OBJECTIVE:
When you have completed this Experiment, you should be able to:

- Construct an equivalent circuit of a transformer on no load.
- Predict the efficiency of a transformer over a range of loads.
- Complete the equivalent circuit.
- Determine the voltage regulation of a transformer with varying loads, and discuss capacitive and inductive loading on transformer regulation.
- Familiar with voltage and current characteristics of an autotransformer, and you will be able to connect a standard transformer as an autotransformer in step-up and step-down configurations.

Overview:

Transformer no-load phasor diagram:

I. The core flux is common to both primary and secondary windings in a transformer and is thus taken as the reference phasor in a phasor diagram. On no-load the primary winding takes a small no-load current $I_0$ and since, with losses neglected, the primary winding is a pure inductor, this current lags the applied voltage $V_1$ by $90^\circ$. In the phasor diagram assuming no losses, shown in Figure 5.1(a), current $I_0$ produces the flux and is drawn in phase with the flux. The primary induced e.m.f. $E_1$ is in phase opposition to $V_1$ (by Lenz’s law) and is shown $180^\circ$ out of phase with $V_1$ and equal in magnitude. The secondary induced e.m.f. is shown for a 2:1 turns ratio transformer.

![Figure 5.1](image_url)

II. A no-load phasor diagram for a practical transformer is shown in Figure 5.1(b). If current flows then losses will occur. When losses are considered then the no-load
current Io is the phasor sum of two components IM, the magnetizing component, in phase with the flux, and IC, the core loss component (supplying the hysteresis and eddy current losses). From Figure 5.1(b):
No-load current, Io = \( \sqrt{I_2M + I_2C} \), where
IM = Io sin \( \varphi_0 \)
and IC = Io cos \( \varphi_0 \)
Power factor on no-load=cos \( \varphi_0 \) = IC / Io

**Equivalent circuit of a transformer:**
Figure 5.2 shows an equivalent circuit of a transformer. R1 and R2 represent the resistances of the primary and secondary windings and X1 and X2 represent the reactances of the primary and secondary windings, due to leakage flux. The core losses due to hysteresis and eddy currents are allowed for by resistance R which takes a current IC, the core loss component of the primary current. Reactance X takes the magnetizing component IM. In a simplified equivalent circuit shown in Figure 5.2.

![Equivalent circuit of a transformer](image)

**OPEN CIRCUIT TEST:**

**Introduction:**
Many electrical machines, particularly transformers, ac motors and generators can be more easily analyzed and their performance better understood with the aid of an equivalent circuit in which the effects of core loss, copper loss, flux leakage, etc. are represented by electrical resistances and inductances. An equivalent circuit will produce the same phasor diagram as the machine itself and the values used to construct either diagram are derived from tests on the actual machine.

**The equivalent circuit:**

**Practical 5.1: open circuit test:**
A real transformer with no load on its secondary may be represented as an ideal transformer with no core loss and which requires zero magnetizing current plus two parallel elements R_C and X_m as in figure 5.3.
The resistance $R_C$ is the core loss element. The current through this will be in phase with the applied voltage and will dissipate power equivalent to that of the core at a specified voltage and frequency. The reactance $X_m$ is the magnetizing element. Its current will lag the applied voltage by $90^\circ$; i.e. it is in quadrature with the applied voltage, and no power is dissipated. The current taken by $X_m$ produces the magneto-motive force which sets up the flux in the core.

By measuring the current and power taken from the supply, as shown in figure 5.4, values for the elements of the equivalent circuit can be derived and the phasor diagram constructed.
We will first calculate the phase angle between the current $I_o$ and the primary voltage $V_1$, and then derive values for the core loss and magnetizing currents.

Let $P_1 = \text{primary power input (wattmeter } W_1)\$

$V_1 = \text{Voltage applied to primary (voltmeter } V_1)\$

$V_2 = \text{Voltage applied to secondary (voltmeter } V_2)\$

$I_o = \text{Total primary current on no load (ammeter } I_1)\$

$I_C = \text{In phase component of current } I \text{ (core loss component)}\$

$I_m = \text{Quadrature component of current } I \text{ (magnetizing component)}\$

$\phi = \text{phase angle between } V_1 \text{ and } I_o.\$

We can now calculate the currents through the core loss resistance $R_C$ and the magnetizing reactance $X_m$ also the phase relationships between these currents and the primary voltage.

A word of explanation is needed as to why we refer to the total primary current on no load as $I_o$ instead of $I_1$. $I_o$ represents the phasor sum of the core loss current $I_C$ and the magnetizing current $I_m$ as shown in figure 5.5. When the transformer is supplying no external load, this is the total current taken by the primary, therefore for this condition $I_o=I_1$. When the transformer is supplying a load, there is a large additional current flowing in the primary and in this case $I_1$ is not equal to $I_o$ but to the phasor sum of $I_o$ and primary load current component.

The apparent power taken by the primary on no load is:

$S = V_1 I_o$

And the power input is: $P_1 = S \cos \phi$

Hence: $\cos \phi = P_1 / (V_1 I_o)$

And:

$I_C = I_o \cos \phi$ (Core loss component in phase with the applied voltage)

$I_m = I_o \sin \phi$ (Magnetizing component in quadrature with applied voltage)

**Procedure:**

1. Ensure that the power supply (unit 8821-25) is switched off.
2. Make the appropriate connections either for virtual or conventional instrumentation shown in figure 5.5 using unit 8341-05.
3. In the virtual instrumentation set the range of ammeters in low mode.
4. Ensure the dial on the power supply is set to zero position.
5. Switch on the power supply unit and using the output voltage dial, set the phase voltage to 200 V as shown on the virtual or conventional voltmeter $E_1$.
6. Measure the primary current and the secondary voltage, and record the results in table 5-1.
7. On virtual or instrumentation, record the primary input power to the transformer in table 5-1.

<table>
<thead>
<tr>
<th>Primary volts $V_1$</th>
<th>Primary current $I_o$</th>
<th>Input power $P_1$</th>
<th>Secondary volts $V_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table (5-1)

**By using the virtual instrumentation ( LVVL Program):**

Repeat the above procedure by using LVVL Program and Switch on the power supply unit and using the output voltage dial set the phase voltage to 100 V, Measure and record all above.
Exercise 5.1:
Calculate \( \cos \varphi \), the angle \( \varphi \), \( I_C \) and \( I_m \) from the test results recorded in table 5-1. Then construct the phasor diagram.

Exercise 5.2:
Now that the currents \( I_C \) and \( I_m \) have been evaluated, we can find the values of the equivalent core loss resistance \( R_C \) and magnetizing reactance \( X_m \). Draw the equivalent circuit for the transformer on no load and insert these values into it. The methods of calculating \( R_C \) and \( X_m \) is detailed in introduction section of this assignment.

Exercise 5.3:
Deduce the turns' ratio from your results in table 5-1.

Exercise 5.4:
A transformer has a turns' ratio of 0.5. An open circuit test is performed on the primary and \( R_C \) is found to be 600\(^\Omega\) and \( X_m \) is found to be 160\(^\Omega\). Calculate the values of \( R_C \) and \( X_m \) which would have been found if you had performed the open circuit test on the secondary winding instead of the primary.

Practical Aspects:
The equivalent circuit which you have constructed in this assignment provides a model of the transformer on no load which is compatible with the phasor diagram. At this stage, it does not provide a complete model, since the effect of load current in the winding impedance has not been considered. In the next assignment, we will add the circuit elements necessary to complete the equivalent circuit of the transformer.

\( \textit{SHORT CIRCUIT TEST} \):

**Winding resistance:**
Each winding of a transformer has resistance. When a current flows this gives rise to a voltage drop and to a power loss, usually referred to as the 'copper loss'

\[
\text{Copper loss} = I_1^2R_1 + I_2^2R_2
\]

**Leakage reactance:**
The flux produced by current flow in the primary turns does not all link with the secondary turns. Similarly, the counter flux produced by load current in the secondary turns does not all link with primary turns.

The effect of leakage flux in a real transformer is similar to having an ideal transformer in which all the flux links both windings, plus separate inductors connected in series with the primary and secondary. In the equivalent circuit, reactance \( X_1 \) and \( X_2 \) will represent the leakage components in series with the primary and secondary windings.
Completing the equivalent circuit:

By adding the winding resistances and leakage reactance to the equivalent circuit of the transformer on no load, we can extend it to form a complete model of the transformer. The degree of complexity to which the equivalent circuit is taken will depend on the particular application for which it is to be used. The complete equivalent circuit is shown in figure 5.6.

The magnitude of the total effective winding resistance and leakage reactance can be found by placing a short circuit across the secondary, and finding out how much voltage at the primary terminals is needed to drive the rated current through the transformer. This voltage will be quite small, so that the core losses (the effect of $R_C$ and $X_m$) will be negligible. The required circuit is shown in figure 5.7.

![Figure 5.6](image1)

There is, however, a preliminary test which we shall undertake in order to overcome some limitations in our laboratory situation. In industry, the testing of a transformer would be carried out with high accuracy instruments, regularly recalibrated. Also it happens that in large transformers (for which open and short circuit tests are most valuable) the results are not usually nearly as dependent on measurement errors as in our small one. The reasons will become apparent later. But to ensure that you get good results it will be advisable to check that the voltmeter, ammeter and electrodynamic wattmeter are consistent with one another if conventional instrumentation is used.
**Calculation of winding resistance and leakage reactance:**

The input power which is measured in the short circuit test is unlikely to be the same as \( V_1 I_1 \) calculated from measurements. Let us suppose for the moment that the impedance at the primary terminals is a series combination of resistance \( R'_1 \) and reactance \( X'_1 \).

Then since there is no power dissipated in the reactance:

\[
W_1 = I_1^2 R'_1
\]

So that:

\[
R'_1 = \frac{W_1}{I_1^2}
\]

Also the total impedance is:

\[
\frac{V_1}{I_1} = Z = \sqrt{R'_1^2 + X'_1^2}
\]

So that \( X'_1 \) can be calculated as

\[
X'_1 = \sqrt{Z^2 - R'_1^2}
\]

Note that only a single resistance and a single reactance value are obtained from these calculations. We must find out how they are related to the individual primary and secondary resistances and reactance.

**Practical 5.2: short circuit test:**

**Procedure:**

1. Ensure that the power supply (unit 8821-25) is switched off.
2. Make the appropriate connections either for virtual or conventional instrumentation shown in figure 5.7 using unit 8341-05.
3. In the virtual instrumentation set the range of ammeters in low mode.
4. Ensure the dial on the power supply is set to zero position.
5. Switch on the power supply unit and using the output voltage dial, set the phase voltage to 200 V as shown on the virtual or conventional voltmeter E1.
6. Measure the primary current and the secondary voltage, and record the results in table 5-2.
7. On virtual or instrumentation, record the secondary input power to the transformer in table 5-2.

<table>
<thead>
<tr>
<th>Primary volts ( V_1 )</th>
<th>Primary current ( I_1 )</th>
<th>Input power ( P_1 )</th>
<th>Secondary current ( I_2 )</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>0.2</td>
<td></td>
</tr>
</tbody>
</table>

Table (5-2)

**By using the virtual instrumentation (LVVL Program):**

Repeat the above procedure by using LVVL Program and Switch on the power supply unit and using the output voltage dial set the phase voltage to 100 V, Measure and record all above.

**Exercise 4.5:**

Calculate the values of \( R'_1 \) and \( X'_1 \). Draw the equivalent circuit of the transformer in the form having all impedances on the primary side of the ideal transformer. Mark in the values calculated in this practical and include values for \( R_C \) and \( X_m \) from part 1.
Practical 4.3:

1. Ensuring that the power supply is switched off, remove the connections to the secondary ammeter.
2. Switch on the power supply and read the power indicated on the virtual wattmeter.
3. The value of the core loss during the short circuit test would have been much less than the quantity measured in this practical. This is because the core flux will have been roughly halved by the reduction in voltage due to the current in the primary resistance and leakage inductance.
4. Since eddy current loss is proportional to the square of the flux density and hysteresis loss, a fair estimate of the core loss in the short circuit test is about one quarter of the loss you measured with the short circuit removed.

Practical aspects:

1. It may seem that it would be far simpler to measure the winding resistance with an ohm meter, and the leakage reactance may seem rather uncertain from your measurements. But consider the situation with a very large transformer.
2. Large transformers have thick conductors in order to pass large currents without excessive heating. The resistance is often too low to measure with an ordinary ohmmeter and in any case may differ between ac and dc values, so $R_1'$ is better determined by the ammeter and electrodynamic wattmeter method using ac.
3. You may have found the reactance uncertain because its calculation involved a small difference between two large quantities. But in a large transformer, the reactance is usually much larger than the resistance and, in this case, the errors of the measurement matter far less.

TRANSFORMER REGULATION:

Introduction:
The load on a large power transformer in a sub-station will vary from a very small value in the early hours of the morning to a very high value during the heavy peaks of maximum industrial and commercial activity. The transformer secondary voltage will vary somewhat with the load, and because motors, incandescent lamps, and heating devices are all quite sensitive to voltage changes, transformer regulation is of considerable importance. The secondary voltage also depends upon whether the power factor of the load is leading, lagging, or unity. Therefore, it should be known how the transformer will behave (its voltage regulation) when connected to a capacitive, an inductive, or a resistive load. Transformer voltage regulation in percent is determined with the following formula:

$$\text{Voltage Regulation (\%)} = 100 \times \frac{E_{NL} - E_{FL}}{E_{NL}}$$

Where:
$E_{NL}$: is the no-load secondary voltage
$E_{FL}$: is the full-load secondary voltage

The result (a percentage value) obtained gives an indication of transformer behavior under load. The smaller the voltage regulation percentage, the smaller the secondary voltage variation with load, and the better the voltage regulation. Note that $E_{NL}$ is measured with the secondary winding open while $E_{FL}$ is measured when nominal current flows in the secondary winding. Several factors affect a transformer's operation. The resistance and inductive reactance of its windings cause internal voltage drops that vary with the amount of current flowing in the windings. If the secondary is lightly loaded, current through the winding resistance and
reactance is small and the internal voltage drops are not significant. As the load increases, current and internal voltage drops also increase. If a transformer was perfectly ideal, its windings would have neither resistance nor inductive reactance to cause voltage drops. Such a transformer would have perfect regulation under all load conditions and the secondary voltage would remain absolutely constant. But practical transformer's coils are made of real wire, and thereby, have resistance and inductive reactance. Therefore, the primary and secondary windings have an overall resistance \( R \), and an overall reactance \( X \). The simplified equivalent circuit of a practical transformer with a 1:1 turns' ratio can be approximated by the circuit shown in Figure 5.8. The actual transformer terminals are \( P_1, P_2 \) on the primary side, and \( S_1, S_2 \) on the secondary side.

![Figure 5.8: Simplified Equivalent Circuit of a Practical Transformer](image)

In this equivalent circuit, the practical transformer is shown to be made up of an ideal transformer in series with an impedance consisting of \( R \) and \( X \) that represents the imperfections of the transformer. When a load \( (Z) \) is connected to the secondary winding terminals (terminals \( S_1 \) and \( S_2 \)), a series ac circuit consisting of the secondary winding of the ideal transformer, \( R \), \( X \), and \( Z \) is obtained. Analysis of this series ac circuit shows that when the load is either resistive or inductive, the load voltage decreases continuously as the load increases (as the secondary current increases). Furthermore, when the load is capacitive, the load voltage increases to a maximum as the load increases from zero (no load condition), and then, the load voltage decreases as the load continues to increase.

- **Procedure:**
  1. Ensure that the power supply (unit 8821-25) is switched off.
  2. Set up the transformer loading circuit shown in Figure 5.9. Ensure that all switches on the Resistive, Capacitive, and Inductive Load modules are open, and connect \( E_1, E_2, I_1, I_2 \) as shown in the figure. Different load values will be used to examine how the secondary (load) voltage changes as transformer loading changes.
  3. In the virtual instrumentation set the range of ammeters in low mode.
  4. Turn on the main Power Supply and adjust the main voltage control to obtain the value of \( E_S \) given in Figure 5.9. With no load on the transformer (all switches open on the load module), Measure \( E_{PRI}, I_{PRI}, E_{SEC}, \) and \( I_{SEC} \) and record them in table (5.3).
5. Adjust the switches on the Resistive Load module to successively obtain the resistance values given in table (5-3). For each resistance value, record the measurements as in step 4.

<table>
<thead>
<tr>
<th>V_{PRI} (V)</th>
<th>V_{SEC} (V)</th>
<th>I_{PRI}(I)</th>
<th>I_{SEC}(I)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>R(Ω)</td>
<td>R(Ω)</td>
</tr>
<tr>
<td>∞</td>
<td>4400</td>
<td>2200</td>
<td>1100</td>
</tr>
<tr>
<td>120</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>180</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>220</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table (5-3)

6. Display the Graph window, select E_{2} as the Y-axis parameter, and I_{2} as the X-axis parameter. Make sure the line graph format and the linear scale are selected. Observe the curve of secondary voltage versus current. What happens to the secondary voltage as the resistive load increases, i.e. load resistance decreases? Try to compare the curves obtained with different loads.

7. Calculate the voltage regulation using the no-load and full-load (R: minimum value) output voltages.

8. Replace the Resistive Load module in the circuit of Figure 5.9 with the Inductive Load module.

9. Repeat steps 4, 5, 6 for the inductive load and record results at table 5.4.

<table>
<thead>
<tr>
<th>V_{PRI} (V)</th>
<th>V_{SEC} (V)</th>
<th>I_{PRI}(I)</th>
<th>I_{SEC}(I)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>R(Ω)</td>
<td>R(Ω)</td>
</tr>
<tr>
<td>∞</td>
<td>4400</td>
<td>2200</td>
<td>1100</td>
</tr>
<tr>
<td>120</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>180</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>220</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table (5-4)

10. Replace the Resistive Load module in the circuit of Figure 5.9 with the capacitive Load module.

11. Repeat steps 4, 5, 6 for the inductive load and record results at table 5.5.

<table>
<thead>
<tr>
<th>V_{PRI} (V)</th>
<th>V_{SEC} (V)</th>
<th>I_{PRI}(I)</th>
<th>I_{SEC}(I)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>R(Ω)</td>
<td>R(Ω)</td>
</tr>
<tr>
<td>∞</td>
<td>4400</td>
<td>2200</td>
<td>1100</td>
</tr>
<tr>
<td>120</td>
<td></td>
<td></td>
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<td>200</td>
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<tr>
<td>220</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table (5-5)

12. What differences do you observe between the three load curves?

13. Ensure that the Power Supply is turned off.
The Autotransformer:

The autotransformer is a special type of transformer with only one winding which serves as both the primary and secondary. When the autotransformer is used to step-up the voltage, only part of the single winding acts as the primary, while the complete winding serves as the secondary. However, when the autotransformer is used to step-down the voltage, primary and secondary use is reversed. The whole winding is connected for use as the primary and only a part serves as the secondary. Figure 5.10 shows the autotransformer connections necessary for step-up and step-down operation.

![Figure 5.10.a: step-up Configuration](image1)
![Figure 5.10.b: step-down Configuration](image2)

Autotransformer operation is basically the same as a standard two-winding transformer. Power is transferred from the primary to the secondary by a changing magnetic flux. The amount of increase or decrease in the voltage depends on the turns ratio between the primary and the secondary. To determine the turns ratio of the autotransformer, each winding is considered as separate even though some turns are common to both the primary and the secondary. Voltages and currents can be found using two simple equations:

\[ EPRI \times IPRI = ESEC \times ISEC \]

and this equation simply states that the apparent power on the primary side (EPRI x IPRI) of the transformer equals the apparent power on the secondary side (ESEC x ISEC).

From Figure 5.10 we obtain the relationships:

\[
\frac{E_{PRI}}{E_{SEC}} = \frac{N_{A-B}}{N_{A-C}} \quad \text{for step-up operation, and}
\]

\[
\frac{E_{PRI}}{E_{SEC}} = \frac{N_{A-C}}{N_{A-B}} \quad \text{for step-down operation}
\]

The autotransformer has a great advantage over a conventional transformer: it can operate at an apparent power level that is twice that of a conventional transformer of the same size. Furthermore, the autotransformer is somewhat more efficient than transformers with separate windings because it has smaller copper and iron losses. It is used mainly when small increases or decreases are required in the secondary voltage. For example, to boost a power line voltage and compensate for losses caused by long transmission lines, or to reduce the starting voltage of a motor, thus holding down its starting current within reasonable values. One major disadvantage of an autotransformer is the lack of electrical isolation between the primary and secondary windings since the windings are not separate. Also, it is generally unadvisable to use an autotransformer as a large-ratio step-down device because the high-voltage primary voltage would be placed across the low-voltage load if the low-voltage section of the winding became defective and opened up.
**Procedure:**

*By using the virtual instrumentation (LVVL Program):*

1. Ensure that the power supply (unit 8821-25) is switched off.
2. Set up the autotransformer circuit shown in Figure 5.11. Connect E1 and I1 as shown, and use E2 and I2 to measure the secondary voltage and current. Note that winding 5-6 is connected as the primary, and that center tap terminal 9 and terminal 6 act as the secondary winding.

![Figure 5.11: Autotransformer Circuit to Decrease Secondary Voltage.](image)

3. Set the Resistive Load module to obtain the value of $R = 600 \, \text{Ω}, R=1200$ at $E_s=100\text{V}$.
4. Measure and record IPRI, ISEC, ESEC, SPRI, SSEC.

$$\begin{align*}
\text{IPRI} &= \_\_\_\_ A, \\
\text{ISCE} &= \_\_\_\_ A, \\
\text{ESEC} &= \_\_\_\_ V
\end{align*}$$

$$\begin{align*}
\text{SPRI} &= \_\_\_\_ VA, \\
\text{SSEC} &= \_\_\_\_ VA
\end{align*}$$

5. Compare the values of SPRI and SSEC.
6. Set up the autotransformer circuit shown in Figure 5.12. Connect E1 and I1 as shown, and use E2 and I2 to measure the secondary voltage and current. Note that winding 9-6 is now connected as the primary, and that terminals 5 and 6 are used for the secondary winding.

![Figure 5.12: Autotransformer Circuit to increase Secondary Voltage.](image)

7. Set the Resistive Load module to obtain the value of $R = 600 \, \text{Ω}, R=1200$ at $E_s=100\text{V}$.
8. Measure and record IPRI, ISEC, ESEC, SPRI, SSEC.
Conclusion:

- You examined the voltage regulation of a transformer, and saw that the secondary voltage varied as the load placed on the transformer changed. Load variation curves for resistive, inductive, and capacitive loads were plotted. These curves showed that under resistive or inductive loading conditions, the secondary voltage decreases as the load increases, and that under capacitive loading conditions, the secondary voltage can rise above its nominal value. Also, inductive loading caused greater voltage drops than resistive loading, hence poorer regulation.

- You connected a standard two-winding transformer to operate as an autotransformer in both step-up and step-down configurations. Measurements of apparent power on the primary and secondary sides of the circuit showed that they are approximately equal except for the small difference caused by transformer losses. You also saw that the voltage and current relationships for an autotransformer are based on the same rules as standard transformers.