AC Excitation

Introduction

Transformers are foundational elements in all power distribution systems. A transformer couples two (or more) coils to the same flux. As long as the flux is changing (ac), power may be transferred from one coil to another. Unfortunately, changing flux in a magnetic material gives rise to losses, as well as changing stored energy (which we represent as VARs).

Figure 1 shows the transformer schematic symbol and the corresponding commonly used Steinmetz model is shown in Figure 2. Therein, the model voltage and current phasors are defined as:

$\hat{V}_1$	Primary side voltage (V)
$\hat{I}_1$	Primary side current (A)
$\hat{V}_2'$	Referred secondary side voltage (V)
$\hat{I}_2'$	Referred secondary side current (A)
$\hat{I}_\phi$	Magnetizing current (A)

The model parameters are:

R_1	Primary coil resistance (Ω)
X_{l1}	Primary coil leakage reactance (H)
R_c	Core loss resistance (Ω)
X_m	Core magnetizing reactance (Ω)
R_2'	Referred secondary coil resistance (Ω)
X_{l2}'	Referred secondary coil leakage reactance (H)
$\frac{N_1}{N_2}$	Transformer turns ratio

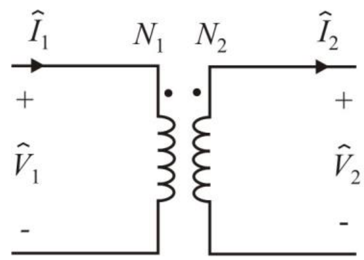

Figure 1. Transformer symbol.

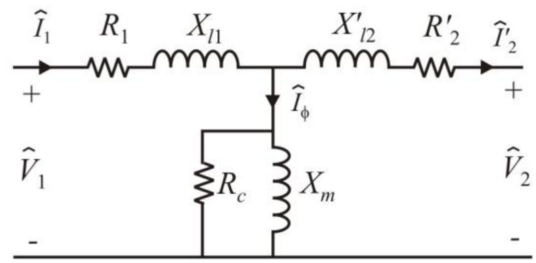

Figure 2. Steinmetz model of a transformer.

This Steinmetz model has been augmented with a core loss term R_c in parallel with X_m that approximately accounts for the hysteresis and eddy current losses in the core.

Measuring Magnetizing Apparent Power and Core Losses

All practical magnetic materials are nonlinear, with hysteresis and saturation. The nonlinearities, along with finite permeability, give rise to magnetizing current that is non-sinusoidal and partly in phase with the applied voltage. Under this condition, the Steinmetz equivalent circuit (including the core loss term) reduces to that shown in Figure 3. However, the circuit is not truly linear—we simply use a linear approximation that is valid near the rated operating conditions.

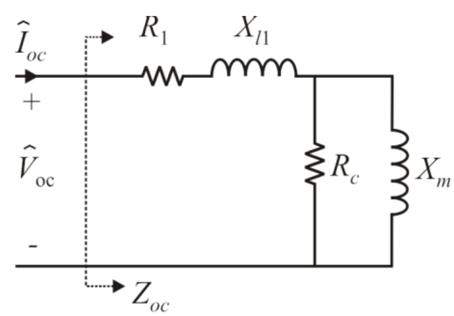

Figure 3. Steinmetz model for open-circuit test.

If we are concerned with behavior over a wide range of conditions, we must measure the active and reactive power consumption and use a graph, as may be seen in Figures 1.12 and 1.14 of *Fitzgerald & Kingsley's Electric Machinery*, 7th Ed., by Stephen D. Umans. Ideally, characteristics are measured for the steel used in the core so that a wide variety of devices may be modeled, as in the book. However, we may also characterize a particular device instead. The material curves plot apparent or active power (S_a or P_c) per kilogram vs. peak flux density (B_{max}). Mass of the core is constant, so that becomes a scale factor on one axis. We know, also, that peak flux density is related to rms applied voltage by

$$V_{rms} = \sqrt{2}\pi f B_{\max} N A_c \tag{1}$$

Where f is the frequency of the applied voltage, N is the number of turns, and A_c is the cross-sectional area of the core. For a given transformer connected to a given source, everything in (1) is constant except V_{rms} and $B_{\max}$, so we can plot power vs. voltage and see the same shape with a different scale.

Laboratory Software

Figure 6 shows a screen-shot of the program used for the single-phase transformer experiments. This program monitors the first two channels of the meter box and displays their waveforms and measurements. Data can be logged by selecting the type of test and clicking **Add**. The type of test can be selected from the drop-down **Test** menu. When the **DC Test** is selected (as shown in Figure 6), channel 1 will read dc values. Due to analog offsets, the dc voltage may have a small value before the measurement is taken (when the dc voltage and current are zero). In this case, the **Zero DC Offset** button can be clicked to zero the meters. When ac tests, such as **Short-Circuit** and **Open-Circuit**, are selected, the meter on channel 1 reads rms values. For this experiment, we will ONLY use **Open-Circuit**.

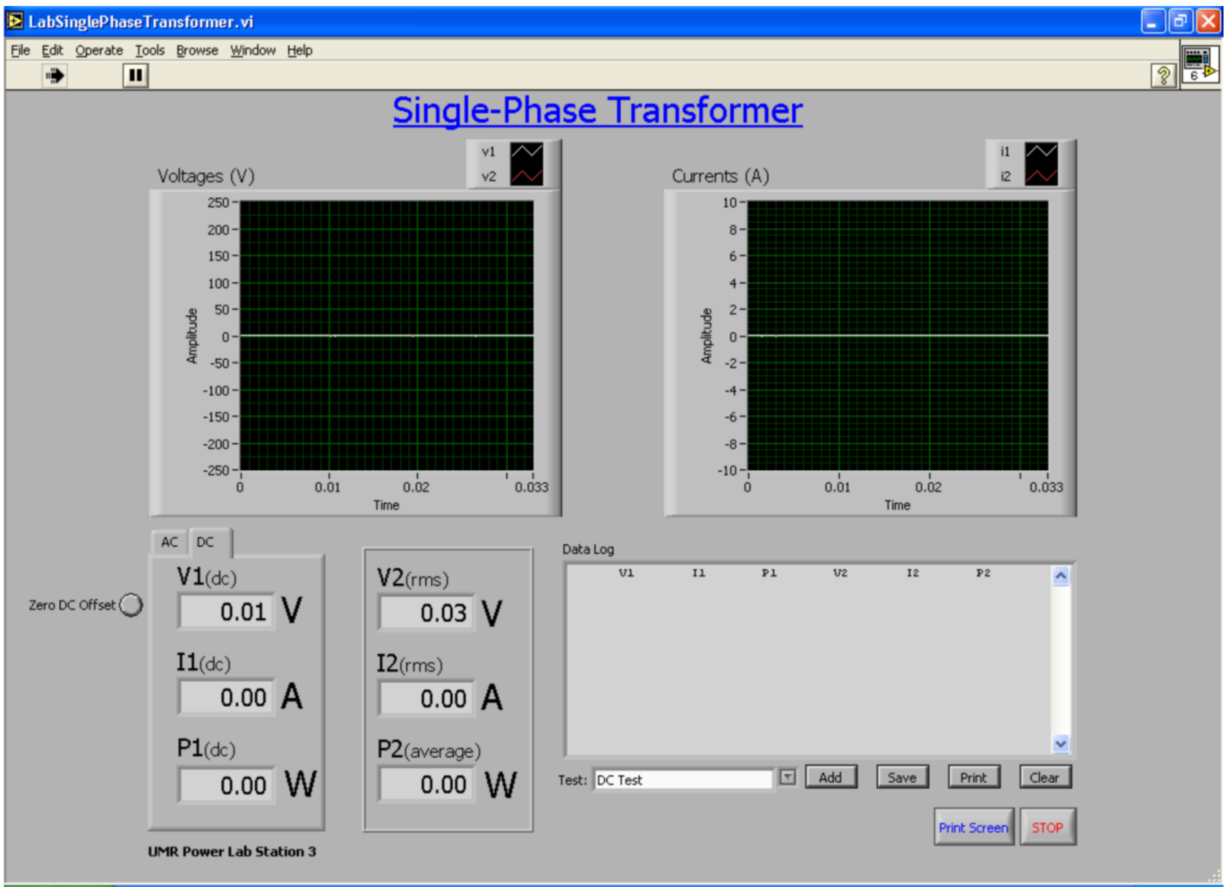

Figure 4. Laboratory software interface for the single-phase transformer experiment.

Laboratory Transformers

Figure 7 shows the laboratory transformer and a corresponding electrical connection diagram. The transformer has multiple primary and secondary windings which may be connected in series or parallel for different voltage ratings. Internally, the primary windings have been connected in series and the secondary has been connected in parallel yielding the ratings show in the table below.

Laboratory transformer ratings.	
$\left\|\hat{V}_1\right\| = 240$ V	$\left\|\hat{V}_2\right\| = 120$ V
$\left\|\hat{I}_1\right\| = 4.17$ A	$\left\|\hat{I}_2\right\| = 8.33$ A

From the voltage ratings, it can be seen that the turns ratio is $\frac{N_1}{N_2} = 2$. The connection diagram also shows the primary taps which are accessible through the connectors.

As can be seen, primary taps at 120 V and 208 V are available using terminals H2-H3 and H4 respectively. In low-power single-phase residential applications, 120 V is a common voltage level. This is typically obtained by splitting a 240 V winding. Alternatively, 120 V can be obtained from the line-to-neutral voltage of a 208 V three-phase system. For these reasons, 120 V and 208 V tap settings are commonly available on many 240 V transformers.

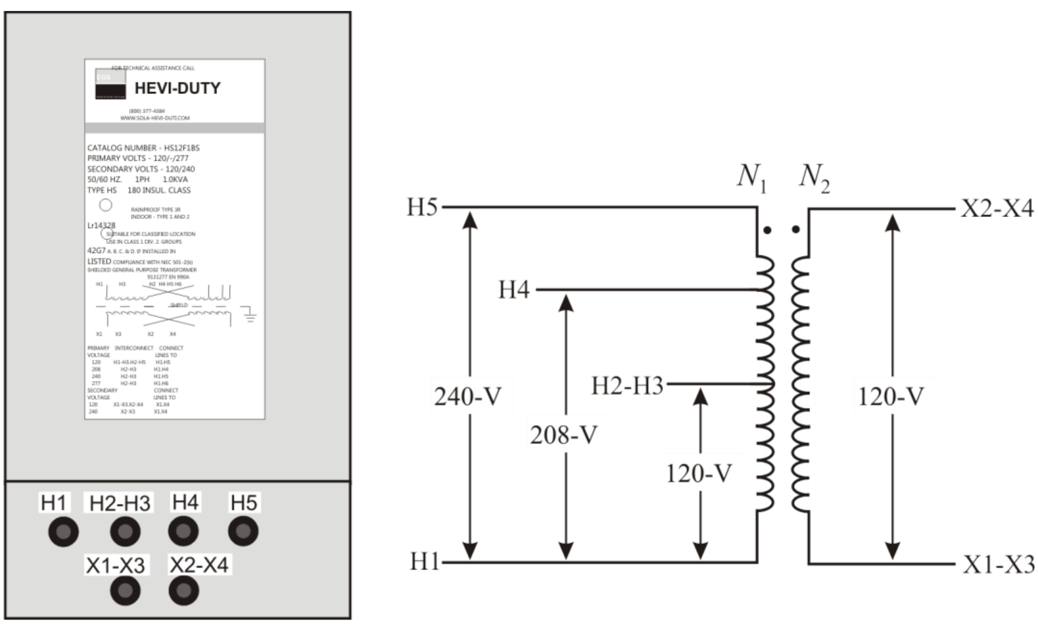

Figure 5. Laboratory transformer and connection diagram.

Laboratory Work

Using two phases of the AC source panel, connect the transformer as shown in Figure 10. Start the **Single-Phase Transformer** program (LabSinglePhaseTransformer.vi) and select **Open-Circuit**. Switch on the source circuit breaker. Log the data values at minimum applied voltage, and then increase the voltage in increments of 5-10 V. At each voltage, log the data values and note the primary current waveform. This is the transformer exciting current and has a non-linear shape due to transformer saturation. Print a few waveforms from the screen that show the qualitatively different shapes that you see. Continue until you reach full voltage on the variac. Then switch off the source and reduce the variac to zero.

Click **Save** to save the voltage, current, and power measurements from the transformer tests.

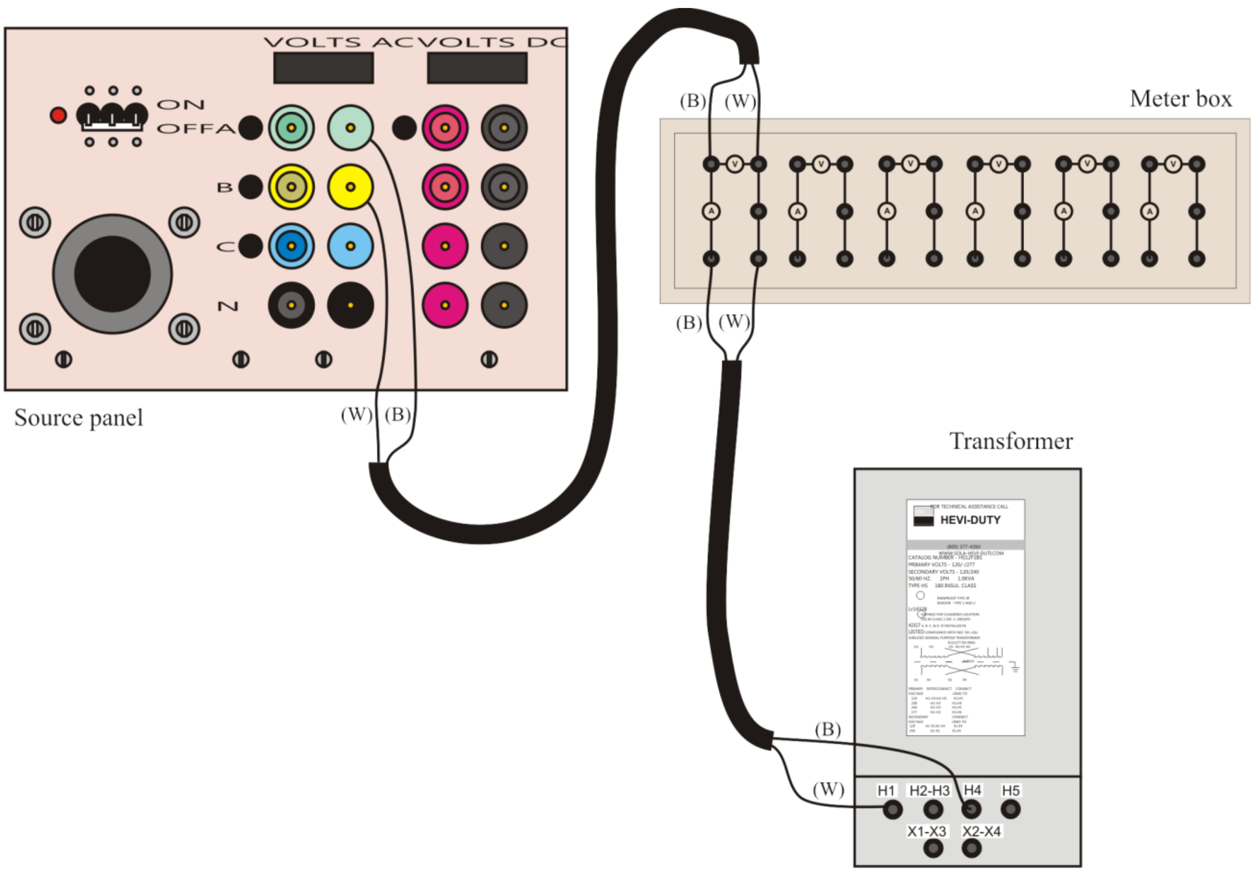

Figure 6. Laboratory connections for the open-circuit test.

Calculations and Questions

1. Plot active power vs. applied voltage and apparent power vs. applied voltage. Apparent power may be calculated from V1×I1. Attempt to replicate Figures 1.12 and 1.14 from the book (although with a different scale, as described above). Be sure to use a semilog grid (log scale on the x axis, linear scale on the y axis). Comment on any differences between your data and the curves in the book.
2. In the book figures, especially Fig. 1.12, saturation is apparent—a substantial increase in power consumption for a small change in flux density. Most likely, your data will not show this same effect, at least not to the same degree. Why? Given the equipment available in the lab, how might you explore the saturated region?
3. Why does the shape of the current change as the applied voltage increases?
4. Suppose core losses are the only source of loss in the transformer. Calculate the efficiency at full current and voltage, and at full current but half voltage.