Synchronous Motor V-Curves

Introduction
Synchronous motors are used in applications such as textile mills where constant speed operation is critical. Most small synchronous motors contain squirrel cage bars for starting. In this experiment, synchronous motor starting is demonstrated. After starting, the motor is locked into synchronism by applying a rotor field current. The field current is then varied to illustrate control of the reactive power from positive to negative. When the reactive power is zero, the machine is operating with unity power factor and the armature current drawn from the source is a minimum. The armature current is plotted versus field current to obtain the classical "V-curves".

Synchronous Motor Starting
Most synchronous motors can not be line-started (suddenly applying rated voltage and frequency to the armature) when the rotor field is established. This is because the rotor starts with zero speed and if it has sufficient inertia will remain stationary while the stator poles rotate at synchronous speed. This causes positive and negative torque pulses, but the average torque is zero. Figure 1 illustrates this principle. Initially, the stator poles are in line with the rotor poles and no torque is produced. At time $\omega t = 90^\circ$, the stator poles are at quadrature to the rotor poles (assuming the rotor hasn't rotated in this short time) and a negative torque is produced by the interaction of the stator and rotor fields (positive torque being defined as shown in Figure 1). At $\omega t = 180^\circ$ the stator poles are again aligned with the rotor poles producing zero torque. At $\omega t = 270^\circ$ the stator poles are aligned such that the torque is positive. The torque versus time plot is shown below the machine cross-sections in Figure 1. As can be seen, the torque oscillates about zero at the fundamental frequency and the average torque is zero. For this reason, the machine will not start and will only emit a buzzing sound.

![Figure 1. Illustration of synchronous machine line-starting with field rotor applied.](image-url)
To facilitate starting, the synchronous motor has a set of short-circuited bars, known as damper windings (or sometimes called amortisseur windings). Figure 2 illustrates the starting process where the rotor field current is removed so that the rotor poles will only come from current induced in the damper windings. First, the damper winding is modeled as one short-circuited coil. From Figure 2, the flux linking this coil from the stator can be seen to be a maximum at \( \omega t = 90^\circ \) then going to zero at \( \omega t = 180^\circ \) and becoming a negative maximum at \( \omega t = 270^\circ \). This can be modeled as

\[
\lambda_d = \Lambda_m \sin(\omega t)
\]

where \( \Lambda_m \) is the peak value of flux linkage. By Farady's law, the induced voltage in the damper coil is the derivative of the flux linkage or

\[
e_d = E_m \cos(\omega t)
\]

where \( E_m \) is the peak induced voltage. If the damper coil inductance is neglected, the damper bar current can be approximated by

\[
i_d = I_m \cos(\omega t)
\]

where \( I_m \) is the peak voltage over the damper winding resistance. According to (3), at \( \omega t = 0 \), the damper bar current is a positive maximum producing a set of rotor poles as shown in Figure 2. It can be seen that these poles will result in a positive torque. The current is a negative maximum at \( \omega t = 180^\circ \) causing a set of poles in the opposite direction. It can be seen from Figure 2 that these poles also produce a positive torque. The torque versus time plot is shown in the bottom part of Figure 2. As can be seen, the torque due to currents induced in the rotor damper bars has a positive average value and oscillates with a frequency of twice the fundamental. When this average torque is sustained on the rotor, it will accelerate the inertia and the machine will come up to speed.

*Figure 2. Synchronous machine line-starting with damper bars (no field rotor applied).*
The above analysis of starting with damper windings is only approximate. In the laboratory, the damper winding will have inductance which will delay the rotor current waveform, but the interaction of the damper winding flux and stator flux will still result in a starting torque with pulsations at twice the fundamental frequency and with a positive average value (in the direction of the stator poles).

After the machine starts, it will not completely reach synchronous speed. This is because if the rotor is moving in synchronism with the stator poles, the flux linking the rotor damper windings will be constant. Thus the induced voltage will be zero and the torque will go to zero. In practice, the rotor accelerates to near synchronous speed since a small amount of torque is required to overcome friction losses. At this point, a DC current can be switched into the rotor field winding to establish rotor poles and the machine will lock into synchronism with the rotor operating at a synchronous speed of

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

(4)

where $f_e$ is the frequency of the stator currents. In RPM, the synchronous speed may be calculated as

$$n_s = \frac{120 f_e}{\text{poles}}$$

(5)

The motor will now remain at synchronous speed unless it is overloaded.

*Motor V-curves*

After the motor is started and is operating under normal conditions, the machine performance can be observed. For this analysis, the traditional per-phase model is shown in Figure 3. One phase of the armature circuit is seen to contain reactance and an induced voltage (back-emf) which is proportional to rotor field current. The rotor circuit is also depicted in Figure 3 as a field winding resistance. Typically the motor is driven by a constant voltage source and is supplying a mechanical load. The motor synchronous mechanical speed is determined by the voltage source frequency $f_e$ using (4)
The input power can be defined from the per-phase model as

\[ P = 3V_a I_a \cos(\theta) \]  \hspace{1cm} (6)

where \( \theta = \angle \hat{V}_a - \angle \hat{I}_a \). It can be shown from the machine equations and power relationships that

\[ X_s I_a \cos(\theta) = E_{af} \sin(\delta) \]  \hspace{1cm} (7)

Therefore, for constant power operation

\[ I_a \cos(\theta) = C_1 \]  \hspace{1cm} (8)
\[ E_{af} \sin(\delta) = C_2 \]  \hspace{1cm} (9)

where \( C_1 \) and \( C_2 \) are constants.

From a KVL equation, the phase voltage is

\[ \hat{E}_{af} = \hat{V}_a - j X_s \hat{I}_a \]  \hspace{1cm} (10)

Using the information from (6-10), the circuit phasors can be plotted for constant power as the field current is varied. This is shown for three values of field current in Figure 4. Note that the synchronous motor can operate with a lagging power factor, unity power factor, or leading power factor. Another important aspect of this is that the reactive power goes from positive to negative as field current is increased. This means that the synchronous motor can absorb or supply reactive power. Since the magnitude of \( \hat{E}_{af} \) is proportional to field current excitation, the lagging power factor condition is sometimes referred to as under-excited operation and leading power factor condition is referred to as over-excited operation for the synchronous motor. These terms refer to the magnitude of the field current. Note that the current \( \hat{I}_a \) and the voltage \( \hat{E}_{af} \) follow the lines of constant power given by (8-9).
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Figure 4. Synchronous motor phasor diagrams.

a) Lagging p.f. 
\[ Q > 0 \quad \theta > 0 \]
underexcited

b) Unity p.f. 
\[ Q = 0 \quad \theta = 0 \]

\[ E_{af} \sin(\delta) \]

\[ E_{af} \sin(\delta) \]

\[ E_{af} \sin(\delta) \]

c) Leading p.f. 
\[ Q < 0 \quad \theta < 0 \]
overexcited
If the armature current is plotted versus field current for several power levels, the regulating plots are the motor V-curves shown in Figure 5. The points marked $a$, $b$, and $c$ on the upper curve correspond to the operating conditions in Figure 4. Note that for $P=0$, the lagging power factor operation is electrically equivalent to an inductor and the leading power factor operation is electrically equivalent to a capacitor. Leading power factor operation with $P=0$ is sometimes referred to as synchronous condenser or synchronous capacitor operation. Typically, the synchronous machine V-curves are provided by the manufacturer so that the user can determine the resulting operation under a given set of conditions.

![Figure 5. Synchronous motor V-curves.](image)
Laboratory Software

Figure 6 shows a screen-shot of the software for this experiment. The synchronous machine armature voltage, armature current, real power, and reactive power are displayed as well as graphs of the armature voltage and armature current. The field quantities are also displayed and a control is built-in for adjustment of the field current. After going through the start-up procedure, the field current will be adjusted and the data is saved at each step for plotting the machine V-curves. The standard "Add", "Clear", "Print", and "Save" buttons are included. Two V-curves will be obtained in this experiment and can be marked by selecting "no-load" (shown in Figure 6) or "load". Technically, the no-load curve has a bit of load due to a dc machine which the synchronous machine is connected to.

Figure 6. Laboratory software for the synchronous motor V-curve experiment.
**Laboratory machines**

Figure 7 shows the diagram of the motor test stand used for this experiment. The synchronous machine is actually a wound-rotor induction machine. It will operate as a synchronous machine when a DC current is supplied to the rotor. Besides the rotor windings accessible from the connector box, the machine also has short-circuited damper windings on the rotor. Both sides of each stator winding (as, bs, cs, an, bn, and cn terminals) are brought out on the connector box for connection in wye or delta. However, in this experiment, the machine will be connected in wye. The rotor is wye-connected internally, and the three terminals are brought out (ar, br, and cr). Synchronization lamps are connected in-between the stator windings and the line connection (terminals a, b, and c). A three-phase switch bypasses these lamps when switched on. This setup can be used for synchronizing the generator to the line or for synchronous motor starting. The synchronous machine is rated at 208-V (line-to-line rms), 60-Hz, 250-W. It is a 4-pole machine and thus has a synchronous speed of 1800-RPM.

The dc machine armature and field terminals are available for connection (A1, A2, F1, and F2). The machine is designed to be shunt-connected (armature and field in parallel) and is used to drive the synchronous machine as a generator or absorb a mechanical load when the synchronous machine is operating as a motor.

![Diagram of laboratory experiment connection](image-url)
Laboratory Work

Figure 8 shows the wiring diagram for this experiment. Start by connecting the dc machine. In this case, the source panel supplies the field voltage through a meter channel. The mechanical power that will be absorbed by the DC machine is in the form of generated armature voltage which is supplied to a resistive load. The load box settings are shown in Figure 9.

Next, connect the Sorenson DC output to the synchronous machine through a meter channel as shown in Figure 8. Note the dashed connection on the meter box. This is a short-circuit connection which must be connected, but will be removed later.

Lastly, connect the synchronous machine armature. Start by connecting the stator neutral point on the synchronous machine connection box. Then connect the armature (terminals a, b, and c) to the meter box as shown in Figure 8. **Make sure the switch on the connection box is in the off position.** As a last step, connect the meter box to the 208-V line voltage. This is the terminals A, B, and C directly below the Sorenson DC supply. Adapter plugs will be necessary to make this connection. Keep in mind that you are connecting into an energized source. For this reason, the switch on the synchronous machine connection box must be off. After connecting into this source, the lamps on the connection box will light up.

The next step is to establish a field current. Start the Synchronous Motor V-Curves experiment on the computer and switch on the Sorenson power supply. Increase the commanded field current to 2.5-A using the software interface. Note that this field current is going through the short circuit on the meter panel.

To start the synchronous motor, flip the switch to the on position. This short-circuits the lamps and applies line voltage to the armature at rated voltage and rated frequency. The machine will start immediately due to the rotor damper bars as described above.

Measure the speed with the hand-held tachometers. Note that it will be slightly less than synchronous speed.

Next, remove the short-circuit wire in the field circuit (shown as the dashed line in Figure 8). The best way to do this is to just disconnect the right side since it is not connected to anything else. When this is disconnected, the 2.5-A dc current will flow into the synchronous motor field. Measure and record the speed under these conditions.

At this point, the synchronous motor is running with a light load. Reduce the field current to 1.5-A. Set the Load Type to Light-load in the software and obtain a set of V-curves by increasing the field current from 1.5-A to 3.5-A and logging the data for each point (by clicking Add). Reduce the field back current to 1.5-A.

Switch on the source panel and increase the source voltage until the synchronous motor is drawing 200-W as seen on the computer screen (note this will be about 30% of the source panel voltage). This will take two people to do. Change the Load Type to Rated-Load in the software and obtain another set of V-curves with a field current from 1.5-A to 3.5-A.

Reduce the source panel voltage to zero and switch off the source panel circuit breaker. Reduce the commanded field current to zero. Switch off the synchronous motor (by the switch on its connector box) and the machine will come to a stop. Switch off the Sorenson power supply.
Figure 8. Laboratory experiment connection diagram.
Figure 9. Load box settings for the synchronous motor load test.
Calculations and Questions

1. Calculate the value of rotor speed $\omega_s$ using (5) and compare it to the measured value. Note: the measured value is in RPM.

2. Create a plot of real power and reactive power versus field current for both levels of loading. Make a separate plot for each load level, but use the same axes scales for both plots. Note that the real power remains constant and the reactive power transitions from positive to negative.

3. Create a plot of power factor versus field current. This should be one plot with both power levels.

4. Create the V-curve plots for this motor by plotting the armature current magnitude versus field current. This should be one plot with both power levels.

5. Sketch the phasor diagrams for three operating points logged in the Rated-Load test; one for leading power factor, one for unity power factor, and one for lagging power factor. For synchronous reactance use a value of $X_s = 152 \, \Omega$. 