

**Strategy**

Once  $\omega$ , the angular velocity, is determined,  $\text{emf}_0 = NAB\omega$  can be used to find  $\text{emf}_0$ . All other quantities are known.

**Solution**

Angular velocity is defined to be the change in angle per unit time:

$$\omega = \frac{\Delta\theta}{\Delta t}. \quad 23.21$$

One-fourth of a revolution is  $\pi/2$  radians, and the time is 0.0150 s; thus,

$$\begin{aligned} \omega &= \frac{\pi/2 \text{ rad}}{0.0150 \text{ s}} \\ &= 104.7 \text{ rad/s}. \end{aligned} \quad 23.22$$

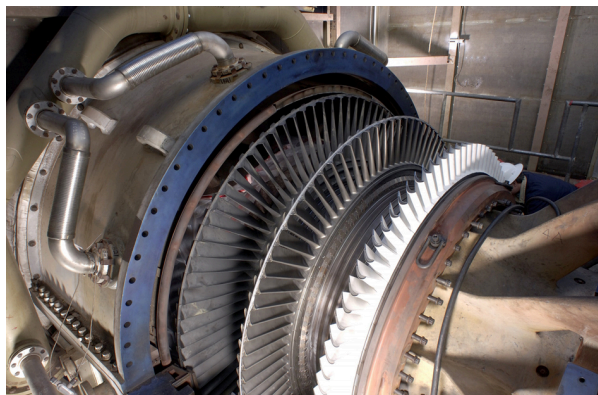
104.7 rad/s is exactly 1000 rpm. We substitute this value for  $\omega$  and the information from the previous example into  $\text{emf}_0 = NAB\omega$ , yielding

$$\begin{aligned} \text{emf}_0 &= NAB\omega \\ &= 200(7.85 \times 10^{-3} \text{ m}^2)(1.25 \text{ T})(104.7 \text{ rad/s}) \\ &= 206 \text{ V} \end{aligned} \quad 23.23$$

**Discussion**

The maximum emf is greater than the average emf of 131 V found in the previous example, as it should be.

In real life, electric generators look a lot different than the figures in this section, but the principles are the same. The source of mechanical energy that turns the coil can be falling water (hydropower), steam produced by the burning of fossil fuels, or the kinetic energy of wind. [Figure 23.24](#) shows a cutaway view of a steam turbine; steam moves over the blades connected to the shaft, which rotates the coil within the generator.



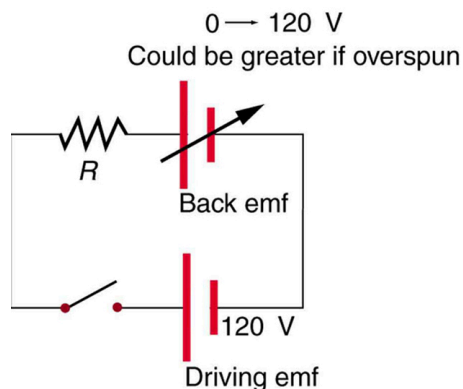
**Figure 23.24** Steam turbine/generator. The steam produced by burning coal impacts the turbine blades, turning the shaft which is connected to the generator. (credit: Nabonaco, Wikimedia Commons)

Generators illustrated in this section look very much like the motors illustrated previously. This is not coincidental. In fact, a motor becomes a generator when its shaft rotates. Certain early automobiles used their starter motor as a generator. In [Back Emf](#), we shall further explore the action of a motor as a generator.

## 23.6 Back Emf

It has been noted that motors and generators are very similar. Generators convert mechanical energy into electrical energy, whereas motors convert electrical energy into mechanical energy. Furthermore, motors and generators have the same construction. When the coil of a motor is turned, magnetic flux changes, and an emf (consistent with Faraday's law of induction) is induced. The motor thus acts as a generator whenever its coil rotates. This will happen whether the shaft is turned by an external input, like a belt drive, or by the action of the motor itself. That is, when a motor is doing work and its shaft is turning, an emf is generated. Lenz's law tells us the emf opposes any change, so that the input emf that powers the motor will be

opposed by the motor's self-generated emf, called the **back emf** of the motor. (See [Figure 23.25](#).)



**Figure 23.25** The coil of a DC motor is represented as a resistor in this schematic. The back emf is represented as a variable emf that opposes the one driving the motor. Back emf is zero when the motor is not turning, and it increases proportionally to the motor's angular velocity.

Back emf is the generator output of a motor, and so it is proportional to the motor's angular velocity  $\omega$ . It is zero when the motor is first turned on, meaning that the coil receives the full driving voltage and the motor draws maximum current when it is on but not turning. As the motor turns faster and faster, the back emf grows, always opposing the driving emf, and reduces the voltage across the coil and the amount of current it draws. This effect is noticeable in a number of situations. When a vacuum cleaner, refrigerator, or washing machine is first turned on, lights in the same circuit dim briefly due to the  $IR$  drop produced in feeder lines by the large current drawn by the motor. When a motor first comes on, it draws more current than when it runs at its normal operating speed. When a mechanical load is placed on the motor, like an electric wheelchair going up a hill, the motor slows, the back emf drops, more current flows, and more work can be done. If the motor runs at too low a speed, the larger current can overheat it (via resistive power in the coil,  $P = I^2 R$ ), perhaps even burning it out. On the other hand, if there is no mechanical load on the motor, it will increase its angular velocity  $\omega$  until the back emf is nearly equal to the driving emf. Then the motor uses only enough energy to overcome friction.

Consider, for example, the motor coils represented in [Figure 23.25](#). The coils have a  $0.400\ \Omega$  equivalent resistance and are driven by a  $48.0\ \text{V}$  emf. Shortly after being turned on, they draw a current  $I = V/R = (48.0\ \text{V}) / (0.400\ \Omega) = 120\ \text{A}$  and, thus, dissipate  $P = I^2 R = 5.76\ \text{kW}$  of energy as heat transfer. Under normal operating conditions for this motor, suppose the back emf is  $40.0\ \text{V}$ . Then at operating speed, the total voltage across the coils is  $8.0\ \text{V}$  ( $48.0\ \text{V}$  minus the  $40.0\ \text{V}$  back emf), and the current drawn is  $I = V/R = (8.0\ \text{V}) / (0.400\ \Omega) = 20\ \text{A}$ . Under normal load, then, the power dissipated is  $P = IV = (20\ \text{A})(8.0\ \text{V}) = 160\ \text{W}$ . The latter will not cause a problem for this motor, whereas the former  $5.76\ \text{kW}$  would burn out the coils if sustained.

## 23.7 Transformers

**Transformers** do what their name implies—they transform voltages from one value to another (The term voltage is used rather than emf, because transformers have internal resistance). For example, many cell phones, laptops, video games, and power tools and small appliances have a transformer built into their plug-in unit (like that in [Figure 23.26](#)) that changes  $120\ \text{V}$  or  $240\ \text{V}$  AC into whatever voltage the device uses. Transformers are also used at several points in the power distribution systems, such as illustrated in [Figure 23.27](#). Power is sent long distances at high voltages, because less current is required for a given amount of power, and this means less line loss, as was discussed previously. But high voltages pose greater hazards, so that transformers are employed to produce lower voltage at the user's location.