Measurement and Analysis of the Operation of a Single-Phase Induction Motor

In class I have shown you the carcass of a four-pole, single phase, ¼ HP motor in varying stages of disassembly. In this lab, I am asking you to measure the properties of an intact copy of that motor to determine its efficiency, power factor and slip frequency as a function of the mechanical load. In doing so, you will reconstruct the electrical equivalent circuit of the motor components including the rotor L/R ratio.

Wear safety glasses whenever applying power to the motor setup!

Whenever the motor overheats and stops running, unplug it or shut it off and leave it alone for a few minutes for the thermal cutout to reset.

If you have any questions about the setup or about how to make it do what you want, please ask – I am glad to help but hope to encourage independence. The Appendix has a series of photographs showing the setup in operation. For color, see the pdf on the class website.

Measure:

- Find the DC resistances of the two stator windings. Use the Kelvin-connection (4-point) technique.
- Measure the apparent 60 Hz impedance (real and imaginary parts) of the run winding under low AC excitation with locked rotor. Use the Variac™ to set a low current, say 2.0 Amp RMS as a compromise between overheating and getting a good reading. There is a switch on the side of the motor that disconnects the start winding. Make sure this is open (down position) before trying to do this measurement. Be careful not to move the rotor while applying AC current as that may start the motor to running. (If you want to verify that the motor can turn in either direction, you might want to try starting the rotor by hand in each direction with the switch off.)
- Similarly measure the locked rotor impedance of the start winding. You can make a connection to the start winding on the switch that disconnects it from the run winding. (I put a short wire on the switched end of the start winding.) Keep current in this winding below 1.0 ampere as this winding has finer gauge wire and is not designed for continuous excitation. Work quickly!
- Measure the rotor speed frequency and the phase and magnitude of the line voltage and current as functions of the load on the motor. The torque on the motor is provided by an aluminum plate over which you move a magnet. The current induced in the plate by the magnet reacts with the static magnetic field to generate a force on the scale under the magnet assembly. The reaction to that force on the plate applies the braking torque. The aluminum plate is 8” in diameter and I estimate the approximate point of load to be 3/16” in along the radius, that is, $R \approx 3.83$ inches. You should calculate in advance what force on the scale would be full load for the motor. Make measurements in 100 gram increments up to the maximum rated load.
- Continue measuring slip (by measuring RPM) and current (magnitude and phase) above rated load in 200 gram increments up to 1600 gram-force load. DO NOT EXCEED 2 KG. If you exceed the peak motor torque, the speed will drop abruptly even though the torque drops too. These

measurements, especially once the speed collapses, are very hard on the motor, causing it to overheat. Please **work quickly** and do not let the motor run at low speed (under 1650 RPM) for any longer than absolutely necessary. Pull the magnet assembly back all the way immediately and allow the motor to pick up speed again.

- Give the motor a chance to cool and then raise the load rapidly until the motor speed collapses, noting the maximum force and the RPM of that maximum. Try to capture the peak torque and slip just as the motor torque collapses. Don't try this measurement too often! Remove the magnet as quickly as possible after the speed collapses!
- The reaction force on the magnet assembly has a significant lateral component. I don't think that contributes very much to the load on the motor because the force is nearly perpendicular to the motion of the plate. Nevertheless, measure that force at the maximum rated motor load to compare with the downward force at that load. The magnet assembly tilts on the scale when it starts to engage the motor plate. I have put a small bubble level and a spring scale (in wooden box) next to the system and I used those for my estimate.
- When you are done measuring, turn off the scale, remove the magnet assembly and relock the scale with the red button on the bottom of the scale.

Size Data:

I have measured the sizes of the most critical parts of the motor. Here is a table of what I measured and another table of useful constants:

Dimension/Property	Value	Units
Rotor outside diameter	3.289 +/- .002	In.
Stator inside diameter	3.3072 +/- .001	In.
Rotor and Stator length	1.28	In.
Width of winding slots in stator face	0.091	In.
Number of stator winding slots	32	
Number of rotor loops (wires/2)	36	
Run winding wire gauge	# 20	AWG.
Run winding wire colors	Blue + Yellow	
Rotor bar cross section:	0.340X0.082	In.
Length of an average run winding turn (approx.)	9.0	In.

Quantity	Value
1 H.P.	746 watts
$\omega = 2\pi f$	377 rad./sec
g	9.81 m/sec^2
Resistivity of aluminum At 20 deg. C	$2.8 \cdot 10^{-6}$ ohm cm.
Temp. coefficient of resistance	.00393 pp deg. C.

Calculations:

- Tabulate the real and reactive electrical power and mechanical power as functions of the rotor speed. Similarly, plot power factor and efficiency against the mechanical power. Mark the point of rated operation. You are really only interested in the range of slip from 0 to 135 % of rated load.
- Plot the data for torque versus RPM. Derive the rotor time constant, τ_R , and the rotor resistance from the power, torque and current measured as functions of slip. There is a (very) long pdf on the class website under class notes, "Induction Motors: Physics and Models" that describes how to extract these parameters.
- Compare the impedance or admittance of the motor at no-load, minimum-slip current conditions to the same at locked rotor condition. Is the difference reasonable in terms of the locked rotor versus zero-slip electrical models? (The two limiting models are near the end of the class PowerPoint™ on motors as well as in the "Induction Motors: Physics and Models" class web notes. If rotor current dominated the two models, what change in impedance or admittance would the model predict?)
- I have made a crude estimate of the length of an average turn by measuring the length of a typical section of the middle one of the three coils that form the run winding of a single pole. That value in in the table above. Estimate the total number of turns in the run winding.
- As a challenge to the bored, use the structure of the motor, the estimate of turns, and the magnetizing current to estimate the peak air gap stator field.

Questions:

1. How did you derive the electrical R-L model parameters from your data? I don't want a big discussion, just a short recap of your procedure.

2. When you fit your torque data to the slip formulae, what did you get for the rotor time constant L/R? In three phase motors, there is a reasonable chance that the locked rotor impedance is roughly the same as the rotor R-L impedance. Is that true of the single phase motor?

3. Starting a motor of this type depends on there being a phase difference between the currents in the start and run windings. What is the phase difference at locked rotor condition for this motor? (The phase differences for the two windings between current to voltage can be found from the ratio of real and imaginary parts of their locked rotor data measurements. The two windings have different ratios.)

4. The motor would have better starting torque if the phase difference were 90 degrees. Suppose, as would be the case if you were designing and building a capacitor run motor, the two windings were the same as the run winding on this motor. What size capacitor would be needed in series with the start winding of this motor to get approximately 90 degrees difference? Calculate this without keeping the magnitude of the impedance constant. What is the ratio of the magnitude of the impedance with and without the start capacitor? How much would such a capacitor cost at wholesale single quantity? (Use www.grainger.com for a price and include the stock number of the capacitor.)

5. The radial air gap on this motor is about ¼ mm while the optimal air gap on your generator designs was several cm. Why the difference?

6. Did you notice anything odd about the nameplate ratings of the motor? (Think VA versus HP.)

Hints and Exhortations:

- Never plug the motor (black cable) into the Variac™ directly! You will trip the building circuit breaker and can damage the instruments.
- Plug the gray isolation transformer into the Variac™ for locked rotor measurements and into a wall outlet for run operations. All power connections to the motor circuitry should come from the output of the isolation transformer.
- Use only one ground wire from the oscilloscope, NEVER two!!
- Listen for a rattle as the motor runs! The setscrews holding the disk on the shaft may loosen up. There are allen wrenches in one of the drawers under the counter. Tighten the screws when you hear a buzz or rattle. Try not to overtighten them.
- It is safest to turn the start winding switch on (up) before plugging in the motor so it will self-start in the correct direction. You are welcome to experiment with starting the motor by hand in either direction but work quickly if you do.

Appendix: The Lab Setup and Measurement Techniques

The first picture below shows the general setup for the lab including the box with the spring scale for lateral force measurement. Notice the orientation of the digital scale that is used to measure the downward force on the magnet assembly. The scale sits on an aluminum plate and you slide that plate left and right to bring the magnet assembly over the wheel to load the motor. Do NOT turn the scale by 90 degrees to make reading it easier as the way the pan is attached leads to incorrect data in that orientation.

The digital scale has a two-position red button on the bottom with locked and unlocked positions. Please leave it in the locked position when it is not in use and turn it to unlocked when you go to use the scale. Turn on the scale by pressing the Zero button on the front of the scale. It will not function properly if the magnet assembly is on the scale when you turn it on. Put the magnet assembly on the scale once the scale is running. You can push the Zero button again to offset the tare weight of the magnets. To keep the magnet assembly from slipping on the scale, you may need two counterweights on it as seen in detail in the second photograph. The larger weight is not attached to the assembly – don't drop it on the scale or your toe.

Use the isolation transformer between the motor and the line power so that scope measurements are safe. You only use the Variac™ on the primary side of the transformer when doing locked-rotor measurements at low voltage and current. Keep the Variac™ turned all the way down when turning it on and off to avoid blowing fuses. The inrush current of the motor starting up will blow the Variac™ fuse if you leave the Variac™ connected when trying to run the motor.

To measure the speed of rotation with adequate accuracy, I put an optical-interrupter around the edge of the wheel and drilled holes in the wheel. The interrupter generates a digital pulse every time a hole passes it. The interrupter runs on 5 VDC from a wall wart. The output of the interrupter goes to a digital counter. Since the signal is a 5 volt unipolar pulse, the counter has to be set for DC input and the trigger level set with the dot on the knob pointing up. There should be no filter turned on in the counter. Adjust the counter measurement time (two buttons with left/right arrows) to get a stable 5 digit reading frequently enough that you don't have to wait long for a good measurement. (Frequent readings are most important when trying to measure peak torque. Readjust reading time if necessary.) In interpreting the counter result, keep in mind that this is a 4-pole motor and there are 8 holes in the wheel.

There are two multimeters with the setup for measuring the line voltage and current easily and simultaneously. The scope is only needed for the phase difference and I suggest measuring that by setting the cursors to give the time difference between zeros crossings of the two waveforms. Synchronize the triggering from the line source in the scope. The DC power supply is only for the DC resistance measurements. As in the transformer lab, you will need to use the 8 ohm power resistor to limit the current in the motor windings to what the power supply can deliver.

The last picture shows my attempt at the lateral force measurement. I noted the inclination of the bubble level with the motor off. Then I tried to find a position of the scale where the scale read the rated motor load while I held level at its original inclination by pressure from the spring scale on the back of the magnets. Experiment and see what you can get.

I suggest taking all the running data in one session as line voltage changes a little from day to day. The thermal state of the motor has a significant effect on data results. Between these two factors it can be difficult to merge different data sets.