Lab 9: Synchronous motor.

Objective: to examine the design of a 3-phase synchronous motor; to learn how to connect it; to obtain its starting characteristic; to determine the full-load characteristic of a synchronous motor; to determine its pull-off characteristic.


Theory:

The synchronous motor has the special property of maintaining a constant running speed under all conditions of load up to full load. This constant running speed can be maintained even under variable line voltage conditions. It is, therefore, a useful motor in applications where the running speed must be accurately known and unvarying. It should be noted that, if a synchronous motor is severely overloaded, its operation (speed) will suddenly lose its synchronous properties and the motor will come to a halt. The synchronous speed of the motor used in this experiment is 1800 rpm.

The synchronous motor gets its name from the term synchronous speed, which is the natural speed of the rotating magnetic field of the stator. As you have learned, this natural speed of rotation is controlled strictly by the number of pole pairs and the frequency of the applied power.

Like the induction motor, the synchronous motor makes use of the rotating magnetic field. Unlike the induction motor, however, the torque developed does not depend on the induction currents in the rotor. Briefly, the principle of operation of the synchronous motor is as follows: a multiphase source of AC is applied to the stator windings and a rotating magnetic field is produced. A direct current is applied to the rotor windings and a fixed magnetic field is produced. The motor is constructed such that these two magnetic fields react upon each other causing the rotor to rotate at the same speed as the rotating magnetic field. If a load is applied to the rotor shaft, the rotor will momentarily fall behind the rotating field but will continue to rotate at the same synchronous speed.

The falling behind is analogous to the rotor being tied to the rotating field with a rubber band. Heavier loads will cause stretching of the band so the rotor position lags the stator field but the rotor continues at the same speed. If the load is made too large, the rotor will pull out of synchronism with the rotating field and, as a result, will no longer rotate at the same speed. The motor is then said to be overloaded.

The synchronous motor is not a self-starting motor. The rotor is heavy and, from a dead stop, it is not possible to bring the rotor into magnetic lock with the rotating magnetic field. For this reason, all synchronous motors have some kind of starting device. A simple starter is another motor which brings the rotor up to approximately 90 percent of its synchronous speed. The starting motor is then disconnected and the rotor locks in step with the rotating field. The more commonly used starting method is to have the rotor include a squirrel cage induction winding. This induction winding brings the rotor almost to its synchronous speed as an induction motor. The squirrel cage is also useful even after the motor has attained synchronous speed, because it tends to dampen rotor oscillations caused by sudden changes in loading. Your synchronous motor/generator module contains
a squirrel cage type rotor.

The **positive reactive power** is needed to create the magnetic field in an alternating current motor. This reactive power has the disadvantage of producing a low power factor. Low power factors are undesirable for several reasons. Generators, transformers, and supply circuits are limited in ratings by their current carrying capacities. This means that the load that they can deliver is directly proportional to the power factor of the loads that they supply. For example, a system can deliver only **70 percent** of the load at 0.7 **power factor** that it can deliver at unity power factor.

The synchronous motor requires considerable reactive power when it operates at no load without any dc excitation to the rotor. It acts like a 3-phase inductance load on the power line. When the rotor is excited, it will produce some of the magnetism in the motor with the result that the stator has to supply less, and the reactive power drawn from the power line decreases. If the rotor is excited until it produces all the magnetism, the power line will only have to supply real power to the stator, and the power factor will be unity. As far as the power line is concerned, the synchronous motor now looks like a **three-phase resistance load**.

If the rotor is excited still further, tending to create more magnetism than the motor needs, then the power line starts supplying negative reactive power to the stator in its attempt to keep the total flux constant. But negative reactive power corresponds to a capacitor, and the synchronous motor now looks like a 3-phase capacitance load to the power line.

At no load, the synchronous motor has the property of acting like a variable inductor/variable capacitor, the value of reactance ($X_L$ or $X_C$) being determined by the amount of DC current flowing in the rotor. It is also possible to vary motor’s power factor under full load conditions.

A synchronous motor when used on the same power system with induction motors improves the overall system power factor.

The **power output** (in horsepower) of the motor delivered to the load is defined as follows:

\[
P_{\text{out, hp}} = \frac{1.4 \cdot \omega_{\text{rpm}} \cdot T_{\text{Nm}}}{10000}
\]  

(09-1)

where $\omega_{\text{rpm}}$ is the motor speed in revolutions per minute, $T_{\text{Nm}}$ is its torque in Newton-meters. Keep in mind that one horsepower equals approximately to 746 W. The **reactive power** [var] can be computed as:

\[
Q = \sqrt{S^2 - P^2}
\]  

(09-2)

where $S$ is the apparent power [VA], $P$ is the real power [W] consumed by the motor. The **efficiency of the motor** is:

\[
\text{efficiency} = \frac{P_{\text{out, W}}}{P} \cdot 100\%
\]  

(09-3)

where $P_{\text{out, W}}$ is the output power delivered to the load in Watts. The **motor losses**, therefore, are
estimated as:

\[ \text{Losses} = P - P_{\text{out,W}} \]  \hspace{1cm} (09-4)

**Experiment:**

1) Examine the front face of the synchronous motor module (Figure 09-1). Note the three separate windings connected to the terminals 1 and 4, 2 and 5, 3 and 6. These windings are identical and located in the stator – a stationary part of the motor. 3-phase power source will be connected to these windings. The winding on the rotor is connected through a 150 Ω rheostat and a toggle switch to the terminals 7 and 8. This winding will carry a DC current.

![Figure 09-1](image)

2) Couple the motor with the dynamometer with the timing belt. Connect the synchronous motor to the power source as indicated in Figure 09-2.
Connect the dynamometer to the fixed low voltage AC source by the grey cable. Using thin red wires, connect the “torque” and “speed” outputs of the dynamometer to the “T” and “N” terminals of the DAI; connect “ground” terminals of dynamometer and DAI. Set the “MODE” switch of the dynamometer to the “DYN” position and the dynamometer load control switch to the “MAN” position. Set the dynamometer control knob to its utmost counter-clockwise position for minimum load to the motor. Do not apply power at this time!

3) The motor is supplied with the DC current only when switch S is closed. Make sure that the switch is open (OFF) at this time (down position). Turn ON the PS. The motor should start running immediately. Record the values of three stator currents to a Data table.

4) Close the switch S and adjust the rheostat control for minimum stator currents as indicated by the meters. Record the values of three (minimum) stator currents to your Data table. Increase the rotor DC excitation by adjusting the rheostat for minimum resistance (utmost clockwise position of the knob). Record the values of three stator currents to your Data table. Reduce the DC excitation until the stator currents are at their minimum values. Note and record the scale position of the rheostat control knob (i.e. 10 o’clock, 2 o’clock etc.). This is the correct position of the rheostat. Do not change it.

5) Turn OFF the PS and open the switch S. Note: the switch must be closed ONLY when the motor is running! Interchange any two of the AC connection leads at the motor stator terminals (1, 2, or 3). Turn ON the PS and note whether the direction of rotation has changed. Turn OFF the PS and return the connection leads to their initial positions. Turn ON the PS and verify that the rotor is rotating in the clockwise direction.

6) Turn ON the PS and close the switch S on the motor. Motor should start running. Make sure that the rheostat is in its correct position as determined in Part 4. Increase the load on the motor to 0.2 Nm. (the dynamometer braking action) by varying the control knob on the
dynamometer. Control the load either by the dynamometer indicator or using the corresponding LabVolt meter. Record the values of three stator currents and the motor speed as measured by the dynamometer to your Data table. Repeat the same measurements, while recording values of currents and motor speed to the data table, for loads of 0.4, 0.6, 0.8, 1.0, 1.2, and 1.4 Nm. Do not keep your motor running overloaded (under the loads greater than 1.0 Nm.) longer than it is necessary to take a measurement since the normal load for the motor is 1.0 Nm.

7) Modify your circuit as indicated in Figure 09-3. Set the dynamometer to the “no-load” position.

![Figure 09-3](image)

With the variable DC output voltage control knob on PS at zero, turn ON the PS. Close the switch S. Observe the value of the stator current. Carefully adjust the rotor DC voltage to 120 V. Record stator current $I_1$ and rotor voltage $E_2$ to the Data table. Repeat measurements for rotor voltages 100, 75, 50, 25, and 0 V while recording stator current and rotor voltage to your Data table. Turn OFF the PS.

8) Modify your circuit as indicated in Figure 09-4 while keeping dynamometer connections unchanged.
Note that the synchronous motor is wired in its normal starting configuration (as a 3-phase squirrel cage induction motor). Set the dynamometer control knob at its utmost clockwise position to provide a maximum starting load for the motor. Close the switch S. Open a new data table to record the values of voltages $E_1$, $E_2$, current $I_1$, and the load torque as indicated by the dynamometer. Turn ON the PS and quickly measure (and record to the Data table) values of $E_1$, $E_2$, $I_1$, and the developed starting torque. Turn OFF the PS.

9) With your circuit unchanged, turn ON the PS and reduce the torque to 1.4 Nm. Record the values of $E_1$, $E_2$, $I_1$, and the torque to your Data table. Repeat the same measurements for the load values of 1.2, 1.0, 0.8, 0.6, 0.4, 0.2, and 0 Nm. Note: the torque of 0 Nm would be obtained if the motor and the dynamometer were uncoupled. Since we keep the motor and the dynamometer coupled, a small load will still be applied to the motor.

10) Modify your circuit as indicated in Figure 09-5 while keeping the motor coupled with the dynamometer.
Figure 09-5

In your Metering window, set the following meters: $E_1$ (AC), $I_1$ (AC), $I_2$ (DC), apparent AC power $S_1$ between $E_1$ and $I_1$ [VA]. Also set the two additional programmable meters: A – to measure a real AC power $P_1$ between $E_1$ and $I_1$ in W and B – to measure the power factor between $E_1$ and $I_1$.

11) Close the switch $S$. Adjust the dynamometer control knob for no load (utmost counterclockwise position). Set the DC excitation to zero. Turn ON the PS. Measure and record in a new Data table the values of stator voltage $E_1$, stator current $I_1$, rotor current $I_2$ (it must be approximately zero this time), apparent and real powers, and the power factor. Repeat the same measurements for the values of rotor current from 0.1 to 0.9 A with a step of 0.1 A. Note: due to line voltage, power supply and motor winding tolerances, some students could not be able to increase the DC excitation to 0.9 A.

12) Increase the motor load to 1.0 Nm and repeat the same measurements as in Part 11 for the same range of values of the DC excitation current. Record these full-load values in your Data table.

In your report:

1) Using Matlab and the data recorded in Part 6, plot the dependence of stator current on the motor load for the loads from 0 to 1.4 Nm. Is this dependence linear? Calculate the developed motor horsepower under the normal load of 1.0 Nm. Does the speed of the synchronous motor depend on the load?

2) Describe and explain what you have observed in Part 7. For the data you have collected, plot the stator current $I_2$ as a function of rotor excitation $E_r$.

3) For the data recorded in Part 8, calculate and report the apparent power of the motor at the starting torque. Calculate and report the full load torque that corresponds to $\frac{1}{4}$ hp at 1800 rpm. Calculate and report the ratio of starting torque to the full load torque.

4) Using Matlab and the data recorded in Parts 8 and 9, plot the dependence of the voltage induced on the rotor winding $E_2$ on the load for all values of torque you used in the experiments. Explain why a large AC voltage was induced in the rotor winding and why it decreased as the rotor speed increased.

5) Using Matlab and the data recorded in Part 11, plot the stator current as a function of the rotor current. On separate axes, plot the dependence of power factor on the rotor current. Comment on the appearance of both no-load curves.

6) Using Matlab and the data recorded in Part 12, plot the stator current as a function of the rotor current. On separate axes, plot the dependence of power factor on the rotor current.
Comment on the appearance of both full-load curves. Estimate and report the motor efficiency for the full-load condition.

7) Plot the difference between two power factor curves obtained for no-load and full-load conditions.