UNIVERSITY OF EDINBURGH

SCHOOL OF ENGINEERING

Testing of Squirrel-Cage Induction Motors at Steady State

Power Engineering Laboratory (MSc) 2021

Dr Konstantinos Gyftakis

SAFE WORKING WITH ELECTRICAL EQUIPMENT

In the Power Generation Laboratory you may be required to assemble and operate equipment which is connected to 400 V, 230 V, 200 V supplies. Every effort has been made to ensure that the equipment and experiments are safe, but we share responsibility for your personal safety. Care and attention must be practised at all times to minimise the possibility of accident.

Electric Shock

Electric shock is caused by an electric current passing through the body. A current of only 60 mA can cause death, so while 3A-13A fuses will protect equipment, they will not protect you. Your body will conduct current if there is a potential difference between two parts. To prevent electric shock, the first rule is not to come in direct contact with, or touch, any LIVE conductors. Treat all conductors as potentially LIVE and always switch off supplies before working on any part of a circuit or equipment.

- Where supplies are generated in the lab, always switch off and wait for the machine to come to rest before touching any components.
- All supplies at the binnacles are switched and all have indicator lamps. Always check that the switches are open and that the lamps are extinguished.

It is possible to receive an electric shock as a result of indirect contact with a live conductor, if you touch an unearthed metallic part which has become LIVE.

- Ensure that all conductors are correctly insulated, terminated and shrouded.
- Ensure that all equipment is solidly earthed, so that casings or frames cannot become LIVE.
- As a further precaution do not lean on equipment while working on it. You may unwittingly create a return path in your body through which current would flow through if the equipment became live.

Injury from Rotating Machines

- Do not remove guards from machines, or operate machines without guards.
- Do not lean over machines and avoid wearing ties, scarves etc, which can become entangled with the machine. Keep long hair tied back.
- Always wait for machines to come to rest before working on them.

Working practice and behaviour

- Bags, coats etc. should be stored near the main door. Avoid wearing jewellery, and watches with metallic wrist straps. Do not sit on chairs or benches near the machines or equipment.
- Lay out equipment neatly. Keep wires as short as possible, but not so short that they are under tension. Use correct colour coding for cables (brown, black, grey, and blue for three phase, brown and blue for dc or single phase ac, and green/yellow for earth).
- Work professionally and responsibly. There will always be a responsible staff member present, and you should consult them if you are uncertain of the safety of your actions.

WE HAVE A GOOD SAFETY RECORD IN THE POWER LABORATORY
PLEASE HELP US TO KEEP IT THAT WAY

Preface

For this exercise, you are required to assemble a system including rotating machines and passive elements such as variable resistances and a variable transformer. The test bed emulates an industrial motor where the mechanical load has been replaced by an electric generator to facilitate the changing of the motor's loading conditions.

Students will normally work in pairs. They will undergo an oral assessment during the first 20-30 minutes and then will spend the remaining 2.5 hours setting up the test bed and collecting experimental results.

Due to safety considerations, it is not possible to allow students to work on the equipment outside formal laboratory hours. It is therefore essential that you arrive on time and well prepared.

Report

A short report (max 10 pages) should be submitted by the deadline published on Learn.

The report should include:

- A short description of how the system operates;
- Answers to all the questions in page 12 of this booklet;
- Discussion of results with critical analysis.

A paper copy and an electronic copy of the report must both be submitted by the deadline published on Learn. Please submit the paper copy to ETO and the electronic copy on Learn. The electronic version will be run through "Turnitin", the plagiarism detection software, to check for any copying.

Please note that the report must be entirely your own work.
Group efforts or blatant copying are not acceptable.
If students are deemed to have copied from one another, the students involved will be reported to the School Academic Misconduct Officer.

1. INTRODUCTION

This exercise deals with the experimental testing of a 3-phase induction motor, while at steady state, with the ultimate goal to estimate its equivalent circuit parameters through a series of tests and produce an analytical model. Please note the following aspects:

1. A healthy 3-phase induction motor can be modelled using a per-phase electric circuit which consists of resistances and inductive reactances. Those parameters can be estimated from a testing procedure including the no-load test and the locked-rotor test.
2. Losses and efficiency under different loading conditions are studied.
3. The students will have the opportunity to perform a comparative analysis between the analytical model and the real motor and critically discuss similarities and differences.
4. The impact of the stator configuration (star or delta) on the performance of the motor is also investigated.

In the Power Generation Laboratory, you are required to design a system to demonstrate operation in both the above modes of operation. An induction motor is used to simulate the mechanical prime mover (this could be a steam turbine powered by coal, oil or nuclear, a gas turbine, a hydro turbine, or a wind turbine), and an appropriate drive system is required to control the speed of the motor.

WARNING

The Electric Power Laboratory involves working with mains voltages and rotating machines. Extreme care should be exercised at all times. Always switch off all power supplies prior to working on equipment, and ***ask the demonstrator to check before you switch on****.*

2. EXPERIMENTAL TEST BED

Each group is provided with one machine test set, comprising of a variable transformer, a 3-phase induction machine (IM), a torque transducer, a 3-phase permanent magnet synchronous machine (PMSM) and a 3-phase variable resistive load bank. The set-up is shown in Fig. 1 below.

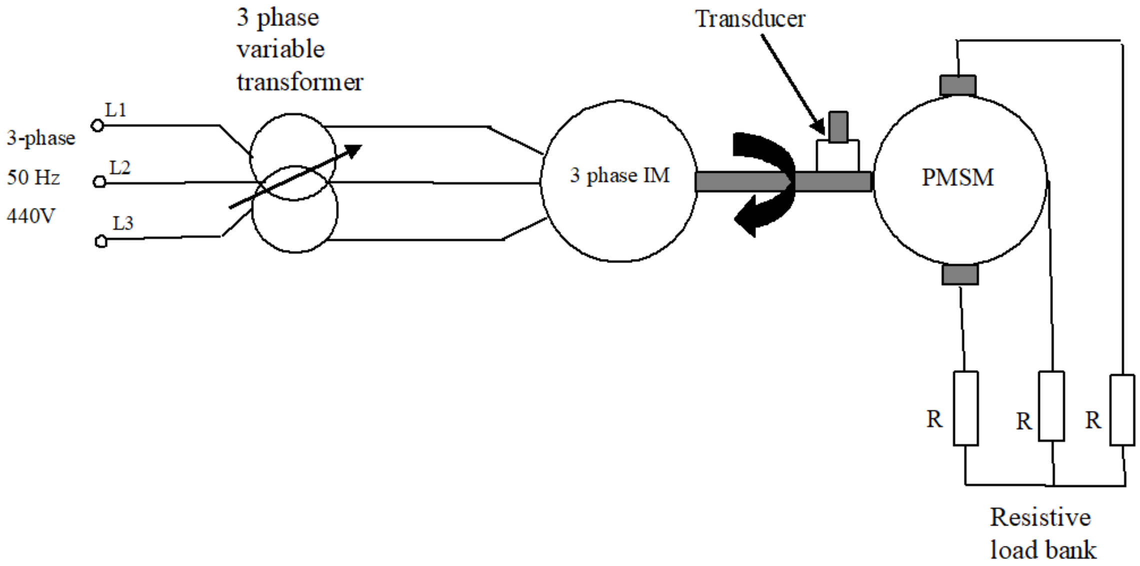


Fig. 1. Complete test set of the studied induction motor.

A) THE 3-PHASE VARIABLE TRANSFORMER

Variable transformers can provide differing amounts of voltage from a fixed input voltage. To achieve different output voltages, a sliding contact is moved along the length of an exposed secondary winding and is capable of connecting with the winding at any point along its length. This effect is similar to having a winding tap at every turn of the winding and switch with poles at each tap position. Variable transformers are often controlled with a dial and are used where there is a requirement for smooth and continuous variation of voltage to the load. This means they are very useful in labs for testing that requires different voltage levels. A single-phase variable transformer is shown in Fig. 2.

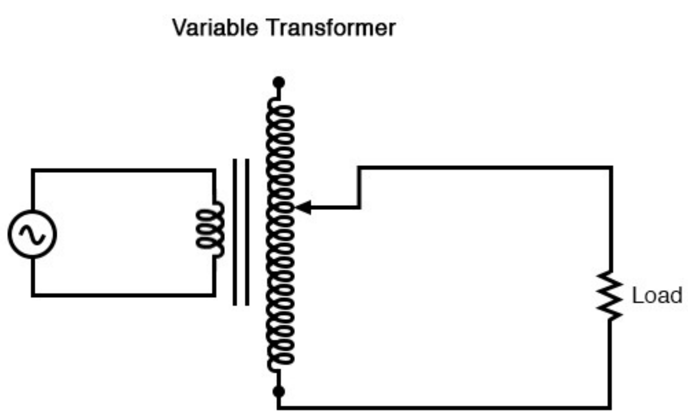


Figure 2: Electric circuit of a single-phase variable transformer.

B) THE 3-PHASE INDUCTION MOTOR

Induction motors operate on the principle of interaction of the stator rotating magnetic field and its induced rotor currents. The induction motor's speed is different from the synchronous speed of the rotating magnetic field creating a slip. The synchronous speed n_s is given by:

$n_s = \frac{60 f_s}{p}$, where f_s: the supply frequency and p: the pole pair number.

A cage induction motor is presented in exploded view in the Fig. 3.

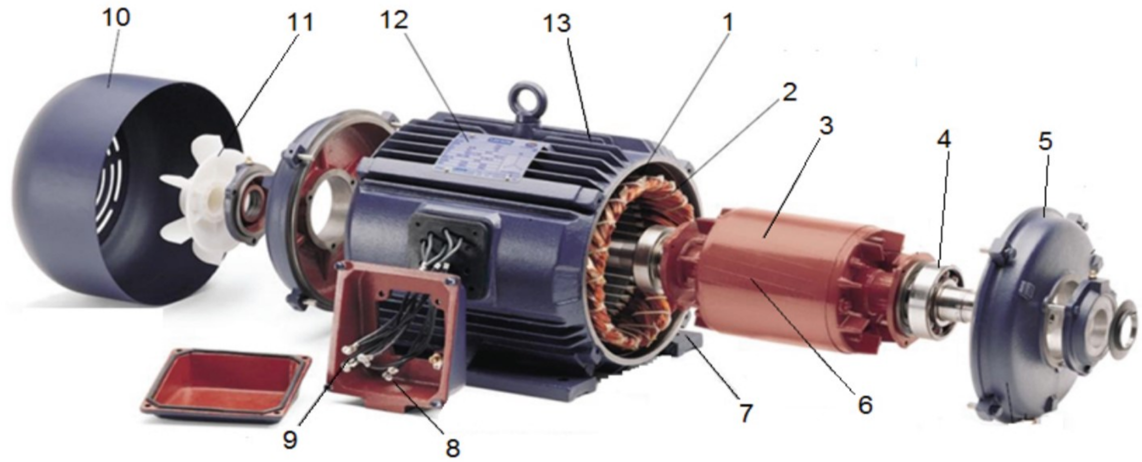


Fig. 3. A squirrel-cage induction motor (IM) in exploded view, where:
1. stator core
2. stator winding
3. cage rotor
4. bearing
5. end plate (end bell)
6. rotor bar
7. cast iron mounting feet
8. terminal box
9. terminal leads
10. fan cover
11. fan
12. nameplate
13. cast iron frame (housing)

The power flow diagram for an induction motor is given below in Fig. 4.

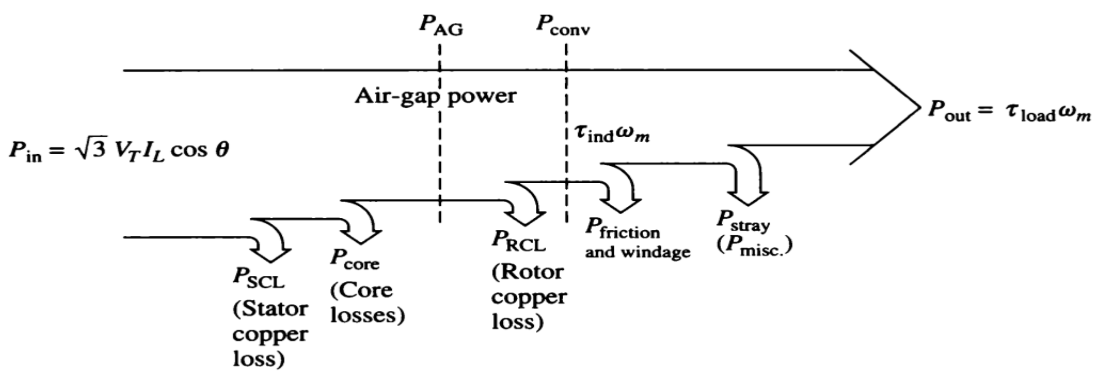


Fig. 4. Power flow diagram for an induction motor.

A 3-phase induction machine's torque versus speed characteristic including all operations, brake, motor and generator, is shown in Fig. 5. Moreover, the stator and rotor currents versus speed are shown in Fig. 6. The rotor current is zero at the synchronous speed due to lack of induction while the stator current is non zero.

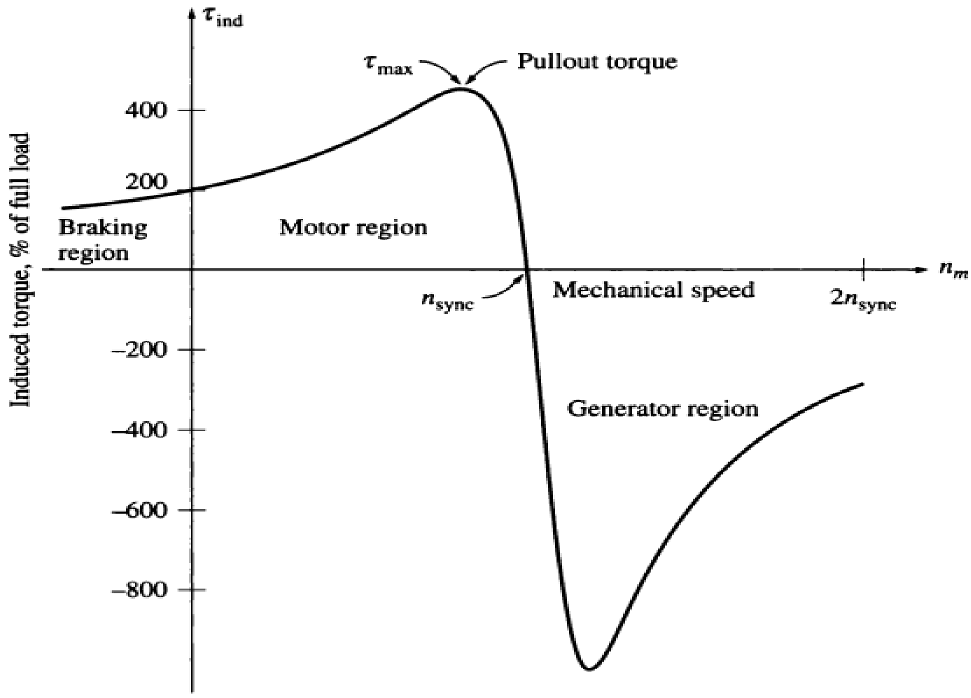


Fig. 5. The complete torque-speed characteristic of a 3-phase induction machine.

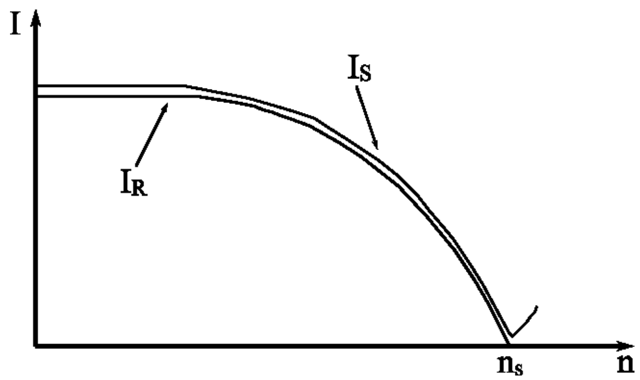


Fig. 6. Stator and rotor currents versus speed characteristics.

The induction motor is modeled by its per phase equivalent electric circuit (Fig. 7).

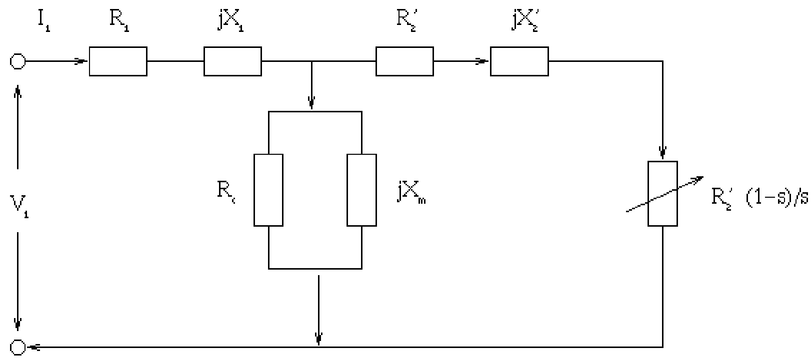


Fig. 7. Per-phase equivalent circuit of an induction motor.

The magnitude of the current in the rotor cage is (if $R_c \to \infty$)

$$I_2 = \frac{V_\varphi \dfrac{X_M}{X_1 + X_M}}{\sqrt{\left(R_1\left(\dfrac{X_M}{X_1+X_M}\right)^2 + R_2/s\right)^2 + \left(X_1 + X_2\right)^2}}$$

and the magnitude of the electromagnetic torque is given by the following formula

$$T_{em} = \frac{3\left(V_\varphi \dfrac{X_M}{X_1+X_M}\right)^2 R_2/s}{\omega_s\left[\left(R_1\left(\dfrac{X_M}{X_1+X_M}\right)^2 + R_2/s\right)^2 + \left(X_1+X_2\right)^2\right]}$$

The connection of the phases in the stator winding of an induction motor can be either in a stator (Y) or a delta (Δ). The electric circuit of each connection is shown in Fig. 8.

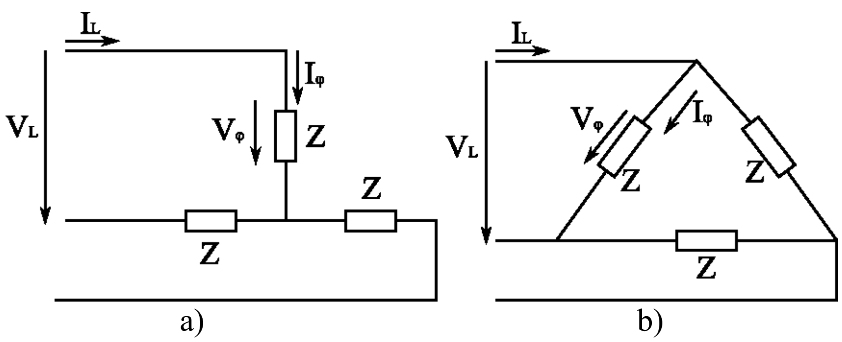


Fig. 8. 3-phase windings under: a) star (Y) and b) delta (Δ) connection.

For star connection (Y) the phase (φ) voltage and current are connected with the line quantities as follows

$$V_\varphi = \frac{V_L}{\sqrt{3}}$$

$$I_\varphi = I_L$$

Whereas for delta (Δ) connection

$$V_{\varphi} = V_L$$
$$I_{\varphi} = \frac{I_L}{\sqrt{3}}$$

The equivalent circuit of an induction motor is a very useful tool for determining the motor's response to changes of the load.

- The parameter R_1 can be determined directly using an ohmmeter (DC test).
- The parameters jX_1, R_2 and jX_2 can be determined using the locked-rotor test.

In this test the rotor remains locked whereas an AC voltage is applied on the motor, and the resulting current and power are measured. This test is run under reduced voltage to keep the current at acceptable levels. In this state, the slip s=1 so the parallel connected elements can be neglected and the equivalent circuit takes the form shown in Fig. 9, where the stator complex impedance is in series with that of the rotor.

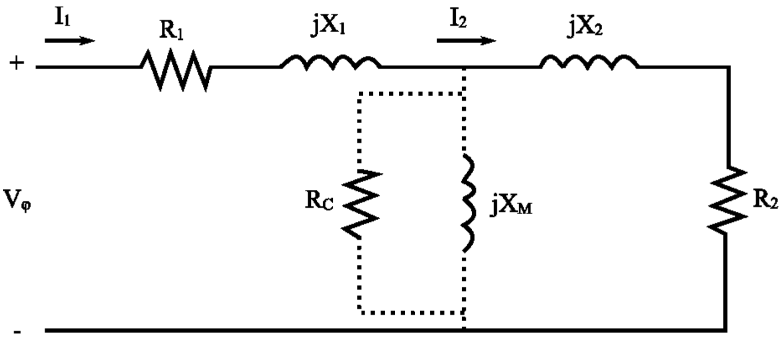
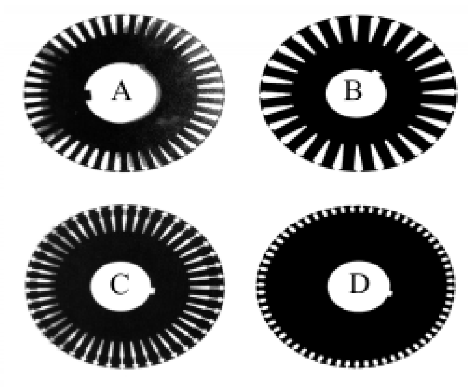


Fig. 9. Per-phase equivalent circuit representation of the induction motor subjected to the locked-rotor test.

The individual estimation of the two reactances X_1 and X_2 cannot be accomplished simply because the total reactive power of the circuit can be measured and not the individual ones. However, NEMA (National Electrical Manufacturers Association) has established some empirical approximations for estimating the two reactances depending on the rotor bar shape. Those are provided in Fig. 10.

	X_1 and X_2 as functions of X_{LR}	
Rotor Design	X_1	X_2
Wound rotor	$0.5\ X_{LR}$	$0.5\ X_{LR}$
Design A	$0.5\ X_{LR}$	$0.5\ X_{LR}$
Design B	$0.4\ X_{LR}$	$0.6\ X_{LR}$
Design C	$0.3\ X_{LR}$	$0.7\ X_{LR}$
Design D	$0.5\ X_{LR}$	$0.5\ X_{LR}$



(a) (b)

Fig. 10. (a) Table providing approximation rules for the stator and rotor leakage reactances according to NEMA convention and (b) the design of the four basic NEMA design classes A, B, C and D.

- The parameters R_C, jX_M can be determined experimentally using the no-load test.

In this test, the motor operates without a coupled load, so the current has a low value. Consequently, the rotor complex impedance can be omitted and the equivalent circuit for this condition is shown in Fig. 11. Using this test, the parallel connected elements can be estimated as long as the stator complex impedance is known.

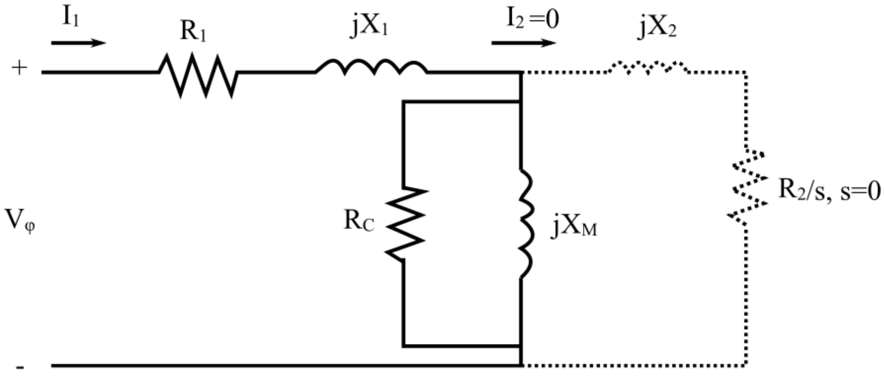


Fig. 11. Per-phase equivalent circuit representation of the induction motor subjected to the no load test.

C) THE PERMANENT MAGNET SYNCHRONOUS GENERATOR

The need for a variable load, in order to study the operation of the induction motor under different operating conditions, is satisfied with the use of a permanent magnet generator (PMG) feeding a variable resistive load.

The generator's EMF *E* is dependant on:

$E \propto n \times \Phi$

where *n* is the rotor speed and Φ is the magnetic flux produced by the permanent-magnets. Since Φ is constant for a permanent magnet synchronous generator,

$E \propto speed$

which means that in a PM generator, the EMF is directly proportional to the rotor speed.

3. EQUIPMENT

Each group will be provided with the following equipment:

- Machine test set (induction machine coupled to a PM synchronous machine),
- 3-phase ac resistive load bank
- Oscilloscope
- 3-phase variable transformer
- Torque transduser **(Convert ratio = 0.04 Nm/V)**
- 3 Multimeters (V, I, P, S, Q, cosφ)
- Tachometer
- 2 Current sensors
- Wires

4. QUESTIONS FOR PREPARATION

Questions to think about before you attend the laboratory:

1. How can you control the speed of the induction motor?
2. What is the physical representation of each equivalent circuit component in the induction motor model?
3. How is the torque produced in an induction motor?
4. What information is given by the nameplate parameters of every electrical machine?
5. Based on the nameplate parameters can you calculate the nominal torque and nominal efficiency of the induction motor?
6. Assuming that the rotor of the induction motor rotates with the synchronous speed, are the stator and rotor currents zero and why?
7. Assuming the test bed of this exercise, what will happen to the induction motor if the resistive load of the PM generator increases?
8. Under on-load operation, if the input voltage of the induction motor is reduced what will happen to the speed, stator current and electromagnetic torque of the induction motor?
9. Does the rotor resistance R_2 has the same value under starting and load operation? If not when the resistance has higher value and which is the phenomenon which affects that?
10. What is the dependency of the motor's torque on the input voltage?
11. Why do we need to start the induction motor with the variable transformer?

5. EXPERIMENTAL PROCEDURE

1. Record the specifications of the Induction Motor (IM) and check that the winding is in a star (Y) connection.
2. Using a multi-meter measure the stator resistances in room temperature.
3. Wire the test set but leave the permanent magnet generator open.
4. The demonstrator checks the connections and the main power switch is turned ON.
5. Use the variable transformer to supply the induction motor 80 V per-phase voltage to start the motor. Then use the transformer to supply 230 V per-phase and record the required data in Table I when the motor is at steady state.
6. Return the transformer's output voltage to 0 and turn the power switch OFF.
7. Connect the resistive load of the generator and turn ON the power switch. Use the variable transformer to supply the induction motor 80 V per-phase voltage. Vary the resistances and record all the necessary data to fill in Table II, for induction motor current increments of 0.1 A. Stop the procedure when the stator current reaches 1.7 A.
8. Perform the locked-rotor test by keeping the last load from step 6 and slowly reduce the induction motor voltage via the transformer until the rotor speed is zero. Record the data for the locked rotor condition in Table III.
9. Increase the variable resistances to their maximum value. Reduce the induction motor's voltage to 0. Turn OFF the main power switch. Unplug the power cable.
10. Using a multi-meter measure the stator resistances again.
11. Disassemble the test bed.

6. ASSESSMENT

This exercise is assessed by:

40% for performance in the lab. This will take account of the following:

- Preparation assessed at the beginning of the lab session.
- Attendance (including punctuality) and satisfactory performance.
- Care and good working practice.
- Intellectual contribution.

60% for the final report. Please read the next session 7 on page 12.

Marking will be based on the University Common Marking Scale:

Mark (%)	Grade	Description
90-100	A1	1st
80-89	A2	1st

70-79	A3	1st
60-69	B	2(i)
50-59	C	2(ii)
40-49	D	3rd
30-39	E	Fail
20-29	F	Fail
10-19	G	Fail
0-9	H	Fail

More detailed descriptions can be found at:
http://www.docs.scieng.ed.ac.uk/office/information_staff/student_admin/taught/exams/Extended%20common%20marking%20scheme%20table.pdf

7. REPORT QUESTIONS

1. Using the experimental results estimate the per-phase equivalent circuit parameters of the induction motor.
2. Based on your measured data plot the mechanical torque, stator current, output power and efficiency versus speed characteristics. Identify the maximum power and maximum efficiency points of operation.
3. Using your estimated per-phase equivalent circuit, produce and plot the torque, stator current, output power and efficiency versus speed characteristics for the same voltage used for in the experiment.
4. Compare the measured and calculated characteristics and critically discuss similarities and differences. Try to list all possible phenomena impacting the real motor’s performance and not taken into consideration by the model thus creating some error on the theoretical representation of the real device.
5. Using your per-phase equivalent circuit, produce the torque versus speed characteristic for operation under nominal voltage and stator winding connection in delta. Additionally, if the motor’s speed is 1400 + the last 2 digits of your student ID number, calculate the torque, stator current, input active power, output power and efficiency for that particular speed.

Student Name: **Date:**

Measurements Sheet

Stator resistances (room temperature): Ru = Rv = Rw =

Table I

Star Connection (Y) (No-load)							
n[RPM]	T[mV]	V_{phase}[V]	I_{Line}[V]	Pin[W]	Qin[Var]	S[VA]	PF

Table II

Star Connection (Y) (On-load)							
n[RPM]	T[V]	V_{phase}[V]	I_{Line}[V]	Pin[W]	Qin[Var]	S[VA]	PF

Table III

Star Connection (Y) (Locked-Rotor)							
n[RPM]	T[mV]	V_{phase}[V]	I_{Line}[V]	Pin[W]	Qin[Var]	S[VA]	PF

Stator resistances (after turning off): Ru = Rv = Rw =

Supervisor's signature