

Experiment No. 4

The Polyphase Induction Motor

The polyphase induction motor is the most commonly used industrial motor, finding application in many situations where speed regulation is not essential. It is simple and relatively inexpensive, and the absence of sliding contacts in the squirrel-cage machine reduces maintenance to a minimum. There are two general types of polyphase induction motors: the squirrel-cage type and the wound-rotor machine. Both motors have an armature or stator structure similar to that of the alternating current generator, consisting of a hollow cylinder of laminated sheet steel in which are punched longitudinal slots. A symmetrical polyphase winding is laid in these slots which, when connected to a suitable voltage source, produces a travelling MMF wave in the air gap, rotating at a synchronous speed equal to:

$$RPM_{sync} = 120 \frac{f}{p} \quad (1)$$

where f is the frequency and p the number of poles for which the stator is wound.

The squirrel-cage type of rotor is made up of sheet steel laminations keyed to the shaft and having slots punched in the periphery. The number of slots in the rotor is never a multiple of the number in the stator, thereby preventing rotor locking under light load conditions. The rotor conductors in most machines are made of aluminum alloy either molded or extruded in place in the slots, with end rings being cast as an integral part of the structure and connecting all bars at both ends. The air-gap length between rotor and stator is kept as short as manufacturing tolerances will allow in order to minimize the magnetizing current necessary for the production of normal air-gap flux. A simple two-pole, three-phase, squirrel-cage induction motor is diagrammed in Fig. 1.

The wound-rotor induction motor has a rotor similar to that of the squirrel-cage machine except that the short-circuited squirrel-cage winding is replaced by a three-phase insulated winding similar to that on the stator. This winding is usually wye-connected with the terminals brought out to three slip rings on the shaft. Graphite brushes connected to the slip rings provide external access to the rotor winding which is connected to a rheostatic controller, the purpose of which is to insert additional resistance in each rotor phase to improve the starting characteristics.

In practically all induction motors, either the rotor or the stator slots are skewed one slot width as shown in Fig. 1(a). The purpose is to smooth the flux transition from

one slot to the next, thereby reducing harmonics in the torque characteristic and improving the operation.

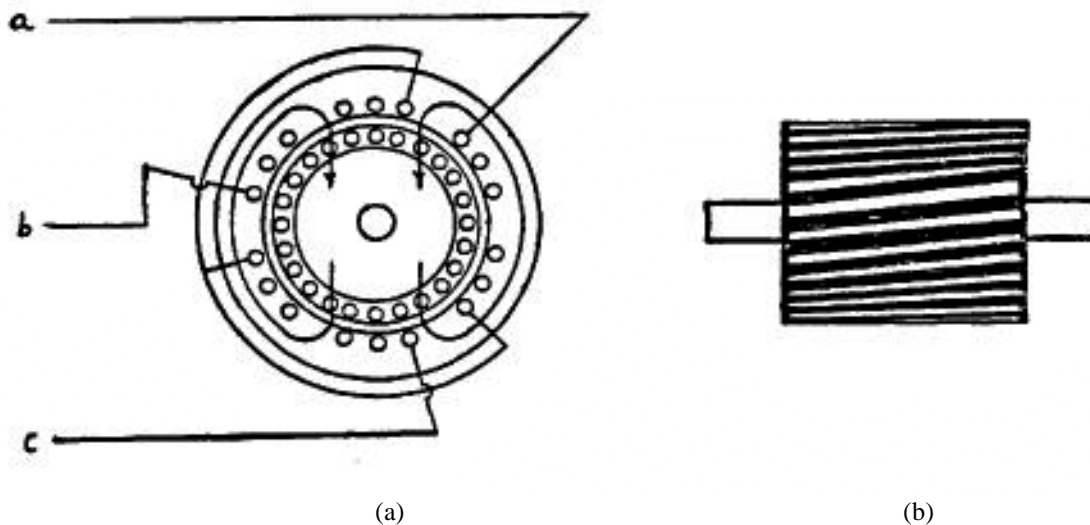


Fig. 1. Physical construction of the squirrel-cage induction motor: (a) cross section showing stator and rotor, (b) rotor construction.

1. Basic operation of the induction motor

As previously shown, the phase displacement between the voltages applied to the stator windings produces a travelling MMF or rotating magnetic field in the uniform air gap. This field links the short-circuited rotor windings, and the relative motion induces short-circuit currents in them, which move about the rotor in exact synchronism with the rotating magnetic field. It is well known that any induced current will react in opposition to the flux linkages producing it, resulting herein a torque on the rotor in the direction of the rotating field. This torque causes the rotor to revolve so as to reduce the rate of change of flux linkages reducing the magnitude of the induced current and the rotor frequency. If the rotor were to revolve at exactly synchronous speed, there would be no changing flux linkages about the rotor coils and no torque would be produced. However, the practical motor has friction losses requiring some electromagnetic torque, even at no-load, and the system will stabilize with the rotor revolving at slightly less than synchronous speed. A mechanical shaft load will cause the rotor to decelerate, but this increases the rotor current, automatically increasing the torque produced, and stabilizing the system at a slightly reduced speed.

The difference in speed between rotor and rotating magnetic field is termed “slip” which is numerically equal to:

$$\text{Slip} = s = \frac{(\text{synchronous speed}) - (\text{rotor speed})}{(\text{synchronous speed})} \quad (2)$$

This varies from a fraction of one per cent at no-load to a maximum value of three or four per cent under full load conditions for most properly designed machines. The speed change between no-load and full-load is so small that the squirrel-cage motor is often termed a constant-speed machine.

2. Equivalent circuit model

Theoretical analyses of the induction machine consider it to be a transformer with a rotating secondary. The stator windings constitute primary windings that induce flux in the rotor and stator iron. The rotor windings constitute a secondary winding that is shorted.

Hence, an equivalent circuit similar to that representing the transformer is derived and appears as in Fig. 2.

Since the rotor frequency in the actual machine is dependent upon the rotor speed, all rotor quantities must be modified to be referred to the frequency and voltage bases of the stator for inclusion in the equivalent circuit.

Since the circuit represents just one phase of the actual polyphase machine, all values are given on a per-phase basis.

Once the equivalent circuit constants have been determined, the operating characteristics may be determined directly from it. The variable load resistance $R_R (1 - s)/s$ models the conversion of power from electrical to mechanical form. The power absorbed by this resistance is equal to the mechanical output power of the machine P_o ; for a three-phase machine, this power is equal to:

$$P_o = 3 \left\| I'_R \right\|^2 \frac{1-s}{s} R_R \quad (3)$$

Similarly, the torque is proportional to the power divided by the speed. Since the speed is proportional to $1 - s$, the torque is given by:

$$T = \frac{P_o}{(1-s)\omega_s} = 3 \left\| I'_R \right\|^2 \frac{R_R}{s\omega_s} \quad (4)$$

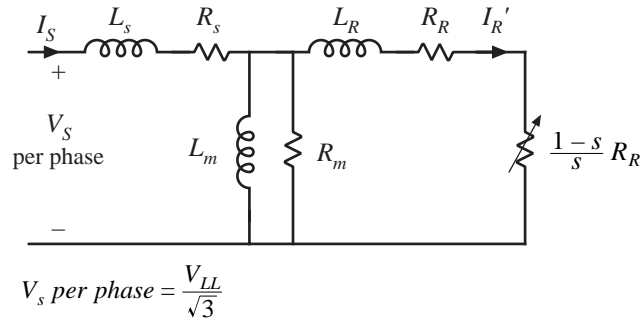


Fig. 2. Equivalent circuit model of the induction machine, per phase.

Here, ω_s is the synchronous speed, in radians per second. The torque is expressed in Newton-meters. Note that the synchronous speed in rpm is related to the applied stator frequency f according to Eq. (1). The torque expressed in the English units of foot-pounds is

$$T = 3K \left\| I_R' \right\|^2 \frac{R_R}{s} \text{ foot-pounds} \quad (5)$$

where $K = 0.058 p/f$.

The losses may be evaluated by realizing that R_s and R_R represent stator and rotor resistances per phase respectively, and that R_m models the core loss. For the usual constant speed application, the mechanical windage (i.e., the resistance of air to rotation of the shaft) and bearing friction losses are constant; then R_m can also model these losses, and the total of these losses is called the *stray power loss*.

The inductance L_m models the magnetization characteristic of the complete flux path; this is dominated by the characteristic of the air gap between stator and rotor. A significant difference between the numerical values of the parameters of the induction machine vs. the transformer is the relatively low value of L_m (transformers typically do not contain air gaps and hence exhibit relatively large values of L_m). This low L_m leads to a substantial magnetizing current that is typically similar in magnitude to the current in the effective load resistance $R_R(1-s)/s$ at full load. In consequence, induction motors exhibit relatively low power factors, especially at light load.

3. Measurement of model parameters

The equivalent circuit constants may be evaluated in much the same manner as those of the transformer. If the shaft coupling is disconnected, the power output will be zero and the load resistance $R_R(1-s)/s$ approaches infinity. For all practical purposes, the series constants may be neglected and the shunt constants obtained by measuring the current, voltage, and power under these conditions where:

$$\begin{aligned} Z_m &= \frac{V}{\sqrt{3} I} \\ R_m &= \frac{V^2}{P} \\ L_m &= \frac{1}{\omega \sqrt{\left(\frac{1}{Z_m}\right)^2 - \left(\frac{1}{R_m}\right)^2}} \end{aligned} \quad (6)$$

with I = line current, P = total three-phase power, and V = line-to-line voltage.

If the rotor is blocked so as to prevent rotation and a balanced low-voltage three-phase source connected to the stator terminals, the load resistance $R_R(1 - s)/s$ will reduce to zero, and the shunt branch may be neglected. Then:

$$\begin{aligned} R_e &= R_R + R_s \text{ per phase} = \frac{P}{3I^2} \\ Z_e &= \frac{V}{\sqrt{3} I} \\ L_e &= L_R + L_s = \frac{1}{\omega} \sqrt{Z_e^2 - R_e^2} \end{aligned} \quad (7)$$

R_s per phase may be determined by passing direct current through any two terminals of the stator, recording the voltage drop, and *dividing the resultant resistance by two*. Then $R_R = R_e - R_s$. It is usually accurate to assume equal stator and rotor leakage inductances, so that $L_s = L_R = L_e/2$.

4. Practical measurement considerations

Examination of the equivalent circuit of Fig. 2 suggests at least two methods for evaluating the shaft power output of the induction motor from test data. Since the currents I_s and I_R differ but slightly under load conditions, R_s and R_R can be combined to the left of the shunt branch without introducing appreciable inaccuracy. Then the total copper losses will be:

$$P_{cu} = 3 \|I_s\|^2 (R_s + R_R) = 3 \|I_s\|^2 R_e$$

and the power output is:

$$P_o = P_{in} - P_{cu} - SP \quad (8)$$

where P_{in} is the total three-phase input power measured at the stator terminals under load conditions, and SP is the stray power loss. Returning to the original equivalent circuit, the power applied to the rotor portion is:

$$P_R = P_{in} - SP - 3 \|I_s\|^2 R_s$$

Since this is all absorbed in the rotor resistance R_R and the load resistance $R_R(1 - s)/s$, the proportion absorbed in the load is $(1 - s)$ of the total. Therefore:

$$P_o = \left[P_{in} - SP - 3 \|I_s\|^2 R_s \right] (1 - s) \quad (9)$$

Theoretically, expressions (8) and (9) should give nearly identical results. From a practical standpoint, (9) does not require the use of a blocked-rotor test for the evaluation of R_e , but its accuracy is dependent upon the accuracy with which the slip is measured. Expression (8) is independent of speed, but does require a blocked-rotor test that is impractical for some types of motors.

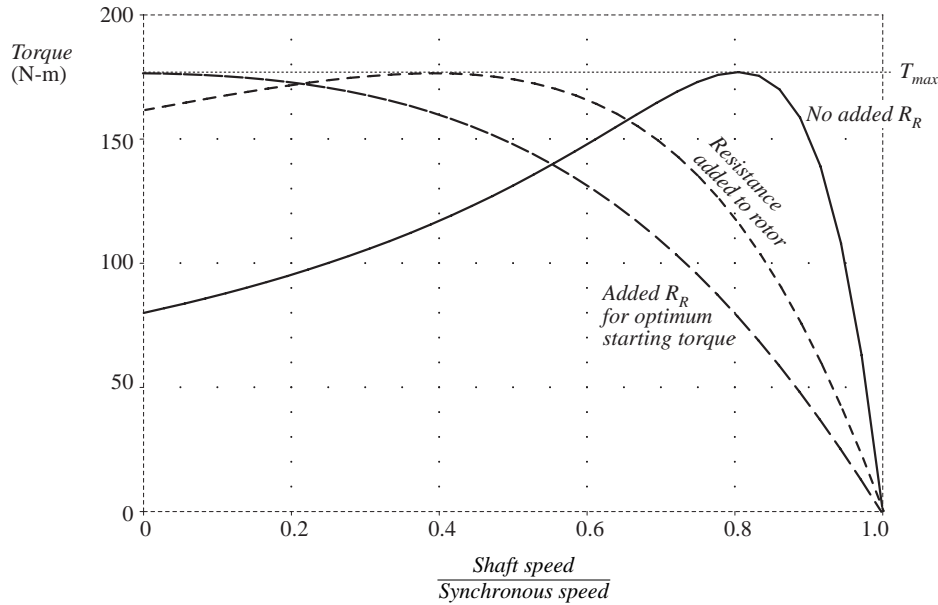


Fig. 3. Torque vs. speed characteristics of an induction machine example. Solid line: basic squirrel-cage machine, or wound-rotor machine with no added rotor resistance. Dashed lines: wound-rotor machine with added external rotor resistance.

5. Characteristics of the squirrel-cage and wound-rotor machines

Evaluation of the torque for various values of slip and constant applied voltage yields a characteristic similar to that shown as a solid trace in Fig. 3.

The maximum torque may be evaluated by maximizing the expression: $T = 3|I_R'|^2 R_R / s$, and will be found to be independent of rotor resistance. However, the slip at which maximum torque is produced does vary with rotor resistance as shown by the dotted characteristics in Fig. 3. Normally the rotor resistance is maintained at as low a value as possible in order to keep the losses low and the efficiency high. This further leads to good speed regulation, i.e., small change in speed between no load and full load.

However, the starting torque of the low-resistance squirrel-cage induction motor is relatively low as seen in Fig. 3. This can be explained in a practical manner by referring to the equivalent circuit and realizing that since the slip is 1 at start, the rotor branch impedance is simply $R_R + j\omega L_R$ and the power factor is low. This low rotor power factor is responsible for the low starting torque. By adding the appropriate value of resistance to the rotor circuit, it is possible to improve the rotor power factor and to produce maximum torque under starting conditions as shown by the dotted characteristic. However, if the motor is allowed to run in this condition, both the efficiency and speed regulation will be poor. The wound rotor is used where high starting torque is necessary so that additional resistance may be placed in the rotor circuit for improvement of the starting performance, and then removed as the motor accelerates towards normal

operating speed. Unfortunately, the wound-rotor machine is more expensive than the squirrel-cage type, and is therefore not generally used where high starting performance is not required.

Another advantage of the wound rotor machine is that of limiting the starting current. The squirrel-cage motor usually draws about seven times rated current for an instant if started at rated voltage. To reduce the effects of this on the system, a few such motors are equipped with starting compensators which allow the motors to start at about one-half rated voltage, and then, after they accelerate to normal speed, apply rated voltage. The disadvantage is that the torque varies as the square of the applied voltage, and the use of a starting compensator worsens the already low starting torque. The wound-rotor machine always starts at rated voltage, and has excellent starting characteristics.

Although it is possible to vary the speed of the wound rotor machine at a given torque by varying the external rotor resistance, this method is rarely used because of the increased rotor losses and lowered efficiency. Sometimes induction motors are equipped with two or more stator windings by means of which the number of magnetic poles may be changed. By this means, several normal operating speeds may be obtained without sacrificing other operating characteristics.

In modern applications requiring variable speed control, a power electronics system is typically used to convert the fixed 50 Hz or 60 Hz utility ac to a variable frequency ac that is fed to the stator of a squirrel cage machine. This effectively varies the synchronous speed of the machine, and hence it allows complete control of the rotor speed. The voltage magnitude must be scaled in proportion to the frequency, to maintain constant stator flux.

6. Simulation via SPICE

Torque-speed characteristics, such as those of Fig. 3, can be generated by simulation of the model of Fig. 2 using SPICE. An example of a PSPICE input file is listed in Fig. 4. For this example, the input line-neutral voltage is 90 Vrms, or 127 V peak. The six-pole 60 Hz induction machine has a synchronous speed of $(2\pi 60)(2/6) = 125.6$ rad/sec. The normalized shaft speed is used as a parameter that varies the effective load resistance $R_R(1-s)/s$. This shaft speed parameter is defined as

$$\text{speed} = (1 - s) = \frac{\text{shaft speed}}{\text{synchronous speed}} \quad (10)$$

The shaft speed parameter is varied from 0.0001 to 0.9995 in increments of 0.02775. For each value of this parameter, an ac analysis is performed at 60 Hz, and the results are

```

ECEN4517 induction machine model
.param speed=0.97 ; speed = 1-slip
.param R2=0.144
.step PARAM speed 0.0001 0.9995 0.02775
Vin 1 0 ac 127
R1 1 2 0.294
L1 2 3 1.3mH
Lm 3 0 35mH
L2 3 4 0.55mH
R2 4 5 {R2}
Rr 5 0 {R2*speed/(1-speed)}
Vslip slip 0 ac {1-speed} ; have the slip available as v(slip)
.ac lin 1 60 60 ; do ac analysis at 60Hz only
.probe
.end

```

Fig. 4. PSPICE input file listing, for generation of induction machine torque-speed characteristics.

saved in PROBE format. The voltage source v_{slip} is numerically equal to the slip, and is saved so that slip can be employed in numerical calculations in PROBE. To plot the torque-speed characteristic in PROBE, Eq. (4) is evaluated and is plotted vs. the parameter *speed*. The data for Fig. 3 was generated in this manner, by plotting the following equation:

$$3 \cdot I(R_r) \cdot I(R_r) \cdot 0.144 / 125.6 / v(\text{slip}) \quad (11)$$

PROBLEMS

1. A certain three-phase 60 Hz induction machine exhibits the following (per-phase) model parameters:

$$\begin{aligned}
 R_S &= 0.20 \, \Omega \\
 L_S &= 0.23 \, \text{mH} \\
 R_m &= 250 \, \Omega \\
 L_m &= 35 \, \text{mH} \\
 R_R &= 0.19 \, \Omega \\
 L_R &= 2.0 \, \text{mH}
 \end{aligned}$$

The nameplate includes the following data:

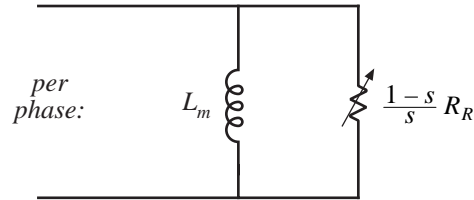
$$\begin{array}{ll}
 \text{Rated speed} & 1745 \, \text{rpm} \\
 \text{Rated voltage} & 230 \, \text{V}
 \end{array}$$

- (a) How many poles does this machine have? What is the synchronous speed? What is the value of the slip at rated speed?

To answer the following questions, simulate this machine using PSPICE, as described in the text.

- (b) For operation at rated speed, determine: the torque, the mechanical output power, the input line current, and the power factor.
- (c) Plot the torque-speed curve of this machine.

2. A 60 Hz three-phase induction motor can be modeled by the conventional T model discussed in the text. For small slip s , the series impedances of this model (i.e., the stator and rotor winding resistances and leakage inductances), as well as the core loss, can be neglected entirely. The resulting simple model then consists solely of a parallel-connected shunt inductor and resistor as shown below. You may use this approximation to solve this problem.



The machine is rated 1160 rpm, 50 hp, 415 V (line-to-line), 70 A.

- (a) How many poles does this machine have? What is the slip under rated conditions?
 - (b) What is the value of R_R ?
 - (c) What is the value of L_m ?
 - (d) Find an expression for how the load torque and slip are related.
 - (e) Find an expression for how the slip and power factor are related. As the load torque goes to zero, what happens to the power factor?
3. A three-phase induction motor is rated as follows:
- 873 rpm
480 V
50 hp
60 Hz

The results of blocked-rotor, no-load, and dc stator resistance tests are as follows:

480V	60V	5Vdc
46A	102A	50A
1.6kW	2.8kW	

- (a) Which data belongs to each test?
- (b) Sketch the equivalent circuit for this machine, and label all element values.
- (c) How many poles does this machine have? What is synchronous speed?

For part (d), to simplify the algebra, you may ignore the stator series impedances (i.e., set $R_s = 0$ and $L_s = 0$).

- (d) The machine now operates at rated speed and voltage. Determine the values predicted by your model of (i) the mechanical output power, and (ii) the power factor.

Experiment 4
Pre-lab assignment
ECEN 4517 / 5017

Polyphase induction motor

1. Read all sections of the text.
2. Do problem 3
3. Read the laboratory procedure

This assignment is due from each student at the beginning of the lab session.