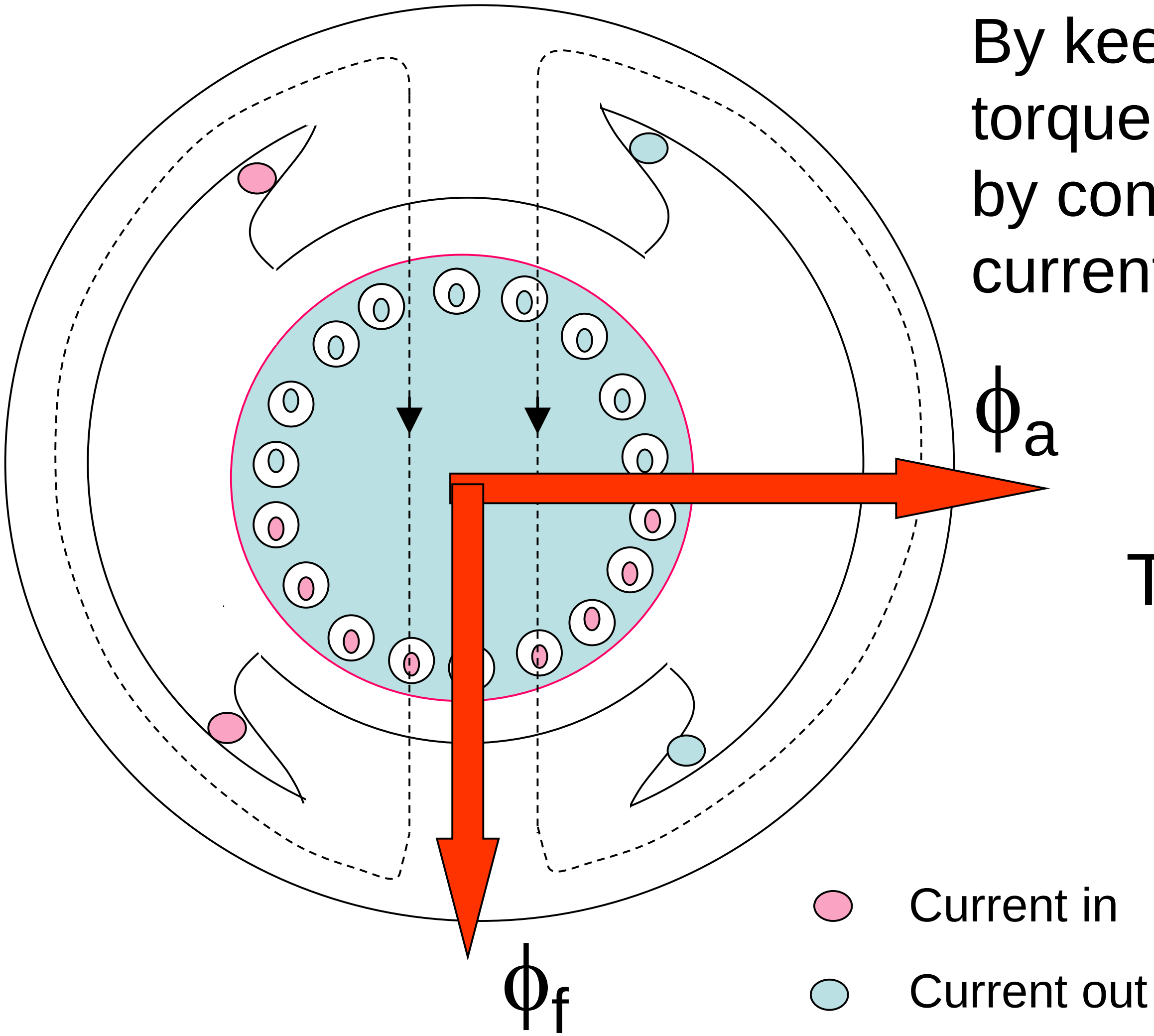
Lecture 24

Field Oriented Control

Why FOC ?

- IM is superior to DC machine with respect to size, weight, inertia, cost, speed
- DC motor is superior to IM with respect to ease of control
  - High performance with simple control due de-coupling component of torque and flux
- FOC transforms the dynamics of IM to become similar to the DC motor’s – decoupling the torque and flux components

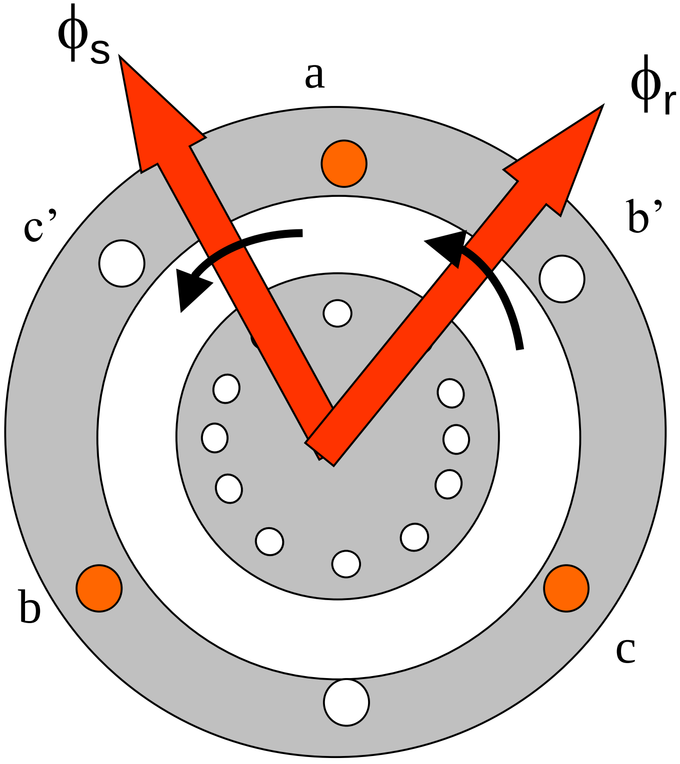
Basic Principles DC machine



By keeping flux constant, torque can be controlled by controlling armature current

$$T_e = k\, I_f\, I_a$$

Basic Principles of IM



Stator current produce stator flux

Stator flux induces rotor current $\rightarrow$ produces rotor flux

Interaction between stator and rotor fluxes produces torque

Space angle between stator and rotor fluxes **varies with load, and speed**

FOC of IM drive

Torque equation :

$$T_e = \frac{3}{2}\frac{p}{2}\overline{\psi}_s \times \bar{i}_s$$

$$T_e = \frac{3}{2}\frac{p}{2}\frac{L_m}{L_r}\overline{\psi}_r \times \bar{i}_s$$

In d-q axis :

$$T_e = \frac{3}{2}\frac{p}{2}\frac{L_m}{L_r}\left(\psi_{rd}\, i_{sq} - \psi_{rq}\, i_{sd}\right)$$

FOC of IM drive

In d-q axis :

$$T_e = \frac{3}{2}\frac{p}{2}\frac{L_m}{L_r}\left(\psi_{rd}\, i_{sq} - \psi_{rq}\, i_{sd}\right)$$

Choose a frame such that:

$$\psi_{rd}^{\psi_r} = \left|\overline{\psi}_r\right| \qquad\qquad \psi_{rq}^{\psi_r} = 0$$

FOC of IM drive

Choose a frame such that:

$$\psi_{rd}^{\psi_r} = \left|\overline{\psi}_r\right| \qquad \psi_{rq}^{\psi_r} = 0$$

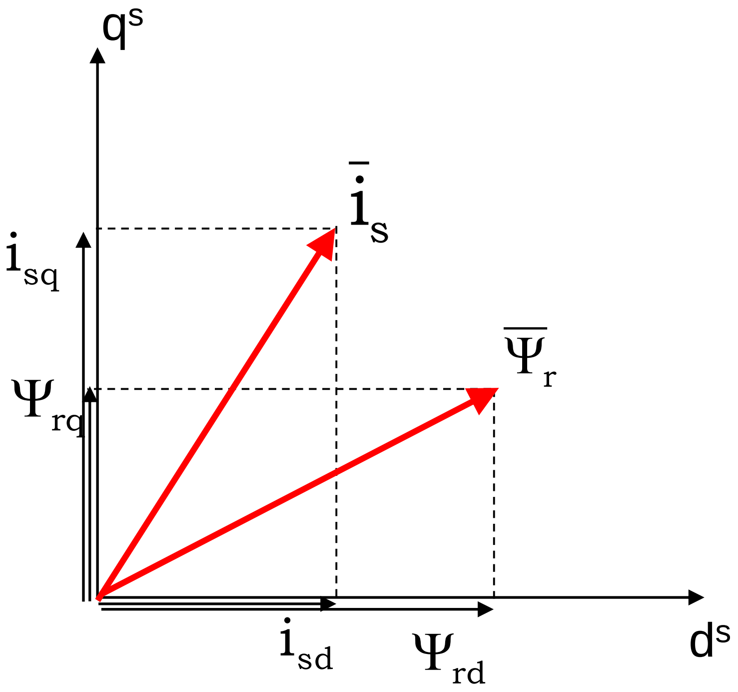
FOC of IM drive

Choose a frame such that:

$$\psi_{rd}^{\psi_r} = \left|\overline{\psi}_r\right| \qquad \psi_{rq}^{\psi_r} = 0$$

As seen by stator reference frame:

$$T_e = \frac{3}{2}\frac{p}{2}\frac{L_m}{L_r}(\psi_{rd}\, i_{sq} - \psi_{rq}\, i_{sd})$$

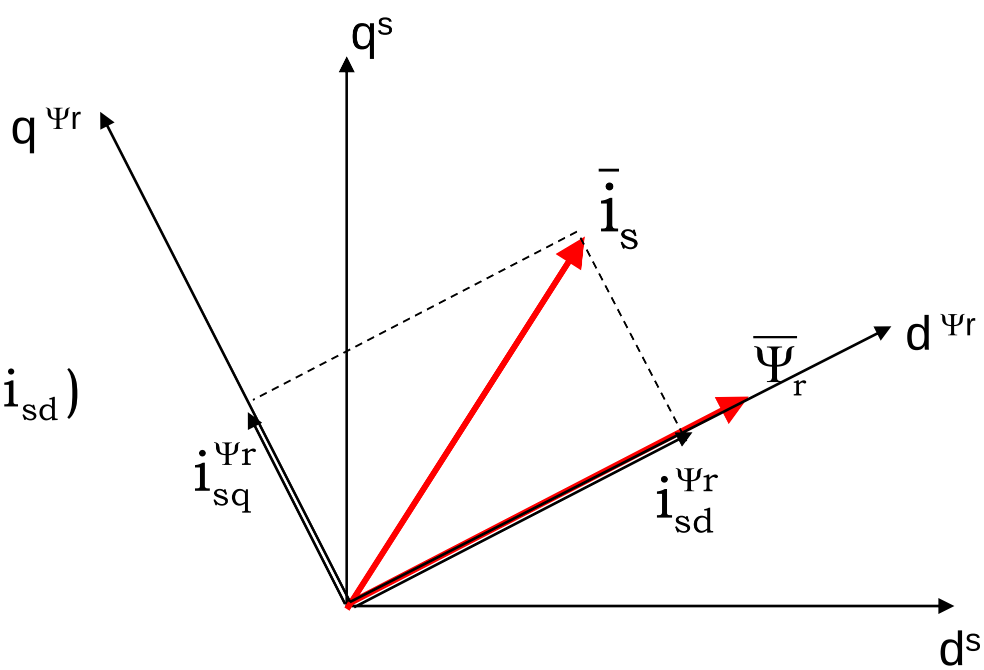


FOC of IM drive

Choose a frame such that:

$$\psi_{rd}^{\psi_r} = \left|\overline{\psi}_r\right| \qquad \psi_{rq}^{\psi_r} = 0$$

Rotating reference frame:



$$T_e = \frac{3}{2}\frac{p}{2}\frac{L_m}{L_r}\left(\psi_{rd}\, i_{sq}^{\psi} - \psi_{rq}\, i_{sd}\right)$$

FOC of IM drive

To implement rotor flux FOC need to know rotor flux position:

(i) Indirect FOC

Synchronous speed obtain by adding **slip speed** and **rotor speed**

Rotor voltage equation:

$$0 = R_r \bar{i}_r^g + \frac{d\overline{\psi}_r^g}{dt} + j(\omega_g - \omega_r)\overline{\psi}_r^g$$

Rotor flux equation:

$$\overline{\psi}_r^g = L_r \bar{i}_r^g + L_m \bar{i}_s^g$$

$$0 = \frac{R_r}{L_r}\overline{\psi}_r^g - \frac{L_m R_r}{L_r}\bar{i}_s^g + \frac{d\overline{\psi}_r^g}{dt} + j(\omega_g - \omega_r)\overline{\psi}_r^g$$

$$\boxed{0 = \frac{R_r}{L_r}\psi_r - \frac{L_m R_r}{L_r}\left(i_{sd}^{\psi r} + j i_{sq}^{\psi r}\right) + \frac{d\psi_r}{dt} + j(\omega_{slip})\psi_r}$$

FOC of IM drive - indirect

d component

q component

$$0 = \frac{R_r}{L_r}\psi_r - \frac{L_m R_r}{L_r} i_{sd}^{\psi_r} + \frac{d\psi_r}{dt}$$

$$0 = -\frac{L_m R_r}{L_r} i_{sq}^{\psi_r} + (\omega_{slip})\psi_r$$

$$\boxed{0 = \frac{R_r}{L_r}\psi_r - \frac{L_m R_r}{L_r}\left(i_{sd}^{\psi_r} + j i_{sq}^{\psi_r}\right) + \frac{d\psi_r}{dt} + j(\omega_{slip})\psi_r}$$

FOC of IM drive - indirect

$$\boxed{0 = \frac{R_r}{L_r}\psi_r - \frac{L_m R_r}{L_r}\left(i_{sd}^{\psi r} + j i_{sq}^{\psi r}\right) + \frac{d\psi_r}{dt} + j(\omega_{slip})\psi_r}$$

d component

q component

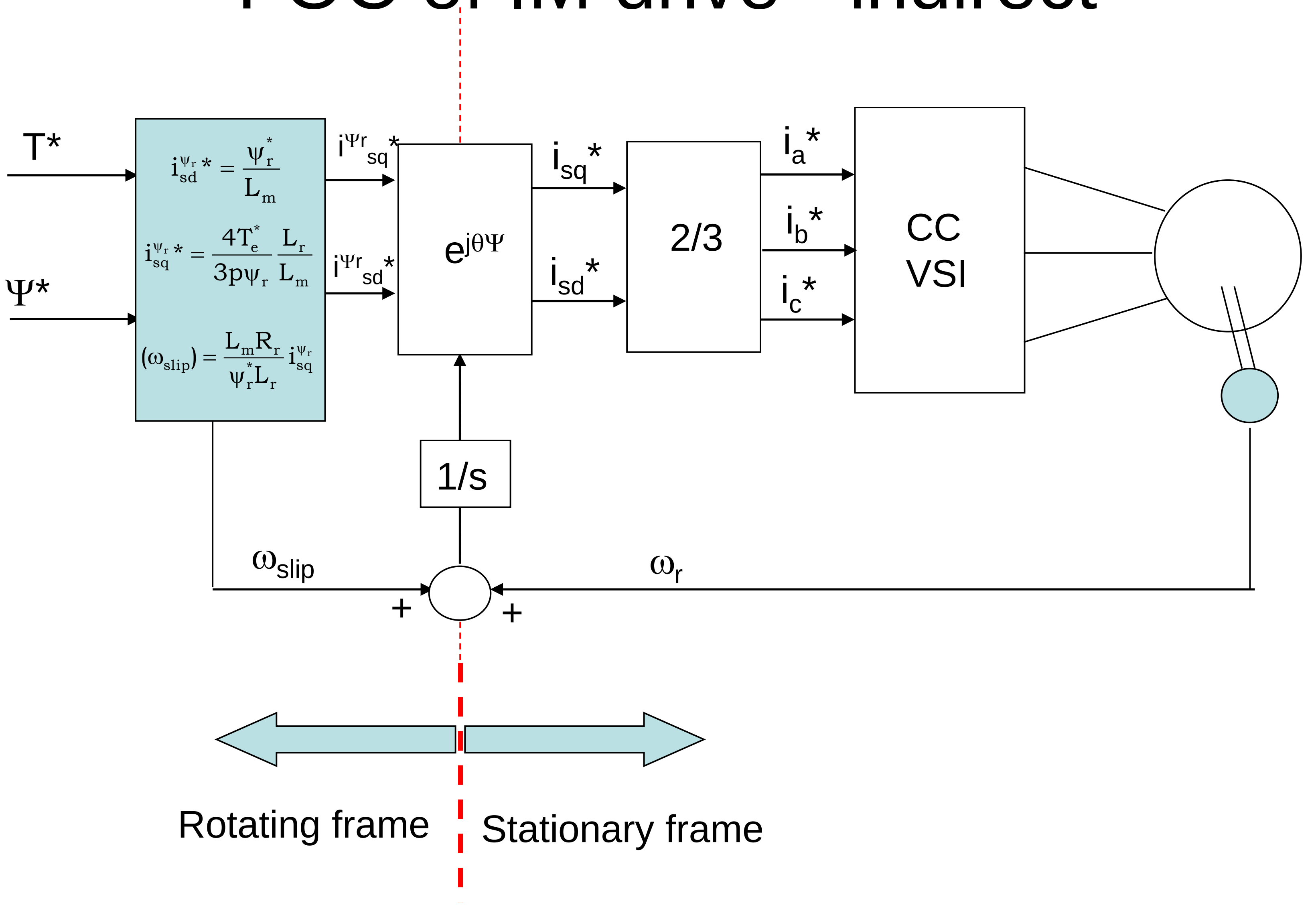
$$0 = \frac{R_r}{L_r}\psi_r - \frac{L_m R_r}{L_r} i_{sd}^{\psi r} + \frac{d\psi_r}{dt}$$

$$0 = -\frac{L_m R_r}{L_r} i_{sq}^{\psi r} + (\omega_{slip})\psi_r$$

$$i_{sd}^{\psi_r}* = \frac{\psi_r^*}{L_m}$$

$$(\omega_{slip}) = \frac{L_m R_r}{\psi_r^* L_r} i_{sq}^{\psi_r} \qquad i_{sq}^{\psi_r}* = \frac{4T_e^*}{3p\psi_r}\frac{L_r}{L_m}$$

FOC of IM drive - indirect



FOC of IM drive

(ii) Direct FOC

Rotor flux estimated from motor's terminal variables

Rotor flux can be estimated by:

$$\left.\begin{aligned} 0 &= \frac{R_r}{L_r}\overline{\psi}_r - \frac{L_m R_r}{L_r}\bar{i}_s + \frac{d\overline{\psi}_r}{dt} - j\omega_r \overline{\psi}_r^{g} \\ T_e &= \frac{3}{2}\frac{p}{2}\frac{L_m}{L_r}\overline{\psi}_r \times \bar{i}_s \end{aligned}\right\} \textbf{Express in stationary frame}$$

FOC of IM drive

(ii) Direct FOC

$$0 = \frac{R_r}{L_r}\overline{\psi}_r - \frac{L_m R_r}{L_r}\bar{i}_s + \frac{d\overline{\psi}_r}{dt} - j\omega_r \overline{\psi}_r^g$$

$$0 = \frac{R_r}{L_r}(\psi_{rd} + j\psi_{rq}) - \frac{L_m R_r}{L_r}(i_{sd} + ji_{sq})\bar{i} + \frac{d(\psi_{rd} + j\psi_{rq})}{dt} - j\omega_r(\psi_{rd} + j\psi_{rq})$$

$$\swarrow d \qquad\qquad \searrow q$$

$$\psi_{rd} = \int\left(\frac{R_r}{L_r}\psi_{rd} - \frac{L_m R_r}{L_r}i_{sd} + \omega_r\psi_{rq}\right)dt \qquad \psi_{rq} = \int\left(\frac{R_r}{L_r}\psi_{rq} - \frac{L_m R_r}{L_r}i_{sq} - \omega_r\psi_{rd}\right)dt$$

$$\Rightarrow \theta_\Psi = \frac{\psi_{rq}}{\psi_{rd}} \qquad \Rightarrow \psi_r = \sqrt{\psi_{rd}^2 + \psi_{rq}^2}$$

FOC of IM drive - direct