

Intro to Power Lab Concepts

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TCIPG PMU Research Group¹*

Table of Contents

1. PRE-LAB	
DC Power-----	2-4
AC Power-----	4-5
RLC Circuits/Phasors-----	6-13
2. EQUIPMENT LIST-----	14
3. PROCEDURE-----	15-17
Resistor Only Circuit	
RC Circuit	
RL Circuit	
RLC Circuit	
4. LAB SETUP HELP-----	18-20
5. OSCILLOSCOPE HELP-----	21
6. POWER FLOW DEMO-----	22-31

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1. PRE-LAB:

Objective: This lab has been created so you can understand the fundamentals necessary for the use of the power lab.

By the end of this lab, you will:

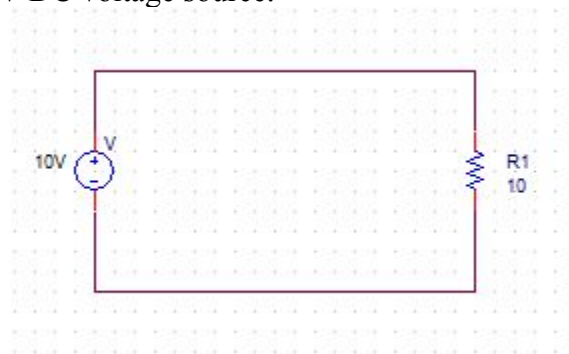
1. Understand what RMS is.
2. Know how capacitors and inductors affect phase difference between voltage and current.
3. Understand how phase difference affects power factor.
4. Differentiate between leading and lagging voltage based on power factor.
5. Know how to take Voltage, Current, and Power measurements using the multimeter, oscilloscope, and power meter.

This pre-lab will review and introduce you the basic knowledge to conduct the lab in this order:

- A. DC Power
 - B. AC Power
 - C. RLC Circuits/Phasors
-

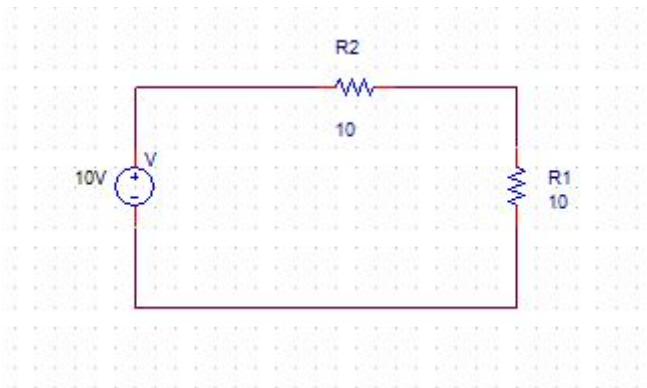
A. DC Power

Shown below is a basic circuit with a DC (direct current) source and a resistor. We have a 10Ω resistor connected to a 10V DC voltage source.



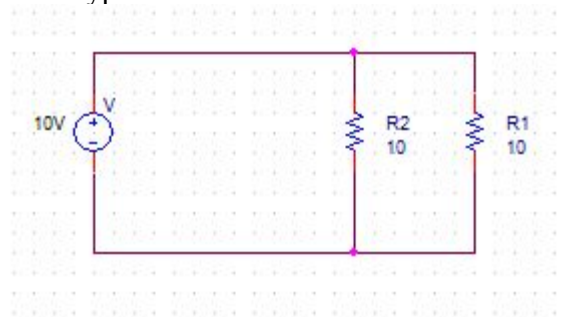
To find the current across the resistor, we use Ohm's Law: $V=IR$. We have a 10V voltage source and a 10Ω resistor, so our current in our diagram is 1A. This current is flowing from the positive end of the voltage source to the negative end of the voltage source around the circuit, or in our case clockwise around the circuit. If you recall this from your introductory physics classes, this should be just a review. Now, to find the power that is consumed by this resistor, we use the power equation $P=VI$. Since our current is 1A and our voltage across the terminal is 10V, our power is 10W.

Next, observe the circuit below.



We have two resistors in **series** with each other. Components are in series when the negative end of one component is connected to the positive end of another. When two resistors are in series with each other, we can simply add the resistance together to form one equivalent resistor so that **$R_{\text{series}} = R_1 + R_2 + \dots + R_n$** . In our case, since each resistor is 10Ω , we can see that the equivalent resistance is 20Ω . When we solve for current across both resistors, we use the equivalent resistance; thus, our current is $I = V/R = 10/20 = 0.5\text{A}$. Furthermore, the power dissipated totally by both resistors is 5W .

Moving on, below is a different type of connection.



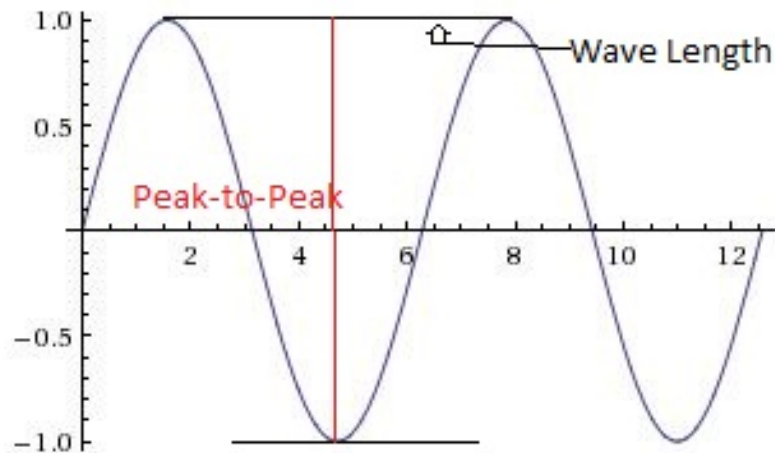
This type of connection is called a **parallel** connection. Components are in parallel when the positive ends of the components are connected together and the negative ends of the components are connected together. When resistors are connected in parallel, the equivalent resistance can be found this way: **$1/R_{\text{parallel}} = 1/R_1 + 1/R_2 + \dots + 1/R_n$** . We use this equation, and we get the equivalent resistance as 5Ω . Thus, our current here is $10/5 = 2\text{A}$. Consequently, our total power is 20W .

Now that we know how to take resistors in series and parallel and form an equivalent resistor, we can do similar things for inductors as well. Inductors, usually denoted as L in the honor of Lenz, can be added the same exact way as resistors: **$L_{\text{series}} = L_1 + L_2 + \dots + L_n$** and **$1/L_{\text{parallel}} = 1/L_1 + 1/L_2 + \dots + 1/L_n$** . However, capacitors, noted as C in circuits, are added in the opposite way as it in resistors and inductors: **$1/C_{\text{series}} = 1/C_1 + 1/C_2 + \dots + 1/C_n$** and **$C_{\text{parallel}} = C_1 + C_2 + \dots + C_n$** . Do not worry about the current and power across these two yet.

B. AC Power

Since we discussed DC sources, we will now discuss AC (Alternating Current) sources. AC sources are sources that often use sine waves or square waves with a set amplitude. The general form of AC sources, whether it be voltage or current, is $\sin(\omega t)$ where $\omega = 2\pi f$ angular frequency.

Look at the graph below.

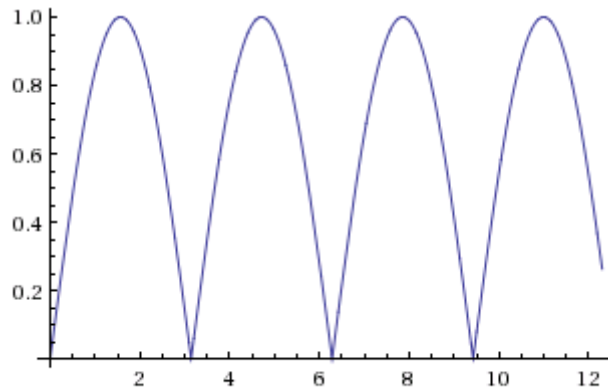


Here is a sine wave with amplitude 1 and angular frequency (ω) is 1. The equation for this is $\sin(t)$. Let us say this is the equation for an AC voltage source $V(t) = \sin(t)V$. The amplitude of this voltage, as stated above, is 1. This means that the voltage ranges from -1V to 1V from time to time. In other words, if we were to simply measure the voltage from the source, we will get a time varying value. If we take the amplitude of this function and double it, we get a type of reading called **Peak-to-Peak**. However, more commonly used is what we call a **RMS** (Root Mean Square) reading. The general way to solve for RMS is shown below.

$$f_{\text{rms}} = \lim_{T \rightarrow \infty} \sqrt{\frac{1}{T} \int_0^T [f(t)]^2 dt},$$

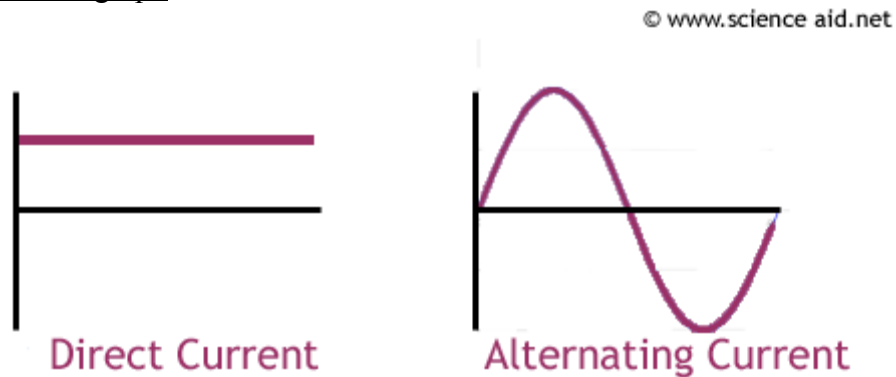
In sine waves, **RMS = Peak-to-Peak / ($2\sqrt{2}$) = Amplitude / ($\sqrt{2}$)**.

Essentially, this is what RMS does in graphical form. We take the graph from above, take the absolute value of it, as shown below, and take the time average of it.



So, what is the purpose of using RMS? Well, RMS eliminates the time factor involved in AC. There is a difference between average and RMS. If you look at the graph previously referenced, the time average voltage would be zero. As a matter of fact, any sine wave without a DC offset would have a time average of zero. For example, if we take the RMS of $V(t)=\sin(t)V$, we get $1/\sqrt{2}$

Summary DC vs AC graph



C. RLC Circuits (R-resistance, L-inductance, C-capacitance)/Phasors

First, we will introduce three very important notions:

1. **POWER FACTOR(PF)** is defined as the cosine of the angle between current and voltage.

$$PF = \cos(\theta) \text{ where } \theta = \theta_v - \theta_i$$

If the current is leading the voltage, our power meter will denote it as negative.

If the current is lagging, our power meter will denote it as positive.

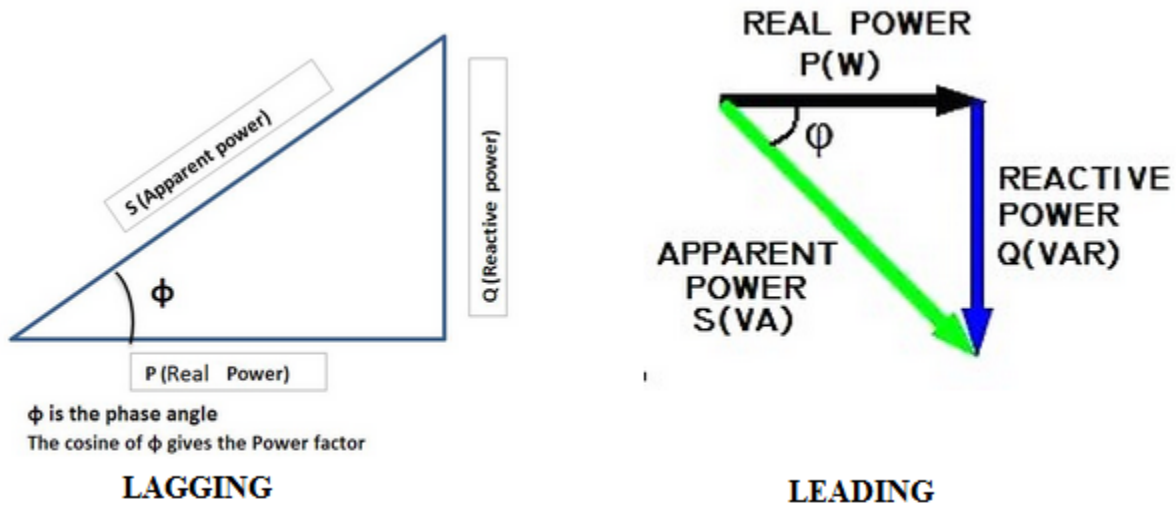
2. **REAL POWER(P)**

$$P = V_{rms} * I_{rms} * PF [W]$$

This is the general power formula. $P=V \cdot I$ for DC circuits is a particular case of the general power formula because $V_{rms}=V$ and $I_{rms}=I$ for constant values of voltage and current. Also, PF(in DC) is 1, therefore $P=VI$ for DC circuits.

3. POWER TRIANGLE

Using P and PF , we can create power triangles as follows:

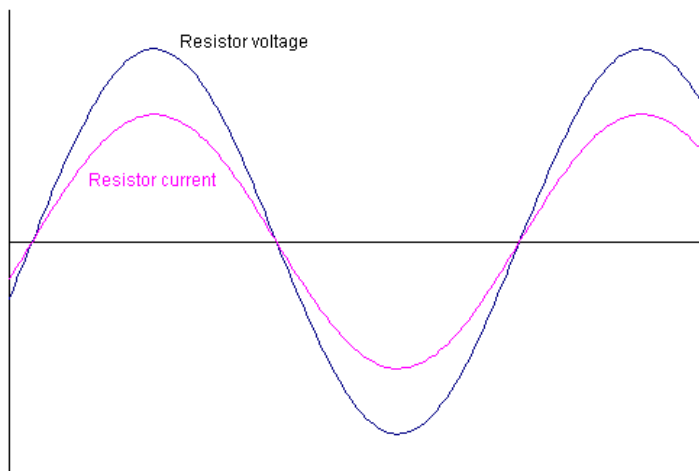
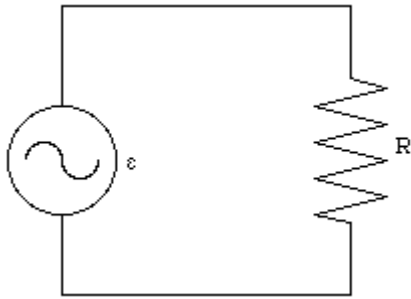


The top triangle shows a lagging power factor, while the triangle on the left is drawn for a leading power factor, by definition.

These triangles will show up in RL and RC circuits because capacitors and inductors provide reactive power. Resistor only circuits do not have reactive power, but these will be further investigated in the different cases below:

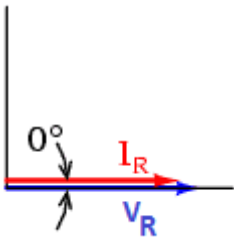
- **Resistor only**

The following circuit consists of an AC voltage source connected across a single resistor:



Note that the current and voltage in the capacitor are in phase, meaning that their peaks occur at the same time. The only difference is in their amplitudes: current amplitude is smaller by a factor of R . Also, since $I=V/R$, as the resistance increases, the amplitude of current decreases.

In phasor notation, the current and voltage are drawn as follows:



This simply shows that the current and voltage are in phase (0° apart) with phasor magnitude representing the amplitude.

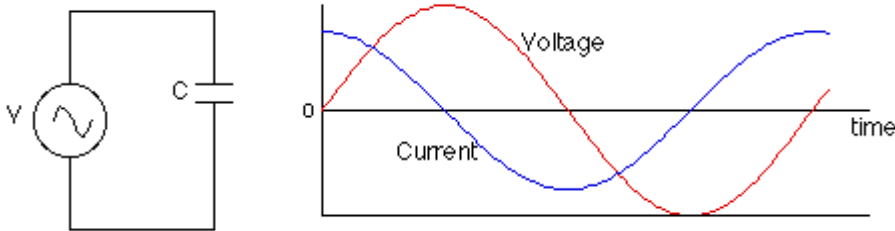
In this case: $\theta = 0^\circ$ therefore $PF = \cos(0) = 1 \Rightarrow$

$P = V_{rms} \cdot I_{rms}$ [W]

Also, since $\theta = 0^\circ$, the power triangle will only consist of a horizontal line representing Real Power. Resistors DO NOT have Reactive Power.

- **Capacitor only**

What happens when an alternating current is applied to a capacitor? Capacitor takes time to charge, and discharge. Because of this, there is a phase shift between current and voltage. More precisely, the current **leads** the voltage by 90 degrees (1/4 cycle).



One important property of a capacitor is its reactance, with the formula given below as it depends on the value of the capacitor in farads as well as the frequency of the AC waveform:

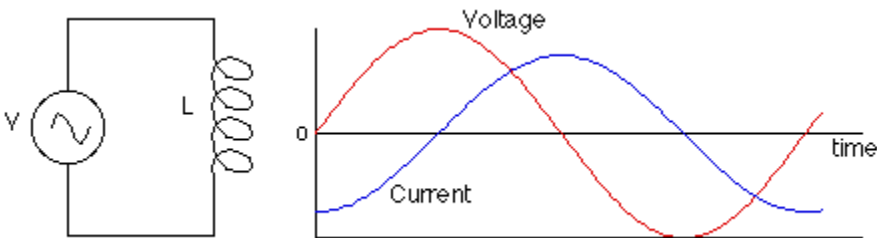
$$X_c = -1/(2\pi fC) = -1/(\omega C)$$

Reactance is given by the symbol X and is also measured in ohms. The larger the capacitance C, the more charge has to flow to build up a particular voltage on the plates, and the higher the current will be. The higher the frequency of the voltage, the shorter the time available to change the voltage, so the larger the current has to be. The current, then, increases as the capacitance and the frequency increase.

In this case: $\theta = -90^\circ$ therefore $PF = \cos(-90) = 0 \Rightarrow P = 0 \text{ [W]}$
 Since $\theta = -90^\circ$, the power triangle will only consist of a **vertical line pointing down** (in accordance to leading power triangle definition) representing Reactive Power. Capacitors DO NOT have Real Power. Also, remember that adding capacitors in parallel increases C, therefore the reactance ($1/\omega C$) decreases. So, as you add more capacitors in parallel the amplitude of the Reactive Power decreases.

- **Inductor only**

What happens when an alternating current is applied to an inductor? Inductors also take time to charge, and discharge. Because of this, there is a phase shift between current and voltage. More precisely, the current **lags** the voltage by 90 degrees (1/4 cycle).



The formula for inductive reactance is given by:

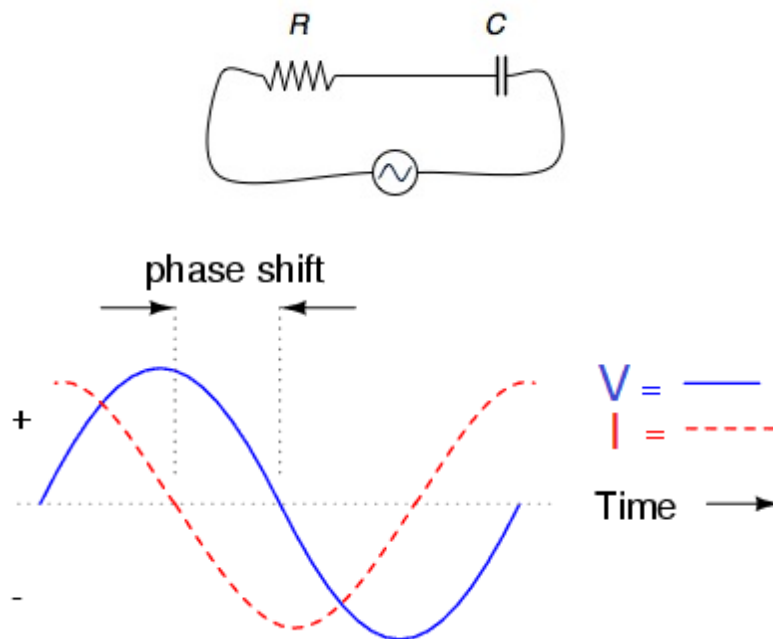
$$X_L = 2\pi f = \omega L$$

Since Ohm's law can also be written as $I = V/X_L$, the larger the inductance L and the lower current will be. The current, then, decreases as the inductance and the frequency increase.

In this case: $\theta = 90^\circ$ therefore $PF = \cos(90) = 0 \Rightarrow P = 0$ [W]
 Since $\theta = 90^\circ$, the power triangle will only consist of a **vertical line pointing upwards** (in accordance to lagging power triangle definition) representing Reactive Power. Inductors DO NOT have Real Power. Also, remember that adding Inductors in series increases L , therefore the reactance (ωL) increases. So, as you add more inductors in series the amplitude of the Reactive Power increases.

- **RC circuit**

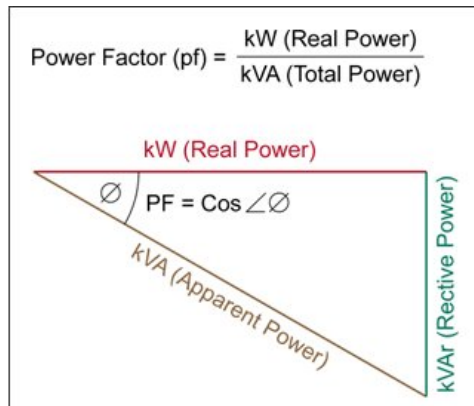
Consider the following circuit, where an AC voltage source is connected across a series RC circuit:



Notice that the phase shift is less than -90 degrees (current still leads voltage), which is because the resistor is trying to bring the voltage and current in phase, while the capacitor is trying to keep them 90 degrees out of phase; so they settle somewhere in between, depending on the given values of R and C .

It follows that $PF = \cos(\text{phase shift})$ and $P = V_{rms} \cdot I_{rms} \cdot PF$. Note that **PF** will be **negative** by definition.

Then, a power triangle can be drawn. Remember that the Real Power phasor corresponding to resistance R is horizontal, while the Reactive Power phasor corresponding to capacitor C is vertical pointing down:

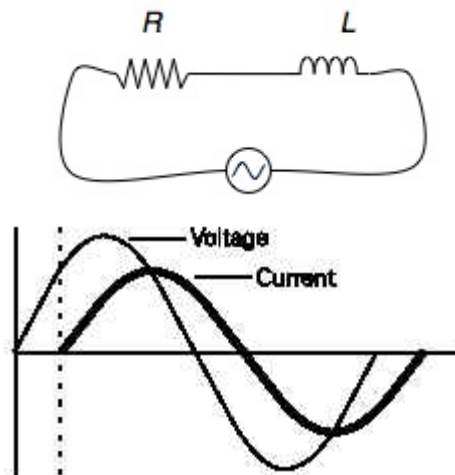


It is very important to understand what will happen to the phase difference as more resistors and capacitors are added in parallel (since the resistors in the resistor box are wired in parallel, as well as the capacitors).

So, as you add resistors in parallel, the total resistance goes down, increases the phase difference. However, as you add capacitors in parallel, the capacitance C increases and decreases the reactance X_C , which in turn, decreases the phase difference.

- **RL circuit**

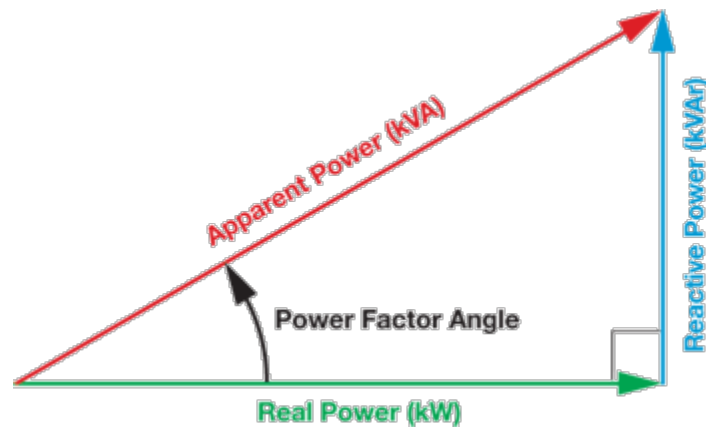
Consider the following circuit, where an AC voltage source is connected across a series RL circuit:



Notice that the phase shift is less than 90 degrees (voltage still leads current), which is because the resistor is trying to bring the voltage and current in phase, while the inductor is trying to keep them 90 degrees out of phase; so they settle somewhere in between, depending on the given values of R and L .

It follows that $PF = \cos(\text{phase shift})$ and $P = V_{\text{rms}} \cdot I_{\text{rms}} \cdot PF$. Note that **PF** will be **positive** by definition.

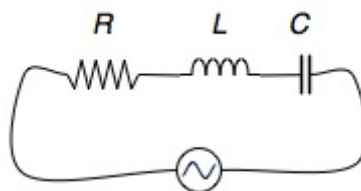
Then, a power triangle can be drawn. Remember that the Real Power phasor corresponding to resistance R is horizontal, while the Reactive Power phasor corresponding to inductor L is vertical pointing up:



So, as you add resistors in parallel, the total resistance goes down and increases the phase difference. However, as you add inductors in series, the inductance L increases, which increases the reactance X_L , which in turn, increases the phase difference.

- **RLC circuit**

Consider the following circuit, where an AC voltage source is connected across a series RLC circuit:

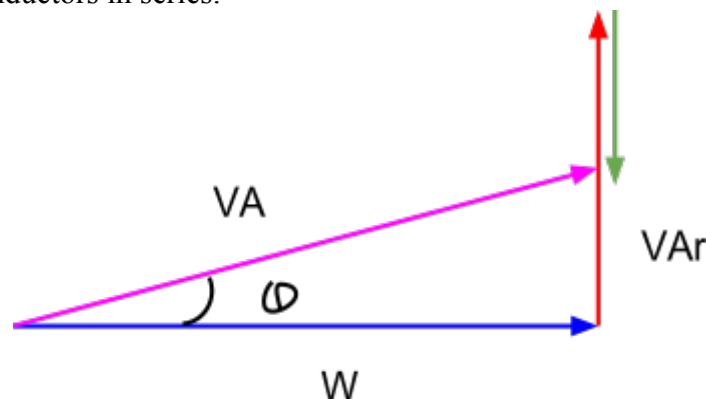


The same formulas for PF and P are used as in the last two examples.

However, the PF can be either negative, positive or zero, depending on the resultant vector addition of capacitive and inductive Reactive Powers.

Below is shown an example where the PF is positive(lagging). This means, as shown in the triangle, that capacitive reactance(green) is smaller than inductive reactance(red), making the overall reactance inductive.

A special case is when the capacitive and inductive reactances cancel each other. In this case, there will only be Real Power (a horizontal phasor). Based on RL and RC circuits described above, you should be able to tell what happens as more resistors and capacitors are added in parallel, as well as inductors in series.



Why is power factor important?

The power factor amplitude can take a value between 0 and 1. PF of 0 means there is only reactive power (which can be either inductive or capacitive), while PF of 1 means there is only Real Power. Ideally, it is good practice to have a PF closer to 1. This is because power companies will charge for reactive power if it is above a certain limit.

How do you keep PF close to 1? Capacitors can be used to cancel out inductive reactance if there is too much of it. On the other hand, if there is too much capacitive reactance, inductors should be used to bring PF to 1.

Below is a concise summary of the power triangle. Make sure you fully understand it.

References:

http://www.eeweb.com/blog/andrew_carter/how-capacitors-behave-in-ac-circuits

<http://people.sinclair.edu/nickreeder/eet155/mod04.htm>

http://keywon.com/wiki/index.php?title=AC_Circuits#AC_Capacitor_Circuit

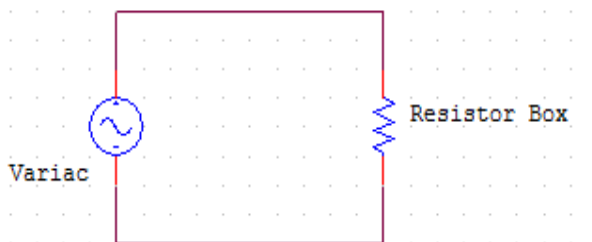
2. EQUIPMENT LIST

Banana Cables
Voltage/Current Probe
Resistor Box
Capacitor Box
Inductor (42mH)
Power meter
Handheld multimeter
Variac

3. PROCEDURE

PART A: Basic “R” Circuit.

1. Construct a basic circuit represented by the diagram below, and switch on one resistor (refer to page X for lab setup help). Make sure the variac is turned off.

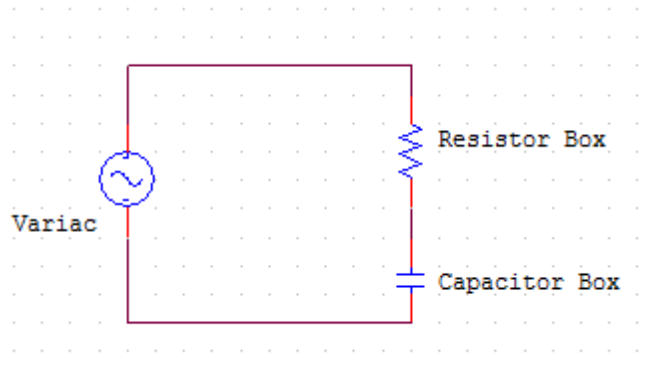


2. Connect the voltage probe to channel 1 and the current probe to channel 2 of the oscilloscope to measure the current and voltage across the resistor.
3. Turn the master switch on, make sure you turn on the oscilloscope.
4. Turn the variac on and turn the knob until 50V from the power meter is read. Make sure the readings from the handheld multimeter match.
 - a. Turn the knob to measure RMS Voltage and probe two nodes you want to measure voltage across. (Resistor box in this case)
5. Measure RMS voltage, RMS current, and phase difference from the oscilloscope. (refer to pg X for help)
 - a. First, you'll have to initialize the equipment by pressing save/recall → recall factory setup → ok
 - b. Make sure both waves are turned on by pressing CH 1 and CH2. You can verify what channels are switched on by looking on the bottom-left of the screen.
 - c. Now, you'll need to adjust the scale by using the knobs. Using scale knobs, re-scale the graphs so they are easily observable. (each channel will have to be scaled separately)
 - d. To measure different values, press measure and press more for appropriate measurement.
 - e. For phase, make sure you're measuring from Ch1 to Ch2. (negative phase should be "leading" and positive should be "lagging")
 - f. If you see any fluctuations in the measurements, you can press Menu → Average to "smooth out" the graphs.
6. Calculate PF and power from oscilloscope measurements.
 - a. Do you see any significant phase difference?
 - b. Do the calculated values match the power meter?
7. Switch on more resistors.
 - a. What changes do you see in current?
 - b. What changes do you see in power?

- After each part you can turn the variac switch off for safety reasons before you add more components in the circuit.

PART B: RC Circuit

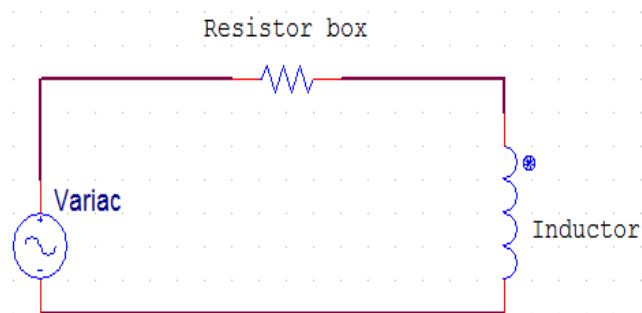
- Add a capacitor box in series. Turn on one capacitor.



- From the oscilloscope, measure phase difference, calculate the PF and verify the result with the power meter.
- From the measurements, determine real power, reactive power, and apparent power, then draw the power triangle.
- Try switching on more capacitors.
 - As you switch on more capacitors, does the phase angle decrease or increase? Why? (Hint: How does the impedance affect the power triangle?)

PART C: RL Circuit

- Construct an RL circuit with one resistor on.

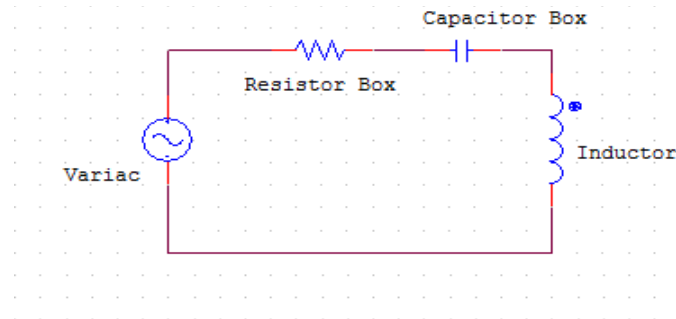


- From the oscilloscope, measure phase difference and calculate the PF and verify the result with the power meter.
- From the measurements, determine real power, reactive power, and apparent power, then draw the power triangle.

- a. What difference do you see from RL circuit?

PART 4: RCL Circuit (Phase “Cancel”)

1. Add an inductor to the circuit in series and switch on one capacitor.

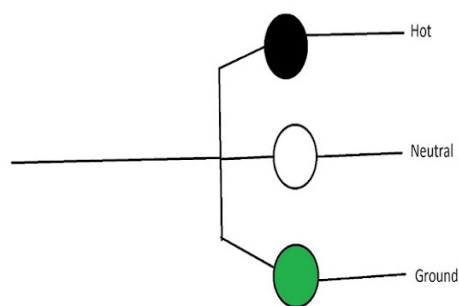
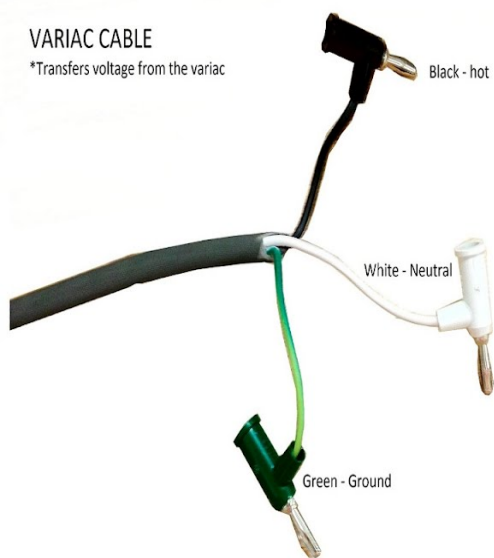


2. Measure the phase difference and calculate the PF and verify the result with the multimeter.
3. Determine the real power, reactive power, and apparent power, then draw the power triangle.
 - a. How much more reactive power should the capacitor draw in order to “cancel” phase difference (in other words, make $PF = 1$)
 - b. What is the necessary capacitance? (Hint: try drawing out the impedance on the complex plane)
4. Switch a few more capacitors on and see how the phase angle changes.

4. LAB SETUP HELP

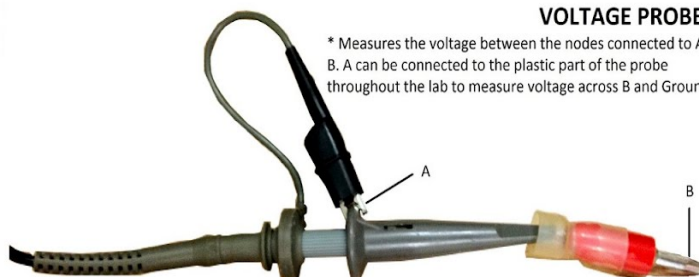
VARIAC CABLE

*Transfers voltage from the variac



VOLTAGE PROBE

* Measures the voltage between the nodes connected to A and B. A can be connected to the plastic part of the probe throughout the lab to measure voltage across B and Ground



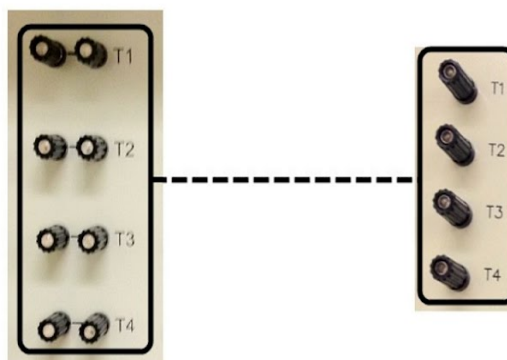
CURRENT PROBE

* Measures current through a wire
Make sure the arrow points away from the wattmeter to obtain correct sign(+ or -) for current

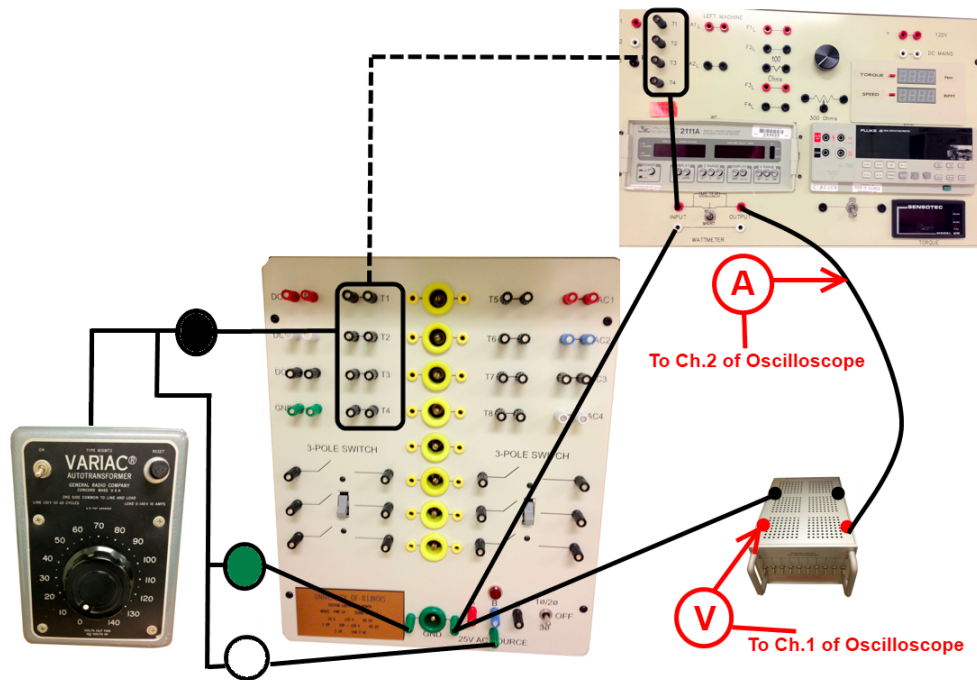


Dashed Line

* Dashed Line represents internal connection behind the benches. You may choose to use any of the terminals within the rectangle as long as you use the same terminal for the other side of the dashed line (ie. T1-T1 or T3-T3)

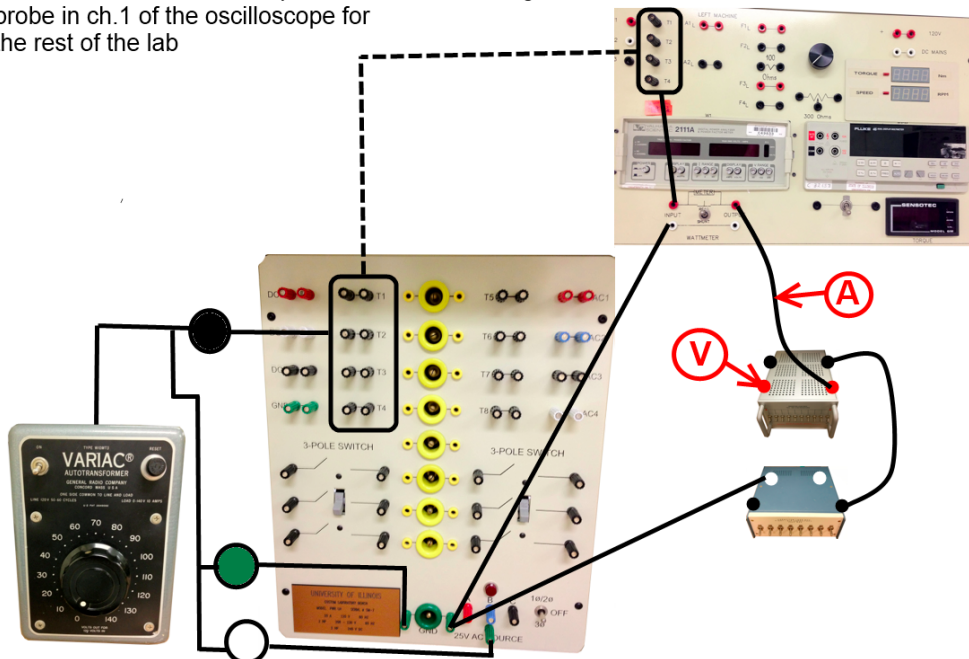


PART A: BASIC "R" CIRCUIT

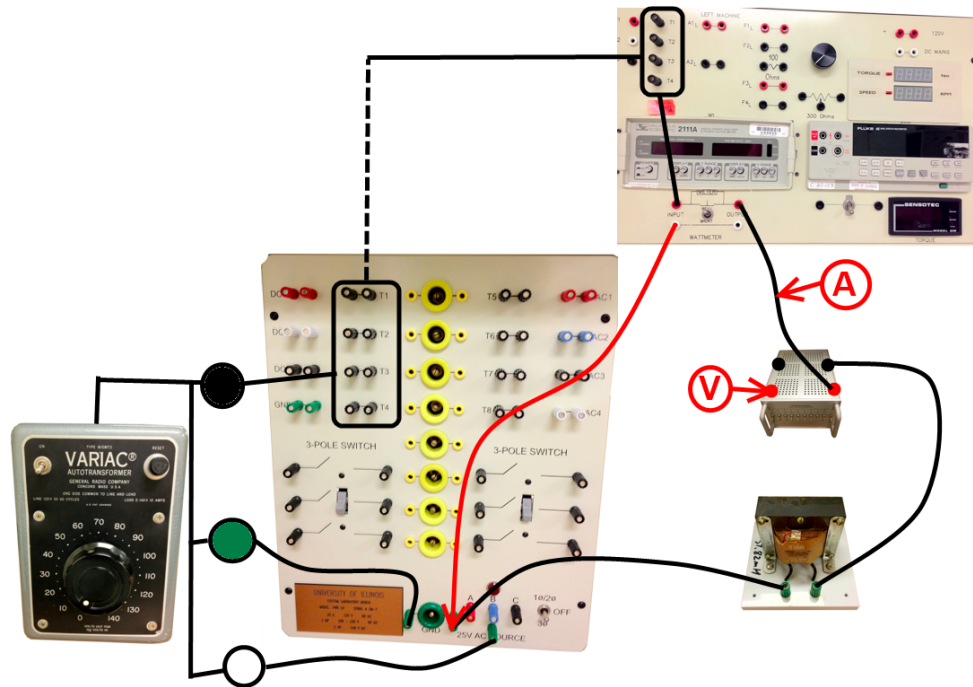


PART B: RC Circuit

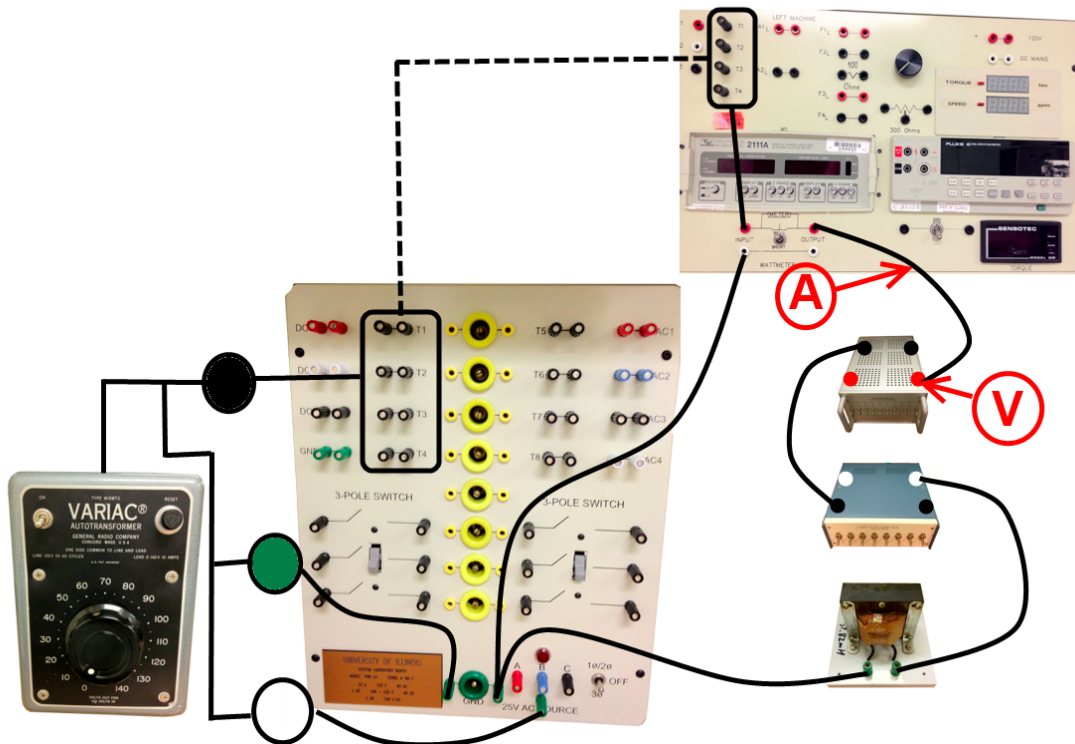
*You can leave the current probe in ch.2 and voltage probe in ch.1 of the oscilloscope for the rest of the lab



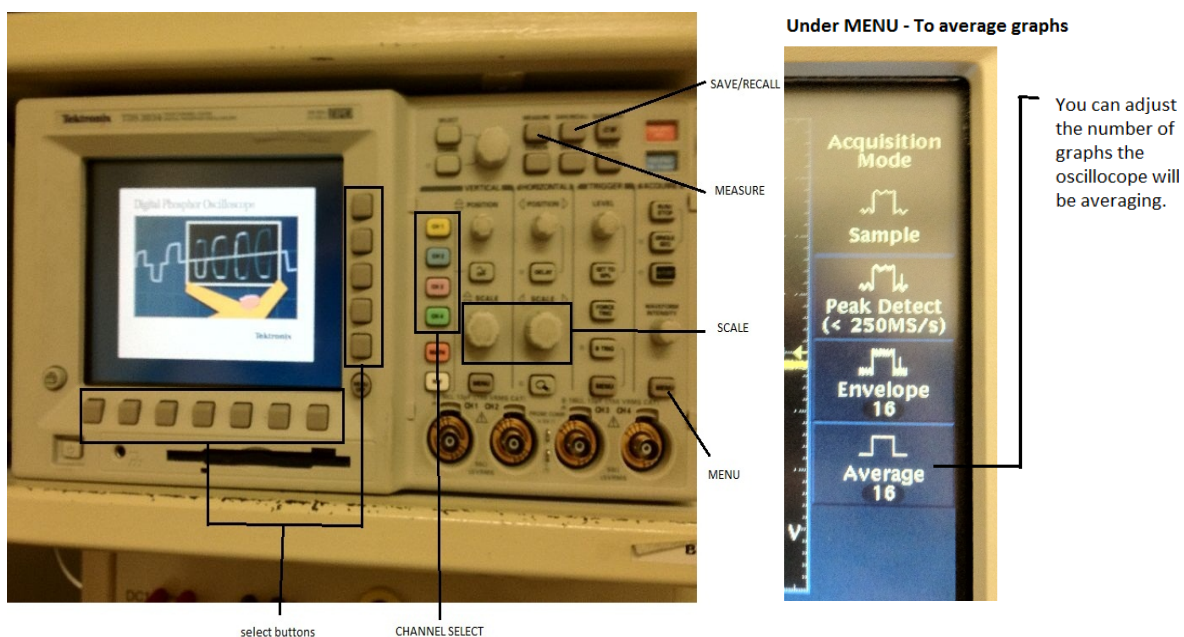
PART C: RL CIRCUIT



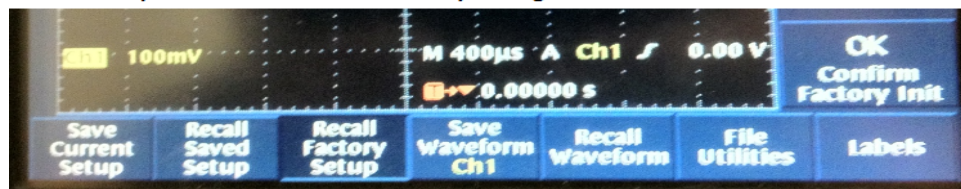
PART D: RCL CIRCUIT



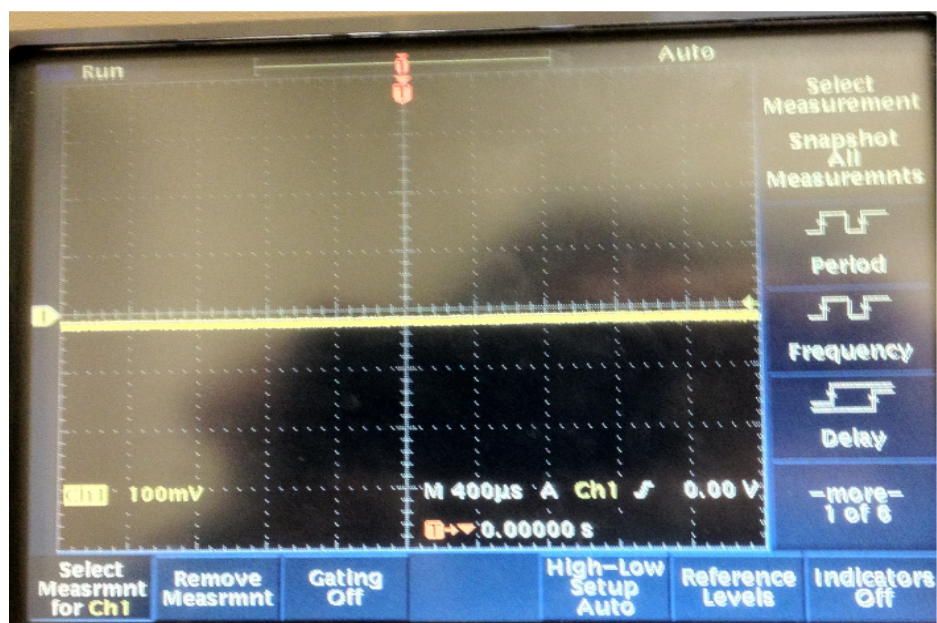
5. OSCILLOSCOPE HELP



Under SAVE/RECALL - To initialize to factory settings



Under MEASURE



6. POWER FLOW DEMO

Review:

From the previous exercises, we were able to demonstrate that we can plot the current or voltage waves through an oscilloscope.

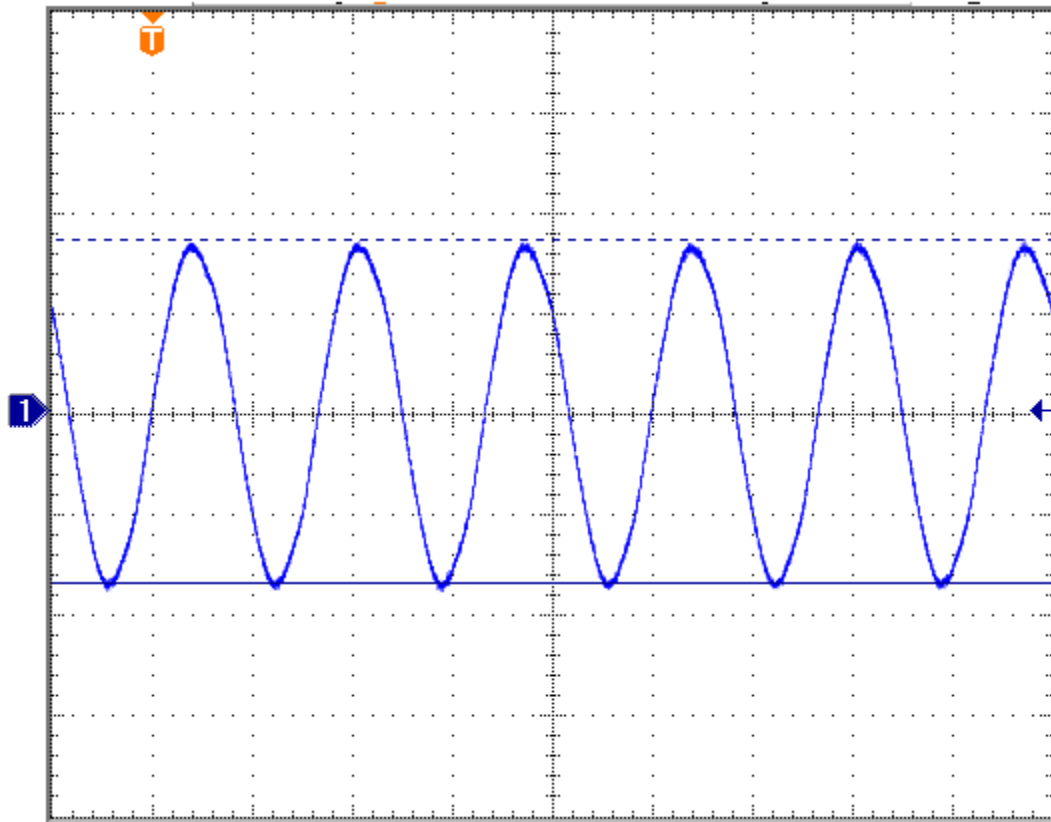


Figure 1: Oscilloscope Wave Output

You can also plot multiple waves simultaneously through an oscilloscope. By doing so, we can see we can see if a wave is (a) in unity with another wave, (b) lagging another wave or (c) leading another wave.

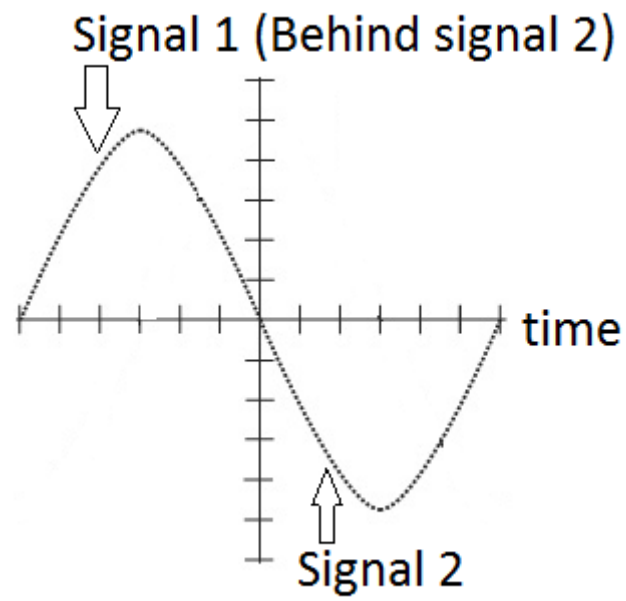


Figure 2a: Signal 1 and Signal 2 are in Unity

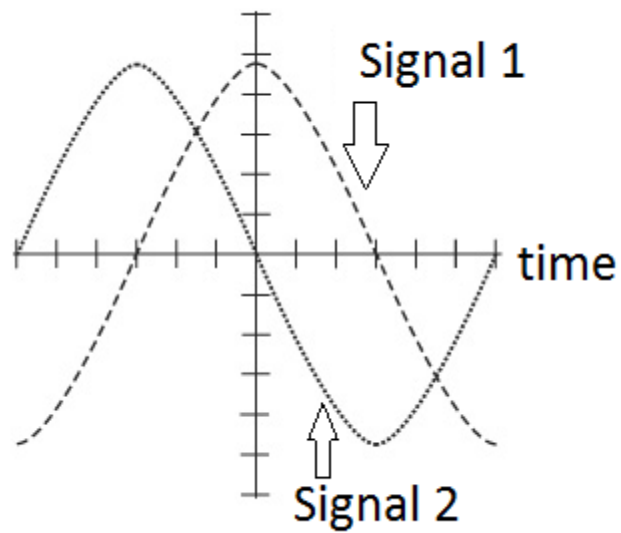


Figure 2b: Signal 1 Lagging Signal 2

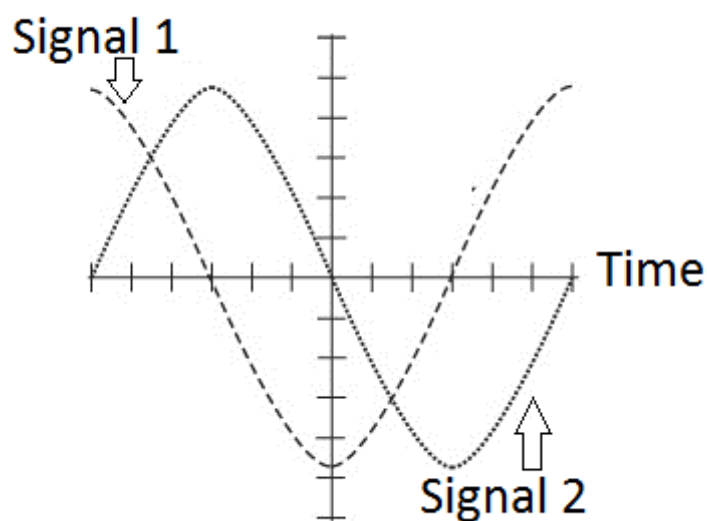


Figure 2c: Signal 1 Leading Signal 2

POWER FLOW

Picture the following set-up: Two machines are connected to its own shaft. On machine 1, the shaft allows the motor to spin as fast as it wants. However, on machine 2, the shaft only allows the motor to spin at a certain speed.

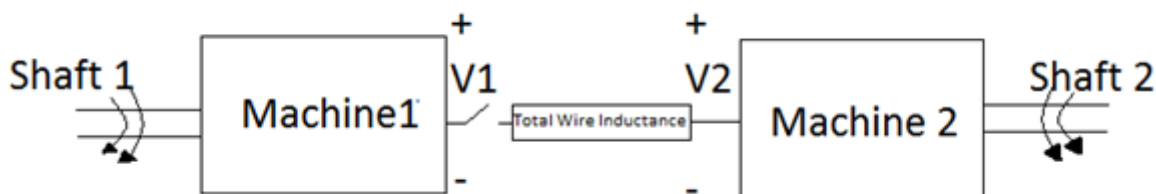


Figure 3: 2 Machines and its corresponding shafts

Initial scenario: Machine 2 is already running at a certain speed, and we set Machine 1 to run as fast as machine 2 by rotating its shaft at a certain speed. The voltages on the terminals of Machine 1 and Machine 2 (V_1 and V_2 respectively) are equal. We then flipped a switch to connect the Machine 1 and the Machine 2 together. What will happen?

Result: The 2 machines will be “synchronized” together. The 2 machines will now be running at the same speed. In the “synchronized” state, the 2 machines will run at the same speed despite changes in the shaft.

In this initial scenario, since the machines are running at the same speed, and there will be no power flowing in between the two machines. If we look at their voltages on oscilloscope, we will see that the 2 voltages are in unity.

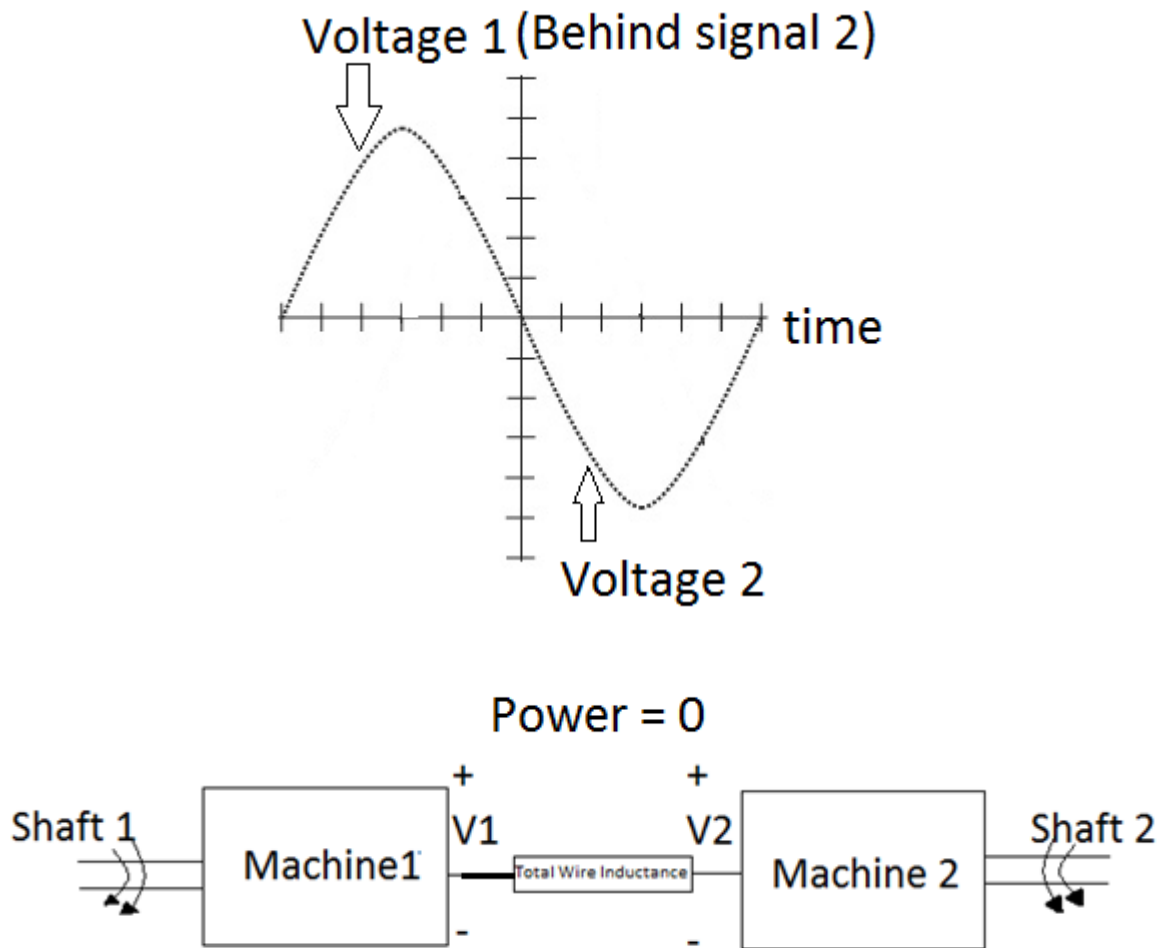


Figure 4: Unity Voltages and Power

Next Scenario: As discussed earlier, since both machines are now “synchronized”, they will both be running at the same speed. What will happen if we rotate Shaft 1 faster?

Result: Since Machine 1 wants to rotate at the same speed, but is receiving more “power” to rotate from shaft 1, it will pass the excess “power” from shaft 1 to machine 2. Machine 2 will now be receiving more power from machine 1 which will cause it to rotate faster. To remedy this, shaft 2 will act as a break and prevent it from happening.

Follow-up Question: How much power does shaft 2 require to act as a break to maintain Machine 2 to run at a certain speed?

Answer: The shaft 2 will need the same amount of power passed from Machine 1. Therefore, the power passed from Machine 1 will be used by shaft 2 to prevent Machine 2 to spin faster than the ‘synchronized’ state. In this case, Machine 1 will be acting as a “GENERATOR” and Machine 2 will be acting as a “MOTOR/LOAD”.

Follow-up Question 2: What will happen to the phase difference between both machines?

Answer: The phase of Machine 1 will shift to the right, causing a phase difference between the 2 phase angles of the voltages.

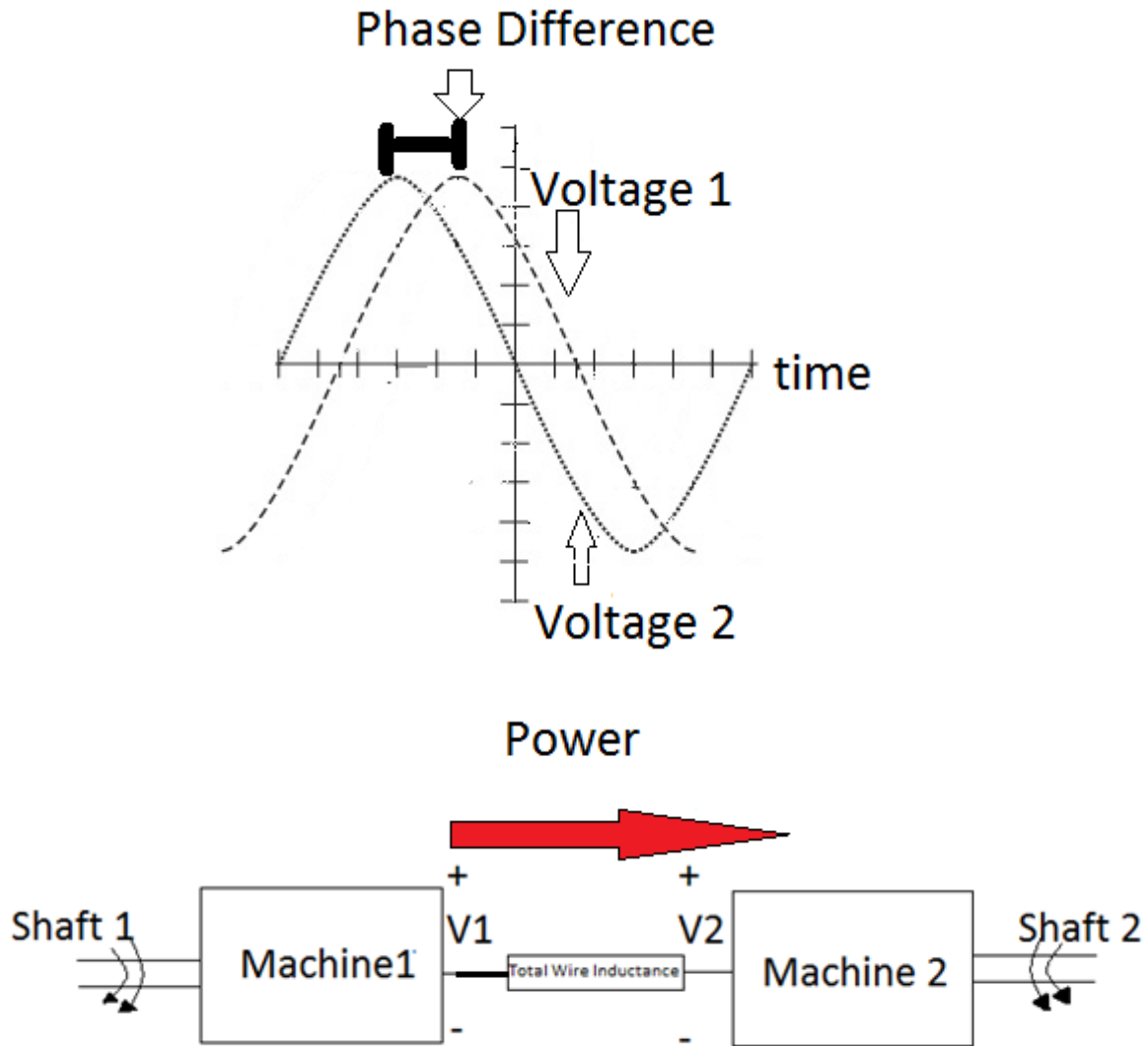


Figure 5: Machine1 as generator, Machine2 as motor.

Next Scenario: What will happen if we rotate shaft 2 even faster (faster than earlier)

Result: More power will be delivered (and consequently, consumed) on shaft 2. The phase of Voltage 1 will shift to the right again, which will cause the phase difference between the two voltages to be greater.

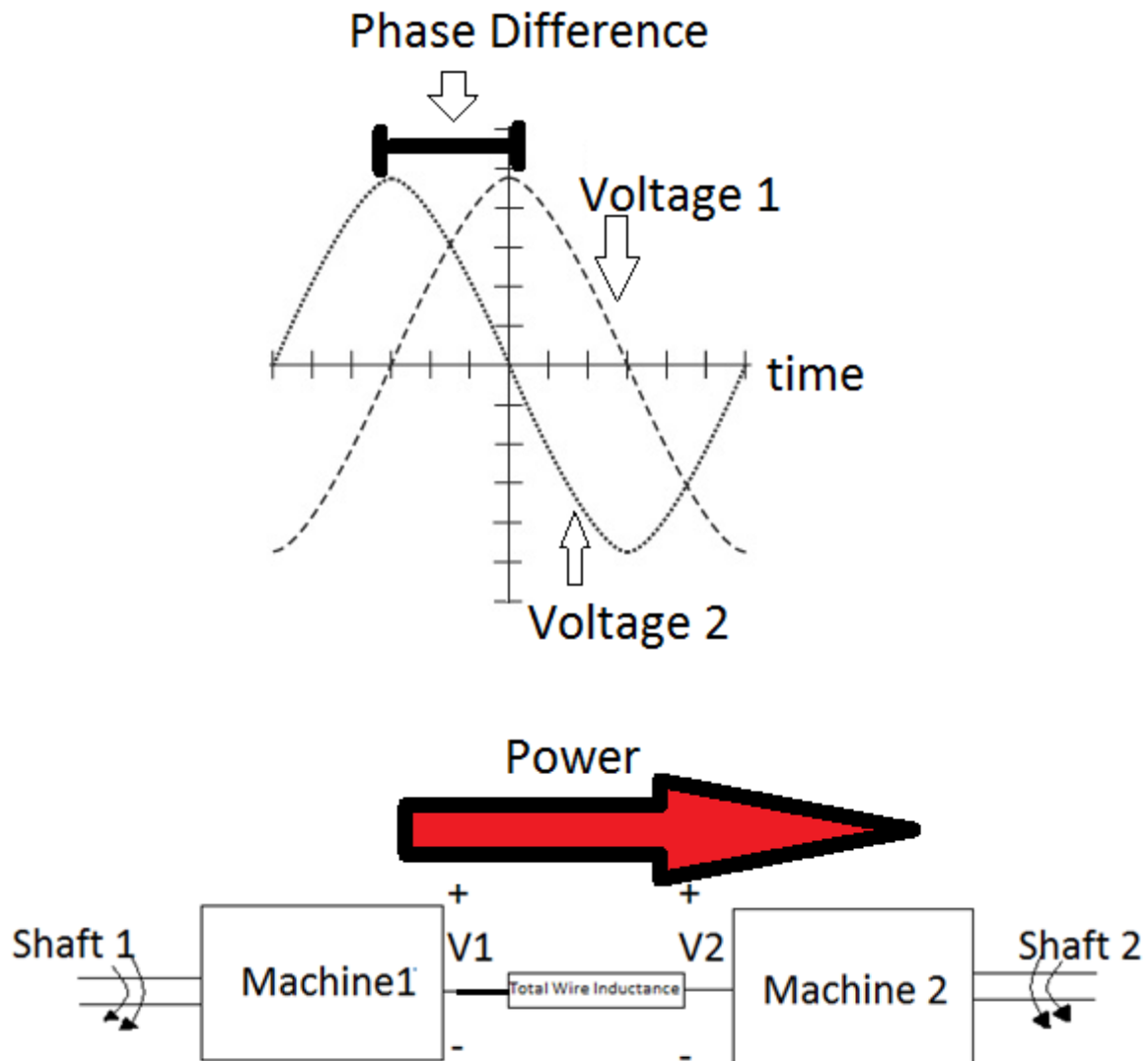


Figure 6: Machine1 as generator, Machine2 as motor, larger power flow

Next Scenario: Let's return the shaft 1 "power" as it was before in synchronous state. What will happen?

Result: The phase voltage of Machine 1 will shift to the left, causing it to be in unity with Machine 2's voltage. There will be no power flowing across in between the two machines.

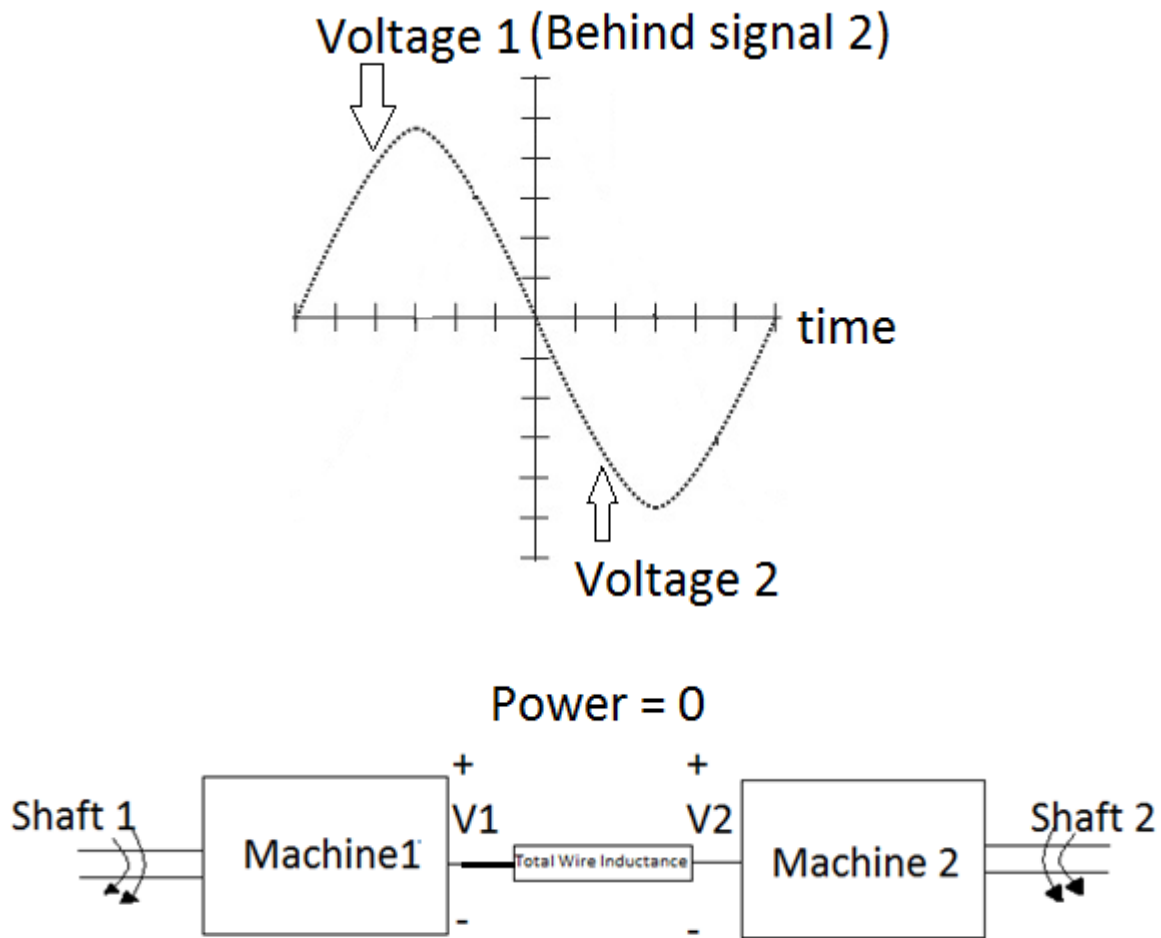


Figure 7: Unity Voltages and Power (Again)

Next Scenario: Set Shaft 1's "power" lower than it was before. What will happen?

Result: Shaft 1 will then require "power" to make Machine 1 spin faster. For this to happen, shaft 2 will generate excess "power" and give it to shaft 1. The phase voltage of Machine 1 will shift to the left and the power will flow from Machine 2 to Machine 1. Machine 2 will now act as a generator and Machine 1 will now act as a motor.

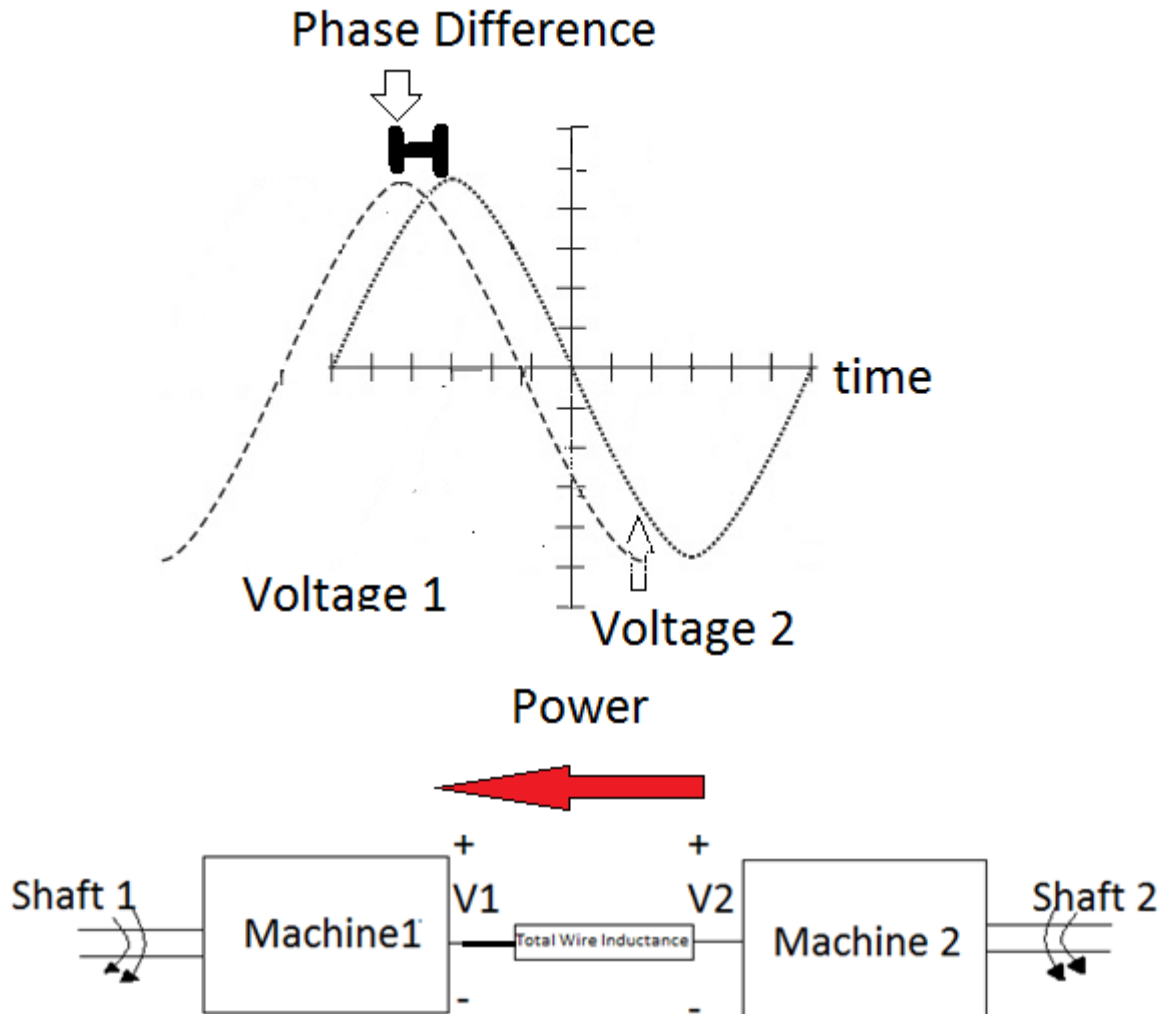


Figure 8: Machine 1 as motor, Machine 2 as generator

Next Scenario: Set Shaft1's "power" to be even lower. What will happen?

Result: More power will be delivered (and consequently, consumed) on shaft 1. The phase of Voltage 1 will shift to the left again, which will cause the phase difference between the two voltages to be greater.

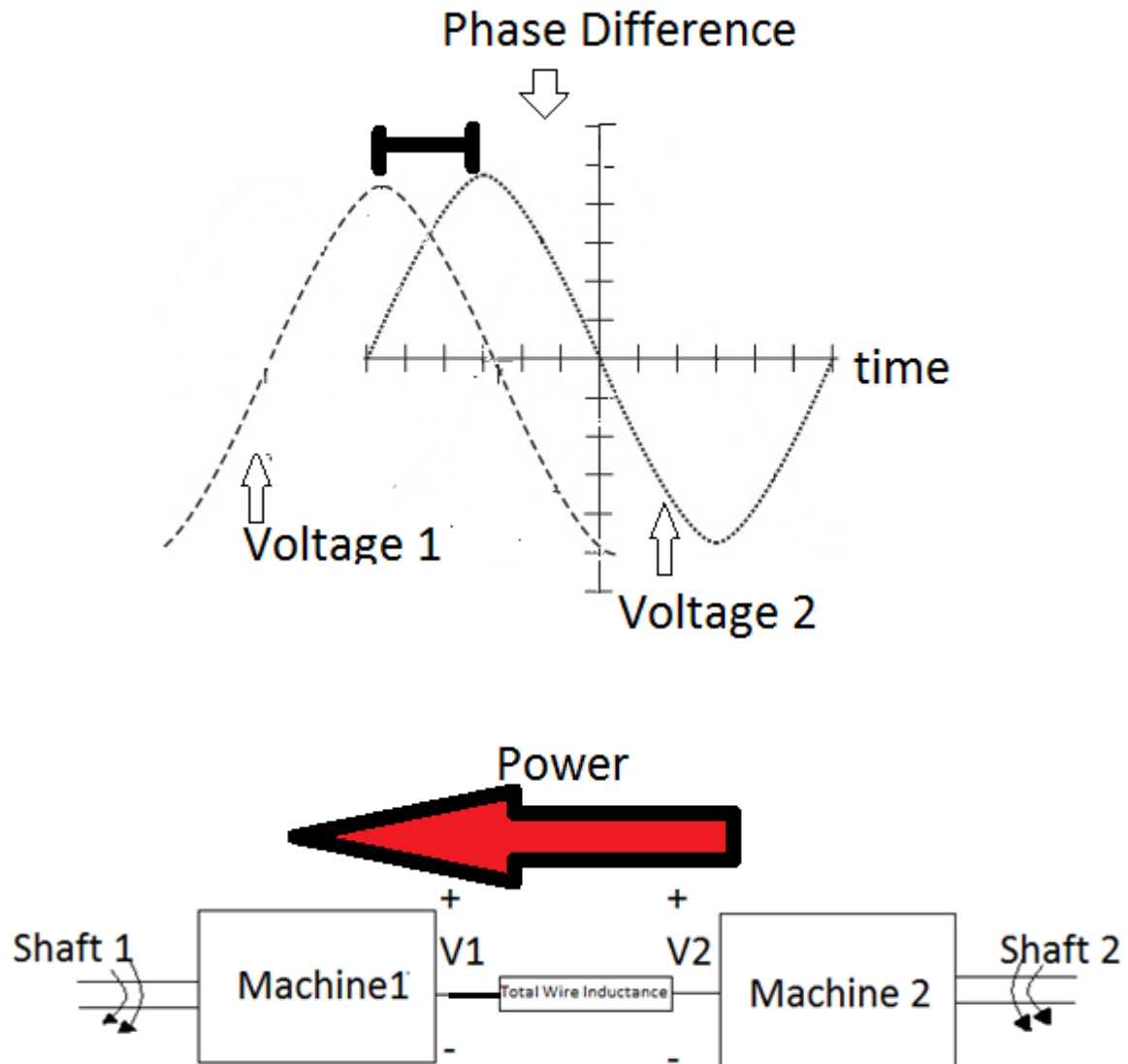


Figure 9: Machine 1 as motor, Machine 2 as generator, larger power flow

Next Scenario: Let's return to the original scenario with 0 "power" flowing between the two terminals. Now, give the shaft1 significantly more "power" to spin 1 OR significantly reduce shaft 1's power. What will happen?

Result: There will be a system breakdown due to instantaneous large power demand. There will be no power flowing in between the two machines and they will be "desynchronized".

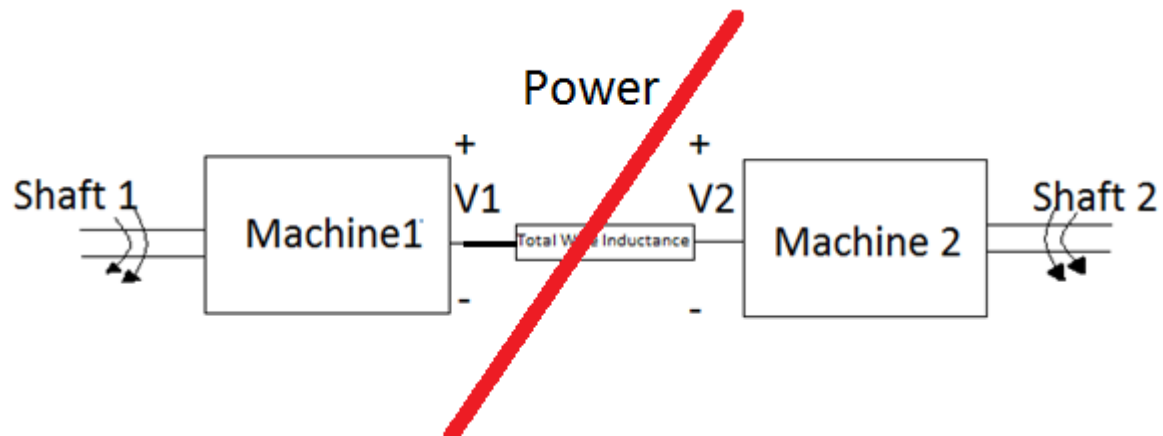


Figure 9: System Breakdown

Conclusion: The Power Flow between the two machines heavily depended on the phase difference on its voltages. Through observation, we determined that the power is (taking right power flowing to the right as positive and power flowing to the left as negative):

0: Voltages are in phase.

Small +: Small Phase difference, Voltage 1 lagging Voltage 2.

Large + : Large Phase difference , Voltage 1 lagging Voltage 2.

Small -: Small Phase difference, Voltage 1 leading Voltage 2.

Large - : Large Phase difference, Voltage 1 leading Voltage 2.

This is because power flow is governed by the equation

$$P_{in} = \frac{|\bar{V}_{a1}| |\bar{V}_{a2}|}{X_s} \sin(-\delta)$$

Where

$$\delta = (\angle V_{a1} - \angle V_{a2}).$$

*NOTE: Abrupt demand of power can cause a system breakdown. A phase shift of over 90 degrees will cause a system breakdown as well