Induction Motors

EE 340
Where does the power generated go?

The electric energy generated purchased by consumers for different needs. This energy is converted to different forms:

- Lighting (indoor/outdoor – CFL, incandescent, LED, Halogen...)
- Heating (electric water heaters, clothes dryers, electric stoves and ovens)
- Power supply of electronic devices (computers, TV, DVD, battery chargers, home automation, etc...)
- Industrial (arc furnaces, welders, manufacturing processes....)
- Conversion to mechanical power by motors (pumps, fans, HVAC, refrigeration – compressors, power tools, food processors, escalators, elevators, ....)
Types of Electric Motors

- DC Motors
  - Shunt motor
  - Separately Excited motor
  - Series Motor
  - Permanent Magnet DC (PMDC)
  - Compounded motor

- AC Motors
  - Induction motor
  - Synchronous motor

- Other Motors
  - Stepper motor
  - Brushless DC motor
  - Hysteresis motor
  - Reluctance motor
  - Universal motor
3-Phase induction machine construction

• 3 stator windings (uniformly distributed as in a synchronous generator)
• Two types of rotor:
  – Squirrel cage
  – Wound rotor (with slip rings)
The basic idea of an electric motor is to generate two magnetic fields: rotor magnetic field and stator magnetic field. The rotor will constantly be turning to align its magnetic field with the stator field.

The 3-phase set of currents, each of equal magnitude and with a phase difference of 120°, flow in the stator windings and generate a rotating field will constant magnitude.
Consider a simple 3-phase stator containing three coils, each 120° apart. Such a winding will produce only one north and one south magnetic pole; therefore, this motor would be called a two pole motor.

Assume that the currents in three coils are:

\[
\begin{align*}
    i_{a'}(t) &= I_M \sin \omega t \\
    i_{b'}(t) &= I_M \sin (\omega t - 120^\circ) \\
    i_{c'}(t) &= I_M \sin (\omega t - 240^\circ)
\end{align*}
\]

The magnetic flux density in the stator at any arbitrary moment is given by

\[
B_{\text{net}}(t) = B_{a'}(t) + B_{b'}(t) + B_{c'}(t)
\]
The rotating magnetic field

• The net magnetic field has a constant magnitude and rotates **counterclockwise** at the angular velocity $\omega$.

• The stator rotating magnetic field can be represented as a north pole and a south pole.

• For a two pole machine, $f_e (Hz) = f_m (rps) = \frac{1}{60} n_s (rpm)$

• For a $p$-pole machine, $f_e (Hz) = \frac{p}{2} f_m (rps) = \frac{p}{120} n_s (rpm)$
Principle of operation

- This rotating magnetic field cuts the rotor windings and produces an induced voltage in the rotor windings.
- Due to the fact that the rotor windings are short circuitcd, for both squirrel cage and wound-rotor, and induced current flows in the rotor windings.
- The rotor current produces another magnetic field.
- A torque is produced as a result of the interaction of those two magnetic fields.

\[ \tau_{\text{ind}} = kB_R \times B_s \]

Where \( \tau_{\text{ind}} \) is the induced torque and \( B_R \) and \( B_S \) are the magnetic flux densities of the rotor and the stator respectively.
Induction motor speed

• At what speed will the induction motor run?
  – Can the induction motor run at the synchronous speed, why?
  – If rotor runs at the synchronous speed, then it will appear stationary to the rotating magnetic field and the rotating magnetic field will not cut the rotor. So, no induced current will flow in the rotor and no rotor magnetic flux will be produced so no torque is generated and the rotor speed will fall below the synchronous speed.
  – When the speed falls, the rotating magnetic field will cut the rotor windings and a torque is produced.
Induction motor speed

• So, the induction motor will always run at a speed lower than the synchronous speed.
• The difference between the motor speed and the synchronous speed is called the *slip speed*.

\[ n_{slip} = n_{sync} - n_m \]

Where:
- \( n_{slip} \) = slip speed
- \( n_{sync} \) = speed of the magnetic field
- \( n_m \) = mechanical shaft speed of the motor
The Slip

Where \( s \) is the slip

Notice that: if the rotor runs at synchronous speed

\[ s = 0 \]

if the rotor is stationary

\[ s = 1 \]

Slip may be expressed as a percentage by multiplying the above by 100. Notice that the slip is a ratio and doesn't have units.
Both induction motor and transformer works on the principle of induced voltage

- Transformer: voltage applied to the primary windings produce an induced voltage in the secondary windings
- Induction motor: voltage applied to the stator windings produce an induced voltage in the rotor windings
- The difference is that, in the case of the induction motor, the secondary windings can move
- Due to the rotation of the rotor, the induced voltage in it does not have the same frequency of the stator voltage.
The frequency of the voltage induced in the rotor is given by

\[ f_r = \frac{p \cdot n_{slip}}{120} \]

Where \( f_r \) = the rotor frequency (Hz)
\( p \) = number of stator poles
\( n_{slip} \) = slip speed (rpm)

\[ f_r = \frac{p(n_{syn} - n_m)}{120} = \frac{p \cdot s \cdot n_{syn}}{120} = s f_e \]
• What would be the frequency of the rotor’s induced voltage at any speed \( n_m \)?

\[
f_r = s \cdot f_e
\]

• When the rotor is blocked \( (s=1) \), the frequency of the induced voltage is equal to the supply frequency.

• On the other hand, if the rotor runs at synchronous speed \( (s = 0) \), the frequency will be zero.
Torque

• While the input to the induction motor is electrical power, its output is mechanical power and for that we should know some terms and quantities related to mechanical power.

• Any mechanical load applied to the motor shaft will introduce a torque on the motor shaft. This torque is related to the motor output power and the rotor speed

\[ \tau_{load} = \frac{P_{out}}{\omega_m} \text{ N.m} \]

and

\[ \omega_m = \frac{2\pi n_m}{60} \text{ rad/s} \]
Another unit used to measure mechanical power is the horse power.

It is used to refer to the mechanical output power of the motor.

Since we, as an electrical engineers, deal with watts as a unit to measure electrical power, there is a relation between horse power and watts:

\[ \text{hp} = 746 \text{ watts} \]
A 208 V, 10 hp, four pole, 60 Hz, Y-connected induction motor has a full-load slip of 5 percent.

1. What is the synchronous speed of this motor?
2. What is the rotor speed of this motor at rated load?
3. What is the rotor frequency of this motor at rated load?
4. What is the shaft torque of this motor at rated load?
Solution

1. \[ n_{\text{sync}} = \frac{120 f_e}{P} = \frac{120(60)}{4} = 1800 \text{ rpm} \]

2. \[ n_m = (1 - s)n_s \]
\[ = (1 - 0.05) \times 1800 = 1710 \text{ rpm} \]

3. \[ f_r = sf_e = 0.05 \times 60 = 3 \text{ Hz} \]

4. \[ \tau_{\text{load}} = \frac{P_{\text{out}}}{\omega_m} = \frac{P_{\text{out}}}{2\pi \frac{n_m}{60}} \]
\[ = \frac{10 \text{ hp} \times 746 \text{ watt} / \text{hp}}{1710 \times 2\pi \times (1/60)} = 41.7 \text{ N.m} \]
The induction motor is similar to the transformer with the exception that its secondary windings are free to rotate. It is easier if we can combine these two circuits in one circuit but there are some difficulties:
Equivalent Circuit

• When the rotor is locked (or blocked), i.e. \( s = 1 \), the largest voltage and rotor frequency are induced in the rotor, Why?

• On the other side, if the rotor rotates at synchronous speed, i.e. \( s = 0 \), the induced voltage and frequency in the rotor will be equal to zero, Why?

\[
E_R = sE_{R0}
\]

Where \( E_{R0} \) is the largest value of the rotor’s induced voltage obtained at \( s = 1 \) (locked rotor)
Equivalent Circuit

• The same is true for the frequency, i.e.

\[ f_r = s f_e \]

• It is known that

\[ X = \omega L = 2\pi f L \]

• So, as the frequency of the induced voltage in the rotor changes, the reactance of the rotor circuit also changes

Where \( X_{r0} \) is the rotor reactance at the supply frequency.

\[ X_r = \omega_r L_r = 2\pi f_r L_r \]

\[ = 2\pi s f_e L_r \]

\[ = sX_{r0} \]
Then, we can draw the rotor equivalent circuit as follows:

\[ E_R = sE_{R0} \]

\[ jX_R = jsX_{R0} \]

Where \( E_R \) is the induced voltage in the rotor and \( R_R \) is the rotor resistance.
Now we can calculate the rotor current as

\[ I_R = \frac{E_R}{(R_R + jX_R)} \]

\[ = \frac{sE_{R0}}{(R_R + jsX_{R0})} \]

Dividing both the numerator and denominator by \( s \) so nothing changes we get

\[ I_R = \frac{E_{R0}}{(R_R + jX_{R0})} \]

Where \( E_{R0} \) is the induced voltage and \( X_{R0} \) is the rotor reactance at blocked rotor condition (\( s = 1 \))
Equivalent Circuit

- Now we can have the rotor equivalent circuit
Now as we managed to solve the induced voltage and different frequency problems, we can combine the stator and rotor circuits in one equivalent circuit.

Where

\[ X_2 = a_{\text{eff}}^2 X_{R0} \]

\[ R_2 = a_{\text{eff}}^2 R_R \]

\[ I_2 = \frac{I_R}{a_{\text{eff}}} \]

\[ E_1 = a_{\text{eff}} E_{R0} \]

\[ a_{\text{eff}} = \frac{N_S}{N_R} \]
Power losses in Induction machines

• Copper losses
  – Copper loss in the stator \((P_{SCL}) = I_1^2R_1\)
  – Copper loss in the rotor \((P_{RCL}) = I_2^2R_2\)

• Core loss \((P_{core})\)
• Mechanical power loss due to friction and windage
• How this power flow in the motor?
Power flow in induction motor

\[ P_{in} = \sqrt{3} V_T I_L \cos \theta \]

\[ P_{out} = \tau_{load} \omega_m \]

- \( P_{AG} \) - Air-gap power
- \( P_{conv} \)
- \( \tau_{ind} \omega_m \)
- \( P_{friction \ and \ windage} \)
- \( P_{stray} (P_{misc.}) \)
- \( P_{SCL} \) (Stator copper loss)
- \( P_{core} \) (Core losses)
- \( P_{RCL} \) (Rotor copper loss)
Power relations

\[ P_{in} = \sqrt{3} V_L I_L \cos \theta = 3 V_{ph} I_{ph} \cos \theta \]

\[ P_{SCL} = 3 I_1^2 R_1 \]

\[ P_{AG} = P_{in} - (P_{SCL} + P_{core}) \]

\[ P_{RCL} = 3I_2^2 R_2 \]

\[ P_{conv} = P_{AG} - P_{RCL} \]

\[ P_{out} = P_{conv} - (P_{f+w} + P_{stray}) \]

\[ \tau_{ind} = \frac{P_{conv}}{\omega_m} \]
We can rearrange the equivalent circuit as follows:

\[ \begin{align*}
\mathbf{V}_\phi &\rightarrow I_1 \rightarrow R_1 \rightarrow jX_1 \rightarrow I_2 \rightarrow jX_2 \rightarrow R_2 \rightarrow \frac{R_2(1-s)}{s} \\
I_M &\rightarrow \frac{R_C}{s} \rightarrow jX_M \\
\end{align*} \]

Actual rotor resistance: 
Resistance equivalent to mechanical load:
Power relations

\[ P_{in} = \sqrt{3} V_L I_L \cos \theta = 3 V_{ph} I_{ph} \cos \theta \]

\[ P_{SCL} = 3 I_1^2 R_1 \]

\[ P_{AG} = P_{in} - (P_{SCL} + P_{core}) = P_{conv} + P_{RCL} = 3I_2^2 \frac{R_2}{s} = \frac{P_{RCL}}{s} \]

\[ P_{RCL} = 3I_2^2 R_2 \]

\[ P_{conv} = P_{AG} - P_{RCL} = 3I_2^2 \frac{R_2(1-s)}{s} = \frac{P_{RCL}(1-s)}{s} \]

\[ P_{conv} = (1-s)P_{AG} \]

\[ P_{out} = P_{conv} - (P_{f+w} + P_{stray}) \]

\[ \tau_{ind} = \frac{P_{conv}}{\omega_m} = \frac{(1-s)P_{AG}}{(1-s)\omega_s} \]
Example

A 480-V, 60 Hz, 50-hp, three phase induction motor is drawing 60 A at 0.85 PF lagging. The stator copper losses are 2 kW, and the rotor copper losses are 700 W. The friction and windage losses are 600 W, the core losses are 1800 W, and the stray losses are negligible. Find the following quantities:

1. The air-gap power $P_{AG}$.
2. The power converted $P_{conv}$.
3. The output power $P_{out}$.
4. The efficiency of the motor.
Solution

1. \( P_{in} = \sqrt{3} V_L I_L \cos \theta \)
   \[
   = \sqrt{3} \times 480 \times 60 \times 0.85 = 42.4 \text{ kW}
   \]

   \( P_{AG} = P_{in} - P_{SCL} - P_{core} \)
   \[
   = 42.4 - 2 - 1.8 = 38.6 \text{ kW}
   \]

   \( P_{conv} = P_{AG} - P_{RCL} \)
   \[
   = 38.6 - \frac{700}{1000} = 37.9 \text{ kW}
   \]

2. \( P_{out} = P_{conv} - P_{F&W} \)
   \[
   = 37.9 - \frac{600}{1000} = 37.3 \text{ kW}
   \]

   \( \eta = \frac{P_{out}}{P_{in}} \times 100\% \)
   \[
   \eta = \frac{37.3}{42.4} \times 100 = 88\%
   \]

3. \( P_{out} = \frac{37.3}{0.746} = 50 \text{ hp} \)

4. \( P_{out} = \frac{37.3}{0.746} = 50 \text{ hp} \)
A 460-V, 25-hp, 60 Hz, four-pole, Y-connected induction motor has the following impedances in ohms per phase referred to the stator circuit:

\[ R_1 = 0.641 \Omega \quad R_2 = 0.332 \Omega \]

\[ X_1 = 1.106 \Omega \quad X_2 = 0.464 \Omega \quad X_M = 26.3 \Omega \]

The total rotational losses are 1100 W and are assumed to be constant. The core loss is lumped in with the rotational losses. For a rotor slip of 2.2 percent at the rated voltage and rated frequency, find the motor’s

1. Speed
2. Stator current
3. Power factor
4. \( P_{\text{conv}} \) and \( P_{\text{out}} \)
5. \( \tau_{\text{ind}} \) and \( \tau_{\text{load}} \)
6. Efficiency
Solution

\[ n_{\text{sync}} = \frac{120f_e}{P} = \frac{120 \times 60}{4} = 1800 \text{ rpm} \]

1.

\[ n_m = (1 - s)n_{\text{sync}} = (1 - 0.022) \times 1800 = 1760 \text{ rpm} \]

\[ Z_2 = \frac{R_2}{s} + jX_2 = \frac{0.332}{0.022} + j0.464 \]

2.

\[ = 15.09 + j0.464 = 15.1 \angle 1.76^\circ \ \Omega \]

\[ Z_f = \frac{1}{1/jX_M + 1/Z_2} = \frac{1}{-j0.038 + 0.0662 \angle -1.76^\circ} \]

\[ = \frac{1}{0.0773 \angle -31.1^\circ} = 12.94 \angle 31.1^\circ \ \Omega \]
Solution

\[ Z_{tot} = Z_{stat} + Z_f \]

\[ = 0.641 + j1.106 + 12.94 \angle 31.1^\circ \Omega \]

\[ = 11.72 + j7.79 = 14.07 \angle 33.6^\circ \Omega \]

\[ I_1 = \frac{V_\phi}{Z_{tot}} = \frac{\sqrt{3}}{14.07 \angle 33.6^\circ} = 18.88 \angle -33.6^\circ \text{ A} \]

\[ PF = \cos 33.6^\circ = 0.833 \quad \text{lagging} \]

\[ P_{in} = \sqrt{3} V_L I_L \cos \theta = \sqrt{3} \times 460 \times 18.88 \times 0.833 = 12530 \text{ W} \]

3. \[ P_{SCL} = 3 I_1^2 R_1 = 3(18.88)^2 \times 0.641 = 685 \text{ W} \]

4. \[ P_{AG} = P_{in} - P_{SCL} = 12530 - 685 = 11845 \text{ W} \]
Solution

\[ P_{\text{conv}} = (1-s)P_{AG} = (1-0.022)(11845) = 11585 \text{ W} \]

\[ P_{\text{out}} = P_{\text{conv}} - P_{F&W} = 11585 - 1100 = 10485 \text{ W} \]

\[ = \frac{10485}{746} = 14.1 \text{ hp} \]

5. \[ \tau_{\text{ind}} = \frac{P_{AG}}{\omega_{\text{sync}}} = \frac{11845}{2\pi \times 1800/60} = 62.8 \text{ N.m} \]

\[ \tau_{\text{load}} = \frac{P_{\text{out}}}{\omega_{m}} = \frac{10485}{2\pi \times 1760/60} = 56.9 \text{ N.m} \]

6. \[ \eta = \frac{P_{\text{out}}}{P_{\text{in}}} \times 100\% = \frac{10485}{12530} \times 100 = 83.7\% \]
Thevenin’s theorem can be used to transform the network to the left of points ‘a’ and ‘b’ into an equivalent voltage source $V_{TH}$ in series with equivalent impedance $R_{TH} + jX_{TH}$. 

[Diagram of electrical circuit with labels $I_1$, $R_1$, $jX_1$, $I_2$, $jX_2$, $V_\phi$, $I_M$, $jX_M$, $V_m$, $\frac{R_2}{s}$]
Torque, power and Thevenin’s Theorem

\[ V_{TH} = V_\phi \frac{jX_M}{R_1 + j(X_1 + X_M)} \]

\[ |V_{TH}| = |V_\phi| \frac{X_M}{\sqrt{R_1^2 + (X_1 + X_M)^2}} \]

\[ R_{TH} + jX_{TH} = (R_1 + jX_1) \parallel jX_M \]
Torque, power and Thevenin’s Theorem

- Since $X_M \gg X_1$ and $X_M \gg R_1$

\[
V_{TH} \approx V_\phi \frac{X_M}{X_1 + X_M}
\]

- Because $X_M \gg X_1$ and $X_M + X_1 \gg R_1$

\[
R_{TH} \approx R_1 \left( \frac{X_M}{X_1 + X_M} \right)^2
\]

\[
X_{TH} \approx X_1
\]
Torque, power and Thevenin’s Theorem

\[ I_2 = \frac{V_{TH}}{Z_T} = \frac{V_{TH}}{\sqrt{\left( R_{TH} + \frac{R_2}{s} \right)^2 + \left( X_{TH} + X_2 \right)^2}} \]

Then the power converted to mechanical \( (P_{\text{conv}}) \)

\[ P_{\text{conv}} = 3I_2^2 \frac{R_2(1-s)}{s} \]

And the internal mechanical torque \( (T_{\text{conv}}) \)

\[ \tau_{\text{ind}} = \frac{P_{\text{conv}}}{\omega_m} = \frac{P_{\text{conv}}}{(1-s)\omega_s} = \frac{3I_2^2 \frac{R_2}{s}}{\omega_s} = \frac{P_{\text{AG}}}{\omega_s} \]
Torque, power and Thevenin’s Theorem

\[
\tau_{\text{ind}} = \frac{3}{\omega_s} \frac{V_{\text{TH}}}{\sqrt{\left( \frac{R_{\text{TH}} + \frac{R_2}{s}}{s} \right)^2 + (X_{\text{TH}} + X_2)^2}} \left( \frac{R_2}{s} \right)^2
\]

\[
\tau_{\text{ind}} \equiv \frac{1}{\omega_s} \frac{3V_{\text{TH}}^2 \left( \frac{R_2}{s} \right)}{\left( \frac{R_{\text{TH}} + \frac{R_2}{s}}{s} \right)^2 + (X_{\text{TH}} + X_2)^2}
\]
Torque-speed characteristics

Typical torque-speed characteristics of induction motor
1. The induced torque is zero at synchronous speed. Discussed earlier.

2. The curve is nearly linear between no-load and full load. In this range, the rotor resistance is much greater than the reactance, so the rotor current, torque increase linearly with the slip.

3. There is a maximum possible torque that can’t be exceeded. This torque is called *pullout torque* and is 2 to 3 times the rated full-load torque.
4. The starting torque of the motor is slightly higher than its full-load torque, so the motor will start carrying any load it can supply at full load.

5. The torque of the motor for a given slip varies as the square of the applied voltage.

6. If the rotor is driven faster than synchronous speed it will run as a generator, converting mechanical power to electric power.
Complete Speed-torque Curve

**MOTOR**

- $P_{js}$
- $P_t$
- $P_{jr}$
- $P_v$
- $P_e$
- $P_r$
- $P_m$

**GENERATOR**

- $P_{js}$
- $P_t$
- $P_{jr}$
- $P_v$
- $P_e$
- $P_r$
- $P_m$

Diagram showing the relationship between speed and torque for a motor and a generator.
Maximum torque

- Maximum torque occurs when the power transferred to $R_2/s$ is maximum.
- This condition occurs when $R_2/s$ equals the magnitude of the impedance $R_{TH} + j (X_{TH} + X_2)$

$$\frac{R_2}{S_{T_{max}}} = \sqrt{R_{TH}^2 + (X_{TH} + X_2)^2}$$

The slip at maximum torque is directly proportional to the rotor resistance $R_2$
Maximum torque

• The corresponding maximum torque of an induction motor equals

\[
\tau_{\text{max}} = \frac{1}{2\omega_s} \left( \frac{3V_{TH}^2}{R_{TH} + \sqrt{R_{TH}^2 + (X_{TH} + X_2)^2}} \right)
\]

The maximum torque is independent of \( R_2 \)
Maximum torque

• Rotor resistance can be increased by inserting external resistance in the rotor of a wound-rotor induction motor.

• The value of the maximum torque remains unaffected but the speed at which it occurs can be controlled.
Maximum torque

Effect of rotor resistance on torque-speed characteristic
Motor speed control by variable frequency (VFD)
A two-pole, 50-Hz induction motor supplies 15kW to a load at a speed of 2950 rpm.

1. What is the motor’s slip?
2. What is the induced torque in the motor in N.m under these conditions?
3. What will be the operating speed of the motor if its torque is doubled?
4. How much power will be supplied by the motor when the torque is doubled?
Solution

1. 

\[ n_{\text{sync}} = \frac{120 f_e}{P} = \frac{120 \times 50}{2} = 3000 \text{ rpm} \]

\[ s = \frac{n_{\text{sync}} - n_m}{n_{\text{sync}}} = \frac{3000 - 2950}{3000} = 0.0167 \text{ or } 1.67\% \]

\[ \because \text{ no } P_{f+w} \text{ given} \]

2. \[ \therefore \text{ assume } P_{\text{conv}} = P_{\text{load}} \text{ and } \tau_{\text{ind}} = \tau_{\text{load}} \]

\[ \tau_{\text{ind}} = \frac{P_{\text{conv}}}{\omega_m} = \frac{15 \times 10^3}{2950 \times \frac{2\pi}{60}} = 48.6 \text{ N.m} \]
3. In the low-slip region, the torque-speed curve is linear and the induced torque is direct proportional to slip. So, if the torque is doubled the new slip will be 3.33% and the motor speed will be

\[ n_m = (1 - s)n_{sync} = (1 - 0.0333) \times 3000 = 2900 \text{ rpm} \]

4. \[ P_{conv} = \tau_{ind} \omega_m \]

\[ = (2 \times 48.6) \times (2900 \times \frac{2\pi}{60}) = 29.5 \text{ kW} \]
Determining motor circuit parameters

- **DC Test** (or use Ohm meter)
  
  Measuring $V, I \to R_1$

- **Locked-rotor Test**
  
  Measuring $V\Phi, I_1, P, Q \to R_1+R_2, X_1+X_2$

- **No-load Test**
  
  Measuring $V\Phi, I_1, P, Q \to \text{Friction + windage}, X_1+X_m$
Rules of thumb for dividing stator and rotor leakage reactances

- Cross section of squirrel cage rotor bars (NEMA Class A, B, C, D)

<table>
<thead>
<tr>
<th>Rotor design</th>
<th>$X_1$ and $X_2$ as functions of $X_{LR}$</th>
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<tr>
<td>Wound rotor</td>
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<td>Design A</td>
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## Motor Specifications

**Specifications: EFM4104T**

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<th>Specification</th>
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Problems

• 7.4
• 7.5
• 7.7*, 7.8, 7.10
• 7.14, 7.15
• 7.18
• 7.19