
Induction Motor Performance

Introduction

Traditionally, the primary disadvantages of the induction motor have been high starting current and difficult speed control. However, modern adjustable speed motor drives eliminated these disadvantages.

Induction Motor Steady-State Performance

Figure 1 shows the equivalent per-phase electric circuit of an induction motor which consists of the traditional five parameters (i.e. stator resistance R_1 , stator leakage reactance X_1 , magnetizing reactance X_m , rotor leakage reactance X_2 , and rotor resistance R_2).

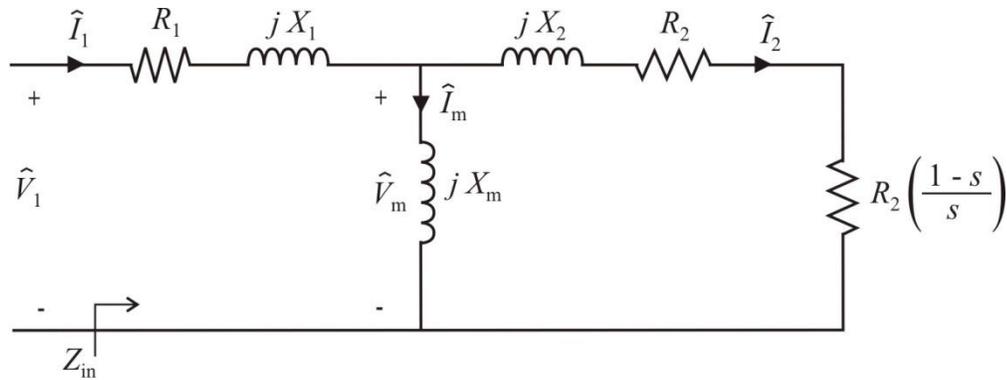


Figure 1. Per-phase equivalent circuit of an induction motor.

The per unit slip s shown in the rotor circuit is a function of the rotor mechanical speed ω_m and the synchronous speed ω_s . Specifically, it is

$$s = \frac{\omega_s - \omega_m}{\omega_s} \quad (1)$$

The speed ω_s is the physical radian speed of the stator poles which is a function of the electrical frequency of the excitation source \hat{V}_1 and the number of stator poles. For a machine operating at a frequency f , the synchronous speed can be calculated (in rad/sec) from

$$\omega_s = \left(\frac{2}{\text{poles}} \right) (2\pi f) \quad (2)$$

From Figure 1, it can be seen that the input impedance Z_{in} can be determined once the slip is calculated. In particular, the input impedance is

$$Z_{in} = R_1 + jX_1 + jX_m \parallel \left(\frac{R_2}{s} + jX_2 \right) \quad (3)$$

If the motor source voltage \hat{V}_1 is known, the stator current can be computed using

$$\hat{I}_1 = \frac{\hat{V}_1}{Z_{in}} \quad (4)$$

The rotor current can then be determined from current division as

$$\hat{I}_2 = \left(\frac{jX_m}{\frac{R_2}{s} + jX_2 + jX_m} \right) \hat{I}_1 \quad (5)$$

The rotor current is flowing through the term $\frac{R_2}{s}$ which may be represented as the series combination of a pure resistance R_2 and a back-emf term $R_2 \left(\frac{1-s}{s} \right)$. The mechanical torque can then be computed as the power into the back-emf term divided by the mechanical speed. This results in

$$T_{mech} = \frac{3I_2^2 R_2 \left(\frac{1-s}{s} \right)}{\omega_m} \quad (6)$$

In (6), the current I_2 is the magnitude of the phasor \hat{I}_2 . From (4-6), the mechanical torque can also be expressed in terms of the applied voltage as

$$T_{mech} = \frac{3 \left(\frac{poles}{2} \right) \frac{s R_2 X_m^2 V_1^2}{\omega_s}}{\left[R_1 R_2 + s (X_m^2 - X_{m1} X_{m2}) \right]^2 + (R_2 X_{m1} + s R_1 X_{m2})^2} \quad (7)$$

where X_{m1} and X_{m2} are defined by

$$X_{m1} = X_1 + X_m \quad (8)$$

$$X_{m2} = X_2 + X_m \quad (9)$$

It is common for a motor manufacturer to provide the mechanical characteristics of the induction motor operating from a constant voltage V_1 at a constant frequency f . Figure 2 shows a typical

speed-torque characteristic of a NEMA class B induction motor as the speed is ranged from zero to synchronous.

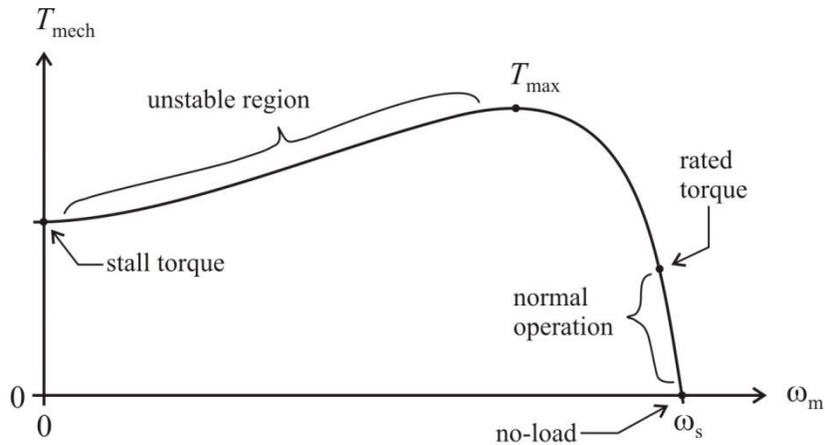


Figure 2. Typical Class B induction motor speed-torque characteristics.

With no mechanical load, the induction motor operates at synchronous speed. In practice, there will be some load due to bearing and load friction. As the load on the machine is increased, the machine slows down; at first operating the normal operation region shown in Figure 2. If the motor is overloaded, it will reach a maximum torque that the machine is capable of producing. When the motor is loaded beyond this, the slope of the torque characteristic changes and the motor provides less torque when speed is reduced. For most mechanical loads, this is an unstable operating mode and the motor speed will decrease to zero. This point is labeled as the stall torque in Figure 2. Incidentally, this is also the amount of torque the machine has available at starting.

It should be noted that the angle of the input impedance is the negative of the angle of \hat{I}_1 since the phase voltage is used as the reference. The cosine of this angle is the power factor

$$pf = \cos(\theta) \quad (10)$$

The input real and reactive power are defined in terms of the impedance angle by

$$P_{in} = 3V_1 I_1 \cos(\theta) \quad (11)$$

$$Q_{in} = 3V_1 I_1 \sin(\theta) \quad (12)$$

Power losses in the induction motor include the stator copper losses P_{stator} , core losses P_c , and rotor copper losses P_{rotor} defined by

$$P_{stator} = 3I_1^2 R_1 \quad (13)$$

$$P_{rotor} = 3I_2^2 R_2 \quad (14)$$

The output power (converted from electrical to mechanical) is defined by

$$P_{\text{mech}} = P_{\text{in}} - P_{\text{stator}} - P_{\text{rotor}} \quad (15)$$

and can also be calculated by subtracting the power losses from the input power. The motor efficiency is then defined by

$$\eta = \frac{P_{\text{shaft}}}{P_{\text{in}}} = \frac{P_{\text{mech}} - P_{\text{rot}}}{P_{\text{in}}} \quad (16)$$

where P_{rot} is the rotational power losses due to friction and windage.

Laboratory Software

Figure 3 shows a screen-shot of the software interface for this experiment. The waveforms show the motor voltage and current. As can be seen, the voltage source is not perfect and contains harmonics. The current also contains harmonics due to the motor tooth saturation. The induction motor input voltage, current, real power, and reactive power are displayed. Also displayed are the armature and field current of a DC generator used to apply a load to the DC motor. The software allows control of the field current for varying the load. In this experiment, several load points will be taken. As the load is increased (through the field current), the motor will slow down. After measuring speed and typing it into the software interface, the data can be logged.

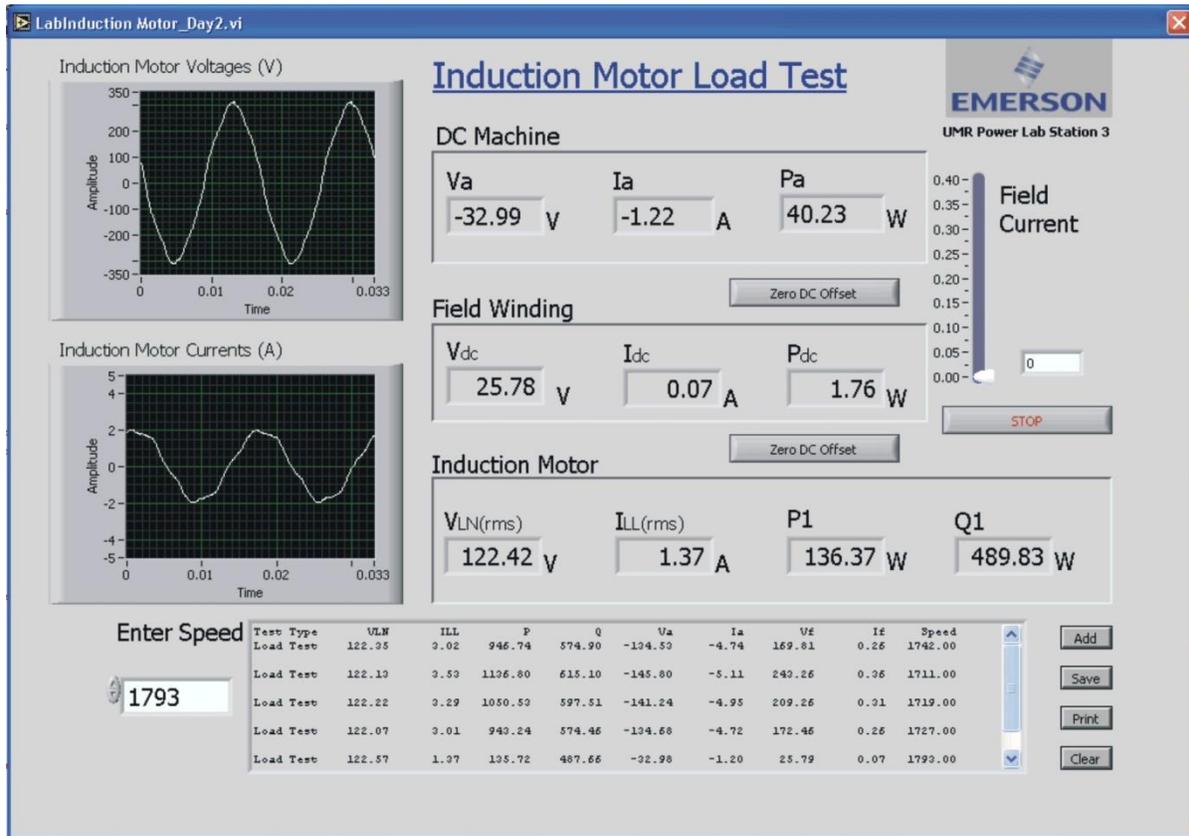


Figure 3. Induction motor load test software.

Laboratory Work

Induction Motor Load Test

Connect the induction and DC motors as shown in Figure 4, and start the laboratory software "LabInduction_Motor_Day2TCP".

Set the load box switches as shown in Figure 5 and **turn on load box fans**.

Switch on the Magna-Power DC power supply. Zero the DC offsets. Increase and decrease the field current and make sure that the power supply control is working. Decrease the field current to zero.

Switch on the source panel circuit breaker and slowly increase the source voltage to 100%. The induction motor should start and operate near its no-load speed. Use the hand-held tachometer to measure the motor speed. Type the speed into the software program and click **Add**.

Increase the field current to 0.05 A. The motor will slow down and at the same time, the input power will increase. Measure the speed for this load point, type it into the software program, and click **Add**. For speed measurement, use the hand-held tachometer. It is necessary to press the button once and wait for the meter to awake, then hold the button and wait for the reading to settle.

Continue to increase the field current in 0.05-A increments up to the maximum. At each point, measure the speed and log the data.

Decrease the field current to zero. Decrease the source panel voltage to zero and switch off the source panel circuit breaker. Switch off the Magna-Power supply.

Save the logged data by clicking **Save**.

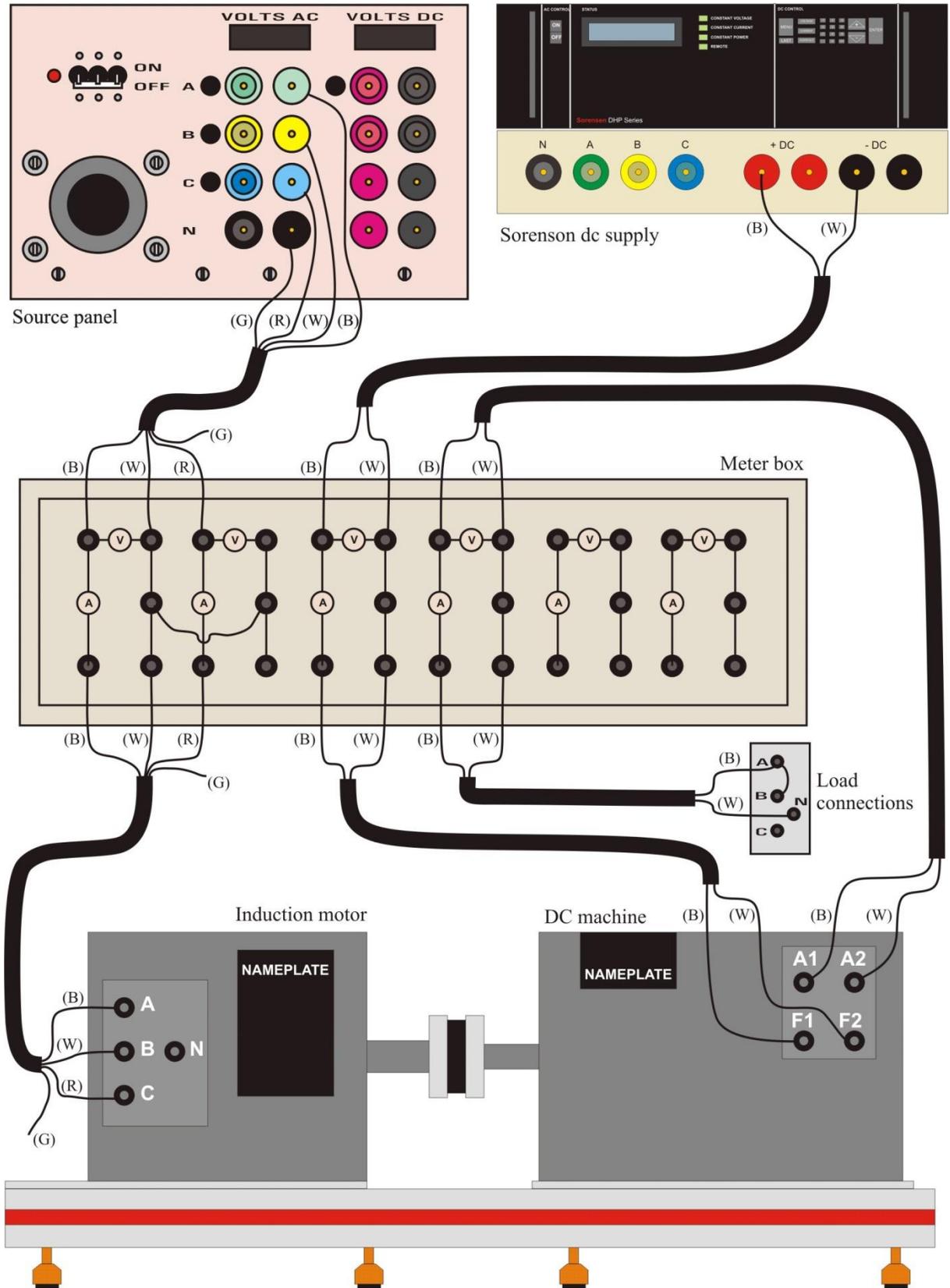


Figure 4. Laboratory setup for the load test.

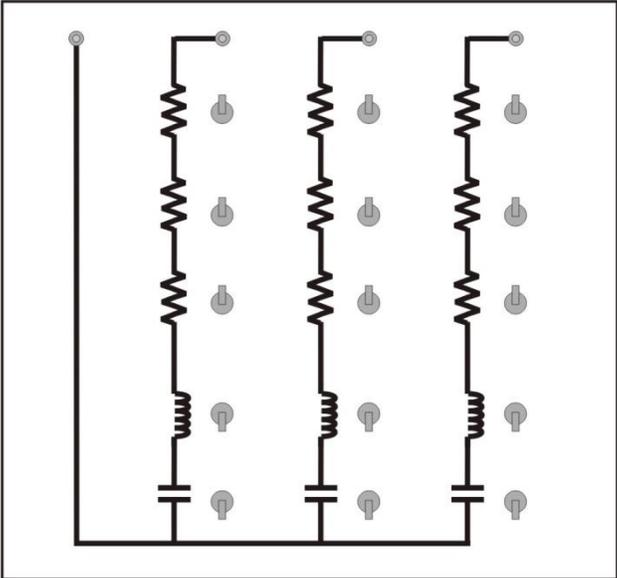


Figure 5. Load box settings for the inductor motor load test.

Calculations and Questions

1. Speed-Torque Performance: Using the induction motor model and the parameters from the "Day 1" experiment, plot the motor torque and current over a speed range from 0 to synchronous speed. Use the rated voltage of $V_1 = 120 \text{ V}$ and rated frequency of 60-Hz.
2. Power and Efficiency: Using the induction motor model and the parameters from the "Day 1" experiment, plot the input power P_{in} , stator losses P_{stator} , rotor losses P_{rotor} , and mechanical power P_{mech} versus speed on the same plot. Plot the motor efficiency versus speed on a separate plot.
3. Power and Power Factor: Using the induction motor model and the parameters from the "Day 1" experiment, plot the input real power P_{in} and input reactive power Q_{in} versus speed on the same plot. Plot the power factor versus speed on a separate plot.
4. Measured Current and Torque: Create a table of measured current and measured torque for the speeds logged in "Day 2". Using the induction motor model calculate values of current and torque which corresponded the measured values and include them in the table for comparison. The measured torque can be determined by dividing the motor mechanical power by the measured speed. The mechanical power is approximately the average of the induction motor input power and the DC generator output power (the armature voltage times the armature current).
5. Measured Active and Reactive Power: Create a table of the measured real and reactive input power for the speeds logged in "Day 2". Also include the calculated real and reactive power in the table.
6. Power Factor: Create a table of measured and calculated power factor for the speeds logged in "Day 2".