LABORATORY SESSION 3
SINGLE-PHASE TRANSFORMERS

CAUTION:
High voltages are present in this Laboratory Experiment! Do not make any connections with the power on! The power should be turned off before the circuit is modified

PURPOSE

- To determine the transformer polarity.
- To study the voltage ratio of a transformer.
- To perform the open-circuit and short-circuit tests and obtain the equivalent circuit of the transformer.
- To obtain the efficiency and voltage regulation from the test results.

BACKGROUND AND THEORETICAL DISCUSSION

The principle of transformer action is based on the work of Michael Faraday, who showed that, when mutual induction exists between two windings, a change in current through one induces a voltage in the other. Transformers are very versatile. They range in size from miniature units in transistor radios to huge units used in ac distribution and transmission systems.

When a transformer is in operation, AC currents flow in its winding and an alternating magnetic field is set up in the iron core. As a result, real power (watts) must be supplied due to the copper and iron losses. These losses cause the transformer to heat up. Also, reactive power is received from the supply to establish flux in the core. Because of the real power losses, the total real power delivered to the primary is always slightly larger than the total power delivered by the secondary winding. However, modern power transformers are highly effective and energy-efficient devices. Very large transformers have efficiencies close to 99 percent. The actual efficiency of a transformer is given by

$$\eta = \frac{\text{Real Power Output}}{\text{Real Power Input}} \tag{3.1}$$

The conventional efficiency of a transformer at n fraction of the full-load power is given by

$$\eta = \frac{n(S)(pf)}{n(S)(pf) + n^2 P_{Cu} + P_C} \tag{3.2}$$

Where S is the full-load rated volt-ampere, P_{Cu} is the full-load copper loss and P_C is the iron loss at rated voltage. Because of the internal impedance, $R_e + jX_e$, the output voltage of a transformer ordinarily changes under load from no-load to full-load. A figure of merit used to compare the relative performance of different transformers is the voltage regulation. Voltage regulation at full-load, usually expressed in percent, is defined by

$$\text{Voltage Regulation} = \frac{\text{Change in voltage magnitude}}{\text{Rated voltage magnitude at full-load}} \times 100 \qquad (3.3)$$

An interesting feature arises with a capacitive load, because partial resonance is set up between the capacitance and the reactance, the secondary voltage may actually tend to rise as the capacitive load value increases. The voltage regulation can be calculated from the equivalent circuit of the transformer.

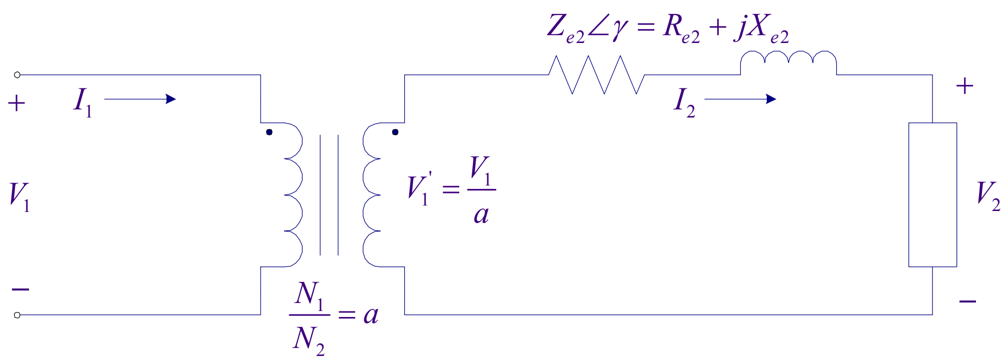


Figure 3.1 The equivalent circuit referred to the secondary

$$V_2' = V_2 + Z_{e2}\angle\gamma I_2\angle\theta \qquad (3.4)$$

Where $Z_{e2}\angle\gamma$ is the transformer equivalent impedance referred to the secondary. θ is the phase angle between the secondary voltage and current. θ is negative for inductive load and positive for capacitive load.

These regulation effects can be illustrated with phasor diagrams as shown in Figure 3.2.

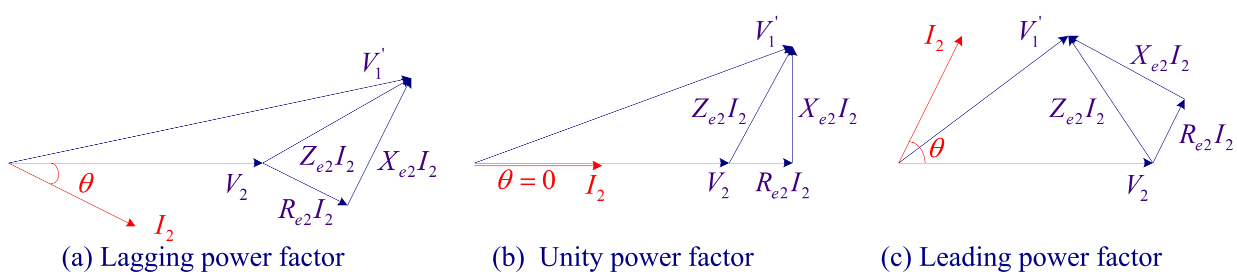


Figure 3.2

Magnetizing current waveform

At no load, $V_1 \simeq E_1 = 4.44 f N_1 \phi$, i.e., if a sinusoidal voltage v_1 is applied to the primary of a transformer the flux produced in the core is also sinusoidal. The production of the flux in the core requires a current in the primary known as the *magnetizing* or *exciting current.* The magnetizing current can be determined from the B-H ($\phi - i_m$) curve and the flux waveform. The magnetizing current is not sinusoidal because of the nonlinearities of the B-H curve. The fundamental component or its harmonics content can be found by using the Fourier series analysis. It can be shown that the exciting current is made up of odd harmonics. With a low grade magnetic material the third harmonic can be as high as 40 percent of the fundamental.

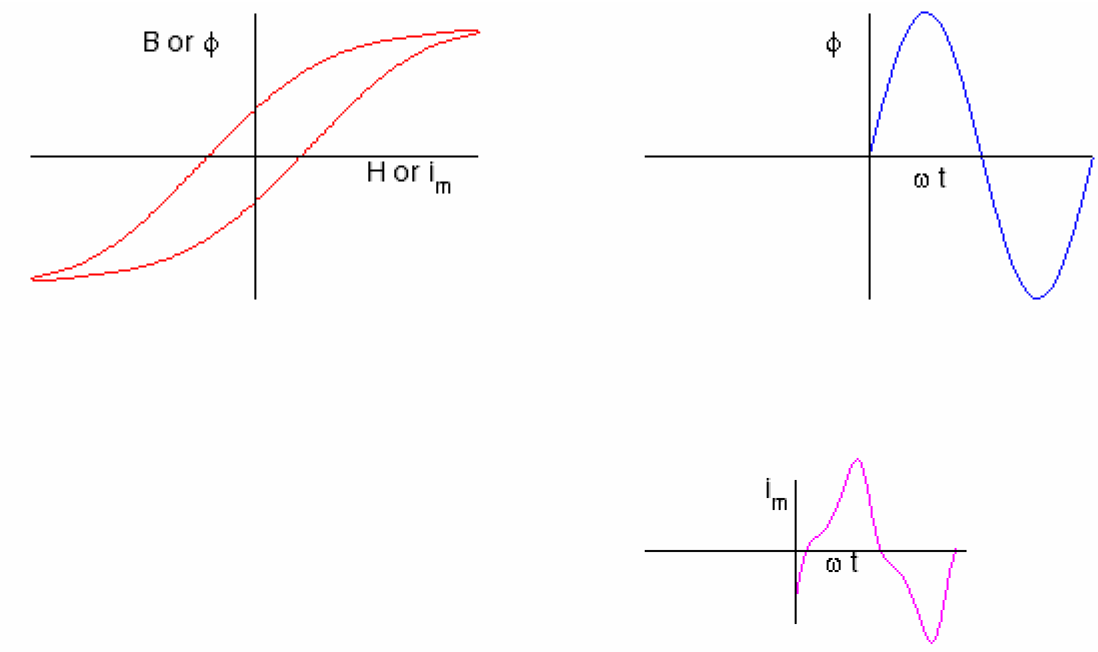


Figure 3.3 Typical B-H curve, flux and magnetizing waveforms

PROCEDURE

1. Rated Currents

Using the nameplate rated voltages (117V/40V) and rated volt-ampere (1.2 KVA) S, calculate the high-voltage and the low voltage rated currents. (Subscripts H and X are used for the high-voltage and the low voltage sides, respectively.)

$S =$ __________ $V_H =$ __________ $V_X =$ __________

$I_H =$ __________ $I_X =$ __________

2. Polarity Test

Polarities of a transformer identify the relative direction of induced voltages in the two windings. The polarities result from the relative directions in which the two windings are wound on the core. The question of the polarity of transformers is of particular importance in making the proper connections for parallel operation. The winding polarities of a single-phase transformer can be checked by a simple test. Connect a primary terminal to one of the secondary terminals, and connect a voltmeter across the other two terminals as shown in Figure 3.4. Apply a voltage to the high voltage side and measure the voltmeter reading. If the voltmeter reads less than the value of the applied voltage, the polarity is subtractive and indicates that the joint terminals have the same instantaneous polarities. If the voltmeter reads the sum of the impressed primary voltage and the induced secondary voltage, it indicates that the joint terminals have opposite instantaneous polarities. The high-voltage terminals are marked H_1, H_2 and the low-voltage terminals are designated X_1, X_2.

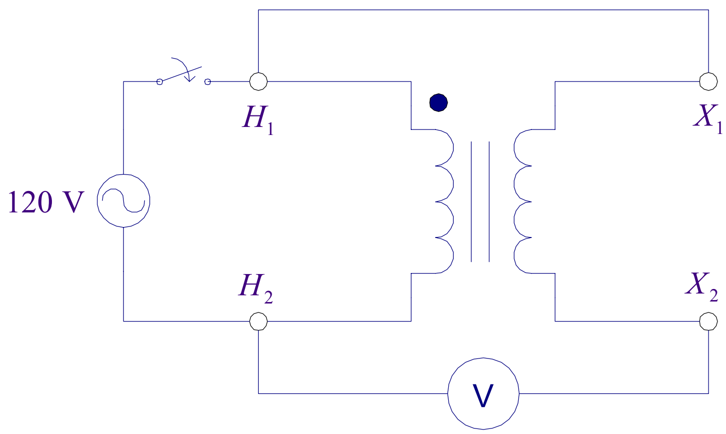


Figure 3.4 Circuit for Polarity Test of a Transformer

Voltmeter reading _______________ LV dotted terminal is ________________

3. Transformer Turns Ratio

Connect the circuit shown in Figure 3.5 and use the 120 V AC power cord to connect the high voltage winding to the 120 V AC power supply.

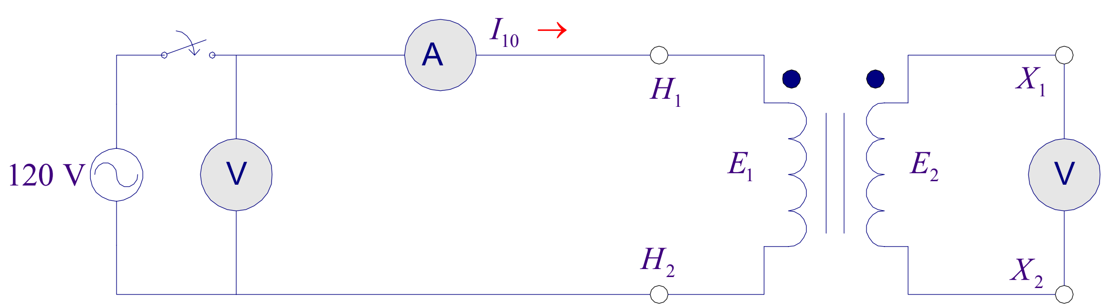


Figure 3.5 Transformer on No-load

Measure the no-load current (exciting current), primary voltage and secondary voltage.

I_{10} =__________ E_1 =__________ E_2 =__________

Calculate the turns ratio $a = \frac{N_1}{N_2} = \frac{E_1}{E_2} =$ ________________

TURN OFF THE POWER SUPPLY EACH TIME BEFORE YOU RECONNECT THE LEADS.

4. Magnetizing waveform

In this part the Fluke Industrial ScopeMeter 123 is used to display the transformer primary voltage and the no-load current. The major component of the no-load current is the magnetization current. This investigation will enable us to determine the harmonic components of the magnetization current. Before you start check out the Fluke AC/DC Current Probe (80i-110s) and a Banana-to-BNC Adapter Plug (BB120, 2X black) from the Technical Support Center.

ScopeMeter Current Probe

Connect the red-shielded test lead (use ordinary lead) from the ScopeMeter input A to the transformer HV-side H_1 terminal and a black lead from the ScopeMeter COM terminal to the high voltage-side H_2 terminal. Connect the Current Probe to the ScopeMeter input B and clamp the Current Probe around the lead connecting the supply voltage to the transformer terminal. Be sure that the arrow marked on the jaw of the Current Probe points toward the direction of current and position the probe perpendicular to the conductor (lead). Turn on the Current Probe and select the least sensitive range (10mV/A). Ensure that the green On-indicator lights. Leave the transformer secondary open.

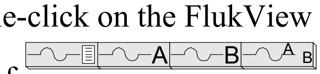
Press the bottom left hand button (power) to turn on the ScopeMeter. Press SCOPE MENU to open the scope inputs menu. For input A , move curser to highlight AC (or DC), press F_4 to select it, highlight Normal and press F_4 to select it. Move cursor to input B, highlight and select AC (or DC) and normal for this input B. With the Scope Menu open press F_3 to display the Trigger submenu. Highlight Input A, and press F_4 to select triggering on the input A waveform. Also make sure that the FREE RUN is selected. With the circuit not energized slowly adjust the zero knob on the probe to have a reading as close as possible to zero. Exit the scope menu.

The Scope reading area can display many values such as VAC, VDC, VAC+VDC, dB, Hz, AMP and PEAK. To make sure that the Input A is set to display the RMS volts press V Hz A Ω to open the Input A highlight VAC and press F_4 to select it. To choose also an RMS Ampere measurement for input B press V Hz B highlight ON and press F_4 to turn input B on, then highlight AMP and press F_4 to select Ampere measurement.

Turn on the AC switch to energize the transformer. Press AUTO to automatically adjust the position, range, time base, and triggering. This assures a stable display on both waveforms. The trace identifier (A) identifies the input A waveform and the zero icon, (−) identifies the ground level for trace A. To move the zero icon ground identifier (−) for trace B to the same level as the ground identifier (−) for trace A press F_4 until you have left any open menu and the following menu appears at the bottom of the screen.

A MOVE | B MOVE | TRIGGER SLOPE | CONTRAST

Press F_2 to choose B MOVE, press the up or down arrow ( ) to position the B ground identifier (−) at the same position as the ground identifier for trace A. If you need to smooth the waveform, do the following: Press the SCOPE MENU, and press F_1 to open the Scope options submenu. Highlight Normal and press F_4 to select it and jump to Waveform Mode. Highlight SMOOTH and press F_4 to select it.

Next turn on the PC and double-click on the FlukView ScopeMeter icon to run the ScopeMeter software. By clicking on one of 

these toolbar buttons you can quickly display the ScopeMeter waveforms. Click on the first icon (the left Display Waveforms) to open its dialog box and check mark Acquisition Memory A and Acquisition Memory B to display the corresponding traces. Select the current waveform, select Tools/Spectrum to create and display the FFT spectrum of the no-load current. You may select Options to add a Description, View Data Block place Cursor and change Color. Record the values in Ampere for the fundamental, third and fifth harmonic components. Double-click on the Spectrum graph and open the Options Spectrum Scale, select Percent and note the fundamental, third, and fifth components in percent.

Print the current waveform and its spectrum. Save the current waveform and its spectrum graphs as a bitmap graphic (*.bmp) file on your F drive for inclusion in your report. Also, save the current and voltage traces with extension FVF, this way you can retrieve them again using Fluke software. You are allowed to install the ScopeMeter on your own computer (check out the software from the Tech Support Center).

5. Open-circuit Test

Add a wattmeter in the primary circuit of Figure 3.5 (high voltage side) and leave the low voltage side open as shown in Figure 3.6. Energize the primary from 120 V supply and record voltmeter, ammeter and wattmeter readings.

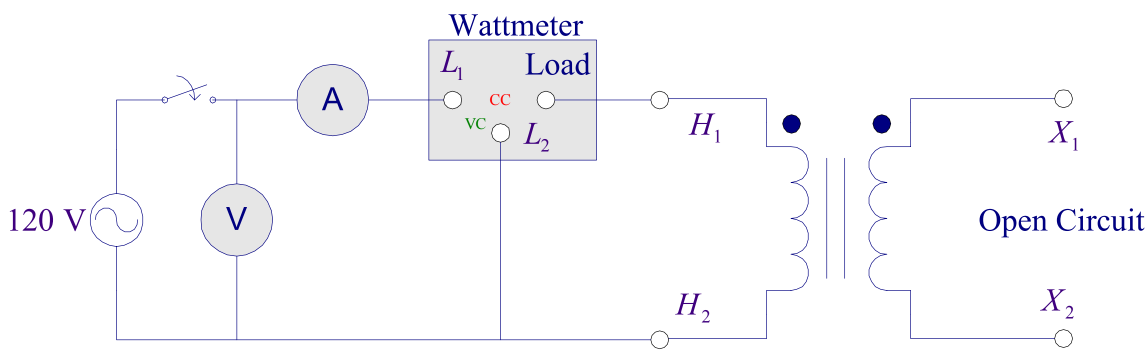


Figure 3.6 The open-circuit test.

$V_1 =$__________ $I_{01} =$__________ $P_{OC} =$__________

With the secondary open-circuited only a small no-load current will be drawn from the supply. The referred secondary current $I_2^{'}$ will be zero, and the equivalent circuit reduces to the form shown in Figure 3.7. The exciting current is only 2 to 6 percent of the full-load current. Therefore, windings copper loss is negligible and the wattmeter reading represents the iron loss, P_c.

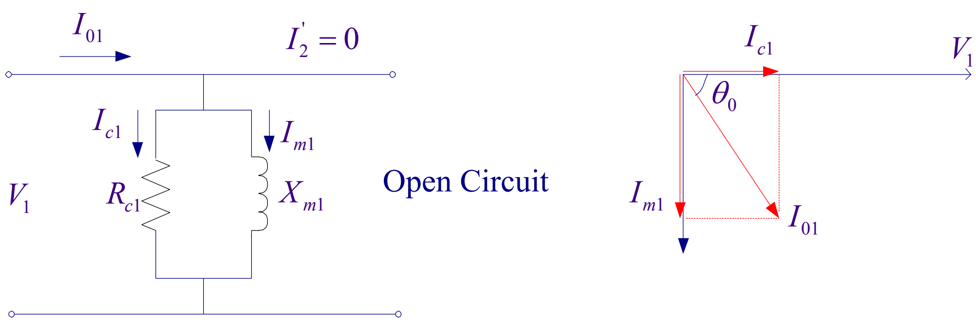


Figure 3.7 Equivalent-circuit for the open-circuit test

From this data determine the shunt branch impedance referred to the high-voltage side.

$R_{c1} = \frac{V_1^2}{P_{oc}} =$ ________________ $\qquad I_{c1} = \frac{V_1}{R_{c1}} =$ ________________

$I_{m1} = \sqrt{I_{o1}^2 - I_{c1}^2} =$ ________________ $\qquad X_{m1} = \frac{V_1}{I_{m1}} =$ ________________ (3.5)

$R_{c2} = \frac{1}{a^2} R_{c1} =$ ________________ $\qquad X_{m2} = \frac{1}{a^2} X_{m1} =$ ________________

6. Short-circuit Test

Replace the ac ammeter with a 0-10 A range and short circuit the low-voltage side as shown in Figure 3.8. The primary is supplied from a variac.

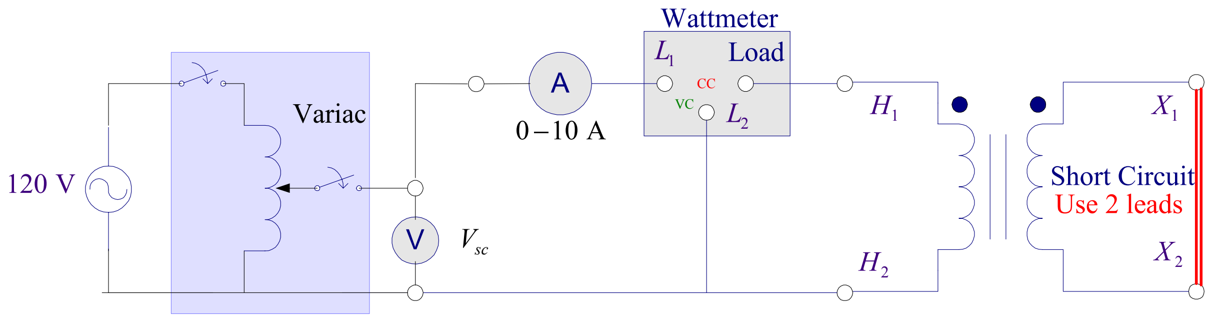


Figure 3-8 Short-circuit Test

IT IS VERY IMPORTANT TO ADJUST THE VARIAC TO ZERO BEFORE TURNING ON THE AC POWER SWITCH.

With the variac set for zero input voltage to the primary turn on the variac. While observing the primary current, increase the primary voltage slowly and with caution until 1/2 full-load rated current ($\simeq 5$ A) flows in the primary.

Record voltmeter, ammeter and wattmeter readings.

$V_{sc} =$ ________________ $\qquad I_1 =$ ________________ $\qquad P_{sc} =$ ________________

Since the input voltage is so low during the short-circuit test, negligible current flows through the excitation branch and all the voltage drop in the transformer can be attributed to the series element. The equivalent circuit reduces to the form shown in Figure 3.9.

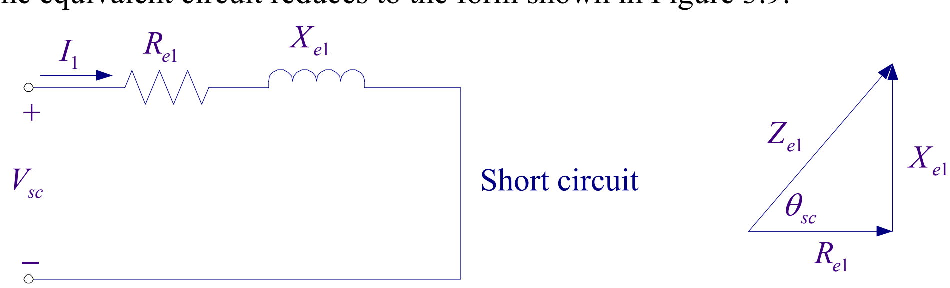


Figure 3.9 Equivalent-circuit for the short-circuit test

The iron loss is negligible and the wattmeter reading represents the windings copper loss. If the test is performed at 1/2 full-load, the power measured represents the copper loss at 1/2 full-load.

From this data determine the equivalent impedance referred to the high-voltage side and the low-voltage side.

$$Z_{e1} = \frac{V_{sc}}{I_1} = \_\_\_\_\_\_\_\_ \qquad R_{e1} = \frac{P_{sc}}{I_1^2} = \_\_\_\_\_\_\_\_ \qquad R_{e2} = \frac{1}{a^2} R_{e1} = \_\_\_\_\_\_\_\_$$

$$X_{e1} = \sqrt{Z_{e1}^2 - R_{e1}^2} = \_\_\_\_\_\_\_\_ \qquad X_{e2} = \frac{1}{a^2} X_{e1} = \_\_\_\_\_\_\_\_ \tag{3.6}$$

Copper loss is proportional to I^2. If P_{sc} is measured at $\frac{1}{2}$ full-load, then the full-load copper loss is

$$P_{cu} = (2)^2 P_{cu(1/2 fl)} \tag{3.7}$$

Construct the equivalent circuit referred to the low voltage side and mark the impedances.

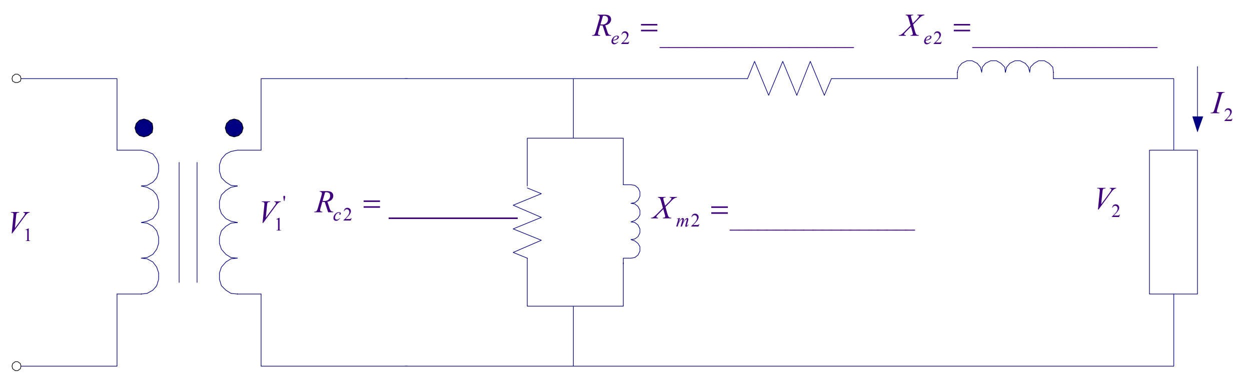


Figure 3.10 Equivalent-circuit referred to the low voltage side

7. Use the **transformer**[1] program and run the transformer tests to check your calculations, and obtain the equivalent circuit and the report requirements in steps 4 and 5 below.

[1]**transformer** A GUI program has been developed in MATLAB and is placed on the WARP network. To run this program type **transformer** at the MATLAB prompt. You may download this program and use it with your own MATAB Student Version, http://www.msoe.edu/~saadat/matlabgui.htm.

REPORT REQUIREMENTS

1. Identify similar polarities by dot marking, and explain why polarity check is important.
2. What does the rated load mean? (Discuss it in connection with the current, voltage, and temperature)
3. Describe the shape of the no-load current. State why the no-load current is not sinusoidal and describe its harmonic contents.
4. Draw the equivalent circuit of the transformer referred to the low-voltage side indicating the numerical values of the equivalent impedance. What are the value of the iron loss at rated voltage and the value of copper loss at full-load for the transformer under test? Why does the open-circuit test essentially show only iron loss and the short-circuit test show only the copper loss
5. From (3.2) determine the transformer efficiency at unity power factor from 20% to 120% of the rated KVA in 10% steps. Plot efficiency versus load KVA. From this curve determine the maximum efficiency, the load KVA at which maximum efficiency occurs and the copper loss. For maximum efficiency, how is winding loss related to iron loss? Using transformer program after finding the equivalent circuit continue with the transformer analysis to obtain the transformer performance at full-load unity power factor and full-load 0.8 power factor lagging.
6. Using (1.3) and (1.4), calculate the full-load voltage regulation at 0.8 lagging power factor, unity power factor, and 0.8 leading power factor. (Check with the transformer program result obtained above)
7. Discuss the voltage regulation versus load at unity power factor, and the effect on voltage regulation, as the power factor becomes more leading power factor.