EE 221L Circuits II Laboratory #3

Capacitors

By

Angsuman Roy

Department of Electrical and Computer Engineering

Background

Capacitors and inductors are components that are found in all sorts of electronics. However, they are treated as ideal components in circuits courses which is not true in the real world. There are lots of details involved in selecting the correct capacitor or inductor for a circuit. In this lab you will learn about real world behavior of capacitors how to select them.

Fundamentally a capacitor is just two conductors separated by an insulating material or dielectric. This is true anywhere this occurs, whether it's the capacitance between a piece of metal next to another piece of metal or whether it's a finger on a touchscreen. Keeping this in mind will help you spot "parasitic" or unwanted capacitances occurring in a circuit. The impedance of a capacitor is given by

$$Z_C = \frac{1}{j\omega C}$$

Where Z_C is in ohms, ω is the frequency in radians/s and C is the capacitance in farads. Qualitatively it is important to think of a capacitor as a device that has infinite impedance at DC that decreases steadily with increasing frequency.

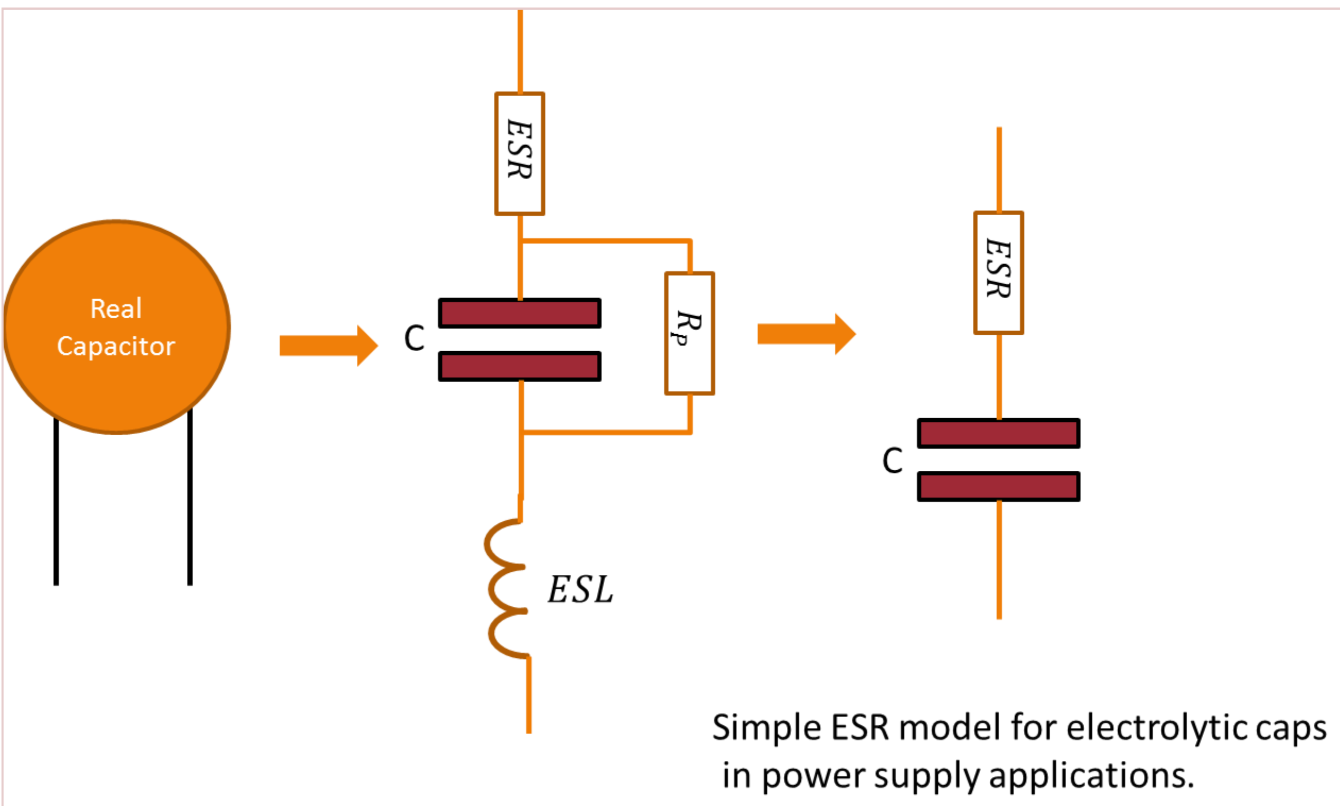

Figure 1. Capacitor model with parasitics. The model on the right is a simplified mode for power supply applications, where high frequency effects are not considered.

This equation holds true for an ideal theoretical capacitor, but a real capacitor actually has some resistance and inductance. There is a frequency range where it behaves close enough to an ideal capacitor that the resistance and inductance can be neglected. But outside of this range, the parasitic resistance and inductance have to be considered. We will extensively characterize these parasitics in the lab. A model of a real capacitor is shown in Fig. 1. There are three parasitic components associated with the capacitor. The first is the series resistance. The connections at the two terminals of the capacitor have a series resistance. For convenience, these are lumped into one series resistance in the model. Ideally, this resistance should be as low as possible. The next parasitic component is the parallel resistance. This is the reason a real capacitor can't hold its charge forever and eventually discharges. Ideally, this resistance should be as high as possible. The final parasitic component is the series inductance. This causes most of the undesired effects at high frequencies. The simplified model with only the ESR is often used for determining whether a particular electrolytic capacitor is suited for a power supply application, since high frequency operation is not a concern.

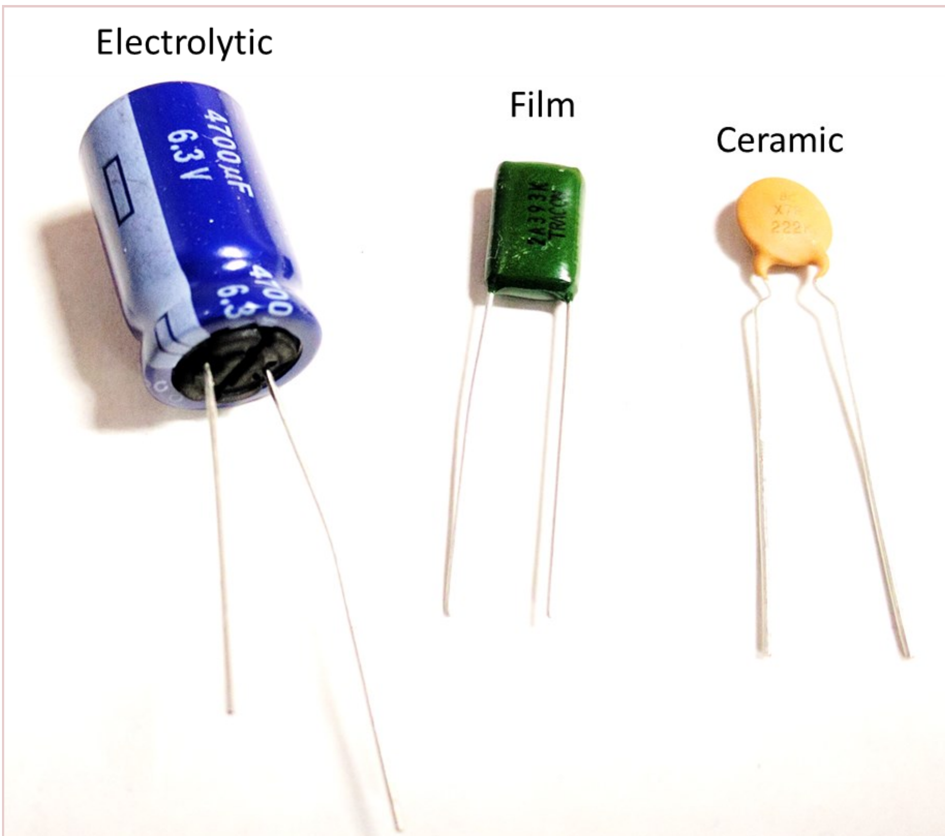

Figure 2. The three main types of capacitors.

Next, let's look at some real physical capacitors. There are three broad categories of capacitors available in our lab. These are electrolytic, film and ceramic. There are other types of capacitors too like paper-in-oil but these are rarely used. A picture of each capacitor type labeled is found in Fig. 2. It is important to select the correct capacitor based on the application. Table 1 shows typical characteristics of each type.

Characteristic	**Electrolytic**	**Film**	**Ceramic**
Practical Range of Values	1uF-100,000uF (standard types) 1F-10F (supercaps)	10 pF-10uF	1pF-1uF
Polarized?	Yes	No	No
Equivalent Series Resistance	0.1 ohm to 1 ohm	Negligible	Negligible
Leakage Current	High (up to 1 uA per uF)	Low	Low
Inductance	High	Medium	Low
Max Frequency Range	Below 1 MHz	10 MHz to 100 MHz	100 MHz to 10 GHz
Physical Size	Pencil Eraser-Soda Can	Mini M&M Candy – Giant Tootsie Roll Candy	Grain of Sand - Donut
Typical Max Voltage Rating	1V-500V	50V-1000V	25V-10,000V
Applications	Power supply filtering, energy storage (supercaps)	Audio circuits, filters, precision applications	Bypassing, filters, RF applications.

Table 1. Properties of different capacitor types. These are all typical characteristics and certain individual products could perform differently from what is listed in the table. Manufacturers are continually improving materials science. Electrolytic capacitors and ceramic capacitors in particular show much improvement.

As it is apparent from the table, there are trade-offs from selecting a particular capacitor. Electrolytic capacitors only work well at lower frequencies (less than 100 KHz) but they offer large capacitance values. This is why they are suited for power supply applications, energy storage and decoupling. Film capacitors are the closest to an ideal capacitor for frequencies up to tens of MHz. Their values change very little with temperature and applied voltage. Due to this, they are popular for audio and precision applications such as filters where it is important that they accurately maintain their value over time and temperature. If you need to design any sort of filter, film capacitors are a good starting point. However they do have disadvantages such as large physical size for a given value and can be expensive. Finally, ceramic capacitors are the best choice for high frequency applications into the GHz range but they tend to have some unique issues. There are many different ceramic materials that have very different properties. Some materials allow for high capacitance but have a significant voltage dependence on their value. This means a capacitor that is 100 pF with 1V across its terminals might be 120 pF when 10V is applied across its terminals. The worst of these types is the Y5V dielectric which can have a 20% temperature coefficient. They can be used in power supply bypassing applications, where the actual value of the capacitance is not important but rather the fact that there is a small, high value capacitor near the supply pins of a chip. The most stable ceramic dielectric is the NP0 type. This is the type to use in a filtering or audio application.

The best way to get insight into the behavior of a real capacitor is to look at the plot of its impedance as a function of frequency. This type of plot is shown in Fig. 3. There's a lot going on in this plot so take the time to carefully look at it. The solid line is the impedance as a function of frequency for the entire real capacitor. In other words, if you measured the impedance of the capacitor at each point, you would get the solid colored line. However, in each different frequency region, one particular portion of the real capacitor is most responsible for the impedance in that region. At DC and extremely low frequencies (periods of seconds, minutes, hours and days), the parallel resistance which causes a leakage current, dominates. The dashed lines indicate what the impedance of just that component looks like. For example, the red dashed line indicates what the impedance would be if there was just an ideal capacitor. The next region, with the solid red line indicates the frequency range where the capacitor behaves close to an ideal capacitor with a steady downward slope with increasing frequency. The upper limit of this region depends on the type of capacitor as indicated in Table 1. The purple region is where the equivalent series resistance (ESL) dominates. In this region the capacitor has a very low impedance, but the resistance in series holds it to a constant value. The final region is indicated in brown and is dominated by the equivalent series inductance (ESL). This is the point where the inductor "wins" and "beats" the capacitor. The real capacitor at this point is more of an inductor than a capacitor.

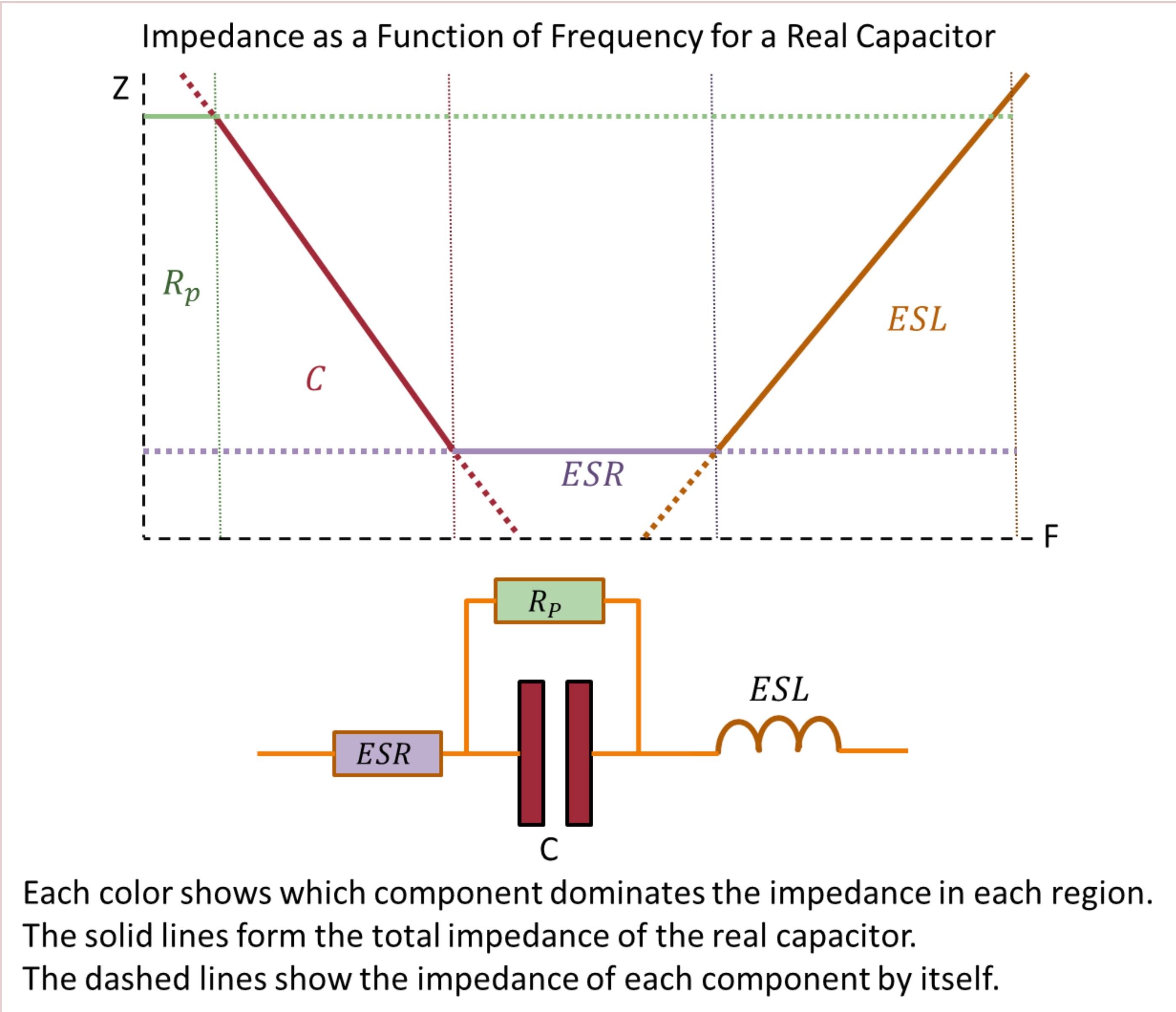

Figure 3. Simplified plot of impedance as a function of frequency.

There are a few important comments that need to be made about this graph. The reason the *equivalent* series resistance and *equivalent* series inductance are called such, is because these values can change wildly with temperature, the applied voltage and the age of the capacitor. Another important comment is that in reality the graph isn't discontinuous and has curves in the transition region. Phase information isn't shown on the graph either. Generally for any graph that is a function of frequency, phase information is valuable. When the impedance is purely capacitive then there is a -90 deg phase shift. When the impedance is purely inductive there is a +90 degree phase shift. Any impedance with a phase angle between these two extremes can be decomposed into their real and reactive parts. To keep things simple we will only focus on the magnitudes in this lab.

Prelab Summary

You will simulate basic capacitor circuits in LTSpice for this prelab. A new skill to learn is how to plot impedance as a function of frequency.

Prelab Tasks

Prelab #1: PCB and Netlist Required

Prelab #2: PCB and Netlist Required

For the PCBs, a single capacitor and appropriate connectors are acceptable.

Prelab

This prelab will extensively use LTSpice. It is assumed that the student has some familiarity with LTSpice and will not go over basic functions. More complex functions will be detailed however. There are many LTSpice tutorial resources available on the web.

Prelab #1

Follow the steps below. Deliverables are in bold.

1. Simulate the schematic shown below in Fig. 4. Plot the current through the capacitor. Next, in the expression editor, divide the input voltage by the current through the capacitor. This will give the impedance of the capacitor as a function of frequency. The Y axis defaults to dB, right click on the Y axis, select manual limits and change to “linear”. This will show the units in Ohms. These steps are shown in Fig. 5. Note that the straight line slope of capacitor impedance as shown in Fig. 3 only occurs on a log-log plot. We are changing to a linear-log plot because dB units aren’t very intuitive when dealing with ohms. **(Schematic, Plot)**
2. Add the parasitic components as shown in Fig. 6. Note that the AC sweep values have changed to make it easier to see the effect of the inductor. Make a plot of impedance vs. frequency as described in the previous step. **(Schematic, Plot)**

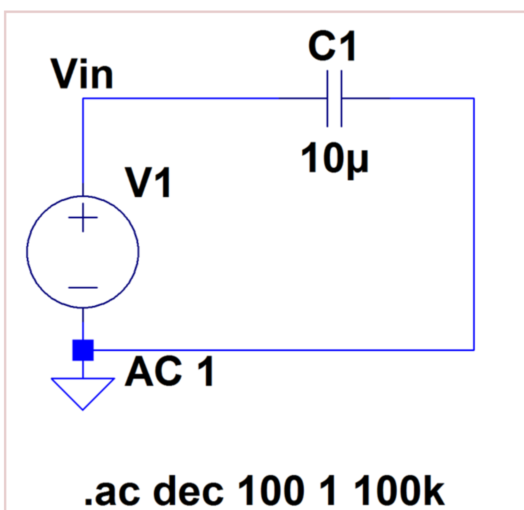

Figure 4. Schematic for Prelab #1, step 1.

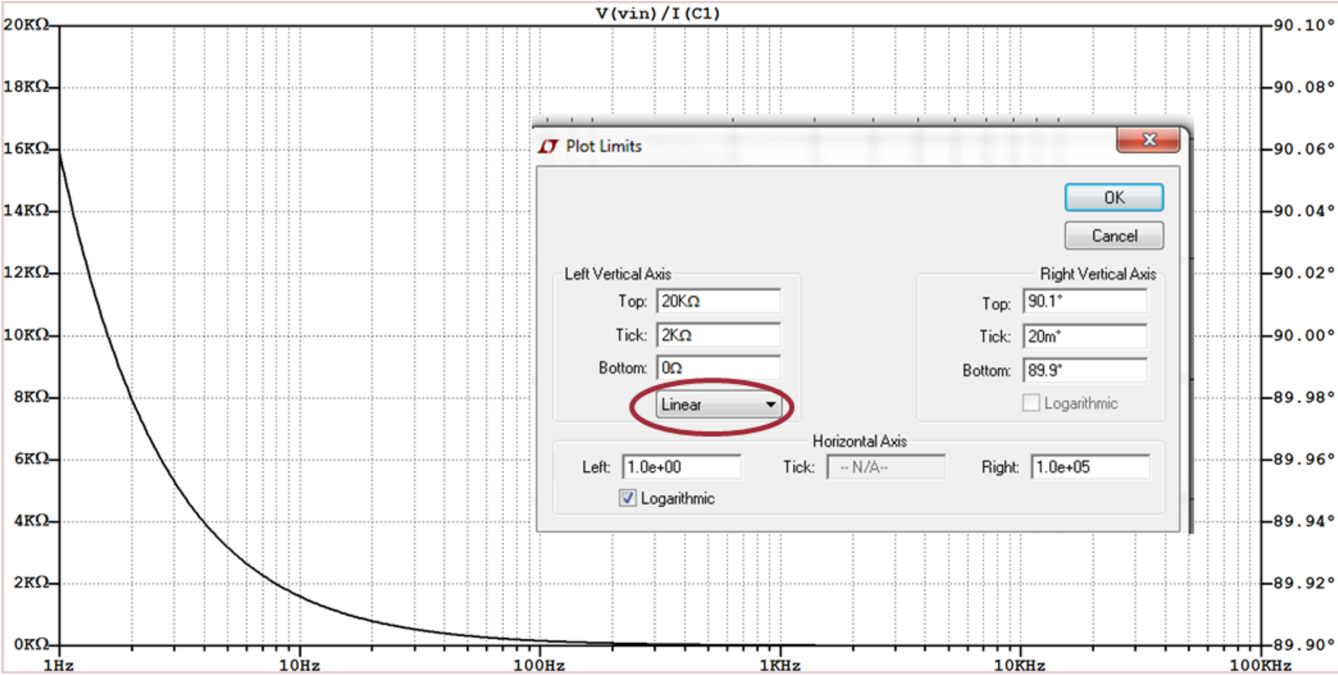

Figure 5. Changing plot settings.

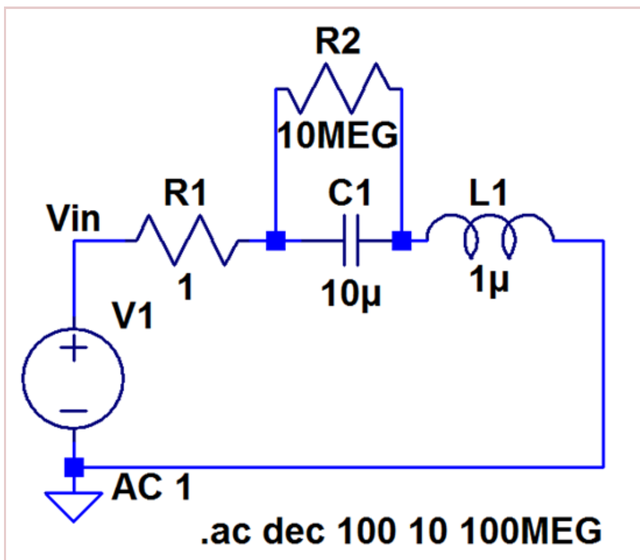

Figure 6. Schematic for Prelab #1, step 2.

Prelab #2

Follow the steps below. Deliverables are in bold.

1. The function generators in the lab have a 50 ohm output impedance. This means that if a 50 ohm load is connected, the output voltage will drop to half. Please note that on most function generators, the level entered on the front panel accounts for this and assumes that it will be connected to a 50 ohm load. To compensate for the drop, it actually outputs double the voltage entered on the panel unless it is set to "high-Z" mode. Calculate the capacitor values that result in a 50 ohm reactance at frequencies of 1 KHz, 100 KHz and 1 MHz. **(Hand calcs)**
2. Simulate the schematic shown in Fig. 7. Replace the "?" with the capacitor values you have calculated. Make sure to also change the input frequency. Verify your hand calculations with your transient analysis plots. **(Schematic, Plots)**

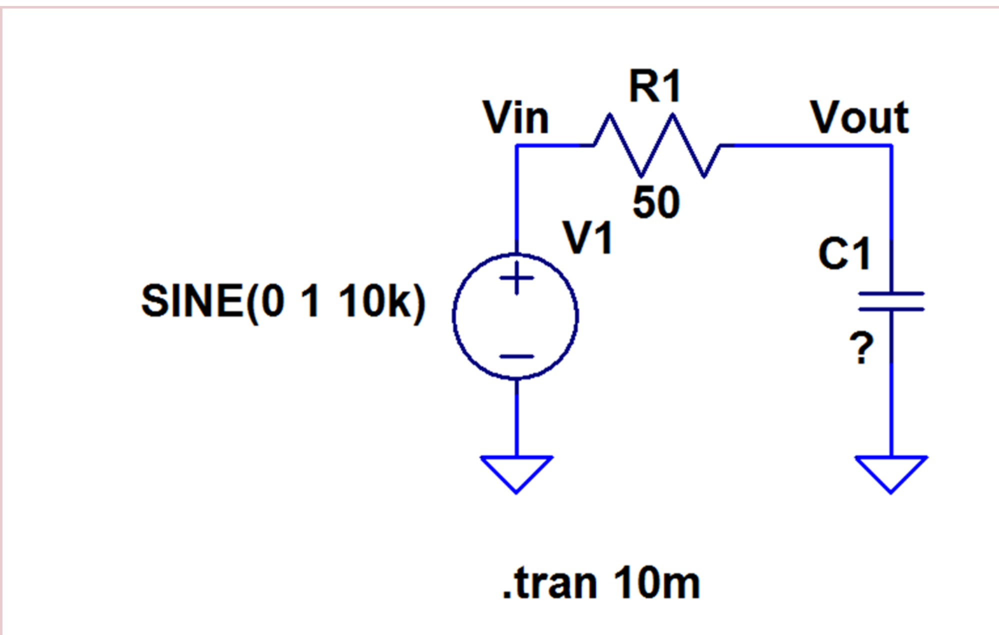

Figure 7. Schematic for Prelab #2.

Required Materials and Equipment

1. **Function Generator**
2. **Oscilloscope**
3. **Oscilloscope Probe**
4. **BNC-BNC and BNC-Alligator Cables**
5. **Capacitors**
6. **T-Coupler and 50-ohm Terminator**

Postlab Tasks

Task 1: Capacitive Reactance

Task 2: Series Inductance

Task 3: ESR Measurement

Measuring Equipment Basics

In this lab, we will be introducing the oscilloscope and function generator. This equipment has many features and functions and it is highly recommended that the student consult the manuals when there is any confusion. Many students get frustrated with modern oscilloscopes and their many menus and buttons. It is highly recommended that all students take a day to read the following documents. A day of reading will yield a lifetime of clear oscilloscope usage. These documents are:

1. ABCs of Probes
   https://faculty.unlv.edu/eelabs/docs/guides/ABC_of_Probes.pdf

2. XYZs of Oscilloscopes

   https://faculty.unlv.edu/eelabs/docs/guides/XYZsOfOscilloscopes.pdf

3. XYZs of Signal Generators

   https://faculty.unlv.edu/eelabs/docs/guides/XYZs_generators.pdf

In this lab only specialized functions will be explained and the student is expected to read the above three documents. Furthermore, the use of auto-set is not allowed. All triggering and set-up must be done by the student. Every action should be carefully thought out. The goal is to have students be able to think independently while using test equipment. The user of an oscilloscope should be constantly thinking about the vertical, horizontal, coupling and triggering settings. For example, if a straight line appears on the oscilloscope when a sine wave is expected, it could mean the vertical divisions are set too high, or the horizontal divisions are too short or an incorrect coupling mode is used. Eventually using an oscilloscope should become as intuitive as driving a car. Please be sure to read any labels on probes for bandwidth and attenuation. While most of the probes in the lab are 10X, always check and use the proper setting on the oscilloscope.

Postlab #1: Capacitive Reactance

Follow the steps below. Deliverables are in bold. All work must be typed.

1. Set up the function generator as shown below in Fig. 8. The offset is there so that electrolytic capacitors are properly polarized. Make sure it is set to output a sine-wave.
2. Find three capacitors in the lab that most closely match your calculated values from prelab #2 for 50 ohm reactance at 1 KHz, 100 KHz and 1 MHz.
3. Set up the oscilloscope with DC coupling; appropriate probe settings; vertical divisions to 1V; horizontal divisions to 4 ms and adjust the triggering until the signal is steady.
4. Add a peak-to-peak measurement to the main display screen. Hit the "measure" button and follow the menus as shown in Fig. 9. If you need additional assistance consult the manual.
5. When properly set up, your oscilloscope should look like Fig. 10.
6. Use a 50-ohm BNC to alligator clip cable and connect the output of the function generator to the capacitor you are testing. Connect the oscilloscope probe to the capacitor as well. Adjust the frequency until the peak-to-peak measurement on the screen is around 50% of the initial value. This corresponds to the output voltage being halved due to the voltage divider formed by the 50-ohm output impedance and the 50-ohm reactance of the capacitor. The test set-up is shown in Fig. 11.
7. Repeat for the other values. If you have to use an electrolytic capacitor for any of the values be sure to observe the polarity. (**Measured Results with Photos)**

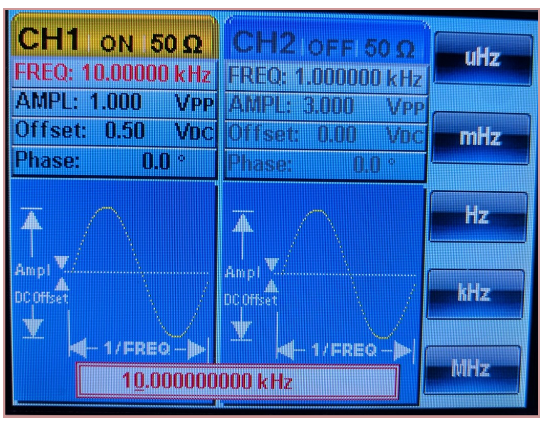

Figure 8. Function generator setup.

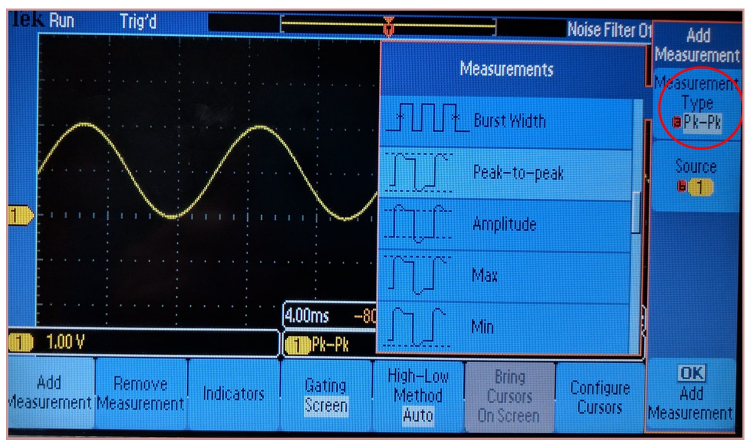

Figure 9. Adding measurements.

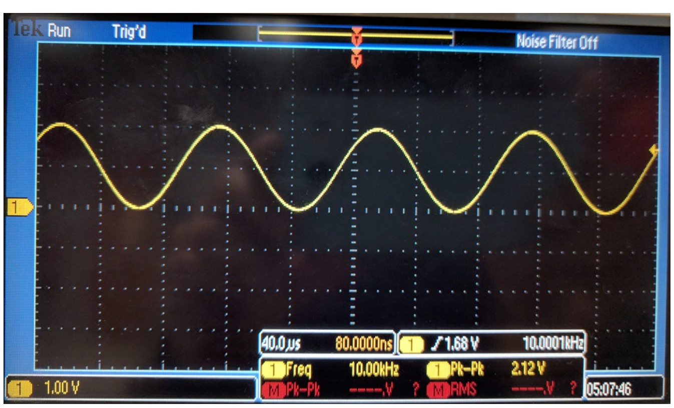

Figure 10. Oscilloscope setup.

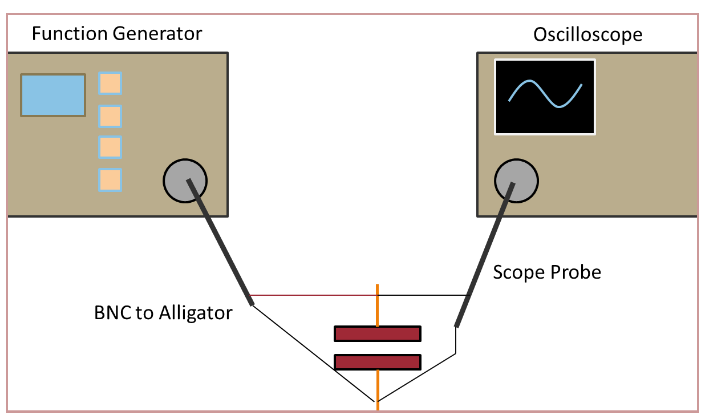

Figure 11. Diagram of test set-up for Postlabs 1 and 2.

Postlab #2: Equivalent Series Inductance

Follow the steps below. Deliverables are in bold. All work must be typed.

1. Keep the same test set-up from Fig. 11. You should have a set of electrolytic capacitors of various values either in your parts kit or provided to you by the instructor.
2. For each capacitor note the value and the voltage rating. Place the capacitor in the test set-up from Fig. 11. Increase the frequency on the function generator and note that measured voltage across the capacitor continues to decline. Keep increasing the frequency until eventually, the measured voltage begins to rise. This is due to the inductive component of the capacitor. Calculate the inductance at a test point. A good point to use the point where the voltage is half. This is because the reactance is 50 ohms at that point and it would be easy to calculate the inductance. For some smaller values of capacitors this may not be possible because the capacitor doesn't have 50 ohms of inductive reactance within the possible frequency range of the function generator.
3. Record all your data and make a table. Write a few comments. **(Table and comments)**

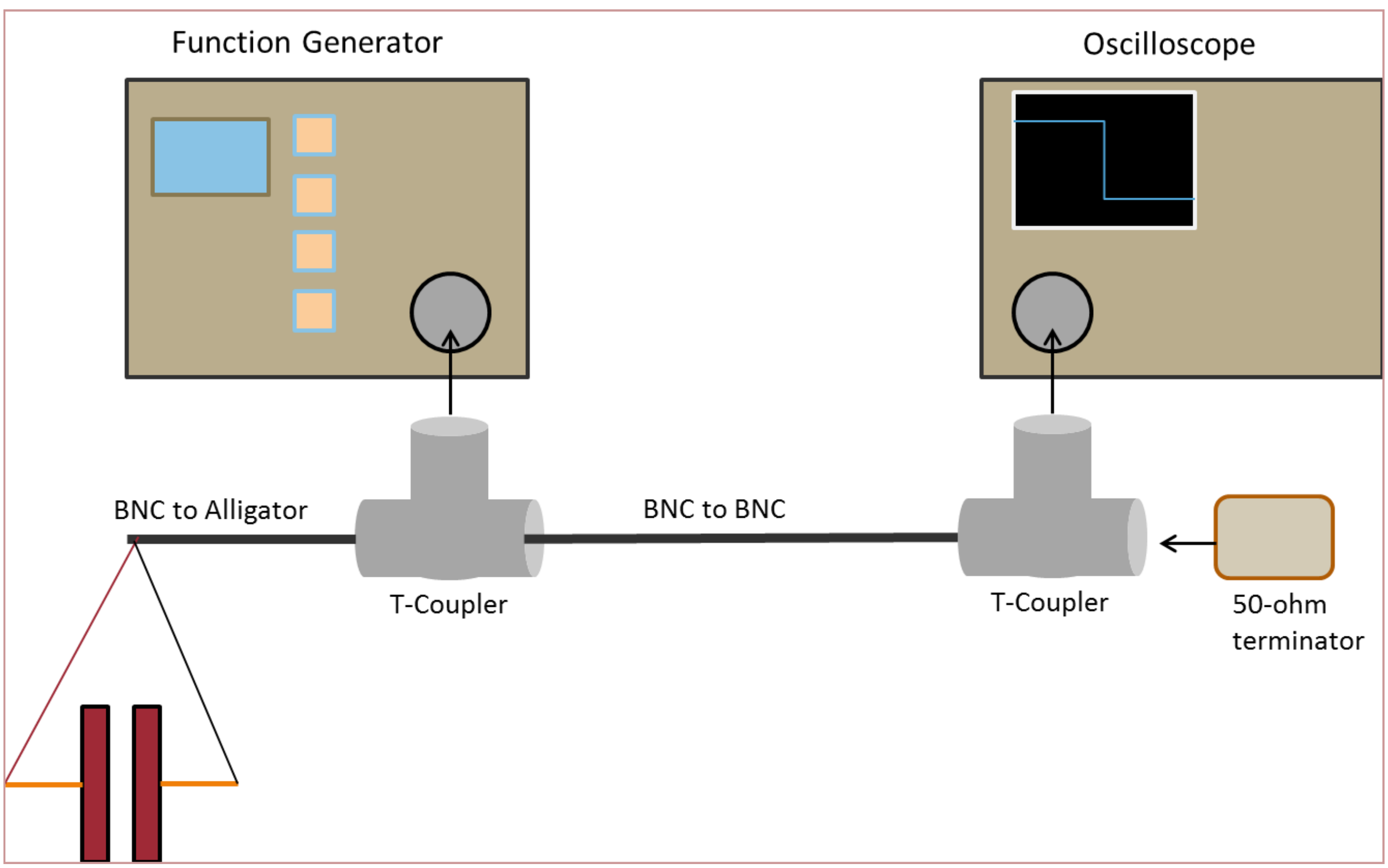

Figure 12. Diagram of test set-up for Postlab 3.

Postlab #3: Equivalent Series Resistance

Follow the steps below. Deliverables are in bold. All work must be typed.

1. Build the test set-up of Fig. 12, but do not connect the capacitor yet.
2. Set the function generator to output a 2V peak to peak (P-P) square wave with a 1V offset and 100 KHz frequency. This frequency is chosen so that it is fast enough that it won't charge up the capacitor but is slow enough that transmission line effects aren't a factor. Without the capacitor connected, your scope screen should look like Fig. 13. This will be your reference waveform. Set up a peak to peak measurement. You can increase the voltage output later if the voltage level drops too low to make a reliable measurement when the capacitor is connected. This will become apparent later. Always ensure that square wave does not go below zero volts.
3. Connect a test capacitor. The square wave will significantly diminish in amplitude since the capacitor represents a short at high frequency. Change the coupling to AC and the scope screen should look similar to Fig. 14. The tall spikes are due to the inductive portion of the capacitor. We are interested in looking at the peak to peak level of the flat part of the square wave. Ignore the scope's peak to peak measurement because it is measuring the sharp inductive peaks and not the flat top.
4. Use the cursors to measure the height of the square wave. The example in Fig. 15 measures 35 mV. The square wave diminished from 2V P-P to 35 mV P-P. The ESR can be calculated based on this using the equivalent circuit of the test set-up shown in Fig. 16. The capacitor behaves as a short due to the high frequency so the voltage develops across the ESR. The better the quality of the capacitor, the smaller the ESR, resulting in a smaller square-wave. This is why for some capacitors you will have to raise the output voltage in order to actually measure the voltage drop. (Hint: find the Thevenin equivalent of the function generator and 50 ohm terminator combination. This will simplify calculations. Refer to the previous DC circuits lab for more information)
5. Repeat the measurement for each provided capacitor and make a table showing the ESR. Include your hand calculations showing how you calculated the ESR for each capacitor. Comment on any trends that you notice. **(Hand calcs, Table, Comments)**
6. For some smaller valued capacitors, the waveform will not look like Fig. 14. Instead there will be an exponential component to it after an initial step as shown in Fig. 17. This is due to capacitor charging due to the frequency being too slow. There are two solutions to this. Either the frequency can be increased or the charging portion of the waveform can be disregarded. Ignore the inductive peak and measure the voltage from the start of the square wave to the point just before the capacitor begins charging as shown in Fig. 18.

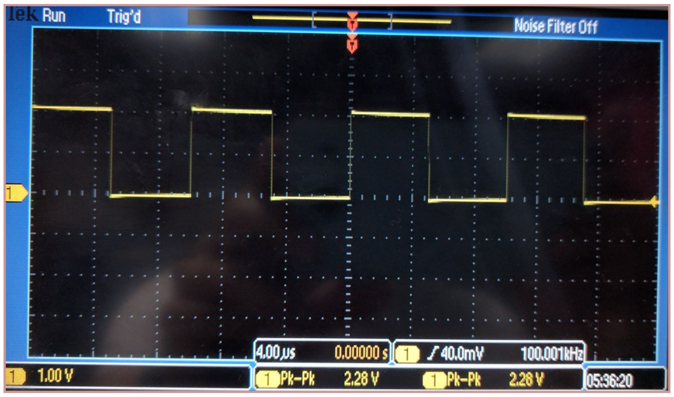

Figure 13. Square wave with no capacitor connected.

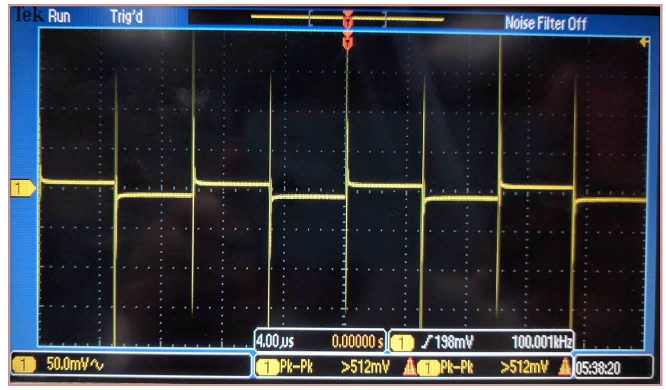

Figure 14. Connecting the capacitor reduces the amplitude.

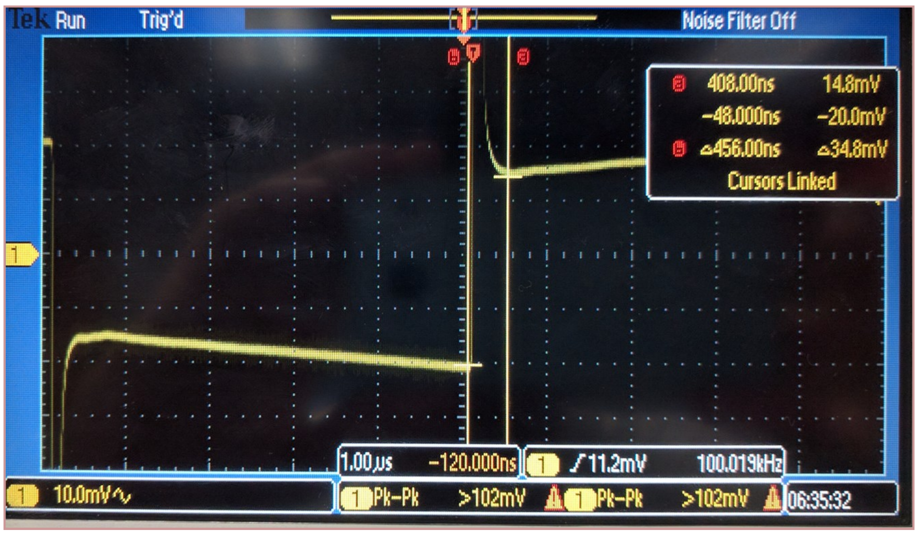

Figure 15. Measurements with cursors.

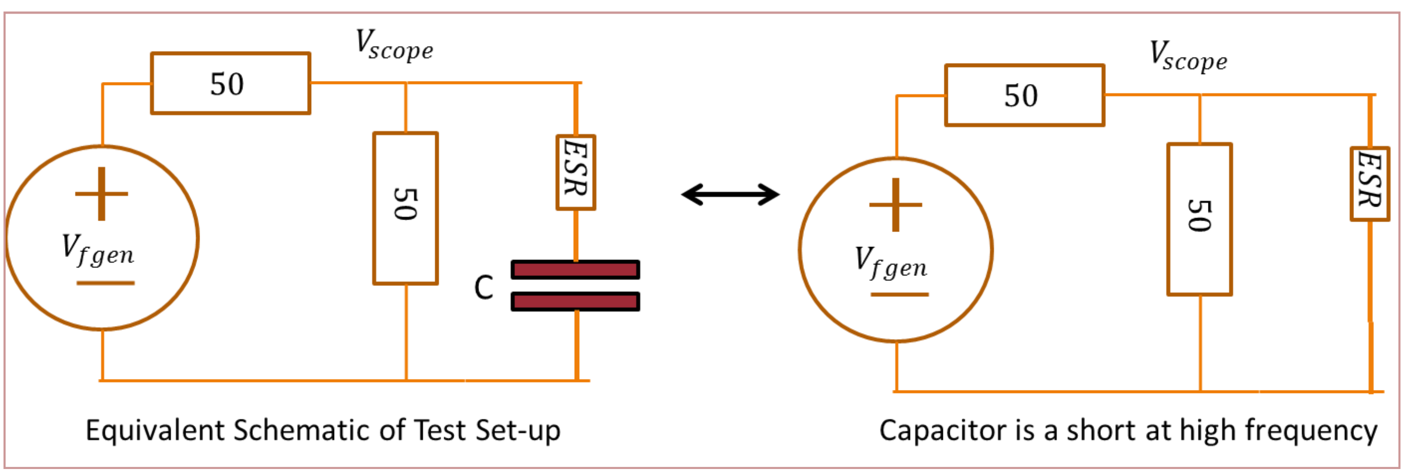

Figure 16. Equivalent circuit of test set-up. Find the Thevenin equivalent for the function generator and 50 ohm terminator combination and use that to simplify your ESR calculations.

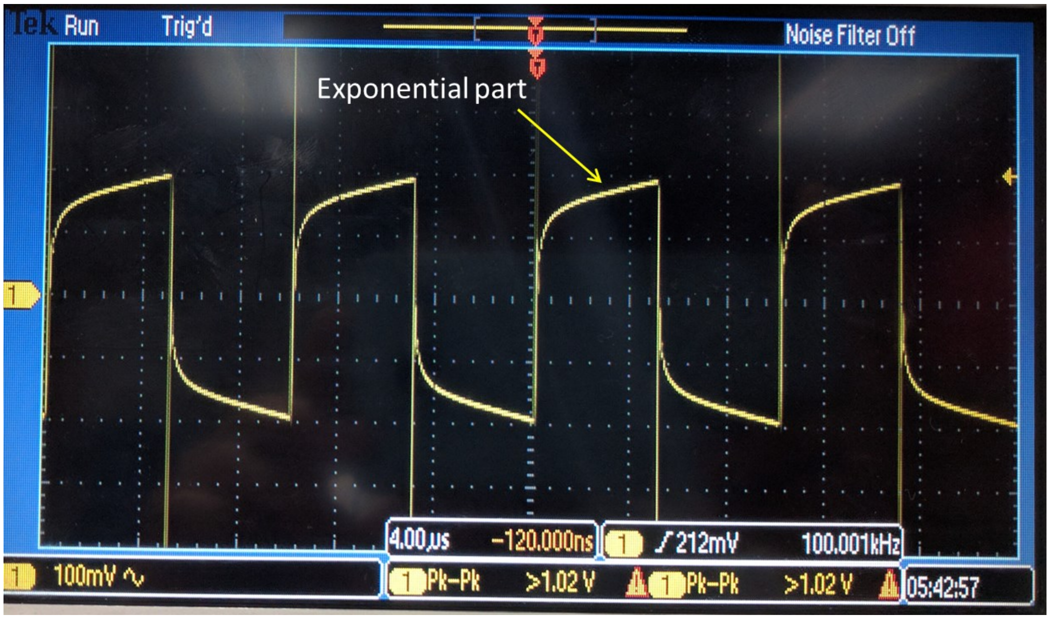

Figure 17. Smaller capacitors may charge up after the initial step.

Either increase the frequency or disregard the exponential part of the waveform.

Figure 18. Measure from the start of the square-wave to the portion just before the exponential charging.