

ECEN 667

Power System Stability

Lecture 17: Load Models, Voltage Stability

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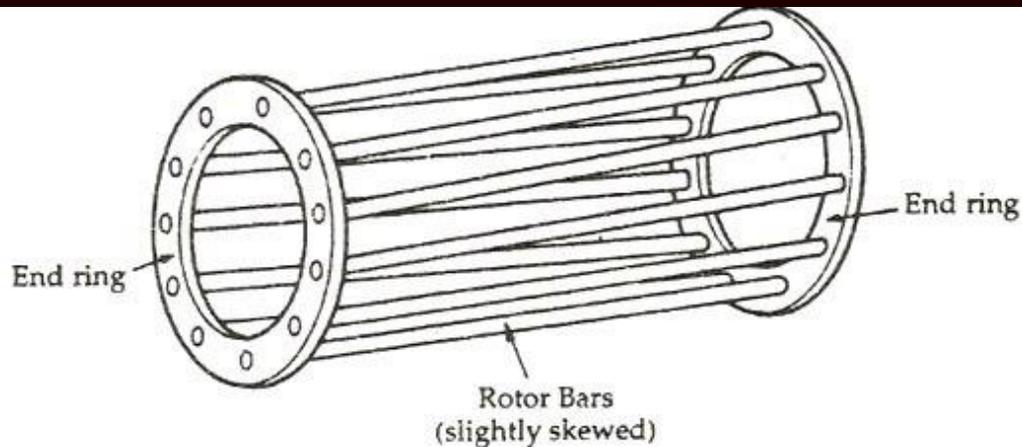
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Announcements

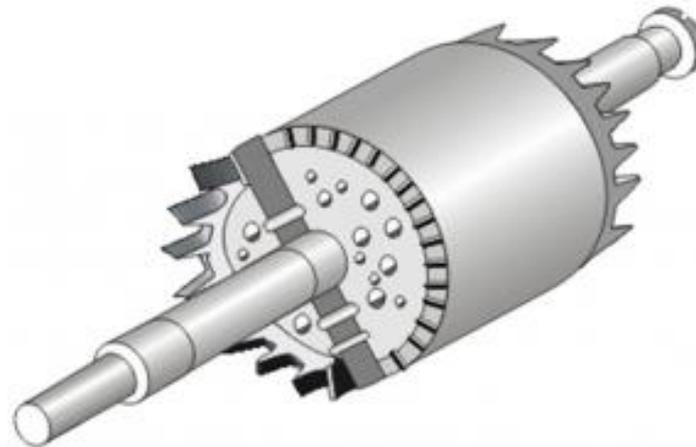


- Read Chapter 7
- Homework 4 is due on Tuesday Oct 29
- Book suggestion (outside of course scope):
Outliers by Malcolm Gladwell (2008)
 - Talks about how to be extremely successful

Squirrel Cage Rotor Picture



[Image 1 Source: www.quora.com/What-will-happen-If-the-Squirrel-cage-motor-rotor-conductors-are-not-skewed](http://www.quora.com/What-will-happen-If-the-Squirrel-cage-motor-rotor-conductors-are-not-skewed)



Embedded in laminated magnetic material

[Image 2 Source: www.polytechnichub.com/squirrel-cage-rotor/](http://www.polytechnichub.com/squirrel-cage-rotor/)

Specifying Induction Machine Parameters



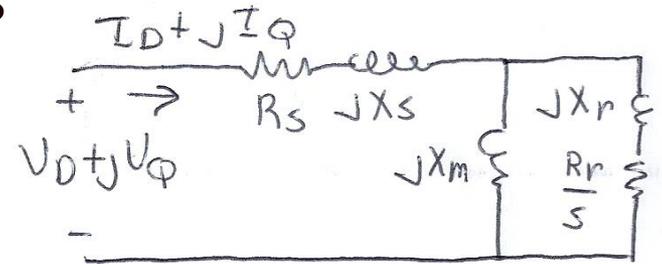
- In transient stability packages induction machine parameters are specified in per unit
 - If unit is modeled as a generator in the power flow (such as CIMTR1 or GENWRI) then use the generator's MVA base (as with synchronous machines)
 - With loads it is more complicated.
 - Sometimes an explicit MVA base is specified. If so, then use this value. But this can be cumbersome since often the same per unit machine values are used for many loads
 - The default is to use the MW value for the load, often scaled by a multiplier (say 1.25)

Determining the Initial Values



- To determine the initial values, it is important to recognize that for a fixed terminal voltage there is only one independent value: the slip, s

- For a fixed slip, the model is just a simple circuit with resistances and reactances



- The initial slip is chosen to match the power flow real power value. Then to match the reactive power value (for either a load or a generator), the approach is to add a shunt capacitor in parallel with the induction machine
- We'll first consider torque-speed curves, then return to determining the initial slip

Torque-Speed Curves



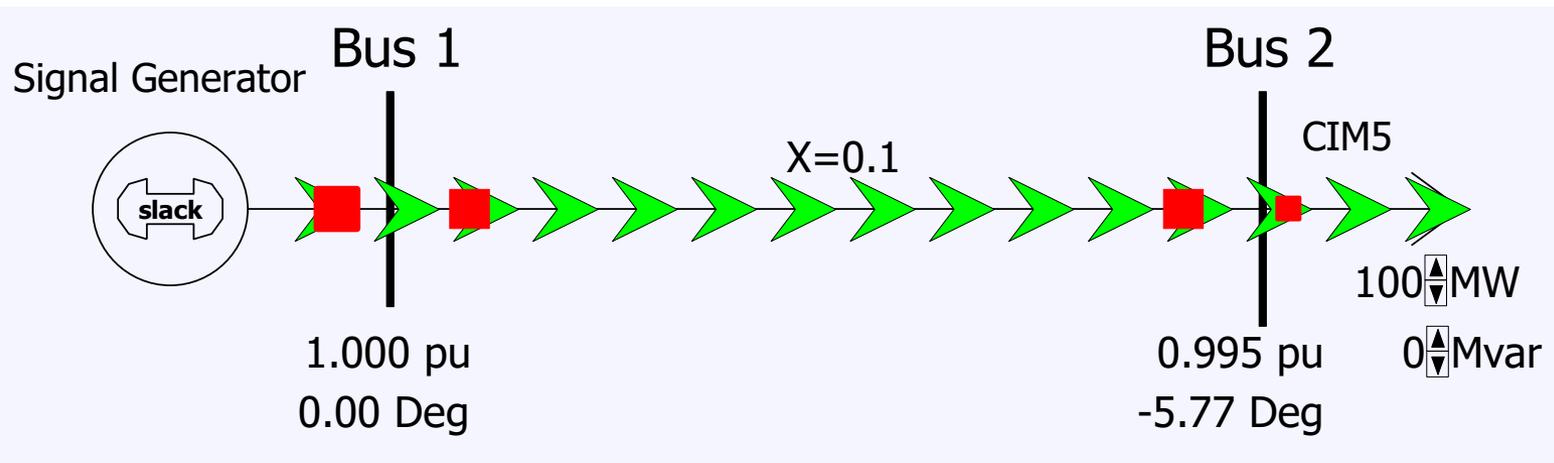
- To help understand the behavior of an induction machine it is useful to plot various values as a function of speed (or equivalently, slip)
 - Solve the equivalent circuit for a specified terminal voltage, and varying values of slip
 - Plot results
 - Recall torque times speed = power
 - Here speed is the rotor speed
 - When using per unit, the per unit speed is just 1-s

$$P_E = T_E (1 - s)$$

Induction Motor Example



- Assume the below 60 Hz system, with the entire load modeled as a single cage induction motor with per unit values on a 125 MVA base of $H=1.0$, $R_s=0.01$, $X_s=0.06$, $X_m=4.0$, $R_r=0.03$, $X_r=0.04$
 - In the CIM5 model $R_1=R_r$ and $X_1=X_r$

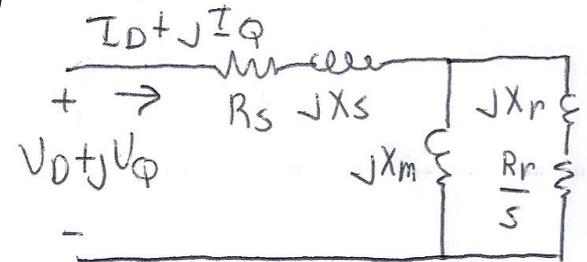


PowerWorld case **B2_IndMotor**

Induction Motor Example



- With a terminal voltage of $0.995 \angle 0^\circ$ we can solve the circuit for specified values of s
- The input impedance and current are



$$Z_{in} = (R_s + jX_s) + \frac{jX_m \left(\frac{R_r}{s} + jX_r \right)}{\frac{R_r}{s} + j(X_r + X_m)}$$

$$\bar{I} = \frac{\bar{V}}{Z_{in}} = \frac{0.995 \angle 0^\circ}{Z_{in}}$$

- Then with $s=1$ we get

Note, values are per unit on a 125 MVA base

$$\bar{I} = \frac{0.995}{0.0394 + j0.0998} = 3.404 - j8.624 \rightarrow S = 3.387 + j8.581$$

Induction Motor Example



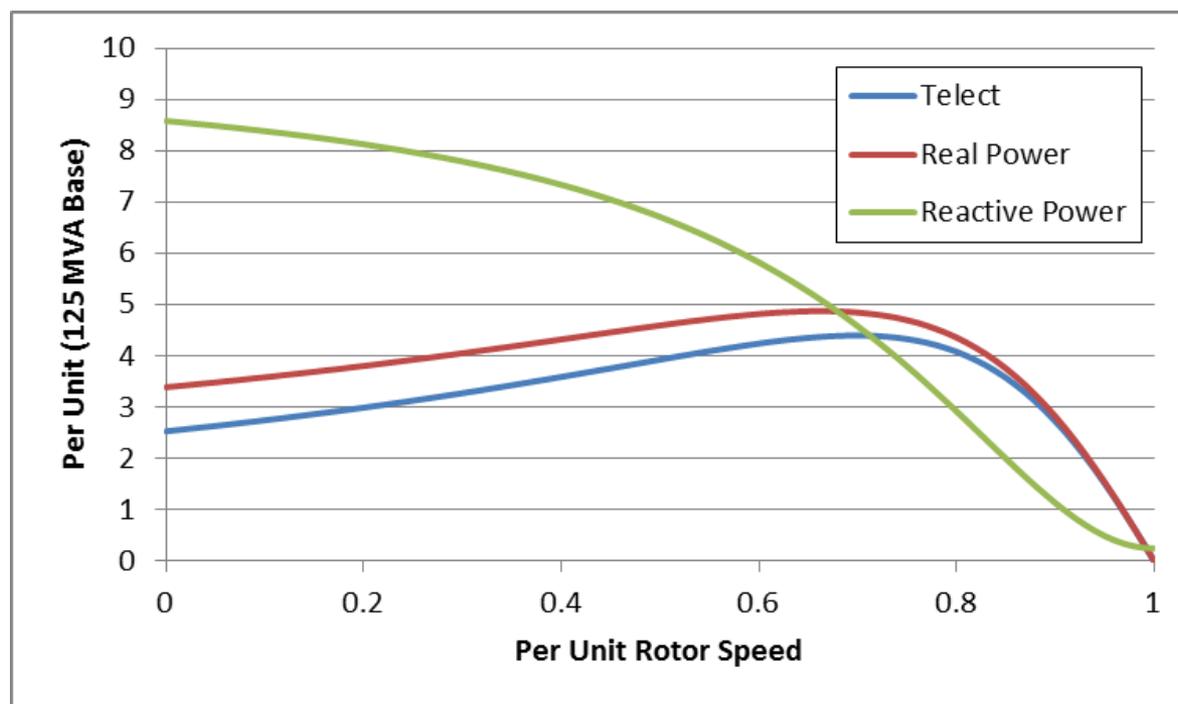
- PowerWorld allows for display of the variation in various induction machine values with respect to speed
 - Right click on load, select Load Information Dialog, Stability
 - On bottom of display click Show Torque Speed Dialog
 - Adjust the terminal voltage and pu scalar as desired; set $v=0.995$ and the pu scalar to 1.0 to show values on the 125 MVA base used in the previous solution
 - Right click on column and select Set/Toggle/Columns, Plot Column to plot the column

Induction Motor Example

Torque-Speed Curves



- The below graph shows the torque-speed curve for this induction machine; note the high reactive power consumption on starting (which is why the lights may dim when starting a cloth dryer!)



From the graph you can see with a 100 MW load (0.8 pu on the 125 MW base), the slip is about 0.025

Calculating the Initial Slip



- One way to calculate the initial slip is to just solve the below five equations for five unknowns (s , I_D , I_Q , E'_D, E'_Q) with P_E , V_D and V_Q inputs

$$P_E = V_D I_D + V_Q I_Q$$

$$V_D = E'_D + R_s I_D - X' I_Q$$

$$V_Q = E'_Q + R_s I_Q + X' I_D$$

$$\frac{dE'_D}{dt} = 0 = \omega_s s E'_Q - \frac{1}{T'_D} (E'_D + (X - X') I_Q)$$

$$\frac{dE'_Q}{dt} = 0 = \omega_s s E'_D - \frac{1}{T'_Q} (E'_Q - (X - X') I_D)$$

These are nonlinear equations that can have multiple solutions so use Newton's method, with an initial guess of s small (say 0.01)

Initial slip in example is 0.0251

Double Cage Induction Machines

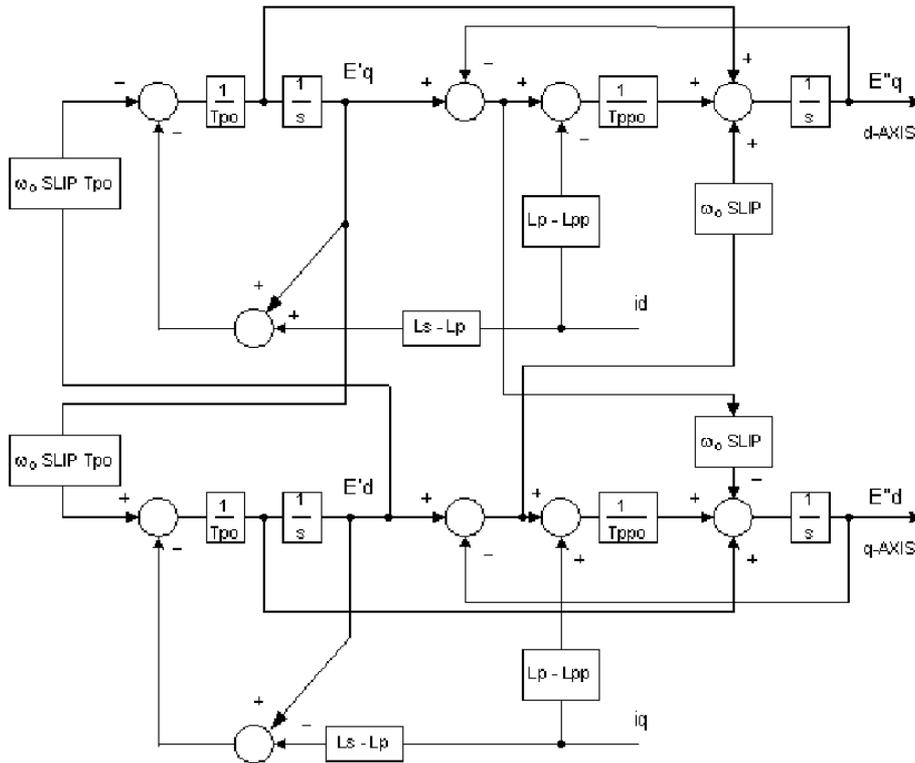


- In the design of induction machines, there are various tradeoffs, such as between starting torque (obviously one needs enough to start) and operating efficiency
 - The highest efficiency possible is 1-slip, so operating at low slip is desirable
- A common way to achieve high starting torque with good operating efficiency is to use a double cage design
 - E.g., the rotor has two embedded squirrel cages, one with a high R and lower X for starting, and one with lower R and higher X for running
 - Modeled by extending our model by having two rotor circuits in parallel; add subtransient values X'' and T'' .

Example Double Cage Model



- Double cage rotors are modeled by adding two additional differential equations



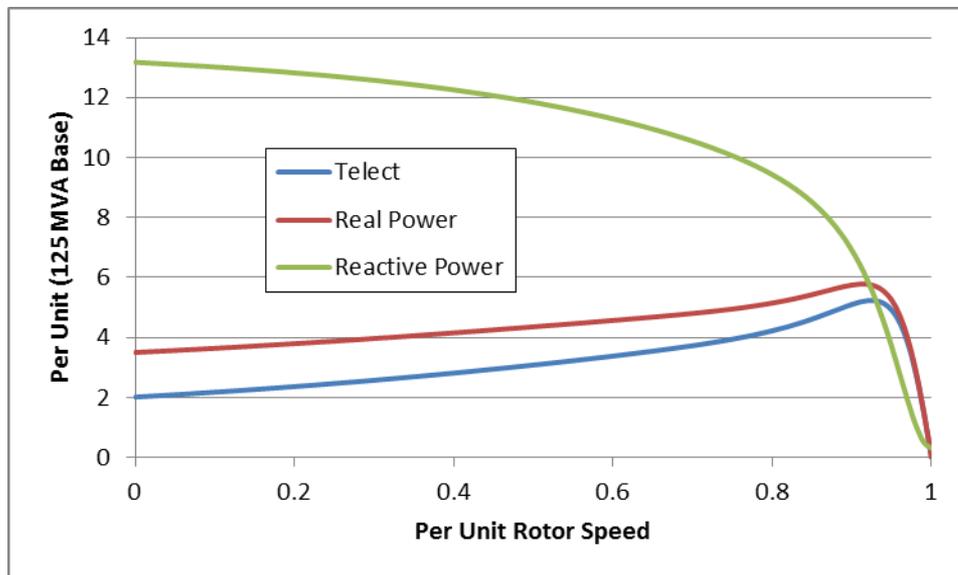
Some models also include saturation, a topic that we will skip

PowerWorld case
B2_IndMotor_DoubleCage

Double Cage Induction Motor Model



- The previous example can be extended to model a double cage rotor by setting $R_2=0.01$, $X_2=0.08$
 - The below graph shows the modified curves, notice the increase in the slope by $s=0$, meaning it is operating with higher efficiency ($s=0.0063$ now!)

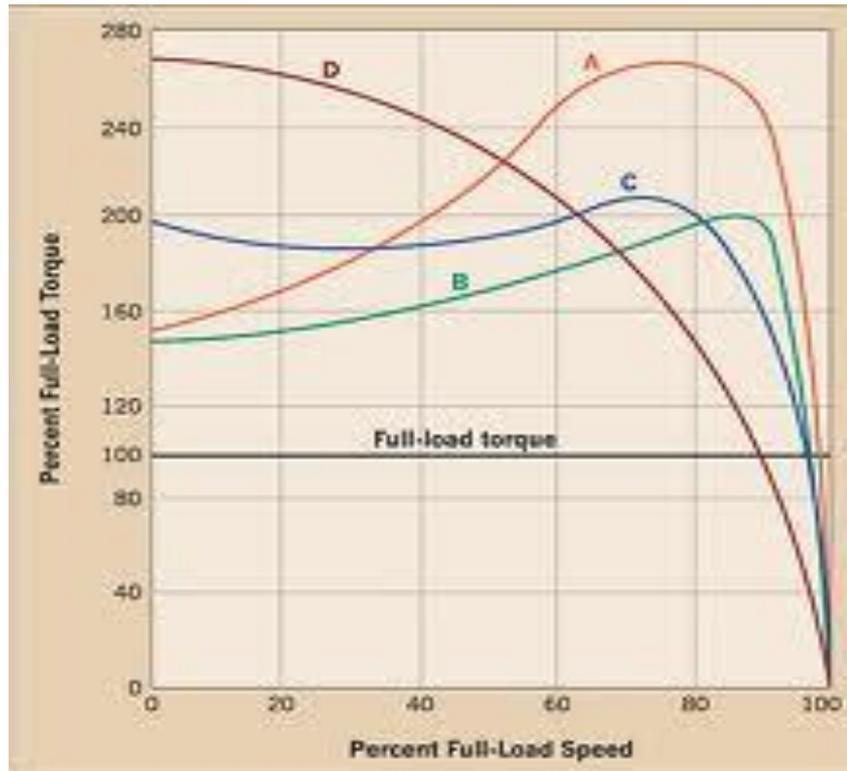


The additional winding does result in lower initial impedance and hence a higher starting reactive power

Induction Motor Classes



- Four major classes of induction motors, based on application. Key values are starting torque, pull-out torque, full-load torque, and starting current



In steady-state the motor will operate on the right side of the curve at the point at which the electrical torque matches the mechanical torque

A: Fans, pumps machine tools

B: Similar to A

C: Compressors, conveyors

D: High inertia such as hoists