Chapter 10

DC circuits

10.1 Objectives

- Practice putting together simple electronic circuits.
- Learn to use voltmeters, ammeters, and ohmmeters.
- Quantitatively establish the relationship between current and applied voltage for an ohmic resistor and a light bulb.
- Measure the resistance of a number of resistors connected in series and in parallel.

10.2 Equipment

Figure 10.1: A pair of digital hand-held multimeters, power supply and assorted resistors.

- DC power supply (0-6 V, 1 Amp)
- light bulb and assorted resistors
- 2 hand-held digital multimeters

10.3 Circuit diagrams

Before actually connecting the components of your circuit, draw a diagram indicating the current flow and polarities in your notebook. Draw it in the style of the diagrams in your textbook, and using the same symbols for the power supply, resistors, and meters. For the measurements in parts A and B of this lab, the main circuit is shown in Fig.10.2. You will want to put meters in this circuit, in order to measure the current through the resistor R and the voltage across it. Include them in your drawing now, as in Fig.10.3.

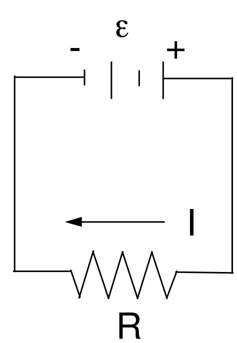

Figure 10.2: Schematic diagram of a simple circuit.

The + and - signs in the diagram indicate how the terminals of the meters have to be connected. Current has to flow from + to - within the meters when measuring current. Therefore the positive terminal of the multimeter is connected to the positive terminal of the power supply. The current in the multimeter runs parallel to the current in the resistor, and the meter is connected accordingly. How would the multimeter be connected if you decided to insert it in the left-hand side of the circuit in Fig.10.3? Make a sketch in your notebook.

10.4 Ohms' law

Circuit setup

Make sure that the power supply is unplugged or turned off and the voltage knob is turned all the way counterclockwise. Get a supply of leads from the test lead holder and connect the main circuit as outlined in Fig. 10.3. The resistor

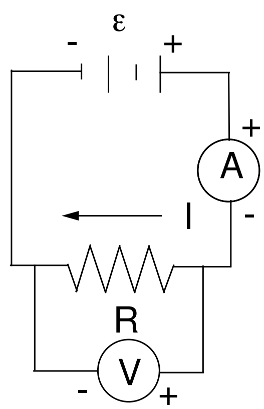

Figure 10.3: Simple circuit with voltmeter and ammeter.

should have a value of nearly 50,000 Ohms-that is: the third band should be yellow or orange. For help in selecting the proper resistor, see the section on resistor color codes. Then connect the multimeters as shown in Fig. 10.3. Make sure that the function selection switches are properly set. For the multimeter with which you will measure the voltage across the resistor, you should turn the knob on the front face so that it reads DC volts, as opposed to AC volts. For the multimeter with which you will measure the current through the circuit, you should turn the knob on the front face so that it reads DC milli-amperes or microamperes. For both devices, you may need to adjust the range setting so that it does not go off scale while reading. Also, for both devices, you need to be sure that the leads are plugged into the correct jacks on the front of the device.

Now turn on the power supply and slowly raise its output voltage up to the maximum desired value by turning the voltage selection knob clockwise. You will want to set your multimeters so that they have maximum sensitivity but so that they do not go off scale. If a meter goes off scale, change the range setting. Now you are ready to begin your measurements. The value of the voltage setting on the power supply may not exactly match that read by the multimeter; trust the multimeter rather than the power supply.

Measurements

Record the resistance value from the color bands of the resistor. Measure the current through the resistor at 6 voltage values between 0 and 15 volts. Again, be sure the multimeter is set to measure voltage!

Analysis

According to Ohm's law, the resistance of a resistor is given by the formula $V = IR$. So make a plot of V vs I and determine the resistance of the resistor from the slope of the graph (R_{slope}). You should make sure that you convert to volts and amperes before plotting your data, so that the slope gives your resistance in Ohms. Be sure to label the axes correctly, including units.

There is one complication here. The current measured by the multimeter does not all flow through the resistor; it is divided up between the parallel combination of the resistor and the voltmeter, whose resistances are R and R_v respectively. Thus, we have been overestimating the current which is flowing through the resistor. Assume the resistance of the voltmeter is 10 MΩ (10^6 Ohms). Use your value of R_{slope}, which you measured, and the formula $R_{slope} = R_v R/(R + R_v)$ to calculate a corrected value of R. You will need to do some rearranging of the above formula to solve for R in terms of R_{slope} and R_v. Does your value of R agree with the resistance indicated by the color bands on the resistor within the tolerance of the resistor?

10.5 Power

Circuit setup

Circuit B is identical to circuit A, except that the resistor is replaced by a light bulb.

Measurements

Measure the current through the light bulb at about 8 voltage values between 0 and 4 volts. Do not raise the voltage above 4 volts or you are likely to burn out the bulb.

Analysis

Again, plot V vs I. Add two more columns to your data table. In the third, calculate V/I, which is the resistance; in the fourth, calculate the power dissipated in your light bulb, which is given by the formula $P = IV$. What trend do you observe in the resistance? Is the resistance constant? Why or why not? In the dissipated power?

10.6 Resistance

Circuit setup

In this section, you will use the multimeter as an ohmmeter. When you turn the function switch to Ω, the terminals of the meter are connected to a battery which is inside the meter. Touch the test leads together; it should read zero.

Various sensitivities for measuring resistances are provided. When using any of these, you have to always check the zero first. When you place a resistor across the test leads, you have effectively constructed the circuit shown in Fig. 10.4. The components within the dotted line are within the multimeter, where is a current limiting resistor selected by the range selection switch. It should be obvious that changing scale (i.e. changing r) necessitates a readjustment of the meter.

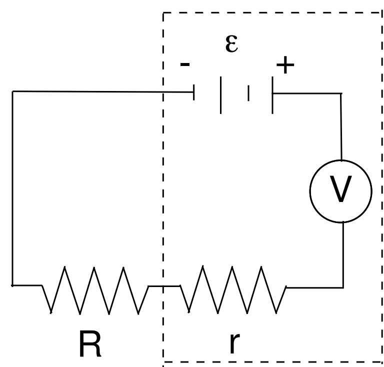

Figure 10.4: Circuit diagram for measuring resistance.

Measurements

You should measure the resistance of series and parallel combinations of three small resistors. Select three carbon resistors, labelled in color code, between 10 and 90 Ω. Using the proper sensitivities of the multimeter and calibrating the meter each time for Ω, measure:

1. The resistance of each of the 3 resistors by itself.

2. The resistance of the series combination.

3. The resistance of the parallel combination.

Please turn off the multimeter when you are finished with it so that the batteries are not depleted.

Analysis

Calculate the expected resistance of the series and parallel combination of the three resistors and compare with your measured values.

10.7 Kirchoff's rules

Setup

1. Connect the resistors and the power supplies into a two-loop circuit as shown in Fig. 10.5. The boxes marked A, B, and C in the circuit diagram will be replaced eventually with the multimeter (set to measure current) when we measure currents in the circuit.

2. Have the lab instructor inspect your work.

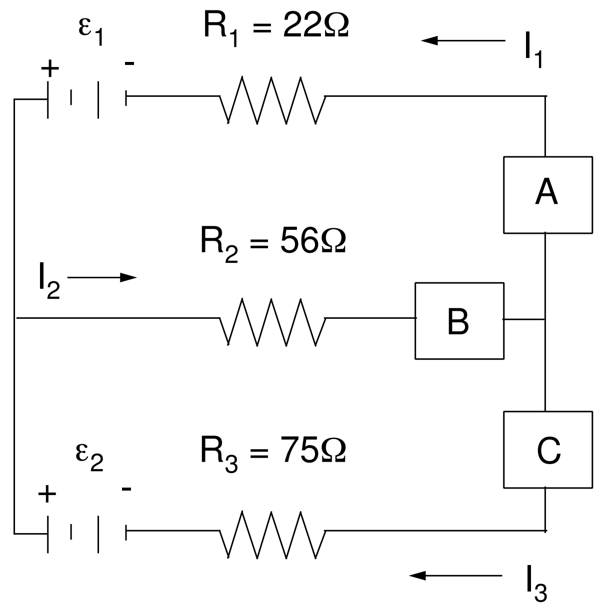

Figure 10.5: Circuit diagram for verifying Kirchoff's rules.

Procedure

1. Turn on both power supplies to 5 volts.

2. Measure the voltages around the top loop as follows. Using the digital multimeter (set to measure DC volts), measure the voltage drop across ϵ_1, R_1 and R_2. Show the sign of the voltage polarity across each resistor on your circuit diagram by writing the + symbol on one end of the resistor and the $-$ symbol on the other end.

3. Measure the voltage drops of all the circuit elements in the bottom loop. Indicate their signs.

4. We are now going to measure the sums of the currents into and out of the node connecting A, B, and C. Replace box A with a digital multimeter (set to measure DC current, probably the 200 mA scale). Measure I_1. Repeat this procedure for boxes B and C, measuring the other currents. Make sure you note a sign for each current.

5. Turn off the digital multimeter to save its batteries.

Analysis

Kirchoff's rules allow us to find the relationship between the current, voltage, and resistance at various points in complicated circuits. Briefly, Kirchoff's rules are:

1. The total voltage drop around any closed loop in a circuit must be zero.

2. The sum of the currents entering any junction must be equal to the sum of the currents leaving that junction.

By applying Kirchoff's rules, it can be found that, for our circuit:

$$I_1 = \frac{(R_2 + R_3)\epsilon_1 - R_2\epsilon_2}{R_1R_2 + R_2R_3 + R_3R_1} \tag{10.1}$$

$$I_2 = \frac{R_3\epsilon_1 + R_1\epsilon_2}{R_1R_2 + R_2R_3 + R_3R_1} \tag{10.2}$$

$$I_3 = I_2 - I_1 \tag{10.3}$$

1. Use the above results from a Kirchoff's rules analysis, along with your values for ϵ_1, ϵ_2, R_1, R_2, and R_3, and calculate theoretical values for all currents. Also, determine the theoretical voltages across each resistor, using Ohm's law.

2. Sum up your measured voltages for the top loop, and again for the bottom loop. Does the sum of the voltage drops equal zero? (That is, in going around the loop, does the sum of the potential drop equal the sum of potential rises?)

3. Sum up your measured currents around the node connecting A, B, and C. How close to zero is the sum? (That is, does the sum of currents into the node equal the sum of currents out of the node?

4. Compare your measured voltages around both loops with the theoretical ones. How close were they? Why? Compare also your measured and theoretical values for the three currents.

Chapter 11

RLC circuits

11.1 Objectives

- Part A: Determine the capacitance of a capacitor by measuring and plotting the time constant in an RC-circuit for different values of R.
- Part B:
  1. Make qualitative observations about the relative phase of current and voltage for a resistor, a capacitor, and an inductor, and for the series combination of these components
  2. At a fixed voltage amplitude, measure and plot the frequency dependence of the current through a resistor, a capacitor and an inductor, and the series combination of these components.
  3. Determine the resonance frequency for the series combination.

11.2 Equipment

- Function generator (BK Precision Model 4011A)
- Oscilloscope (Tektronix Model 2205)
- Decade resistance box
- Variable inductor, resistor, and capacitor boxes
- Various cords

11.3 Electromagnetic time constant

In this experiment you will charge and discharge a capacitor, C, through different resistors, R, and measure the time constant, τ.

Figure 11.1: Clockwise from top right: oscilloscope, cords, inductor and capacitor boxes, resistor box, decade resistance box, and function generator.

Instrumentation

Refer to Fig.11.2. Instead of opening and closing switches manually, you will use a pulse generator which will perform the necessary switching in rapid succession by delivering a square wave voltage signal at its output terminals. For our purposes, this is equivalent to throwing the switch S into positions A and B, and we can therefore let the function generator (dotted line in Fig.11.2) represent that part of the circuit.

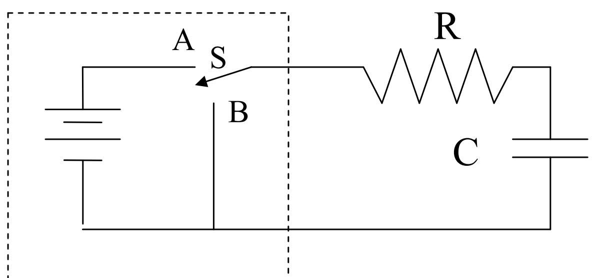

Figure 11.2: Schematic diagram of function generator circuit.

When the switch in the circuit of Fig.11.2 is in position A, the capacitor will be charged with a current that drops exponentially with time constant $\tau = RC$ from its initial value, ϵ/R, to zero. When the switch is thrown into position B, current flows in the other direction through R, dropping from $-\epsilon/R$ to zero and discharging the capacitor.

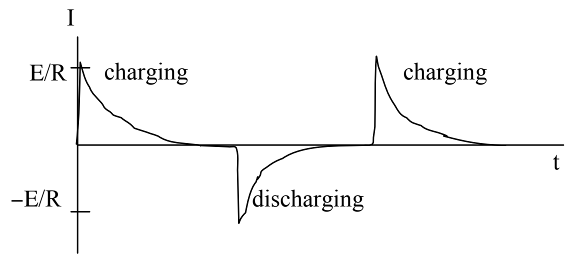

Figure 11.3: Current through resistor R as a function of time.

Fig.11.3 shows the time-dependence of the current through R. You can measure this current by measuring the voltage across R. Your voltmeter is an oscilloscope (about 10 M input resistance) that displays the voltage across R as a function of time.

Turn on the oscilloscope and let it warm up. Turn on the function generator. Set the frequency to 2 kHz using the appropriate buttons and the two knobs on the left side of the front panel. Be sure to press the square wave button, rather than the sinusoidal or triangle wave buttons, on the upper right corner of the front panel. The knob on the right side of the front panel controls the voltage amplitude.

First, let us become acquainted with the oscilloscope. Connect the oscilloscope input labeled CH1 across the terminals of the function generator and see if you can observe the square wave which the function generator is generating. First, set the switch below the vertical scale to ground, rather than AC or DC. Then use the vertical position knob to move the trace up or down so that it is in the middle of the screen. This sets the zero voltage position. Then you will want to set the same switch to AC so that you can read AC voltages. The trigger mode can be set to auto or to normal. You may have to adjust the trigger level knob to get a signal trace on the screen. You will also want to set the horizontal scale of the oscilloscope to about 500 S/DIV and the vertical scale to 1 Volt/DIV. If you cannot observe the square wave, check with the instructor.

Circuit and measurements

Fig.11.4 shows how to set up your circuit. The inner and outer conductor of a coaxial connector serve as the two terminals of the function generator. Using a suitable adaptor, connect the outer connector to the resistor (use a black decade resistor box set at 1k to start). The other end of the resistor connects in series to the capacitor (use a variable capacitor box set to 25 nF to start). The other capacitor terminal connects to the other terminal of the function generator. This is the circuit you will want to study.

Now connect the oscilloscope input labeled CH1 across the resistor as shown in Fig.11.4 and see if you can observe the voltage across the resistor. You may need to adjust the oscilloscope horizontal or vertical scales. The trace should

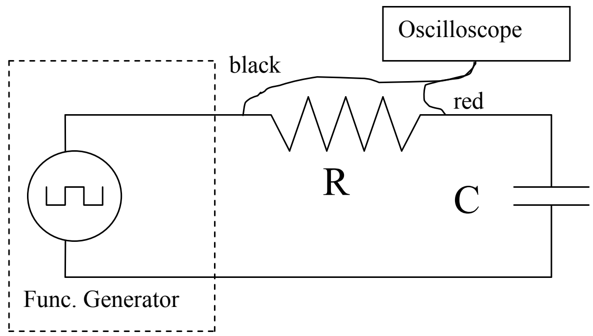

Figure 11.4: Schematic diagram of circuit.

look something like what is shown in Fig.11.4. The time constant, τ, is the time it takes for the current to decrease by a factor $e \cong 2.7$ (the same as multiplying by $1/e$). It is conveniently measured by adjusting the function generator such that the initial voltage on the scope screen is at 2.7 divisions and the final voltage is at zero. Turn the sweep time to perhaps 50 or 100 S/DIV temporarily to check for these two voltage values. You can then switch back to perhaps 10 S/DIV and read on the horizontal scale how long it takes to go from 2.7 divisions to 1 division. Measure τ in this way for 5 values of R between 200 and 1000

Analysis

Plot the measured values of τ versus R and determine the value of C from the slope of the graph. Compare your value to the known value.

11.4 Electromagnetic resonance

The purpose of this part of the lab is to study the behavior of capacitors and inductors in circuits with alternating voltages and currents, in particular the frequency-dependence of the current at a fixed voltage.

Instrumentation

The alternating EMF (electromotive force) is supplied by the function generator. There will be three quantities to measure: f (frequency), V and I. For current and voltage measurements, you use the two input channels, CH1 and CH2, of the oscilloscope. I suggest you use CH1 for the current and CH2 for the voltage. The current is given by the voltage across a series resistor, R_1 (the decade box). Fig.11.5 shows how the oscilloscope and R_1 can be connected to measure the current through a circuit element X.

Connecting the circuit

First, connect the main circuit for measuring the current through a resistor, , at different frequencies. Go from the function generator to (decade box set at 1000), then to (resistance box set at 200), and from the other side of back to the function generator.

Connect CH1 and CH2 across R_1 and R as shown in Fig.11.5 (X stands for R now). The vertical deflection sensitivity switches for CH1 and CH2 can be set to 1 or 2 Volts/DIV for a start. You will have to change to different settings during the measurements. In order to display both signals, the display mode switch has to be set to DUAL or ALT or CHOP.

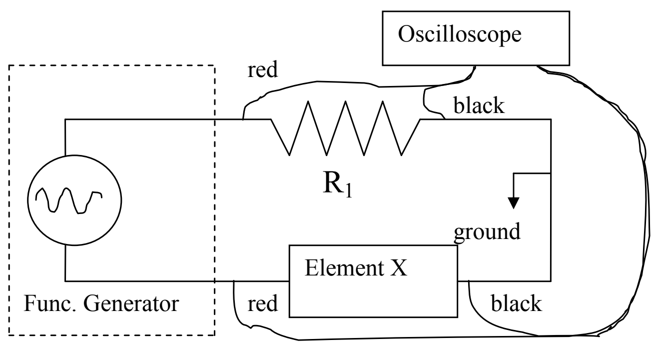

Figure 11.5: Schematic diagram of circuit.

It is important that the function generator be floating-that is: neither terminal should be grounded. Normally, the shield of the coaxial terminal is grounded through the third prong of the plug to the 120 VAC wall socket. You should therefore use a 3-prong/2-prong adaptor to plug in the function generator so that it is not connected to earth ground. It is also important that the oscilloscope be floating. Use a 3-prong/2-prong adaptor to plug in the oscilloscope, too. Be sure the black terminals of CH1 and CH2 of the oscilloscope are connected to the same place in the circuit, namely between R_1 and X. If these two connections were to end up in different places in the circuit, there could be no voltage across the components located between them, and hence no current through these components. Connecting the oscilloscope in this manner does, of course, switch the polarity of the signal on CH2 relative to the signal in CH1. To compensate for this, press the switch called CH2 INV to its INV position.

Check that the function selection button of the function generator is set so as to generate sinusoidal wave output, and that the amplitude knob is somewhere in the middle of its range. Set the frequency at 3 kHz for a start. You should be able to get two sinusoidal traces on the scope screen that are in phase with each other (if they are opposite, press CH2 INV). In order to see these traces, you may also have to fiddle with the position controls, the trigger level, the vertical sensitivity controls for CH1 and CH2, and the horizontal deflection sensitivity.

Relative phase measurements

The point of using two oscilloscope channels is that we will be able to measure the voltage across element X at the same time that we are measuring the current through the resistor R_1. Since we have a one-loop circuit, the current through the resistor R_1 is the same as the current through any part of the circuit.

Of course, the oscilloscope does not measure current directly. You will need to read the voltage across R_1 and divide by the known value of R_1 to convert the oscilloscope reading to a current.

Check that the voltage across R (the trace on CH2) is in phase with the current (the trace of CH1). Make a sketch the two traces. Then replace R by the capacitor (a box set at 25 nF). Make sure that CH2 now measures the voltage across the capacitor. Sketch the traces for current and voltage, paying attention to the relative phase. Repeat for the inductor (a box set at 30 mH).

Frequency dependence of current measurements

For these measurements we have to keep the voltage amplitude V_x (measured on CH2) constant. This will keep the voltage amplitude across element X constant. Two volts peak-to-peak is a good choice. You may notice that as you change the frequency at which you are driving your circuit, V_x changes. You can use the amplitude knob of the function generator to increase or decrease V_x so as to keep it as 2 V peak-to-peak. You will need to check this every time you change the frequency.

You may also notice that the current amplitude measured using CH1 changes as you change the driving frequency. We are interested in how the current amplitude changes with frequency when the voltage amplitude across element X is kept the same. Maintaining the voltage amplitude V_x constant at 2 V peak-to-peak, measure the current amplitude I_x (measured on CH1) for about 10 frequencies between, say, 0.5 kHz and 15 kHz for the following circuit elements X:

1. resistor R (200)

2. inductor L (30 mH)

3. capacitor C (25 nF)

4. the series combination R, L, and C

Remember to check and readjust V_x to 2V peak-to-peak. In case (1), two or three measurements are enough. For the RLC-combination, be sure to take several extra data points near the resonance frequency. Determine the resonance frequency by watching the two traces on the scope as you vary the frequency. They should be in phase at resonance. Why?

Analysis

Plot I_x vs. frequency for all four sets of measurements in one, and only one, graph. Do not plot four separate graphs. Answer the following questions.

1. What are the relative phases of current and voltage in a resistor (capacitor, inductor)?

2. How does the current through a resistor (capacitor, inductor) change with increasing frequency?

3. Compare your measured resonance frequency with the theoretical resonance frequency for an RLC circuit:

$$f_o = \frac{1}{2\pi\sqrt{LC}}. \tag{11.1}$$

4. Optional: Compare the current in the RLC circuit at resonance with the current through the resistor by itself, and make an estimate of the ohmic resistance of the windings of your inductor. You can check your estimate by measuring the resistance of the inductor with an ohmmeter.