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AC Induction Motor Characterization
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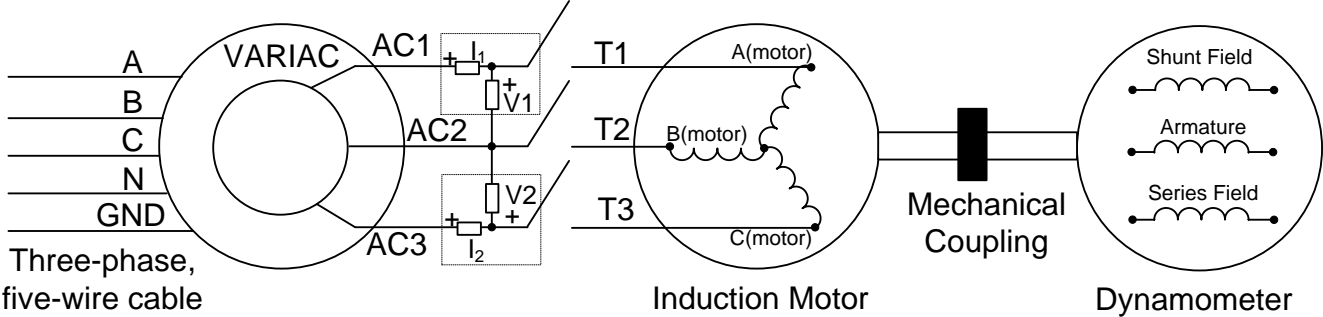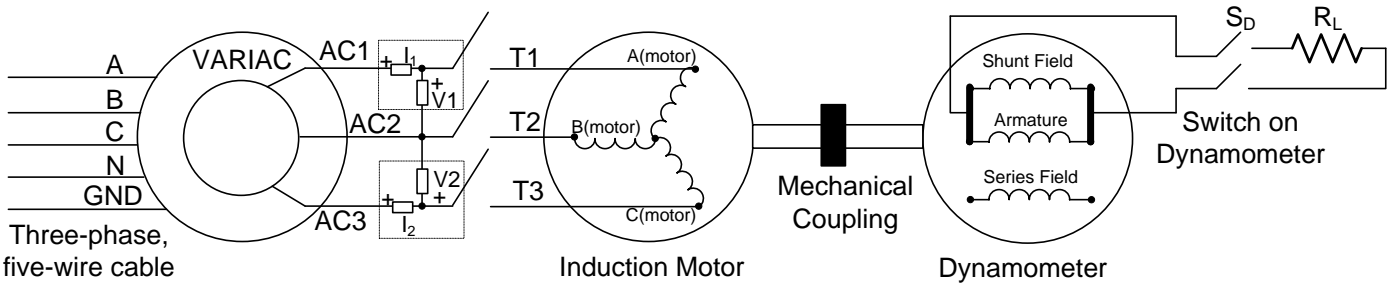
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Electrical Engineering Science Education Title: AC Induction Motor Characterization

Overview:

The objectives of this experiment are to find the equivalent circuit parameters of a three-phase induction motor using the per-phase equivalent circuit and tests similar to those used in transformer characterization. Another objective is to operate the motor in the linear torque-speed region.

The three-phase induction motor is fed by three-phase voltages or currents that, which induce three-magnetic fields that add up to a cumulative magnetic field, which rotates in space at constant amplitude and is termed the stator magnetic field. The magnetic field induces current in metal rotor bars or coils, which in turn, induce their own magnetic field, termed the rotor magnetic field. The rotor hangs inside the stator, and therefore the rotor magnetic field tries to lock to the rotating stator magnetic field, causing the rotor to spin, and therefore, rotational motion is induced. It is typical to have the rotor being formed of rotor bars tied with end rings, forming what is commonly known as a "squirrel cage."-

The per-phase equivalent circuit models the stator- and rotor-side winding resistance R_1 and R_2, respectively, leakage inductance due to leaked flux between the rotor and stator (L_1 is the stator leakage inductance, and L_2 is the rotor leakage inductance), mutual magnetizing inductance (L_m or reactance X_m), and core losses in the core loss equivalent resistance R_C. These are similar to the transformer's equivalent circuit model, but include the effect of rotor magnetic field lag behind the stator, which is termed the slip.

In order to find the equivalent circuit model of the motor, several tests (no-load, locked-rotor, DC, and load tests) should be performed. These tests require the knowledge of motor ratings. For the rated voltage of 208 V at 60 Hz, the following should be noted down from the nameplate: rated power (hp and W, where 1 hp = 746 W), rated current (A), and rated speed (RPM and rad/s). From these ratings, the rated torque (N·m) can be found by dividing the rated power in Watts over the rated speed in rad/s (1 RPM = $2\pi/60$ rad/s), which is not shown on the nameplate.

In order to load the induction machine shaft, a DC generator (dynamometer setup) is mechanically coupled to the shaft. The induction motor acts as the prime mover of the generator. As the electrical load increases on the generator, the mechanical power increases into the generator and out of the induction motor, thus increasing the load on the induction motor shaft.

Procedure:

1. DC Test

    1.1. Note that a squirrel-cage induction machine has only stator terminals accessible.

    1.2. Turn on the low-power DC power supply and limit the current to 1.8 A.

    1.3. Turn the supply off.

Commented [AM1]: Please provide basic principles of operation for an induction motor to give context to the tests.

Commented [AM2]: More information needed.

Commented [AM3]: What tests, and what does each one tell us?

Commented [AM4]: How do you find this? Provide more background.

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1.4. Connect the supply terminals across two of the induction motor terminals (labeled A, B, and C).

1.5. Turn the supply on and record the output voltage and current.

1.6. Repeat for the two other phase combinations.

1.7. Note that the measured resistance is for two phases in series, and thus, the per-phase resistance is half the measurement.

2. No-Load Test

2.1. Test the induction machine with no load to find the per-phase magnetizing branch parameters X_m and R_C. For this test, make sure the load dynamometer has all its terminals disconnected, where it is generating no power and supporting no load.

2.2. Make sure the three-phase source is off.

2.3. Check that the VARIAC is at 0% and then wire the VARIAC to the three-phase outlet, and connect the setup (**Figure 1**).

2.4. Check the circuitDouble--check that the circuit connections are as shown in **Figure 1**, and then turn on the three-phase source.

2.5. Quickly increase the VARIAC output until each of the digital power meters reads around 208 V.

2.6. Record the power, voltage, and current readings from both meters.

2.7. Measure the speed using the strobe light (tune the strobe light to a reasonable speed), and label the measurement as ω_o.

2.8. Record the torque reading in N·m or lb·ft, and label the measurement as T_o just in case the torque transducer or torque-measuring apparatus is not well calibrated. This is the no-load torque.

2.9. Set the VARIAC back to 0% then turn off the three-phase source. Leave the rest of the circuit intact.

3. Locked-Rotor Test

3.1. Test the induction machine with a locked rotor in a manner similar to the short-circuit test of a transformer. Use this test to find the per-phase series resistances and leakage inductances. For this test, make sure the load dynamometer has all its terminals disconnected.

3.2. Make sure the three-phase source is off.

3.3. Check that the VARIAC is at 0%.

3.4. Lock the rotor on the dynamometer side using a mechanical clamp or a zero torque setting, if the dynamometer is digitally controlled.

3.5. Note that the setup is still similar to that of **Figure 1**, except with a locked rotor.

3.6. Double-check that the circuit connections are as shown in **Figure 2**.
3.6. Check the circuit.

3.7. Turn on the three-phase source and the induction machine switch.

3.8. Slowly and carefully increase the VARIAC until rated current is reached on one or both of the digital power meters.

3.9. Record the power, voltage, and current readings from both meters.

3.10.　　　Set the VARIAC back to 0% then turn off the three-phase source. Leave the rest of the circuit intact.

4. Load Test

   4.1. Use this test to trace the linear torque-speed characteristic of the induction machine. For this test, use the dynamometer with a shunt-field as a generator (more on this operating condition is given later in the DC machines video, but the armature is the generator output port).

   4.2. Make sure the three-phase source and induction machine switch are off.

   4.3. Check that the VARIAC is at 0%.

   4.4. Remove the locking clamp from the rotor shaft.

   4.5. Connect the circuit (**Figure 2**). Use R_L=300Ω but keep S_D off.

   4.6. Do not use the series field.

   4.7. Check the circuit, then turn on the three-phase source and the induction machine switch.

   4.8. Quickly increase the VARIAC output until each of the digital power meters reads around 208 V.

   4.9. Record the power, voltage, and current readings from both meters.

4.10. Measure the speed and label it as ω_1. To measure the speed, adjust the "Coarse" frequency knob on the strobe light until the shaft looks almost stationary, and then fine-tune the frequency setting using the "Fine" knob.

4.11. Record the torque reading and label it as T_1.

4.12. Note that this operating point (ω_1, T_1) is not the same as no load, because the field winding is also acting as a load in parallel with the armature. As S_D is turned later and R_L is decreased, the load is increased since the load current increases as R_L decreases.

4.13. Turn on S_D. Measure the speed and label it as ω_2.

4.14. Record the torque reading and label it as T_2.

4.15. Turn off S_D. Change R_L to 200 Ω, then turn on S_D.

4.16. Measure the speed and label it as ω_3.

4.17. Record the torque reading and label it as T_3.

4.18. Turn on S_D. Change R_L to 100 Ω. Turn on S_D.

4.19. Measure the speed and label it as ω_4.

4.20. Record the torque reading and label it as T_4.

4.21. Set the VARIAC to 0%, turn off the three-phase source, and disassemble the circuit.

Representative Results:

A common mistake in finding the equivalent circuit parameters of induction machines is to use the three-phase measured power in calculations of the per-phase equivalent circuit, while one third of the power should be used: three phases consume the measured power, and thus, one third of the power is in one phase.

Calculations of the equivalent circuit parameters are similar to those of the transformers, but it is common to split X_1 and X_2' per the NEMA frame of the machine. For example, if the motor is of NEMA frame A or D, then X_1 and X_2' are assumed to be equal, while if the motor is of NEMA frame B, then X_1 and X_2' are split as 40% and 60% of X_{eq}, respectively, and if the motor is of NEMA frame C, then X_1 and X_2' are split as 30% and 70% of X_{eq}, respectively. It is expected to find that X_1 and X_2' are 1-10% of X_m, R_1 and R_2' are on the order of mΩ to several Ω depending on the motor power rating, and R_C would be on the order of tens to hundreds of Ω, as it is several orders of magnitude larger than R_1 and R_2'.

The linear region of the induction motor torque-speed curve is found using the load test and can be extrapolated from no-load to full- or rate-load conditions. A typical torque-speed curve is

shown in **Figure 3**~~4~~ for several NEMA frames and the linear region is the right-most region close to the 90-100% speed.

Applications:

Three-phase induction machines, especially induction motors, are the workhorses of modern industry. Appropriately characterizing an induction motor provides engineers and technicians with information on the motor's efficiency and torque-speed characteristics. These are essential in determining which motor size and frame best fits an application. Once a motor is characterized and the torque-speed curve is known from equivalent circuit parameters using the tests described, different NEMA frames have different curve shapes. For example, an elevator application requires high-starting torque; therefore, frames, such as NEMA frame D, are more suitable than A or B. When dealing with the induction motor's integral parts of larger systems that consume considerable amounts of energy (*e.g.*, chillers), knowing the equivalent circuit parameters of a motor can provide good estimates of the motor's efficiency and its contribution to energy consumption in that larger system.

Legend:

Figure 1: Setup for no-load test.

Figure 2: Setup for load test.

Figure 3: Typical torque-speed curves for various NEMA frames. [Source: http://ecmweb.com/site-files/ecmweb.com/files/archive/ecmweb.com/mag/405ecm08fig1.jpg]