EC1: DETERMINATION OF EQUIVALENT CIRCUIT PARAMETERS AND LOAD CHARACTERISTICS OF A SINGLE-PHASE TRANSFORMER

EC2: LOAD TEST ON A THREE-PHASE INDUCTION MOTOR

Note: On-the-spot evaluation will be carried out during or at the end of the experiments. The lab report must be submitted at the end of lab session.

Students are advised to read through this lab sheet before doing experiment. Your individual performance during on-the-spot evaluation, participation in the lab experimental work, teamwork effort, and learning attitude will count towards the lab marks, in addition to the lab discussion questions.
EC1: DETERMINATION OF EQUIVALENT CIRCUIT PARAMETERS AND LOAD CHARACTERISTICS OF A SINGLE-PHASE TRANSFORMER

Aim:
1) To determine the equivalent circuit parameters of a single phase transformer by conducting the open circuit and short-circuit tests.
2) To determine the load characteristics of a single phase transformer.

Theory:
The windings of a standard single-phase transformer are called the primary winding and the secondary winding as shown in Figure 1. The primary winding is the power input winding which is connected to the ac power source.

![Figure 1](image)

The secondary winding is connected to the load and is physically and electrically isolated from the primary winding. The voltage and current that flow in the secondary are related to the primary voltage and current by the transformer turns ratio \( \frac{N_1}{N_2} \) (or \( \frac{N_P}{N_S} \)). The ratio of primary voltage to secondary voltage equals \( \frac{N_1}{N_2} \), while the ratio of primary to secondary current is equal to the inverse of the turns ratio, \( \frac{N_1}{N_2} \). This can be written as

\[
\frac{E_P}{E_S} = \frac{N_1}{N_2}, \quad \therefore \ E_S = \frac{E_P \times N_2}{N_1}
\]

and,

\[
\frac{I_S}{I_P} = \frac{N_1}{N_2}, \quad \Rightarrow \ I_S = \frac{I_P \times N_1}{N_2}
\]

Transformers are normally designed with fixed ratios between primary and secondary voltages, and are widely used to step-up (increase) or step-down (decrease) voltages and currents. The single-phase transformer module used in this exercise has its nominal ratings indicated on the front panel. It has two secondary windings which can be used independently or connected in series.

**Open-Circuit (or No-load) Test:**
In the open-circuit test, a transformer’s secondary winding is open-circuited, and its primary winding is connected to a full-rated line voltage. Under this condition, all the input current flows through the excitation branch of the transformer and so, essentially, all the input voltage is dropped across the excitation branch.

Full line voltage is applied to the primary of the transformer, and the input voltage, input current, and input power to the transformer are measured. From this information, it is possible to determine the power factor of the input current and therefore the excitation impedance. The no-load power loss is equal to the wattmeter reading in this test; core loss is found by...
subtracting the Ohmic loss in the primary, which is usually very small and may be neglected. The easiest way to calculate the values of $R_C$ and $X_M$ is to find first the admittance of the excitation branch.

$$Y_E = G_C - jB_M = \frac{1}{R_C} - j\frac{1}{X_M}$$

The magnitude of the excitation admittance (referred to the primary circuit) can be found from the open-circuit test voltage and current as follows:

$$|Y_E| = \frac{I_O}{V_O}$$

The angle of the admittance can be found from knowledge of the circuit power factor. The open-circuit power factor (PF) is given by:

$$PF = \cos\theta = \frac{P_O}{V_O \times I_O}$$

and the power factor angle is given by:

$$\theta = \cos^{-1}\left(\frac{P_O}{V_O \times I_O}\right)$$

The power factor is always lagging for a real transformer, so the angle of the current always lags the angle of the voltage by $\theta$ degrees. Therefore, the admittance $Y_E$ is

$$Y_E = \frac{1}{R_C} - j\frac{1}{X_M} = \frac{I_O}{V_O} \angle -\theta$$

from which it is possible to determine the values of $R_C$ and $X_M$.

**Short-Circuit Test:**

In the short-circuit test, the secondary terminals of the transformer are short-circuited, and the primary terminals are connected to a fairly low voltage source. The input voltage is adjusted until the current in the short-circuited winding is equal to its rated value. The input voltage, current, and power are again measured.

Since the input voltage is so low during the short-circuit test, negligible current flows through the excitation branch. If the excitation current is ignored, then the voltage drop in the transformer can be attributed to the series elements in the circuit. The magnitude of the series impedances referred to the primary side of the transformer is

$$|Z_{SE}| = \frac{V_{SC}}{I_{SC}}$$

The power factor is given by:

$$PF = \cos\theta = \frac{P_{SC}}{V_{SC} \times I_{SC}}$$

and is lagging. The overall impedance angle $\theta$ is:

$$\theta = \cos^{-1}\left(\frac{P_{SC}}{V_{SC} \times I_{SC}}\right)$$

Therefore,
\[ Z_E = R_{eq} + jX_{eq} = \frac{V_{SC}}{I_{SC}} \angle \theta = (R_p + a^2 R_s) + j(X_p + a^2 X_s) \]

It is possible to determine the total series impedance referred to the primary side by using this technique, but there is no easy way to split the series impedance into primary and secondary components. Figure 2 shows the equivalent circuit of the transformer, referred to the primary side.

Figure 2: Equivalent circuit, referred to the primary side of the transformer

Also these same tests may be performed on the secondary side of the transformer if it is more convenient to do so because of voltage levels or other reasons. If the tests are performed on the secondary side, the results will naturally yield the equivalent circuit impedances referred to the secondary side of the transformer instead of to the primary.

**Load Test:**
The load test is performed with one winding (usually secondary side) connected across a variable loading resistor, and a rated voltage is applied to the other winding. With rated voltage applied to the primary winding and varying the loading resistor connected across the secondary winding, the primary current, primary input power, secondary voltage and current are measured.

**Equipment required:**

<table>
<thead>
<tr>
<th>Test</th>
<th>Equipments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Open-circuit test</td>
<td>Single-phase transformer, Voltmeter (2 units), Ammeter (1 unit), Wattmeter (1 unit), and Equipment platform.</td>
</tr>
<tr>
<td>Short-circuit test</td>
<td>Single-phase transformer, Wattmeter (1 unit), Voltmeter (1 unit), Ammeter (1 unit), and Equipment platform.</td>
</tr>
<tr>
<td>Load test</td>
<td>Single-phase transformer, Variable load resistor (1 unit), Voltmeter (2 units), Ammeter (2 units), Wattmeter (1 unit), and Equipment platform</td>
</tr>
</tbody>
</table>
PROCEDURE:

From the nameplate rating of the transformer, note down the followings.

Volt-Ampere (VA) rating = _______VA
Rated primary voltage = _______V; Rated Secondary voltage = _______V,
Rated primary current = _______A ; Rated Secondary Current = _______A

OPEN CIRCUIT TEST: (5 marks)
1. Establish the connections for measurements on the unloaded transformer according to the circuit diagram shown in Figure 3.

Figure 3: Open circuit test circuit connection

2. Switch on the power supply to the transformer. Adjust the supply voltage such that, $V_o = 220$ V. Measure the no-load current $I_o$, no-load power $P_o$, and no-load voltages $V_o$ and $V_{2-o}$. Record the values on the table.

<table>
<thead>
<tr>
<th>$V_o$ / V</th>
<th>$I_o$ / mA</th>
<th>$P_o$ / W</th>
<th>$V_{2-o}$ / V</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tbody>
</table>

3. Calculate the values of $R_C$ and $X_M$

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SHORT-CIRCUIT TEST: (5 marks)
1. Establish the connections according to the circuit diagram shown in Figure 4.
2. Make sure that the input power supply is changed to 24V AC.

![Figure 4 Short-circuit test circuit connection](image)

2. Switch on the power supply to the transformer. Increase the supply voltage starting from 0 V until a rated current of 0.91 A flows in the primary winding. Measure the primary voltage (V_{SC}) and the input power (P_{SC}) at the rated current (I_{SC}) and tabulate them.

<table>
<thead>
<tr>
<th>V_{SC}/V</th>
<th>I_{SC}/mA</th>
<th>P_{SC}/W</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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</tbody>
</table>

3. Calculate the values of R_{eq} and X_{eq}

4. Draw the equivalent circuit of the transformer, referred to its primary side:
LOAD TEST (5 marks)

1. Modify the circuit according to the circuit diagram shown in Figure 5 for performing the load test.

![Load test circuit connection](image)

Figure 5: Load test circuit connection

2. Switch on the power supply to the transformer. Adjust the supply voltage such that, $V_1 = 220V$. Adjust the loading resistor ($R_L$), starting from the maximum resistance value, slowly towards 0 until the rated current, $I_2 = 0.91A$, flows in the secondary side. Measure the primary current $I_1$, primary input power $P_1$, the secondary voltage $V_2$ and the secondary current $I_2$.

3. Vary the load in steps and record $I_1$, $P_1$, $V_2$ and $I_2$ for different load currents in the table below.

<table>
<thead>
<tr>
<th>Load current, $I_2$ (A)</th>
<th>$V_1$ (V)</th>
<th>$I_1$ (A)</th>
<th>$P_1$ (W)</th>
<th>$V_2$ (V)</th>
<th>$P_2$ (W)</th>
<th>$\eta$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.91</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.8</td>
<td></td>
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<td></td>
</tr>
<tr>
<td>0.7</td>
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<tr>
<td>0.6</td>
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<td></td>
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<tr>
<td>0.4</td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>0.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\approx 0.0$</td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
</tr>
</tbody>
</table>
4. Calculate the current transformation ratio of the given transformer at the rated secondary current.

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5. Calculate $P_2$ and efficiency, $\eta$, for different load currents using the formula:

\[ P_2 = V_2 I_2 \]

\[ \eta = \left( \frac{P_2}{P_1} \right) \times 100\% \]

6. Plot $I_2$ versus $\eta$ and $I_2$ versus $V_2$

DISCUSSION QUESTIONS

OPEN-CIRCUIT TEST

1. Explain the main objective(s) of conducting the open-circuit test on a transformer. (4 marks)

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2. What are the current components that constitutes the excitation current of a transformer? How are they modeled in the transformer’s equivalent circuit? (4 marks)

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3. Conclude on the results obtained in procedure step 3. (4 marks)

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SHORT-CIRCUIT TEST

1. Explain the main objective(s) of conducting the short-circuit test on a transformer. (4 marks)

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2. What is understood by steady short-circuits current? (4 marks)

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3. Evaluate the effect of a load current on the output voltage, when a transformer is having a low short-circuit voltage. (4 marks)

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LOAD TEST

1. Explain the main objective(s) of conducting the load test on a transformer. (4 marks)

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2. Why does the power output, $P_2$, is less than power input $P_1$? (3 marks)

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3. Discuss why does the transformer draw more current on load than at no-load (3 marks)
4. Explain why the secondary voltage of a transformer decreases with increasing resistive load (3 marks)

5. Conclude on the two curves which you have drawn. (4 marks)
EC2: LOAD TEST ON A THREE-PHASE INDUCTION MOTOR

Aim:

To verify the load characteristics of a three-phase induction motor with squirrel-cage rotor for Y connection.

Theory:

The induction motor is the most popular type of ac motor because of its simplicity and ease of operation. A three-phase induction motor has two main parts: a stationary stator and a revolving rotor. The rotor is separated from the stator by a small air gap that ranges from 0.4 mm to 4 mm, depending on the power of the motor. The stator consists of a steel frame that supports a hollow, cylindrical core made up of stacked laminations. There are two different types of induction motor rotors which can be placed inside the stator. One is called a squirrel-cage rotor or simply a cage rotor, while the other is called a wound rotor.

A squirrel-cage induction motor rotor consists of a series of conducting bars laid into slots carved in the face of the rotor and shorted at either end by large shorting rings. This design is referred to as a squirrel-cage rotor because the conductors would like one of the exercise wheels that squirrels or hamsters run on.

When a three-phase set of balanced voltages is applied to the stator, a three-phase set of currents will be flowing in the stator winding. These currents produce a magnetic field $\mathbf{B}_S$, which is rotating in a counterclockwise direction. The speed of the magnetic field’s rotation is given by

$$n_{sync} = \frac{120f_e}{P}$$

where $f_e$ is the system frequency in Hz and $P$ is the number of poles in the machine. The rotating magnetic field $\mathbf{B}_S$ passes over the rotor bars and induces a voltage in them.

The induced voltage in a given rotor bar is given by the equation

$$e_{ind} = (\mathbf{v} \times \mathbf{B}).l$$

where $\mathbf{v}$ = velocity of the bar relative to the magnetic field
$\mathbf{B}$ = magnetic field density vector
$l$ = length of conductor in the magnetic field

It is the relative motion of the rotor compared to the stator magnetic field that produces induced voltage in a rotor bar. The velocity of the upper rotor bars relative to the magnetic fields is to the right, so the induced voltage in the upper bars is out of the page, while the induced voltage in the lower bars is into the page. This results in a current flow out of the upper bars and into the lower bars. However, since the rotor assembly is inductive, the peak rotor current lags behind the peak rotor voltage. The rotor current flow produces a rotor magnetic field $\mathbf{B}_R$. 

Therefore, the induced torque in the machine (motor) is given by

\[ \tau_{\text{ind}} = kB_R \times B_S \]

Since the rotor induced torque is counterclockwise, the rotor accelerates in that direction. In normal operation both the rotor and stator magnetic fields \( B_R \) and \( B_S \) respectively rotate together at synchronous speed \( n_{\text{sync}} \), while the rotor itself turns at a slower speed.

**Equipment required:**

- Power supply,
- Pendulum machine (brake),
- Control unit,
- Circuit breaker,
- on/off switch,
- Coupling collar,
- Coupling cover,
- Shaft end cover,
- Voltmeter,
- Ammeter,
- Wattmeter,
- Power factor meter,
- Three phase induction motor with squirrel cage rotor.

**PROCEDURE:** (15 marks)

1. Establish the connections for recording the load characteristics in star connection according to the current diagram shown in Figure 1:
2. Before starting the motor, adjust the operating elements of the control unit in the following manner:

<table>
<thead>
<tr>
<th>Type of power</th>
<th>300 W</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating switch on position:</td>
<td>off</td>
</tr>
<tr>
<td>Switch “n&lt;sub&gt;const&lt;/sub&gt;, M&lt;sub&gt;const&lt;/sub&gt;” position:</td>
<td>M&lt;sub&gt;const&lt;/sub&gt;.</td>
</tr>
<tr>
<td>Switch “Torque range” position:</td>
<td>10 Nm</td>
</tr>
<tr>
<td>Switch “speed range” position:</td>
<td>1500</td>
</tr>
</tbody>
</table>

- Switch on the control unit with the master switch.
- Press the reset button. Now the red LED should not be lit anymore, otherwise check the following:
- the coupling hoop guard
- the hoop guard for the shaft end cover
- the jack plug for the motor temperature control (probably has not been plugged in)
- the motor (perhaps the motor is too hot).

3. **Step 1:** Start the motor and measure the input voltage, V

**Step 2:** Measure the required quantities at no-load (the torque \( M \) is about 0 Nm). Enter the measured values on the table 1.

**Step 3:**
- Switch the function selector from “off” to “\( n_{\text{const.}} \), \( M_{\text{const}} \)”. The corresponding green LED lights up. (The speed of the pendulum machine automatically adjusts to the motor speed).
- Adjust the given load at the control unit of the pendulum machine by pressing the push button “down”. When exceeding the selected value, press push button “up”.
- Read the corresponding values measured. Enter the measured values on the Table 1.

<table>
<thead>
<tr>
<th>Table 1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input Voltage, ( V = ) ...............</strong></td>
</tr>
<tr>
<td><strong>( \frac{M}{Nm} )</strong></td>
</tr>
<tr>
<td>Mechanical shaft speed, ( n ) (min(^{-1}))</td>
</tr>
<tr>
<td>( I ) (A)</td>
</tr>
<tr>
<td>( \cos \varphi )</td>
</tr>
<tr>
<td>( P_1 ) (W)</td>
</tr>
<tr>
<td>( P_2 ) (W)</td>
</tr>
<tr>
<td>( S ) (VA)</td>
</tr>
<tr>
<td>( \eta )</td>
</tr>
<tr>
<td>Slip, ( s ) (%)</td>
</tr>
</tbody>
</table>

4. Calculate the following:
   
The power output \( P_2 = \frac{Mn(2\pi)}{60} \)
The apparent power \( S = V \cdot I \cdot \sqrt{3} \)

The efficiency \( \eta = \frac{P_2}{P_1} = \frac{P_2}{3 \cdot P_1} \)

The slip \( s = \frac{n_s - n}{n_s} \times 100\% \) (relative speed expressed on a pu or percentage basis)

\[ s = \frac{1500 - n}{1500} \times 100\% \]

Enter the calculated values in the table.

5. Plot \( n, I, \cos \varphi, \eta, P_2 \) and \( s \) as a function of \( M \)

DISCUSSION SHEET

1) What is the meaning of ‘synchronous speed’ for an induction motor? Write down the equation of the ‘synchronous speed’. (5 marks)

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2) Based on the plotted graph in Procedure no.5, explain how will the speeds, the slip and the efficiency of the change, with increasing load. (8 marks)

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3) What happens when the speed of an induction motor reaches the synchronous speed? (8 marks)

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4) Illustrate the purpose of starter in a three-phase induction motor? (7 marks)
5) Evaluate the efficiency of the motor as a function of load within the range of no-load/rated load. (7 marks)

Marking Scheme

<table>
<thead>
<tr>
<th>Lab (10%)</th>
<th>Assessment Components</th>
<th>Details</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hands-On &amp; Efforts (2%)</td>
<td>The hands-on capability of the students and their efforts during the lab sessions will be assessed.</td>
<td></td>
</tr>
<tr>
<td>On the Spot Evaluation (2%)</td>
<td>The students will be evaluated on the spot based on the lab experiments and the observations on the machine characteristics.</td>
<td></td>
</tr>
<tr>
<td>Lab Report (6%)</td>
<td>Each student will have to submit his/her lab discussion sheet and recorded experimental data on the same day of performing the lab experiments EC1 and EC2.</td>
<td></td>
</tr>
</tbody>
</table>