Experiment Name: Charge_Storage_in_Capacitors

Overview

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Fundamental Concepts in Electrical Engineering Lab4 - Transient Effects and Charge Storage in Capacitors

Objectives

- Learn an intuitive and an analytical view of capacitance and capacitors
- Analyze charge storage mechanisms in capacitors
- Built an experiment and study the capacitor chagring from a constant current source
- Built an experiment and study the capacitor chagring from a voltage source through a resistor

Components

- Resistors: 1Ohm (1%, 0.25W),100Ohms (10%, 0.5W), 1kOhms(10%,0.25W), 120kOhms(10%, 0.25W)
- Capacitor: 100nF
- Circuit prototyping breadboard
- Electric wires

Equipment

- Tektronix TBS 1202B-EDU Oscilloscope
- Function Generator (1Hz - 2MHz)

Theory

Capacitance

Two conductors separated by air or any dielectric material form a capacitor. Capacitors store electric charge, and capacitance measures the ratio between the amount of charge stored and the voltage between the two conductors. Capacitance uses the symbol C, and is measured in Farads (F).

$C=Q/V$

where

C = capacitance (F)
Q = charge stored (C)
V = voltage between the two conductors (V)

Besides storing energy, capacitors have the property of conducting transient currents. The conduction process does not occur through charge transfer from one conductor to the other since there is an insulator in between, but rather by charge displacement in one conductor due to charge variation in the other conductor. This current is equal to:

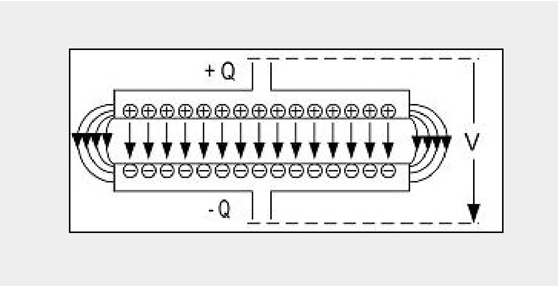
I=CdV/dt

where

I = transient current through the capacitor (A)
C = capacitance (F)
dV/dt = how fast the voltage changes (V/s)

A Simple Capacitor: Parallel Plate Capacitor

A well-known and very simple to analyze capacitor is made of two parallel conductive plates separated by a dielectric, as shown in the following figure.



The charge +Q equals the charge –Q and is called charge stored in the capacitor. The electric field is generated between the two conductive plates, and consists of uniformly distributed field lines inside the capacitor and fringe field lines at the edges. The typical analysis neglects the fringe field and simplifies the calculation of capacitance as:

C=ε0·εr·S/t

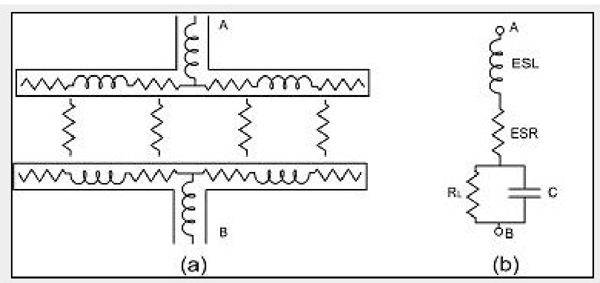
where

C = capacitance (F)
ε0 = permitivity of free space (ε0 = 8.854 x 10-12 F/m)
εr = relative permitivity of the dielectric material
S = area of the conductive plate (m2)
t = separation between the two plates (m)

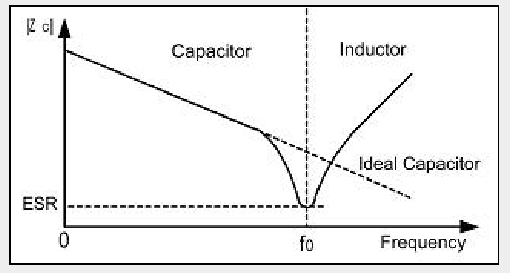
Notice that the capacitance increases with area and decreases with separation. The capacitance also depends on the dielectric material. The lowest capacitance occurs for air dielectric, and it increases for different materials depending on their relative permitivity.

In integrated circuits, packages and printed circuit boards, the capacitance of power and ground planes can often be approximated as parallel plates capacitance. However, for thin wires, the fringe field starts to play a significant role, and the parallel plate approximation is no longer valid.

If we manufacture a parallel plate capacitor, we get a similar device as shown in the figure below diagram (a).



The parallel plates have their own resistance and inductance, and the terminals are dominantly inductive. The equivalent circuit of a real capacitor, shown in diagram (b), consists of the capacitor C in series with an “equivalent series inductance” (ESL) and an “equivalent series resistance” (ESR). A high value leakage resistor RL is placed in parallel with the capacitor. Because of the parasitic elements, the frequency dependence of impedance does no longer look like an ideal capacitor, but more like a resonant circuit as shown in the figure below (logarithmic scale).



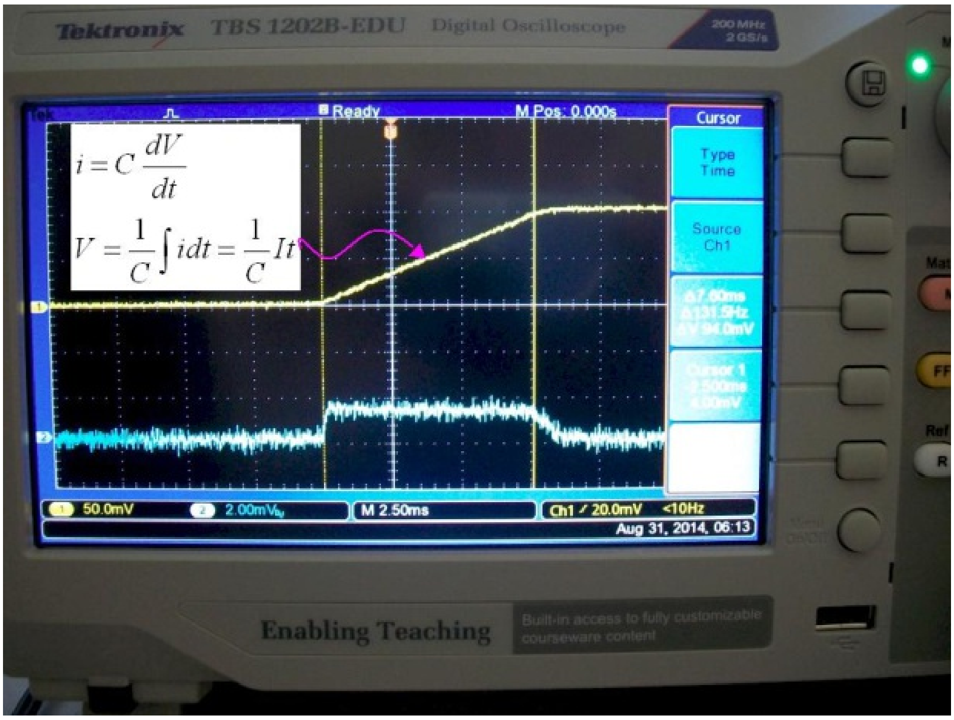
The impedance decreases with frequency up to the "self resonance frequency" f0, after which it starts to increase. The impedance increase with frequency after f0 makes the capacitor behave like an inductor. The minimum impedance equals the ESR value.

Capacitors Charging

Capacitors charge and discharge following the formula: I=CdV/dt. Let's look at two examples: charging from a constant current source and charging from a constant voltage source through a resistor.

Charging from a Constant Current

When charging -a capacitor from a constant current source "I" is constant in I=CdV/dt formula. Solving for V(t) we find out that V=(1/C)*I*t, which is a linear variation in time (a straight line). To visualize this I have setup an experiment in which I charged a 100nF capacitor from a constant current source and I probed the voltage on the capacitor and the charging current with the Tektronix TBS1202B-EDU oscilloscope. The figure below shows the measured waveforms of voltage and current during capacitor charging.

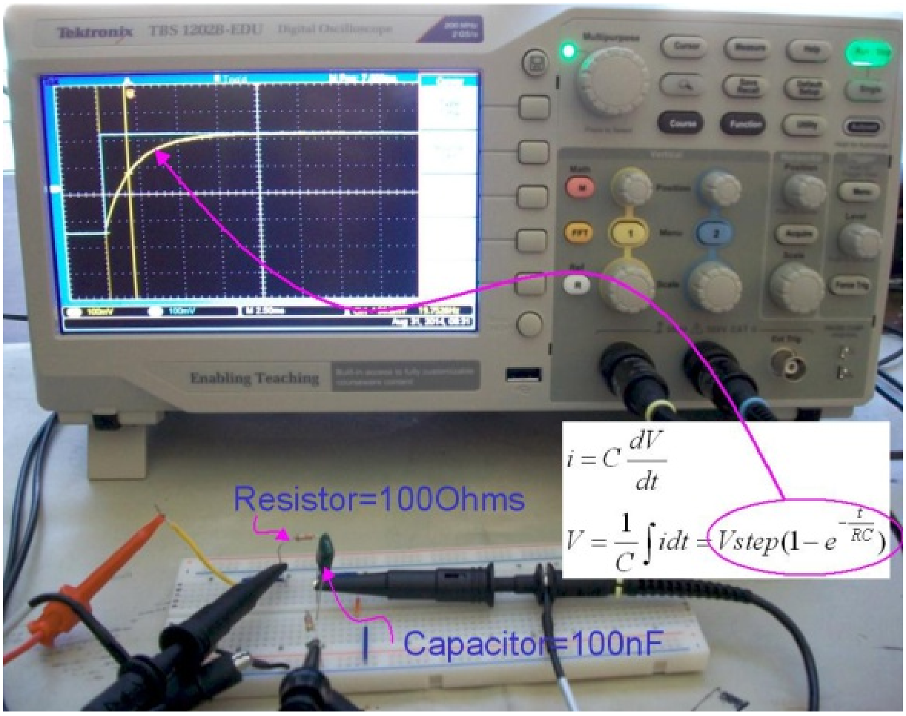


The yellow trace represents the voltage on the capacitor and the blue trace represents the charging current. The charging current is measured as voltage drop on a 1.5kOhm resistor connected in series with the capacitor. At the beginning the current is equal to zero, then it starts flowing at constant intensity for about 7.5ms, after which it stops flowing. The value of the current can be calculated using Ohm's law applied on the 1.5kOhm series resistor as V=IR => I=V/R, where we can read V from the blue waveform as about 1.8mV (2mV/division), so I=1.8mV/1.5kOhms=1.2uA.

Going now back to the capacitor charging formula, V=(1/C)*I*t, we can insert the values for C and I so the charging formula becomes: V=(1/100e-9)*1.2e-6*t=12*t. Based on this, we expect the voltage on the capacitor to increase linearly with time following the formula: V(t) = 12*t. Let's see if this formula correlates with the experimental measurement. The charging voltage is shown by the yellow trace, and indeed it varies linearly with time starting from 0V and reaching about 100mV (2 vertical divisions multiplied by 50mV/division) in about 7.5ms (3 horizontal divisions multiplied by 2.50ms/division). And our calculated formula predicts that the voltage on the capacitor will charge in the 7.5ms to a value equal to V(7.5ms)=12*7.5=90mV. This value is close to the measured 100mV considering all the variations involved here like +/-10% tolerance of resistor value from the nominal 1.5kOhm, and +/-10% tolerance in capacitor value from 100nF.

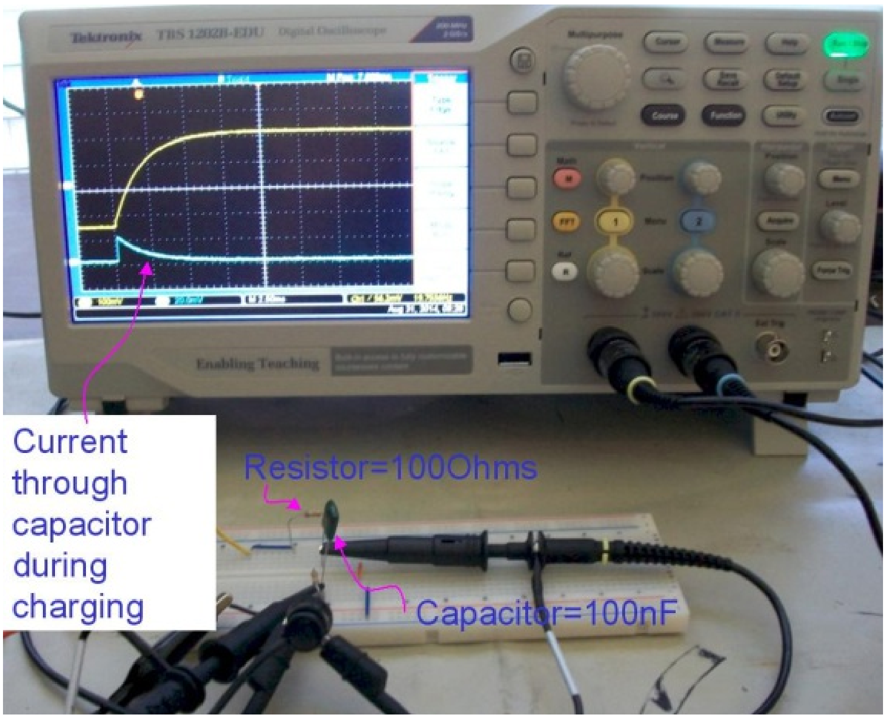
Charging From a Constant Voltage through a Resistor

When charging a capacitor from a constant voltage source through a resistor the same formula I=CdV/dt applies, but the voltage variation on the capacitor is no longer a straight line. As I have annotated on the figure below, solving the integral we get an exponential type variation for the voltage on the capacitor.



The square type trace (blue trace) represents the voltage applied to the capacitor through a 100Ohm resistor and the yellow trace represents the voltage variation on the capacitor. We can notice the exponential increase of voltage on the capacitor, which approaches asymptotically the voltage level of the blue trace.

The picture below shows how the current varies during capacitor charging:



So the current has a step right at the beginning after which it gradually decreases until it reaches asymptotically the zero value.

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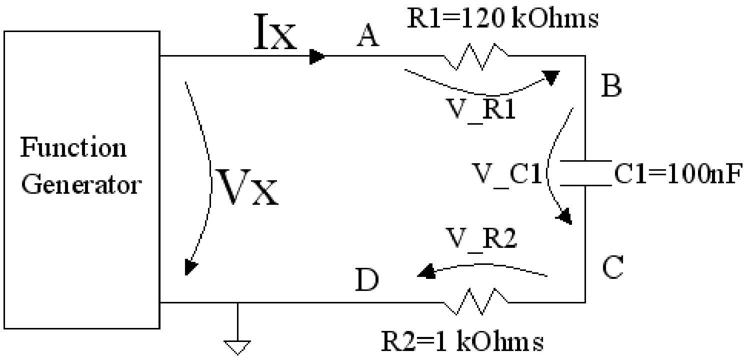
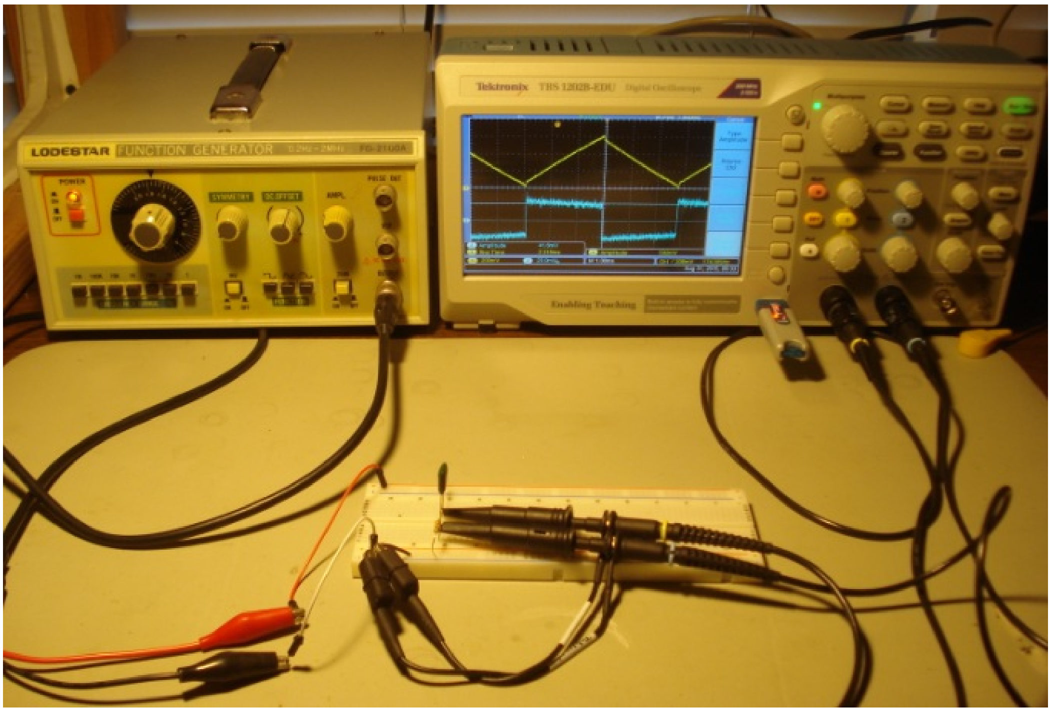
Procedure

Step 1

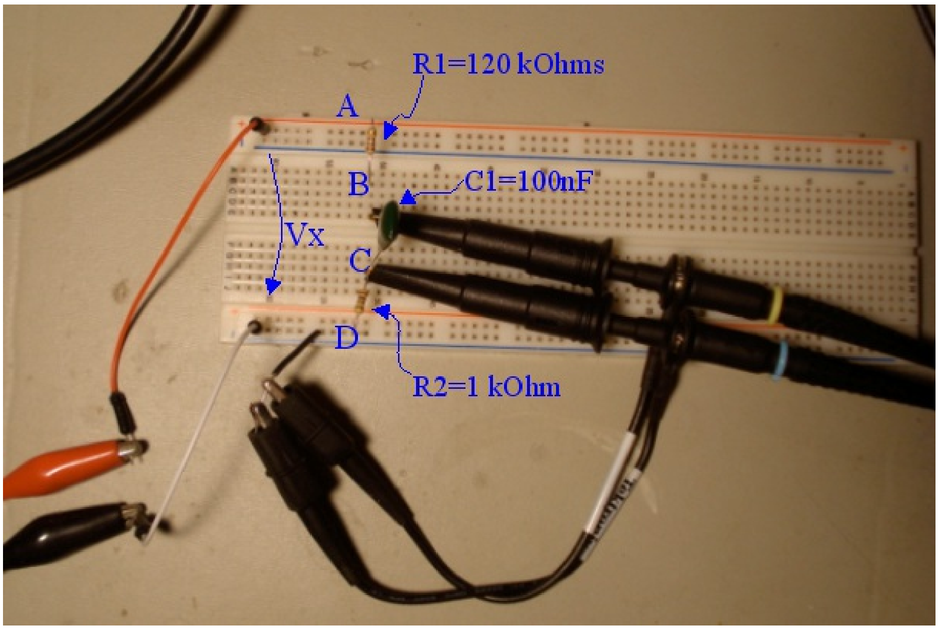
- Construct the circuit in the diagram below:



- Here is a picture of the testbench setup:



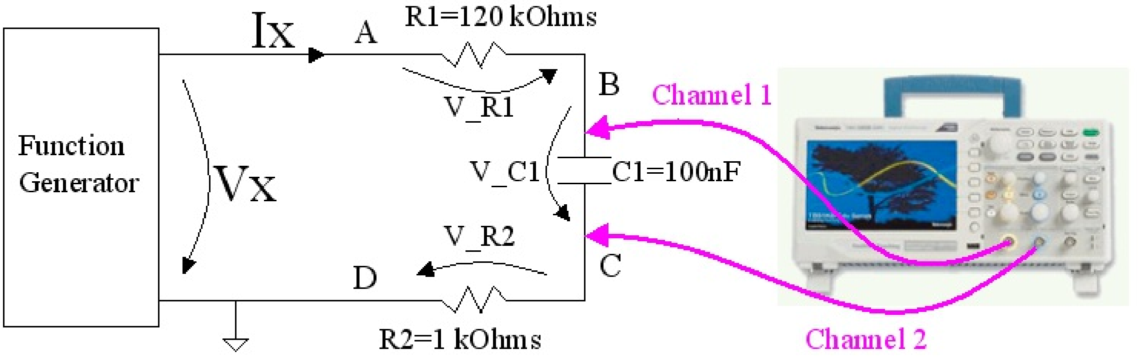
- And here is a more detailed view of the circuit on the breadboard:



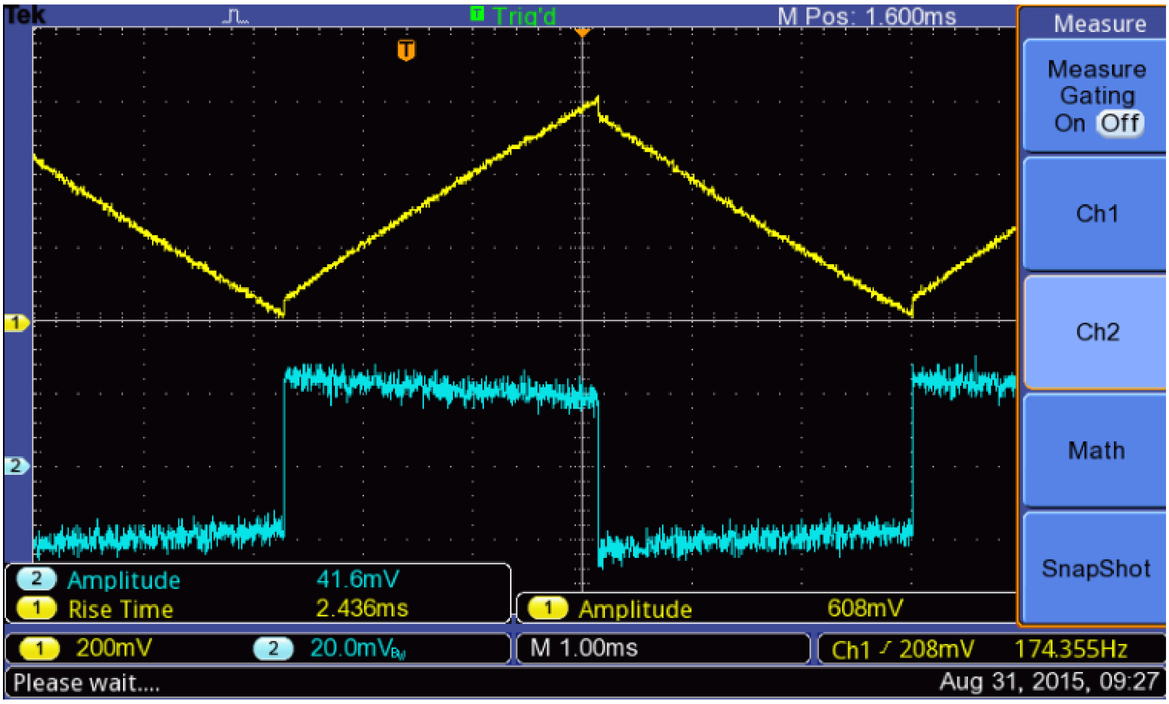
- In this setup R1 has a very large value to create an almost constant current source that charges the capacitor, and R2 is used to indirectly probe the current flow through the capacitor.

Step 2

- Connect Channel 1 of the oscilloscope to node B of the circuit and Channel 2 to node C, as shown in the diagram below:



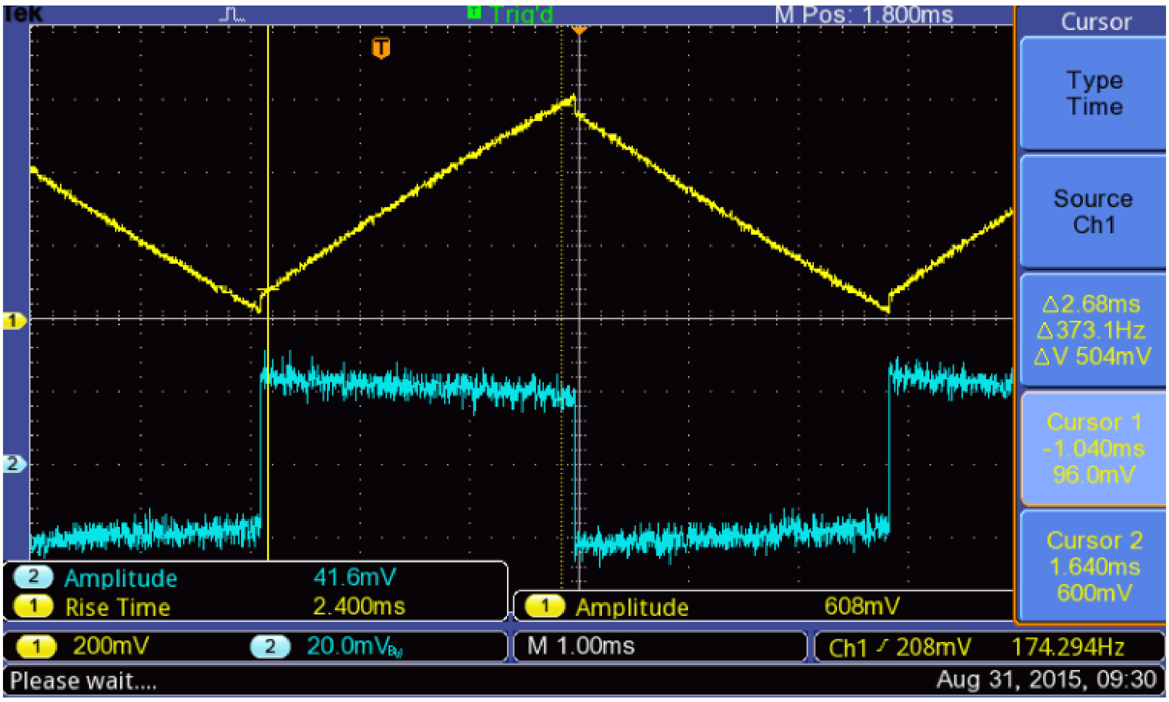
- Set the function generator to rectangular wave of about 5V amplitude and about 200Hz frequency.
- Configure Channel 1 settings to 200mV/div and Channel 2 to 20mV/div.
- Set the oscilloscope time base to 1ms/div.
- Configure the oscilloscope trigger source to Channel 1, rising edge, and adjust the level to be within the signal range.
- With these settings the oscilloscope should display two waveforms similar to the screenshot below:



- In this picture channel 1 (yellow trace) represents the voltage on the capacitor, and channel 2 (blue trace) represents the voltage drop on R2=1kOhm. This voltage can be converted into the current flowing through the capacitor during the charging and discharging phases. Notice the charging current is positive (about 20mV/1k = 20uA).
- Insert a screenshot of the displayed waveforms in this step.
- Why the voltage on the capacitor varies linearly during charging and discharging phases?

Step 3

- Use the built-in cursor functions of the oscilloscope to measure the slope of the voltage variation on the capacitor during the charging phase, as shown in the screenshot below:

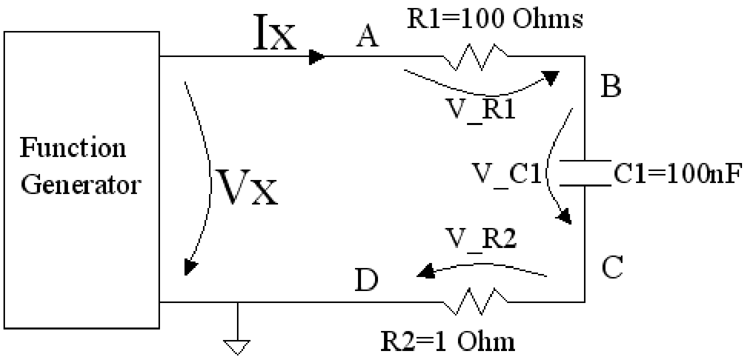


- In the example shown above delta V = 504mV and delta T = 2.68ms.
- Insert a screenshot of the oscilloscope displayed waveforms and cursor readings.

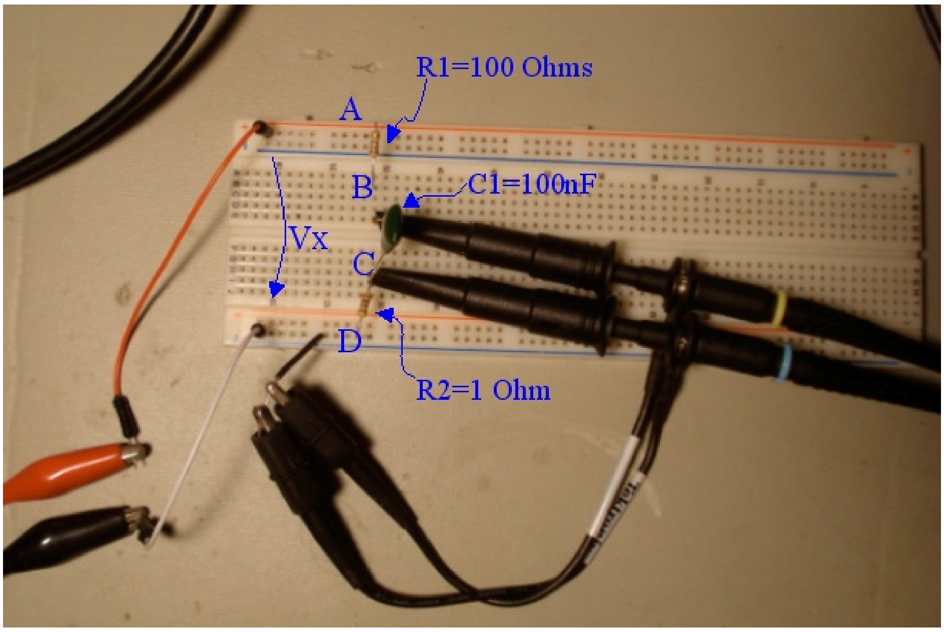
- Determine the value of the charging and discharging current from the voltage drop on R2 displayed by Channel 2 waveform.
- From the delta V and delta T measurements in your experiment derive the value of the charging current using the equations presented in the Theory section of the lab.
- Compare the calculated current with the measured current and comment on the result.

Step 4

- Construct the circuit in the diagram below:



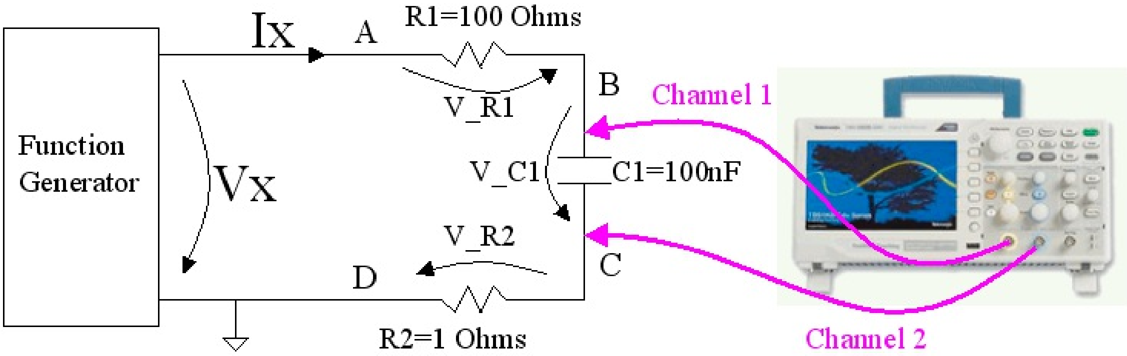
- Here is a detailed view of the circuit on the breadboard:



- In this setup the capacitor charges and discharges through the resistor R1 (100Ohms) and the resistor R2 (1 Ohms) is used to probe the current flowing through the capacitor during the charging and discharging phases.

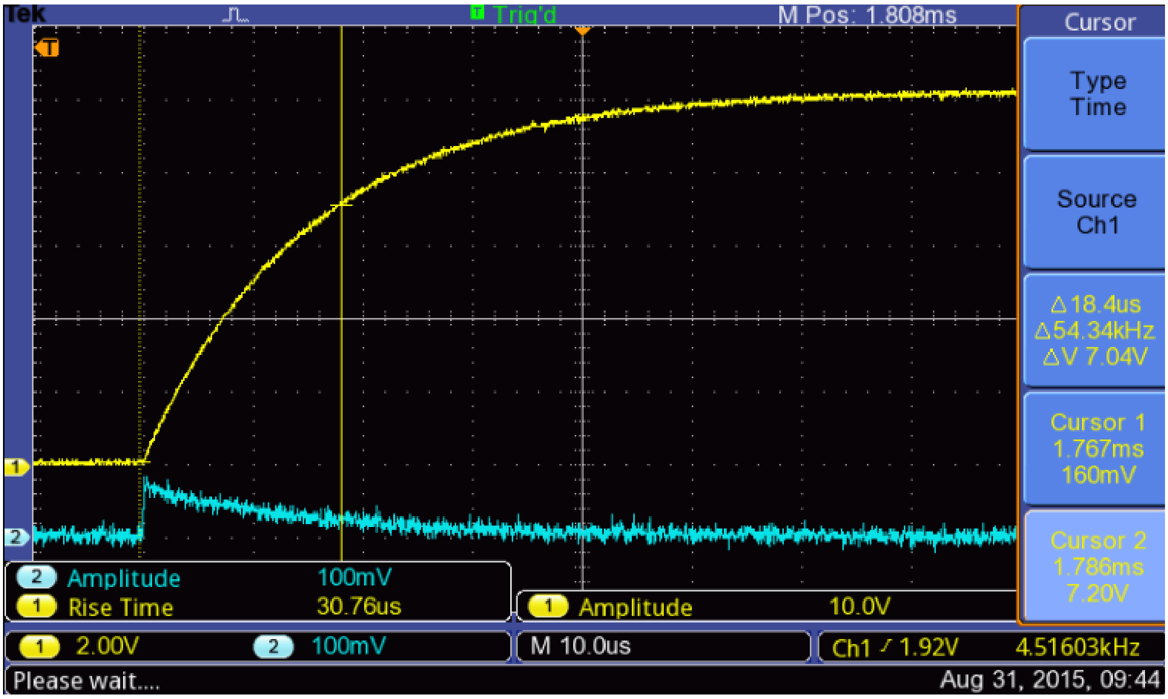
Step 5

- Connect Channel 1 of the oscilloscope to node B of the circuit and Channel 2 to node C, as shown in the diagram below:



- Set the function generator to rectangular wave of about 10V amplitude and about 200Hz frequency.
- Configure Channel 1 settings to 2V/div and Channel 2 to 100mV/div.
- Set the oscilloscope time base to 10us/div.
- Configure the oscilloscope trigger source to Channel 1, rising edge, and adjust the level to be within the signal range.

- With these settings the oscilloscope should display two waveforms similar to the screenshot below:



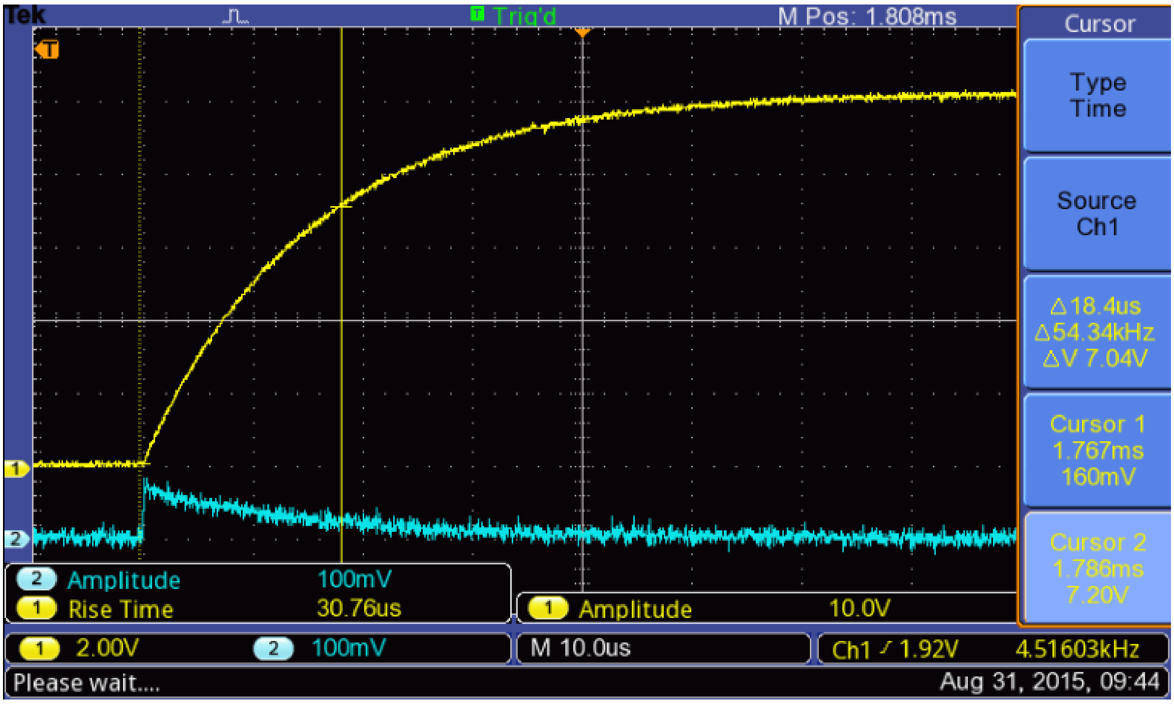
- In this picture channel 1 (yellow trace) represents the voltage on the capacitor, and channel 2 (blue trace) represents the voltage drop on R2=1Ohm. This voltage can be converted into the current flowing through the capacitor during the charging and discharging phases.

- Insert a screenshot of the displayed waveforms in this step.

- Why the voltage on the capacitor does not vary linearly during charging and discharging phases like it did in steps 1-3?

Step 6

- Use the built-in cursor functions of the oscilloscope to measure the time constant of the voltage variation on the capacitor during the charging phase, as shown in the screenshot below:



- In the example shown above cursor 1 has been placed at the beginning of the charging phase and cursor 2 has been placed so that delta V = 7.04V, which is close to 0.707*10V amplitude. With these settings, delta T = 18.4us represents the time constant of the circuit, which theoretically should be equal to R*C. If we multiply R*C = 100Ohms*100nF = 10us; however, notice that the measured value is larger = 18.4us. The difference comes from the output impedance of the function generator, which is equal to 50 Ohms. Adding 50 Ohms we calculate 15us, which is close to the measured 18us.

- Insert a screenshot of the oscilloscope displayed waveforms and cursor readings.

- From the delta V and delta T measurements in your experiment determine the measured time constant of the circuit.

- Calculate the time constant and compare the result with the measured value. Comment on any discrepancy between calculated and measured values.