Iowa State University
Electrical and Computer Engineering
E E 452. Electric Machines and Power Electronic Drives

Laboratory #9
Squirrel-Cage Induction Machine – Steady State Performance

Summary

In this lab, you will analyze the steady state performance of the squirrel-cage induction machine (SCIM), which is the most widely used type of motor in the industry.

Learning objectives

- Become familiar with the squirrel-cage induction machine equivalent circuit.
- Use the TI MCU to drive the machine at different conditions.
- Measure the torque-speed curve.

Background material (should be read before coming to the lab)

- Trzynadlowski chapter 7
- Lecture notes on three-phase inverters and space vector modulation
- Wind Energy notes on squirrel-cage induction machines (chapter 2)
- F28035 V/Hz controller developed in Lab 8

Exercises and Questions

Instructions: every student should deliver his/her own report at the end of the lab session, even though the experiments are conducted in groups. You may want to answer the questions as you go along the exercises. Time yourselves according to the recommendations below.

1. Pre-lab assignment

a) Squirrel-cage machine equivalent circuit

The steady state circuit model for the squirrel cage induction machine is given in Figure 1. This is a per-phase (line-to-neutral) model for a symmetric three-phase machine.

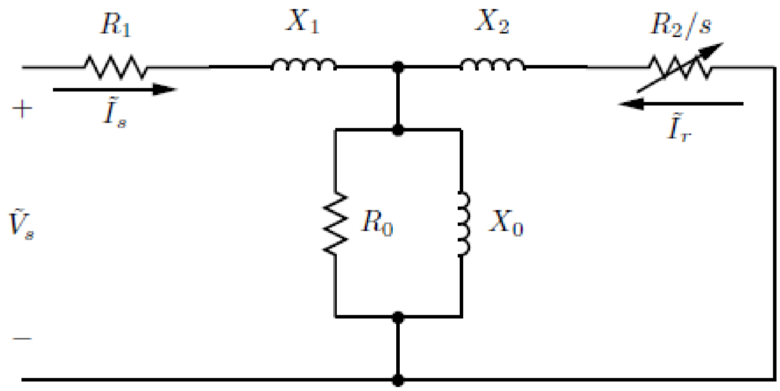

Figure 1. Steady state circuit model of the squirrel-cage induction machine.

In the model, R_1 is the stator winding resistance, X_1 is the stator leakage reactance, R_2 is the rotor resistance, X_2 is the rotor leakage reactance, R_0 represents the iron core loss, and X_0 represents the magnetizing inductance. V_s is the applied line-to-neutral stator voltage, I_s is the stator line current, and I_r is the rotor current (which cannot be measured directly). The slip is defined as

$$s = \frac{\omega_e - \omega_r}{\omega_e}.$$

The rotor mechanical speed and electrical speed are related by

$$\omega_r = \frac{P}{2}\omega_{rm}..$$

Based on the equivalent circuit, the applied stator voltage creates a magnetic field that induces a current in the rotor. The interaction of the two magnetic fields creates an electromagnetic torque, which turns the rotor shaft.

The electromagnetic torque can be computed by

$$T_e = 3\frac{P}{2}\frac{V_{Th}^2 R_2}{(s\omega_e)\left[\left(R_{Th} + \frac{R_2}{s}\right)^2 + (X_{Th} + X_2)^2\right]}$$

where

$$\tilde{V}_{Th} = \frac{jX_0}{R_1 + jX_1 + jX_0}\tilde{V}_s$$

$$Z_{Th} = \frac{1}{\frac{1}{R_1 + jX_1} + \frac{1}{jX_0}}$$

$$P = Number\ of\ Poles$$

$Z_{Th} = R_{Th} + jX_{Th}$ is the Thevenin equivalent impedance looking towards the stator from the rotor side, immediately after the magnetizing branch. $\underline{\tilde{V}_{Th}}$ is the Thevenin voltage phasor. Notice that the generated torque depends not only on the stator voltage and current magnitudes, but also on the slip.

Mechanical power delivered by the motor shaft is computed as

$$P_{sh} = T_{sh}\omega_{rm}$$

where T_{sh} is the net torque on the rotor shaft, in units of Nm, and ω_{rm} is the mechanical rotor speed, in rad/s. The power supplied to the stator is

$$P_s = 3Re\{\tilde{V}_s\tilde{I}_s^*\},$$

and the efficiency of the motor's electrical-to-mechanical energy conversion is

$$\eta = \frac{P_{sh}}{P_e}.$$

A common performance metric used in characterizing a machine is the Torque-Speed curve. A typical torque-speed curve for the SCIM is shown in Figure 2.

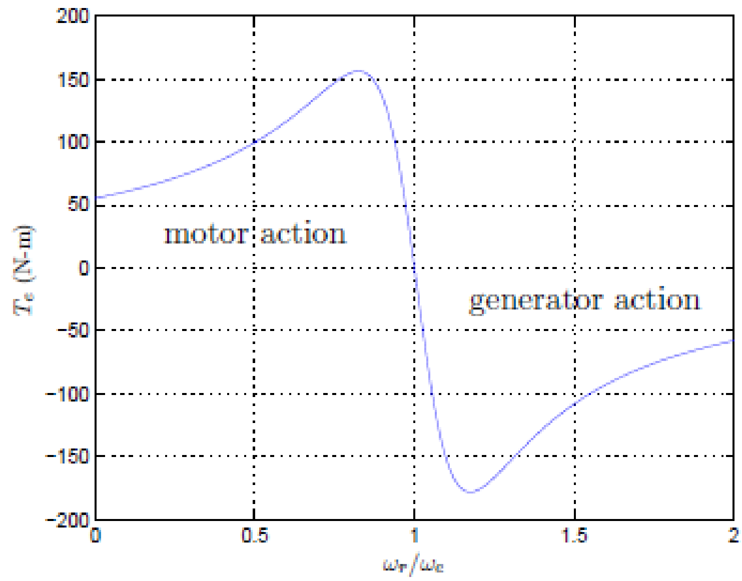

Figure 2. A typical torque-speed curve for the squirrel-cage machine.

The torque at 0 rpm is the *Starting Torque*, and the peak torque is the *Pull-out Torque*. The slope of the curve at rated speed is negative. In this region, if the rotor speed is reduced by addition of a mechanical load, the rotor torque is increased , and a new equilibrium will be reached. If the speed of the rotor is increased by removing a mechanical load, the rotor torque is reduced and the operating point moves closer to the synchronous speed. We will run experiments later on to get points along this curve.

The region of operation around synchronous speed is a stable operating region. This means that along the region of the curve where the slope is negative, the machine has a natural tendency to regulate its speed, and the speed is close to the synchronous speed. If the machine is loaded too much, i.e. the torque rises above the Pull-out Torque, the machine will stall, as the operating point along the Torque-speed curve moves to the left. This is a potentially dangerous situation, as the machine stator currents will rise well above their rated value. We will observe this later with an experiment.

Based on the equivalent circuit model, it is possible to generate the theoretical Torque-Speed curve.

b) Generate the theoretical torque vs. speed curve

Use the provided MATLAB code (*TorqueSpeed.m*) to generate the theoretical torque vs. speed curve for the Lab-Volt squirrel-cage induction motor.

Note: R_0 is neglected in the script.

The machine parameters (previously measured by a PhD student) are given as follows:

Stator Resistance = 12.3 Ω
Reflected Rotor Resistance = 12.3 Ω
Stator Leakage Inductance = 68.6 mH
Rotor Leakage Inductance = 68.6 mH
QD0 Mutual Inductance = 440 mH
Number of Pole Pairs = 2
Stator to Rotor Turns Ratio = 1

DELIVERABLE 1: In addition to generating the theoretical torque-speed curve, add code to plot the rms stator current and power factor, as functions of rotor speed. You can derive these equations from the equivalent circuit. Email your code to the T.A.

Note: You can use the "hold on" command in MATLAB to superimpose additional data on a given plot.

In the next section of this lab, you will conduct tests to measure actual quantities, and you will superimpose the measured values over the calculated values.

2. Steady State Performance of the Squirrel-Cage Induction Motor

[165 minutes]

The V/Hz controller you developed in Lab 8 will be used to drive the machine. The Simulink model should be similar to that shown in Figure 3.

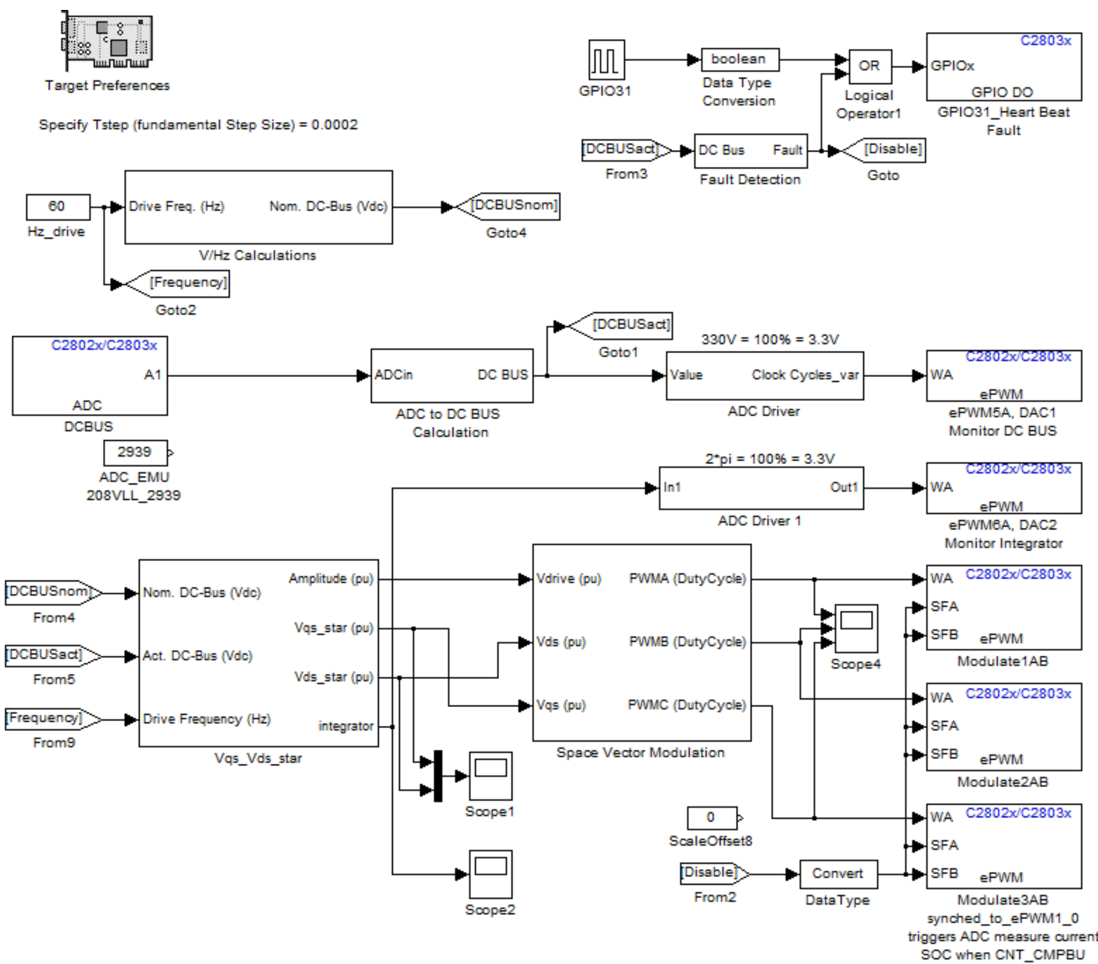

Figure 3. Simulink model for the three phase AC induction motor drive, using space vector modulation and open-loop V/Hz control.

Configure the Lab-Volt *Three Phase Power Supply* and *Power Diodes* to generate a 0-294 V DC-bus voltage, as you did in Lab 8.

WARNING! The DC-bus (-) terminal is **NOT** connected to Earth ground. Use only isolated probes, or you will damage the oscilloscope.

Connect the TMDSHVMTRPFC to drive the Lab-Volt squirrel-cage motor using the DC-bus you just made.

CAUTION!
Verify you hardware configuration with your group members and your T.A.

We will generate the torque vs. speed curve for three conditions. The drive frequency will be 60 Hz for each case. Voltages will be fixed at 208 V, 150 V, and 100 V. The shaft speed will be controlled by the dynamometer. Current and torque will be measured across the motoring speed range.

Ensure the DC-bus voltage is at the minimum value before starting. Configure the drive for the desired voltage and frequency. Load the code and run the program. Set the dynamometer for *CW Prime Mover/ Brake.* Set the speed to 1800rpm, and start the dynamometer; there may be some torque to overcome friction and windage. Increase the DC-bus voltage; the motor should start providing electrical torque. Gather the following quantities:

Mechanical Torque	(measure from dynamometer)
Rotor Speed	(measure from dynamometer)
Current rms	(measure)
Shaft Power = Torque*Speed	(Calculate based on measurements)
Input electrical real power	(Calculate based on measurements)
Input electrical reactive power	(Calculate based on measurements)

Make measurements at various speeds from 1800 rpm down to 0 rpm. Enter this data in a MATLAB script as you conduct your tests. Plot these quantities against the rotor speed. Superimpose the measured quantities over the theoretical ones.

CAUTION! When gathering data for the Lab-Volt motor, you might see that the torque continues to increase nearly to 0 rpm. When supplying 208 V at low speeds, the current might be several times the rated value. If desired, only gather data for a limited speed range. The starting torque can be safely obtained by setting the speed to 0 rpm, and then enabling the dynamometer control for a brief period.

WARNING! Operating the machine beyond rated value can damage the machine. Do not operate in this condition for an extended period of time.

After the necessary information is gathered, reduce the DC-bus voltage and turn off the drive.

After gathering the required data, do the same for voltages of 150 V and 100V. For these voltages, you should be able to obtain measurements over the entire motoring speed range.

DELIVERABLE 4: What do you observe about the speed of the machine across the full operating torque range? What is the pull-out torque at rated voltage and frequency? How does the torque characteristic change with voltage?

DELIVERABLE 5: Submit all performance curves, saved as .jpg files and in a .zip folder. Properly annotate all figures. How does the measured torque vs. speed curves compare to the theoretical ones? Try to explain any differences between the theoretical and actual quantities.

3. **Conclusion** [15 minutes]

Write about one or two things you learned in this lab that you think are important or interesting, and why.