UNIVERSITY OF EDINBURGH

SCHOOL OF ENGINEERING

Analysis of the Induction Motor's Start-up Transient

Power Engineering Laboratory (MSc) 2021

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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 practiced at all times to minimize 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 will partially work with the same test bed that you used in the previous lab exercise entitled: “Testing of Squirrel-Cage Induction Motors at Steady State”. However, for the purposes of this exercise which is to test and analyze transient behavior of induction motors, one more electromechanical test bed will be used comprising of an inverter-fed induction motor driving a wound rotor synchronous generator.

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 11 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

The purpose of this exercise is to study the impact of the starting transient of an induction motor on its performance. For this reason we are considering Direct Online Starting (DOL) induction motor cases. The possible voltage dip during the starting of the motor will be studied as well as a normal startup from a strong grid. During this exercise the electrical input parameters such as the voltage and current waveforms as well as the output torque will be monitored and extracted. The motor that is studied in this lab exercise has been tested at steady state and its equivalent circuit model has been created by the students in the previous week. Please note the following aspects:

1. The induction motor's transient operation will be studied and analysed.
2. The voltage dip during starting will impact the accelerating performance of the motor.
3. A comparison between a normal starting and one under voltage dip will be performed.
4. The input and output signals of the motor will be extracted and analysed over time.
5. The accelerating time between start-up and steady state will be measured.
6. The students will estimate the starting time using their per-phase equivalent circuit. Then they will compare with the measured one and critically appraise the two results.

In the Power Generation Laboratory, you are required to design a system to demonstrate operation in both the above supplying modes. The starting under a strong grid requires only the interconnection of the main induction motor system to the grid via a transformer. Then, to emulate the voltage dip of a large induction motor, the power supply needs to be reduced and match the power of the tested motor. This is why the induction motor will be supplied by an isolated generator in the lab. A second induction motor is used to simulate the mechanical prime mover to the generator (under real conditions this could be a steam turbine powered by coal, oil or nuclear, a gas turbine, a hydro turbine, or a wind turbine). An inverter is required to control the speed of the generator's prime mover.

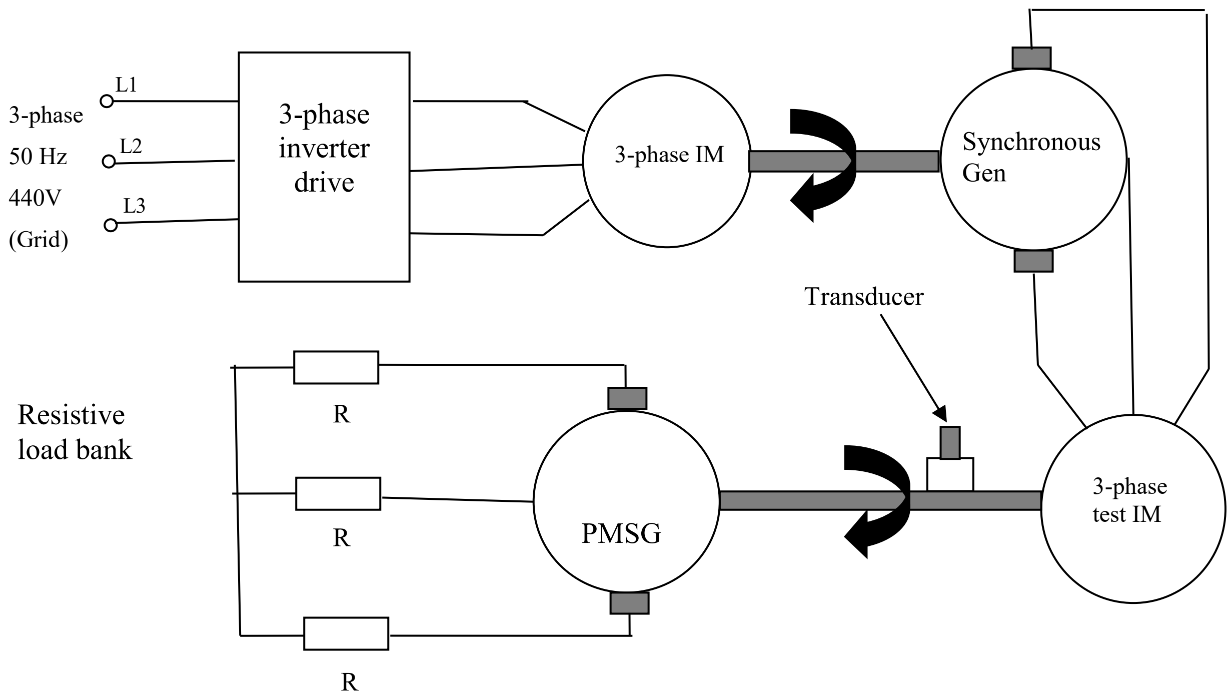
WARNING

The Power Generation 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.***

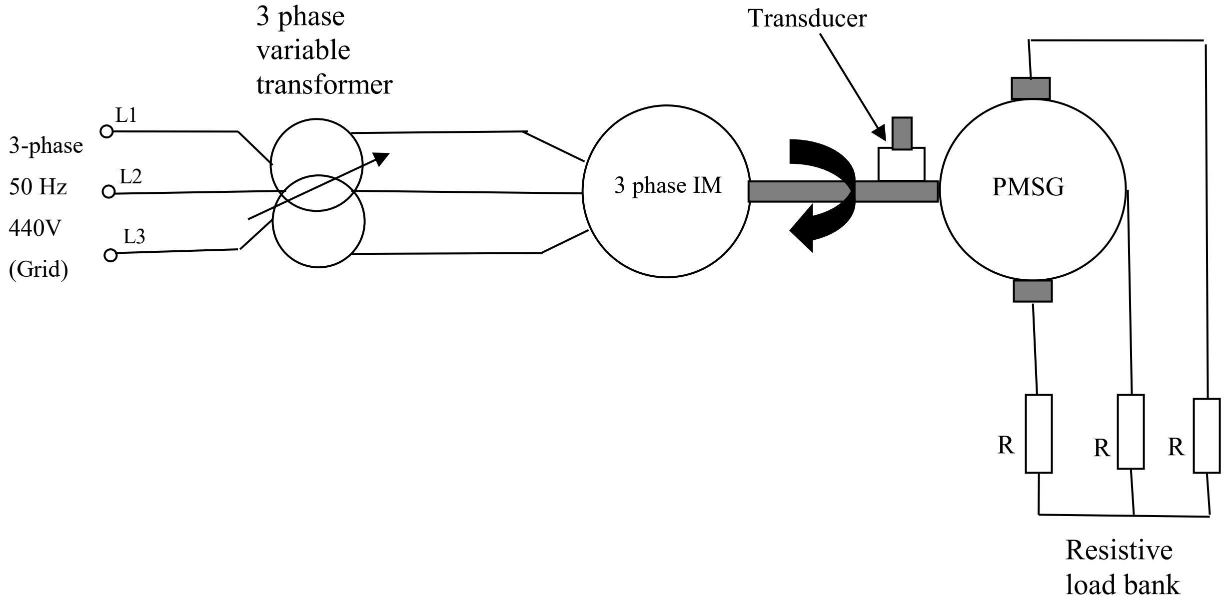
2. EXPERIMENTAL TEST BED

Each group is provided with one lab test set, comprising a 3-phase inverter, a 3-phase variable transformer, two 3-phase induction motors, a torque transducer, a wound rotor synchronous generator and a permanent magnet synchronous generator. Before using the electrical machines, it is important that you look at the nameplates on each machine assigned to you and record the nominal characteristics, rated speed, current etc.

The complete experimental set-up is shown in Fig. 1-a for supplying the induction motor by an isolated generator and expect a voltage dip. On the other hand, the second part of the exercise where the motor is fed from a strong grid is shown in Fig. 1-b.



a)



b)

Figure 1: (a) Electric diagram for the first part of the experiment that includes supplying of the tested induction motor from a generator and (b) second part of the experiment where motor is fed by the grid via a power transformer.

3. STARTING TIME OF INDUCTION MOTOR

It is desirable and necessary to reduce the magnitude of stator current during starting. Large motor overcurrent protection is normally set to trip prior to the locked-rotor withstand time (LRWT) provided by the motor manufacturer, after the calculated motor start time. The locked-rotor withstand time is determined by the motor designer based on the heating of the rotor parts for locked-rotor condition, where the motor continuously requires a large value of inrush current. At the time of starting, an induction motor draws high values of current (motor is a constant impedance device during the starting condition), that are very close to the motor's locked rotor value and remains at this value for the time required to start the motor. This is the reason why the locked-rotor withstand time is used as an allowable time limit for starting the motor across the line, full voltage.

Figure 2 shows the torque speed curve of induction motor. At starting, the slip of the induction motor is 1 and with the increase in speed there is reduction in slip. The motor comes to rated speed near its synchronous speed and the time taken to reach this point is called starting time. If the difference between the motor torque and load torque is high, the motor will have a fast acceleration. The area between these two torques is the accelerating torque available to accelerate the motor up to steady-state operating speed demanded by the mechanical load. This occurs at the cross over point in Figure 2 between the two curves, provided that the cross over occurs in the negative slope of the motor's torque curve, in which case the steady state will be obtained.

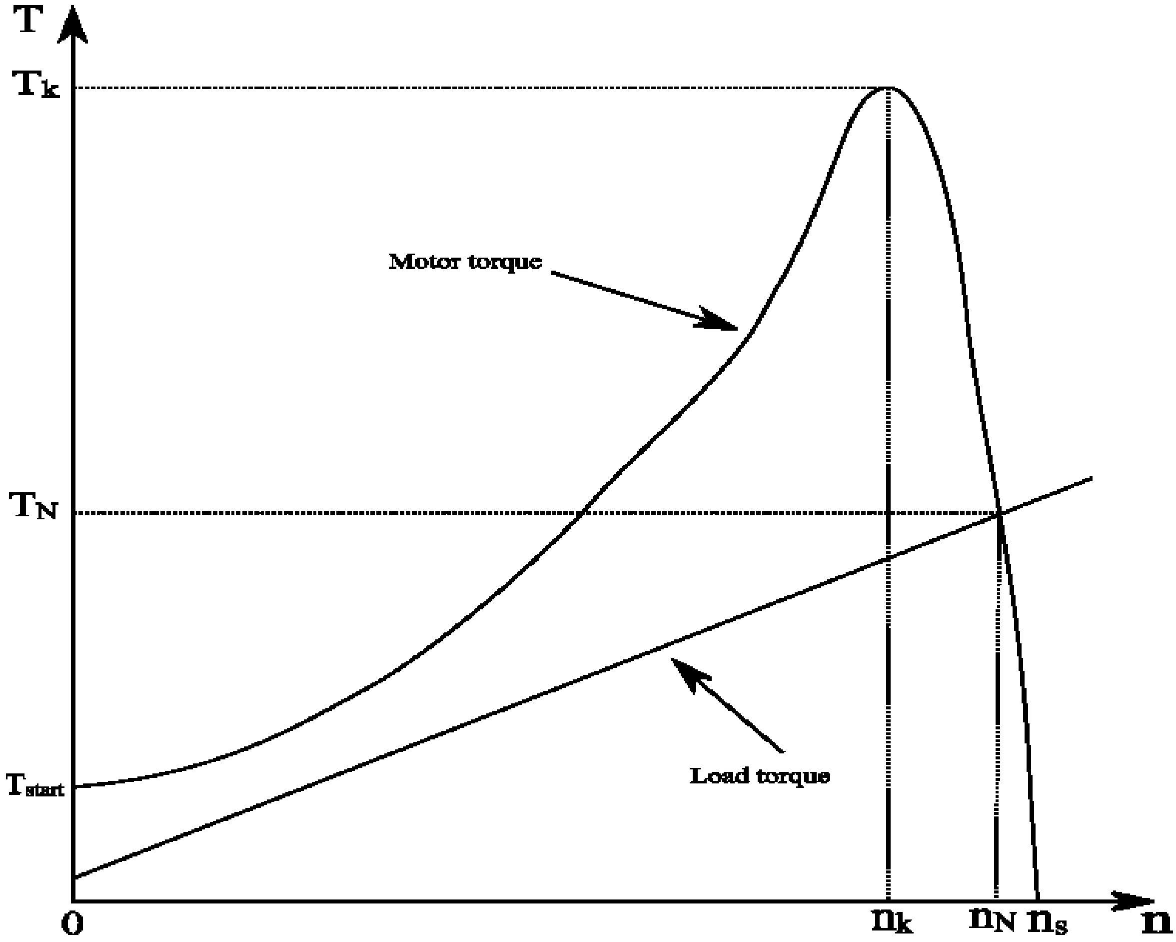


Figure 2: Torque-speed characteristic of an induction motor

The torque required from the motor to drive the load is given by (and using metric units).

$$T_m = T_{ma} + T_L$$

T_m = total torque from motor, N-m
T_{ma}= accelerating torque to start the motor and overcome its inertia (J), N-m
T_L = load torque, N-m

A step-by-step mathematical integration solution can be used to calculate the run-up time. The accelerating torque is:

$$T_{ma} = J\frac{d\omega_r}{dt}$$

$$\int dt = \frac{J}{T_{ma}}\int_{\omega_{r1}}^{\omega_{r2}} d\omega$$

$$t = \frac{J}{T_{ma}}\left(\omega_{r2} - \omega_{r1}\right)$$

If small steps in $\Delta\omega=\omega_{r2}-\omega_{r1}$ are taken, it is assumed that the curve is linear during each step, there the time for the motor to accelerate in that period can be calculated. The smaller the step in Δω the more accurate is the assumption of linearity. In the illustration of Figure 3 a low number of steps is used to demonstrate the concept. The greater the number of steps of Δω, the more accurate is the result for the total run-up time t. The average accelerating torque is taken directly from the curves and the Δt time is determined between the two curves as shown in Figure 3. All the Δt times are then used to plot the run-up time versus the speed from zero up to the steady-state speed.

$$\Delta t = \frac{J}{T_{average}}\left(\omega_{r2} - \omega_{r1}\right)$$

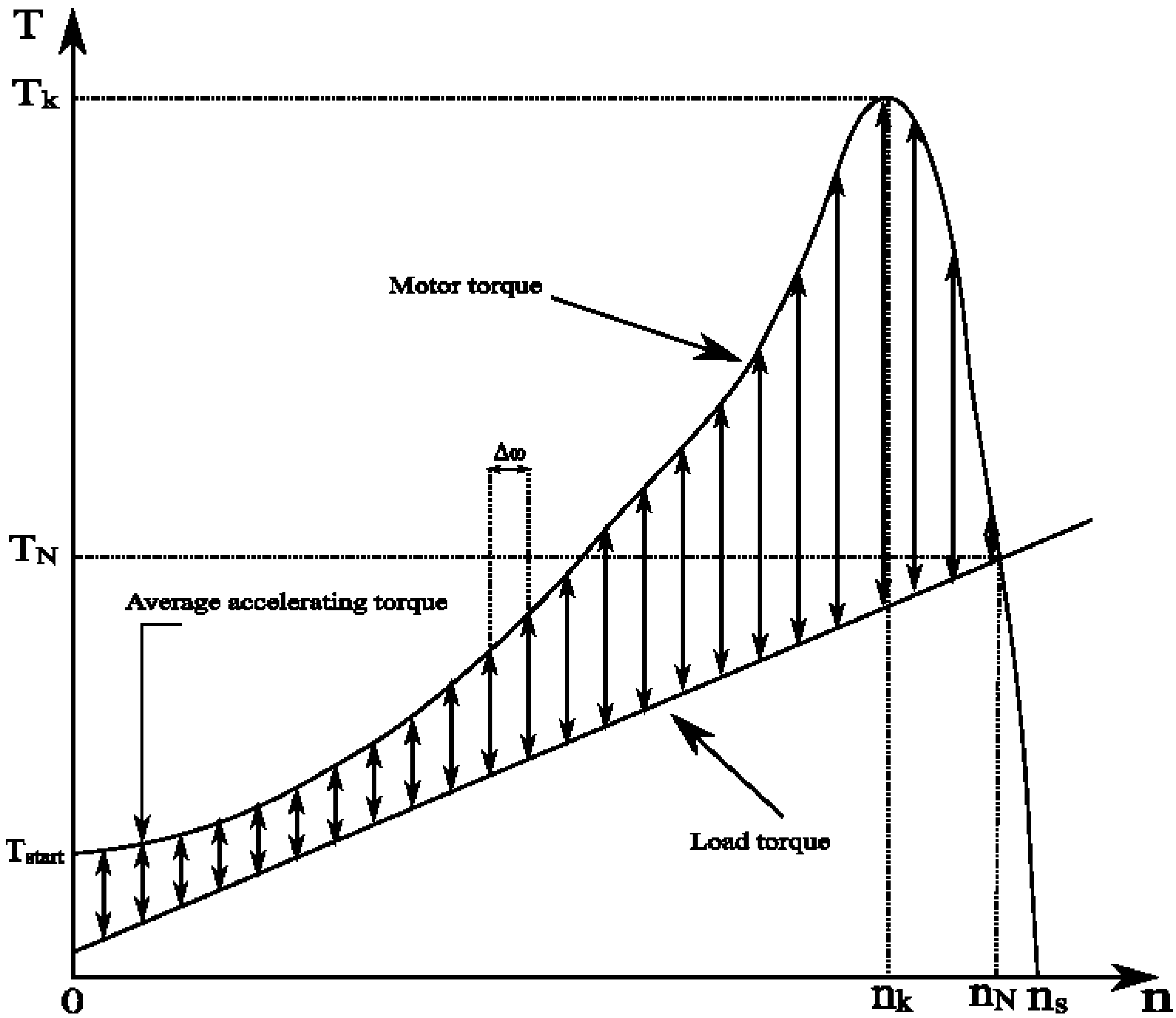


Figure 3: Torque-speed characteristic of an induction motor

All the analysis above is assuming that the voltage of the induction motor is kept fixed. If however there are voltage changes, such as a voltage dip, they will impact the torque significantly because the electromagnetic torque of the induction motor is proportional to the square of the voltage.

4. Wound-Rotor Synchronous Generator

In this exercise the induction motor will be fed by an isolated wound-rotor synchronous generator. To be more specific, the used machine is a salient pole synchronous generator.

This machine has a concentrated winding mounted on the rotor poles which is fed by DC voltage. Then a DC current will flow creating a static magnetic field in the rotor. Then the rotor of the generator is rotated by the prime mover inside the stator. The stator is a hollow iron tube with evenly spaced slots carrying the 3-phase armature winding. The phase windings are placed in the slots in such a way that they have 120 electrical degrees spatial phase difference.

When the DC fed rotor rotates inside the stator, the magnetic field becomes rotating from the stator's perspective and therefore voltages are induced in the three windings due to Faraday's Law of Induction. Due to symmetry, the three phases will have the same amplitude, frequency and phase difference 120 degrees to each other.

Each induced voltage has an rms value as follows:

$$E_f = 4.44 f \Phi_f N K_w$$

Where:

Φ_f: flux per pole

N: number of phase turns

K_w: Winding factor

The active power produced by a salient-pole synchronous generator is given by the following formula:

$$P = 3\frac{V_t E_f \sin\delta}{X_d} + \frac{3}{2} V_t^{\,2} \left(\frac{1}{X_q} - \frac{1}{X_d}\right) \sin 2\delta$$

Where:

$\boldsymbol{V_t}$: the terminal phase voltage

$\boldsymbol{\delta}$: the power angle

$\boldsymbol{X_d}, \boldsymbol{X_q}$: the d and q axis reactances.

Like in all wound rotor synchronous machines, the power factor can be manipulated via the change of the field current in the rotor. In generator mode, the over-excitation condition leads to a lagging power factor and the generator is producing reactive power. Under normal excitation, the generator is producing unity power factor. Finally, the under-excitation condition leads to leading power factor meaning that the generator is consuming reactive power.

5. EQUIPMENT

Each group will be provided with the following equipment:

5.1 1st machine test set (induction machine coupled to a PM synchronous machine)

5.2 2nd machine test set (induction machine coupled to a salient-pole synchronous machine)

5.3 Power meter
5.4 3-phase ac resistive load bank
5.5 Instrumentation (as detailed in Section 8).
5.6 Oscilloscope
5.7 3-phase variable transformer
5.8 Torque transduser
5.9 Multimeter (V,I,P,S,Q,cosφ)
5.10 Tachometer
5.11 Current transformer
5.12 Inverter

6. QUESTIONS FOR PREPARATION

Questions to think about before you attend the laboratory:

1. Draw the phasor diagrams of a salient pole synchronous generator delivering lagging current, normal current and leading current.
2. Why do voltage dips appear when large induction motors start directly from the grid?
3. What happens to the accelerating time of the induction motor when a voltage dip is present?
4. What are the consequences of a voltage dip on the electromagnetic performance and variables of the induction motor?
5. What is the impact of the loading level of the motor on its starting performance?
6. Motors that are designed for long steady state operations typically have low rotor resistance. Do those motors have high or low starting torque? What is the impact of a voltage dip on such motors?

7. EXPERIMENTAL PROCEDURE

1. Record the nameplate parameters of the second machine test bed comprising of an induction motor and a salient-pole synchronous generator.
2. Connect the new induction motor to the inverter.
3. Connect the DC supply to the rotor of the salient-pole generator using a diode box to avoid negative circulating currents.
4. Connect the stator of the salient-pole generator to the variable 3-phase transformer's primary.
5. The secondary of the variable transformer is now connected to the tested induction motor. The permanent magnet generator remains open.
6. Connect leads to measure the induction motor's voltage, current and torque with an oscilloscope.
7. The lab demonstrator checks that the circuit is complete. Then gives permission to connect the power cable of the inverter to the grid and turn ON.
8. The generator's phase voltage is regulated anywhere between 100-120 V.
9. The secondary of the transformer is regulated to 80 V, then supplied to the induction motor.
10. When switching on, the team records all waveforms with the oscilloscope and stores. Also, recording the steady state parameters after the acceleration is complete.
11. Safely turn OFF the system under the supervision of a lab demonstrator

12. Disconnect the generator from the primary of the transformer.
13. Connect the primary of the transformer to the grid.
14. The lab demonstrator checks the connections and gives permission to turn ON.
15. Repeat the previous procedure.
16. Turn OFF the system safely.
17. Disassemble the test rigs.

8. 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 9 on page 11.

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

9. REPORT QUESTIONS

1. Use the equivalent circuit that you estimated in the previous lab exercise and generate the torque versus speed characteristic of the induction motor for phase voltage input 80 V.
2. Based on your calculated torque-speed characteristic of question 1, estimate the starting time of the motor between speed 0 and the speed that you have experimentally recorded for steady state, if it starts without a coupled load.
3. Assume a load straight line that starts from (0,0) and ends at the steady state condition that you experimentally measured. Recalculate the starting time of the motor under this particular loading conditions.
4. Extract the starting time of the motor from your measurements for both conditions (grid –fed and isolated generator-fed) and compare them.
5. Compare and critically discuss the experimental results with those from the equivalent circuit model. Explain in detail all the possible mechanisms that may introduce errors in the theoretical calculation of the accelerating time.

Student Name: **Date:**

Measurements Sheet

Table I

Steady State parameters – Motor fed by the salient pole generator							
n[RPM]	T[mV]	V_{phase}[V]	I_{Line}[V]	Pin[W]	Qin[Var]	S[VA]	PF

Table II

Steady State parameters – Motor fed by the grid							
n[RPM]	T[mV]	V_{phase}[V]	I_{Line}[V]	Pin[W]	Qin[Var]	S[VA]	PF

Oscilloscope measurement details

Supervisor's signature