

Chapter 7

RC Circuits and The Oscilloscope

There are two important concepts involved in this experiment. In part **A** we examine an effect which occurs with its own unique *clock*, a *clock* whose basic time unit (the time constant, τ) is determined by the electrical characteristics of the circuit, i.e. by the particular values of R and C. A common graph for many kinds of time-varying phenomena can be produced in terms of the intervals called time constants. We can relate these graphs to our own time system (sec., min., hrs., etc.) by knowing how a time constant is related to the electrical characteristics of a particular circuit. In part **B** we see how we can use our knowledge of electricity and magnetism to create an important instrument for measuring effects which change with time. Like many modern instruments, the oscilloscope requires us to convert the effect which we wish to observe into a voltage. This is quite easy for this particular experiment, but that is not always the case.

This lab consists of two parts. Part **A**: RC Circuits (manual and computer-based) and part **B**: Oscilloscope.

Objective

1. To study charging and discharging of a capacitor.
2. To perform basic electrical measurements using an oscilloscope.

Apparatus PASCO Essential DC Circuits equipment, PASCO voltage sensor, power supply, capacitors, resistors, three-pole switch, digital multimeter, linear graph paper, digital oscilloscope, signal generator, coaxial cables, connecting wires, laptop.

7.1 Introduction

A capacitor consists of two metal surfaces separated by a non-conductor. The electric charge can be stored on the metal surfaces of the capacitor. The amount of charge Q stored is

proportional to the voltage V applied across the capacitor:

$$Q = CV$$

The proportionality constant C in the above relation is the capacitance. The SI unit of capacitance is the Farad [F]. Commonly used subunits of the Farad are $\mu F = 10^{-6}F$ and $pF = 10^{-12}F$. The capacitance of a capacitor is determined by the geometry of the conductor(s) and the material separating them. Commercial capacitors are often made by spacing two metallic foils with a sheet of paraffin-coated paper. These layers are then rolled into the shape of a cylinder to form a small package. For such a capacitor the capacitance is given by:

$$C = \frac{k\epsilon_0 A}{d}$$

A = Surface area of the metal plate (m^2)

d = separation between plates (m)

k = dielectric constant (for paper $k = 3.7$)

$\epsilon_0 = 8.85 \times 10^{-12}F/m$ - constant called permittivity of free space

High-voltage capacitors consist of interweaving metal plates immersed in silicon oil. Small capacitors are constructed using ceramic materials (e.g. $BaTiO_3$), which have a high dielectric constant $k \approx 1 \times 10^{-8}F/m$. The process of charging or discharging a capacitor doesn't happen instantaneously. It takes some time. This time is determined by the resistance in the circuit and the capacitance (Fig. 7.1).

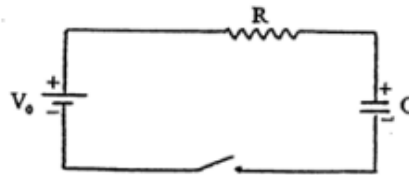


Figure 7.1: Simple RC circuit.

The sum of voltages (Conservation of Energy) around the circuit shown in Fig. 7.1 leads to the following equation:

$$V_0 = V_R + V_C = IR + \frac{Q}{C}$$

Immediately after closing the switch, $Q = 0$, so that $V_R = V_0$, and the current I jumps to its maximum value $I = V_0/R$. As the capacitor accumulates charge, it begins to resist the flow of charge because the positive side tends to hold electrons, and the negative side tends to oppose the addition of more electrons. The complete mathematical treatment of charging of a capacitor (see the textbook) shows that the magnitude of charge accumulated

by the capacitor changes with time according to the equation.

$$Q = Q_0(1 - e^{-t/RC})$$

$$\text{Where } Q_0 = CV_0$$

and $e =$ base of natural logarithm ≈ 2.72

Since $Q = CV$, C - being constant, the voltage across the capacitor changes with time in a similar way as the charge changes.

$$V = V_0(1 - e^{-t/RC})$$

The product RC , called the time constant τ , has the dimensions of time (seconds). The time constant $\tau = RC$ determines the rate of the charging process. Now let's consider a charged capacitor being discharged through resistor R . The initial charge on the capacitor is Q_0 . When the switch is closed, the charge begins to move through the resistor, and the current is maximum. The initial current is not constant, since as charge leaves the capacitor the voltage across the capacitor decreases; therefore, the current decreases as well. The theory shows that charge on the capacitor during the discharge changes according to the equation:

$$Q = Q_0e^{-t/RC} \quad \text{Where } Q_0 \text{ is the initial charge on the capacitor}$$

The time constant $\tau = RC$ also determines how quickly the capacitor will discharge. The voltage across the capacitor is given by an analogous formula since $Q = CV$.

$$V = V_0e^{-t/RC}$$

The current I for the charging and discharging processes is given by the same formula:

$$I = I_0e^{-t/RC}$$

Obviously, the direction of current for charging and discharging is opposite.

7.1.1 Prelab Exercise 1

1. If the experimental set up in Fig. 7.2 has a 12.0V battery and a 0.22 μ F capacitor, determine the time it would take for the fully charged capacitor to decrease the voltage from 12.0V to 8.0V (switch will be in the discharging position A-C).
2. The two resistors, 100 Ω and 1M Ω , in this circuit (Fig.7.2) are different by orders of magnitude. Explain why?

7.2 Part A: RC Circuits

7.2.1 Manual Measurement

1. Connect the circuit in Fig. 7.2 using the modules and the 5V constant output of the BK Precision power supply. Remember to use the metal jumpers to complete the circuit.

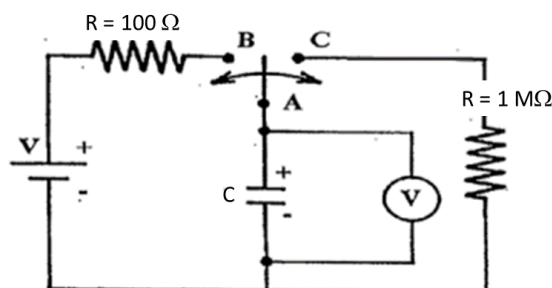


Figure 7.2: Circuit for studying charging and discharging of an RC circuit.

2. After setting up the circuit, use the following procedure to set up data collection in SPARKvue using the provided laptop. (a) Connect the PASCO voltage sensor alligator clips across the capacitor (note polarity +, -) and connect the voltage sensor to the laptop using the USB cable. (b) Start SPARKvue software by double-clicking on the icon on the desktop. (c) Select **Sensor Data**. (d) Under **Templates** on the right side select **Table and Graph**. (e) Ensure the power supply is off and the switch is in the open position. Note, the voltage reading from the voltage sensor located on the bottom left corner of the SPARKvue window should be near zero. (f) Turn on the power supply.
3. Charge the capacitor by moving the two-pole switch to the position B. The time constant for charging is short because of the small value of the resistance (100Ω) of the circuit. After about 3 seconds the voltage across the capacitor is essentially identical to that of the power supply, 5 V. You can monitor the charging voltage across the capacitor on the voltage display at the bottom left of the screen in SPARKvue.
4. Once the capacitor is fully charged, quickly move the switch to position C and simultaneously click the **Start** button (green circle located in the bottom middle of the SPARKvue window). Collect data for 1 minute as the capacitor discharges. After 1 minute click **STOP**.
5. In this experiment, the voltage discharges exponentially with time, t (not a straight line on a graph of V vs t). To manually extract useful information from the data, you will create a graph of $\ln(V)$ vs. t using the following procedure.
6. First extract data points from the graph using the **Add coordinates tool** located on the toolbar below the graph (small square with circle in the middle). Place the arrow on the line and left click, and select the little box on the left that appears right

above the arrow. Obtain coordinates for about 8-10 points along the entire curve and create a table of **time**, t (s), **voltage**, V (V).

7. Create a third column beside **voltage (V)** labelled **ln(V)** and calculate the $\ln V$ for each voltage reading extracted.
8. Using the provided graph paper, plot the graph of $\ln(V)$ vs. t . This should give a straight line whose slope is $-1/RC$, where R is the equivalent resistance of the circuit. Determine the slope and compute τ . You do not need to perform any uncertainty analysis on the slope.
9. Determine the value of the capacitor, C , from the time constant. Note, the resistance in your RC constant is the equivalent resistance between the resistor in the discharging circuit ($1M\Omega$ and the internal resistance of the voltage sensor ($1M\Omega$). Since the two resistances are in parallel, the equivalence resistance is $0.5M\Omega$.
10. Sketch what you think the *current vs time* graph would look like.

7.2.2 Computer-based Measurement

Using the laptop you will now fit your data to the exponential equation using the SPARKvue software.

1. Create a fit using the **curve fit** tool also located on the toolbar below the graph. Click on curve fit and select **Natural Exponent Fit** then click **OK**.
2. A line of best fit and a box with the fit parameters will appear on the graph. Record the equation with the fit parameters. Note, parameter c is equal to $-1/RC$.
3. Determine the value of the capacitor, C from the time constant. Reminder, R is the equivalent resistance.
4. Compare this value with the capacitor value determined in Section 7.2.1 above.

7.2.3 Questions

1. The resistor in the circuit is in parallel with the resistance of the voltage sensor resulting in the equivalent resistance of $0.5M\Omega$. Using the resistors in parallel equation

$$\frac{1}{R_p} = \frac{1}{R_1} + \frac{1}{R_2} \implies R_p = \frac{R_1 R_2}{R_1 + R_2}$$

and the known resistance values of the discharging circuit and the internal resistance of the voltage sensor show the equivalent resistance is $0.5M\Omega$. Show all your work including units.

7.3 Oscilloscope

7.3.1 Introduction

An oscilloscope is a device which is used to display a voltage vs time graph in real time. It is particularly useful when investigating voltages which change with time in a periodic manner. In modern digital oscilloscopes, this is done using an on-board fast analog-to-digital converter, and a colourful display screen. The parameters such as the scales of the axes, offsets can be set by the user. In addition, there are many other useful functions which you may wish to investigate such as cursors, and automatic measurements. In addition, a digital oscilloscope has a multitude of other functions which more advanced users would appreciate.

7.3.2 Experimental

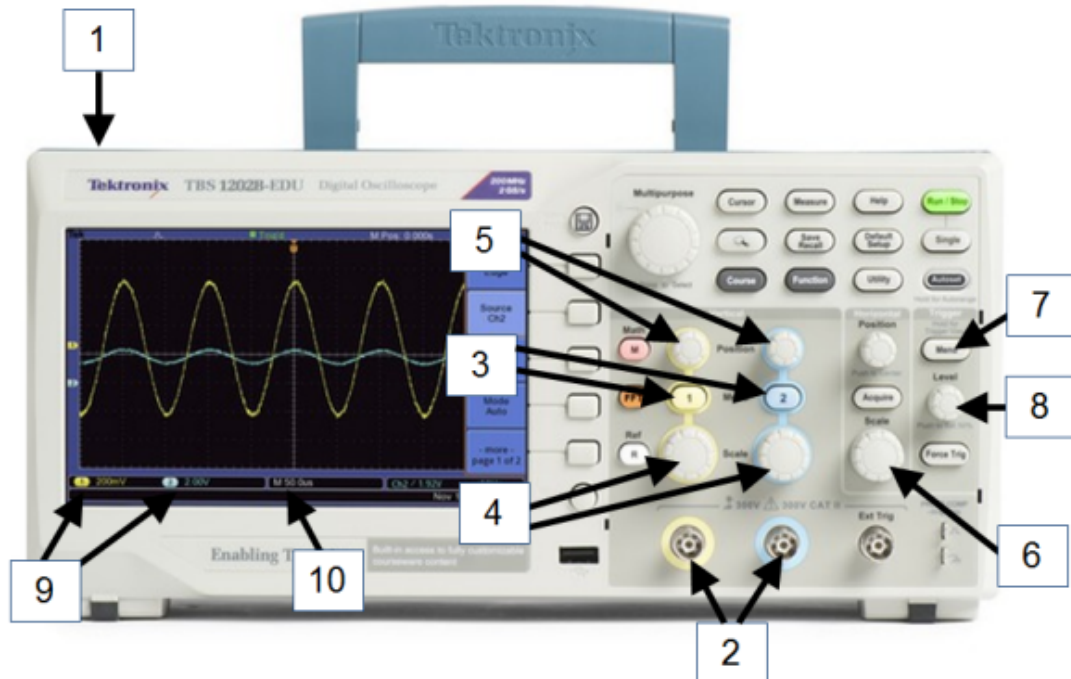
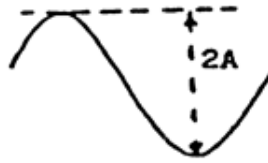


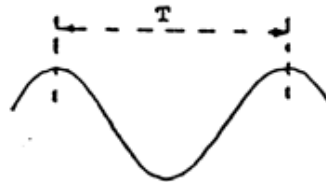
Figure 7.3: Digital Oscilloscope

1. Power Switch
2. Input signals attached here. This oscilloscope can display two signals simultaneously.
3. Show Channel input.
4. Adjust the y-axis (Voltage/Division) scaling Channels. Use to “zoom in” on waveform.

5. Adjust the y position on the screen of the Channel.
 6. Adjust the x-axis (Time/Division)
 7. Set the triggering of the oscilloscope (see below)
 8. Trigger Level control (see below)
 9. Volt/Div for each channel are displayed here. (Each division is one large square).
 10. Time/Div is displayed here. (Each division is one large square).
- To **measure the amplitude** of the voltage signal (waveform) count the number of divisions (large squares) from peak-to-trough and multiply by the selected value of the Volts/Div displayed in the bottom left corner of the screen. Divide this result by 2 to obtain the amplitude.



- To **measure the frequency**, count the number of divisions (large squares) from peak-to-peak and multiply by the selected value of the Time/Div displayed in the bottom left corner of the screen. The frequency is $f = 1/T$.



7.3.3 Measurement and Calculations

1. Use the spring module to mount the provided capacitor, the 10 k Ω resistor module and the signal generator to connect the circuit shown in Fig. 7.4. **Note the ground symbol in the figure and always connect all the ground wires (black in colour) to the circuit at the same point.** This RC circuit is similar to the circuits studied in the first part of this lab. The only difference is that the battery (source of constant voltage) has been replaced by a signal generator (source of variable voltage).
2. Select sinusoid signal on the signal generator (push the \sim button and the 100 button) and adjust its frequency to about 100 Hz on the digital display using the frequency dial. Connect the signal AG to CH 1 of the oscilloscope and measure the frequency

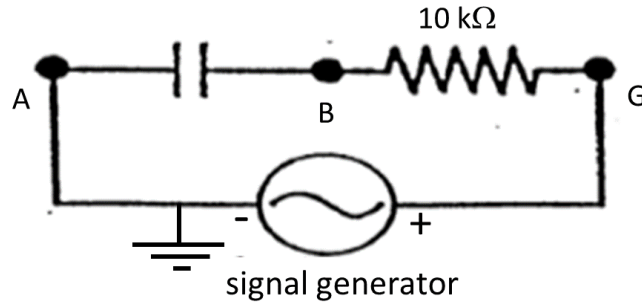


Figure 7.4: RC circuit with a signal generator voltage source.

and the amplitude of the signal displayed on the oscilloscope as described in section 7.3.2.

3. Connect the capacitor at points AB to CH 1 with a coaxial cable. Select a square wave on the signal generator and adjust its frequency to about 75 Hz. The alternating voltage from the signal generator will charge the capacitor when the voltage is not equal to zero. When the voltage is momentarily equal to zero, the capacitor discharges through the resistor in this RC circuit.

Sketch the signal you observe on the screen of the oscilloscope on a piece of graph paper. Using the charging and discharging portions of the signal on the screen (Fig.7.5) estimate the time constant of your RC circuit. Remember that the time constant τ is the time for the voltage to drop to 37% of its maximum value during the discharging process, and the time to increase to 63% of its maximum value during the charging process. Use the grid on the oscilloscope screen or the cursors, located in the **cursor** menu, to obtain the best estimate of τ .

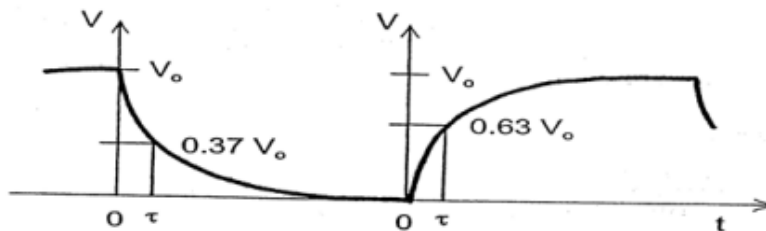


Figure 7.5: Charging and discharging of a capacitor

Use the relation $\tau = RC$ to determine the capacitance C . With the resistance R already known from the colour code chart, what is the value of C ?

7.3.4 Questions

1. Would your measurements of amplitude and frequency be different if you set VOLTS/DIV and the TIME/DIV differently? Explain!
2. What is the largest and the smallest voltage (full signal displayed) that can be measured with your oscilloscope? What is the lowest and the highest frequency that can be measured with your oscilloscope?

END OF LAB

Was this lab useful, instructive, and did it work well? If not, send an email to thatlabsucked@gmail.com and tell us your issues. In the subject line, be sure to reference your course, the experiment, and session. example subject: *PHYS1010 Linear Motion monday 2:30*. We won't promise a response, but we will promise to read and consider all feedback.