Lab-2: AC Transformers

Objectives and Overview

The objectives for this sequence of laboratory experiments are:

- to experiment and fully characterize a small two-winding transformer by identifying the equivalent circuit parameters;
- to learn the basic properties of practical (non-ideal) single-phase transformers, investigate their loading characteristics when supplying purely resistive loads and mixed (inductive and capacitive) loads;
- to observe the effects of magnetic saturation in steady-state and analyze the harmonics in the magnetizing current;
- to observe and measure the inrush current when the transformer is energized at different time instances;
- to evaluate how accurately the equivalent circuit predicts the steady-state characteristics of the real transformer.

It is important to keep in mind that the equivalent circuit is a model that is used to analyze and/or approximate the actual physical device – your real/actual transformer. During the lab, the students will perform the **Open-Circuit** and **Short-Circuit Test(s)** and identify the equivalent circuit parameters. Once these parameters are known, the equivalent circuit will be used to predict the transformer behavior under load. These theoretical predictions will then be compared with the measured data obtained during the **Load Test**. The students will have to save some of the measured data and use it for the future plotting and analysis included in the Lab Report.

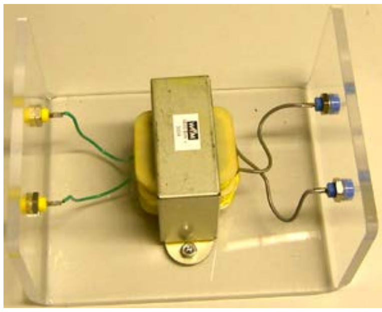
Preparation (Pre-lab)

It is expected that the students have read and understood the textbook chapter and reviewed the lecture notes module corresponding to AC Transformers, identification of equivalent circuit parameters, phenomena of magnetic saturation and the inrush current in transformers. In particular, the students should review the T-equivalent circuit of a two-winding transformer and the tests that are performed to extract the circuit parameters. The Pre-Lab page should include the following:

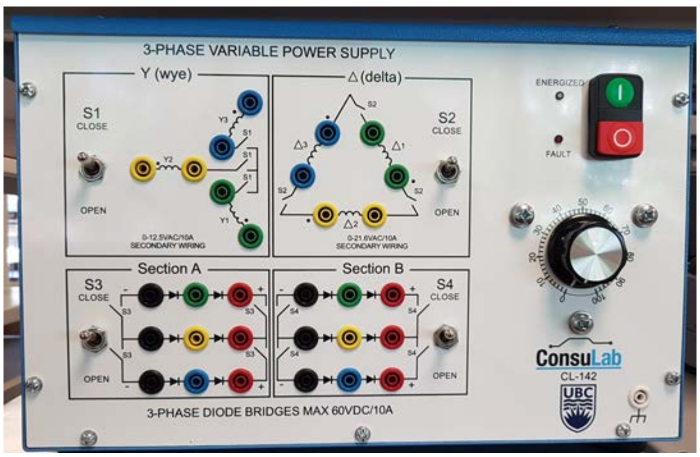
- Prepare a list of equations for calculating the T-equivalent circuit parameters using the Open-Circuit and Short-Circuit Tests.
- Write down the expressions/solutions for the current in an ideal inductor when it is being supplied with the sinusoidal voltage: a) assuming the inductor is energized at the moment when the applied voltage is at its peak value; b) assuming that the inductor is energized when the voltage is at its zero.
- You are expected to use Matlab and/or Simulink for post-processing some of your measurements. So, get familiar how to read the measured data into Matlab/Simulink.

Apparatus & Equipment

This lab includes the following components:



Transformer: This is a low-voltage single-phase transformer with two windings. The windings are rated for up to 5A. In this lab, you will be working with this transformer to identify the equivalent circuit parameters, as well as to observe the effect of magnetic saturation.



3-Phase AC Power Supply: This flexible 3-phase Power Supply has two 3-phase transformers inside. The secondary windings can readily be configured into a 'Y' (wye) and "Δ" (delta) configurations. The front panel shows the transformer wiring and has several switches and connectors for configuring the output. It also has two 3-phase diode bridges for producing the DC output.
The Power Supply transformers are fed from an internal 3-phase **Variac** (variable auto transformer) that can be used to adjust the output voltage. The Variac knob is located on the right of the front panel. By varying the Variac knob from 0 to 100%, the output AC voltages may be changed in the range from 0 to about 25 V (rms) per phase.

Measurement Box:

Each bench is equipped with a multi-functional **Measurement Box** that can measure up to 3 voltages and up to 3 currents simultaneously with the sampling rate of 2.5 MS/sec (2.5MHz). The measured waveforms and their values can be displayed on the PC screen as well as recorded for possible post-processing. Its front panel has 3 current channels (**A1, A2, and A3**) and 3 voltage channels (**V1, V2, and V3**), respectively. The current channels are rated to measure and withstand a continuous current of up to 20 A (peak). The voltage channels are rated to measure and withstand the voltage of up to 50 V (peak). For special measurements only, the voltage measurement in each channel can be re-scaled by a factor of 10, thus raising the measurement limit to 500 V (peak). The **Measurement Box** is connected to the Data Acquisition (DAQ) card inside the PC. The **Measurement Box** has one power switch on its back panel on the right side. The power switch should be normally turned ON, and the three green LEDs on the front panel should also be ON indicating its normal operation.
The channels are color-coded. It is strongly recommended that you use appropriate and consistent color wires for each channel of measurements. This will make it easier for you to wire-up your circuits and subsequently check it and find any mistakes.

<table>
<tr>
<td>
</td>
<td>Load Resistor Box: The Load Box contains several resistors from 100 to 50 Ohms, which can be switched on in parallel to each other. The box is equipped with a cooling fan to help dissipate the heat in case there is a significant power delivered to the load. Be careful! This box may get very hot, especially its heat-sink that is on the bottom. When the box dissipates more than 50W turn on the internal fan.</td>
</tr>
<tr>
<td></td>
<td>RL Load Box: This box contains three 20 Ohms resistors and three 40 mH inductors. In this Lab, you will be using one of the inductors from this box to implement an inductive RL load for the transformer under test.</td>
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<tr>
<td></td>
<td>RC Load Box: This box contains three 60 Ohms resistors and three 40 μF capacitors. In this Lab, you will be using three capacitors from this box connected in parallel to implement a capacitive RC load for the transformer under test.</td>
</tr>
<tr>
<td>
</td>
<td>Multimeter: Each bench also has HP 34401A Multimeter that you will use to measure the dc resistance of transformer windings (with and without the wires). This measurement will be only used to double-check your calculated resistances.</td>
</tr>
</table>

Setting-Up the DAQ System

Login to your local PC and locate the program **Transformer Analysis**. Double-click on the icon and start the program. A window shown in Fig. 1 should appear on your PC screen indicating that you are ready to start taking measurements. The **Transformer Measurement** program interface is set up to display the two voltages (channels V1 and V2) and two currents (channels A1 and A2), as will be needed for single-phase measurements in this lab. The measurement window can be triggered using either voltage or current signal of the first measuring channel (Ch1). The point of triggering also defines the relative angle of the measured signals. The user can select or un-select voltage and current measurements, but the first channel signals (V1 and A1) are always selected. For this lab, select the two voltages and currents to be measured.

All measured signals (voltages and currents) are displayed in two ways: On the left side of the panel, all selected variables are displayed as real-time instantaneous waveforms – just like in an Oscilloscope. On the right side of the panel, the RMS values of the voltages (in Volts) and the RMS values of currents (in Amps), their phase angle (in degrees) with respect to the trigger point,

The **average real power** in each channel (in Watts) is calculated using the instantaneous voltage and current in that channel. The power is calculated by averaging the instantaneous power over the length of the measurement window. For this measurement to be correct, you have to make sure that the voltage and the current measurements are from the same Channel (V1 with A1, and V2 with A2), and the polarities of both voltage and current channels are correctly wired.

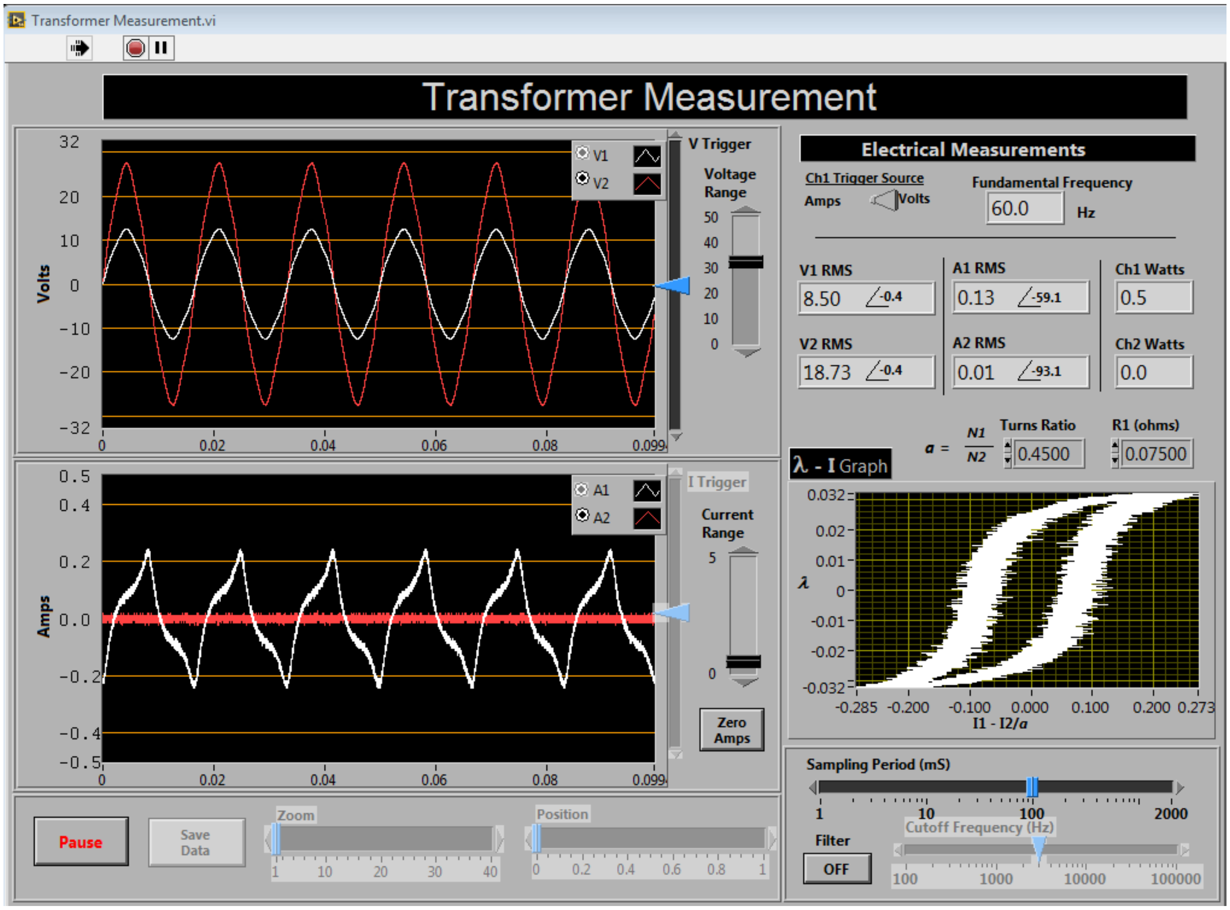

Fig. 1: LabView program interface Transformer Measurement.

Hysteresis Loop: The program also calculates and displays the flux-linkage versus current ($\lambda - i_m$) graph. The magnetizing current is assumed to be just the primary current i_1 when the transformer is open-circuit. When the transformer is loaded, the magnetizing current is approximated as $i_m = i_1 - i_2' = i_1 - i_2 / a$. In steady state, the $\lambda - i_m$ should look like a Hysteresis Loop shown in Fig. 1 and give you an idea of how much you are saturating the core of the transformer or inductor under test.

The **Sampling Period** (in ms) can be adjusted during the process of taking measurements in order to better capture the desired waveforms and to see the details. Remember to push **ZERO Amps** button before each test to remove any offset when measuring currents. The program can **PAUSE** and SAVE the measured data in a text file for further analysis in programs such as **Excel** or **Matlab**. Once the measurement is **PAUSED**, the user can also zoom-in into any fragment of the recorded window by using the slide buttons **ZOOM** and **POSITION** on the bottom of the panel. Pushing the button **SAVE** opens the window for saving the data file. The user should name the file and save it into appropriate location/folder for future analysis.

Ask a TA and/or Technician responsible for the lab if you have any difficulty locating and/or running this program.

Experimental Part

Mandatory: As you are performing the experiments and taking measurements, provide brief answers to the questions listed in your report below each Table of measurements, based on your observations and understanding.

Setting up the AC Power Supply

The students will be using the multi-purpose **3-Phase AC Power Supply** to provide a variable AC voltage to supply the **Transformer** under study. The **Power Supply** has two sets of windings, 'Y' (wye) and "Δ" (delta). To provide a single-phase AC source with sufficient available maximum voltage, one can use two windings connected in series as depicted in Fig. 2.

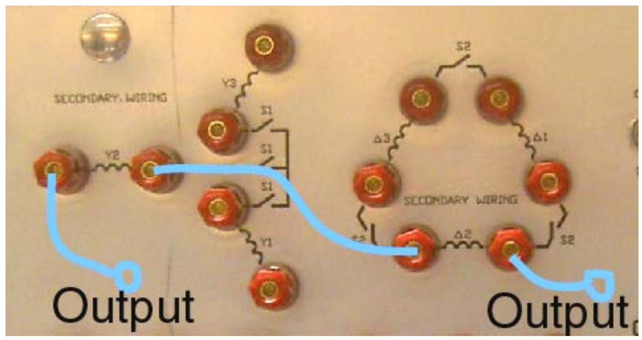

Fig. 2: Wiring of 3-Phase AC Power Supply to provide a single-phase variable AC source.

Make sure that the switches S1 and S2 are **open**. The output voltage is taken from the two terminals as shown above in Fig. 2. In this configuration you should be able to obtain the voltages up to 35 V rms. You will then use the Variac knob (on the right side of the Power Supply) to adjust the voltage magnitude to the desired level. Turn the knob contraclockwise (CCW) all the way for the minimum output.

Task 1: Measuring the DC Resistance

In this Task you will measure the DC resistance of **Transformer** windings with and without the long wires. These measurements will be used only to double-check the values of resistance that you will calculate in the subsequent Short-Circuit Test in Task 3.

You can arbitrarily choose which side will be the **primary** and which side will be your **secondary**. However, once you have made this choice, **you must preserve it throughout this lab experiment for consistency of your results**!

(a) Turn ON the **Multimeter** and set it up for measuring the DC resistance by pressing the button with the sign Ω. Take the **Transformer** and using two long color wires measure the resistance of both sides. Record the measured values in the Table 1.

(b) Then, connect four long color wires (two wires in series in each set) to the Transformer terminals and measure the combined resistance of each winding plus the four long wires. Also record the measurements in Table 1. This will allow you to estimate the resistance of one wire.

Task 2: Open-Circuit Tests

Take the **Transformer** and wire it for the Open-Circuit Test as shown in the Fig. 3 below. Assume that one of the sides is Primary and the other one is Secondary as you did before and be consistent with Task 1. Remember, you will have to be consistent with it throughout the entire lab. Use the **Power Supply** configured as shown in Fig. 2 to provide the variable AC voltage to the Primary Side as depicted in Fig. 3. Use the **Measurement Box** to measure the primary voltage v_1 and current i_1 and the secondary voltage v_2. Use the first Channel (V1 and A1) for the Primary Side and the second Channel (V2 and A2) for the Secondary Side measurements, respectively. Pay particular attention to the polarity of each measurement channel as it will affect how the variables will be displayed on the screen. Maintain the consistency in your wiring and use the color-coded wires to make it easier to trace your circuit. Ask your TA for help if needed.

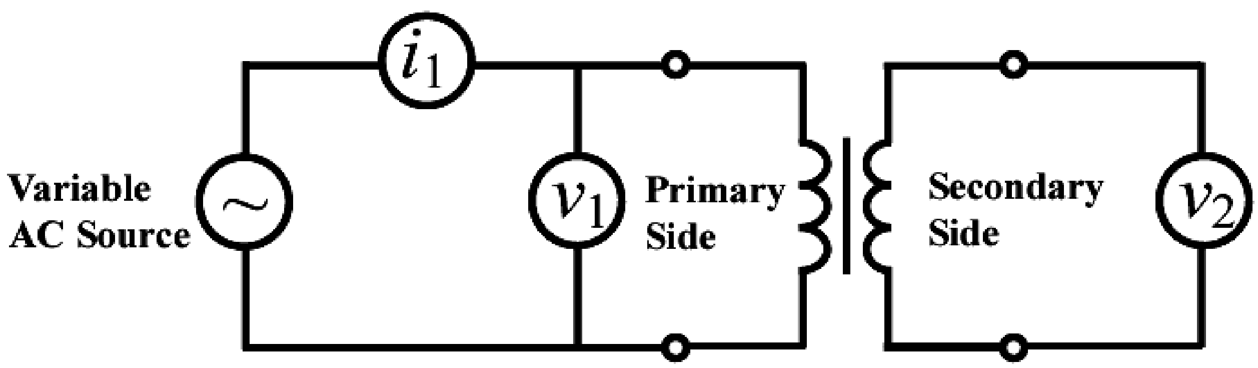

Fig. 3: Wiring diagram for the Open-Circuit Tests.

Task 2 A: Open-Circuit Nominal Condition

a) Make sure that the program **Transformer Measurement** is running on your PC. Turn on the **AC Power Supply** and keep monitoring the voltages and currents on the computer screen. For good results, you can trigger on the primary side voltage and adjust its angle close to zero.

b) Slowly increase the voltage v_1 until you start noticing distortions in the primary current i_1 (this may happen around 8.5 V at low voltage side or 18.5 V at high voltage side). These distortions are caused by the magnetic nonlinearity of the transformer core known as core saturation. Most transformers are designed to operate slightly into the saturated region, but not too far, in order to avoid very high currents.

c) Assume that the applied voltage found in part (b) corresponds to the **Nominal Condition** for the given transformer. Write your measurements in Table 2. Include the RMS values and the respective angles. You should see that the primary current i_1 is (mostly inductive) lagging the applied voltage v_1. You may try to increase the number of cycles taken for measurement to get more stable values.

Task 2 B: Determining the Transformer Polarity

d) Observe the phase shift between the voltages v_1 and v_2, and fill-in the appropriate boxes in Fig. A in your report (see p. 13 on this Manual). Make sure to write on Fig. A the following:
   i) the nominal voltages as you have determined in part (b),
   ii) identify the color of each terminal,
   iii) label the H-X polarity of each terminal
   iv) and label the transformer polarity with the "dots", as appropriate.

Task 2 C: Open-Circuit Saturated Condition (up to 200%)

(a) Slowly increase the voltage v_1 to about 160% of the value found in part (b). You should observe very pronounced distortions in the primary current i_1. **(DO NOT EXCEED 3A peak in currents in any circumstances**). Very high current may damage (burn, melt) the transformer winding. At the same time, the software program **Transformer Measurement** should also display the $\lambda - i$ curve that should look similar to a hysteresis loop that you have seen in class. Write down your measurements into Table 3.
(b) The **Transformer Measurement** software allows you to save the waveforms that are being displayed on the screen. First **PAUSE** and then **SAVE** several cycles of data for the future use. You will need these measurements to reproduce the $\lambda - i$ hysteresis loop and calculation of the core losses. For comparison, you can also save your screen (Print Screen) into a bitmap file and then compare it with the reproduced hysteresis loop.
(c) Reduce the voltage to zero and turn OFF the **AC Power Supply.**

Task 3: Short-Circuit Test

Update the circuit with **Transformer** for the Short-Circuit Test as shown in the Fig. 4 below. Use the **Measurement Box** first Channel (V1 and A1) to measure the primary voltage v_1 and current i_1, and the second Channel (A2) to measure the secondary current i_2. Make sure not to apply very high current that may overheat (melt) the **Transformer**. Use the Variac on the **AC Power Supply** to control the applied voltage and current. Maintain the consistency in your wiring.

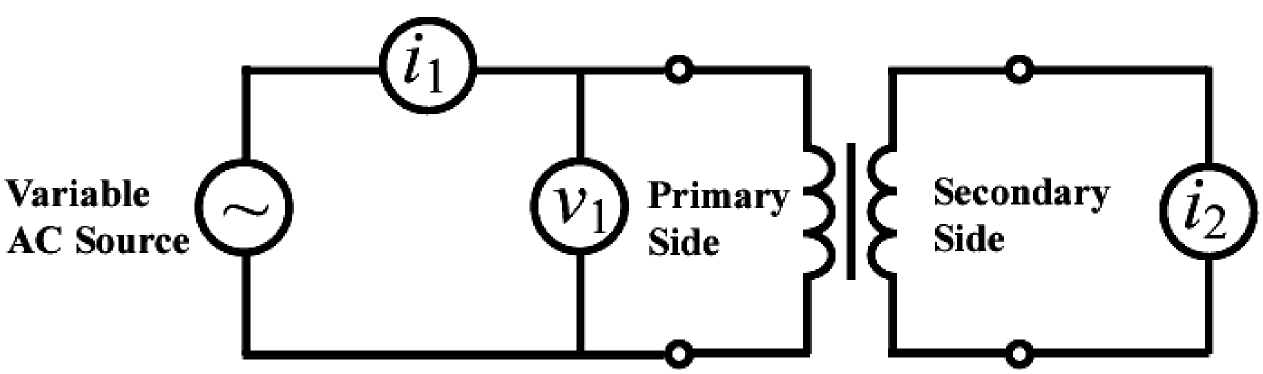

Fig. 4: Wiring diagram for the Short-Circuit Test.

(a) Turn on the **AC Power Supply** and keep monitoring the voltages and currents of the computer screen.
(b) Slowly increase the voltage v_1 until one of the currents i_1 or i_2 reaches the maximum allowable value (about 5A peak). Write your measurements for i_2 in Table 4. For better accuracy, when recording the values for the Primary side, short-circuit the Secondary side with a separate short wire. This will reduce the total resistance in the loop. Then, write down the remaining measurements in Table 4.
(c) Reduce the voltage to zero and turn OFF the **AC Power Supply.**

Task 4 A: Load Test using Resistive Load

Update the circuit for the Load Test as shown in Fig. 5 below by adding the **Load Resistor Box** to the secondary side of the **Transformer.** Use the **Measurement Box** Channel 1 (V1 and A1) to measure the primary voltage v_1 and current i_1, and Channel 2 (V2 and A2) to measure the secondary voltage v_2 and current i_2. Use the Variac on the **AC Power Supply** to control the applied voltage and current. Maintain the consistency in your wiring.

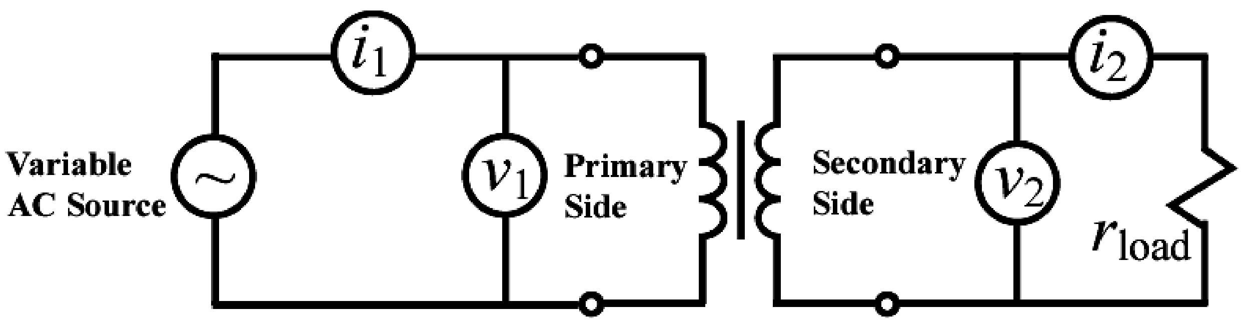

Fig. 5: Wiring diagram for the Load Test.

(a) Turn on the **AC Power Supply** and keep monitoring the voltages and currents of the computer screen. Make sure that the circuit is working correctly, and then turn all of the switches on the **Load Resistor Box** to the **OFF** position (no load).
(b) Slowly increase the voltage v_1 until the Nominal Value that was determined in Task 2(b). This operating point should correspond to the Open-Circuit condition determined in Task 2.
(c) Apply the load by switching ON the 100Ω resistor in the **Load Resistor Box**. Take up to 5 measurements by adding more 50Ω resistors in parallel. While taking the measurements, **maintain the primary voltage** v_1 **constant** by adjusting the Variac knob (slightly increasing the output). Record the measurements into Table 5.
(d) The currents and voltages should be close to sinusoidal. **PAUSE** and then **SAVE** several cycles of data corresponding the highest load (highest current form part (c)) for the future use. For future comparison, you may also save your screen (Print Screen). You will need to explain why you do not see the effect of saturation in the primary and/or secondary currents.
(e) Reduce the voltage to zero and turn OFF the **AC Power Supply.**

Task 4 B: Load Test using RL (Inductive) Load

Update the circuit of Fig. 5 by adding two inductors (inductors connected in series) from the **RL Load Box** in **parallel** to the **Load Resistor Box.** This will make your load to have lagging (inductive) power factor. Then repeat the measurements of Task 4 A, steps (a) through (c). Remember to maintain the same primary voltage as you had in Task 4 A. You may notice that the secondary voltages are now somewhat lower than what you had in Task 4 A, and that your currents now have pronounced lagging angle. Record the measurements into Table 6.

Task 4 C: Load Test using RC (Capacitive) Load

Update the circuit of Fig. 5 by adding all three capacitors (capacitors connected in parallel) from the **RC Load Box** in parallel to the **Load Resistor Box.** This will make your load to have leading (capacitive) power factor. Then repeat the measurements of Task 4 A, steps (a) through (c). Remember to maintain the same primary voltage as you had in Task 4 A. You may notice that the secondary voltages are now somewhat higher than what you had in Task 4 A and 4 B, and that your currents now may have leading angle. Record the measurements into Table 7.

Task 5: Recording Inrush Current

As you remember from the lectures, the energizing of transformer may result in a very high transient current known as the **inrush current**. In this Task, you will be recording the transformer energizing transients to verify that the time instance (and the value of voltage) at which the transformer winding is connected to the source has a very pronounced effect on the inrush current. Configure the circuit as in Fig. 3 for open circuit test, but <u>this time make sure to use one special wire that has a **built-in switch** on it to replace the wire that connects the power supply and the current channels of the measurement box for easy disconnection of the source.</u>

Turn ON the **AC Power Supply**, close the **Switch** and adjust the voltage slightly above of the Nominal Condition found in Task 2 A, to about 120 to 130%. The primary current peak should not exceed the 1.5 A to 2 A peak level. On the **Transformer Measurement** program, set the **Sampling Period** to the highest values 2000ms = 2sec. Now your measurement window will be updated every 2 seconds and you will be able to capture the Switching-ON transients.

Leave the **AC Power Supply** ON and open the **Switch**. After all the waveforms on the **Transformer Measurement** program go to zero, close the **Switch** and press the **PAUSE** button once you see the result is being updated and displayed on the screen. In this way, you should be able to capture the energizing transient. You may need to repeat this procedure many times in order to capture the right transient event. Adjust the current range to the highest value. In doing these experiments you should notice that sometimes the first peak of the current can be very high – up to 10 to 20 A, and some other times the peak of the current can be only slightly higher (if at all) of the steady state value.

Your goal is to capture one transient study with the highest current peak and one more transient with almost no peak at all. Once you have captured the transient that you like, you can then change the **POSITION** and **ZOOM** in (by using the corresponding buttons on the panel) to see more details of the captured data. After that, you can **SAVE** the data for future analysis and plotting in your report. For your analysis, you will need to plot the voltage and current waveforms and correlate them with what you know about the saturation and inrush current.

Task 6: Calculations and Analysis

Task 6 A: Determining the Equivalent Circuit Parameters

Write the calculation of parameters based on the measured data. For calculating the DC resistances of the windings, use the values calculated from the Short-Circuit Test. How close are these values to what you have measured in Task 1 using the Multimeter? Explain what might have contributed to possible differences in these results. Write down your parameters in Fig. B in appropriate boxes. Also state whether you have used this transformer as a Step-Up or a Step-Down transformer.

Task 6 B: Equivalent Circuit vs. Measured Comparison

Use the equivalent circuit of Fig. B as the model for your **Transformer**. Assume the same primary voltages V_1 and the load resistance R_{load} as were obtained in Task 4 A, step (c), and recorded in Table 5, as the input values, and then calculate the remaining values in Table 8. Also, using Matlab, add few more points by assuming smaller load resistor all the way to zero (short-circuit). Plot the output voltage $V_2(I_2)$, input power factor angle $\varphi_1(I_2)$, and the efficiency $\eta(I_2) = P_2/P_1$. On each plot, show and compare the measured and calculated quantities.

What can you say about accuracy of the equivalent circuit? How well does it predict the loading characteristics of your transformer? Where is the maximum efficiency of this transformer?

Task 6 C: Effect of Load Power Factor on the Loading Characteristics

Remember that in Task 4, you had the same primary voltage used with different loads. Using the measurements from Tasks 4 A, B, and C, plot and superimpose the output voltage $V_2(P_2)$, input power factor angle $\varphi_1(P_2)$, and the efficiency $\eta(P_2) = P_2/P_1$ for all three cases.

How can you explain these results? How does the load power factor affect the output voltage? How did the real power change (in each step) when you connected either inductor or capacitor in parallel to the resistive load?

What can be used to boost the secondary voltage on the transformer output, inductors or capacitors? Why?

Task 6 D: Hysteresis Loop

Use the saved data from the Task 2 C (Open-Circuit Test: Saturated Condition). You need to calculate the flux linkage $\lambda(t)$. Based on the voltage equation $v_1 = i_1 r_1 + \frac{d\lambda}{dt}$, the flux linkage can be found as $\lambda(t) = \int (v_1 - i_1 r_1)dt + C_\lambda$. You may use **MATLAB** or **EXCEL** to perform the necessary integration. In particular, you can find it very easy to use the **MATLAB/Simulink** and its standard library blocks (from file, summers and integrators) to input your measured data and implement this equation directly in the Simulink model. The constant C_λ should be chosen to make the $\lambda(t)$ centered about zero. To do that, you will need to calculate the average and then subtract it. On a separate graph, plot the $\lambda - i_1$ loop and include it with your report. How does this result look similar or different from the Screen Captured view of the $\lambda - i$ curve that you have saved?

Also, calculate the harmonic spectrum for the input current i_1 for the saturated condition of Task 2 C using FFT or a similar tool (as you did in Lab-1). Plot this spectrum on a separate plot and conclude what kinds of harmonics are produced by the transformers if the transformers are heavily saturated?

Task 6 E: Core Losses

Calculate the area of one cycle of the $\lambda - i_1$ loop. Relate this area to the core losses and compare it to the measured dissipated input power in Task 2 C. This may be best done using Matlab.

Task 6 F: Analysis of Inrush Current

Based on your recorded data of the inrush current transient in Task 5, plot the current and voltage for the case with very small inrush current transient. Then, also plot current and voltage for the case corresponding to the very high peak of the inrush current. Compare the value of voltage at the energizing instance and conclude which case would be more favourable for connecting the transformer to the power source. Conclude/elaborate on how the inrush current could affect large transformers and the power network?

Task 6 G: Questions

(a) Why do you think it is not a good idea to operate a transformer above its nominal (rated) voltage?

(b) How can you describe the waveform of the primary current $i_1(t)$ when the transformer is loaded as in Task 4 A (last measurement)? How this waveform is different from $i_1(t)$ under the no load case in Task 2 A and C?

(c) What can you say about the accuracy of the equivalent circuit? Does it predict all of the phenomena that you have observed during this lab experiment?

(d) Assuming that you have a two-winding transformer that you have used in this lab, sketch the step-up and step-down **auto-transformer** connections. In each case, label the input and output voltages based on the nominal voltages found in Task 2.

Task 7: Reporting

Prepare the Lab Report according to the General Requirements for this course and Lab. Your Report should include:

(a) Title Page (all filled-in, with electronic signatures).

(b) Pre-Lab, (scanned or pictures of pages)

(c) Pages with the measured data and figures (pages 13 – 17).

(d) Additional pages with **Calculations and Analysis** including discussions and answers to questions in Task 6. Include appropriate equations, calculations, comments, and picture of the Simulink model for Task 6 D if you used it.

(e) Summary Section: Briefly state and summarize what you have learned doing the experiments and subsequent calculations.

(f) Appendix: Please include any additional Matlab code or windows of Simulink models that you have used for this lab.

Note: The lab reports must be typed. No exception!

ELEC 342

Lab Experiment: ___

Section: ___

Bench #: ___

Partners	Student ID #:	% participation	Signatures

Date Performed:

Date Submitted:

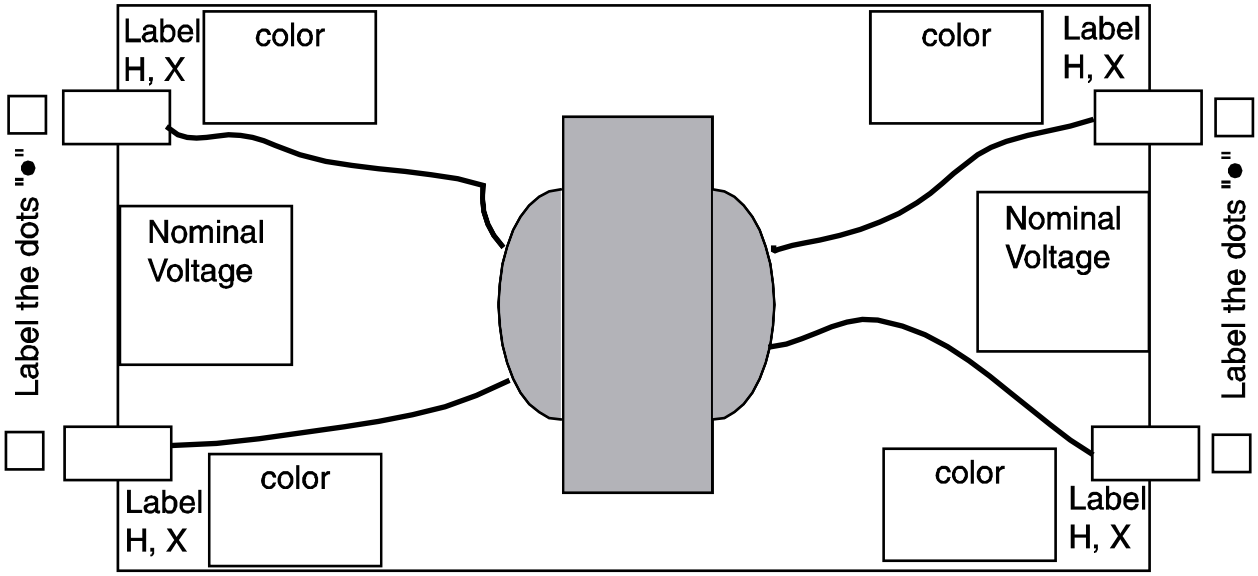

Fig. A: Transformer connection diagram (to be completed in class).

Table 1: Measured DC resistance with two and four long wires using the Multimeter.

Measurement	Primary Side Resistance, Ohms	Secondary Side Resistance, Ohms
Windings plus two long wires		
Windings plus four long wires		

Based on these measurements, calculate resistance of a single wire: R_{wire} = _______________

Table 2: Open Circuit Measurement: Nominal Condition (100%)

$V_1(rms), V$			$V_2(rms), V$	
$I_1(rms), A$			$I_2(rms), A$	
$P_1(ave), W$			$P_2(ave), W$	
$\varphi_1 = \theta_{V1} - \theta_{I1}$			$\varphi_2 = \theta_{V2} - \theta_{I2}$	
$a = V_1/V_2$				

Table 3: Open Circuit Measurement: Increased Voltage (~160%)

$V_1(rms),V$			$V_2(rms),V$	
$I_1(rms),A$			$I_2(rms),A$	
$P_1(ave),W$			$P_2(ave),W$	
$\varphi_1=\theta_{V1}-\theta_{I1}$			$\varphi_2=\theta_{V2}-\theta_{I2}$	
$a=V_1/V_2$				

Table 4: Short Circuit Measurement: Nominal Condition (up to 5A peak current)

$V_1(rms),V$			$V_2(rms),V$	
$I_1(rms),A$			$I_2(rms),A$	
$P_1(ave),W$			$P_2(ave),W$	
$\varphi_1=\theta_{V1}-\theta_{I1}$			$\varphi_2=\theta_{V2}-\theta_{I2}$	
$a=I_2/I_1$				

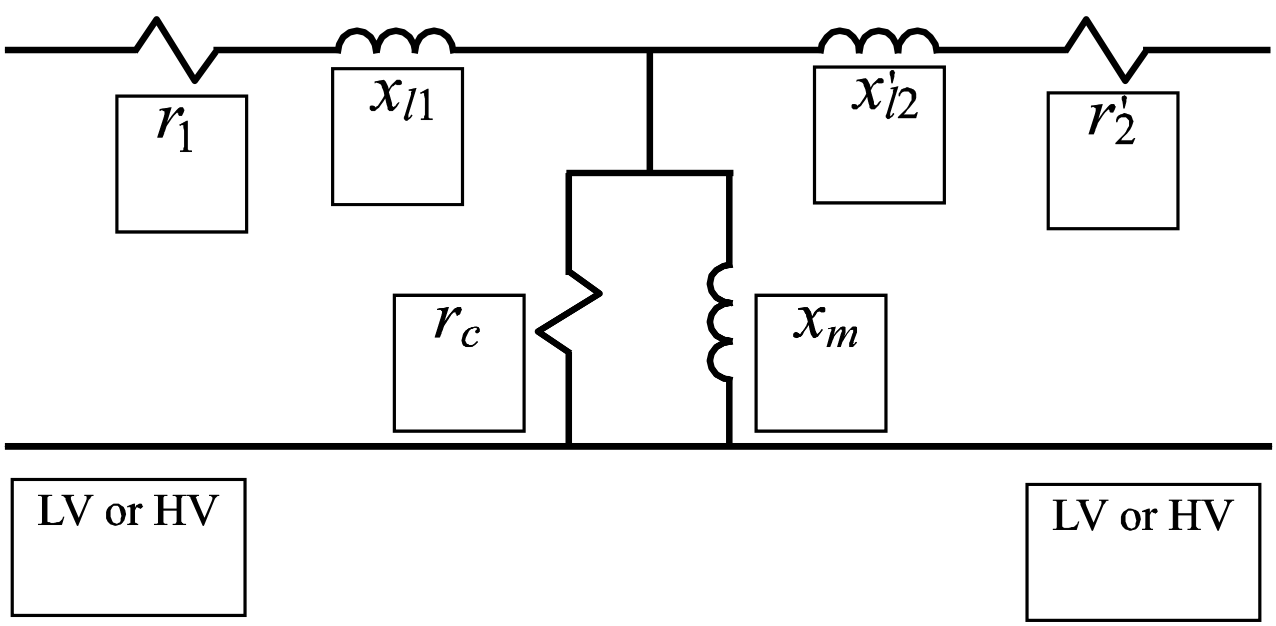

Fig. B: Transformer equivalent circuit diagram (to be completed for report). Here you must write the values referred to the Primary Side, as they come directly from your calculations. Note: the Primary Side (on the left) may be LV or HV Side depending on your initial choice.

Table 5: Resistive Load Test Measurement: (up to 5 measurement points)

Measurement #	1	2	3	4	5
$V_1(rms), V$					
$I_1(rms), A$					
$P_1(ave), W$					
$\varphi_1 = \theta_{V1} - \theta_{I1}$					
$V_2(rms), V$					
$I_2(rms), A$					
$P_2(ave), W$					
$\varphi_2 = \theta_{V2} - \theta_{I2}$					
P_2 / P_1					
$R_{load} = V_2 / I_2$					
$VR = (V_{2,oc} - V_{2,load}) / V_{2,load}$ (take the values from the last measurement)					

Table 6: RL (Inductive) Load Test Measurement: (up to 5 measurement points)

Measurement #	1	2	3	4	5
$V_1(rms), V$					
$I_1(rms), A$					
$P_1(ave), W$					
$\varphi_1 = \theta_{V1} - \theta_{I1}$					
$V_2(rms), V$					
$I_2(rms), A$					
$P_2(ave), W$					
$\varphi_2 = \theta_{V2} - \theta_{I2}$					

P_2 / P_1					
$Z_{load} = V_2 / I_2$					
$VR = \left(V_{2,oc} - V_{2,load}\right) / V_{2,load}$ (take the values from the last measurement)					

Table 7: RC (Capacitive) Load Test Measurement: (up to 4 measurement points)

Measurement #	1	2	3	4
$V_1(rms), V$				
$I_1(rms), A$				
$P_1(ave), W$				
$\varphi_1 = \theta_{V1} - \theta_{I1}$				
$V_2(rms), V$				
$I_2(rms), A$				
$P_2(ave), W$				
$\varphi_2 = \theta_{V2} - \theta_{I2}$				
P_2 / P_1				
$Z_{load} = V_2 / I_2$				
$VR = \left(V_{2,oc} - V_{2,load}\right) / V_{2,load}$ (take the values from the last measurement)				

Table 8: Resistive Load Test: Calculated values based on your equivalent circuit.

Calculated points #	1	2	3	4	5
$V_1(rms), V$					
$I_1(rms), A$					
$P_1(ave), W$					
$\varphi_1 = \theta_{V1} - \theta_{I1}$					
$V_2(rms), V$					
$I_2(rms), A$					
$P_2(ave), W$					
P_2 / P_1					
$VR = \left(V_{2,oc} - V_{2,load}\right) / V_{2,load}$ (take the values from the last calculation)					

(HINT: For this Table, you need to include just 5 points, but in your Matlab code, you can assume more points for smooth plot! You will also need to include few more points assuming decreasing values of load resistance all the way to zero – short-circuit.)