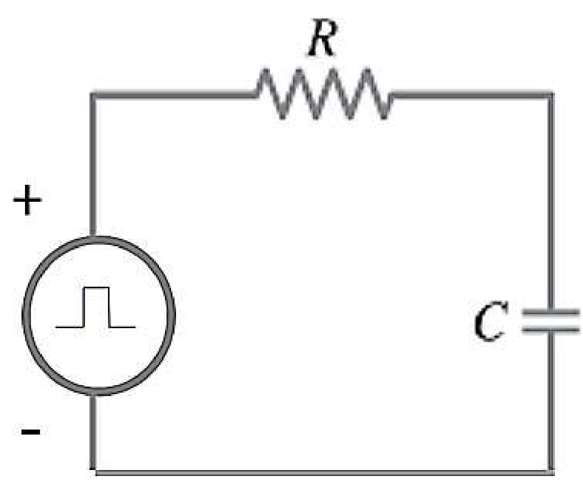
Figure 5: An example rectangular waveform that is output from the signal generator

Part 1

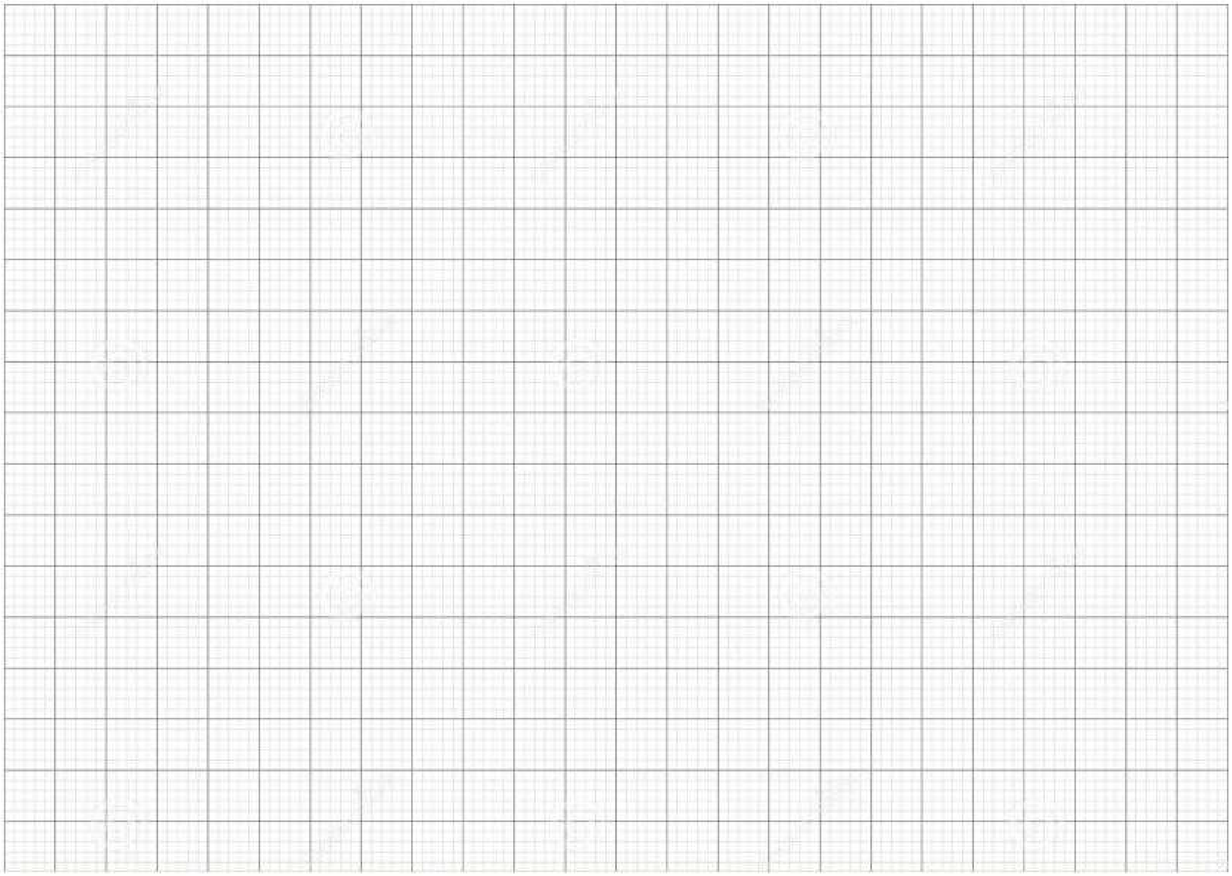
- In order to achieve a small time constant τ **= 10** μs, we must choose a capacitor and/or resistance with a very low value. Let us take a **0.1** μF ceramic capacitor for this task. The resistance needed will be **100 ohms**.
- Assuming the capacitor takes **5-time constants** to fully charge (i.e., 50μs), we must choose a pulse width greater than this value. Let's set the pulse width at 100μs. This makes the period = ? μs (Find out) or the Frequency = ? (Find out) Kilo Hertz
- Connect the circuit as shown below. Set the $\mathbf{V_{p\text{-}p}}$ to 4V on the signal generator
- Connect **CH1** of your oscilloscope to the appropriate points on your breadboard in order to capture the input waveform
- Connect **CH2** of your oscilloscope to the appropriate points on your breadboard in order to capture the voltage across the capacitor

- Plot the two waveforms in the graph provided below. **Timescales, voltage scales and units must be clearly marked (you can use another software for graphing : MsExcel)**
- On the graph paper, **show the approximate value of the time constant you obtain.**

Hint: Use the definition for 1 time constant



Graph

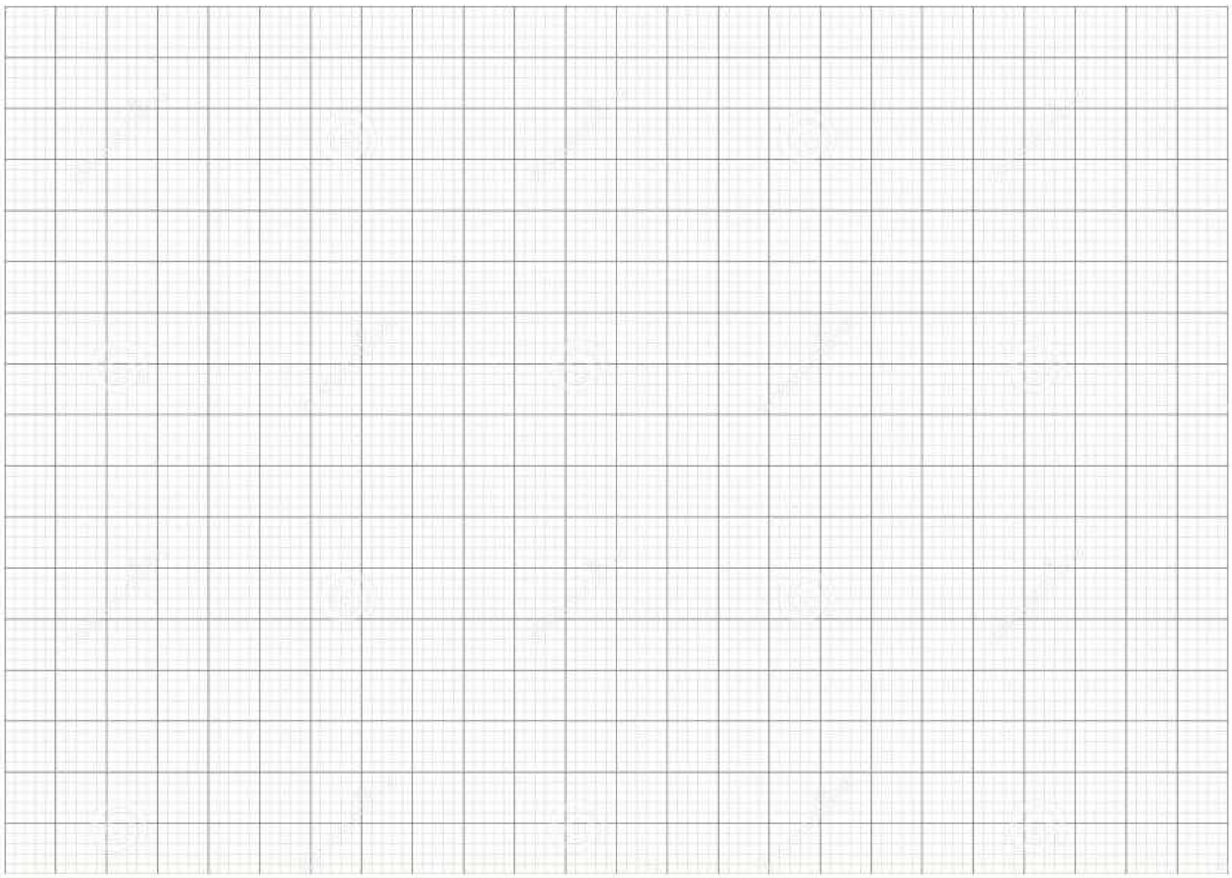


Part 2

In this part of the experiment, we will make use of a potentiometer to vary the resistance in an RC circuit

- Replace the 100-ohm resistor with a **10 Kilo-Ohm potentiometer**
- For a fixed capacitor value **0.1 μF**, you will get the maximum time constant when the potentiometer is adjusted to its maximum resistance position (i.e., **10 kohms**)
- Find this maximum time constant, multiply the value by 10 and use that value to find the frequency that you need to set your rectangular pulse in order to fully capture the charging and discharging behavior on your oscilloscope
- Once you get the expected curves, plot them in the graph provided below
- Now, adjust the potentiometer to an intermediate R setting and then to the lowest R value. Notice if the charging and discharging time are changing or not.
- Show these changes in the plot provided**(you can use another software for graphing : MsExcel)**
- **Find the time constant for each case**

Graph



TASK 2 (10 points)

In order to obtain a high enough time constant in an R-L circuit that will allow us to see changes happening at time scales we are accustomed with; it will be necessary to have a large inductance and a small resistance $\tau = L/R$. For instance, if we desire τ **= 2s**, we will need a **2 Henry inductance** and **1 ohm resistor**. While it is possible to get small, valued resistances, it is not easy to find large value inductors. Usually, μH and mH are the norm. A 2 Henry inductor will be much larger in size and will not be very practical for use in our lab. We will therefore turn towards our signal generator and oscilloscope for help. Our signal generator will be setup to output a rectangular pulse. The rising and falling edge serves as the switches to charge and discharge the inductor.

Part 1

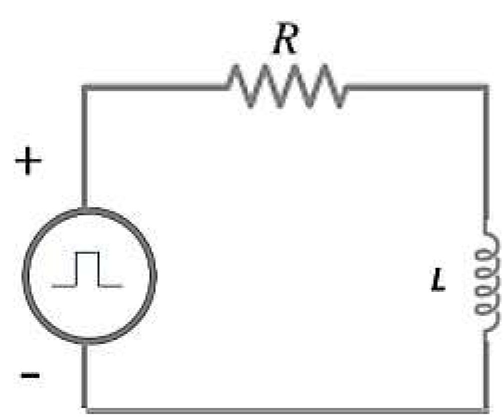
- We will make use of a **1mH** inductor that is available in our lab. Let's choose a time constant of **10μs**, similar to what we did for the R-C circuit in Task 1. We will therefore need a resistor **R = 100 Ω**.
- Build the L-R circuit as shown below. Set the **Vp-p to 4V**
- Similar to Task 1, we will set the frequency to **50 Kilo Hertz**
- Connect **CH1** of your oscilloscope to the appropriate points on your breadboard in order to capture the input waveform

Now comes the tricky part. We cannot directly observe the current flowing through the inductor. This is because we do not have enough oscilloscope current probes. These are very expensive, and we have only a handful of them. However, instead of probing the current, we can probe the voltage across the resistor using regular voltage probes! The voltage across the resistor should have the same variation as the current in the inductor, correct?

To properly connect your CH2 probe to your breadboard, you will now need to switch the positions of R and L. Connect inductor L to the signal generator first and then follow by it with the resistor R

- Connect CH2 of your oscilloscope to the appropriate points on your breadboard in order to capture the voltage across the resistor R
- Plot the two voltage waveforms in the graph provided below. Timescales, voltage scales and units must be clearly marked **(you can use another software for graphing : MsExcel)**
- **On the graph paper, show the approximate value of the time constant you obtain.**

Hint: Use the definition for 1 time constant



Part 2

Let's now replace the 100 ohms resistor with a 50 ohm and a 10-ohm resistor. Watch what happens to your time-constants. **Plot the variations in the graph below.**

Graph