Physics 221
Experiment 4: Capacitors

August 23, 2007

Introduction

We are all familiar with batteries as a source of electrical energy. We know that when a battery is connected to a fixed load (a light bulb, for example), charge flows between its positive (+) and negative (-) terminals. The magnitude of this flow, which we call current, is measured in units of Coulombs per second or Ampères. Under normal operation, the battery provides a constant current throughout its life. Furthermore, the voltage across its terminal will not vary appreciably - and when it does, it is an indication that the battery needs replacement.

Capacitors are devices in which positive and negative electric charges can be located in different regions. In fact, any object in which positive and negative charges can be separated acts as a capacitor. Practical capacitors are made of two conducting surfaces separated by an insulating layer, called a dielectric. The symbol used to represent capacitors in schematics reflects their physical construction. There are many different types of capacitors: tubular, mica, variable, and electrolytic to name a few.

Capacitors have a simple proportionality relationship between the charge they carry and the voltage existing across their terminals,

$$Q = CV \tag{1}$$

where Q is the charge, in Coulombs (symbol C, which may be confusing), V is the voltage in volts, and C is the capacitance, in Farads (F). A Farad is the unit of measurement used when describing capacitors. It is ridiculously large. So large, in fact, that most capacitance measurements use microFarads (μF), nano (nF), and picoFarads (pF) as their unit of measure. From Equation 1, we can define the capacitance of a capacitor as the amount of charge that can be stored per unit voltage.

The development of the equations describing the properties of capacitors in series and in parallel is similar to that of resistors but not quite identical. The circuit layouts are the same once the resistors are replaced with capacitors. The effective capacitances for N capacitors in series and parallel are as follows:

$$\textbf{Series}: \quad \frac{1}{C} = \frac{1}{C_1} + \frac{1}{C_2} + \frac{1}{C_3} + \ldots + \frac{1}{C_N} \tag{2}$$

$$\textbf{Parallel}: \quad C = C_1 + C_2 + C_3 + \ldots + C_N \tag{3}$$

The derivation of these equations will be left as an exercise.

Part A: Capacitors in Series and in Parallel

Procedure and Analysis :

1. Using a Capacimeter, measure the capacitance of each of the three capacitors given.
2. Connect them in series and in parallel and measure the effective capacitance of each combination.
3. Compare the experimental values with the ones calculated using Equations 2 and 3.

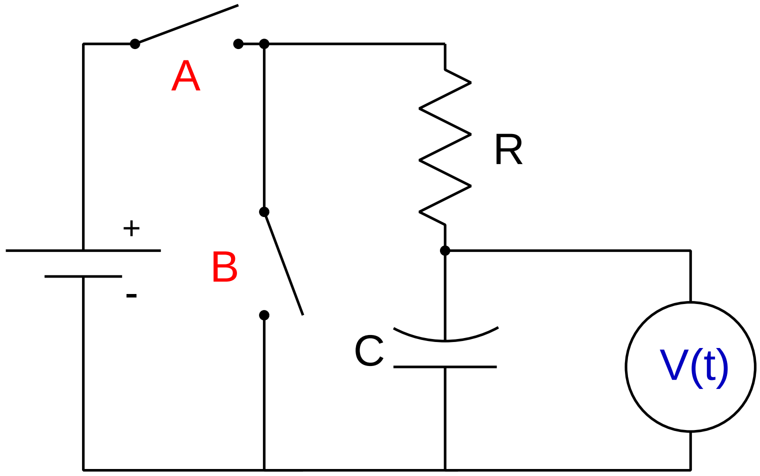

Figure 1: Circuit for RC charge-discharge measurement

RC Circuits

In this part, we will measure the time constant of a capacitor in two situations - one where the time constant is several seconds long, and the other for time constant the order of several milliseconds long. To accomplish this, we construct a RC circuit, which contains a power supply (DC or AC), a resistor R, and of course a capacitor C (see Figure 1). If at time t = 0 the Switch A is closed (Switch B remains open), charges will begin to build up in the capacitor. These charges do not accumulate within the capacitor instantaneously due to the "resistance" provided by the resistors. The potential difference across the capacitor can be expressed as

$$V(t) = V_o \left(1 - e^{-t/\tau}\right) \tag{4}$$

where $\tau = RC$ is defined as the time constant of the RC circuit, and V_0 is the maximum potential difference across the capacitor.

After a sufficiently long time (much larger than the time constant), if Switch A is opened while Switch B is closed, the capacitor will discharge all of its accumulated charges. The potential difference across the capacitor for this process can be expressed as

$$V(t) = V_o e^{-t/\tau} \tag{5}$$

The time dependence of the potential difference $V(t)$ for the charging and discharging process is shown in Figure 2.

The time constant can be determined by observing either the charging or discharging process. For the charging process, τ is equal to the time for V(t) to reach 63% of its "final" value. For the discharging process, τ is equal to the time for $V(t)$ to fall to 37% of its initial value, i.e.

Part B : Measurement of a Long Time Constant

In this experiment, you will measure V(t) across the capacitor as it discharges.

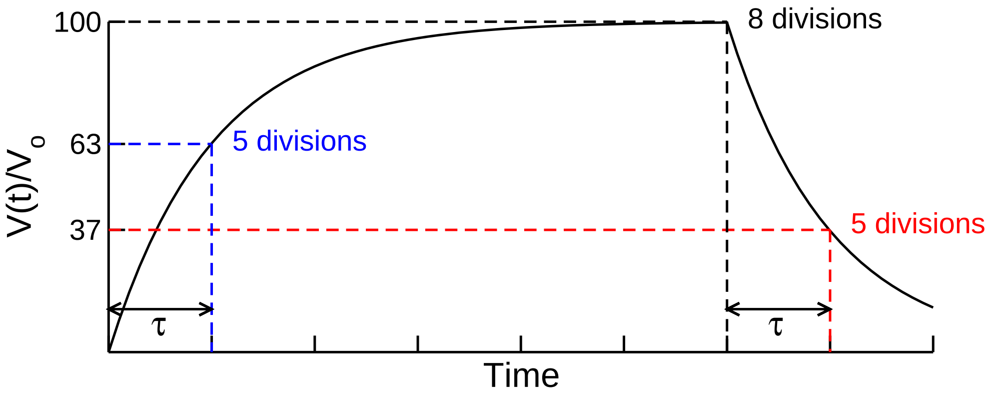

Figure 2: RC circuit charge-discharge curve

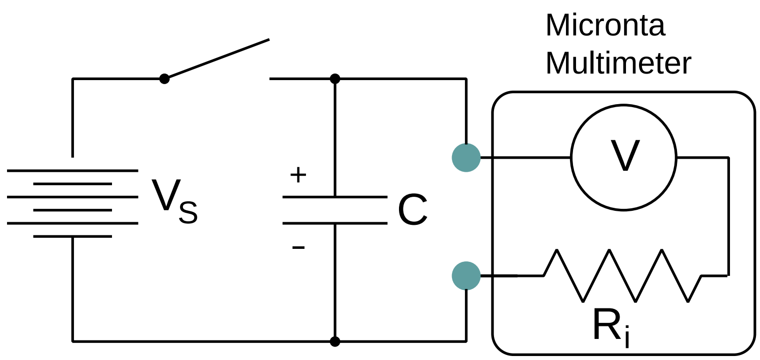

Figure 3: Setup for long time constant measurement

Procedure :

1. Using a Capacimeter, find the capacitance of the given capacitor for the part (nominal value, 330 mF).

2. Construct the circuit as shown in Figure 3, making sure the electrolytic capacitor is connected with correct polarity. Notice that when the switch is closed, current will flow until the capacitor is completely charged, after which the current flow stops. When the switch is opened, the capacitor discharges. The current flows through the Micronta Multimeter (which is being used as a voltmeter) which contains an internal resistor R_i. The voltmeter acts as the load resistor for the circuit, as well as a measuring device. In other words, the resistor in the voltmeter is the R in the RC circuit.

3. Use the 10 V setting of the voltmeter even though the meter may be somewhat overloaded. Note that the voltmeter also has a slide switch for the A/2 setting. This means that when the voltage range is set at 10 V full scale, the full scale reading is really 5 V. The needle on the meter will go to full-scale deflection when a current of 20 μA passes through the meter. This full scale deflection also corresponds to 5 V, so using Ohm's Law, one can figure out the internal resistance R_i, of the meter acting as a voltmeter. Record R_i.

4. Charge the capacitor by closing the switch. This should take only a few seconds for the voltage reading to go beyond 10 V.

5. Open the switch and start time (t = 0) when the voltmeter reads exactly 10 V (i.e. $V_o = 10$ V). Record the subsequent times when the voltage reads 9 V, 8 V, 7 V, ... etc. Depending on how slow the decay rate is, you may not want to wait for it to reach 1 V. Note that the first few readings may go too fast. If so, you may have to recharge the capacitor and then find the time just for it to discharge from 10 V to 8 V, for instance. Do this as often as necessary.

6. Create a two-column data table. The first column for Mt and the second column for $V(t)$. Be sure to record C and R_i.

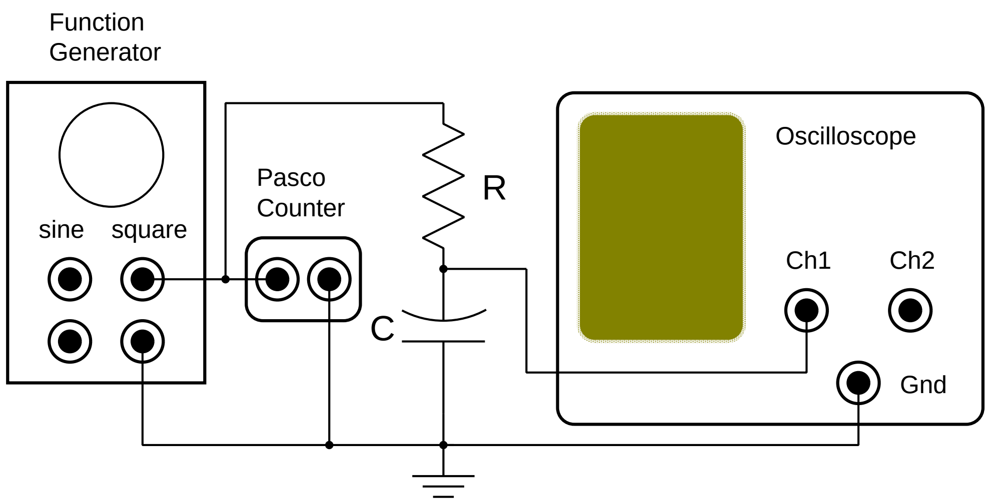

Figure 4: Setup for measurement of fast RC time constant

Analysis :

1. Equation 5 can be written as $lnV(t) = lnV_o - t/\tau$. This means that if we plot $lnV(t)$ versus t, the slope will correspond to $-t/\tau$. Find the natural logarithm of $V(t)$ from your data and plot $lnV(t)$ versus t.

2. Find the slope of the best-fit line and thus obtain the experimental value of the time constant. Compare it with the value calculated directly from the values of R_i and C.

Part C : Measurement of a Short Time Constant

In this part, we measure the short time constant of another RC circuit by continuously charging and discharging the capacitor. We accomplish this by connecting the RC combination to a power supply producing a square wave voltage pattern as shown in Figure 4. During the period when the applied voltage is V, the capacitor is charging, whereas during the period when the applied voltage is zero, the capacitor is discharging.

Since this charging and discharging processes occur very rapidly, a convenient way to study these processes is using the oscilloscope to directly observe $V(t)$ across the capacitor.

Procedure :

1. Using a Capacimeter and an Ohmmeter, find the capacitance and resistance of the capacitor and resistor given for this part (nominal values 0.01 μF and 47 kΩ, respectively).

2. Connect the RC circuit as shown in Figure 4. Pay attention to the side that should be connected to the ground end of the function generator/oscilloscope.

3. The oscilloscope should be set in the NORM trigger mode, to display the signal from CH1.

4. Switch on the function generator and set it to 250 Hz.

5. Adjust the vertical and horizontal positioning knob, the time/div scale, and the V/div scale for Channel 1 until you obtain the charging/discharging trace. Expand the trace so that it extends across the whole 8 divisions of the screen, only making visible one complete period of the square wave. The screen on your oscilloscope should look similar to Figure 3.

6. Now record the value of$t$t when the charging voltage is 63% of the highest voltage. Similarly, record t when the discharging voltage is 37% of the initial voltage. These two values should be roughly identical. Find the average and use this as the experimental time constant.

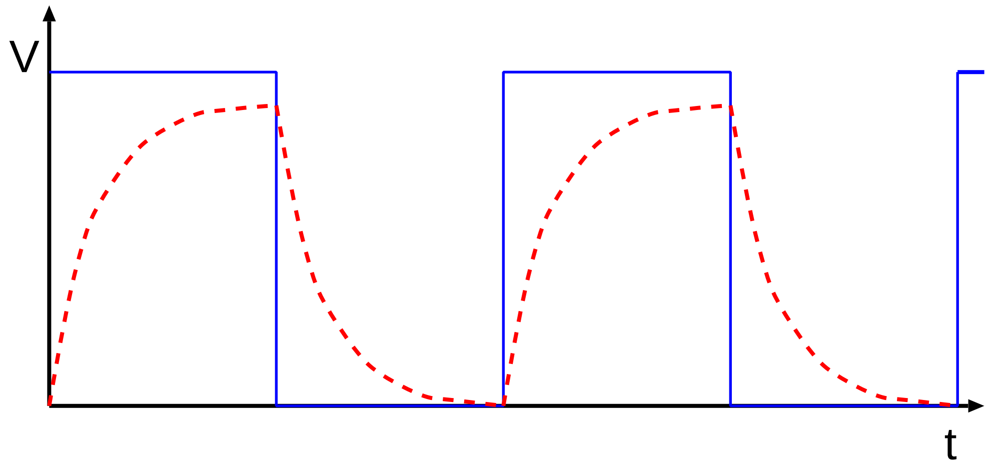

Figure 5: Response of an RC circuit (dashed line) to a square wave voltage (solid line)

7. Compare this with the product of RC obtained from the individual values of *R* and *C* found earlier.
8. Plot the oscilloscope trace and include it in your laboratory report. Illustrate in your sketch how you obtained the time constant and the values you used.