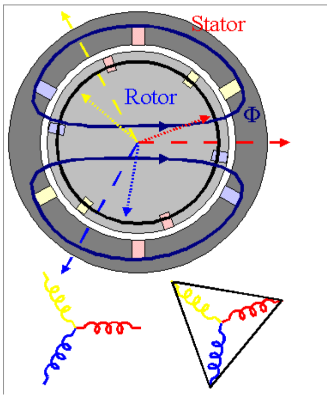
8. Induction motors

- 8.1 What does one look like?
- 8.2 How does it work?
- 8.3 What is the model?
- 8.4 How does one find the parameters?
- 8.5 How are induction machines used?
- 8.6 What's missing?

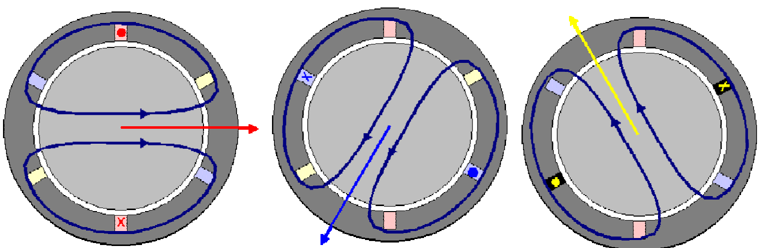
8.1 What does one look like?

- Stator winding
  - 3 phase.
  - V_1, I_1, N_1.
- Rotor winding
  - 3 phase or cage.
  - V_2, I_2, N_2.
  - Short circuited
- Flux Φ links 1 and 2
- Same number of poles.



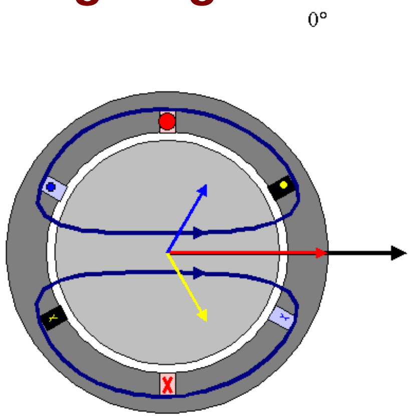
8.2 How does it work?

- Stator 3 phase:
  - Winding:120° *space*
  - Current: 120° *time*
  - *Rotating* magnetic field
  - Synchronous speed: $f = n_0 p$



Rotating Magnetic Field

- .



Rotor stationary : E

- Simplified Approach- (*like sc transformer*:)
- Flux, EMF:
  - AC Voltage, V_1 applied to stator.
  - Small AC current, I_0, flows ⇒ $\mathcal{F}_0$ ⇒ Φ at n_0.
  - $E_1 = N_1 d\Phi/dt = 4.44\, f\, N_1\Phi \approx V_1$.
  - $E_2 = N_2\, d\Phi/dt = 4.44\, f\, N_2\Phi$. (f=f)
  - $\mathbf{E_2 = E_1 N_2 / N_1 = E_1/k = E_{2\,(n=0)}}$
  - Note: N_1 , N_2 *not* usually integral

Rotor stationary : I

- Balance of Ampere Turns:
- Rotor SC, but R_2, X_2 .
  - $I_2 = E_2/(R_2+jX_2)$ flows ⇒ $\mathcal{F}_2$ ⇒ decrease in Φ ⇒ ↓ E_1.
  - BUT $E_1 \approx V_1$ so ↑I_1 ,such that $\mathcal{F}_1 = \mathcal{F}_2$.
  - $N_1 I_1 = N_2 I_2$
  - $\mathbf{I_1 / I_2 = N_2 / N_1 = 1/k}$
- Effective rotor resistance seen by stator R'_2:
  - $R'_2 = V_1/I_2 = kV_2/(I_2/k) = k^2 V_2/I_2$.
  - $R'_2 = k^2 R_2$, $X'_2 = k^2 X_2$

Rotor rotating : E

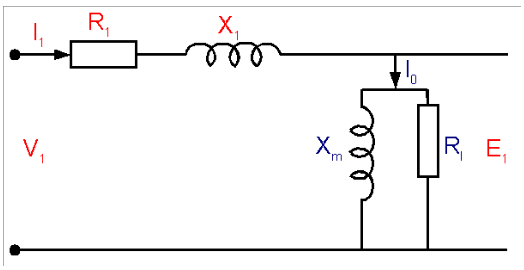
- Rotor spins at n_r in same direction as n_0.
- Now frequency in rotor windings *decreases* as n_r ↑.
  - **Slip** $s = \frac{n_0 - n_r}{n_0}$ ($n_r = 0 \Rightarrow s=1$; $n_r = n_0 \Rightarrow s = 0$)
  - $f_2 = s\, f_1$
- Flux, EMF:AC Voltage, V_1 at f_1 applied to stator.
  - Small AC current, I_0, flows $\Rightarrow \mathcal{F}_0 \Rightarrow$ Φ at n_0
  - $E_1 = N_1 d\Phi/dt = 4.44\, f_1 N_1 \Phi \approx V_1$.
  - $E_2 = N_2\, d\Phi/dt = 4.44\, f_2\, N_2 \Phi = 4.44\, s f_1\, N_2 \Phi$.
  - $E_2 = s\, E_1 N_2 / N_1 = s\, E_1 / k = s\, E_{2\,(n=0)}$.

Rotor rotating : I

- Balance of Ampere Turns:
- Rotor SC, but R_2, X_2 .
- *BUT* $X_2 = j\, 2\pi\, f_2 L_2 = s\, X_{2\,(n=0)}$.
  - $I_2 = E_2/(R_2 + jX_2)$
    $= sE_{2\,(n=0)}/(R_2 + s\, jX_{2\,(n=0)})$
  - Keeping I_2 the same
    $= E_{2\,(n=0)}/(R_2/s + jX_{2\,(n=0)})$
  - BUT f_2 has changed!!!!
    - (We have effectively jumped onto the stator!)

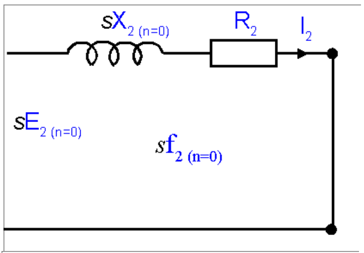
8.3 What is the model?

- Assumptions
- Stator (*per phase)*
- All at f_1.
  - R_1
  - X_1
  - X_m or B
  - R_l or G



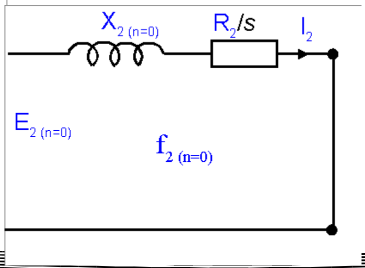
Model of rotor

- $sf_{2\,(n=0)}$, $sX_{2\,(n=0)}$, $sE_{2\,(n=0)}$ speed dependant.
- R_2 conductor loss



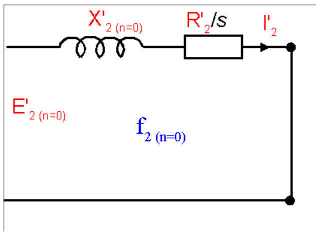
- Move to stator frame, keep I_2 the same ⇒ /*s*

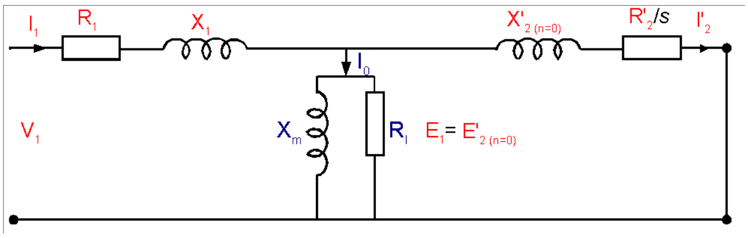
- $f_{2\,(n=0)}$, $X_{2\,(n=0)}$, $E_{2\,(n=0)}$ *NOT* speed dependant.
- R_2 conductor loss
- $R_2/s - R_2$ mechanical output power.



Combining Stator and Rotor

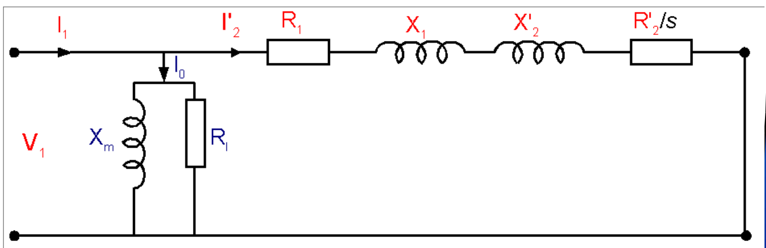
- Refer quantities to stator
- Stator and rotor E equivalent, combine.





Approximate Equivalent Circuit

- ***If*** $R_1, X_1 \ll X_M, R_I$ then move parallel branch to left.
- Drop (n=0)



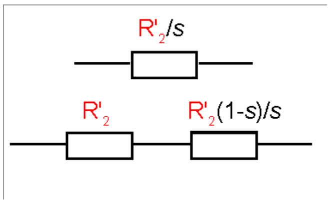
Output Power and Power

- Mechanical power given by $R'_2(1-s)/s$.

$$P_{out} = 3\frac{I'^2_2 R'_2(1-s)}{s}$$

$$T = \frac{P_{out}}{\omega_r} = \frac{P_{out}}{\omega_0(1-s)}$$

$$T = \frac{3}{\omega_0}\frac{I'^2_2 R'_2}{s}$$



- Torque given by R'_2/s, using ω_0.

8.4 How does one find parameters?

- R_1 from DC measurements (V_1 / I_1)
- Light running test ($s \simeq 0$)

$$R_l = \frac{V^2}{P}$$

$$I_x = \sqrt{I^2 - \left(\frac{V}{R_l}\right)^2}$$

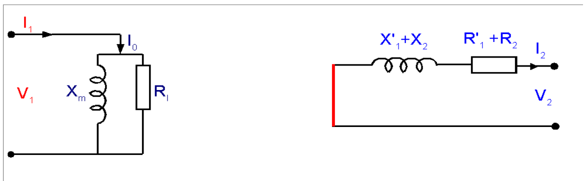
$$X = \frac{V}{I_x}$$

Locked rotor test ($s=1$)

$$R = \frac{P}{I^2}$$

$$Z = \frac{V}{I}$$

$$X = \sqrt{Z^2 - R^2}$$



8.5 How are induction machines used?

- Ratings
- Performance parameters
- Starting
- Variable speed

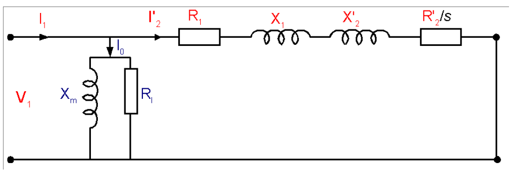
Ratings

- Voltage (Star, Delta)
- Frequency
- At rated operating point:
  - Output power (kW)
  - Current (Star, Delta) (A)
  - Speed (rpm)
- Starts per hour

Performance parameters

- Current
- Torque
- Power and Efficiency

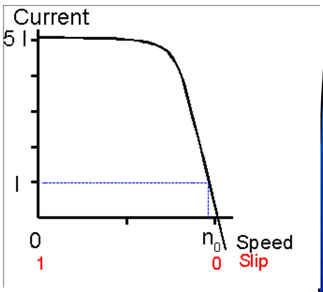
Current



- $I_1 = I_0 + I'_2$
- $I'_2 = \dfrac{V_1}{\left(R_1 + \dfrac{R'_2}{s}\right) + j(X_1 + X'_2)}$

$$|I'_2| = \frac{V_1}{\sqrt{\left(R_1 + \dfrac{R'_2}{s}\right)^2 + (X_1 + X'_2)^2}}$$

$$I_0 = V(G - jB)$$



Torque

- General equation

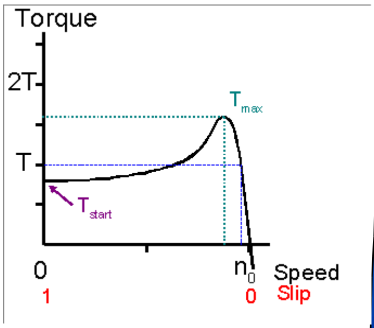
$$T = \frac{3}{\omega_0}\frac{I'^2_2 R'_2}{s}$$

$$T = \frac{3}{\omega_0}\frac{V_1^2 \frac{R'_2}{s}}{\left(R_1 + \frac{R'_2}{s}\right)^2 + (X_1 + X'_2)^2}$$

- Maximum Torque

$$s_{Tmax} = \frac{R'_2}{X_1 + X'_2} \qquad (R_1 \ll X)$$

$$T_{max} = \frac{3}{\omega_0}\frac{V^2}{2(X_1 + X'_2)}$$



Power and Efficiency

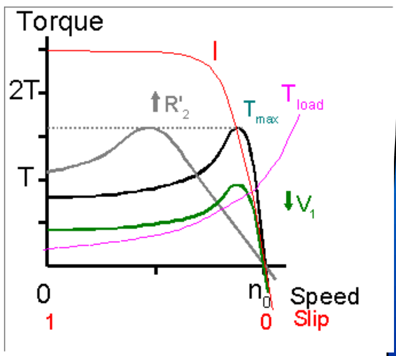
- $P_{Out} = 3\, I'_2 R'_2 (1-s)/s$
- $P_{In} = 3\, V_1 I_1 \cos\theta = P_{Out} + P_{Cu} + P_{Fe}$
- Efficiency

$$\eta = \frac{P_{Out}}{P_{In}} = \frac{P_{Out}}{(P_{Out} + P_{Cu} + P_{Fe})}$$

$$\eta_{max} \Rightarrow P_{Cu} = P_{Fe}$$

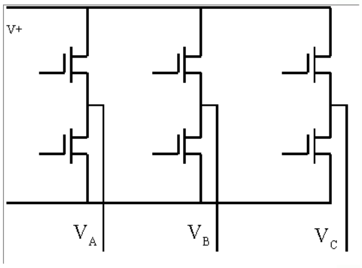
Starting

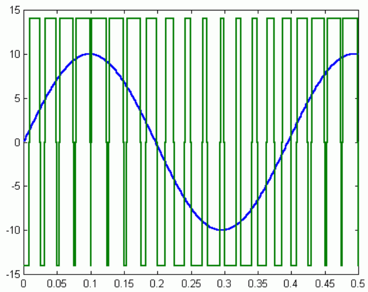
- Problem : High current during starting.
- Increase R'_2:
  - Wound rotor machine
  - Deep bar squirrel cage
- Reduce voltage
  - Star-delta changeover
  - Transformer
  - Series inductance
  - Power electronic soft-starter



Variable speed

- f_0=np, change f.
- Use *PWM Inverter*





8.6 What's missing?

- Transient performance
- Deep bar (skin) effect.
- Space and Time harmonics
- Saturation
- Cooling
- Mechanical Resonance