University of Utah
Electrical & Computer Engineering Department
ECE 3600 Lab 2

Model of a Power Transformer

Based on labs by: L. D. Harris & D. K. Gehmlich
A. Stolp, 9/23/08, rev, 9/23/10

Objectives

1. Observe that the current is nonlinear, implying that the permeability is not linear.
2. Observe the dynamic B-H curve, called the hysteresis loop.
3. From measurements and calculations, derive an equivalent circuit for an iron-core inductor, in this case, the primary of a transformer.
4. From additional measurements and calculations, derive a model for a power transformer.
5. Measure the power efficiency of the transformer and compare the measurements to calculations made from the model.
6. Measure the voltage regulation of the transformer and compare the measurements to calculations made from the model.

Equipment and materials to be checked out from stockroom:

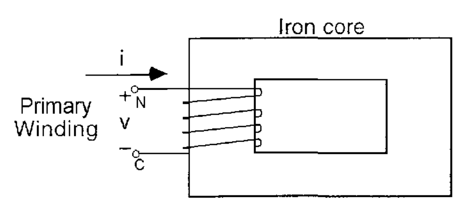
- Power wire kit
- Wattmeter panel
- Two multimeters
- Power strip
- "Suicide" cord
- 3-prong to 2-prong adapter
- Vari-AC (Auto-transformer)
- MTC (Mountain Transformer Company) Transformer

Parts to be supplied by the student:

- Resistors: 1 MΩ -¼ watt and 5 Ω -½ watt (You can make the 5 Ω -½ watt resistor out of two 10 Ω -¼ watt resistors in parallel.)
- 0.1 µF Capacitor
- bread-board and wires

Experiment 1 (Characteristics of an iron-core inductor)

Background



Ignoring winding resistance and core flux leakage, the applied voltage (v) is related to the flux (ϕ) in the core

by $$v = N\frac{d\phi}{dt}$$

and the current (i) is related to the flux by

$$H = \frac{Ni}{l_m} = \frac{B}{\mu} \quad \text{or} \quad i = H\frac{l_m}{N} = \frac{l_m B}{\mu N} = \frac{l_m \phi}{\mu N A}.$$

These equations for v and i should appear in your lab notebook with some explanation. The equations imply that if v is sinusoidal, so is the flux and the current. However, you will soon see that even with an applied sinusoidal voltage, the current in the iron-core inductor will be nonsinusoidal, implying that the iron-core device is nonlinear.

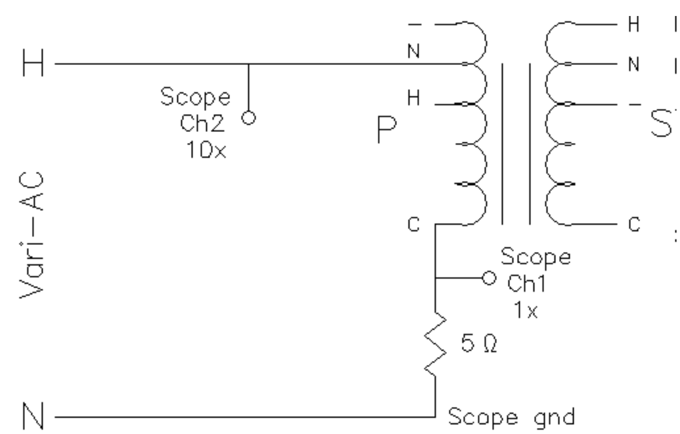
Setup

Switch off the power strip and plug it in. Switch off the vari-AC, turn it to 0V and plug it into the power strip. Make sure the suicide cord's leads are free and clear and plug it into the vari-AC using the 3-prong to 2-prong adapter. Hook one lead of an AC voltmeter to a ground. There is a ground terminal on the bench power supply or use one of the oscilloscope grounds.) Switch on the power strip and check that both the suicide cord's leads are at near-ground potential. Switch on the vari-AC and check again. If you measure AC line voltage on either lead in either case something is wired incorrectly and is dangerous-- inform your TA. If there are no problems, turn up the vari-AC to about 30 V and see which lead is hot. If it's not the red lead, turn the plug over in the vari-AC. This will be your AC source for the rest of this lab. Turn the vari-AC back down to 0 V and switch it off. Always turn down the voltage before switching it off or on to avoid current surges in the transformer windings. Whenever you perform some task like this as part of the lab, you should include some description in your lab notebook.

All work described below should be performed on the primary winding of an MTC transformer (rated 115/115 volts, 60 Hz, 250 VA). The effective cross-sectional area (A) of the iron core is 13.3 cm^2 and the effective magnetic path length (l_m) is 23.5 cm. There are 260 turns (N) on the primary. The secondary winding should be left unconnected, so the transformer primary will look a simple iron-core inductor.

The primary side of the transformer is labeled "P". You will use the "C" (common) and the "N" terminals on this side of the transformer. ("N" refers to "normal" voltage, "H", to "high" and "-" to "low".) Make sure that all other leads are free and clear when the C and N terminals are hooked to the Vari-AC.

Procedures and Measurements

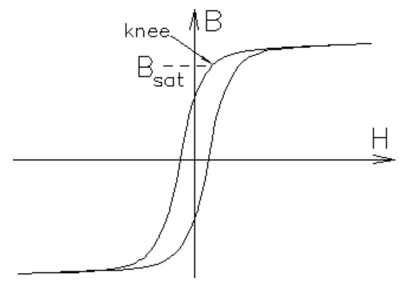


We would like to simultaneously display both the applied voltage, v and the resulting current, i on an oscilloscope. Since the scope only measures voltage, we'll use the 5Ω resistor to get a measurable voltage that depends on the current ie, make the current flow through the 5Ω resistor and use Ch1 to see the voltage across it. That part's easy, but remember that the two oscilloscope channels and the power cord have a **common ground**, so make certain that the scope ground is connected to the neutral "N" side of the power. Unfortunately, that also means that we can't get a perfect voltage trace on Ch2. It will include a small error due to the 5Ω resistor, but because the resistor is small, we can live with it.

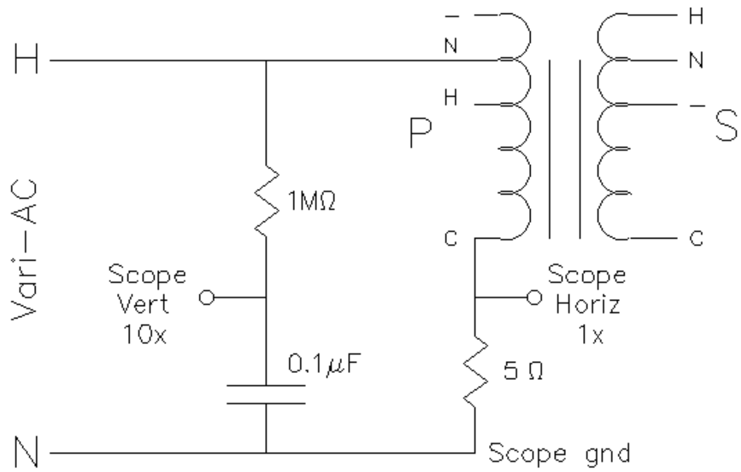
Implement the setup shown, switch on the vari-AC and slowly turn it up to 115 V as you watch the current trace. Sketch both v and i your notebook. Include units of voltage and current in your sketch. That will require that you calculate the current peak from the scope measurement. Comment on the shape of v and i.

Determine the peak voltage (V_p) and the peak current (I_p) from your scope or sketches. Look back at the equations relating v and flux (ϕ) and i. Calculate the peak flux (ϕ_p), the peak flux density (B_p) and the peak magnetic-field intensity (H_p) in the core. Also calculate an average permeability (μ_{ave}) from these peak values.

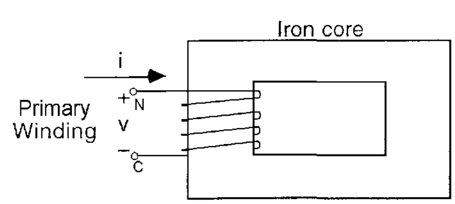
It should be very obvious that the current is not a sinusoid. That means that something in the iron core is not linear and one of the constants in the equations you were using isn't really a constant. Can N or A or l be anything but constants? What has to be the source of the nonlinearity?



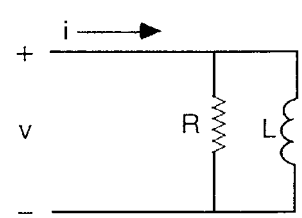
The permeability of the iron-core is often described by a B-H curve. Your next objective is to plot the B-H curve for your iron core. Look at the circuit below. Show that the 1-MΩ resistor and the capacitor will do a reasonable job integrating the applied voltage to give you a measurement of ϕ and thus B. (This calculation may be done later to save time now, but be sure to leave room in your notebook. The 5-Ω resistor used to measure current should already be familiar to you.I will remind you of such calculations at the end of the lab.) Implement the circuit to observe a dynamic B-H curve (also called a hysteresis loop) for the transformer on an oscilloscope. Caution: Be sure the scope ground is also source ground and remember that both horizontal and vertical inputs have a common ground. Sketch the loops for several values of applied voltage below the rated voltage. Also sketch the loop at 115 V and again at 130 V. Find the knee of your 115-V curve and calculate flux density at which this core saturates (B_{sat}) from your measurements. Typical iron saturation values are 1.6 to 1.8 Tesla.



Experiment 2 (Equivalent circuit of an iron-core inductor)



If we ignore the nonlinearities that we just saw, we can model (an equivalent circuit is a model) the performance of an iron-core inductor reasonably well with the parallel combination of a resistor and pure inductor. You will make measurements and calculations that will lead to the numerical values of R and L of the model shown. A series combination of a different R and different L could be also used as a model of the

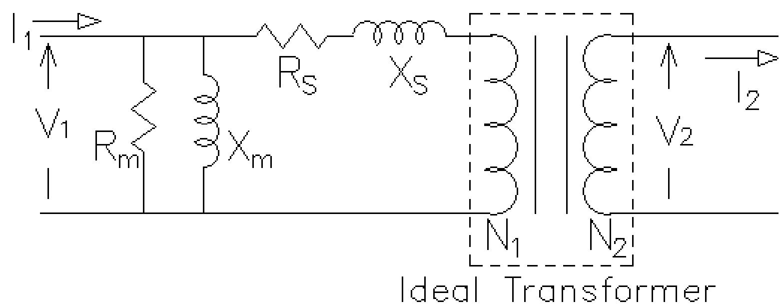


inductor; however, for this laboratory job, we will use the parallel combination. This has some advantages that are not necessarily obvious at this point.

Make appropriate measurements to find an R and L in the model to best represent the iron-core circuit at 115 V. I suggest you use the power meter an ammeter (true RMS, if available) and a voltmeter much like you did in lab 1. Turn down the vari-AC, switch it on and turn it up to 115 V for the measurements. Since you are looking for a linear model, assume a sinusoidal current. Draw your setup in your notebook, record your measurements, calculate R and L and draw the model of the inductor (the primary).

Experiment 3 (Model of a Power Transformer)

Background



Refer to section 3.5 (esp. Starting p105) in your text and your transformer notes handed out in class. The transformer model we will use is shown at right. X_m represents the inductance of the primary and is called the "magnetizing reactance". R_m accounts for the no-load core power losses. These are due to the hysteresis in the B-H curve and to eddy-currents in the core. The series impedances, R_S and X_S account for winding resistance and leakage reactance. Both of these effects depend on the load current, I_2.

In experiment 2, you found the equivalent circuit of an iron-core inductor which happened to be the primary of a transformer. Thus, you essentially performed an open-circuit (OC) test on this transformer and found R_m and L_m, which can be translated to X_m. In this experiment you will perform a short-circuit (S.C.) test and find R_S and X_S to complete the transformer model. Finally, you will compare some lab measurements to calculations made using the model.

Setup

The setup for the short-circuit test is the same as it was for the open-circuit test, however, now it is critical that the voltmeter connections (including the voltmeter part of the wattmeter) are on the transformer-side of any ammeters. That is necessary because there can be a significant voltage drop across the ammeters which can throw off your measurements. (In fact it can make it appear as though the real power is greater than the apparent power.) Make adjustments to your connections as needed.

Short-Circuit Test

This MTC transformer is rated 115/115 volts, .25 kVA, 60 Hz. Determine the rated primary current. Make sure that your ammeter can handle that current. If it can't, use another ammeter (or the 10 A connection). With the Vari-AC turned down to zero, short the secondary winding. **Slowly** and **carefully** turn up the Vari-AC until the rated current flows in the primary. Take measurements of P, V, and I. If you ignore the effects of X_m and R_m at this low voltage (very reasonable to do) then the transformer is just X_S in series with R_S.

Find X_S in series with R_S from your measurements.

Draw the entire transformer model in your notebook with all the values that you have found.

Voltage Regulation and Power Efficiency

Prepare to connect various load resistors to the secondary of the transformer. Move ammeter from the primary side to the secondary side to measure I_2. Add the second multimeter to the secondary to measure V_2. Since you will connect resistors, you can simply calculate the P_{out} as I_2V_2. You will measure P_{in} , I_2 , and V_2 for 4 different loads, approximately; 0 W, 50 W, 150 W, and 250 W. Make a table with 4 rows and columns for P_{in} , I_2 , V_2 , P_{out} , VR and η.

VR is voltage regulation: $VR = \frac{V_{noload} - V_{load}}{V_{load}} 100\%$

η is power efficiency: $\eta = \frac{P_{out}}{P_{in}} 100\%$

For the 0 W, well... if you don't know what to do it's time to look for a different major. Turn the primary up to 115 V (measured) and record P_{in} , I_2 , and V_2 in the table. Turn down the primary voltage. For all the other loads, your TA will have some large resistors preset and labeled for the loads. Take one at a time, not necessarily in order. Repeat the measurements for each.

You are now done with the lab measurements, assuming they were made correctly. If you need to leave the lab, you can check-off now and do the calculations and plots later.

Calculate VR, P_{out} and η for each load from measured data (VR is 0 for the 0-W load). Plot VR vs P_{out} and η vs P_{out} Make nice plots (a computer is the recommended plot tool).

Calculations From the model

For the 150 W load, calculate the load resistor, R_L. Draw your model with this R_L transformed to the primary side in place of the ideal transformer. Use your model to calculate VR and η. Compare these numbers to those you found from measurements.

Repeat for the 250 W load.

Check-off and Conclude

If you skipped showing that the resistor and the capacitor used in the circuit of experiment 1 to display the B-H curve did a reasonable job integrating the applied voltage to give a measurement of ϕ and thus B, don't forget to do that now.