

## **EXPERIMENT Transformer Equivalent Circuit using DACI**

### **Steady-State Testing and Performance of Single-Phase Transformers**

#### **OBJECTIVE**

The voltage regulation and efficiency of a distribution system are affected by the electrical and magnetic characteristics of the transformers operating in the network. The design of such a distribution system must consider these effects. This experiment demonstrates the concept of open-circuit and short-circuit testing of transformers. From these tests, it is possible to determine the equivalent circuit of the transformer. The experiment also studies the excitation current, magnetization current, and core-loss current.

#### **REFERENCES**

1. "Electric Machinery", Fourth Edition, Fitzgerald, Kinglsey, and Umans, McGraw-Hill Book Company, 1983, Chapter 1.
2. "Electromagnetic and Electromechanical Machines", Matsch, Leander W., Intext Educational Publishers, 1972.
3. "Electromechanical Devices for Energy Conversion and Control Systems", Del Toro, Vincent, Prentice-Hall, Inc., 1968.

#### **BACKGROUND INFORMATION**

The basic theory of transformer operation is adequately explained in Reference 1. For our purposes here we will concentrate on the test methods and the experimental set-up of Figure 2.

Figure 1 shows the traditionally accepted electrical equivalent circuit for a power transformer in steady-state. This particular equivalent circuit's parameters are referred to side 1. All relevant impedances, voltages, and currents are shown in the figure.

#### **Determine the transformer polarity**

Mark your transformer polarity dot, apply a 10v peak to peak to one of the winding (primary) and positive signal with a dot, tape, or permanent marker. Connect channel 1 of the scope to the primary where the signal source is connected. Connect channel 2 on the other winding (secondary) if the signal are in phase mark the positive of the scope is marked with the dot indication. If they are out of phase by 180 then reverse the secondary scope connection and mark.

**Equivalent circuit**

We will use the results of short circuit (SC) test and open circuit (OC) test to find the values for a transformer equivalent circuit as shown in figure 1. Our transformer is a 1:1 120V: 120V. We will perform both the SC test and OC test from the primary.

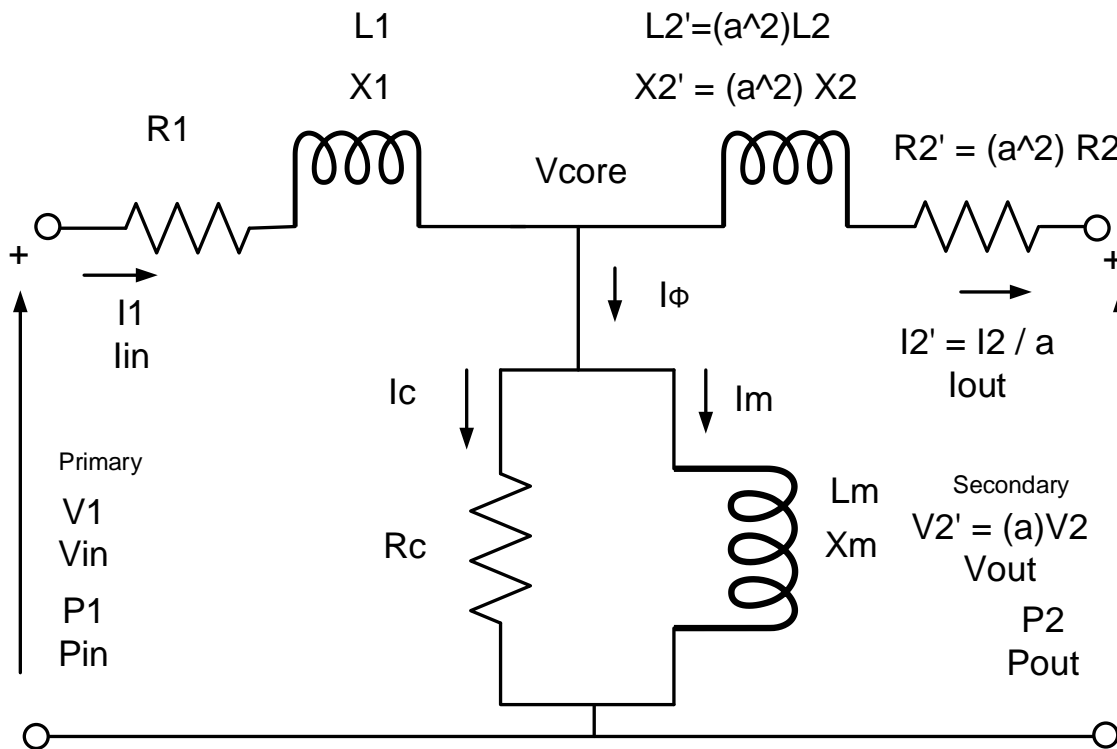
If we have 12KV primary and 120V secondary we will perform the SC test on the primary in the SC test the will be a lower voltage and current when at the secondary rated current. The OC test is preformed the secondary the instrumentation will only need to measure 120V not the 12KV.

Referring to the diagram, a practical transformer's physical behavior may be represented by an equivalent circuit model, which can incorporate an ideal transformer.

The following series loop impedances of the equivalent circuit represent winding copper losses and leakage reactance.

- Primary winding:  $R_1, X_1$
- Secondary winding:  $R_2, X_2$ . Secondary referred to the primary  $R_2', X_2'$

In normal course of circuit equivalence transformation,  $R_2$  and  $X_2$  are in practice usually referred to the primary side by multiplying these impedances by the turns ratio squared,  $(N_p/N_s)^2 = a^2$ .



**Figure 1. Transformer equivalent circuit**

The following shunt leg impedances of the model represent core loss and magnetizing reactance:

- Core or iron losses:  $R_C$
- Magnetizing reactance:  $X_M$ .

$R_C$  and  $X_M$  are collectively termed the *magnetizing branch* of the model.

## Transformer Model

Core losses are represented by  $R_C$  which include hysteresis and eddy current effects. The finite permeability core requires a magnetizing current  $I_M$  to maintain mutual flux in the core. Magnetizing current  $I_M$  is in phase with the flux, the relationship between the two being non-linear due to saturation effects. However, all impedances of the equivalent circuit shown are by definition linear and such non-linearity effects of core saturation are not reflected in transformer equivalent circuits. With sinusoidal supply, core flux lags the induced EMF by  $90^\circ$ . With open-circuited secondary winding, magnetizing branch current  $I_\phi$  equals transformer no-load current.

### Short Circuit test: find $R1, R2, X1, X2$

The Short Circuit test applies the appropriate rated current to the primary or secondary terminals of transformer. The other winding is shorted. If current is applied to the primary, the secondary is shorted.

The current  $I_1 \approx I_2'$  because the  $V_1$  applied to the primary is less than  $V_1$  rated to meet the  $I_1$  rated requirement. The core current  $I_\phi$  is small compared to  $I_1$  rated because the  $Z_{core}$  is higher than  $R_1 + X_1$  and the core voltage  $V_{core}$  is lower, so we will ignore  $I_\phi$ .

$$R_{eq} = P_{sc} / (I_{sc}^2) = R_1 + (a^2) R_2 \text{ referred to primary therefore } (a^2) R_2 = R_1 = R_{eq}/2$$

Find  $X_1$  and  $X_2'$  from  $Q_{sc}$

$$X_{eq} = Q_{sc} / (I_{sc}^2) = X_1 + (a^2) X_2 \text{ referred to primary therefore } (a^2) X_2 = X_1 = X_{eq}/2$$

$$X_2 = X_2' / (a^2)$$

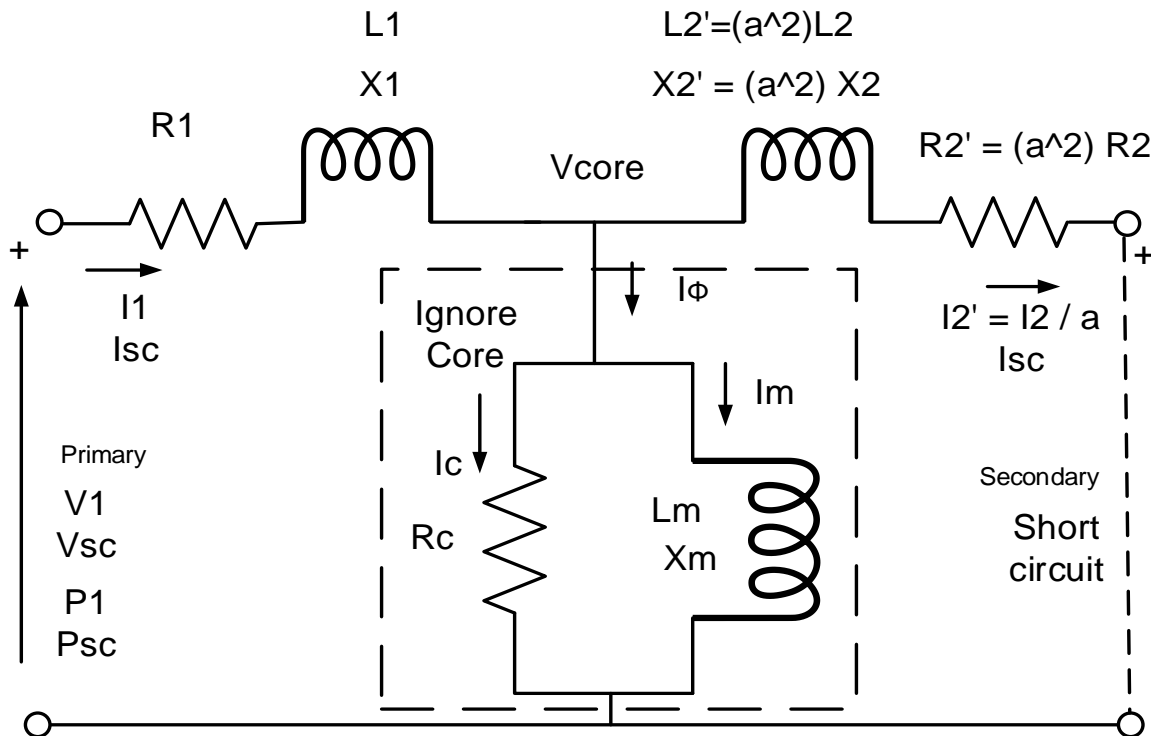


Figure 2 Short circuit test.

### Open Circuit test:

The Open Circuit test applies the rated voltage to the primary terminals of transformer with the secondary winding open circuited.

Solve for the core as a series branch. Then convert to a parallel branch for the transformer equivalent circuit.

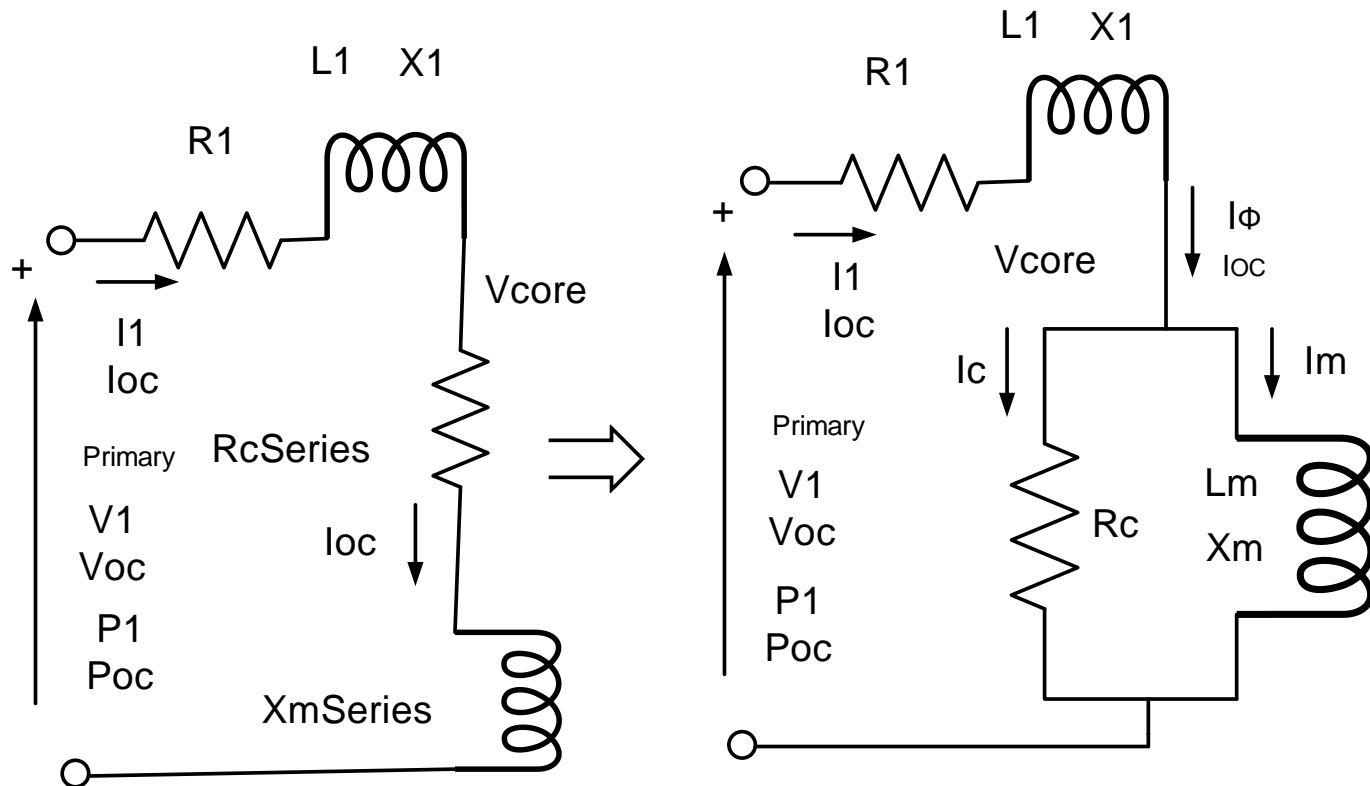
The transformer real impedance looking into the primary:

## Transformer Model

$R_{\text{primarySeries}} = R_1 + R_{\text{cCoreSeries}} = P_{\text{oc}} / (I_{\text{oc}}^2)$   
 The transformer imaginary impedance  $I$  looking into the primary:  
 $X_{\text{primarySeries}} = X_1 + X_{\text{mCoreSeries}} = Q_{\text{oc}} / (I_{\text{oc}}^2)$   
 $Z_{\text{primarySeries}} = V_{\text{oc}} / I_{\text{oc}}$   
 $\text{Angle} = \arctan ( X_{\text{primarySeries}} / R_{\text{primarySeries}} )$

Note: If you calculate using a series core branch you must convert to a parallel core branch.

$Z_s = R_s + j X_s \quad Z_p = R_p \parallel j X_p$   
 Convert series to parallel.  $U = R_s^2 + X_s^2 \quad R_p = U / R_s \quad j X_p = U / X_s$   
 Convert parallel to series.  $W = R_p / X_p \quad R_s = R_p / (W^2 + 1) \quad j X_s = ( X_p * W^2 ) / (W^2 + 1)$



**Figure 3 Open circuit equivalent circuit with a series core or a parallel core. Energy losses**

Transformer energy losses are dominated by winding and core losses. Transformers' efficiency tends to improve with increasing transformer capacity. The efficiency of typical distribution transformers is between about 98 and 99 percent.

As transformer losses vary with load, it is often useful to tabulate no-load loss, full-load loss, half-load loss, and so on. Hysteresis and eddy current losses are constant at all load levels and dominate at no load, while winding loss increases as load increases. The no-load loss can be significant, so that even an idle transformer constitutes a drain on the electrical supply. Designing energy efficient transformers for lower loss requires a larger core, good-quality silicon steel, or even amorphous steel for the core and thicker wire, increasing initial cost. The choice of construction represents a trade-off between initial cost and operating cost.

## Transformer Model

### Transformer losses:

Copper winding losses  $R_1$ , and  $R_2$

Current flowing through a winding's conductor causes heating due to the resistance of the wire. As frequency increases, skin effect and proximity effect causes the winding's resistance losses to increase.

Core losses = Hysteresis losses + Eddy current losses.

Hysteresis losses:

Each time the magnetic field is reversed, a small amount of energy is lost due to hysteresis within the core,

Eddy current losses:

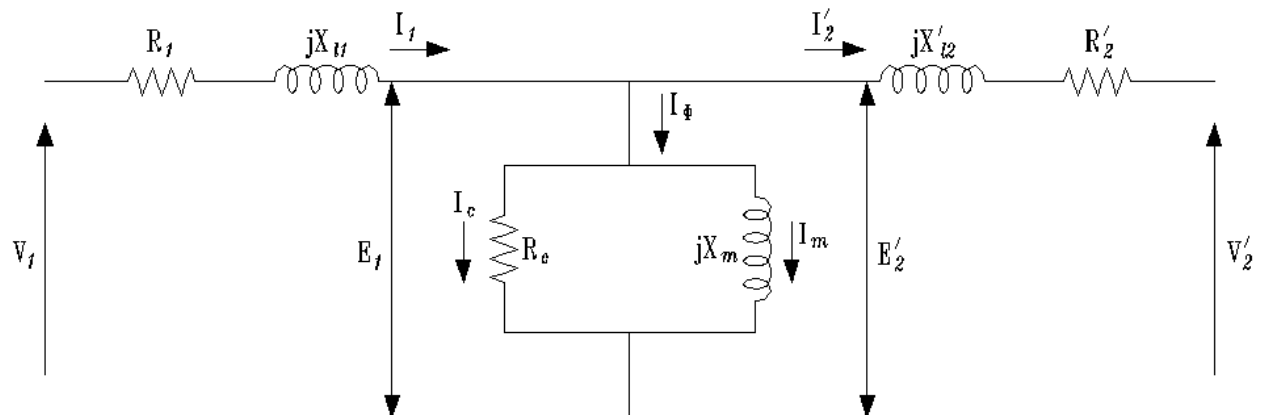
The changing magnetic field induces Eddy currents in the conductive metal transformer core. The loss from the current flowing through the resistance of the iron core. Eddy current losses can be reduced by making the core of a stack of laminations (thin plates) electrically insulated from each other. All transformers operating at low frequencies use laminated cores.

Transformer hum:

Magnetic flux in a ferromagnetic material, such as the core, causes it to physically expand and contract slightly with each cycle of the magnetic field, an effect known as magnetostriction, the frictional energy of which produces an audible hum. This transformer hum is especially objectionable in transformers supplied at power frequencies and in high-frequency flyback transformers.

Stray losses:

Leakage inductance is by itself largely lossless, since energy supplied to its magnetic fields is returned to the supply with the next half-cycle. However, any leakage flux that intercepts nearby conductive materials such as the transformer's support structure will give rise to eddy currents and is converted to heat.



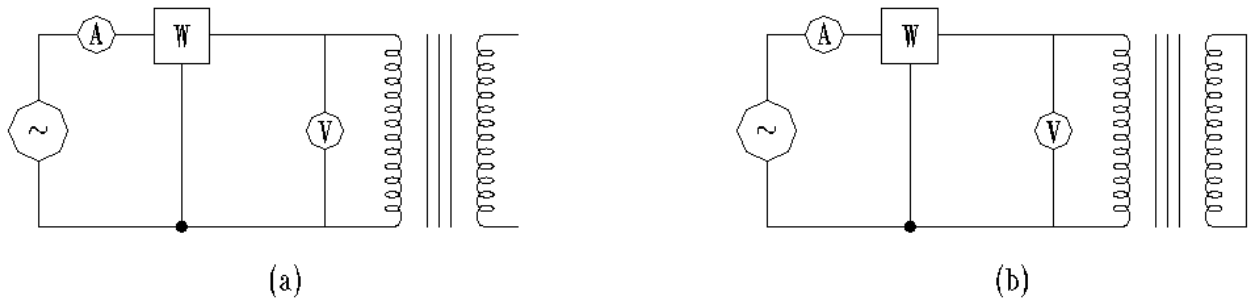
**Figure 1:** Steady-state equivalent circuit for power transformer.

## Transformer Model

It is important to note that for a typical power transformer the ratio of the parallel combination of the common leg impedances to the total impedance of either winding will exceed 200. Algebraically, this can be described as

$$\frac{|R_c // X_m|}{|R_1 + jX_{\ell_1}|} > 200 \quad (2.1)$$

Figure 2 shows the experimental concept for the open-circuit and short-circuit tests.



**Figure 2:** (a) Instrumentation for open-circuit test. (b) Instrumentation for short-circuit test.

The **open-circuit** test is run at rated voltage and yields the following quantities;

$I_{oc}$  = exciting current as read by ammeter  $A$ .

$V_{oc}$  = applied voltage as read by voltmeter  $V$ .

$P_{oc}$  = power as measured with wattmeter  $W$ .

$R_1$  and  $X_{\ell_1}$  are very small values, thus, their voltage drop is minimal. The voltage is small enough for us to assume that the open-circuit voltage  $V_{oc}$  appears across  $R_c$  and  $X_m$ , and that all power  $P_{oc}$  is dissipated by  $R_c$ . Therefore,

## Transformer Model

$$R_c = \frac{V_{oc}^2}{P_{oc}} \text{ ohms} \quad (2.2)$$

The reactance  $X_m$  can be found by determining the reactive part of the test quantities.

Thus, the power factor is

$$\text{pf} = \frac{P_{oc}}{V_{oc} I_{oc}} \quad Q = \sqrt{S^2 - P^2} \quad (2.3)$$

and

$$I_m = I_{oc} \sin [\cos^{-1}(\text{pf})] \quad (2.4)$$

from which

$$X_m = \frac{V_{oc}}{I_m} = \frac{V_{oc}^2}{Q_{oc}} \quad \text{Ohms} \quad (2.5)$$

The **short-circuit** test is run at rated current and provides the following information:

$V_{sc}$  = applied voltage as read by voltmeter  $V$

$I_{sc}$  = input short-circuit current as read by ammeter  $A$ .

$P_{sc}$  = input power as read by wattmeter  $W$

Recalling Eq. 2.1, the equivalent impedance seen by the instruments is

## Transformer Model

$$Z_{eq} = (R_1 + R_2) + j(X_{l1} + X_{l2}) = R_{eq} + jX_{eq} = \frac{V_{sc}}{I_{sc}} \quad (2.6)$$

Since the parallel combination of the common leg impedance is very large, the majority of the input short-circuit current passes through only the winding impedances. Therefore, the core losses are negligible and the following is true:

$$R_{eq} = \frac{P_{sc}}{I_{sc}^2} \quad (2.7)$$

and

$$X_{eq} = \sqrt{Z_{eg}^2 - R_{eg}^2}$$
$$R_1, R_2 = \frac{R_{eq}}{2} \quad X_1, X_2 = \frac{X_{eq}}{2} \quad (2.8)$$

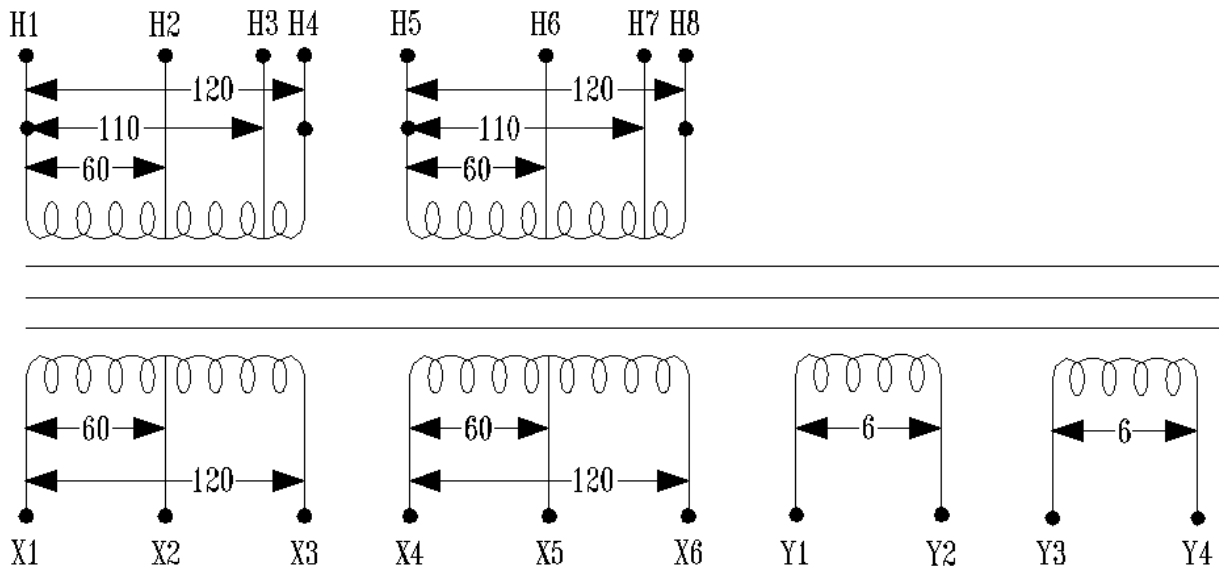
In the absence of more definitive information, the components of  $R_{eq}$  and  $X_{eq}$  are split equally between the two sides of the transformer. The power rating of the transformer can be calculated from the rated voltage (Voc) and the rated current (Isc) on the same side of the transformer.

$$\text{Power rating} = V_{oc} * I_{sc}$$

This completes the development necessary to derive the steady-state equivalent circuit from the test data.



## Transformer Model



**Figure 3: Winding configuration of laboratory transformers.**

### **SUGGESTED PROCEDURE**

The transformers used for this experiment are rated 120V-120V, 0.6kVA. There are three of them on each set of wall shelves. The set of windings connected to the source side of the transformer are called primary windings, and those connected to the load are named secondary windings. To achieve a 600 volt-ampere rating, these two sets of main primary and secondary windings must be in parallel. The other two windings are information (instrumentation) windings and are not designed to support a load.

Figure 1 defines the currents that are referred to throughout the experiment. The Fluke bench meters are always used for safety in case the DACI were to fail you will still have a meter. The fluke meters must be manually set a **current range of amps (A)** on both on AC and DC current. The voltage is to be set on auto.

1. Figure 6 shows the connections for performing the open-circuit and short-circuit tests. Since the turns ratio is 1:1, both tests are done on the same side of the transformer. The open-circuit test is performed at rated voltage (120V), and the short-circuit test is performed at rated current (5 AMPS).

## Transformer Model

The open circuit and short circuit test both use the 40A connection for the current with DACI.

### OPEN CIRCUIT TEST

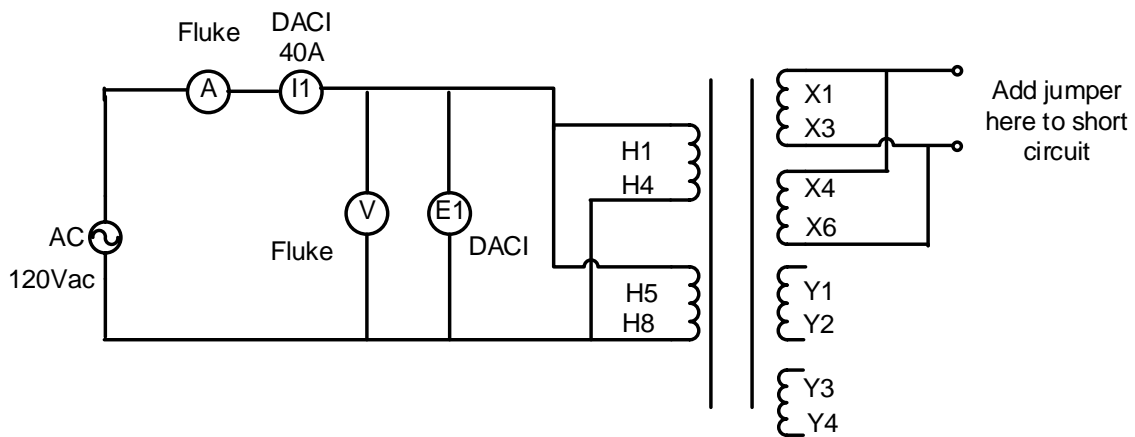
The secondary jumper must be disconnected for the open circuit-test, while applying rated voltage, 120 V, from the Single-Phase AC Source to the primary side of the transformer. Record Power, Current, and Voltage.

Voltage OC	Current OC	Power OC
<b>120V</b>		

### SHORT CIRCUIT TEST

The short-circuit test is run with the secondary jumper connected. **SLOWLY** increase (the **voltage is less than 3.0 Vrms**) the Single-Phase AC Source from the zero setting until a 5 AMP reading is achieved on the meter. Allow a little time for the system to stabilize at 5 AMPS and then, record Power, Current, and Voltage.

Voltage SC	Current SC	Power SC
	<b>5A</b>	



**Figure 6**

**REPORT**

**Study questions**

**Explain the concept and procedure for open- and short-circuit testing of transformers.**

**Open-Circuit Test**

This test allowed us to find..... (Continue expanding in your own words, say what you did and why you did it. Include all equations, table, data, plots, and results for this part)

**Short-Circuit Test**

This test allowed us to find ..... (Continue expanding in your own words, say what you did and why you did it. Include all equations, table, data, plots, and results for this part)

**Explain why the tests should be performed on the high or low voltage sides as appropriate.**

**Why did we use the same side in our experiment?**

**Derive the equivalent circuit for the transformer tested during this experiment.**

**Find  $R_c$ ,  $X_m$ ,  $X_1$ ,  $X_2$ ,  $R_1$ ,  $R_2$ ,  $Z_{eq}$ ,  $R_{eq}$ ,  $X_{eq}$ ,  $Q_{sc}$ ,  $Q_{oc}$ , power rating, pf oc, and pf sc. Draw the equivalent circuit.**