## Control of Motor Characteristics by Squirrel-Cage Rotor Design

The reactance $X_2$ in an induction motor equivalent circuit represents the referred form of the rotor's leakage reactance. Recall that leakage reactance is the reactance due to the rotor flux lines that do not also couple with the stator windings. In general, the far-

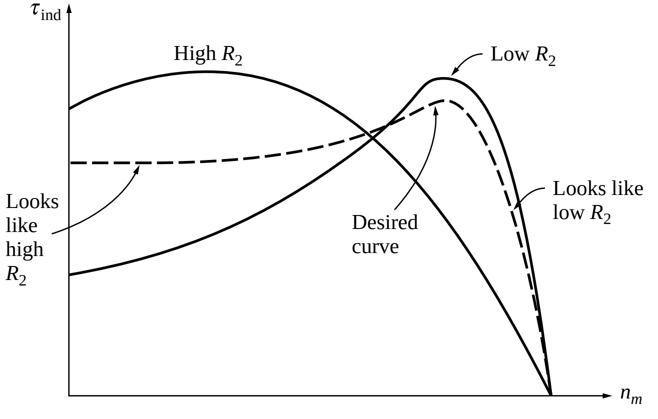


**FIGURE 7–24**
A torque–speed characteristic curve combining high-resistance effects at low speeds (high slip) with low-resistance effects at high speed (low slip).

ther away from the stator a rotor bar or part of a bar is, the greater its leakage reactance, since a smaller percentage of the bar's flux will reach the stator. Therefore, if the bars of a squirrel-cage rotor are placed near the surface of the rotor, they will have only a small leakage flux and the reactance $X_2$ will be small in the equivalent circuit. On the other hand, if the rotor bars are placed deeper into the rotor surface, there will be more leakage and the rotor reactance $X_2$ will be larger.

For example, Figure 7–25*a* is a photograph of a rotor lamination showing the cross section of the bars in the rotor. The rotor bars in the figure are quite large and are placed near the surface of the rotor. Such a design will have a low resistance (due to its large cross section) and a low leakage reactance and $X_2$ (due to the bar's location near the stator). Because of the low rotor resistance, the pullout torque will be quite near

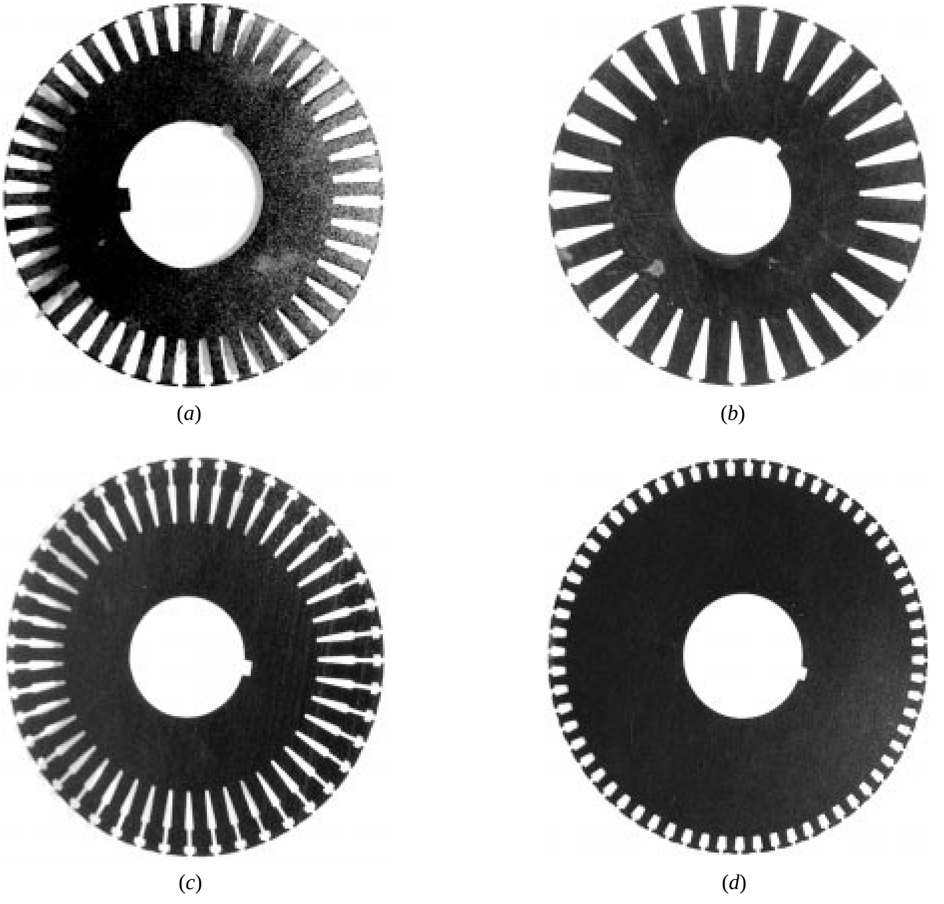


**FIGURE 7–25**
Laminations from typical squirrel-cage induction motor rotors, showing the cross section of the rotor bars: (*a*) NEMA design class A—large bars near the surface; (*b*) NEMA design class B—large, deep rotor bars; (*c*) NEMA design class C—double-cage rotor design; (*d*) NEMA design class D—small bars near the surface. (*Courtesy of MagneTek, Inc.*)

synchronous speed [see Equation (7–53)], and the motor will be quite efficient. Remember that

$$P_{\text{conv}} = (1 - s)P_{\text{AG}} \tag{7–33}$$

so very little of the air-gap power is lost in the rotor resistance. However, since $R_2$ is small, the motor's starting torque will be small, and its starting current will be high. This type of design is called the National Electrical Manufacturers Association (NEMA) design class A. It is more or less a typical induction motor, and its characteristics are basically the same as those of a wound-rotor motor with no extra resistance inserted. Its torque–speed characteristic is shown in Figure 7–26.

Figure 7–25*d*, however, shows the cross section of an induction motor rotor with *small* bars placed near the surface of the rotor. Since the cross-sectional area of the bars is small, the rotor resistance is relatively high. Since the bars are located near the stator, the rotor leakage reactance is still small. This motor is very much like a wound-rotor induction motor with extra resistance inserted into the rotor. Because of the large rotor resistance, this motor has a pullout torque occurring at a high slip, and its starting torque is quite high. A squirrel-cage motor with this type of rotor construction is called NEMA design class D. Its torque–speed characteristic is also shown in Figure 7–26.

## Deep-Bar and Double-Cage Rotor Designs

Both of the previous rotor designs are essentially similar to a wound-rotor motor with a set rotor resistance. How can a *variable* rotor resistance be produced to combine the high starting torque and low starting current of a class D design with the low normal operating slip and high efficiency of a class A design?

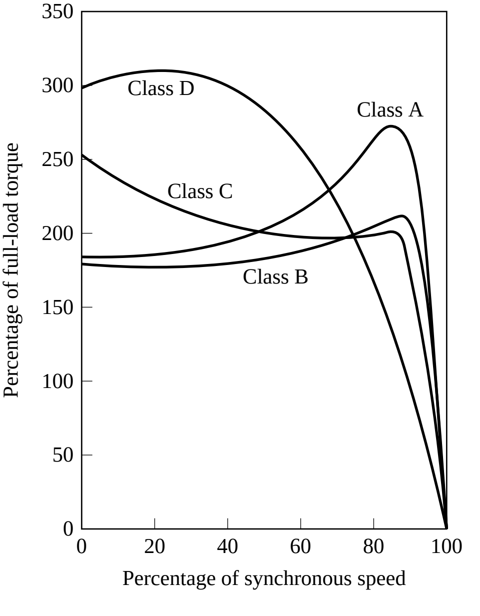


**FIGURE 7–26**
Typical torque–speed curves for different rotor designs.

It is possible to produce a variable rotor resistance by the use of deep rotor bars or double-cage rotors. The basic concept is illustrated with a deep-bar rotor in Figure 7–27. Figure 7–27*a* shows a current flowing through the upper part of a deep rotor bar. Since current flowing in that area is tightly coupled to the stator, the leakage inductance is small for this region. Figure 7–27*b* shows current flowing deeper in the bar. Here, the leakage inductance is higher. Since all parts of the rotor bar are in parallel electrically, the bar essentially represents a series of parallel electric circuits, the upper ones having a smaller inductance and the lower ones having a larger inductance (Figure 7–27*c*).

At low slip, the rotor's frequency is very small, and the reactances of all the parallel paths through the bar are small compared to their resistances. The impedances of all parts of the bar are approximately equal, so current flows through all parts of the bar equally. The resulting large cross-sectional area makes the rotor resistance quite small, resulting in good efficiency at low slips. At high slip (starting conditions), the reactances are large compared to the resistances in the rotor bars, so all the current is forced to flow in the low-reactance part of the bar near the stator. Since the *effective* cross section is lower, the rotor resistance is higher than before. With a high rotor resistance at starting conditions, the starting torque is relatively higher and the starting current is

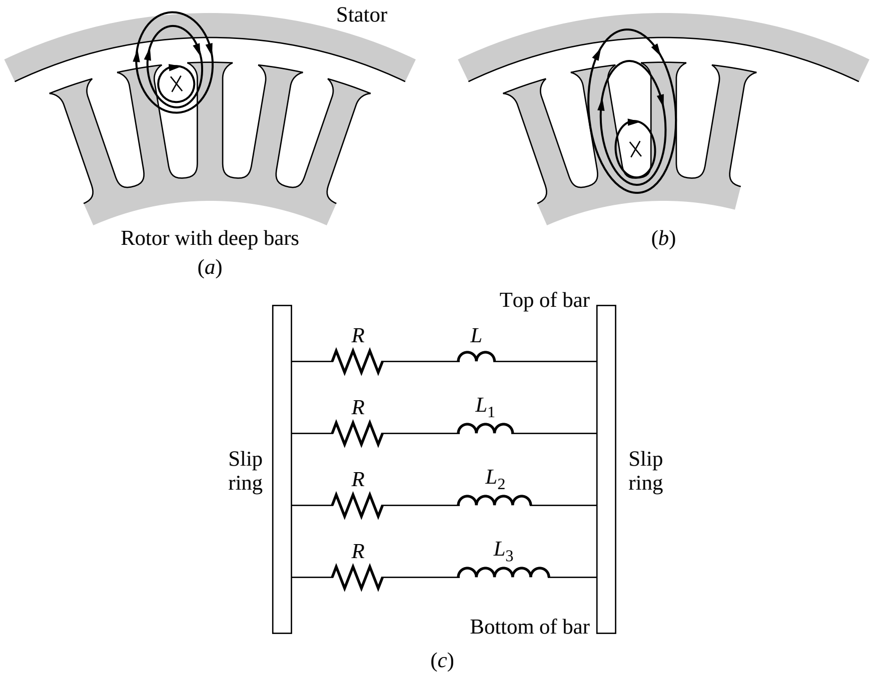


**FIGURE 7–27**
Flux linkage in a deep-bar rotor. (*a*) For a current flowing in the top of the bar, the flux is tightly linked to the stator, and leakage inductance is small; (*b*) for a current flowing in the bottom of the bar, the flux is loosely linked to the stator, and leakage inductance is large; (*c*) resulting equivalent circuit of the rotor bar as a function of depth in the rotor.

relatively lower than in a class A design. A typical torque–speed characteristic for this construction is the design class B curve in Figure 7–26.

A cross-sectional view of a double-cage rotor is shown in Figure 7–25*c*. It consists of a large, low-resistance set of bars buried deeply in the rotor and a small, high-resistance set of bars set at the rotor surface. It is similar to the deep-bar rotor, except that the difference between low-slip and high-slip operation is even more exaggerated. At starting conditions, only the small bar is effective, and the rotor resistance is *quite* high. This high resistance results in a large starting torque. However, at normal operating speeds, both bars are effective, and the resistance is almost as low as in a deep-bar rotor. Double-cage rotors of this sort are used to produce NEMA class B and class C characteristics. Possible torque–speed characteristics for a rotor of this design are designated design class B and design class C in Figure 7–26.

Double-cage rotors have the disadvantage that they are more expensive than the other types of squirrel-cage rotors, but they are cheaper than wound-rotor designs. They allow some of the best features possible with wound-rotor motors (high starting torque with a low starting current and good efficiency at normal operating conditions) at a lower cost and without the need of maintaining slip rings and brushes.

## Induction Motor Design Classes

It is possible to produce a large variety of torque–speed curves by varying the rotor characteristics of induction motors. To help industry select appropriate motors for varying applications in the integral-horsepower range, NEMA in the United States and the International Electrotechnical Commission (IEC) in Europe have defined a series of standard designs with different torque–speed curves. These standard designs are referred to as *design classes*, and an individual motor may be referred to as a design class X motor. It is these NEMA and IEC design classes that were referred to earlier. Figure 7–26 shows typical torque–speed curves for the four standard NEMA design classes. The characteristic features of each standard design class are given below.

**DESIGN CLASS A.** Design class A motors are the standard motor design, with a normal starting torque, a normal starting current, and low slip. The full-load slip of design A motors must be less than 5 percent and must be less than that of a design B motor of equivalent rating. The pullout torque is 200 to 300 percent of the full-load torque and occurs at a low slip (less than 20 percent). The starting torque of this design is at least the rated torque for larger motors and is 200 percent or more of the rated torque for smaller motors. The principal problem with this design class is its extremely high inrush current on starting. Current flows at starting are typically 500 to 800 percent of the rated current. In sizes above about 7.5 hp, some form of reduced-voltage starting must be used with these motors to prevent voltage dip problems on starting in the power system they are connected to. In the past, design class A motors were the standard design for most applications below 7.5 hp and above about 200 hp, but they have largely been replaced by design class B motors in recent years. Typical applications for these motors are driving fans, blowers, pumps, lathes, and other machine tools.

**DESIGN CLASS B.** Design class B motors have a normal starting torque, a lower starting current, and low slip. This motor produces about the same starting torque as the class A motor with about 25 percent less current. The pullout torque is greater than or equal to 200 percent of the rated load torque, but less than that of the class A design because of the increased rotor reactance. Rotor slip is still relatively low (less than 5 percent) at full load. Applications are similar to those for design A, but design B is preferred because of its lower starting-current requirements. Design class B motors have largely replaced design class A motors in new installations.

**DESIGN CLASS C.** Design class C motors have a high starting torque with low starting currents and low slip (less than 5 percent) at full load. The pullout torque is slightly lower than that for class A motors, while the starting torque is up to 250 percent of the full-load torque. These motors are built from double-cage rotors, so they are more expensive than motors in the previous classes. They are used for high-starting-torque loads, such as loaded pumps, compressors, and conveyors.

**DESIGN CLASS D.** Design class D motors have a very high starting torque (275 percent or more of the rated torque) and a low starting current, but they also have a high slip at full load. They are essentially ordinary class A induction motors, but with the rotor bars made smaller and with a higher-resistance material. The high rotor resistance shifts the peak torque to a very low speed. It is even possible for the highest torque to occur at zero speed (100 percent slip). Full-load slip for these motors is quite high because of the high rotor resistance. It is typically 7 to 11 percent, but may go as high as 17 percent or more. These motors are used in applications requiring the acceleration of extremely high-inertia-type loads, especially large flywheels used in punch presses or shears. In such applications, these motors gradually accelerate a large flywheel up to full speed, which then drives the punch. After a punching operation, the motor then reaccelerates the flywheel over a fairly long time for the next operation.

In addition to these four design classes, NEMA used to recognize design classes E and F, which were called *soft-start* induction motors (see Figure 7–28). These designs were distinguished by having very low starting currents and were used for low-starting-torque loads in situations where starting currents were a problem. These designs are now obsolete.

**Example 7–6.** A 460-V, 30-hp, 60-Hz, four-pole, Y-connected induction motor has two possible rotor designs, a single-cage rotor and a double-cage rotor. (The stator is identical for either rotor design.) The motor with the single-cage rotor may be modeled by the following impedances in ohms per phase referred to the stator circuit:

$$
\begin{aligned}
R_1 &= 0.641\ \Omega \qquad R_2 = 0.300\ \Omega \\
X_1 &= 0.750\ \Omega \qquad X_2 = 0.500\ \Omega \qquad X_M = 26.3\ \Omega
\end{aligned}
$$

The motor with the double-cage rotor may be modeled is a tightly coupled, high-resistance outer cage in parallel with a loosely coupled, low-resistance inner cage (similar to the structure of Figure 7–25*c*). The stator and magnetization resistance and reactances will be identical with those in the single-cage design.

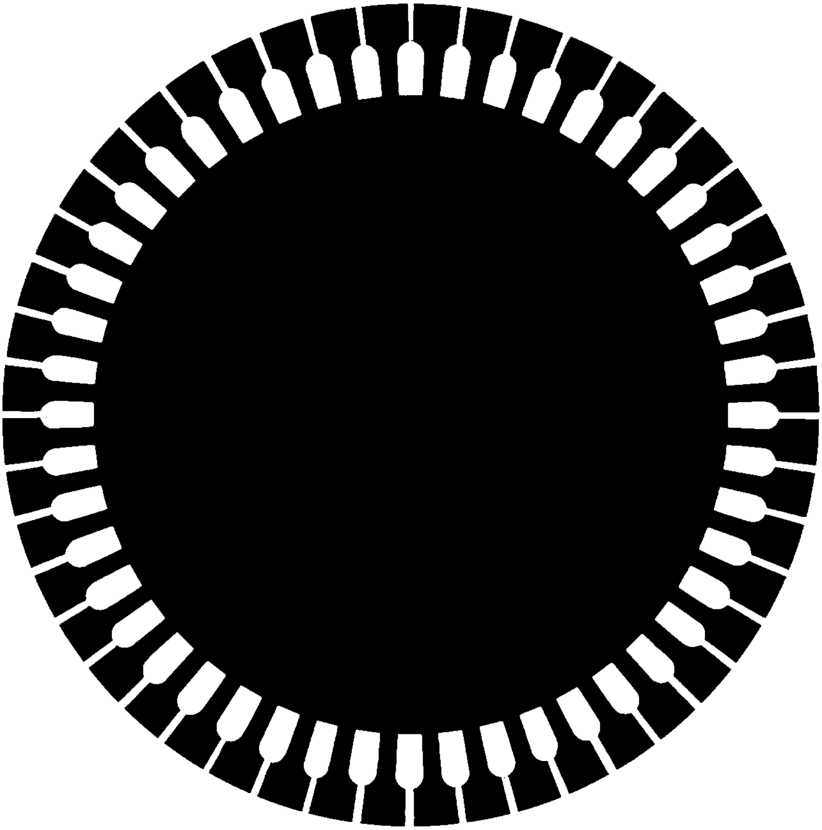

**FIGURE 7–28**
Rotor cross section, showing the construction of the former design class F induction motor. Since the rotor bars are deeply buried, they have a very high leakage reactance. The high leakage reactance reduces the starting torque and current of this motor, so it is called a *soft-start design*. (*Courtesy of MagneTek, Inc.*)

The resistance and reactance of the rotor outer cage are:

$$R_{2_0} = 3.200\ \Omega \qquad X_{2_0} = 0.500\ \Omega$$

Note that the resistance is high because the outer bar has a small cross section, while the reactance is the same as the reactance of the single-cage rotor, since the outer cage is very close to the stator, and the leakage reactance is small.

The resistance and reactance of the inner cage are

$$R_{2i} = 0.400\ \Omega \qquad X_{2i} = 3.300\ \Omega$$

Here the resistance is low because the bars have a large cross-sectional area, but the leakage reactance is quite high.

Calculate the torque–speed characteristics associated with the two rotor designs. How do they compare?

***Solution.*** The torque–speed characteristic of the motor with the single-cage rotor can be calculated in exactly the same manner as Example 7–5. The torque–speed characteristic of the motor with the double-cage rotor can also be calculated in the same fashion, *except* that at each slip the rotor resistance and reactance will be the parallel combination of the impedances of the inner and outer cages. At low slips, the rotor reactance will be relatively unimportant, and the large inner cage will play a major part in the machine's operation. At high slips, the high reactance of the inner cage almost removes it from the circuit.

A MATLAB m-file to calculate and plot the two torque–speed characteristics is shown below:

```
% M-file: torque_speed_2.m
% M-file create and plot of the torque–speed curve of an
%   induction motor with a double-cage rotor design.

% First, initialize the values needed in this program.
r1 = 0.641;                  % Stator resistance
x1 = 0.750;                  % Stator reactance
r2 = 0.300;                  % Rotor resistance for single-
                             %   cage motor
r2i = 0.400;                 % Rotor resistance for inner
                             %   cage of double-cage motor
r2o = 3.200;                 % Rotor resistance for outer
                             %   cage of double-cage motor
x2 = 0.500;                  % Rotor reactance for single-
                             %   cage motor
x2i = 3.300;                 % Rotor reactance for inner
                             %   cage of double-cage motor
x2o = 0.500;                 % Rotor reactance for outer
                             %   cage of double-cage motor
xm = 26.3;                   % Magnetization branch reactance
v_phase = 460 / sqrt(3);     % Phase voltage
n_sync = 1800;               % Synchronous speed (r/min)
w_sync = 188.5;              % Synchronous speed (rad/s)

% Calculate the Thevenin voltage and impedance from Equations
% 7-41a and 7-43.
v_th = v_phase * ( xm / sqrt(r1^2 + (x1 + xm)^2) );
z_th = ((j*xm) * (r1 + j*x1)) / (r1 + j*(x1 + xm));
r_th = real(z_th);
x_th = imag(z_th);

% Now calculate the motor speed for many slips between
% 0 and 1.  Note that the first slip value is set to
% 0.001 instead of exactly 0 to avoid divide-by-zero
% problems.
s = (0:1:50) / 50;           % Slip
s(1) = 0.001;                % Avoid division-by-zero
nm = (1 - s) * n_sync;       % Mechanical speed
```

```
% Calculate torque for the single-cage rotor.
for ii = 1:51
  t_ind1(ii) = (3 * v_th^2 * r2 / s(ii)) / ...
       (w_sync * ((r_th + r2/s(ii))^2 + (x_th + x2)^2) );
end

% Calculate resistance and reactance of the double-cage
% rotor at this slip, and then use those values to
% calculate the induced torque.
for ii = 1:51
  y_r = 1/(r2i + j*s(ii)*x2i) + 1/(r2o + j*s(ii)*x2o);
  z_r = 1/y_r;              % Effective rotor impedance
  r2eff = real(z_r);        % Effective rotor resistance
  x2eff = imag(z_r);        % Effective rotor reactance

  % Calculate induced torque for double-cage rotor.
  t_ind2(ii) = (3 * v_th^2 * r2eff / s(ii)) / ...
       (w_sync * ((r_th + r2eff/s(ii))^2 + (x_th + x2eff)^2) );
end

% Plot the torque–speed curves
plot(nm,t_ind1,'Color','k','LineWidth',2.0);
hold on;
plot(nm,t_ind2,'Color','k','LineWidth',2.0,'LineStyle','-.');
xlabel('\itn_{m}','Fontweight','Bold');
ylabel('\tau_{ind}','Fontweight','Bold');
title ('Induction motor torque–speed characteristics', ...
    'Fontweight','Bold');
legend ('Single-Cage Design','Double-Cage Design');
grid on;
hold off;
```

The resulting torque–speed characteristics are shown in Figure 7–29. Note that the double-cage design has a slightly higher slip in the normal operating range, a smaller maximum torque and a higher starting torque compared to the corresponding single-cage rotor design. This behavior matches our theoretical discussions in this section. ●

## 7.7 TRENDS IN INDUCTION MOTOR DESIGN

The fundamental ideas behind the induction motor were developed during the late 1880s by Nicola Tesla, who received a patent on his ideas in 1888. At that time, he presented a paper before the American Institute of Electrical Engineers [AIEE, predecessor of today's Institute of Electrical and Electronics Engineers (IEEE)] in which he described the basic principles of the wound-rotor induction motor, along with ideas for two other important ac motors—the synchronous motor and the reluctance motor.

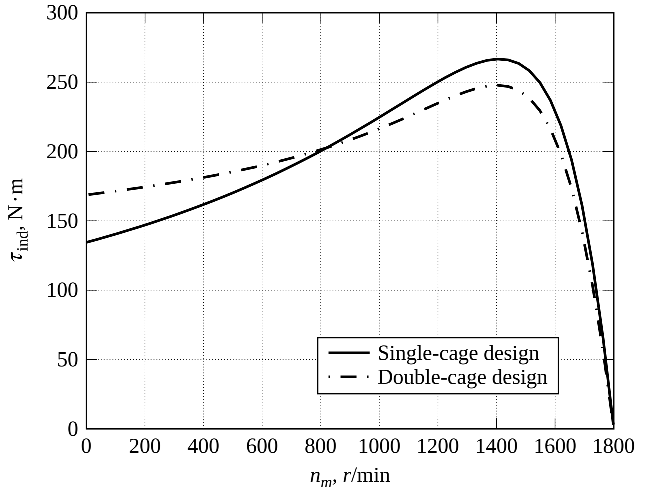


**FIGURE 7–29**
Comparison of torque–speed characteristics for the single- and double-cage rotors of Example 7–6.