Physics 120 Lab 2 (2018) - Capacitor Circuits

We will analyze resistor (R), capacitor (C), and inductor (L) circuits in different configurations and in different frequency bands to gain intuition into how electronic components compute derivatives and integrals.

Reminder on triggering: Use the function generator's TRIGGER OUTPUT to drive the oscilloscope's AUXILIARY TRIGGER. This will ensure that the trace is always in phase with the input signal and that triggering does not dependent on either the amplitude of the input or the output of the circuit under investigations. Critically, this trigger will enable phase shifts between the input and output to be readily discerned.

2-1. RC circuits

We begin with the time dependence of an RC circuit, configured as a low-pass filter (Figure 2.1):

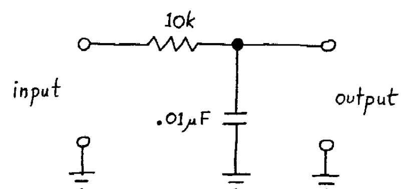

Figure 2.1: RC Circuit as a low-pass filter.

Construct the circuit and verify that it behaves in the time domain as a low-pass filter. Recall that, for a step input, theoretical calculations for ideal components predict that the voltage should rise as $V_{app}[1 - exp(-t/\tau)]$ at the onset of a long pulse and decay at the offset of a long pulse as $V_{app} \cdot exp(-t/\tau)$, where $\tau \equiv RC$ $(\cong 100\ \mu s$ in the above example$)$.

Measure the time constant τ by determining the time for the output to drop to $exp(-1)$= 0.37 of the initial amplitude (**1 pt**). You can read the amplitudes on the screen. Better yet, the cursors are handy for this measurement.

Does the measured time constant equal the product **RC** (**1 pt**)? Recall that **R**s and **C**s have tolerances, so measure the exact values for your components .

Measure the time to climb from 0 % to 63 %. Is it the same as the time to fall to 37 %? (**1 pt**). If not, identify what is amiss in your way of taking these readings!

Record the input wave and the output of the RC circuit as a **SCREENSHOT** from the oscilloscope (**1 pt**) and put enter it into your report along with the estimates of τ.

Try varying the frequency of the square wave.

2-2. Differentiator

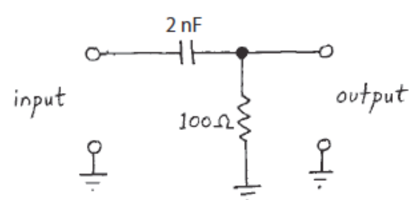

Figure 2.2: RC differentiator.

Construct the *RC differentiator* shown above. Use the function generator to drive it with a square wave with an initial amplitude of 0.I V and a frequency of 100 kHz. Does the output make sense? Show the results as a **SCREENSHOT** (**1 pt**) and explain what you see (**1 pt**). Try a 100 kHz triangle wave and show a **SCREENSHOT** and explain what you see (**1 pt**). Lastly, try a sine wave and show a **SCREENSHOT** and explain what you see (**1 pt**).

Input Impedance

Here's a chance to try getting used to quick *worst-case* impedance calculations.

- What is the magnitude of the impedance presented to the signal generator, defined as the input impedance, by this circuit at f = 0 (**1 pt**)? Assume no load at the circuit's output.
- What is the magnitude of the input impedance at infinite frequency (**1 pt**)?

2-3. Integrator

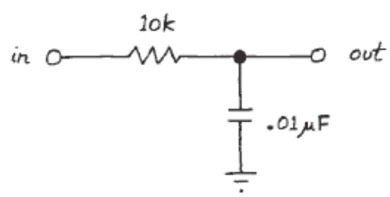

Figure 2.3: RC integrator.

Construct the *integrator* circuit shown above (Figure 2.3) . Drive it with a 100 kHz square wave at the maximum output level of the function generator, about 10 V. Take a **SCREENSHOT** (**1 pt**) and report what you see (**1 pt**).

What is the input impedance at DC (**1 pt**)? At infinite frequency (**1 pt**)? Drive the circuit (Figure 2.3) with a triangle wave and take a **SCREENSHOT** (**1 pt**); what is the shape of the waveform? *Hint: it is not a sine wave*.

This circuit, of course, is only an *approximation* to an integrator. To see this, drop the input frequency. Step your way down to 1 kHz or so, take **SCREENSHOTs** along the way and report what happens (**1 pt**). Why does the circuit fail as an integrator at low frequencies (**1 pt**)?

2-4. Low-pass filter

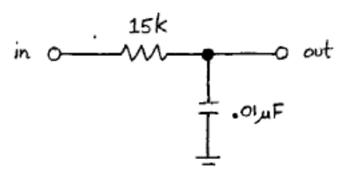

Figure 2.4: RC low-pass filter.

Construct the low-pass filter shown in Figure 2.4. Yes, this is the same as the "integrator" above and close to the original circuit of Figure 2.1. We are just going to look at its features in a different way.

The frequency for which the amplitude falls by a factor of $1/\sqrt{2}$, is denoted as the "the -3 dB point" where $f_{-3dB} = 1/(2\pi RC)$. Drive the circuit with a sine wave, sweeping over a large frequency range, to observe its low-pass property. What is f_{-3dB} (**1 pt**)? Show a **SCREENSHOT** that includes the input and output sinusoids (**1 pt**).

What is "dB"? One deciBell or dB is defined by dB ≡ 20 log (V_{out}/V_{in}). Thus a drop in signal by 3 dB is equal to attenuation by a factor of $10^{-3/20}$ = 0.708, which is close to $1/\sqrt{2}$ = 0.707. Hence the colloquial notation.

Lets now quantify the filter. Measure the attenuation starting at $f = 0.1 f_{-3dB}$ and extend to $f = 10 f_{-3dB}$ in about 20 logarithmically-spaced steps (10 per decade). Plot these the magnitude of these data on a log-log scale, either by hand or with a program (**2 pts**); this is called a Bode plot. Why is a log-log plot useful (**1 pt**)? Plot the phase shift on a linear-log plot (**2 pts**). What is the limiting value of the phase, both at very low and at very high frequencies (**1 pt**)?

2-5. High-pass filter

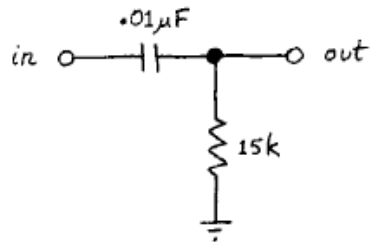

Figure 2.5: RC high-pass filter.

Construct a high-pass filter (Figure 2.5) with the components that you used for the low-pass filter but clearly in different positions. Choose a reasonable voltage for a sine output and determine this circuit's -3 dB point (**1 pt**). Check to see if the output amplitude at low frequencies, i.e., well below the -3 dB point, is proportional to frequency. Construct the bode plot (**2 pts**). What is the limiting phase shift, both at very low frequencies (**1 pt**) and at very high frequencies (**1 pts**); include one or more **SCREENSHOTS**.

2-6. Filter application I: High-pass filter to isolate "noise"

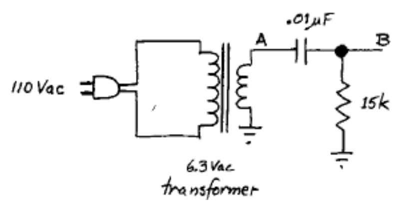

Figure 2.6: High-pass filter applied to the 60Hz AC power.

The circuit in Figure 2.6 will let you see the "electronic noise" on the 110-Volt power line. The transformer reduces the 110 VAC (or more properly 110 V RMS) to a more reasonable 6.3 V RMS and it "isolates" the circuit we're working on from the potentially lethal power line voltage. First look at the output of the transformer, at point **A**. It should appear more or less like a classical sine wave.

To see glitches and wiggles on top of the 60 Hz sine wave, look at point **B**, the output of the high-pass filter. All kinds of interesting stuff should appear, some of it curiously time-dependent. What is the filter's attenuation at 60 Hz? (No complex arithmetic is necessary; use the fact, which you confirmed above, that amplitude grows linearly with frequency well below f_{-3dB}) (**1 pt**). Document your finding(s) with a **SCREENSHOT** (**1 pt**).

2-7. Filter application II: Selecting signal from signal plus noise

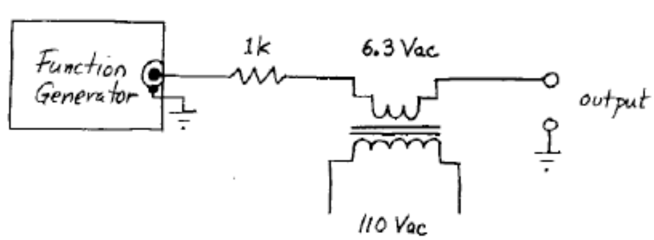

Figure 2.7: Composite signal, consisting of two sine waves. <u>The output of the transformer is now is series and "floats"</u>; the 1 kΩ resistor protects the function generator in case the composite output is accidentally shorted to ground

Now we will try using a high-pass filter to attenuate a large amplitude 60 Hz sine wave that adds to the output of the function generator (Figure 2.7). Pick reasonable parameters for the function generator output, say a 10 V sine wave at 10 kHz.

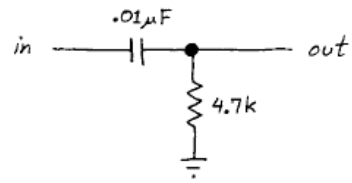

Figure 2.8: High-pass filter.

The 60 Hz is considered "noise" in this example. Thus run the composite signal through the high-pass filter shown in Figure 2.8. Look at the resulting signal. Calculate the filter's -3 dB point (**1 pt**); show a **SCREENSHOT** that illustrates the filtering (**1 pt**). Is the attenuation of the 60 Hz waveform about what you would expect? Why (**1 pt**)?

2-8. LRC filter

It is possible to construct filters (high pass, low pass, band pass, and band reject) with a frequency response that is far more abrupt than that of the simple RC filters you have been building. To get a taste of what can be done, build the filter shown above. It should have a 3 dB point of about 16 kHz and $\boldsymbol{V_{out}}$ should drop like a rock at higher frequencies.

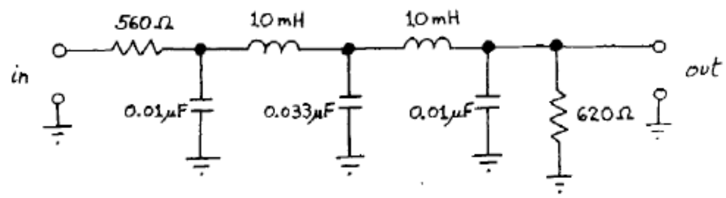

Figure 2.10: A very sharp low-pass filter.

Measure its -3dB frequency (**1 pt**), then measure its response starting at $f = 0.1f_{-3dB}$ and extend to $f = 10f_{-3dB}$ in about 20 logarithmically-spaced steps, like in section 2.4. Plot the magnitude of these data on a log-log scale (Bode plot) (**1 pt**) and the phase on a semi-log scale (**1 pt**). Compare these measurements against the response of the *RC* low-pass filter that you measured back in section 2.4.

Note that you must consider a redefinition to "f_{-3dB}" of this LRC filter, because the filter attenuates to ½ amplitude even at DC. One must define the LRC's -3 dB point as the frequency at which the output amplitude is down 3 dB *relative* to its amplitude at DC.

The best way to enjoy the performance of this filter is to *sweep* the frequency output of the function generator. Try it and take a **SCREENSHOT** of the effect (**1 pt**). You may, incidentally, find that the frequency range where the filter passes nearly all the signal is actually not quite flat. Small dips and bump can result from using standard values of L, R, and C, with tolerances, rather than using the exact calculated values.

39 points total