PART IB EXPERIMENTAL ENGINEERING

SUBJECT: ELECTRICAL ENGINEERING — EXPERIMENT E3 (SHORT)

LOCATION: ELECTRICAL AND INFORMATION ENGINEERING TEACHING LABORATORY

THREE-PHASE INDUCTION MOTOR

1 OBJECTIVES

1. To determine the equivalent circuit parameters of a three-phase induction motor by carrying out no-load and locked-rotor tests.

2. To perform load tests on the motor.

3. To compare the values of input power, input current, and torque measured during the load tests with those predicted using the equivalent-circuit.

4. To investigate the effect of adding extra resistance in the rotor circuit.

2 SAFETY

For obvious reasons, the machines used in a student laboratory are small and well protected. You are most unlikely to injure yourself or damage the equipment, but nevertheless you should exercise care. If you get clothing or your hair entangled in the shaft, the results will be very unpleasant. You should also make quite certain that you have turned the variable-voltage supply to zero before switching it on. Never attempt to stop a rotating shaft manually.

1 Introduction

The induction motor is the most widely used type of electrical motor. It is simple, cheap to make and robust. It need have no electrical connection to the rotating member – the rotor – although the machine used in this experiment has rotor connections via slip-rings. For many applications, the induction motor is connected directly to the three-phase alternating current mains supply although electronic frequency conversion enables it to be used as a variable speed drive.

In this experiment you will carry out tests to determine the equivalent-circuit parameters for a small slip-ring induction motor supplied from 50 Hz three-phase mains. You will then use the equivalent circuit to predict performance under different operating conditions, and compare your predictions with measurements made on the test motor.

The demonstrator will show you how to excite the machine and how to vary the terminal voltage applied to it. **Do not start the experimental work until you have received these instructions**.

2 Machine Data

The motor you are going to test is a four-pole machine. The name-plate which is attached to it reveals the following additional data:

Full-load output power	3 kW
Supply frequency	50 Hz

	Rated **line** voltage	Rated **line** current
Stator windings delta-connected	220 V	14.7 A
Stator windings star-connected	380 V	8.5 A

From these we can deduce that the rated **phase** voltage of the motor is 220 V, and the rated **phase** current is 8.5 A. (If you do not understand this, ask the demonstrator.) As far as voltage is concerned, 'rated' means the operating voltage for which the motor was designed. The rated current, on the other hand, is the maximum input current that can be sustained by the motor without it overheating.

Note that the voltmeter and ammeter in the panel read stator phase voltage and stator phase current, respectively, whereas the wattmeter reads total input (not power per phase).

The test motor is coupled to an eddy-current brake which is fitted with a strain gauge. The output from the strain gauge is amplified to give the torque in Nm, which may be read directly from a digital meter that is mounted in the instrument panel.

3 Equivalent Circuit

An equivalent circuit is a simple model with an electrical behaviour which is similar to that of the device being modelled. You have, of course, already used equivalent circuits to model the small-signal behaviour of a FET in Part IA. The equivalent circuit of an induction motor as seen from the supply terminals is given in Figure 1.

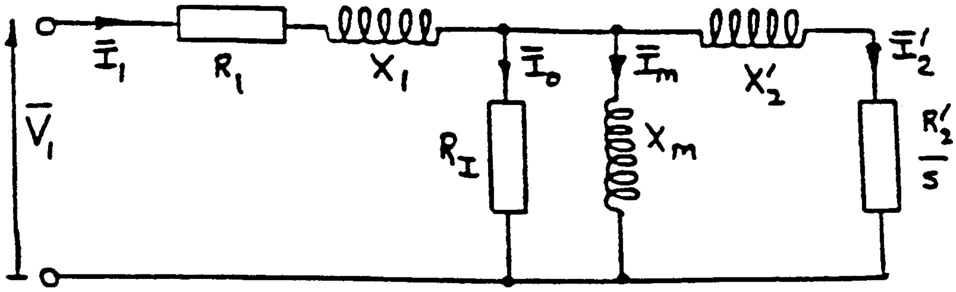

Figure 1

For the purpose of this experiment, we will simply present it to you as an act of faith – it will be derived and discussed in detail in the Electrical Power course. The components of the equivalent circuit are as follows:

- X_1 is the leakage reactance per phase of the stator (ie stationary part). The voltage drop across X_1 accounts for the emf induced in the stator winding by flux which does not link the rotor.
- R_1 is the resistance per phase of the stator windings.
- X_2' is the leakage reactance per phase of the rotor winding, referred to the stator (ie 'as seen by' the stator).
- R_2' is the rotor resistance per phase, referred to the stator.
- X_m is the magnetising reactance. The current through X_m, known as the magnetising current, sets up the field which links both stator and rotor.
- R_I is the iron loss resistance. The loss in this component is equal to the losses due to hysteresis and eddy currents flowing in the iron parts of the machine.

The physical principles governing the operation of the induction motor can be explained in simple terms. A three-phase winding on the stator produces a rotating magnetic field which induces currents in the rotor. The induced rotor current interacts with the rotating field to produce a torque, which makes the rotor attempt to catch up with the stator field.

The speed at which the stator field rotates is called the synchronous speed, which (in rpm) is given by 60 × supply frequency/number of **pairs** of poles. The test machine has 4 poles.

Synchronous speed = ... rpm

For emfs and currents to be induced in the rotor, there must be relative motion between the rotor and the synchronously-rotating stator field. The relative speed, expressed as a fraction of the synchronous speed, is called the slip, s.

$$S = \frac{\text{Synchronous speed - Rotor speed}}{\text{Synchronous speed}}$$

Notice that the referred rotor resistance (R_2') in Figure 1 is divided by s. As the rotor speed changes, s varies, so that the input impedance varies with speed. As will be seen in the lectures, the loss in this component is proportional to the torque developed by the machine.

4 Tests to Determine Equivalent Circuit Parameters

The performance of an induction motor can be determined using its equivalent circuit, once all the circuit parameters (ie component values) are known. Indeed, these parameters are calculated at the design stage in order to check that the motor being designed will meet the customer's specification. If, however, we are not privy to the design details, then equivalent circuit parameters must be determined from tests. In this part of the experiment, you will be performing such tests.

4.1 Standstill Test

If the rotor is stationary, the slip s = 1. X_m and R_I are much larger that the other parameters in the equivalent circuit, which at standstill therefore looks as shown in Figure 2.

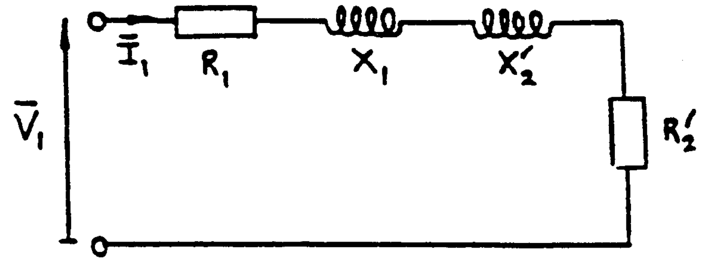

Figure 2

The total power flowing into the machine at standstill is given by

$$P = 3\, I_1^2\, (R_1 + R_2')$$

❖ *(Remember that the equivalent circuit refers to one phase of the machine, so that I_1^2 (R_1 + R_2') is the input power per phase and V_1 and I_1 are both phase quantities in the following expression.)*

The input impedance at standstill is given by

$$\frac{V_1}{I_1} = \sqrt{(R_1 + R_2')^2 + (X_1 + X_2')^2}$$

i) Turn up the eddy current brake to maximum;
ii) Check that the variable voltage autotransformer (‘Variac’) is set to zero volts;
iii) Check that the extra resistors are switched out of the rotor circuit (see panel);
iv) Turn on the supply and **slowly** increase the voltage until rated current is flowing in the stator. Do not worry if the rotor is rotating slowly (20 - 30 rpm) as the error this introduces is small. Take the following readings:

Input power, P = ... W

Stator current, I_1 = ... A

Stator voltage, V_1 = ... V

v) Reduce the supply voltage to zero as soon as you have taken the readings.

Calculate $R_1 + R_2'$ and $X_1 + X_2'$ using the expressions given above.

∴ R_1 = ... ohms

R_2' = ... ohms

R_1 and R_2' are usually separated using a simple measurement of the stator resistance, but this is not easily done with the current experimental set up. This has therefore been done for you, and the resistance per phase of the stator circuit is given on the machine panel.

It is not possible to distinguish between X_1 and X_2', but a reasonable approximation is to assume them to be equal.

$X_1 = X_2' =$ .... ohms

4.2 Standstill Test with Added Rotor Resistance

During the load tests you will be investigating the effect that adding extra resistance to the rotor circuits has on motor performance. Resistance is added simply by means of a switch located on the instrument panel. At this stage you can determine the value of the extra resistance that you will be adding by performing a second standstill test. The procedure is as follows:

i) Check that the eddy current brake is still at maximum;
ii) Check that the Variac is set to zero volts;
iii) Switch in the extra resistance;
iv) Repeat the measurements made in Section 4.1. (You may find that you have to use a lower current in order to limit the rotor speed to 20 – 30 rpm, but this does not matter.)

Input power, P = ... W

Stator current, I_1 = ... A

Stator voltage, V_1 = ... V

v) Reduce the supply voltage to zero as soon as you have taken the readings.

As the rotor resistance has been increased (by switching in the extra resistance), R_2' in Figure 2 has been increased to $R_2' + R'_{ex}$.[†]

The input power is therefore now given by

$$P = 3\, I_1^2\, (R_1 + R_2' + R_{ex}')$$

$\therefore$ R_{ex}' = ... ohms

Note that R_1 and R_2' were determined in Section 4.1. In order to check for consistency, it is worthwhile recalculating $X_1 + X_2'$. This is done by the method used in Section 4.1, with $R_1 + R_2'$ replaced by $R_1 + R_2' + R_{ex}'$.

$X_1 + X_2'$ = ... ohms

The reactance calculated here should agree within about 10% with that calculated in section 4.1. If it does not, ask the demonstrator for help.

Mean value for X_1 and X_2' = ... ohms
(average from sections 4.1 and 4.2)

4.3 No-Load Test

When un-loaded, the motor will run close to synchronous speed, so that s is small and R_2'/s becomes very large (see Figure 1). If $s = 0$, R_2'/s is infinite, and the equivalent circuit looks approximately as shown in Figure 3.

i) Switch the extra resistance out of the rotor circuit;
ii) Turn of the eddy-current break;
iii) Check that the Variac is set to zero;

[†] The dash ′ added to the symbol R_{ex} implies that it is *referred to the stator*. In other words, although we are physically switching the resistance into the rotor circuit we are measuring its effect in terms of the extra resistance 'seen' at the input terminals (ie the stator terminals). This process of referral is powerful, enabling us to represent complicated interactions in a straightforward and simple manner. It is used extensively in dealing with transformers as well as induction motors.

iv) Turn on the supply voltage and gradually increase the stator voltage to its rated value. Make sure that the stator current does not exceed its rated value as the rotor accelerates.

Input power, P = ... W

Stator current, I_1 = ... A

Stator voltage, V_1 = ... V

v) As before, turn the voltage down to zero before doing the calculations.

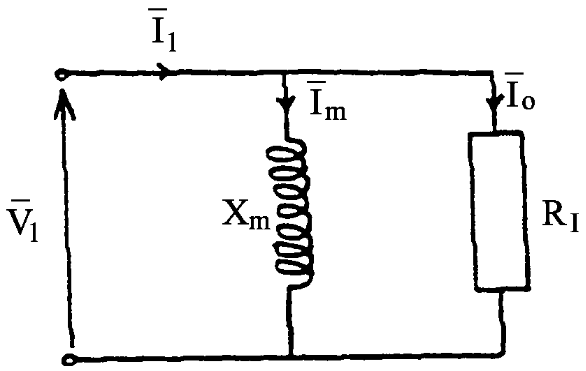

Figure 3

From Figure 3:

$$P = \frac{3V_1^2}{R_I} \quad \therefore \quad R_I = \frac{3V_1^2}{P}$$

$$I_0 = \frac{V_1}{R_I}$$

$$I_m = \sqrt{I_1^2 - I_0^2}$$

$$X_m = \frac{V_1}{I_m}$$

From which R_I = ... ohms

X_m = ... ohms

5 Performance Measurements and Simulation

Once the equivalent circuit parameters have been calculated, the performance of the motor can be determined. In this part of the experiment you will make use of the computer program to predict the performance of the motor, and check the accuracy of its predictions by performing load tests.

5.1 Simulation

Whilst the equivalent circuit is relatively simple, using it to determine performance is tedious, even with the help of a calculator. We have therefore programmed a PC to perform the calculations for you, and to print out performance characteristics.

If you get to this stage and find that the computer is busy, proceed to section 5.2 and then return when it becomes free. The order in which you perform these two sections is not important.

Enter the equivalent circuit values in the on-screen Data Entry dialogue box.

Select *Display Graphs* to view the performance graphs on the screen.

Select *Print Graphs* to obtain a hardcopy from the nearby laser printer

Select *Close* to return to the Data Entry screen.

Use *Clear Previous Data* to clear the data for the next user.

5.2 Load Tests

i) Start the motor, following steps (i)-(iv) of section 4.3.
ii) Gradually apply the brake until (close to) rated current is obtained. Maintain the stator voltage at its rated value. Take the readings called for by the table below.
iii) Now release the brake until about half the torque measured at full load current is obtained. Repeat the readings and record in the table as indicated.
iv) Release the brake completely. Switch in the extra rotor resistance and increase the brake until rated stator current is again flowing. Repeat the readings as for parts (ii) and (iii) above.

	No Added Resistance		**With Added Resistance**	
Readings	Full Load	Half Load	Full Load	Half Load
Input power, P Input current, I_1 Stator phase voltage, V_1 Rotor speed, N Torque				
Output power Efficiency Slip				

Table for Measurements

5.3 Results Processing

i) Complete the table by calculating power, efficiency and slip.
ii) Mark your measured points on the computer plots.

6 Conclusions and Final Remarks

Draw conclusions regarding the following:

A) The validity of the equivalent circuit as a means of calculating the performance of the motor.

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B) How the characteristics of the machine change when rotor resistance is added.

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Now that you have completed the body of the experiment you are free, if you wish, to make further measurements and mark more points on your computer print outs. If you do so, be careful not to exceed the rated current in the stator.

Original Script – Dr R.A. McMahon
Revisions 2006-2015
Dr D M Holburn, September 2015