EE 221L Circuits II Laboratory #8

Transformers

By

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Background

Transformers are found everywhere from the easily visible utility power transformers to microscopic ones inside communication ICs. Transformer design is a broad and deep subject that can form the basis of a lifelong career. As with inductors, transformers tend to deviate significantly from non-ideal behavior and can be daunting for students and seasoned engineers alike to understand. Many engineers would rather not deal with transformers at all. However, the understanding of a few basic parameters of transformers makes them more approachable. This lab will introduce the basic theory of transformers from an applications perspective, their simulation and how to use them in practice.

Physically, a transformer is two inductors that share magnetic flux. Two inductors next to each other can be viewed as a transformer. A change in magnetic flux in one inductor is transferred to the other. If the inductors are physically far apart the coupling is weak and the transformer action is minimal. In many situations it is important to keep separate inductors far enough that they do not interact. If transformer action is desired then the inductors should be as close to each other as possible. Often this manifests itself as two coils being wound on the same magnetic core as illustrated in Fig. 1. As many coils as physically possible can be wound on the same magnetic core.

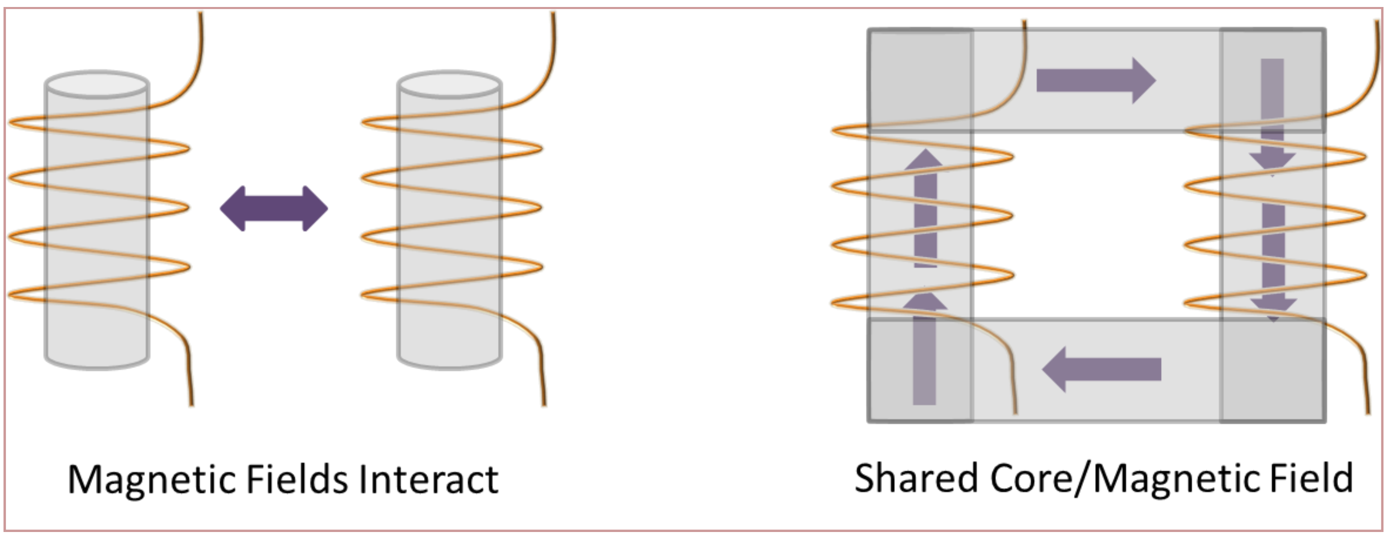


Figure 1. Magnetic field is shared by all the inductors within a transformer.

There are many schematic symbols for transformers. A selection of these is shown in Fig. 2. An air-core transformer is depicted in Fig. 2a. These transformers have poor coupling but have good high frequency performance and are used in RF circuits. An iron-core transformer is shown in Fig. 2b. The "iron" core name is archaic and can refer to a wide variety of materials such as steels and ferrites. Most transformers are of the iron core variety. A transformer with multiple secondary windings is shown in Fig. 2c. Finally a transformer with a center-tapped secondary winding is shown in Fig. 2d. A center tap is a connection made halfway on a coil. The "dot" in the schematics represents the polarity of the winding. A positive voltage applied to a terminal with a dot will result in a positive voltage on the other side at the terminal with a dot. Physically, this is done by winding the coils in the same direction. If the dots are in the same position on the primary and secondary winding then the coils have been wound in the same direction. If the dots are on opposite position it would mean that one coil was wound clockwise and the other counter-clockwise for example. This would invert the phase of the signal between primary and secondary. The primary and secondary refer to the two sides of the transformer. The names are determined by the intended usage. Transformers are bidirectional and can be operated in reverse although the user must understand whether this is appropriate for their particular situation.

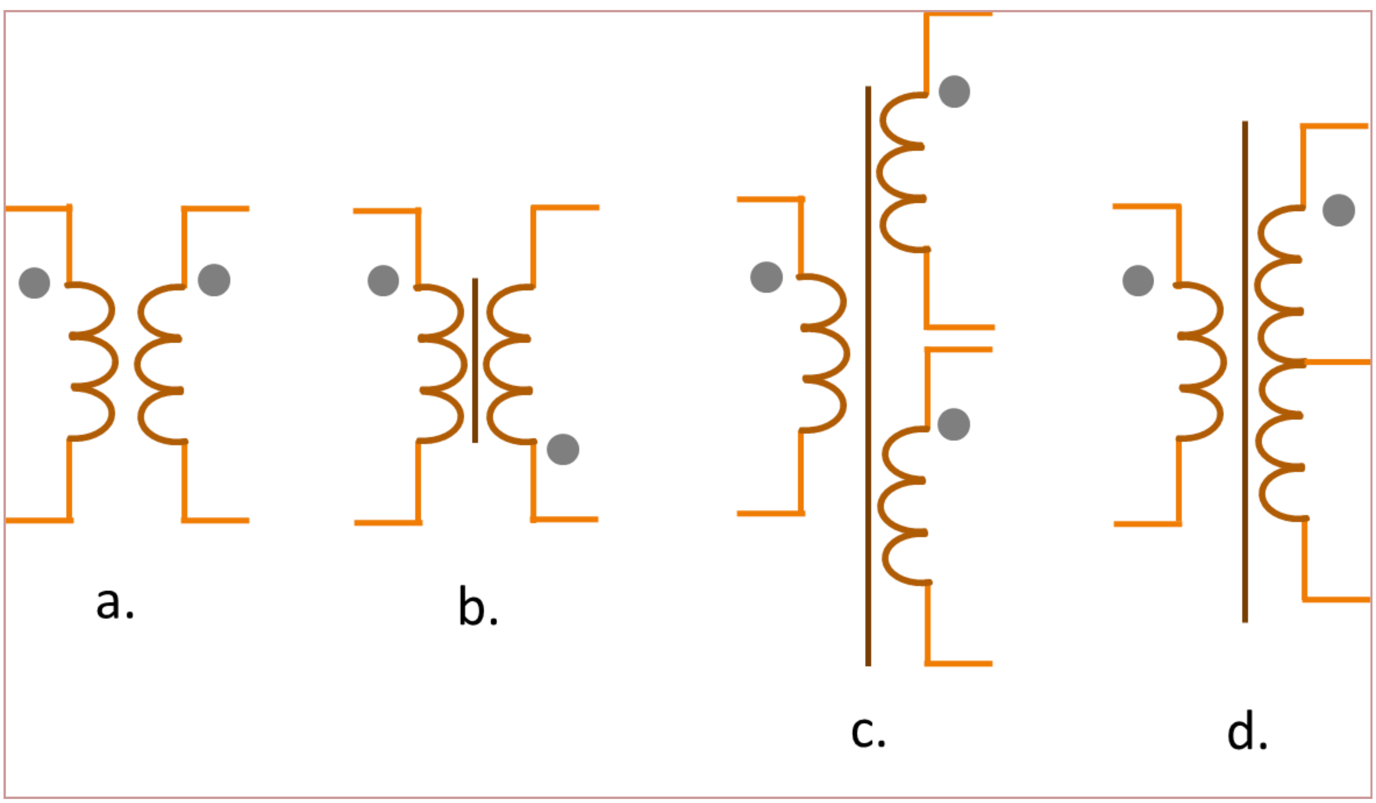


Figure 2. An air-core noninverting transformer (a); An iron-core inverting transformer (b); An iron-core transformer with multiple secondary windings (c); and a center-tapped iron-core transformer (d).

In this lab we will be using transformers for both signal processing and power applications. We will first examine what happens to signals as they pass through transformers to get an intuitive understanding before analyzing power losses and similar issues. In many signal processing applications the ideal transformer approximation is valid. When analyzing transformer problems it is important to always keep track of the polarity of the windings. The effect of the polarity dot is shown in Fig. 3. Note that if you have a noninverting transformer and an inverting one is desired, you would simply reverse the connections on the secondary side. The polarity marking does become critical for applications where transformers are connected in series or parallel and will be explained later. A voltage applied to the primary side of the transformer will be scaled up by the turns ratio of the transformer at the secondary side. This is illustrated in Fig. 4 where the secondary voltage is scaled by N times the primary voltage. The turns ratio is given by,

$$N = T_s/T_P$$

Where T_P and T_S are the number of turns on the primary side and secondary side respectively. For example a transformer with 100 turns on the secondary and 10 turns on the primary would have a turns ratio of 10. The secondary voltage is given by,

$$V_S = V_P \cdot N$$

For the above example, 1 V applied to the primary becomes 10 V at the secondary. The current relationship in the transformer is given by,

$$I_S = I_P/N$$

This means that for the above example a current of 1 A would flow in the primary side if there was a load drawing 100 mA on the secondary side. If a transformer has no load connected on the secondary side than ideally no current flows in the primary side, although in reality there is a small leakage current. It is important to understand that power is not created by a transformer. That is why there is an inverse relationship between the voltage and the current which keeps the power flowing into and out of the transformer constant.

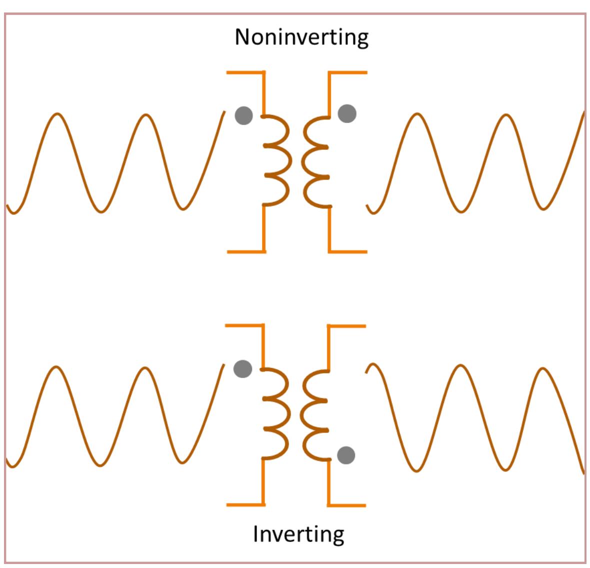


Figure 3. Effect of polarity dot.

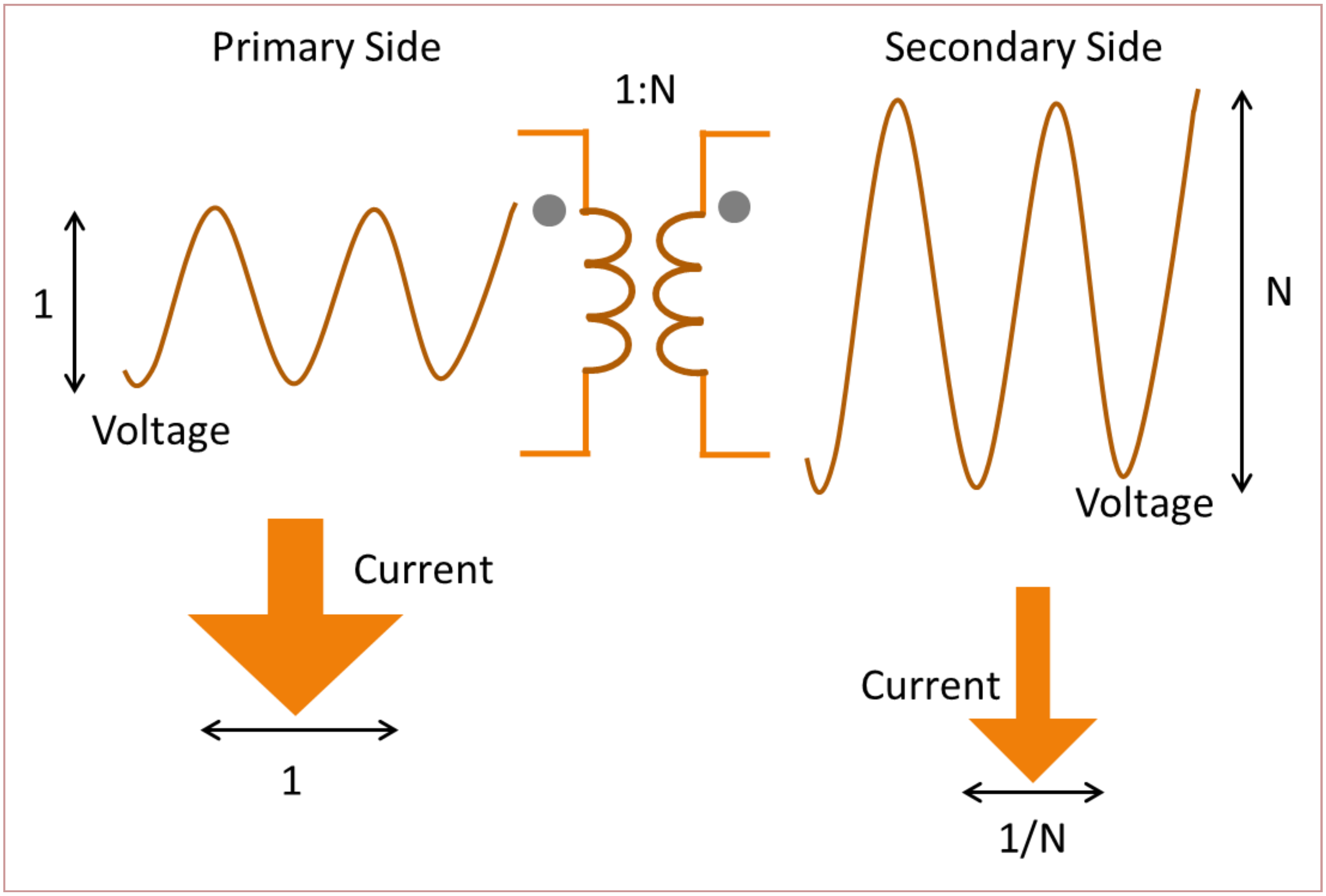


Figure 4. Illustration of voltage and current relationships between the primary and secondary side.

Next let's look at series and parallel connection of transformer windings. Multiple windings can be found on both the primary and secondary side of a transformer. Two physically separate transformers can be treated the same as two windings on the same transformer for analysis purposes. For the following examples, a single winding on the primary side and two identical windings on the secondary side will be used. If two windings on the secondary side are connected in series, then the output voltage will be double that of a single secondary as shown in Fig. 5. Basically, series connections add just as they do for resistors. However the phases must add together. This is similar to the plus and minus signs when adding voltage sources. If the windings are connected with opposite polarity as shown in Fig. 6, the outputs will cancel out to zero volts. Any set of windings on the secondary side can be connected in series. For example a transformer with a 24V winding, a 12V winding and a 5V winding can be wired in any combination. The 12V winding can combine in series with the 24V winding to create a 36V winding. However the current rating for the new combined winding is limited by the lowest rated winding. This makes sense because an equal current flows through all the windings.

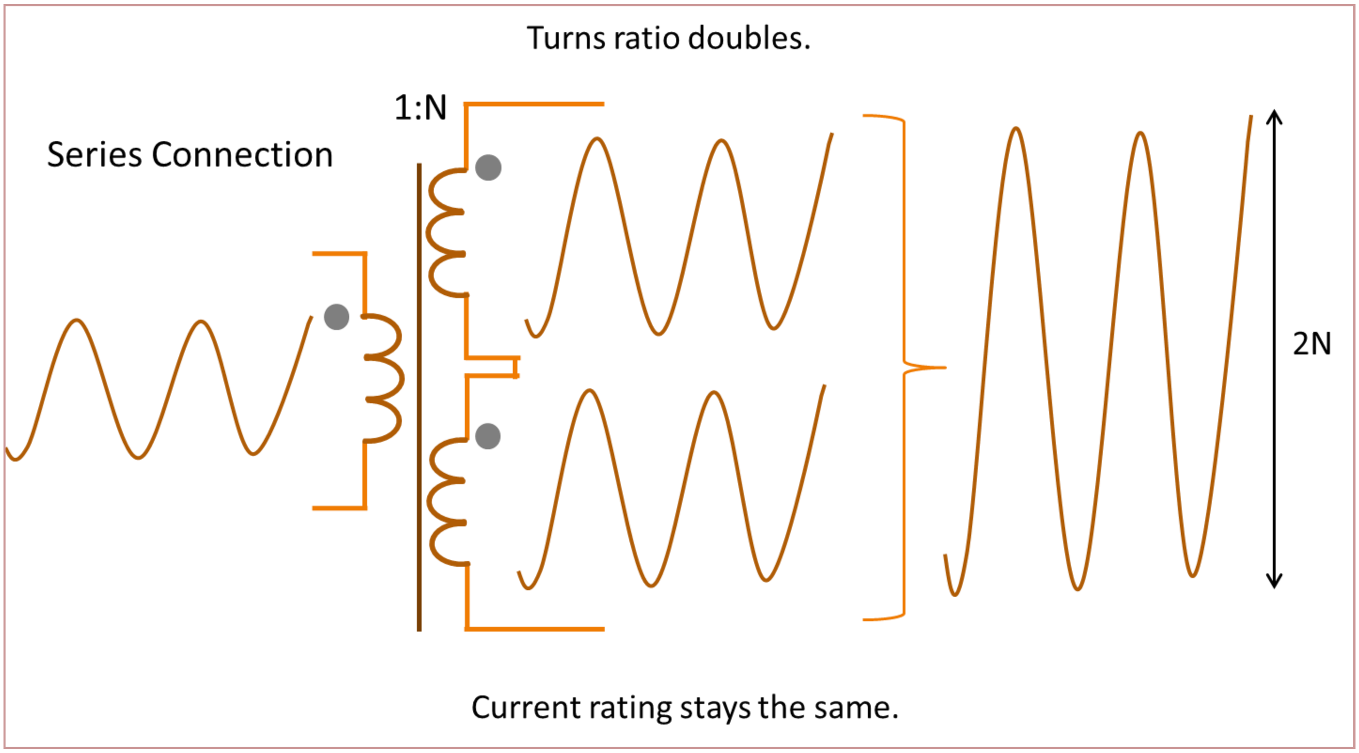


Figure 5. Proper series connection of windings. The 1:N refers to the ratio between one primary coil and one secondary coil not their combination. If secondary coils are not identical then the ratio must be explicitly stated.

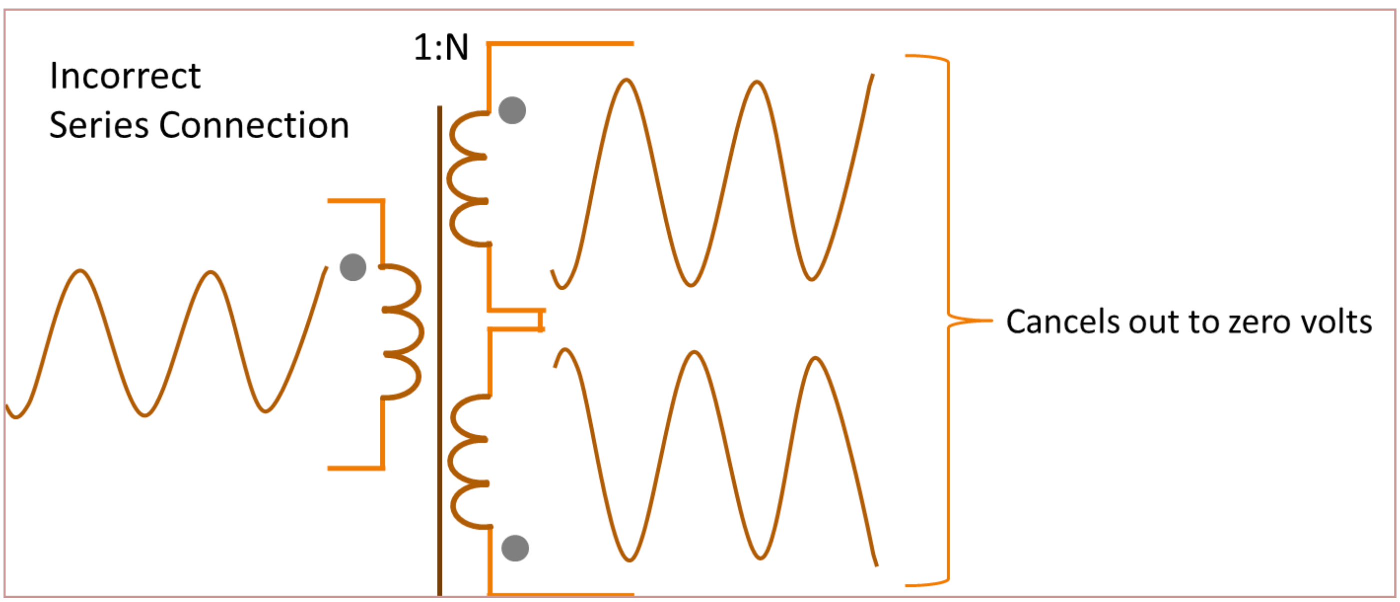


Figure 6. Incorrect series connection of windings. No damage will occur but the voltage will cancel out.

Windings are connected in parallel if more output current capability is required. Connecting two windings in parallel can double the current that the transformer can supply to the load as shown in Fig.7. However the turns ratio remains the same. This is important to understand; the voltage and current relationships are identical to a single winding connection on the secondary. All that changes is that the transformer can handle more current if needed. There are two important conditions for parallel connection of windings. The windings must have the same amount of turns and consequently the same voltage. If they don't have the same voltage, a high current can flow until their voltage equalizes which will dissipate a lot of heat. There will always be some mismatch in the windings and some excess heat caused by the parallel connection. A transformer with a small tolerance should be used. The worst example of a voltage mismatch is if the coils are connected with the wrong polarity. This is shown in Fig. 8 and should never be done. You should always double check your connections and use a fuse if you are connecting a high power source like the mains outlet. The transformer's insulation can melt and can cause a fire. In our lab we will be connecting our transformers to the function generator whose limited drive capability ensures safety.

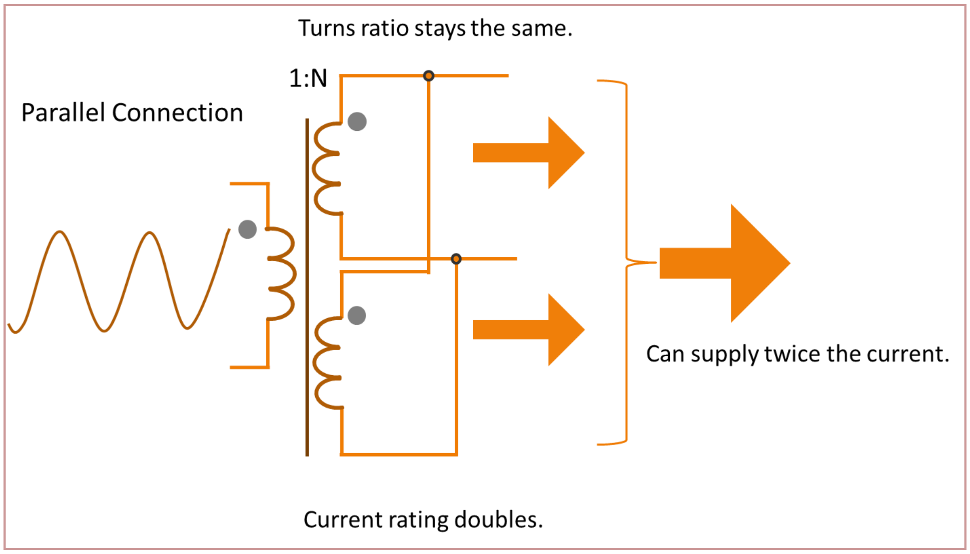


Figure 7. Proper parallel connection. Always double check polarity.

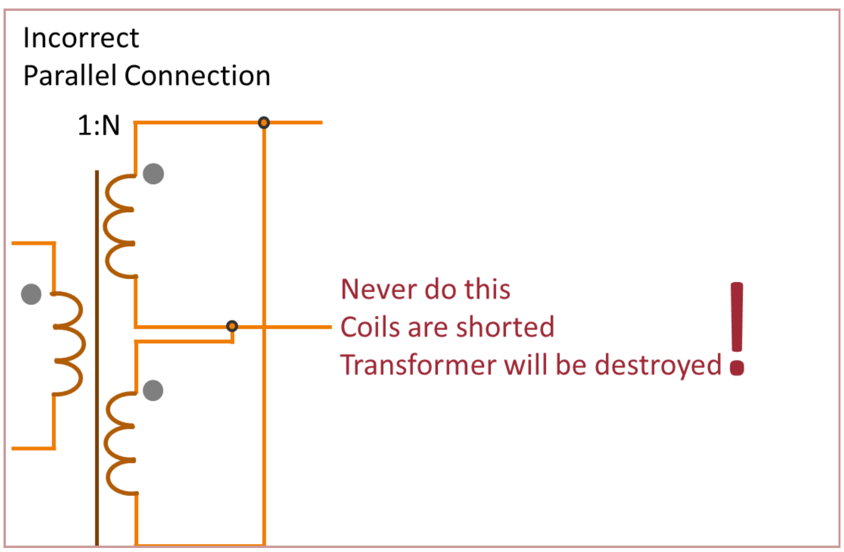


Figure 8. Incorrect parallel connection!

In most cases you will not be able to find out the actual number of turns on the primary and secondary side of a transformer. However there is a relationship between the inductance and the turns ratio. The square roots of the inductances of both sides result in the turns ratio given by

$$T_P : T_S = \sqrt{L_P} : \sqrt{L_S}$$

For example if the primary inductance measures 400 uH and the secondary inductance measures 1600 uH, then there are 20 primary turns to 40 secondary turns. Simplifying this results in a turns ratio, N of 2. This relationship is important for modeling transformers in SPICE, because you have to enter inductances rather than turns. For example a 1:4 transformer could be modeled by a 1 mH primary inductance and a 16 mH secondary inductance.

The turns ratio also "transforms" impedances between primary and secondary sides. The impedance on one side of the transformer is simply the voltage at that side divided by the current flow. The turns ratio relates the impedances across the transformer and the impedance "seen" by the primary side is given by

$$Z_P = Z_S / \sqrt{N}$$

This means that a 100 ohm load on the secondary side will appear to be a 10 ohm load on the primary side of a 1:100 transformer. Conversely, a 10 ohm load on the secondary side would appear to be a 100 ohm load to the primary side of a 1:0.01 (or 100:1) transformer. This property is known as the reflected impedance and is useful for impedance matching two systems with significantly different native impedances with minimal power loss. Matching transformers are commonly used in audio or RF. For example, a transformer may be marketed as a 100 ohm to 50 ohm transformer. This means that a 50 ohm load connected on the secondary of the transformer would appear to be a 100 ohm load on the primary side. In this case, the turns ratio is implied to be 4. Of course, you don't have to connect a 50 ohm load to the secondary side and the reflected impedance would change accordingly. This is illustrated in Fig. 9.

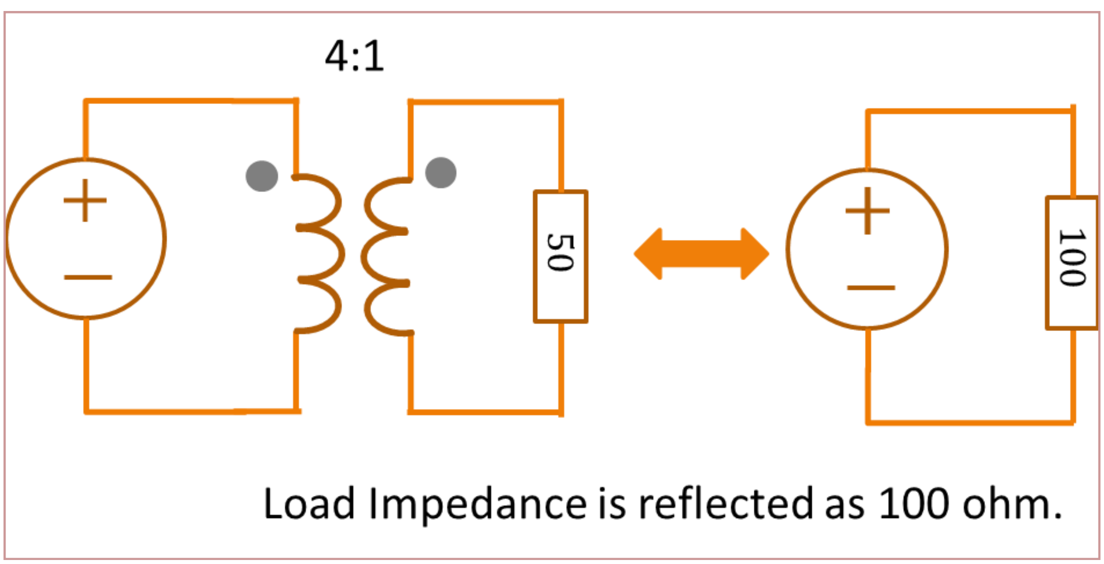


Figure 9. Reflected impedance from secondary to primary.

All transformers have a usable bandwidth range. Power transformers are optimized to operate at 60 Hz for maximum power transfer at this frequency. Audio transformers are optimized to operate over the audio bandwidth of 20 Hz to 20 KHz. A pulse transformer is a term used to describe a transformer with a bandwidth spanning a few decades such as 100 KHz to 100 MHz. These transformers are critical in modern digital communication systems to faithfully transmit pulses with short rise times and relatively long durations. An example frequency response for a pulse transformer, the Coilcraft WBT4-1 is shown in Fig. 10. This is a 1:3 transformer that is center tapped on both the primary and secondary. The 3 dB bandwidth is 50 KHz to 150 MHz. How this frequency response relates to a pulse is shown in Fig. 10 as well. The upper 3 dB frequency determines the rise-time of a pulse passing through the transformer. The relationship between bandwidth and rise time is given by

$$Bandwidth\ in\ Hz = \frac{0.35}{T_R}\ or\ Rise\ time\ in\ seconds = \frac{0.35}{BW}$$

More details are given in “EE221L Circuits II Laboratory #5: RC Circuits”. Please review this document for cases where rise-times of components are close to each other. Let’s assume a simple case for understanding. With the 150 MHz bandwidth the minimum rise-time that could pass through the transformer would be 2.3 ns. The lower 3 dB frequency determines how long a pulse duration could be faithfully passed through the transformer. At first glance it is tempting to just convert the lower 3 dB frequency to an equivalent period. In this case the 50 KHz lower 3 dB frequency corresponds to a 20 us period. A 50 KHz sine wave passing through this transformer would have its shape faithfully preserved but have a 3 dB attenuation and a 45 degree phase shift. However for a pulse the phase relationship between all the frequency components (think Fourier series) is important to preserve the pulse shape. A good rule of thumb is to limit the frequency of a square wave to 10 times the lower 3 dB frequency, in this case 500 KHz. This will ensure minimal phase shift. Additional analysis of pulse transformers is outside the scope of this lab.

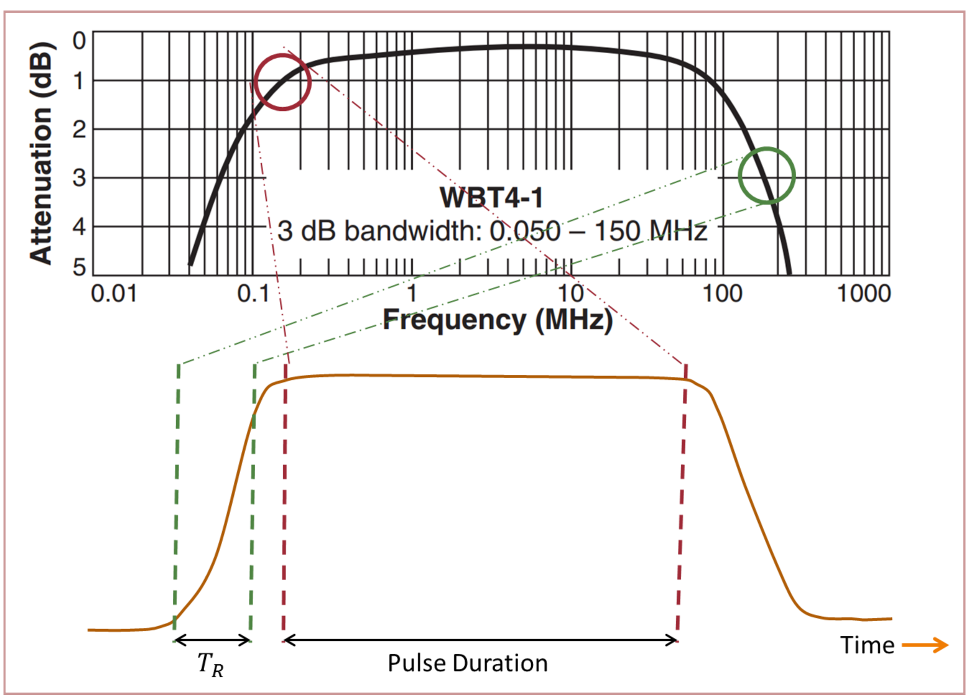


Figure 10. How frequency response translates to the time domain for a pulse.

Next, let's take a look at power transformers. We will analyze power transformers using the very simple model shown in Fig. 11. Most transformer models are more complex and include various capacitances and additional inductances. These are useful for very detailed analysis but can be daunting for the beginner. The model in Fig. 11 ignores negligible parasitics and distills the model to the most important parameters.

Two components are added to the ideal transformer; these are the resistance of the winding R_W, and the primary coil inductance, L_P. Recall that an ideal transformer has infinite inductances. This presents an infinite impedance to AC voltage sources and therefore an ideal transformer draws no current with no load on the secondary. However a real transformer does draw current due to the finite inductance and also has power losses due to the resistance. The no load current is given by

$$I_{NL} = \frac{V_P}{j\omega L_P}$$

The magnitude and frequency of the voltage applied to the primary winding are needed to calculate the no load current. The power loss is due to the resistance of the wire in the primary winding. This is given by

$$P_{loss} = I_{NL}^2 \cdot R_W$$

There are other losses in the transformer due to eddy currents and other magnetic phenomenon and these can be quite significant. For simplicity we will ignore them in this lab.

A power transformer is rated in terms of VA. This is the product of volts and amps. It is important to note that a *Volt-Ampere* is not a watt. For the DC case, VA is equal to watts. For AC, the phase angle between the voltage and current determine the real power (watts), reactive power (vars) and complex power (VA). If a purely resistive load is connected to the secondary of the transformer then the VA rating can be substituted with watts. For example a 10 VA transformer can power a 10 W load only if the load is purely resistive. If the load is purely capacitive, the transformer can supply a combination of voltage and current that is equal to 10 VA; 10V and 1A for example. Even though no power is dissipated by the capacitor, the transformer still has to generate the 10V and the 1A which uses the magnetic flux capacity of the transformer. A good analogy is peddling on an exercise bike. You aren't going anywhere and therefore no work is being done, but you still have to maintain the rotation of the wheels which uses up your physical ability.

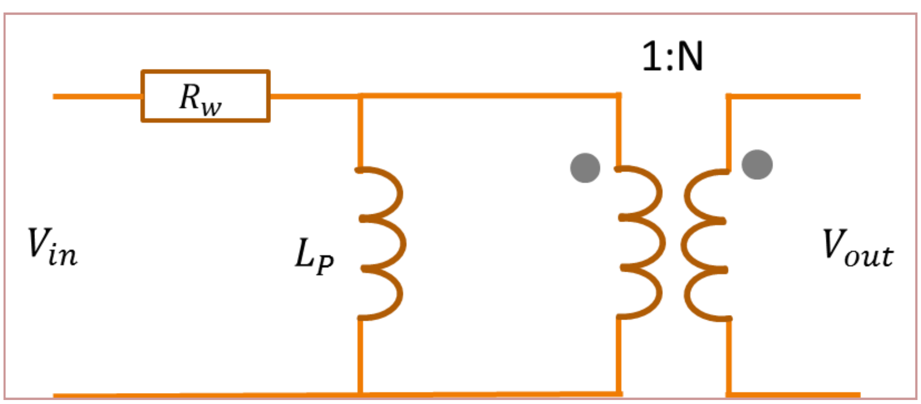


Figure 11. Simple model of power transformer to calculate losses.

A good way tool to visualize and calculate the real, reactive and apparent power is the power triangle. The power triangle is shown in Fig. 12. The length of the triangle is the real power; the height of the triangle is the reactive power and the hypotenuse is the apparent power. The triangle can be analyzed using the Pythagorean Theorem, and the apparent power is calculated by the equation,

$$S = \sqrt{P^2 + Q^2}$$

The real power is calculated with the equation,

$$P = \frac{1}{2} V_p I_p \cos\theta = V_{rms} I_{rms} \cos\theta$$

These quantities are measured at the load end of the transformer. The easiest way to measure this would be using an oscilloscope to look at the voltage and current waveforms and the phase relationship between them. Generally, the current waveform would be measured using a sampling resistor. This will be explained further in the lab. Finally, the power factor is given by,

$$PF = \cos\theta = \frac{P}{S}$$

The power factor is the ratio of real power to apparent power. If the power factor is 1, then the load is purely resistive. If the power factor is 0 then the load is purely reactive. From these equations the following relationships can be derived,

$$P = S\cos\theta$$

$$Q = S\sin\theta$$

All three parts of the power triangle can be calculated using measured values of the voltage and current and the angle between them.

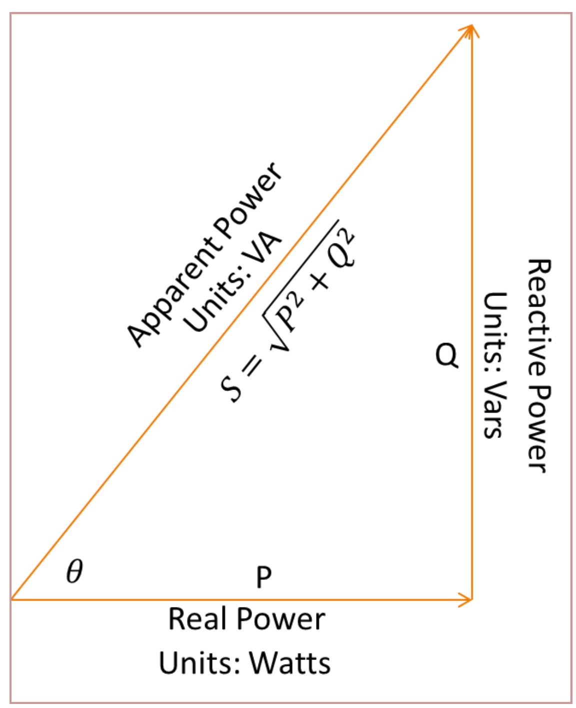


Figure 12. Power triangle and relationships between all variables.

It is important to have a grasp of phase before continuing any further. The phase used in the power triangle is the phase of the impedance. For a purely inductive load, the phase is positive because the voltage is leading by 90 degrees with respect to the current. For a purely capacitive load the phase is negative because the voltage is lagging the current by 90 degrees. This is illustrated in Fig. 13. Let's solve two examples to see how this works.

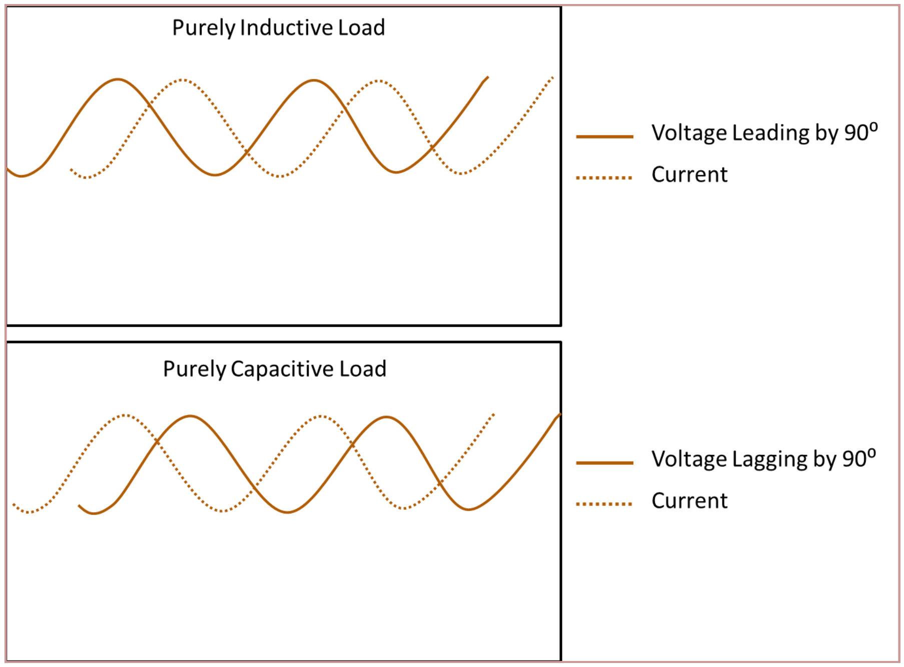


Figure 13. Phase relationships between voltage and current for reactive loads.

Suppose you measure the real power consumed in a circuit as 10 watts and you know that the load is a 5 ohm resistor connected in series with a 10 mH inductor. At 377 rad/s (60 Hz) the reactance of the inductor is j3.77 ohms. The total impedance is 5+j3.77. The resulting phase angle is 37 degrees. Using this angle and the measured real power, we can calculate the apparent power with,

$$\cos\theta = \frac{P}{S} \rightarrow \boldsymbol{S} = \frac{P}{\cos\theta} = \frac{10}{\cos(37^\circ)} = \frac{10}{0.8} = \mathbf{12.5\ VA}$$

The reactive power can be calculated with

$$\boldsymbol{Q} = S\sin\theta = 12.5\sin(37^\circ) = 12.5 \cdot 0.6 = \mathbf{7.5\ Vars}$$

Another example would be calculating all the power quantities when only the voltage, current and their phase angle is known. This could be a case where the actual load is not known. Suppose you measure the voltage at the load to be 10 V peak and the current at the load to be 20 mA peak. On the oscilloscope it appears that the voltage is lagging the current by 50 degrees, meaning that the phase angle is -50 degrees. First you should convert all the peak values to RMS resulting in 7.07 V RMS and 14.14 mA RMS. Multiplying these together gives us the apparent power of 0.1 VA. Knowing the phase angle of -50 degrees we can calculate P and Q as

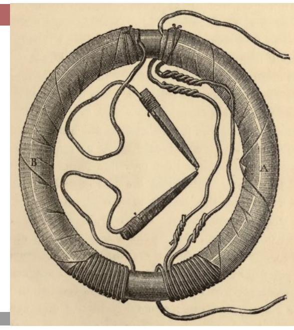
$$\boldsymbol{P} = S\cos\theta = 0.1\cos(-50^\circ) = 0.1 \cdot 0.64 = \mathbf{64\ mW}$$

$$\boldsymbol{Q} = S\sin\theta = 0.1 \cdot \sin(-50^\circ) = 0.1 \cdot -0.76 = \mathbf{-76\ mVars}$$

The result of negative Vars is noteworthy and means that the load is capacitive. This makes sense since the impedance phase angle is -50°.

Prelab Summary

You will simulate transformers in LTSpice using coupled inductors.



Prelab Tasks

Prelab #1: PCB and Netlist Required
Prelab #2: PCB or Netlist Not Required
Prelab #3: PCB or Netlist Not Required
Prelab #4: PCB or Netlist Not Required

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. For this prelab we will model a 120V to 24V transformer. First let's model an ideal transformer with just one primary and one secondary winding.
2. Simulate the schematic shown in Fig. 14. The inductor symbol with a dot is found by clicking on the "Select Component Symbol" button and selecting "ind2". The spice code "K1 L1 L2 1" tells LTSpice that there is coupling between the inductors L1 and L2. The value can be between 0 and 1, with 1 indicating perfect coupling. The values for the inductors are very high at 25H and 1H. These values are unrealistic but very high inductance values are needed to approximate an ideal transformer. The ratio of the inductances here is 25, the square root of which is 5, the voltage ratio of this transformer. The input voltage is 170 V because that is the peak value of 120 V RMS. You will have to add a small series resistance to the input voltage source because otherwise, LTSpice has issues calculating a solution. Note that both sides of the transformer are grounded. This is done because circuits can't be left floating in LTSpice. In practice you would not ground both sides of the transformer since this removes the isolation.
3. Verify that the output voltage is around 35V peak. **(Schematic, Plot)**

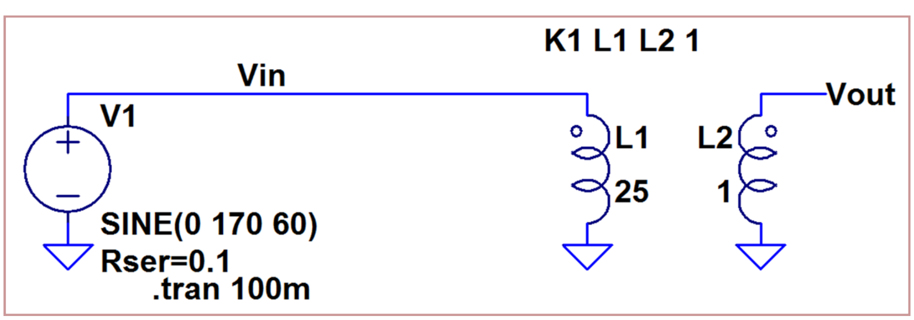


Figure 14. Coupled inductors in LTSpice.

Prelab #2

Follow the steps below. Deliverables are in bold.

1. Simulate the schematic shown in Fig. 15. The transformer has 4 inductors representing two identical primary coils and two identical secondary coils. The coupling statement has changed to reflect the coupling between all 4 coils. You must also add some series resistance to each coil. Right click on each inductor and add a series resistance of 0.01 ohm as shown in Fig. 16. LTSpice doesn't like two ideal inductors connected directly in parallel.
2. The transformer circuit shown in Fig. 15 has the primary coils connected in series and the secondary coils connected in parallel. If you drew the circuit correctly then the output voltage will be 17V peak.
3. An example with primary coils in series and secondary coils connected in a center-tapped configuration is shown in Fig. 17. The outputs from this are shown in Fig. 18 and are 17V and -17V.
4. Simulate the following transformer configurations: series-primary with parallel-secondary; parallel-primary with parallel-secondary; series-primary with series- secondary; parallel-primary with series-secondary; parallel-primary with center-tapped secondary; and series-primary with center-tapped secondary. There are a total of 6 configurations. Make a table listing the input and output voltages of each configuration. **(Schematic of each configuration, Table)**

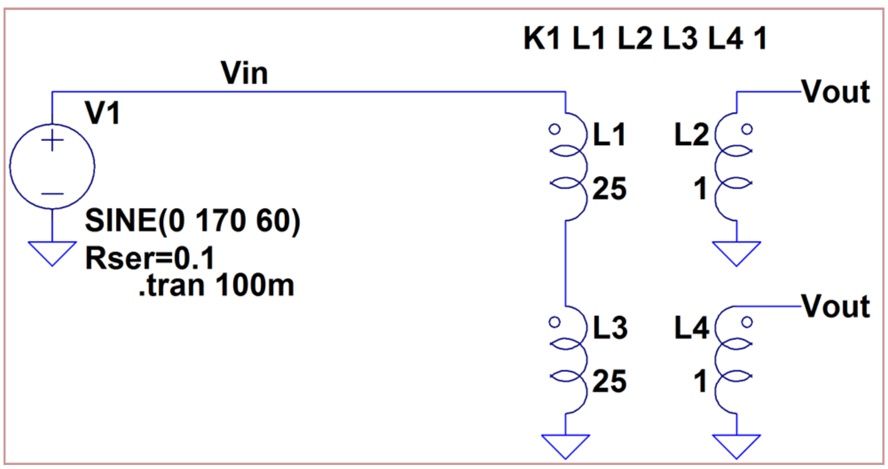


Figure 15. Series primary windings and parallel secondary windings.

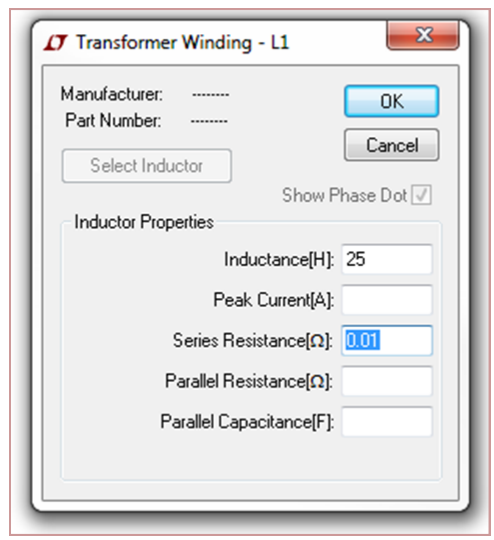


Figure 16. Adding series resistance.

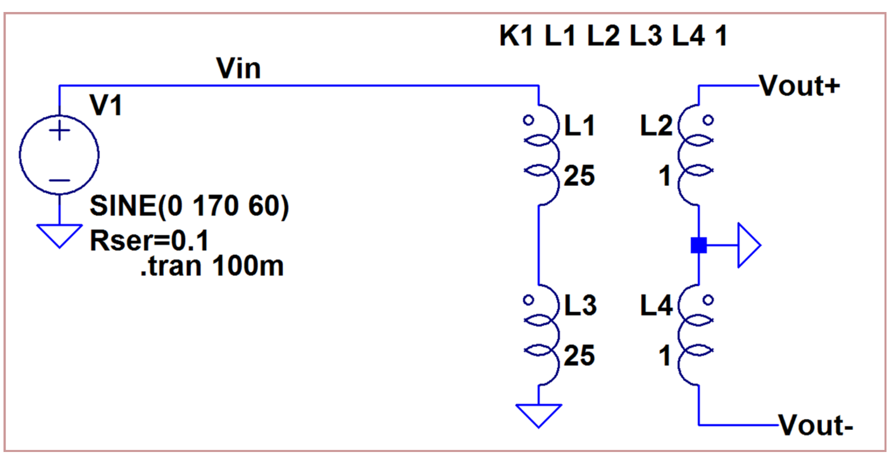


Figure 17. Center-tapped secondary.

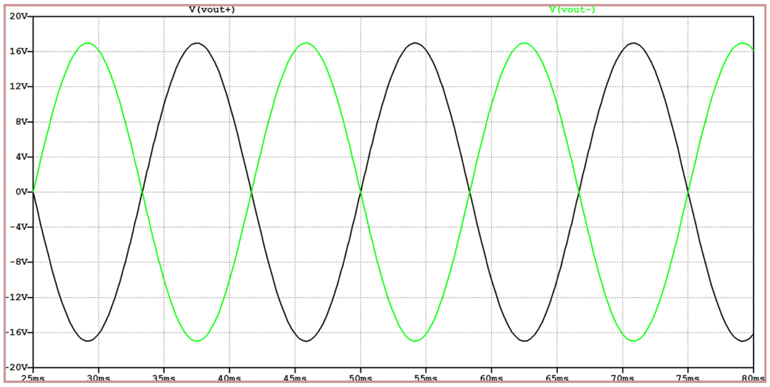


Figure 18. Outputs from center-tapped secondary.

Prelab #3

Follow the steps below. Deliverables are in bold.

1. Simulate the schematic shown in Fig. 19. Plot the output voltage and the current flowing through R1. Estimate the phase angle between these two waveforms. Use the phase angle and the RMS values of the voltage and current to calculate the real power, reactive power and apparent power. **(Output Plot, Hand Calcs)**

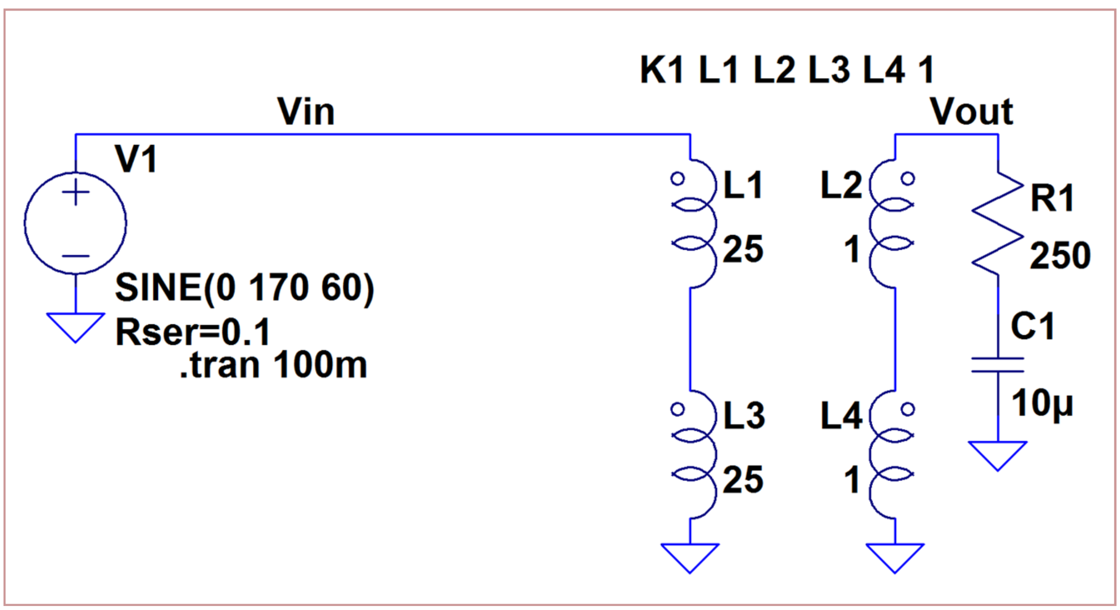


Figure 19. Adding a complex load to the transformer.

Prelab #4

Follow the steps below. Deliverables are in bold.

1. Simulate the schematic shown in Fig. 20. This represents a very simple model of the pulse transformer we will be using in the lab. The small values of the inductors result in a roll-off at low frequencies. What is the -3dB frequency? This is defined from whatever the voltage gain of the transformer is. If the flat portion of the frequency response is at 4 dB, the -3dB frequency will be found at the frequency where the amplitude is 1 dB. This simple model provides a value that is quite off from the measured value on the datasheet but it provides an intuitive understanding of how the inductance of the coils affects the lower frequency limit. **(Plot, Answer)**

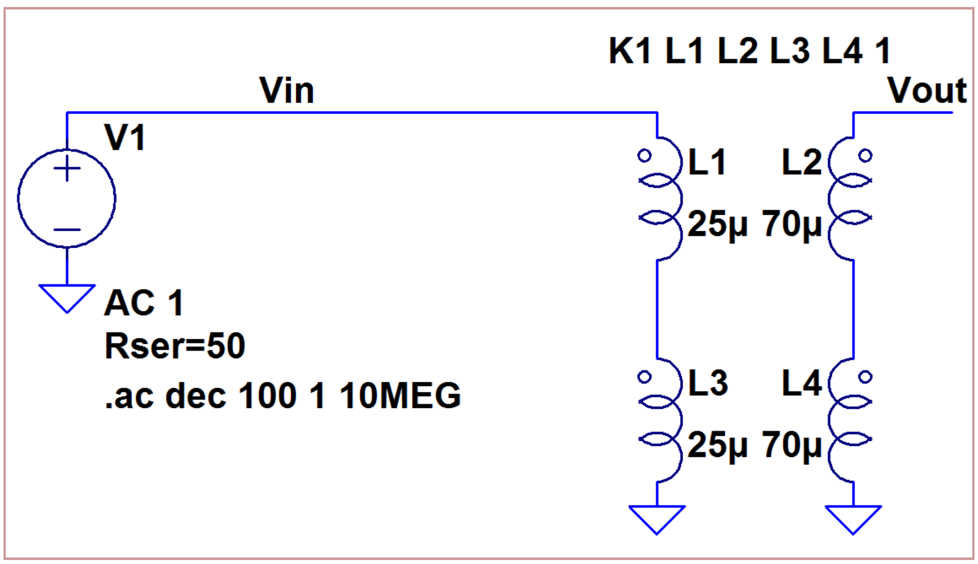


Figure 20. Modeling the frequency response of a pulse transformer.

Required Materials and Equipment

1. Function Generator
2. Multimeter
3. Resistors and Wire
4. Power and Pulse Transformers
5. Banana Jack Cables
6. Scope Probes
7. Oscilloscope

Postlab Tasks

Task 1: Rise-time adjustment
Task 2: RC Low-pass
Task 3: 555 Timer
Task 4: Differentiator

Measuring Equipment Basics

In this lab we will be using differential measurements. A differential measurement is one that takes the difference in levels between two inputs. The inputs of a multimeter are generally differential. This is why you can measure voltages with a battery powered multimeter that has no ground reference to the circuit being measured. It simply subtracts the voltages between the positive and negative terminals to give the voltage difference. A normal single-ended measurement is done with reference to ground. For some circuits connecting a ground probe will disturb the circuit. Most transformer measurements need to be differential to maintain isolation.

Let's consider a basic example. The current flowing through a resistor can be calculated by measuring the voltage across the resistor and knowing its resistance. If one end of the resistor is grounded and the other is connected elsewhere, the correct measurement can be obtained by connecting a scope probe to the ungrounded terminal and the ground clip the circuit ground. However if neither end is grounded, connecting the scope probe and the ground clip across the terminals of the resistor will not give a proper measurement value. This is because all the current from the resistor will shunt to ground instead of flowing through the rest of the circuit downstream of the resistor. The solution to this is to use two scope probes. The ground leads need to be clipped together and nothing else. One probe will be the positive input and the other probe will be the negative input. This is determined by the math menu in the oscilloscope. You may need to refer to the user manual for your specific oscilloscope. If the math function is set up to be channel 1 minus channel 2, then channel 1 is the positive input and channel 2 is the negative input.

You must use differential measurements for three common cases. The first case as described above is when a voltage needs to be measured and one side of the device is not grounded. The second case is when isolation between two sides need to be maintained (as with transformers). The third case is for differential output electronics. A good example of this is a high powered bridged audio amplifier. If you connect a single-ended probe to the output of a bridged amplifier, the output will be short circuited and a high current will flow through the ground clip. In some cases this can melt the insulation and even weld the ground clip to the circuit! When in doubt, always use a differential measurement. Finally, there are dedicated differential probes available but these can be quite costly.

Postlab #1: Step-Down Transformer

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

1. Set the function generator to output the maximum amplitude of 5V at a frequency of 60 Hz. Make absolutely sure that the DC offset is set to 0, otherwise the transformer could be destroyed. Connect the output from the function generator to a primary coil of the power transformer. A schematic diagram of the transformer used in the lab is shown in Fig. 21. Connect the scope probe tip and ground lead across one of the secondary coils of the power transformer. Verify the transformer works by noting that the output is approximately 1/5th of the input since this is a 5:1 step-down transformer. **(Photo)**

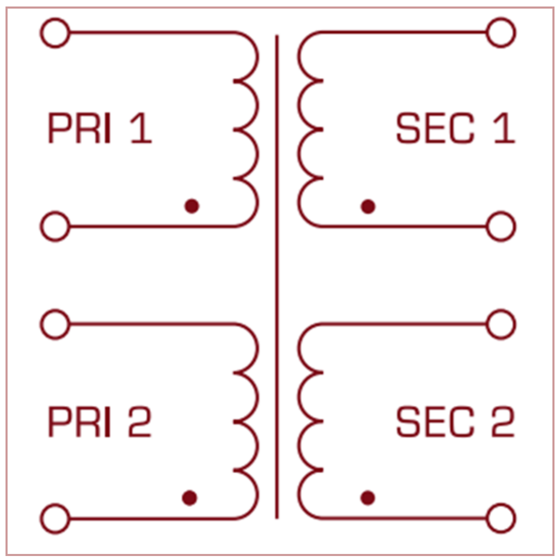


Figure 21. Schematic diagram of the power transformer.

Postlab #2: Primary Coil Current

Follow the steps below. Deliverables are in bold.

1. Next we are going to do some clever measurement techniques so pay close attention to what you are doing. Our goal will be to characterize the primary inductance, winding resistance and power loss. Normally, this transformer would be connected to the power outlet but we can't do that in this lab for safety purposes. Instead we will use the function generator to best simulate the power line.
2. The function generator can only output 5V peak amplitude. But since our function generator has two channels we can combine the outputs to create 10V peak amplitude. Connect a BNC to alligator cable to each of the two outputs of the function generator. Then clip the two black leads together as shown in Fig. 22. This is known as a differential configuration. Next set-up the function generator as shown in Fig. 23. Set the function generator to its maximum possible amplitude which is 20V p-p as shown when in high Z mode. If yours is set to 50 ohm mode, the amplitude will be exactly the same but it will be displayed as 10V p-p. You may want to change the setting to be consistent. Next, set the frequency to a 60 Hz sine wave and set channel 2 to have a phase of 180 degrees. When these two signals combine in the differential configuration, they will add and result in double the amplitude of 40V p-p.
3. For convenience measure the resistance of the primary coil of the transformer first. This way you don't need to dismantle your circuit just to measure the resistance. Write down this resistance. We will be connecting the primary coils in parallel, so halve the value of this resistance for calculations. **(Value)**

Figure 22. Differential output configuration.

Figure 23. Function generator set-up.

4. Connect the two primary coil windings in parallel on the breadboard. The schematic diagram of the transformer is shown in Fig. 21. The primary windings are labeled "0-115V" Be sure to observe correct polarity and connect the terminals labeled "0" together and the terminals labeled "115V" together. Connect the two red clips to the parallel windings.
5. Set up two oscilloscope probes to be differential as shown in Fig. 24. The ground leads are clipped together. Set the coupling to AC and enable both channels 1 and 2. Adjust the controls until your screen looks like Fig. 25. The two waveforms are in opposite polarity. Add measurements for peak to peak and RMS. Refer to the manual if you need to know how to do this. Next, hit the math button on the oscilloscope and set up "dual waveform math" to subtract the channels. A red trace, the difference between channel 1 and 2 appears as shown in Fig. 26. In the figure the trace was not set-up correctly as there was an offset and the vertical scale is not the same as the channels. Make any corrections if needed. Your screen should look like that shown in Fig. 27. Note that the red trace is twice the amplitude of a single channel. **(Photo)**

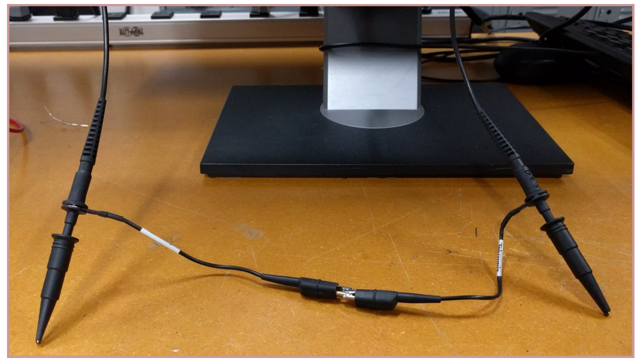


Figure 24. Differential output configuration.

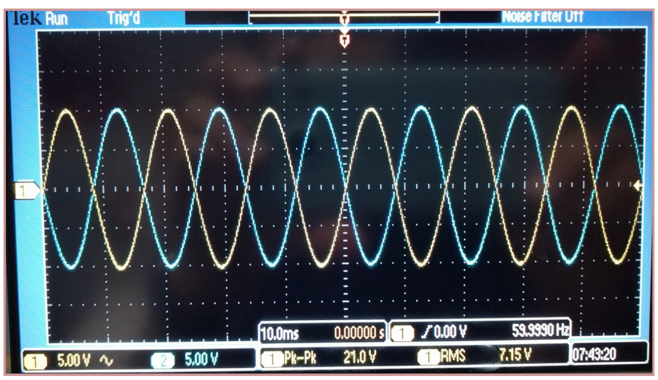


Figure 25. Channels 1 and 2 before differential math function.

Figure 26. Adding math function and measurements.

Figure 27. Your screen should look like this.

6. Now we will measure the no-load input current flowing into the transformer. Add a resistor in series with one side of the paralleled primary windings as shown in Fig. 28. This resistor is called a sampling resistor and the voltage drop across it is used to calculate the current flowing through it. Ideally this resistor should be as small as possible so as not to disturb the circuit. However in this application the current is quite small and a larger resistor around 50-100 ohms is needed to see the voltage clearly. This should be quite small compared to the primary impedance and should not affect accuracy too much. The waveform will be very noisy and you should use averaging to smooth it out. This is found in the “Acquire” menu. Refer to the user manual if you need more instructions. If you did the measurement correctly, then you’ll get a waveform like that shown in Fig. 29. The reason the current isn’t perfectly sinusoidal is because of the nonlinear magnetic materials in the transformer. Calculate the current flowing into the primary. Using the voltage applied across the primary and the winding resistance calculate the power dissipated in the transformer. **(Photo, calculations of current and power)**
7. Next, we will measure the input current using the multimeter because it is more accurate than our oscilloscope. Simply connect the multimeter in series with the function generator and the primary of the transformer. Replace the resistor in Fig. 28 and put the multimeter in series in AC current mode. Measure the current, and use that to calculate the power dissipation. How do your values differ from the previous step? **(Measured current, calculations of power)**

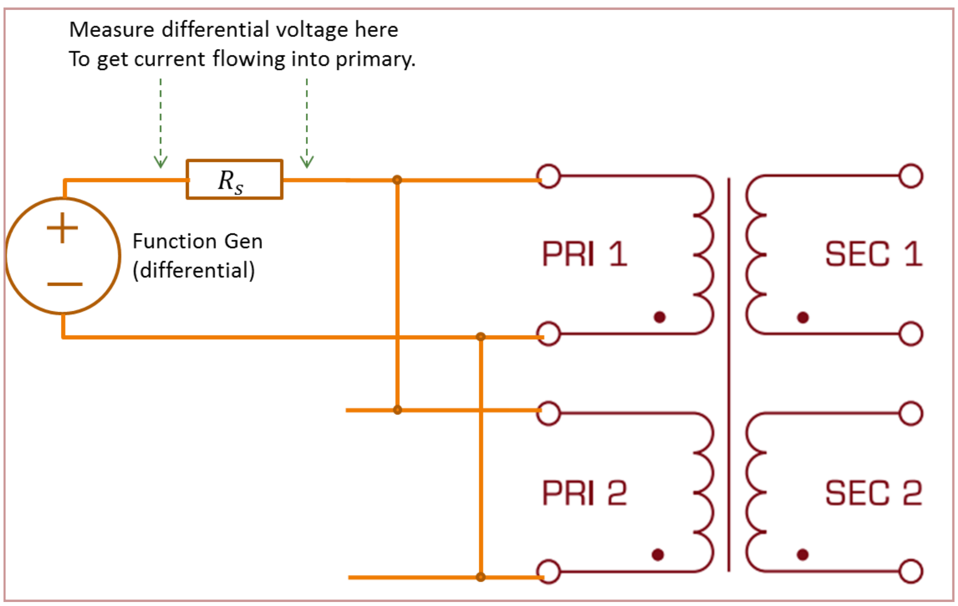


Figure 28. Measuring primary current.

Figure 29. Primary current waveform.

Postlab #3: Power Factor

Follow the steps below. Deliverables are in bold.

1. Set-up your circuit as shown in Fig. 30. In this set-up, the function generator is wired to be differential as the previous experiment. The two primary coils are in series this time so you'll need to rewire it. The secondary coils are also in series. The load is represented by the 250 ohm resistor and 10 uF capacitor. The resistor at the bottom is the sampling resistor that we will be using to measure the current through the circuit. The smaller the value of this resistor the better. 10 ohms is a good starting point but if the measurement is too noisy then you may have to increase the value. **(Picture of circuit)**

2. The secondary side is grounded. When you clip the scope probe ground leads to this point it will reference the secondary side to earth ground. You can also connect a wire through your breadboard into a banana jack that connects to the green earth ground connection on a power supply.

3. Connect scope probes to the points indicated on the schematic and display the waveforms on the screen. Scale the vertical divisions until the waveforms are close to each other in size as shown in Fig. 31. **(Picture of waveforms)**

4. Measure the RMS amplitudes of both waveforms, and the phase between the waveforms. This can be done either manually, by visually measuring the peak waveform and then converting to RMS or using the measurements function on the oscilloscope. The measurements are shown on the screen in Fig. 32. Please note that the RMS value for the voltage across the sampling resistor was mistakenly left out. Be sure to have both RMS voltage values so that you can do proper calculations. The phase measurement may fluctuate a lot due to the fact that the voltage across the current sense resistor is very small and is hard for the oscilloscope to measure. Turn on averaging from the acquire menu to reduce the noise and stabilize the phase measurement as shown in Fig. 32. The phase should be measured between the probe connected to the top of the load and the probe connected to the top of the sampling resistor. This will give the phase of the voltage minus the phase of the current flowing through the load. Remember, the voltage developed across the sampling resistor is proportional to the current ($I_s=V_s/R_s$), and this voltage is also in phase with the current through the load. Be sure to divide the voltage across the sampling resistor by the value of the resistor to get the current. **(Measurements)**

5. Next, draw the power triangle representing this load. To do this you need the measured voltage across the load; the measured current through the load; and the phase angle between voltage and current. Use the equations on page 11 and this should be straightforward. **(Calculations)**

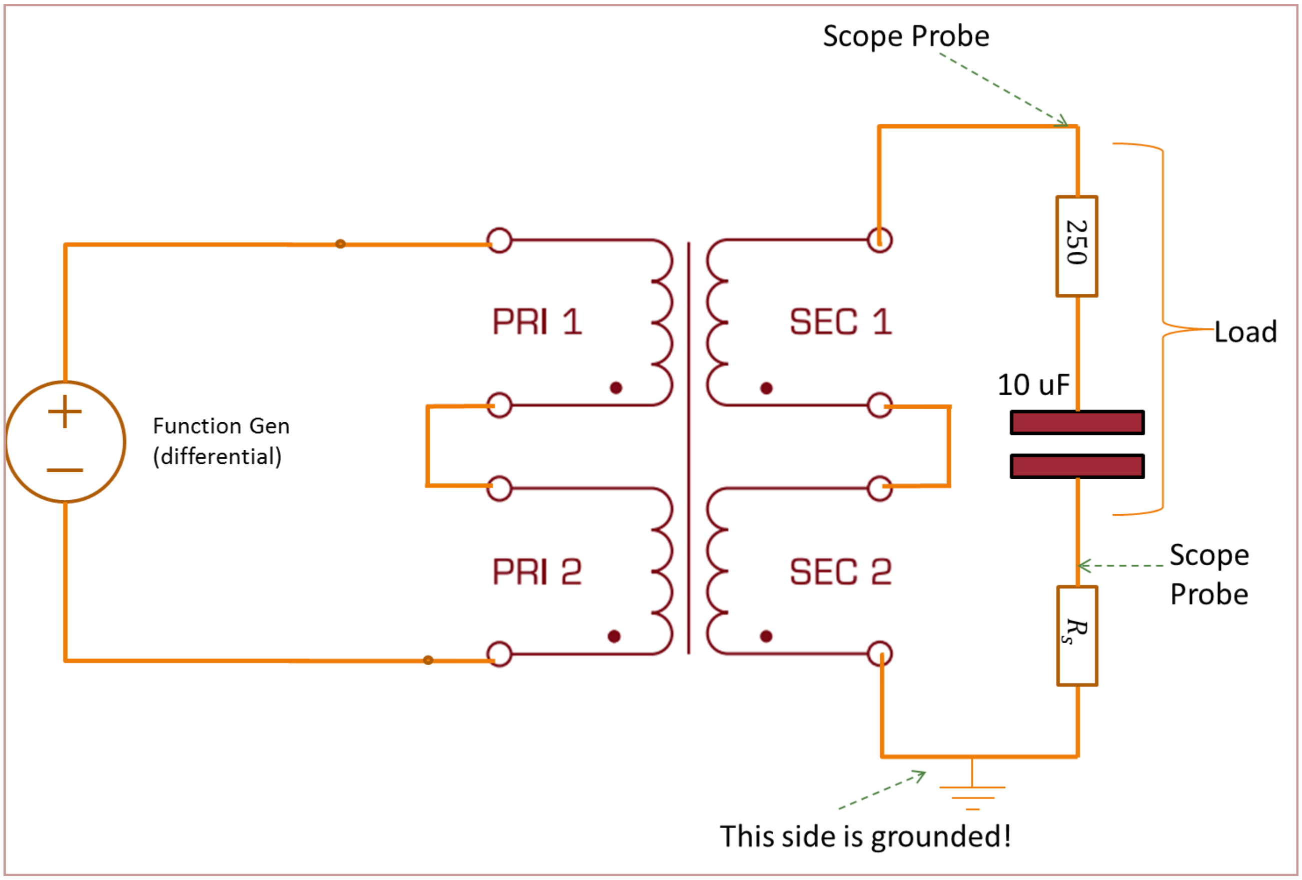


Figure 30. Set-up for post-lab #3.

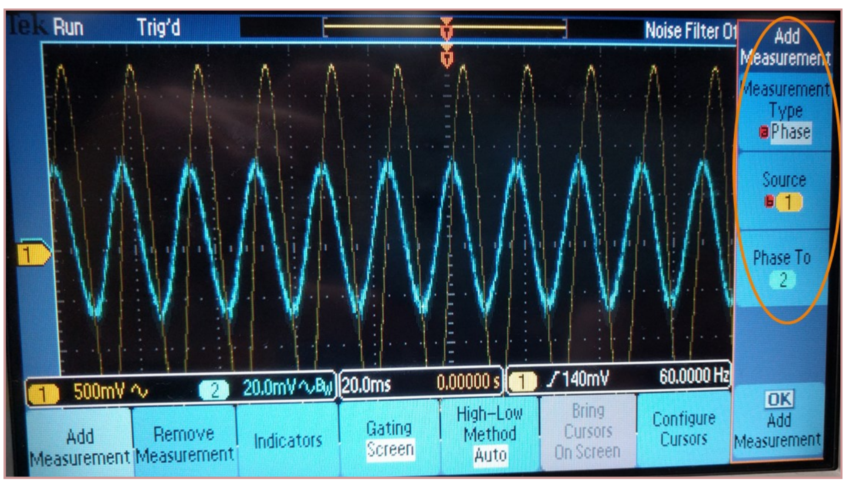


Figure 31. Adding a phase measurement.

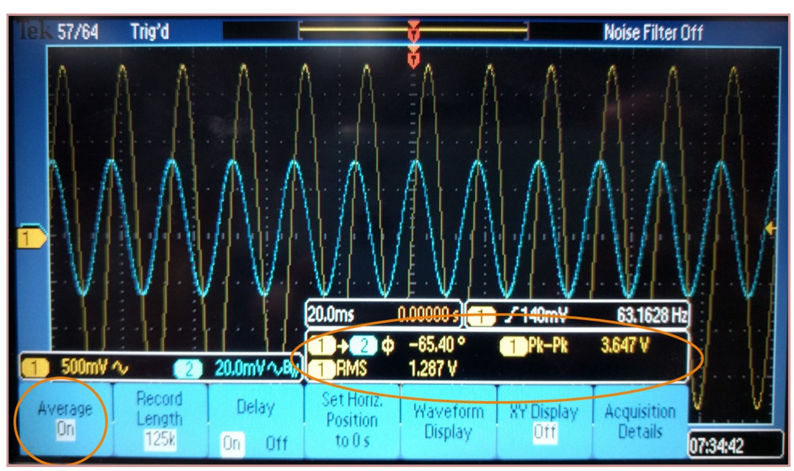


Figure 32. Adding averaging to reduce noise.

Postlab #4: Pulse Transformer

Follow the steps below. Deliverables are in bold.

1. In this experiment we will be doing two things. The first will be to use the center-tap to create two waveforms of opposite polarity. The second will be to measure the low frequency limit of the pulse transformer.

2. Connect the pulse transformer as shown below in Fig. 33. This transformer is a Coilcraft WBT4-1L. This is a 1:3 pulse transformer with center taps on both sides. The frequency response is specified as 40 KHz to 150 MHz. The pin numbers are from the datasheet and the dot on the transformer's DIP-6 package indicates pin 1. Connect only one channel of the function generator to the primary side. Be sure the output is off before connecting to the transformer. Set the DC offset to be 0. Since transformers don't pass DC, any offset will just cause the transformer to heat up. Connect a scope probe to each side of the secondary and connect their ground clips together to the center tap on the secondary side. On your breadboard, be sure to use the shortest possible connections. Ideally, use 1 inch wires to make the connections. Clip the function generator leads and scope probe as close to the transformer as possible. This is because the inductance of the wires will cause significant ringing.

3. Set the function generator to output a 10 Vpp sine wave at 1 MHz with a DC offset of 0V. Only one scope probe is needed for now. Look at the waveform on the scope, this amplitude is the baseline for our measurements. Next begin reducing the frequency until the amplitude drops to roughly 70% of the baseline value. The frequency that this occurs at is the lower –3dB frequency. **(Picture, Measurement)**

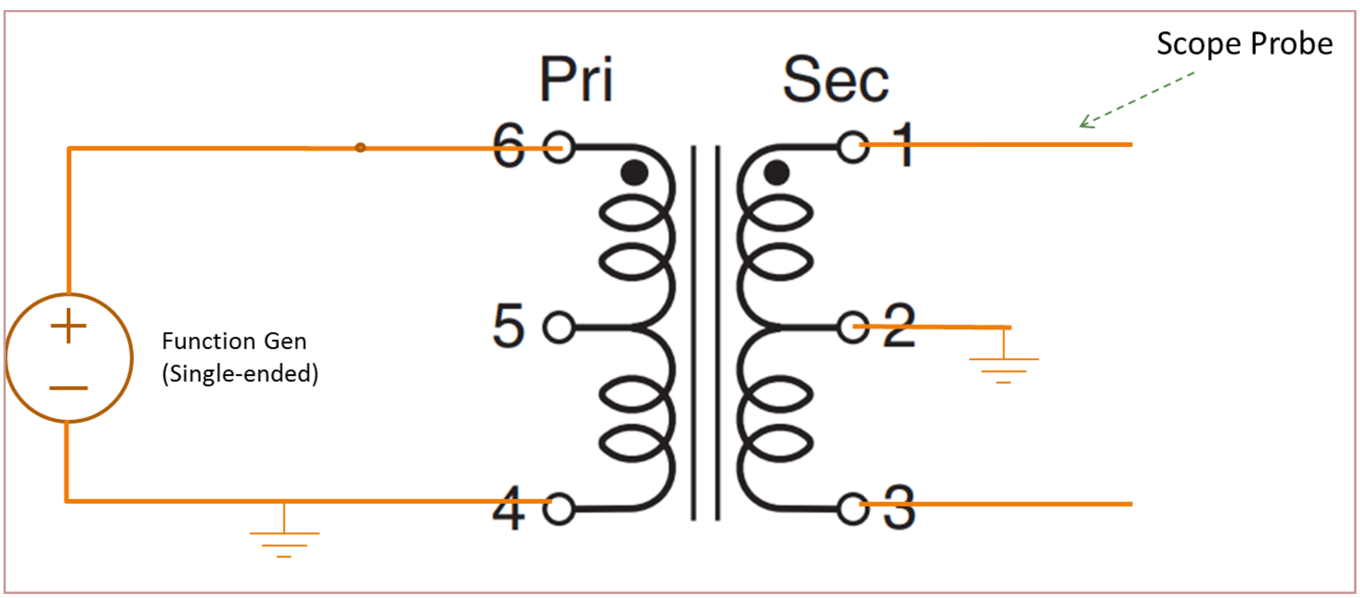


Figure 33. Set-up for post-lab #4. Pin numbers are from the datasheet.

4. Next, we will use the transformer to create two opposite (differential) signals. Add two scope probes to the circuit as shown in Fig. 34. Set up the function generator to output a 10 Vpp square wave with a frequency around 3-5 MHz. This is quite high and the edges are rounded due to the rise time of the function generator. The function generator screen is shown in Fig. 35.

5. The oscilloscope screen has a lot going on in Fig. 36 and needs to be carefully explained. Three probes are used and connected as shown in Fig. 34. Trace #3 is the scope probe connected on the primary side. Trace #1 and #2 are connected on the secondary side. Notice that it's hard to see trace #1 because trace #3 is directly on top of it. The red trace, is the math channel. You need to set up the math function for trace #1 minus trace #2 to get the red trace. This is the combined differential signal. Finally, set up peak-to-peak measurements on all the channels including the math channel. If you did this correctly, the screen will appear similar to Fig. 36. **(Picture and measurements)**

6. You may be confused by the amplitudes. This is a 1:3 transformer meaning that our red trace should be 3 times the purple trace, but the measurements show that it is only 2 times the amplitude. This is due to the "insertion loss" of the transformer which turns out to be 0.5 dB which is around 1. So our final ratio ends up being 3-1=2.

7. Next, we will examine pulse drooping. At lower frequencies, the flat portion of the pulse begins to droop. Figure 38 shows pulse drooping at a frequency of 1 MHz. Here the droop is about 25% from the amplitude at the start of the pulse.

8. Find the frequency at which the pulse droop is 50%. Don't use the measurements on the scope. Rather, visually verify the frequency at which the tail end of the pulse is 50 % of the initial amplitude. Ignore any ringing or overshoot at the beginning of the pulse. In Fig. 38 there is some overshoot visible and the initial amplitude was determined as the point right after the overshoot. **(Picture and measurements)**

9. Notice that this frequency is quite higher than the lower –3dB corner. Try a square wave with the measured lower corner frequency from earlier. Note that the waveform is significantly distorted. **(Picture)**

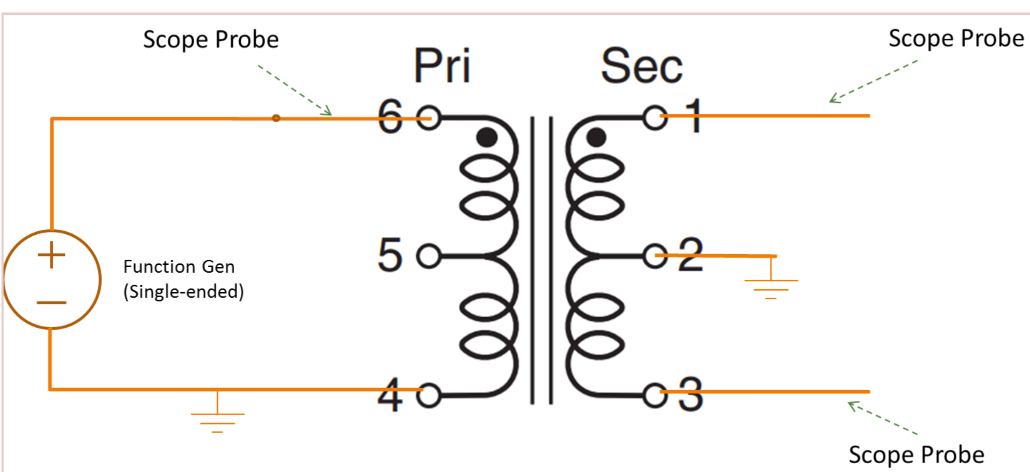


Figure 34. Set-up for post-lab #4 with 3 total scope probes.

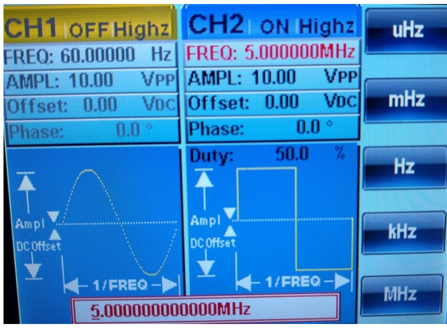


Figure 35. Function gen set-up .

Figure 36. Oscilloscope set-up. See text for all the details.

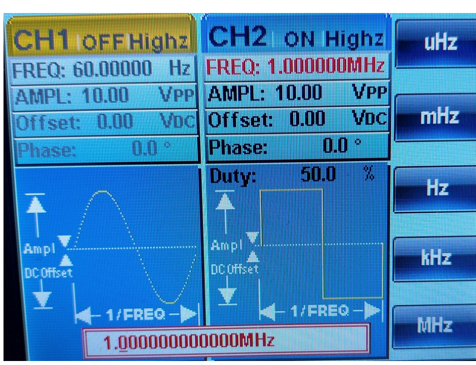


Figure 37. Function gen set-up .

Figure 37. Pulse droop.