**DC Generator Characteristics**

**Introduction**
DC machines may be used as either motors or generators. As motors, they are typically used where speed control is needed as they are the easiest to control. As generators, they are used wherever a dc source is needed, e.g., to power other dc motors.

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 may be varied to adjust the reactive power consumption or generation. For this experiment, you will use the synchronous motor as the prime mover for the dc generator.

**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.
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 Faraday'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 divided by 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.
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

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

(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.

**DC Generator Behavior**

After the synchronous motor is started and is operating under normal conditions, it may be used as the prime mover for a generator (similar to an engine or turbine). In this experiment, we will be exploring a self-excited generator. This means that the machine is shunt-wound and the field
current is supplied by the generated voltage on the armature. The equivalent circuit is shown in Figure 3. However, this equivalent circuit is linear and does not illuminate the key requirements to be self-excited.

![DC Generator Equivalent Circuit](image)

Figure 3. DC generator equivalent circuit.

The generated voltage is proportional to the flux in the field winding $\Phi_d$ and the mechanical speed $\omega_m$:

$$E_a = K_a \Phi_d \omega_m$$  \hspace{1cm} (6)

In general, we assume that the flux is determined entirely by the field current, that is,

$$\Phi_d = K_I I_f$$  \hspace{1cm} (7)

However, you may recall that all magnetic materials are nonlinear, with saturation and hysteresis. Near zero field current, hysteresis dominates and adds to the flux produced by the field current:

$$\Phi_d = K_I I_f + \Phi_{rem}$$  \hspace{1cm} (8)

Here, $\Phi_{rem}$ is the remanent flux. If this were the only nonlinearity, then the generated voltage would escape to infinity. However, there is also saturation, as shown conceptually in Figure 4. The remanent flux effect is exaggerated here. Also indicated on Figure 4 is the load line of the shunt field resistance. In steady-state, the generator will remain at the voltage indicated by the intersection of the two curves.

![Generated Voltage vs. Field Current](image)

Figure 4. Generated voltage vs. field current. Exaggerated.

When a load is applied, some current flows through the armature. The armature flux interacts with the field winding flux. As a result, some parts of the steel structure approach saturation earlier than in the no-load case. This behavior is called armature reaction and results in the third curve shown in Figure 4.
Laboratory Software

Figure 6 shows a screen-shot of the software for this experiment, “LabDCGeneratorTCP.” The synchronous machine armature voltage, current, and active power are displayed numerically along with the field parameters. More importantly, the dc machine armature and field voltage and current are displayed. You will be plotting generated voltage vs. field voltage for the dc machine, where generated voltage is armature voltage less the drop across the armature resistance. To help visualize the experiment, an XY plot of field voltage and current is also provided. The standard "Add", "Clear", "Print", and "Save" buttons are included. Two curves will be obtained in this experiment and can be marked by selecting "no-load" (shown in Figure 6) or "full load". Technically, the no-load curve has a bit of load due to friction, windage, and other parasitic losses. As of this writing, you will only be performing the no-load test.
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.

Figure 7. Laboratory experiment connection diagram.
Laboratory Work

Figure 8 shows the wiring diagram for this experiment. Start by connecting the dc machine. The armature supplies field current through the rheostat, and through the meter box so that armature and field current may be separately measured. For this test, though, the machine will be running at no-load, so that both field and armature should be the same (though possibly of different signs). Make sure that the rheostat is turned to maximum ohms, that is, fully clockwise.

Next, connect the Magna-Power 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 across the synchronous machine field winding 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 Magna-Power 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 in the synchronous machine. Switch on the Magna-Power DC supply and start the DC Generator (“LabDCGeneratorTCP”) experiment on the computer. 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 synchronous machine 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.

Now observe the dc generator characteristics. From the drop-down box, choose No Load. Our objective is to plot field voltage vs. current all the way down to very low currents. With the rheostat set to maximum ohms (turned all the way clockwise), record data points as the voltage comes up, approximately every 10 V. Record additional data points as you decrease the rheostat resistance until either the armature voltage reaches 200 V or the rheostat reaches minimum resistance. If the voltage does not increase above 10 V, swap the leads indicated with a double-ended arrow on Figure 8. Depending on how quickly you act, you may need to shut down and restart in order to capture low voltage data points.

To shut down, reduce the commanded (synchronous motor) 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 Magna-Power DC supply. Save your data and stop the LabView program.
Magna-Power dc supply

Figure 8. Laboratory experiment connection diagram.
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. Plot the field characteristic, that is, generated voltage vs. field current, of the dc generator.

3. Determine the total resistance (internal field winding resistance plus external rheostat resistance) that would be needed for steady-state operation at 120 V.