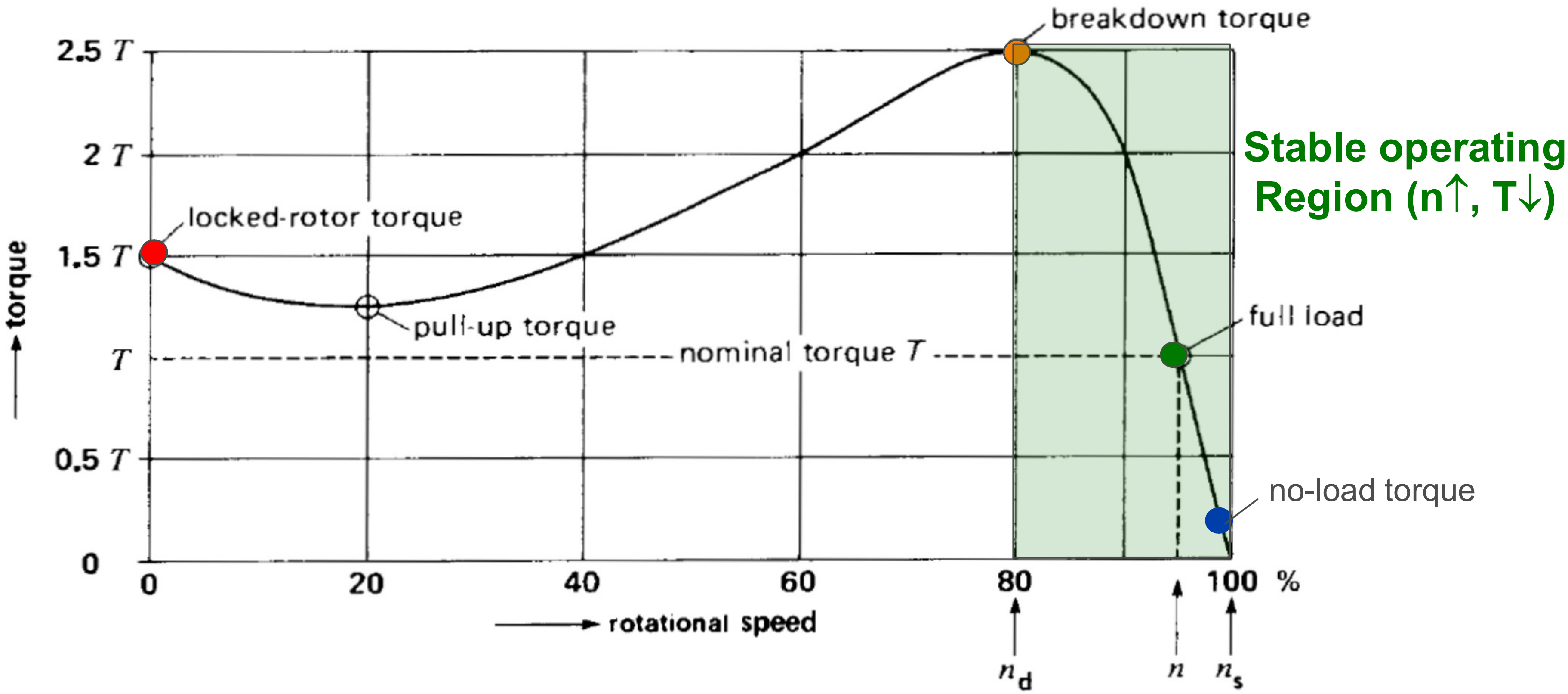
Torque-Speed Curve

$$s = \frac{n_s - n}{n_s}, \quad P_r = |I_1|^2 \frac{R_2}{s}, \quad I_1 = \frac{E_g}{Z_1 + \frac{R_2}{s}}$$

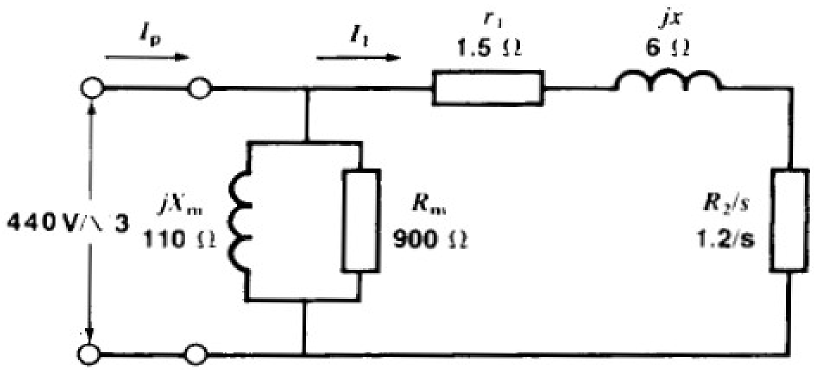
$$T = \frac{9.55 P_r}{n_s} = \frac{9.55 |E_g|^2 R_2}{\left| Z_1 + \frac{R_2}{s} \right|^2 s n_s} = \frac{9.55 |E_g|^2 R_2}{\left| Z_1 + \frac{R_2 n_s}{n_s - n} \right|^2 (n_s - n)}$$



- The curve is nearly linear between no-load and full-load because s is small and R_2/s is big (Z_1 is ignored)

$$I_1 \approx sE_g / R_2 \qquad T \approx \frac{9.55 |E_g|^2}{R_2 n_s^2}(n_s - n) = \frac{9.55 |E_g|^2}{R_2 n_s} s$$

Two practical squirrel-cage induction motors



Motor rating:

5 hp, 60 Hz, 1800 r/min, 440 V, 3-phase
full-load current: 7 A
locked-rotor current: 39 A

r_1 = stator resistance 1.5 Ω

r_2 = rotor resistance 1.2 Ω

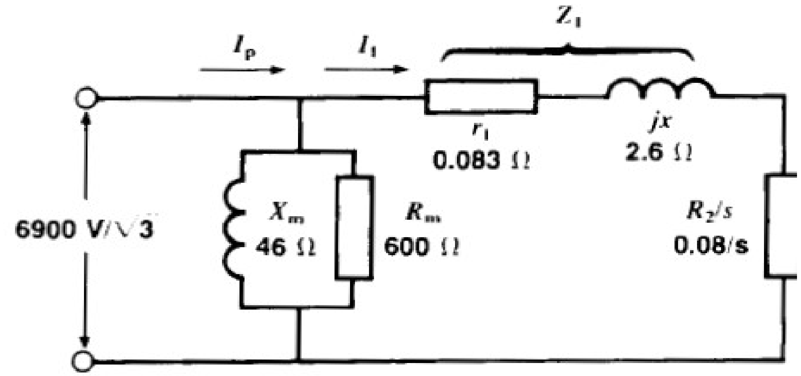
jx = total leakage reactance 6 Ω

jX_m = magnetizing reactance 110 Ω

R_m = no-load losses resistance 900 Ω

(The no-load losses include the iron losses plus windage and friction losses.)

Figure 15.12
Equivalent circuit of a 5 hp squirrel-cage induction motor. Because there is no external resistor in the rotor, $R_2 = r_2$.



Motor rating:

5000 hp, 60 Hz, 600 r/min, 6900 V, 3-phase
full-load current: 358 A
locked-rotor current: 1616 A

r_1 = stator resistance 0.083 Ω

r_2 = rotor resistance 0.080 Ω

jx = total leakage reactance 2.6 Ω

jX_m = magnetizing reactance 46 Ω

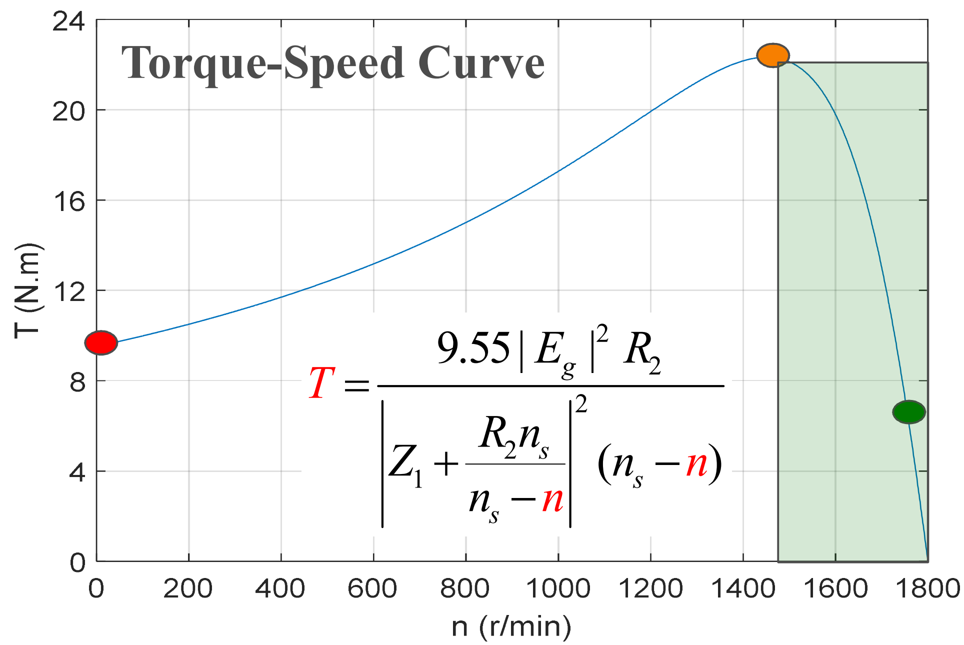
R_m = no-load losses resistance 600 Ω

The no-load losses of 26.4 kW (per phase) consist of 15 kW for windage and friction and 11.4 kW for the iron losses.

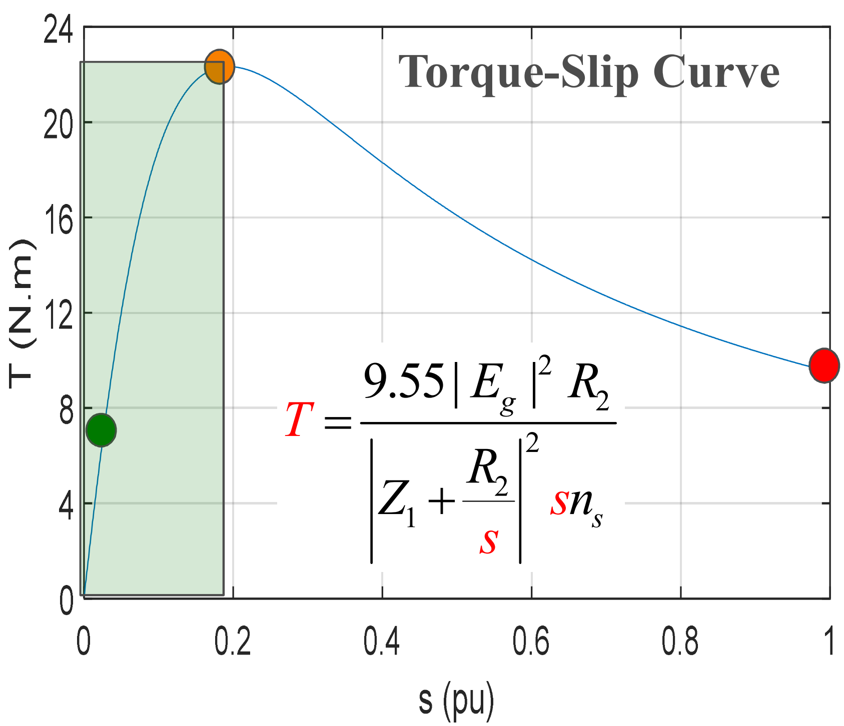
Figure 15.13
Equivalent circuit of a 5000 hp squirrel-cage induction motor. Although this motor is 1000 times more powerful than the motor in Fig. 15.12, the circuit diagram remains the same.

The 5 hp induction motor

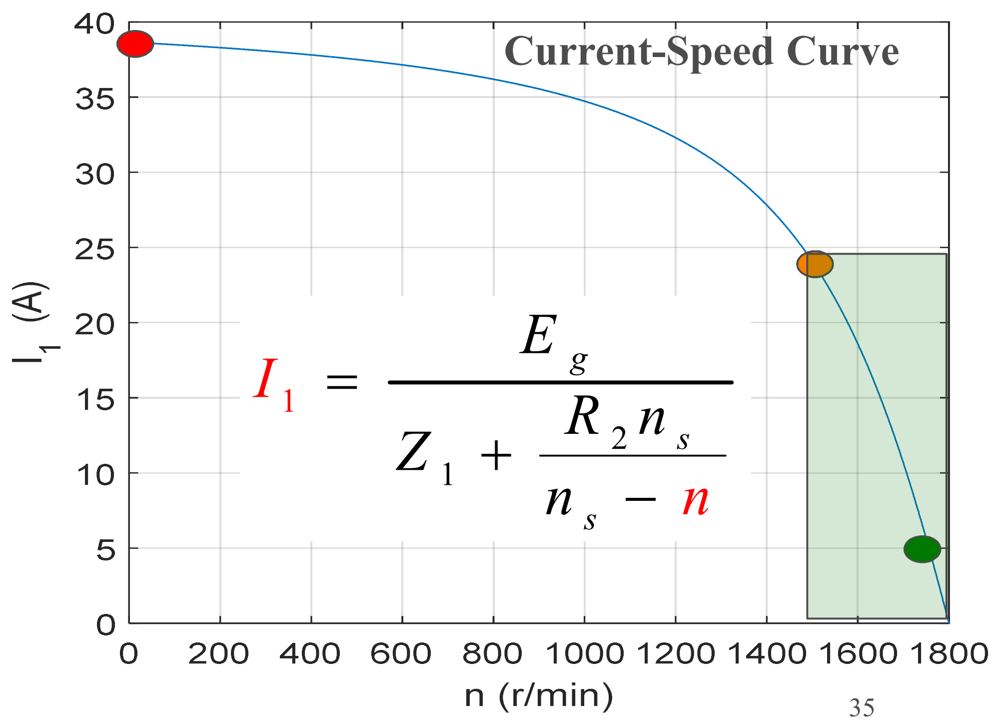
E_g=440/1.73 V
R_2=1.2 Ω
Z_1=1.5+6j Ω
n_s=1800 r/min



$$T=\frac{9.55|E_g|^2 R_2}{\left|Z_1+\frac{R_2 n_s}{n_s-n}\right|^2 (n_s-n)}$$



$$T=\frac{9.55|E_g|^2 R_2}{\left|Z_1+\frac{R_2}{s}\right|^2 s n_s}$$



$$I_1=\frac{E_g}{Z_1+\frac{R_2 n_s}{n_s-n}}$$

Torque-Speed Curve: 5 hp motor

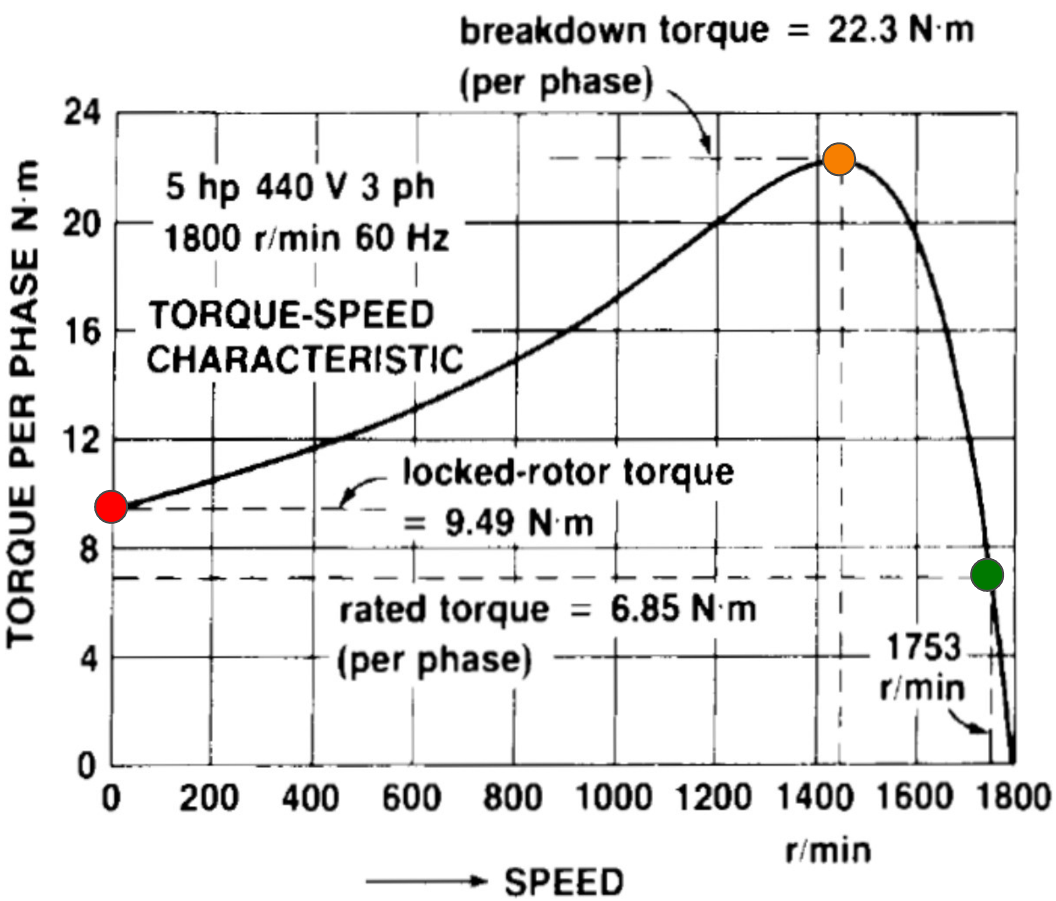


TABLE 15A TORQUE-SPEED CHARACTERISTIC

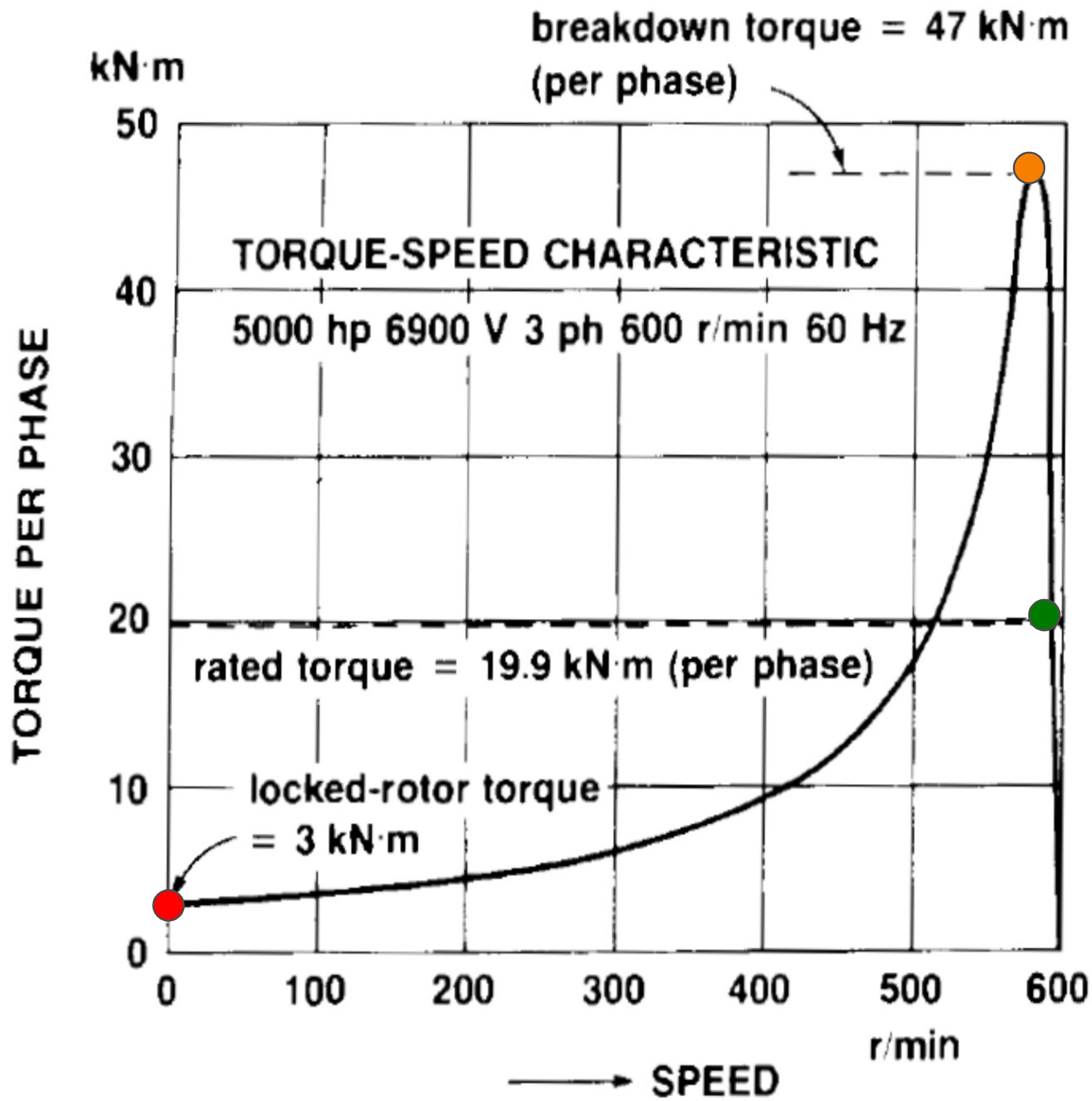
5 hp, 440 V, 1800 r/min, 60 Hz squirrel-cage induction motor

s	I_1	P_r	T	n
	[A]	[W]	[N·m]	[r/min]
0.0125	2.60	649	3.44	1777
0.025	5.09	1243	6.60	1755
0.026	5.29	1291	6.85	1753
0.05	9.70	2256	12.0	1710
0.1	17.2	3547	18.8	1620
0.2	26.4	4196	22.3	1440
0.4	33.9	3441	18.3	1080
0.6	36.6	2674	14.2	720
0.8	37.9	2150	11.4	360
1	38.6	1788	9.49	0

The rated power of 5 hp is developed at $s = 0.026$.

- When the motor is stalled, i.e. locked-rotor condition, the current is 5-6 times the full-load current, making I^2R losses 25-36 times higher than normal, so the rotor must never remain locked for more than a few second
- Small motors (15 hp and less) develop their breakdown torque at about 80% of n_s

Torque-Speed Curve: 5000 hp motor



Big motors (>1500 hp) :

- Relatively low starting (locked-rotor) torque
- Breakdown torque at about 98% of n_s
- Rated n is close to n_s

Effect of rotor resistance (5 hp induction motor)

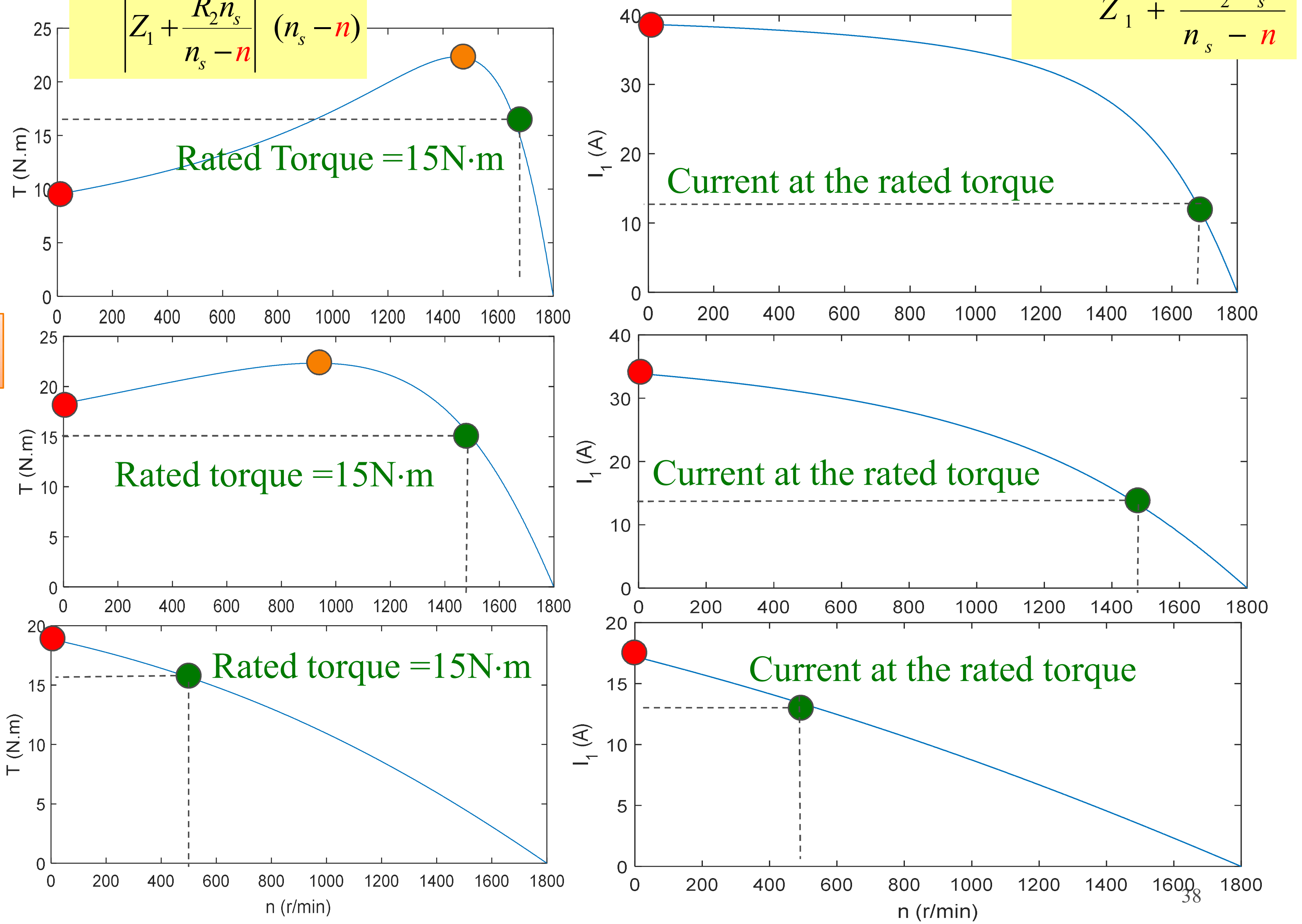
$$T = \frac{9.55 |E_g|^2 R_2}{\left| Z_1 + \frac{R_2 n_s}{n_s - n} \right|^2 (n_s - n)}$$

$$I_1 = \frac{E_g}{Z_1 + \frac{R_2 n_s}{n_s - n}}$$

R_2

$2.5R_2$

$10R_2$



Effects of rotor resistance

- When $R_2 \uparrow$, starting (locked-rotor) torque $T_{LR} \uparrow$, starting current $I_{1,LR} \downarrow$, and breakdown torque T_b remains the same

$$T_{LR} = \frac{9.55|E_g|^2 R_2}{|Z_1 + R_2|^2 n_s} \approx \frac{9.55|E_g|^2}{|Z_1|^2 n_s} R_2 \qquad I_{1,LR} = \frac{E_g}{Z_1 + R_2} \qquad P_{jr} = |I_1|^2 R_2 \qquad T_b = \frac{9.55|E_g|^2}{4n_s|Z_1|\cos^2\frac{\alpha}{2}}$$

- Pros & Cons with a high rotor resistance R_2
  - It produces a high starting torque T_{LR} and a relatively low starting current $I_{1,LR}$
  - However, because the torque-speed curve becomes flat it produces a rapid fall-off in speed with increasing load around the rated torque, and the motor has high copper losses and low efficiency and tends to overheat
- Solution
  - For a squirrel-cage induction motor, design the rotor bars in a special way so that the rotor resistance R_2 is high at starting and low under normal operations
  - If the rotor resistance needs to be varied over a wide range, a wound-rotor motor needs to be used.

Asynchronous generator

Connect the 5 hp, 1800 r/min, 60Hz motor to a 440 V, 3-phase line and drive it at a speed of 1845 r/min

$s=(n_s\text{-n})/n_s=(1800\text{-}1845)/1800=$ $-0.025<0$

$R_2/\text{s}=1.2/(-0.025)=$ -48Ω <0

The negative resistance indicates the actual power flow from the rotor to the stator

Power flow from the rotor to the stator:

$|E|=440/1.73=254$ V

$|I_1|=|E|/\ |-48+1.5+\text{j}6|=254/46.88=5.42$A

$P_r=|I_1|^2R_2/s=$ -1410 W (in fact, rotor → stator)

Mech. power & torque inputs to the shaft:

$P_{jr}=|I_1|^2R_2=35.2$ W

$P_m=P_r+P_{jr}=1410+35.2=1445$W

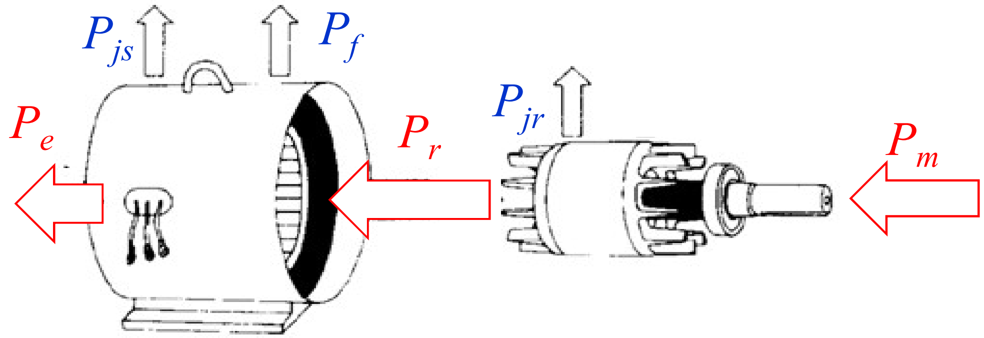
$T=3\times 9.55\times P_m/n=22.3$ N·m

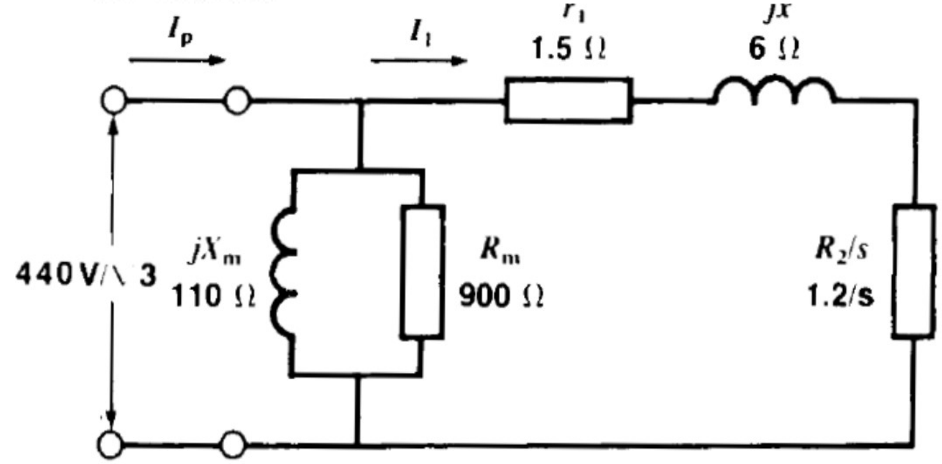
Total active power delivered to the line:

$P_{js}=|I_1|^2r_1=44.1$ W, $P_f=|E|^2/R_{\text{m}}=71.1$ W

$P_e=P_r-P_{js}-P_f=1410\text{-}44.1\text{-}71.7=1294$ W

$P_{3\phi}=3P_e=3882$W





Reactive power absorbed from the line:

$Q_{3\phi}=(|I_1|^2x+|E|^2/X_{\text{m}})\times 3=(176+586)\times 3=2286$ var

Complex power delivered to the line:

$S_{3\phi}=P_{3\phi}-Q_{3\phi}=3882-\text{j}2286$ VA

$\cos\theta=86.2\%$

Efficiency of this asynchronous generator

$\eta=P_e/P_m=1294/1445=89.5\%$