MACH: Induction Machine

2nd Year Electronics Lab

IMPERIAL COLLEGE LONDON

v2.01

Table of Contents

Equipment

- Lab computer with MATLAB
- Magnetic Circuit
- 20A Pulsed PSU
- Oscilloscope
- 20V, 20A Meters
- Hall Effect Flux Probe

Aims

- Synthesize the per-phase model of an induction machine in steady state
- Use the per-phase model to calculate expected terminal quantities
- Verify your model against experimental results
- Discuss the transient properties of an induction machine
- Understand the operation of an induction machine from fundamental electromagnetic principles.

Objectives

1. Observe, record, and comment on:
    a. The torque-speed characteristic of the induction machine around synchronous speed ($|s|<0.033$) with a constant stator voltage. Compare your results with the theoretical torque-speed characteristics you have generated in MATLAB.
    b. The machine performance (how "good" is the machine running?) and operating values when operating the induction machine at rated speed, synchronous speed and one point in between. Note differences between the operating points.
    c. The starting current of the machine*
2. During the machine starting process*, observe and provide explanations for:
    a. The torque-speed characteristic of the machine during the acceleration process (hint: look at torque-time and speed-time plots and try and approximate a torque-speed graph from this). Compare with the steady state torque-speed characteristic for a typical induction machine in your notes.
    b. The magnitude and frequency of the rotor current.

*NOTE: Due to limitations of the torque sensor, transient torque loads must be kept below 50Nm. All startup tests must therefore be run at a reduced stator voltage not exceeding 50% of the maximum. You will be unable to energize the induction machine if the initial voltage is set too high.

Recommended Timetable

This experiment consists of 2 parts. There are 4 timetabled lab sessions for this experiment. You should aim to complete both parts within set time.

Introduction

This experiment is designed to be student led. You will need to decide on the tests and experiments to perform in order to achieve the objectives and verify your models. Be sure to read and understand the appendices before you begin the laboratory session, otherwise it is likely that you will not be able to complete the experiment. The lab demonstrators are here to help – if you don't understand how to use the experimental apparatus or are stuck with one of the objectives please ask them for assistance.

Task

1. Familiarize yourself with the experimental apparatus, this is described in Appendix A. Be sure to calculate the induction machine's rated torque using the nameplate data in Appendix A, this will aid in familiarizing yourself with the machine and its expected operating values. You are encouraged to do this before the laboratory session.
2. Extract the per-phase equivalent circuit model of the induction machine by performing locked rotor and no-load tests. This process is explained in Appendix B. Use the provided MATLAB scripts to aid some of your calculations and generate theoretical torque-speed plots. Instructions for use of the provided MATLAB scripts are given in Appendix C.

Further work for brave students

Choose either:

- Investigate the effect of rotor resistance on the torque-speed characteristic of the machine.
- Investigate the effect of a reduced supply voltage on machine performance.

Appendix

A. Experimental Apparatus

The experimental apparatus consists of three items, the coupled induction machine – DC motor pair, the control unit and the LabVIEW application software running on a standard PC. A simplified functional diagram of the apparatus is given in figure 1. This appendix explains the design and operation of all parts of the experiment.

The interface to the experiment is the software application running on the computers at each bench. The software is designed to be fairly intuitive and should not require a great deal of guidance if you are familiar with induction machine operation. The software is introduced at the end of this appendix.

Be sure to read this entire appendix before attempting to operate the experimental apparatus.

The coupled induction machine – DC motor pair

Look carefully at the machine layout. You will see two motors connected together with a drive shaft. Identify the induction machine and the DC motor. The induction machine is a two pole pair motor rated at 2.25kW, 110V line to line and the DC motor is rated at 4.5kW, 200V armature voltage. The 'nameplate' attached to an electrical machine provides further useful information regarding the specifications of the device. A reproduction of the induction motor nameplate is given at the end of this appendix in Figure 3.

The induction machine has six electrical connections, three stator and three rotor connections. On a standard induction machine there are only stator connections, but for this experiment you require access to the rotor so that you can measure rotor current and also insert extra rotor resistance. In order to make an electrical connection to the rotating parts of the machine an arrangement of slip rings is used. Identify the slip ring connections to the rotor. Why would slip rings be undesirable in an industrial environment?

The DC motor has four electrical connections, two field winding connections and two armature connections. Again, an electrical connection is required between the rotating parts of the machine and the stationary outside world, in this case a brush and commutator arrangement is used. Identify the brushes and the commutator. Notice the slots in the commutator that run parallel to the axis of the machine.

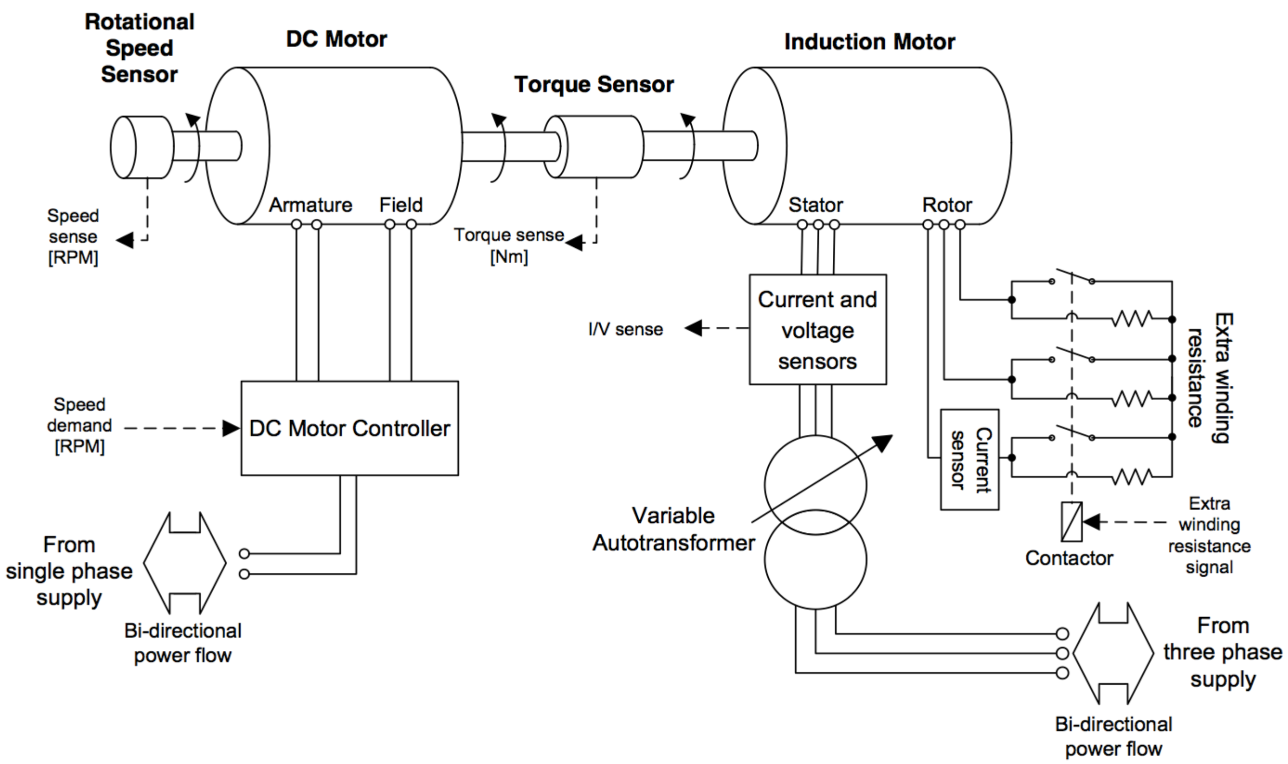

Figure 1 - Simplified diagram of the experimental apparatus

The induction machine and DC motor shafts are directly coupled to one another so that they rotate at the same speed. Mounted at the coupling between the motors is a torque sensor. The output of this sensor is an analogue voltage which is processed by the cRIO and displayed in the Labview application window on the PC screen; its units are Newton-meters (Nm).

Also connected to the motor shafts is a rotational speed sensor. The sensor is a quadrature slotted disk type that produces 10,000 pulses per revolution. This signal is processed by the cRIO and displayed in the Labview window in units of revolutions per minute (RPM).

The control unit

The control unit houses the variable autotransformer, a DC motor controller, a control device known as a cRIO (or 'compact-rio'), the extra rotor resistance, current and voltage sensors and several contactors along with various circuit breakers and fuses to protect the machines from overload conditions.

The variable autotransformer is the device on the side column of the control unit. It can be thought of as a transformer with a variable turns ratio, allowing adjustment of the scaling between primary and secondary voltage and current. However, an autotransformer contains only one electrical winding per phase (rather than two as in a normal transformer), each of which has a sliding connection that is moved up or down to adjust output voltage. It is important to note that an autotransformer does not provide electrical isolation from input to output.

The DC motor controller is located in the top left of the control unit. It is a solid state device incorporating a thyristor H-bridge that allows full four quadrant control of the DC motor. 'Four quadrant' control refers to the fact that the motor may be run in either rotational direction and may produce negative or positive torque (i.e. there are four quadrants, or combinations, of rotational direction and torque direction). For this experiment the motors will be run in one direction only but the torque will vary through both positive and negative values (i.e. 'two quadrant' control).

The cRIO is placed on the 2nd row on the left of the control unit, opposite the DC motor controller. The cRIO is a modular high speed monitoring and control device containing a dedicated processor, memory and FPGA and may be configured with an extensive combination of digital and analogue inputs and outputs. The cRIO is used to monitor all sensor outputs and control the internal contactors within the control unit. The cRIO includes an Ethernet connection for communication with other devices on a network, in this case it is communicating with the host PC that is running the LabVIEW software on your desk.

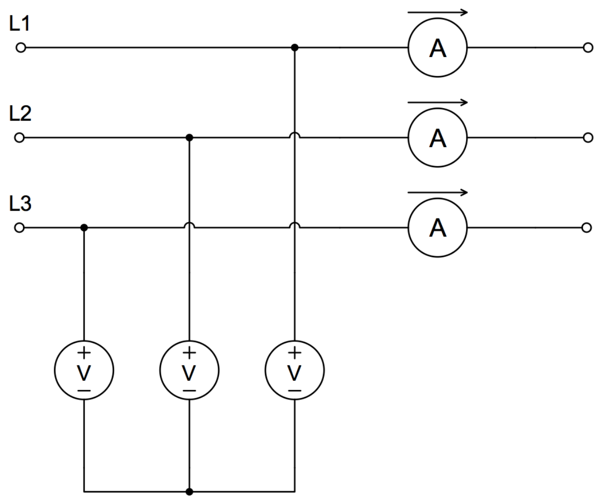

Figure 2 - Arrangement of voltage and current sensors. Note the false neutral created at the common terminal of the voltmeters.

The extra rotor resistance is a bank of three power resistors mounted at the top left of the control unit. They have a value of 0.75Ω. They are connected in series with the rotor bars and can be used to modify the machine characteristics for some sections of the experiment. The rotor resistance can be bypassed with a contactor under control of the cRIO (see Figure 1).

The stator voltage and stator current is monitored by a set of voltage and current sensors arranged as shown in figure 2. One phase of the rotor current is also measured. The current sensors are of the nulling Hall- effect type. They work by measuring the magnetic force required to cancel the flux flowing in a ferrite core that encircles the current carrying wire.

Because the autotransformer has considerable leakage impedance, you may not be able to get

110% of nominal voltage. In such situation, adjust the torque-speed calculation in MATLAB to a voltage say 100V or whatever maximum you can get from the Variac.

The control unit has only one control that you must be familiar with, the emergency stop button.

Identify the emergency stop button on the right hand side of the control unit. When the emergency stop button is pressed, all power is removed from the motors and they will come to a halt if they were rotating. CAUTION: the emergency stop does not disconnect the single phase supply or the mains sockets on your desk.

The LabVIEW application

When you login to one of the computers on the Experiment P benches you will see a shortcut on your desktop labeled 'Experiment P – Induction Machine'. Double clicking on the shortcut will run a National Instruments LabVIEW application that will operate the experimental apparatus for the duration of the experiment.

The LabVIEW window displays a graphical representation of the induction machine-DC motor pair and displays the basic connections between them. Identify the various indicators for machine speed and torque, voltage and current measurements, power (real, reactive and apparent) and the dynamic display of voltage and current waveforms.

The variable autotransformer knob allows you to change the voltage applied to the induction machine stator from 0-110% of its nominal value (110V line-to-line). This knob must be adjusted slowly and smoothly to avoid possibly overloading the equipment and causing a protection mechanism to disconnect power to the system.

Also identify the various controls that will allow you to start and stop the induction machine and DC motor. The function of these controls should be fairly self-evident. However, if you are unsure on how to use a particular control ask a demonstrator who will be happy to help.

Operating the induction machine apparatus

You will need to conduct several experimental tests using the induction machine apparatus. In order to safely operate the equipment you should follow the power up sequence given below.

After any experimental test you must power down the apparatus, following the power down sequence also provided below.

Important notes

You may need to make small speed adjustments around synchronous speed and this will be hard to do safely and accurately using only the 'coarse' control knob in the LabVIEW application. Use the 'fine' knob to achieve precise control around synchronous speed by first setting the coarse knob to synchronous speed and using the fine knob for all further adjustments.

The LabVIEW application has several in-built rules that should prevent you from causing serious damage to the machine. However, you must still be careful not to cause excessive power demands that will put unnecessary stress on the machine.

If there is a fault or error detected in the equipment or you make a mistake whilst operating the machine and cause an overload condition the cRIO and the LabVIEW application will automatically shutdown the equipment. The LabVIEW application may then be locked and require a password to be entered in order to re-establish control. If this happens ask a demonstrator to enter the password and discuss the cause of the fault with you.

It is very important that you do not drive the induction machine to a slip $|s|>0.04$ whilst it is energized at full line voltage and without extra rotor resistance inserted. Be careful adjusting the speed controls. Why might operation at large slips at full line voltage be damaging to the induction machine and the rest of the experimental apparatus?

Power up sequence

1. Insert or remove the extra rotor resistance as required
2. Check that the DC motor speed is set to zero
3. Check that the stator voltage is set to zero
4. Switch the DC motor on using the control in the LabVIEW application
5. Switch the induction machine supply on using the control in the LabVIEW application
6. Slowly increase the speed of the DC motor to the desired speed using the control knob in the LabVIEW application
7. Adjust the variable autotransformer to apply an appropriate stator voltage for the test you are conducting
8. Record readings from the power analyser and torque sensor readings displayed in the LabVIEW application
9. Make adjustments to the motor speed and stator voltage and take further readings as required

Power down sequence

1. Reduce the stator voltage to zero
2. Switch off the induction machine
3. Reduce the DC motor speed to zero
4. Switch off the DC motor

SLIPRING MOTOR

kW. 2.25			
ph. 3	Hz. 50	V. 110	A. 19
r/min. 1450	R.V. 300	R.A. 4.8	
Duty Type. S1	Ins. Class. F	Conn. S△RY	
Amb. °C. 40	Alt. m. 1000		

Figure 3 - Induction motor nameplate (some information has been omitted)

B. Induction Machine Per-phase Model

The induction machine model is shown in Figure 4. The induction machine is represented as an equivalent circuit. This is a model of one phase of the machine. Each of the electrical components in this equivalent circuit represents a particular characteristic of the real induction machine, as listed below.

R_S	The resistance of the stator windings.
X_S	Leakage reactance of the stator
R'_R	The resistance of the rotor windings, referred to the stator side of the machine.
X'_R	The leakage reactance of the rotor windings, referred to the stator side of the machine.
R_M	Used to represent the energy losses that occur in the steel of the induction machine, due to eddy currents and hysteresis.
X_M	The magnetizing reactance of the induction machine and the current that flows in it is the current necessary to set up the flux.

There is another term used in the equivalent circuit that is extremely important. This is the term 's' that is combined with the R'_R term. It is known as the slip. Slip is a measure of the difference in speed between the rotation of the flux, ω_S and the physical rotation of the rotor, ω_R. The difference is normalized by dividing by ω_S. Slip is calculated as:

$$s = \frac{\omega_S - \omega_R}{\omega_S}$$

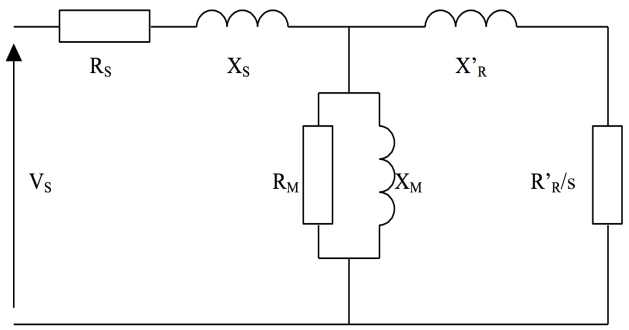

Figure 4 - Induction Machine Model

The R'_R term in the equivalent circuit model represents the referred resistance of the rotor. As current flows through this resistance heat will be generated and an energy loss will occur through the rotor, at the rate of $3{I'_R}^2 R'_R$ (remember that the model represents only one phase so the power in the whole machine includes a factor of 3). The equivalent circuit, however, has a resistance of R'_R/s. It dissipates more energy than the physical resistance of R'_R, by converting electrical energy to mechanical energy. This energy conversion constitutes the mechanical output power of the machine plus any losses due to friction.

It is possible to calculate mechanical output torque from the induction machine model. Torque is related to the power and the rotational speed, as given below:

$$T = \frac{P}{\omega_R}$$

To verify that the equivalent circuit is a good representation of an induction machine it is necessary to do a comparison between model and system. To allow us to model the system accurately it is necessary to obtain values for the equivalent circuit model parameters. In other words, values for R_S, X_S, R'_R, X'_R, R_M, and X_M need to be found. To find values for these parameters various tests can be done on the induction machine.

Finding R_S

To obtain R_S we need to find the resistance of a stator phase winding. This can be done by connecting a DC voltage across a stator phase winding and measuring the current flow. R_S is then determined simply from Ohm's law.

The determination of R_S has already been done for you and is found to be 0.095 ohms per phase.

Finding R'_R, X'_R and X_S

To establish the parameter values for R'_R, X'_R and X_S, a standstill test is conducted. The standstill test, as its name implies, is conducted with a rotor speed of zero. With a stationary rotor, the slip for the induction machine is one, hence the R'_R/s term in the equivalent circuit reduces to just R'_R. If it is assumed that the values of R_M and X_M are large compared to $R'_R + jX'_R$, then R_M and X_M can be ignored. This results in the simplified equivalent circuit shown in Figure 5.

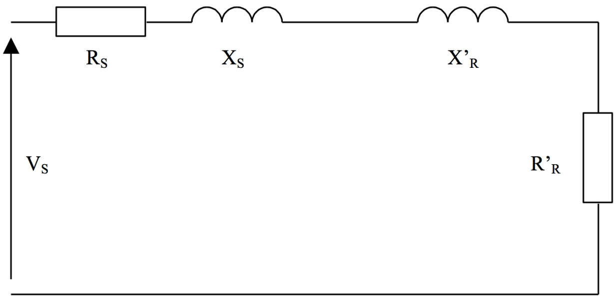

Figure 5 - Simplified Equivalent Circuit for Standstill Test

Two equations can be written to describe the circuit of Figure 5. Ohm's law:

$$V_S = IZ$$

and an equation relating input power to circuit parameters:

$$P = I^2(R_S + R'_R)$$

Hence, if readings of P, I and V_S are taken when the rotor is stationary, the terms R'_R and $X_S + X'_R$ may be determined by manipulation of the above equations.

Unfortunately it is difficult to split the terms X_S and X'_R. It is possible by applying a voltage to the rotor with the stator left open-circuit. However, this is not practical with the experimental set-up here. As an approximation it is assumed $X_S = X'_R$.

To discover the parameter values for R_M and X_M a synchronous test is conducted. The synchronous test involves running the motor to synchronous speed, when this happens the slip for the motor is zero. Hence the R'_R/s term in the equivalent circuit is infinite. If it is now assumed that $R_S + jX'_S$ is much smaller than $R_M||jX_M$ the equivalent circuit may be further reduced to that of Figure 6. By measuring real power in, current and voltage for this circuit values for X_M and R_M may be calculated.

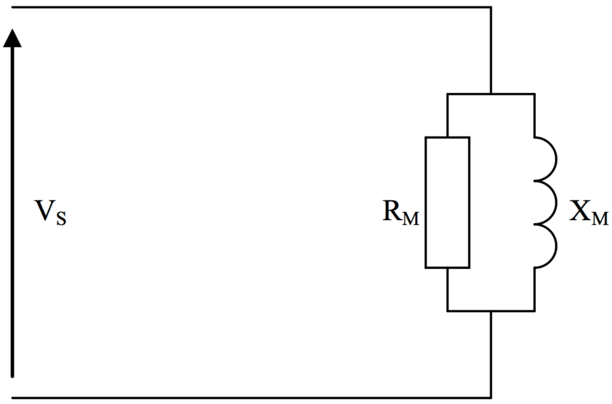

Figure 6 - Simplified Equivalent Circuit for Synchronous Test

C. MATLAB Files

At certain points in the experiment you may wish to use some MATLAB m-files that are provided to help you avoid repetitive calculations.

These are executed by simply typing their name in at a MATLAB command prompt (the m-files need to be in the current working directory). Copies of the MATLAB m-files are available via the department's Intranet under 2nd year laboratory.

Simulation of induction machine operation

An animated simulation of induction machine operation, showing the interaction between rotor and stator fields, can be found in the MATLAB m-file **`ind_sim.m`**.

Automated generation of torque-speed graphs

A MATLAB m-file, **`ind_mach.m`**, has been written for you that allow you to input the equivalent circuit parameters, it then produces two torque/speed graphs for the modeled induction machine. The first torque speed/graph plots torque over full speed range for the induction motor, the second graph only plots the speed range close to the synchronous speed.

Execute the MATLAB script **`ind_mach.m`** from the MATLAB command line and input the circuit parameters by entering them into the 'Model Parameters' boxes. Click on the 'Plot Graphs' button to create the torque/speed graphs.

Note, the **`ind_mach.m`** script places a graphical interface on the m-file **`inducti.m`**. The **`inducti.m`** file does the model calculations for the system.

Look at the file `inducti.m` by opening it in a text editor, see if you can understand the calculations that are being made.

Making a comparison between model and experiment

The MATLAB script **`ind_mach2.m`** now lets you plot the actual machine torque/speed characteristics and the modeled torque/speed characteristics on the same set of axis. Execute **`ind_mach2.m`** from the MATLAB command line. Once again, fill in the 'Model Parameter' boxes with the determined parameter values. Then input torque/speed readings into the 'Actual Machine Readings' boxes. Click on the 'Plot Graphs' button to create the torque/speed graphs for the induction machine model and actual machine.