ECE-385L-001- Electric Machine Lab

Lab Instruction Sheet- Session 3 (Experiment-2)

Experiment #2: Single-phase Transformers

The purpose of the experiment is to become familiar with the design of the core and winding of a practical single-phase transformer; to derive the transformer magnetization characteristic; and to perform the open-circuit and short-circuit tests on the transformer in order to compute its equivalent circuit.

1. Background

1.1. Transformer Construction

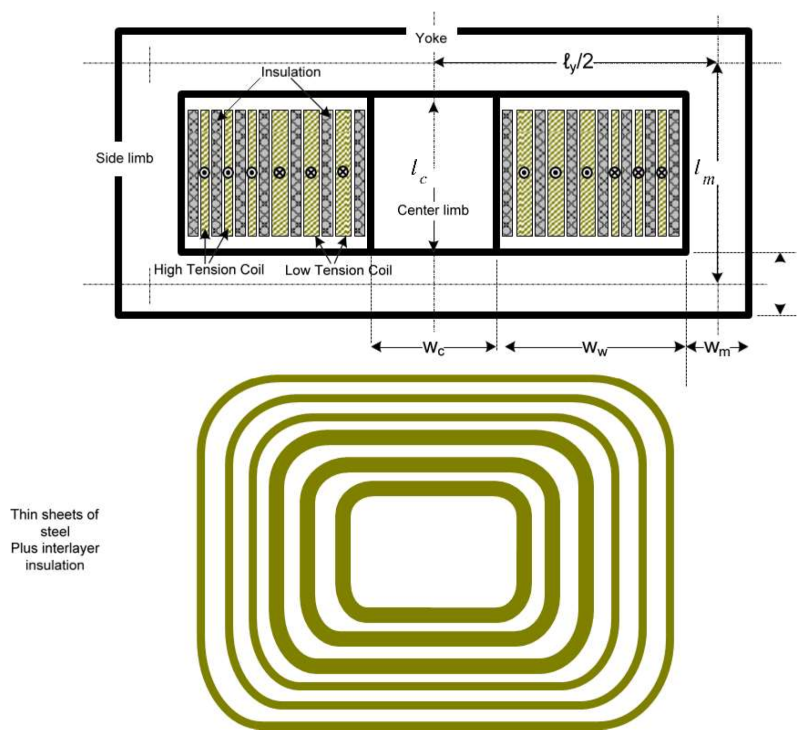


Fig. 1: The winding and core configuration of a single-phase two-winding transformer: face and top views.

Fig. 1 shows the schematic structure of a practical transformer. The core, in this example, is a shell type. The core is laminated, e.g., it is created out of several thin sheets of steel insulated from each other and held together by glue and screws. The reason for using thin lamination is to reduce the eddy currents generated when the transformer is excited by an alternating voltage. The eddy currents together with the hysteresis constitute the excitation losses of the transformer (also called the no-load losses).

The various core parts and typical dimensions are also shown in the figure. In practical core designs the side limbs are equal and have half the cross section of the center limb, so that the magnetic excitation is equal everywhere inside the core.

The two coils of the transformer are wound around the center limb, with the inner-most winding having the low-tension voltage to achieve sufficient electrical insulation. The coils are wound in layers.

Insulation is added between layers to prevent air break-down and flash-over in normal operation. Note that the winding currents are defined in opposite directions as a result of Lenz's law (e.g., the current in each winding induces an opposite direction current in the other winding). It is also important to note that the cross-section of the low-tension wire is larger than that of the high-tension wire as it carries more current. The wire cross-section defines the gauge of the wire (AWG).

1.2. The Core under Sinusoidal Excitation

Fig. 2 shows the B-H characteristic of the magnetic core. The characteristic is dominated by the saturation behavior of the core material. Hysteresis is present, but not shown in this figure for simplicity. When the primary coil is excited by the sinusoidal voltage $v(t) = \sqrt{2}V_{rms}\cos(\omega t)$ where ω is the angular frequency of the voltage, then the flux linkage of the primary coil is $\lambda(t) = \int_0^t v(t')dt' = \frac{\sqrt{2}V_{rms}}{\omega}\cos(\omega t - \frac{\pi}{2})$. From this the flux density inside the core is, $B(t) = \frac{\lambda(t)}{N_1 A_c} = \frac{\sqrt{2}V_{rms}}{N_1 A_c \omega}\cos(\omega t - \frac{\pi}{2})$ where N_1 is the turn number of the coil and A_c is the cross section area of the center limb. The peak value of the flux density is directly proportional to the voltage rms by:

$$B_{\max} = \frac{\sqrt{2}V_{rms}}{N_1 A_c \omega} \quad (1)$$

The excitation current of the transformer and the core magnetic intensity are related by Ampere's law. Therefore, the peak value of the magnetic intensity is:

$$H_{\max} = \frac{\sqrt{2}N_1 I_0}{l_{eff}} \quad (2)$$

where I_0 is the rms value of the excitation current and l_{eff} is the effective length of the Ampere integral. e.g., for the symmetric core of fig. 1 and with the side-limb cross sections equal to half of that of the center limb, $l_{eff} = l_c + l_y + l_m$.

The excitation current and magnetic intensity when a large sinusoidal voltage is applied across the primary are shown in Fig. 2. We see that the flux density is also sinusoidal. As the flux density moves from point 0 to point 4, we move through points 0-1-2-3-2-1-0-4 on the $B - H$ characteristic; the transformer is driven into saturation soon after point 1. The corresponding values of the excitation current and field intensity are also shown in the same figure. Note that as we trace the operating point from 0 to 3 and back to 4, the excitation current is not sinusoidal. This is the general shape of the excitation current as a result of saturation and hysteresis.

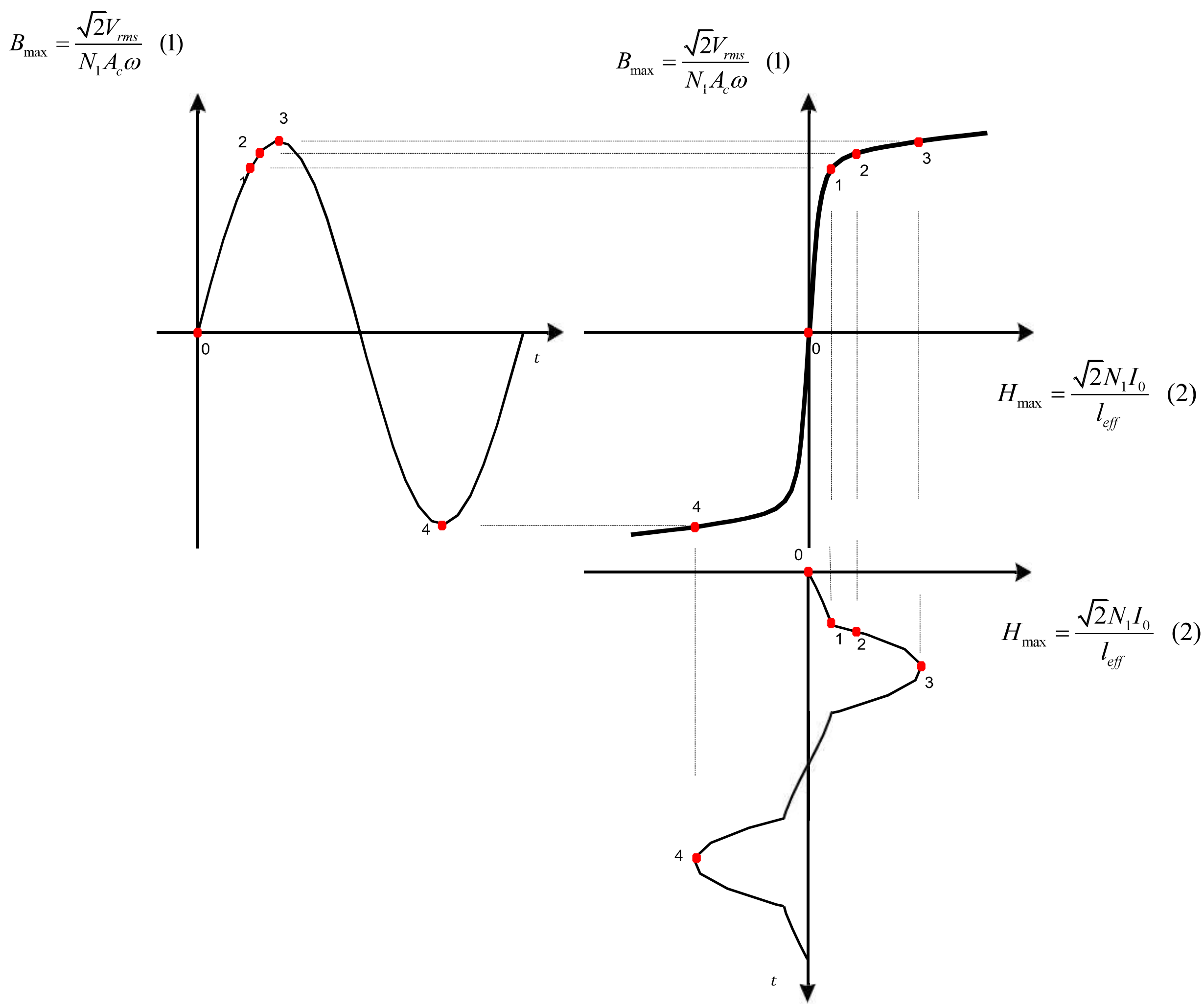


Fig. 2. Magnetic and electric quantities under sinusoidal operation—effects of magnetic saturation.

The core design proceeds by choosing the core cross section area and the coil number of turns in order to limit the peak value of the flux density below the saturation knee, point 1 In Fig. 2.

1.3. Determination of the parameters of transformer equivalent circuit

Fig. 3 shows the equivalent circuit of a two-winding transformer referred to the primary side. R_1 and R'_2

are the winding ohmic resistances seen from the primary side, X_1 and X'_2 are the winding reactances attributed to the leakage flux, these elements together constitute the series impedance of the transformer; R_c is the equivalent core resistance to account for hysteresis and eddy current losses and X_m is the core magnetizing reactance which accounts for the mutual linkage flux of the windings. These two elements together constitute the excitation branch of the transformer. With reference to the same figure, V_1 is the primary voltage (supply) and V'_2 is the voltage across the load referred to the primary side, likewise I_1 and I'_2 are the primary and referred secondary currents respectively. In practical transformers the impedance of the excitation branch is several times greater than the series impedance and, therefore, the excitation current I_e is several times smaller compared to the nominal current of the transformer (usually <1% for small transformers, <5% for larger ones).

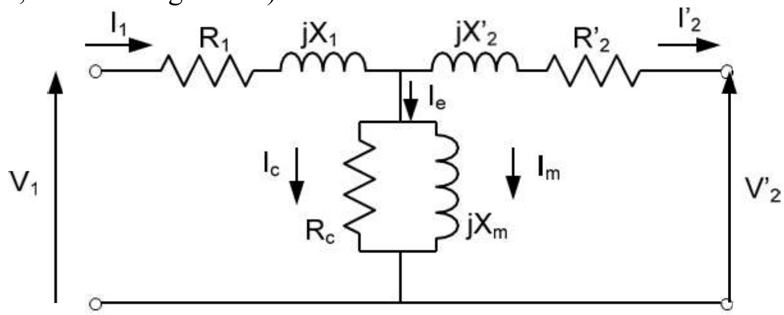
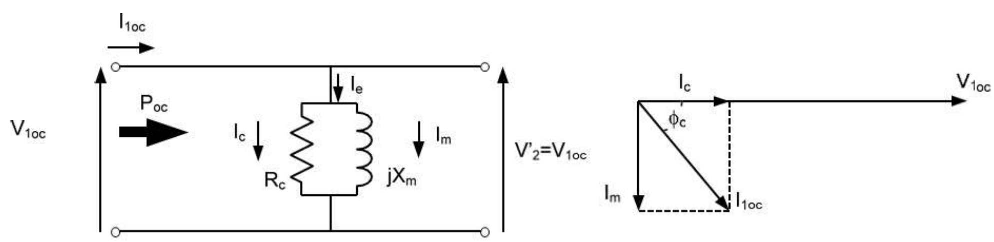
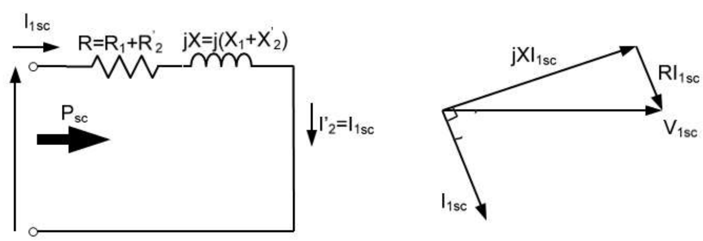


Fig. 3. The Equivalent Circuit of a Two-Winding Transformer

Two tests are used in the laboratory to obtain the parameter values of the equivalent circuit experimentally: the open circuit and the short circuit tests.



(a) The transformer representation for the open-circuit test



(b) The transformer representation for the short-circuit test

Fig. 4. The Transformer Equivalent Circuit under the Open Circuit and Short Circuit Tests

The open circuit or no-load test is used to estimate the elements of the excitation branch. The transformer secondary terminals are open. The terminals of the primary winding are connected to an ac source with nominal voltage. Under this condition the core is fully excited and, since the load is not present, the current of the primary winding equals the excitation current; all the real power absorbed by the transformer supplies the core loss. A good approximation of the transformer is the circuit in Fig. 4(a) containing only the excitation branch. The phasor diagram in the same figure depicts the two components of the excitation current, the magnetizing current I_m, which generates the core flux, and I_c, which supplies the core losses.

In the open circuit test the measurements include the rms primary voltage V_{OC}, the rms primary current I_{OC}, and the real power P_{OC}. Consequently, the branch power angle is:

$$\cos\theta_{OC} = \frac{P_{OC}}{V_{OC} I_{OC}} \quad (3)$$

Seeing that the branch admittance is $Y_{sh} = G_c + jB_m \Rightarrow |Y_{sh}| = \sqrt{G_c^2 + B_m^2} = \frac{I_{OC}}{V_{OC}}$ we obtain[1]

$$G_c = \frac{1}{R_c} = \frac{I_{OC}}{V_{OC}} \cos\theta_{OC} \quad (4a)$$

$$B_m = \frac{1}{X_m} = \frac{I_{OC}}{V_{OC}} \sin\theta_{OC} \quad (4b)$$

<u>It should be noted that under normal transformer operation (i.e., when the transformer voltages do not deviate appreciably from the rated values), the core excitation varies only slightly and, therefore, the core loss measured under the open circuit test remains constant even as the load varies. This is referred to as the no-load loss of the transformer and it is often provided on the transformer name plate data.</u>

The short circuit test estimates the series impedance of the transformer. In this test, the secondary winding terminals are shorted; the voltage across the primary winding is raised until the current drawn by the primary equals the winding rated current. Under this condition, the core of the transformer is not excited, hence the excitation branch in the equivalent circuit can be ignored: all the real power consumed goes to supply the winding resistive losses. The equivalent circuit for the short circuit test is shown in Fig. 4(b) along with the phasor diagram showing the voltage distribution on the winding resistance and reactance.

The measurements in this test include the primary rms voltage V_{SC}, the primary rms current I_{SC} and the real power consumed at the primary P_{SC}, Following the same approach as in the previous test we have:

The power angle of the series impedance is:

$$\cos\theta_{SC} = \frac{P_{SC}}{V_{SC} I_{SC}} \quad (5)$$

---

[1] For two parallel elements the power angle is the same as the angle of the combined admittance

Seeing that the branch impedance is $Z_{eq} = R_{eq} + jX_{eq} \Rightarrow |Z_{eq}| = \sqrt{R_{eq}^2 + X_{eq}^2} = \dfrac{V_{SC}}{I_{SC}}$, we obtain:

$$R_{eq} = \frac{V_{SC}}{I_{SC}} \cos\theta_{SC} \quad (6)$$

$$X_{eq} = \frac{V_{SC}}{I_{SC}} \sin\theta_{SC} \quad (7)$$

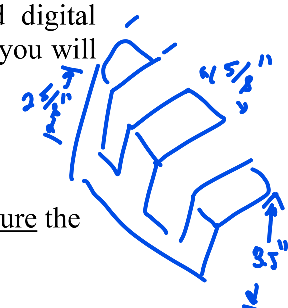
A usual approximation to obtain the detail equivalent of Fig. 3 is:

$$R_1 = R_2^{'} = \frac{R_{eq}}{2}, \quad X_1 = X_2^{'} = \frac{X_{eq}}{2}, \qquad (8)$$

If the short circuit test is conducted under rated current, the losses measured are the rated copper losses. The sum of the rated copper losses and the no-load loss of the transformer equals the full load losses. The full load losses are often included on the name plate.

2. Experiment Procedure

Equipment (all procedures): 115-230 V transformer with shell-type core exposed; handheld digital voltmeter; hand-held analog wattmeter; ac ammeter on the Hampden console. Also, for part 2.1 you will need a ruler in cm.



2.1. **Become familiar with the 115-230 V transformer**.

Unscrew the top yoke and remove the winding. Observe the winding and core structure. Measure the core dimensions including depth. Record the data on the winding.

$R_{LS} = 0.8\Omega$

$R_{HS} = 3.5\Omega$

1. Reassemble the winding and yoke onto the core. Do not place the screw tightly yet—leave it loose.
2. With the console power turned off, connect the primary side coil (115 V) of the transformer between one of the AC source phases and the ground. Use the variable AC source on the console. Make sure the source knob is turned down to the zero-volt position. Perform the connection through the console AC ammeter and the hand-held wattmeter, as shown in Fig. 5.
3. Turn-on the console power and the AC source switch. With the handheld voltmeter measure the primary voltage. Slowly move the source knob to raise the voltage to 50 V. Record the current. Listen to the humming noise of the transformer.
4. Attempt to move the loose yoke (e.g., use a pencil and push one side of the yoke slowly. Do not push the core out of alignment totally. Mind the current not to exceed 1.5 A). Observe the magnetic forces excreted. Record what happens to the current.
5. Turn the source knob all the way down. Power down the source and console. Prepare for the next part.

$V_{pri} = 50V$

$V_{sec} = 110V$

H

2 : 1

$a = 2$

$a^2 = 4$

$\frac{H}{L} = 4$

@ 50Vac the current is 0.15Aac

when moving yoke ↑I = 0.2Aac

Humming gets louder

Vsec↑, ↑Ipri

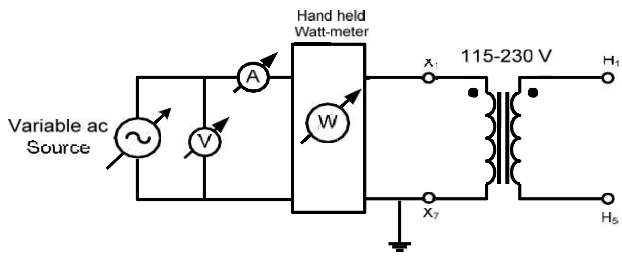


Fig. 5. Measurement Set-up for the O.C. test

2.2. **Open circuit tests.**

Leave the transformer and instrumentation connected as in Fig. 5 but tighten the screw on the yoke. Make sure the console is off and the source is turned down to zero.

1. Use the hand-held voltmeter across the primary. Turn the console and variable source on. Increase the source voltage to 30 V. Measure the source current and power and the voltage across the secondary coil (use the same voltmeter). For best readability set the ammeter sensitivity to 0.5 A.
2. Repeat 1 for the source values given in the table below.

Source voltage (V)	*Source Current (A)*	*Source power (W)*	*Secondary coil voltage (V)*
30	0.085	~0	65.5
60	0.18	1.0	133.2
90	0.29	2.1	196.7
115	0.435	5.1	251.1
120	0.490	6.5	261.6
125	0.5	8.3	276.5

2.3. **Short circuit test.**

Leave the circuit connected and instrumented as in the previous test. Connect a short wire between the terminals of the secondary coil. Before powering up, make sure the console and source are turned off.

Attention! In this test, the current is very sensitive to the source voltage: raise voltage slowly.

1. Power up the console. SLOWLY increase the source voltage until the primary current is 1.5 A. Record the source voltage, current and power.
2. Turn the source down. Power down the console. Break the connections. You are done.

4V, 1.505A, 4W

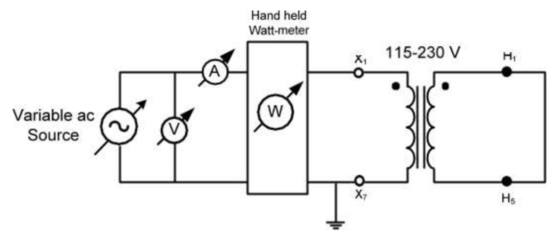


Fig. 6. Circuit arrangement for the short circuit test.

3. Report

For the report:

- Explain the humming of the transformer in under AC excitation. Is a humming noise expected from a transformer under a DC excitation?
- Explain the magnetic forces resisting the movement of the yoke in 2.2.4. Explain the current rising in the same test. Is the core reluctance increasing or decreasing as we attempt to remove the yoke?
- For each measurement in 2.2 (1,2) apply the core dimensions in 2.1 and compute the peak values of the density and intensity of the magnetic field inside the core (may assume uniform core excitation). Plot B vs. H and the excitation voltage vs. the excitation current from the same measurements. Discuss the results.
- Use the data measured at 115 V and compute the magnetizing branch elements in the equivalent circuit of this transformer.
- Compute the core reluctance at 115 V.
- Use MATLAB to calculate and plot the following quantities from the previous B-H curve:
    - The magnetizing current of the transformer, if the primary is excited by a sinusoidal source having 115 V rms value.
    - The previous, if the source has a 120V rms value.
    - Repeat for 125V rms value.

Use the interpolation function in MATLAB with the B-H data. Extend the curve to the third quadrant using symmetric data.

- Obtain the values of the series impedance elements in the transformer equivalent circuit using the measurements from 2.3. Draw the complete circuit seen from both the primary and the secondary coils. What is the source voltage range for which this equivalent is valid? Why?

4. Equipment Pictures

1. 115-230 V transformer with shell-type core exposed

2. Handheld Digital Multi Meter

3. Handheld Digital Wattmeter

4. Hampden Console