Induction Motors

Three-phase
The magnetic flux inside the motor rotates at the "synchronous" speed.

\[ n_{\text{sync}} = \frac{120 \cdot f}{N_{\text{poles}}} \]

\( f = \) electrical frequency
\( n \) denotes \( \text{rpm} \)

2-pole, 3-phase stator winding and the rotating flux

If you place a rotor with a magnet or electromagnet inside this rotating magnetic flux, it would rotate at the synchronous speed. This is the way a synchronous motor works.

If you place a rotor with wire loops (typically a squirrel-cage winding) inside this rotating magnetic flux, currents would be induced in these windings as in the secondary of a transformer. These currents would, in turn, create a magnetic field which would tend to follow the rotating magnetic field and cause the rotor to turn. It would NOT rotate at the synchronous speed because the closer it gets, the smaller the induced currents in the rotor windings. (If the rotor ever did turn at the synchronous speed, the induced currents and torque would be zero.) This is the way an induction motor works.

A typical rotor of an induction motor includes a number of thick conductors called "rotor bars". Current is induced in these bars because the rotor normally turns at speed which is slower than the synchronous speed (the speed of the rotating flux caused by the stator windings). By Lenz’s law, those currents will be induced in a direction to oppose the change that caused them. Thus the interaction between the induced current and the rotating flux provides the motor torque.

\[ n_{\text{slip}} = n_{\text{sync}} - n_{\text{m}} = s \cdot n_{\text{sync}} \]

\( s \) = slip

\[ \text{slip} \quad s = \frac{n_{\text{slip}}}{n_{\text{sync}}} = \frac{n_{\text{sync}} - n_{\text{m}}}{n_{\text{sync}}} \]

\( n_{\text{m}} \) = the mechanical speed of the rotor = \( (1 - s) \cdot n_{\text{sync}} \)

Reactances overpower resistances in the equivalent circuit.

A typical torque-speed curve:

\[ \omega = n \left( \frac{2 \cdot \pi \cdot \text{rad}}{\text{rev}} \right) \left( \frac{\text{min}}{60 \cdot \text{sec}} \right) \]

\( \omega \) = \( \text{rad sec}^{-1} \)

\( n \) = \( \text{rpm} \)

Figure 7.17: A typical induction motor torque-speed characteristic curve.

No slip so no induced voltage and current in the rotor and thus no torque
Model of an Induction Motor

\[ jX_1 \]  
\[ I_1 \]
\[ R_1 \]
\[ jX_M \]
\[ R_C \]
\[ jX_2 \]
\[ E_1 \]
\[ I_2 \]
\[ R_2 \]
\[ \frac{3}{s} \left( I_2^2 R_2 \right) = P_{AG} \]

= Power that crosses the Air Gap

\[ 3 \left( I_1^2 R_1 \right) = P_{SCL} \]

= Stator Copper Losses

\[ 3 \left( I_2^2 R_2 \right) = P_{RCL} \]

= Rotor Copper Losses

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

= Power converted to mechanical

\[ P_{out} = P_{conv} - P_{mech} - P_{misc} \]

induced torque = \[ \tau_{ind} = \frac{P_{conv}}{\omega_m} \]

OR: \[ \tau_{ind} = \frac{P_{AG}}{\omega_{sync}} \] (N·m)

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

Power Flow

\[ P_{in} = \sqrt{3} V_L I_L \text{pf} \]

\[ P_{SCL} \]

Stator Copper Losses

\[ P_{core} \]

Core loss

\[ P_{RCL} \]

Rotor Copper Losses

\[ P_{mech} \]

friction & windage

\[ P_{misc} \]

or P_stray

Induction Motors  p2
Typical torque-speed and power-speed curves for a 4-pole Induction motor

These curves are greatly affected by the rotor resistance ($R_2$ in our model).

Low $R_2$: Higher efficiency at normal running
- Lower startup torque
- Higher startup current

High $R_2$: Lower efficiency at normal running
- Higher startup torque
- Lower startup current

By manipulating the design of the rotor cage, you can mix some of the benefits of both.

NEMA Designs
Single-Phase Induction Motors

No Starting Torque without a Start winding

Capacitor-run

90° out-of-phase winding

Main winding

Capacitor-start

Start winding

Run winding

An ideal capacitor value would cause the current in the start winding to be 90° out-of-phase with the current in the run winding. That value turns out to be more for a stalled (or not-yet started) motor than one that is running at rated speed and output.

Split-Phase

The run winding has a large inductance and little resistance.

The start winding has little inductance and lots of resistance.

Start Direction: Reverse the leads to either of the windings to get the motor to start in the opposite direction.