UTS Engineering
48531 Electromechanical Systems
Laboratory 3

Transformer

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EMS Lab3.doc

EACH STUDENT ATTENDING THIS LAB SHOULD READ CAREFULLY THE SAFETY PRECAUTIONS BELOW, SIGN THIS COVER SHEET AND RETURN IT TO YOUR LAB TUTOR

• STUDENTS ARE WARNED OF POSSIBLE ELECTRIC SHOCK RISK AND FIRE RISK IN THE LAB AREA
• STUDENTS ARE REQUIRED TO WEAR STOUT SHOES OR BOOTS WITH ENCLOSED TOES. BARE FEET, THONGS, OPEN TOE SANDALS AND HIGH HEELS ARE NOT ACCEPTABLE. TUTORS AND LAB STAFF MAY REFUSE ADMITTANCE TO THE LAB TO STUDENTS WITH INADEQUATE FOOTWEAR
• NO FOOD OR DRINK IS ALLOWED IN THE LAB
• DO NOT TURN ON THE SUPPLY UNTIL YOU HAVE DRAWN THE CIRCUIT DIAGRAM AND YOUR CONNECTIONS HAVE BEEN CHECKED BY YOUR TUTOR.
• DO NOT DISCONNECT ANY LEADS WHILE THE SUPPLY IS ON.
• ALWAYS SET THE VARIABLE VOLTAGE TO ZERO BEFORE TURNING ON THE SUPPLY.
• RETURN THE VOLTAGE TO ZERO BEFORE SWITCHING OFF, UNLESS THERE IS AN EMERGENCY.
• FIND OUT THE LOCATION OF YOUR NEAREST EMERGENCY STOP BUTTON.
• REMEMBER TO DIAL 6 FOR EMERGENCY.
• REMEMBER TO DIAL 0000 FOR AMBULANCE.

I have read these precautions and shall carry them out.
Signed: (Please sign)
**Aims**  
To measure the equivalent circuit parameters of a power transformer.  
To calculate the transformer performance with a resistor and capacitor loads and compare with measured performance.  
To measure AC voltage, current and power at mains frequency and amplitude (50 Hz, 240 V).  
To note the approximate magnitude of transformer power losses.  
To observe safe operating procedures when working with a power transformer.

**Methodology**  
A single-phase 1.5-kVA, 50-Hz power transformer is provided (rated voltage 240 V x rated current 6.25 A = 1500 VA). Resistance, open-circuit and short-circuit tests are performed to determine the parameters in an approximate electrical equivalent circuit. The model is used to calculate performance with resistor and capacitor loads. The calculated performance is compared with measured performance. (A resistor simulates a heating load, and a capacitor simulates a long power cable on open circuit). Transformer losses are presently an inescapable part of any electrical power transmission or electromechanical system where voltage transformation takes place.

**Equipment**  
*Provided by UTS in Room 1916*  
Single-phase variable voltage AC supply ("variac") as shown in Figure 1.

![Figure 1](image1.png)

*This variac is an auto-transformer with one winding only and a variable contact tapping.*

1.5 kVA Standard Waygood single phase transformer as shown in Figure 2. (or 4.5 kVA 3 phase 3 limb transformer)

![Figure 2](image2.png)

*The transformers have a primary of 6 ampere max rating with tappings at points in the winding corresponding to rated voltages of 0, 206, 240, 360 and 415 V.*

*The transformers have two secondaries of 12 ampere max rating with tappings corresponding to open circuit voltages of 0, 60, 120 V (secondary 1) and 0, 120 V (secondary 2). (The open circuit voltage ratio is the turns ratio).*
YEW model 2433 clip-on wattmeter, shown in Fig. 3, that can be used as ammeter/voltmeter.

Figure 3

GDM8045 digital multimeters (2)
110 ohm ±5% power resistor
10, 20, 30 µF power capacitor
Connecting leads with retractable shrouds on the plugs

*Provided by student:*
Graph paper, further writing paper.

**Theory (gaps and choices to be completed before the laboratory)**

**Open circuit test**

The transformer primary is connected to the supply and the secondary is left unconnected (or vice versa). In this connection, the transformer looks like a simple inductor, as the secondary winding carries no current. The transformer primary equivalent circuit is an inductor in series with a resistor (winding resistance) as shown in Figure 4. Since the inductor has a laminated steel core, it is modelled for an AC supply as an inductance in parallel (usually) with a resistor to model the core eddy current and hysteresis losses.

Voltages at the rated frequency up to and slightly beyond the rated voltage may be applied.

![Diagram of open circuit test](Image)

Assume the 240 V primary winding is excited at $V_1 = 240$ V rms AC at 50 Hz, and that $R_1 = 1.0$ ohm, $L_m = 1.0$ H, $R_C = 2000$ ohm (these are typical values for the transformer supplied).

[i] The reactance of the inductance is:

$$X_m =$$ ohm.
Thus the impedance of the "magnetising" elements $X_m$ and $R_C$ is high compared to the winding resistance and the voltage drop across $R_1$ may be neglected so that the approximate equivalent circuit can be obtained as shown in Figure 5.

Figure 5.

[ii] The power lost in the core is approximately:
\[ P_C = = = \text{W}. \]

[iii] The amplitude of the current through the inductance (magnetising current) is approximately:
\[ I_m = = = \text{A}. \]

[iv] The phase angle of the magnetising current with respect to the supply voltage is approximately:
\[ \angle I_m = \text{deg}. \]

[v] The amplitude of the current through the core loss resistance is approximately:
\[ I_C = = \text{A}. \]

[vi] The phase angle of the core loss current with respect to the supply voltage is approximately:
\[ \angle I_C = \text{deg}. \]

[vii] The total current amplitude is approximately:
\[ I_1 = = = \text{A}. \]

[viii] The power lost in the winding resistance is approximately:
\[ P_{w1} = = \text{W}. \]

[ix] If the turns ratio is 2:1, the voltage induced in the secondary is approximately:
Short circuit test

The transformer primary is connected to the supply and the secondary is short circuited (or vice versa). In this connection, the transformer also looks like an inductor. The transformer equivalent circuit is an inductor representing leakage flux in series with a resistor representing the total winding resistance referred to the primary, as shown in Figure 6.

![Figure 6](image)

The impedance of the short circuit and leakage reactance is so low that the current through the magnetising inductance $L_m$ may be neglected. The equivalent circuit when neglecting the current through $L_m$ and $R_C$ is shown in Figure 7,

![Figure 7](image)

which is the same as in Figure 8.

![Figure 8](image)
Low voltages at the rated frequency are applied until the current is equal to or slightly beyond the rated value.

Assume the 240 V primary winding is excited with the 120 V secondary winding short circuited, and the voltage is such that $I_1 = 6.0$ A rms AC at 50 Hz.
Also assume $R_1 = 1.0$ ohm, $L_x = 10.0$ mH, and $R_2 = 0.1$ ohm.

[i] The secondary current referred to the primary is:
$$I_2' = = A.$$

[ii] The secondary current is:
$$I_2 = = A.$$

[iii] The reactance of the leakage inductance is:
$$X_x = = = \text{ohm}.$$

[iv] The secondary resistance referred to the primary is:
$$R_2' = = = \text{ohm}.$$

[v] The total resistance is:
$$R = = = \text{ohm}.$$

[vi] The total circuit impedance is:
$$Z = = = \text{ohm}.$$

[vii] The voltage applied to the primary is:
$$V_1 = = = \text{V}.$$

[viii] The angle between the current and the voltage is:
$$\angle I_1 = = = \text{deg}.$$

[ix] The power loss in the total winding resistance is:
$$P_w = = = \text{W}.$$
Load test

The transformer secondary is connected to a load impedance $Z_L$ (a resistor, inductor, capacitor, or combination). The approximate equivalent circuit referred to the primary for steady state AC supply is shown in Figure 9.

**Resistance load**

Assume the load is a 100 ohm resistor $R_L$ connected to the 120 V secondary (i.e. $Z_L = R_L$), and the 240 V primary is excited at 50 Hz. Assume the primary voltage is 240 V.

Assume the transformer parameters are as above, i.e. $R_1 = 1.0$ ohm, $L_m = 1.0$ H, $R_C = 2000$ ohm, $L_f = 10.0$ mH, and $R_2 = 0.1$ ohm.

[i] The load resistance referred to the primary is:

$$R_L' = \quad \text{ohm.}$$

[ii] Using phasor notation, the total impedance of the winding resistance, leakage reactance and load resistance referred to the primary is:

$$Z = \quad \text{ohm.} \quad \text{(magnitude and phase)}.$$  

[iii] Using $V_1 \angle 0$ as reference phasor, the secondary current referred to the primary is:

$$I_2' = \quad \text{A.} \quad \text{(magnitude and phase)},$$

or

$$= \quad \text{A.} \quad \text{(real and imaginary parts).}$$
Hence the secondary voltage referred to the primary is:
\[ V'_2 = \text{magnitude and phase}. \]

The actual secondary current is:
\[ I'_2 = \text{magnitude and phase}. \]

And the actual secondary voltage is:
\[ V_2 = \text{magnitude and phase}. \]

Check that ohm's law applies to the secondary quantities:
\[ V_2 = I'_2 \cdot R_L = \text{magnitude and phase}. \]

Now calculate the core loss current:
\[ I_c = \text{real and imaginary parts}. \]

and the magnetising current:
\[ I_m = \text{real and imaginary parts}. \]

Calculate the total exciting current:
\[ I_0 = \text{real and imaginary parts}. \]

Using KCL, calculate the total primary current:
\[ I_1 = \text{real and imaginary parts}. \]
or
\[ = \text{magnitude and phase}. \]
• Capacitance load

Assume the load is a 30 µF capacitor $C_L$ connected to the 120 V secondary (i.e. $Z_L = 1/(j\omega C_L)$, and the 240 V primary is excited at 50 Hz. Assume the primary voltage is 240 V. Assume the transformer parameters are as above, i.e. $R_1 = 1.0$ ohm, $L_m = 1.0$ H, $R_C = 2000$ ohm, $L_l = 10.0$ mH, and $R_2 = 0.1$ ohm.

Repeat the above calculations to find the secondary voltage and current, and the primary current:

[i] The load impedance referred to the primary is:

$$Z_L' = \text{ohm.}$$

[ii] Using phasor notation, the total impedance of the winding resistance, leakage reactance and load impedance referred to the primary is:

$$Z = \text{ohm.}$$

(magnitude and phase).

[iii] Using $V_1 \angle 0$ as reference phasor, the secondary current referred to the primary is:

$$\hat{I}_2' = \text{A.}$$

(magnitude and phase),

or

$$= \text{A.}$$

(real and imaginary parts).

(iv) Hence the secondary voltage referred to the primary is:

$$\hat{V}_2' = \text{V.}$$

(magnitude and phase).
The actual secondary current is:
\[ I_2 = \ldots = \ldots = A. \] (magnitude and phase).

And the actual secondary voltage is:
\[ V_2 = \ldots = \ldots = V. \] (magnitude and phase).

Check that ohm's law applies to the secondary quantities:
\[ V_2 = I_2 \cdot Z_L = \ldots = V. \]

Now calculate the core loss current:
\[ I_c = \ldots = \ldots = A. \] (real and imaginary parts).

and the magnetising current:
\[ I_m = \ldots = \ldots = A. \] (real and imaginary parts).

Calculate the total exciting current:
\[ I_o = \ldots = \ldots = A. \] (real and imaginary parts).

Using KCL, calculate the total primary current:
\[ I_1 = \ldots = \ldots = A. \] (real and imaginary parts)
\[ = \ldots = \ldots = A. \] (magnitude and phase).

Optional: Draw a diagram showing voltage and current phasors.
Method and results

Resistance
1. Using the ohm range of the digital multimeter, measure the resistance of the primary and secondary windings, and the leads:
   Leads (short the leads together) \( R_{\text{leads}} = \) ohm.
   Primary 240 V:
   \( R_1 = \) reading - leads = ohm.
   Secondary 120 V:
   \( R_2 = \) reading - leads = ohm.

2. Calculate the secondary winding resistance referred to the primary:
   \( R_2' = \) ohm.
   Hence the total resistance referred to the primary is:
   \( R = \) ohm.

The following tests can be lethal. Safety precautions must be observed.

Open circuit test

1. Connect the variac line to neutral output to the 0 - 240 V tappings of the transformer primary winding (using one phase only if your station has a 3-phase transformer).
2. To measure the primary voltage, connect the voltage leads of the clip-on wattmeter to the transformer primary 0 - 240 V tappings as well.
3. To measure the primary current, clip the wattmeter tongs around the transformer supply lead. (The wattmeter electronically multiplies the voltage and current to measure the mean power, and also displays the rms voltage and current amplitudes).
4. Connect a digital multimeter set to 1000 V AC to the transformer 120 V secondary terminals.
5. Draw the circuit diagram:

6. Have your connections checked by your tutor.
7. With the variable voltage at zero, turn on the supply, and cautiously increase the voltage. Note the meter readings as the voltage is increased to ensure the rated current and voltage is not being exceeded. Record at least 4 readings of primary voltage, current, power and
secondary voltage as the primary voltage is increased from 150 to 240 V:

<table>
<thead>
<tr>
<th>Primary voltage (V)</th>
<th>Primary current (A)</th>
<th>Primary power (W)</th>
<th>Secondary voltage (V)</th>
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8. Reduce the voltage to zero and turn off the supply.
9. Plot the readings of the primary current, power and secondary voltage against the primary voltage.
10. Also plot the power against the primary voltage squared

**Short circuit test**

1. Without changing the primary connections, reconnect the 120 V secondary to the digital multimeter 20 A inputs, and set the range to 20 A AC. This short circuits the secondary through an ammeter.
2. Draw the circuit diagram:

3. Have your connections checked.
4. Check the variac is set to zero, and turn on the supply.
5. Very carefully increase the voltage, monitoring the currents. Do not exceed the rated currents. The primary voltage will not need to exceed about 15 V. Record at least 4 readings of primary voltage, current, power and secondary current as the primary current is increased from 0 to 6 A:
6. Reduce the voltage to zero and turn off the supply.
7. Plot the readings of the primary voltage, power and secondary current against the primary current.
8. Also plot power against the primary current squared.

### Load test with resistor load

1. Without changing the primary connections, connect a 110 ohm power resistor in series with the 120 V secondary and the digital multimeter 20 A inputs, leaving the multimeter range on 20 A AC, thus connecting the secondary to the resistor load through the ammeter. Connect a second multimeter set for 1000 V AC across the secondary terminals to measure the secondary voltage.
2. Draw the circuit diagram:

3. Have your connections checked.
4. Check the variac is set to zero, and turn on the supply.
5. Very carefully increase the voltage, monitoring the currents. Do not exceed the rated currents. The primary voltage should be able to be increased to the rated 240 V. Record at least 3 readings of primary voltage, current, power and secondary voltage and current as the primary voltage is increased from 150 to 240 V:
Load test with capacitor load

1. Without changing the primary connections, connect a 30 µF power capacitor in series with the 120 V secondary and the digital multimeter 20 A inputs, leaving the multimeter range on 20 A AC, thus connecting the secondary to the capacitor load through the ammeter. Connect a second multimeter set for 1000 V AC across the secondary terminals to measure the secondary voltage.

2. Draw the circuit diagram:

3. Have your connections checked.

4. Check the variac is set to zero, and turn on the supply.

5. Very carefully increase the voltage, monitoring the currents. Do not exceed the rated currents. The primary voltage should be able to be increased to the rated 240 V. Record at least 3 readings of primary voltage, current, power and secondary voltage and current as the primary voltage is increased from 150 to 240 V:
6. Reduce the voltage to zero and turn off the supply.
7. Check that ohm's law is obeyed for the secondary readings.
8. Tidy up all equipment and return leads.

**Report**

1. Before arriving for the laboratory, complete the gaps in the theory section.
2. On extra sheets (with your name clearly marked) complete the following calculations.
   Attach the sheets and graphs to this document.
3. From the open circuit test calculate the core loss resistance (using the voltage and power), core loss current, magnetising current, magnetising reactance, magnetising inductance and turns ratio (using the voltage ratio) for at least 1 value of primary voltage.
   Optional: Calculate for several values of voltage and plot the results against primary voltage.
4. For the largest primary current from the short circuit test, calculate the total resistance referred to the primary (using the current and power), the leakage reactance, the leakage inductance and the turns ratio (using the current ratio).
   Compare the resistance with the value calculated from the directly measured resistance.
   Optional: Calculate for several values of current and plot the results against primary current.
5. For the resistor load test, using the calculated parameters, calculate the secondary voltage and primary current for at least 1 value of primary voltage. (Refer to the Prework for the method.) Compare with the measured values.
6. For the capacitor load test, using the calculated parameters, calculate the secondary voltage and primary current for at least 1 value of primary voltage. (Refer to the Prework for the method.) Compare with the measured values. Note the difference between the resistor and capacitor load results.
7. Before leaving the laboratory, complete the results, calculations and comments. Hand in your report.

**Reading**

1. Lecture notes on AC circuit theory and transformers.
2. Powell "Electromagnetism".
3. Slemon "Electrical machines and drives".
4. Fitzgerald "Electric machinery".
5. Many other books in the library on electric machines and transformers.