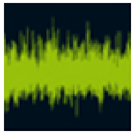
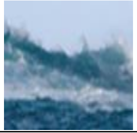
Field oriented control of Induction Motors

1. Introduction – the basic idea
2. Indirect rotor flux oriented controller
3. Direct rotor flux oriented controller – a brief discussion



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Introduction – borrow some ideas from PMSM control

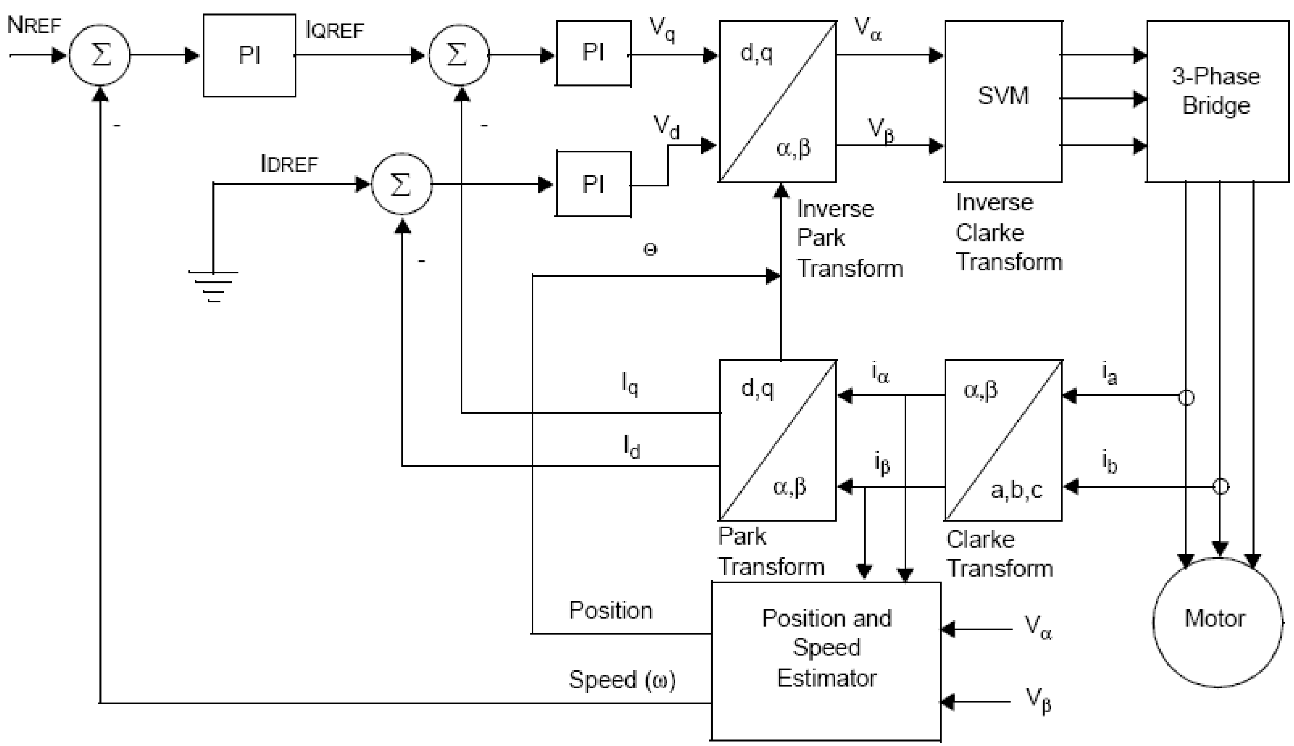
Machine equations

$$u_q = Ri_q + p\lambda_q + \omega_r \lambda_d \qquad \lambda_q = L_q i_q$$

$$u_d = Ri_d + p\lambda_d - \omega_r \lambda_q \qquad \lambda_d = L_d i_d + \lambda_{mpm}$$

$$T_e = \frac{3}{2} p\left[\lambda_{mpm} i_q + \left(L_d - L_q\right) i_d i_q\right]$$

$$T_e = \frac{3}{2} p\left(\lambda_{mpm} i_q\right)$$



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Introduction – borrow some ideas from PMSM control

- Controller is realized based on the torque equation – targeting at current control.
- The torque is generated from the interaction of the q-axis current and d-axis flux.
- Due to the constant d-axis flux from the permanent magnets, the d-axis current bias should be zero.
- In the controller design, the voltage equation is not needed (besides using the back-EMF decoupling network)
- PI controllers are used to generate the motor terminal voltage command from the current references.

For the induction machine

Machine equations

$$u_{qs} = r_s i_{qs} + p\lambda_{qs} + \omega_e \lambda_{ds} \qquad \lambda_{qs} = L_{ls} i_{qs} + L_m \left(i_{qs} + i_{qr}\right)$$

$$u_{ds} = r_s i_{ds} + p\lambda_{ds} - \omega_e \lambda_{qs} \qquad \lambda_{ds} = L_{ls} i_{ds} + L_m \left(i_{ds} + i_{dr}\right)$$

- Voltage equations are similar to that for PMSM – (different reference frame!)
- Be aware of the difference in the flux linkage equation.

$$u_{qr} = r_r i_{qr} + p\lambda_{qr} + \left(\omega_e - \omega_r\right)\lambda_{dr} \qquad \lambda_{qr} = L_{lr} i_{qr} + L_m \left(i_{qs} + i_{qr}\right)$$

$$u_{dr} = r_r i_{dr} + p\lambda_{dr} - \left(\omega_e - \omega_r\right)\lambda_{qr} \qquad \lambda_{dr} = L_{lr} i_{dr} + L_m \left(i_{ds} + i_{dr}\right)$$

For the induction machine

The torque equations could have many different forms

$$\tau = \frac{3}{2} p L_m \left(i_{qs} i_{dr} - i_{ds} i_{qr} \right)$$

$$\bar{i}_{dqs} = i_{ds} + j i_{qs} \qquad \bar{i}_{dqr} = i_{dr} + j i_{qr}$$

$$\mathrm{Im}\left(\bar{i}_{dqs} \cdot \bar{i}^{*}_{dqr} \right) = \mathrm{Im}\left[\left(i_{ds} + j i_{qs} \right) \cdot \left(i_{dr} - j i_{qr} \right) \right] = i_{qs} i_{dr} - i_{ds} i_{qr}$$

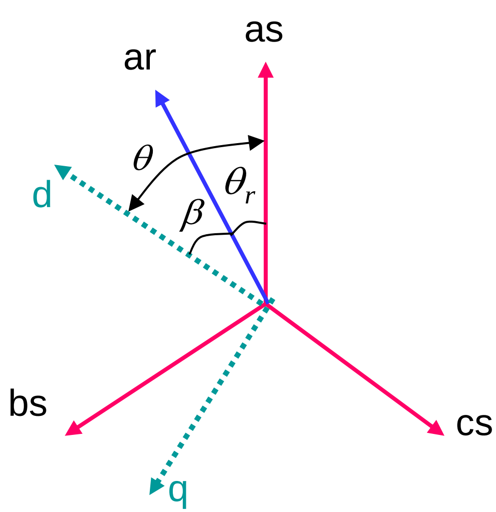
$$\tau = \frac{3}{2} p L_m \,\mathrm{Im}\left(\bar{i}_{dqs} \cdot \bar{i}^{*}_{dqr} \right)$$

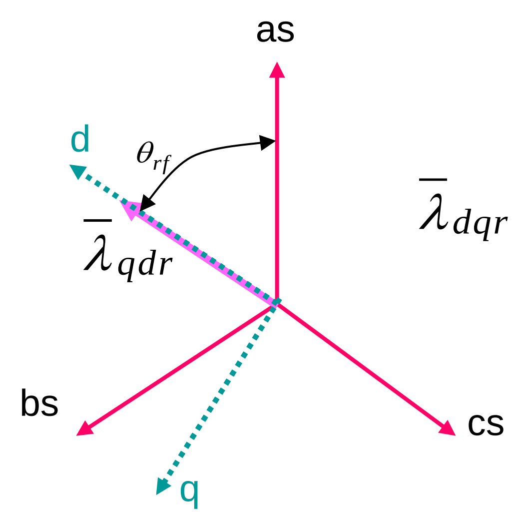
and more:

$$\tau = \frac{3}{2} p \,\mathrm{Im}\left(\bar{i}_{dqs} \cdot \bar{\lambda}^{*}_{dqs} \right) \qquad \tau = \frac{3}{2} p \frac{L_m}{L_r} \mathrm{Im}\left(\bar{i}_{qds} \cdot \bar{\lambda}^{*}_{qdr} \right)$$

One great simplification may be obtained

It is ARBITRARY reference frame for IM!





$$\overline{\lambda}_{dqr} = \lambda_{dr} = \lambda_r$$

$$\tau = \frac{3}{2} p \frac{L_m}{L_r} \mathrm{Im}\left(\bar{i}_{dqs} \cdot \overline{\lambda}^*_{dqr} \right)$$

$$\tau = \frac{3}{2} p \frac{L_m}{L_r} (i_{qs} \lambda_r)$$

Therefore, based on the new torque equation

$$T_e = \frac{3}{2} p \left(\lambda_{mpm} i_q \right)$$

PMSM

$$\tau = \frac{3}{2} p \frac{L_m}{L_r} (i_{qs} \lambda_r)$$

IM

- Possible to control the IM as controlling the PMSM – by holding the rotor flux constant, the torque is proportional to the stator q-axis current.

Challenge here!

- The rotor flux is already constant for PMSM – how to hold the rotor flux constant for an IM?

- The rotor flux position is not directly linked to the rotor physical position!

Indirect vs. direction rotor flux orientation

Indirect method

- The rotor field rotates at the synchronous rotating speed
- If the rotor speed is measurable, then, knowing the slip, the synchronous speed may then be calculated.
- The rotor flux position is obtained by integrating the speed.

Direct method

- The rotor flux position is estimated directly from e.g. terminal voltage, line current and motor parameters.

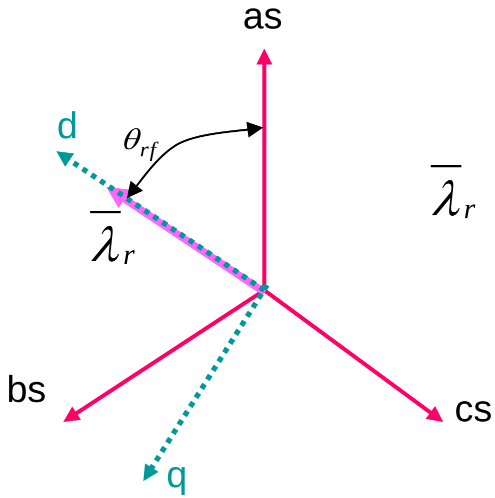
Indirect rotor flux orientation

$$\tau = \frac{3}{2} p \frac{L_m}{L_r} (i_{qs} \lambda_r)$$

Key point – to calculate the slip

Be ware of that in this situation, we have

$$\lambda_{qr=0}$$



$$\bar{\lambda}_r = \lambda_{dr} = \lambda_r$$

Play with machine equations to obtain the controller topology!

Principle – get rid of the rotor currents! Need to rely on the rotor side voltage and flux linkage equations

Therefore:

$$u_{qr} = r_r i_{qr} + p\lambda_{qr} + (\omega_e - \omega_r)\lambda_{dr} \qquad \lambda_{qr} = L_{lr} i_{qr} + L_m (i_{qs} + i_{qr})$$

$$u_{dr} = r_r i_{dr} + p\lambda_{dr} - (\omega_e - \omega_r)\lambda_{qr} \qquad \lambda_{dr} = L_{lr} i_{dr} + L_m (i_{ds} + i_{dr})$$

$$\Big\Downarrow \quad \lambda_{qr=0}$$

$$0 = r_r i_{qr} + (\omega_e - \omega_r)\lambda_{dr} \qquad 0 = L_r i_{qr} + L_m i_{qs}$$

$$0 = r_r i_{dr} + p\lambda_{dr} \qquad \lambda_{dr} = L_r i_{dr} + L_m i_{ds}$$

$$\lambda_{dr} = \lambda_r$$

Estimate the slip

From q-axis equation

$$i_{qr} = -\frac{L_m}{L_r} i_{qs}$$

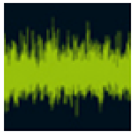
$$\boxed{0 = r_r i_{qr} + (\omega_e - \omega_r)\lambda_r}$$

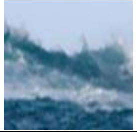
$$0 = L_r i_{qr} + L_m i_{qs}$$

$$s\omega_e = r_r \frac{L_m}{L_r} \frac{i_{qs}}{\lambda_r}$$

The rotor flux may be hold constant (but not always)

knowing the stator q-axis current and the rotor flux, the slip may then be found.



Estimate the rotor flux

From d-axis equations

$$0 = r_r i_{dr} + p\lambda_r \quad + \quad \lambda_r = L_r i_{dr} + L_m i_{ds} \Rightarrow \boxed{(1+\frac{L_r}{r_r}p)\lambda_r = L_m i_{ds}}$$

Relation between stator d-axis current and rotor flux

In S.S. $\lambda_r = const.$

$$i_{dr} = 0 \longrightarrow \lambda_r = L_m i_{ds}$$

Rotor time constant

$$\tau_r = \frac{L_r}{r_r}$$

$$s\omega_e = r_r \frac{L_m}{L_r}\frac{i_{qs}}{\lambda_r} \Rightarrow s\omega_e = \frac{1}{\tau_r}\frac{i_{qs}}{\frac{i_{ds}}{(1+\tau_r p)}} \xrightarrow{\text{In S.S.}} s\omega_e = \frac{1}{\tau_r}\frac{i_{qs}}{i_{ds}}$$

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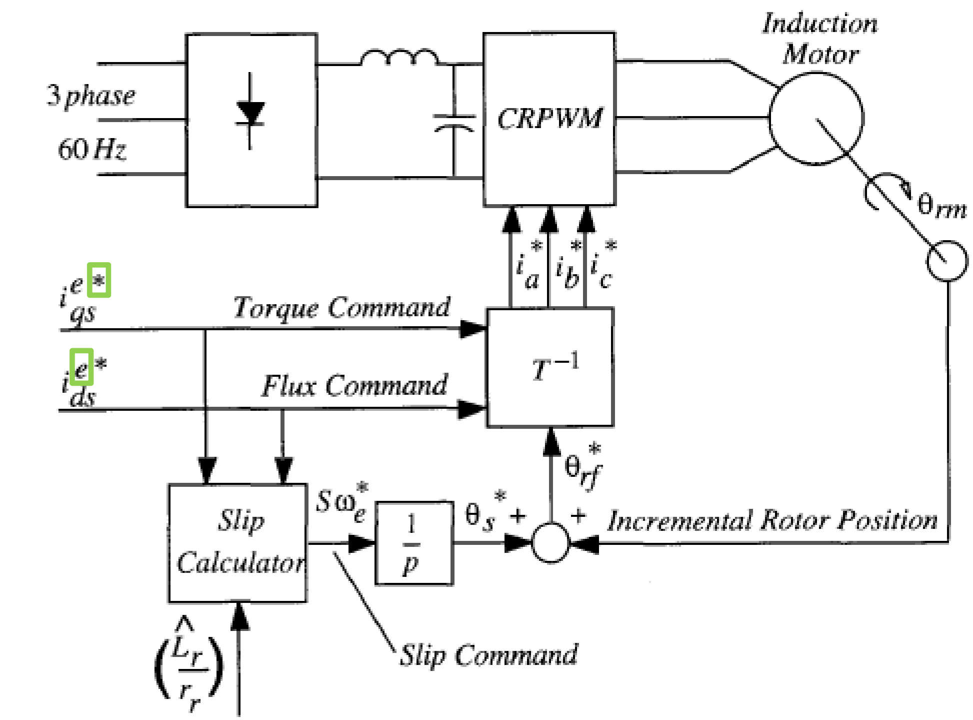
The controller block diagram may be



'*' means reference value

'e' means rotating reference frame

- Rely on the stator side currents in a synchronous rotating dq-frame
- If VSI is used, stator dq-axes currents will be regulated by using two PI controllers in the sync. rotating reference frame – just like for PMSM!

Control topology - 1

$$\boxed{(1+\tau_r p)\lambda_r = L_m i_{ds}}$$

$$\boxed{s\omega_e = \frac{1}{\tau_r}\frac{i_{qs}}{\frac{i_{ds}}{(1+\tau_r p)}}}$$

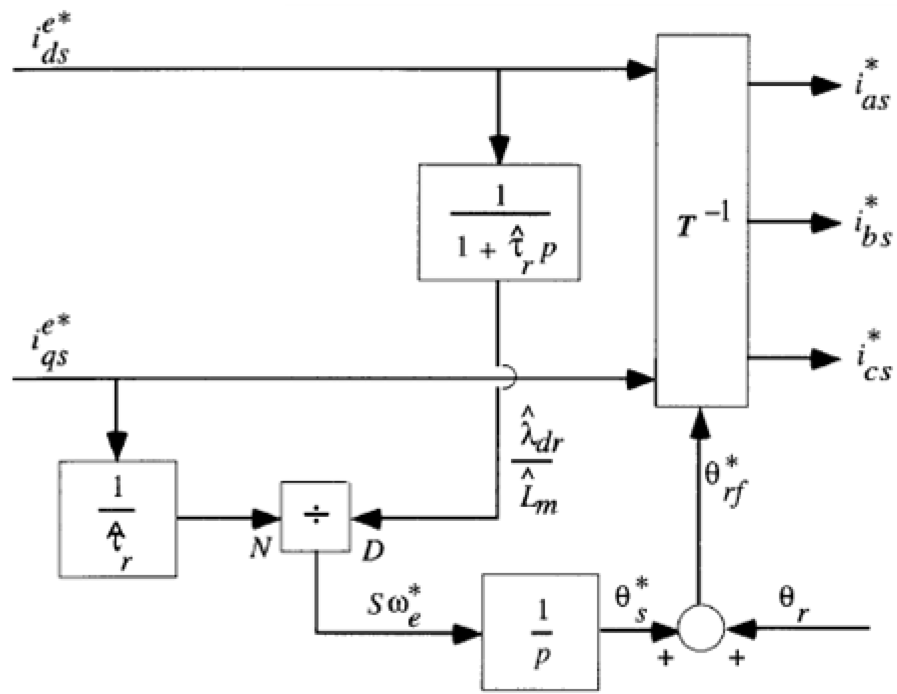


Figure 6.6 Indirect field orientation controller using input current commands (uncompensated flux response)

- The rotor position needs to be measured.
- Knowing the rotor time constant is important.
- What if the estimated rotor time constant is not correct?

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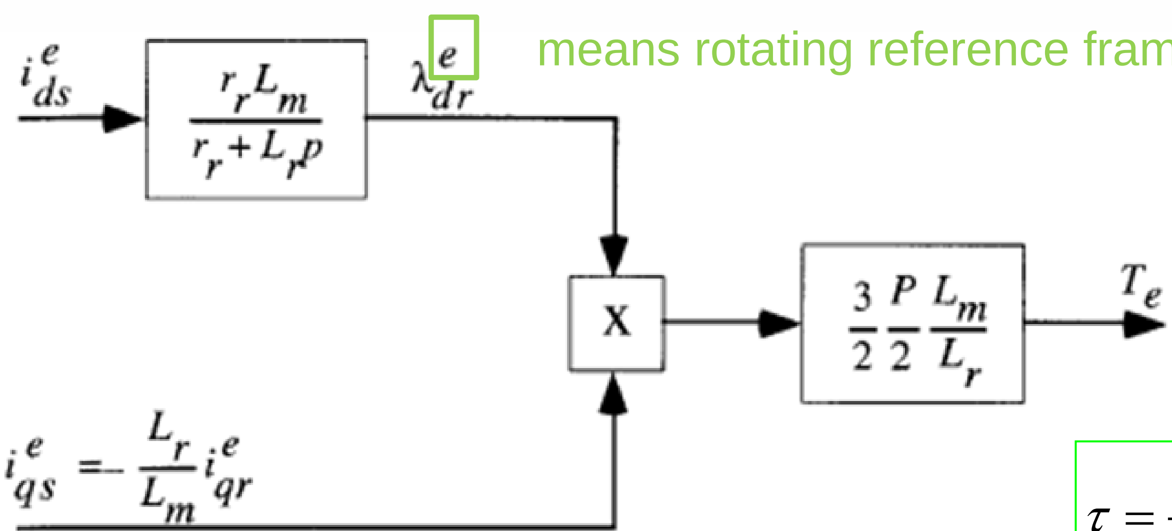
Be aware of the instantaneous torque in relation to the stator currents:



$\boxed{e}$ means rotating reference frame

$$\boxed{\tau = \frac{3}{2} p \frac{L_m}{L_r} (i_{qs} \lambda_r)}$$

- Stator q-axis current acts on the torque with NO delay.
- Stator d-axis current acts on the torque with a first-order delay determined by the rotor time constant.

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Control topology - 2

$$\boxed{(1+\tau_r p)\lambda_r = L_m i_{ds}}$$

$$\boxed{s\omega_e = \frac{1}{\tau_r}\frac{i_{qs}}{\dfrac{i_{ds}}{(1+\tau_r p)}}}$$

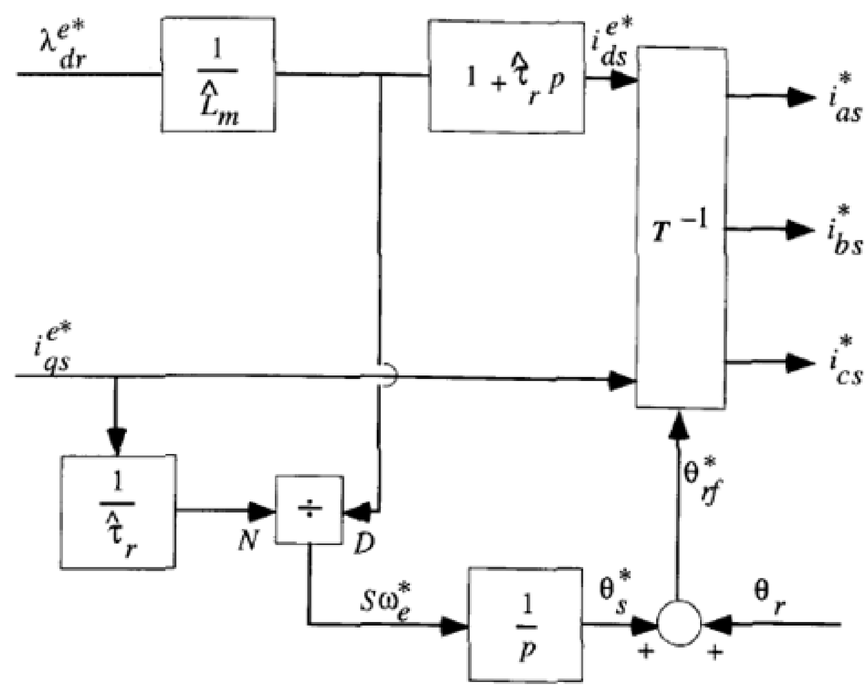


Figure 6.7 Indirect field orientation controller using flux and torque current commands (compensated flux response)

- A flux change alerts the slip immediately. It also gives a compensation term to compensate to keep the torque constant.

- Differentiation of the flux command is involved. Its output should be limited.

Control topology - 3

$$\boxed{(1+\tau_r p)\lambda_r = L_m i_{ds}}$$

$$\boxed{s\omega_e = \frac{1}{\tau_r}\frac{i_{qs}}{\dfrac{i_{ds}}{(1+\tau_r p)}}}$$

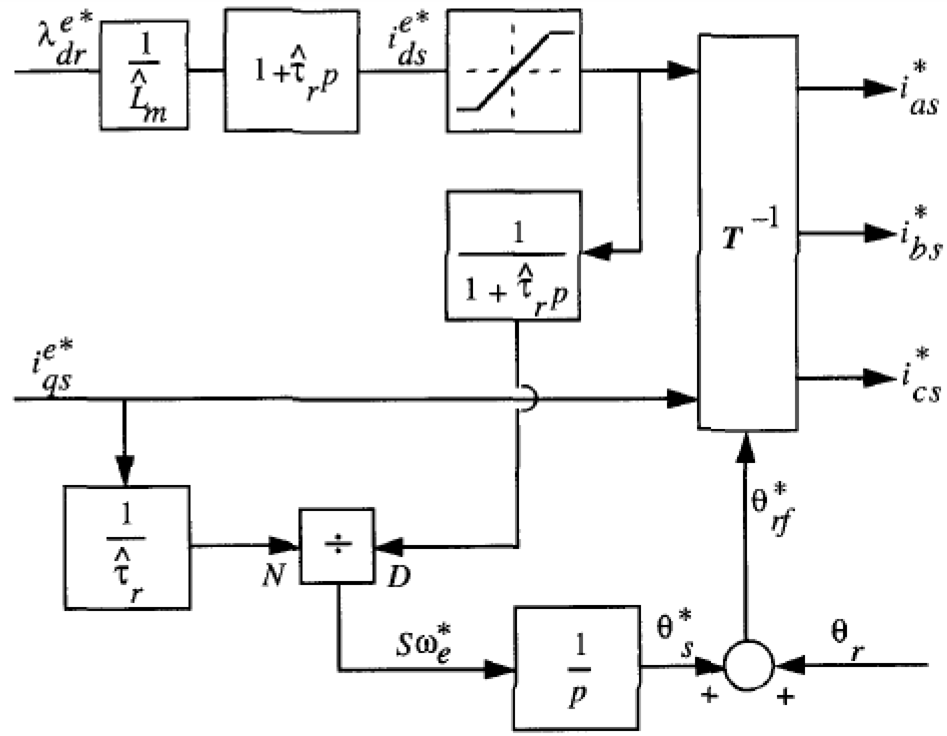


Figure 6.8 Indirect field orientation controller using flux and torque current commands with flux command current limiter

What about rotor currents in dynamics?

$$0 = L_r i_{qr} + L_m i_{qs} \quad \Rightarrow \quad i_{qr} = -\frac{L_m}{L_r} i_{qs}$$

$$0 = r_r i_{dr} + p\lambda_r \quad + \quad \lambda_r = L_r i_{dr} + L_m i_{ds}$$

$$\Downarrow$$

$$i_{dr} = -\frac{L_m p}{(r_r + L_r p)} i_{ds}$$

Therefore we have

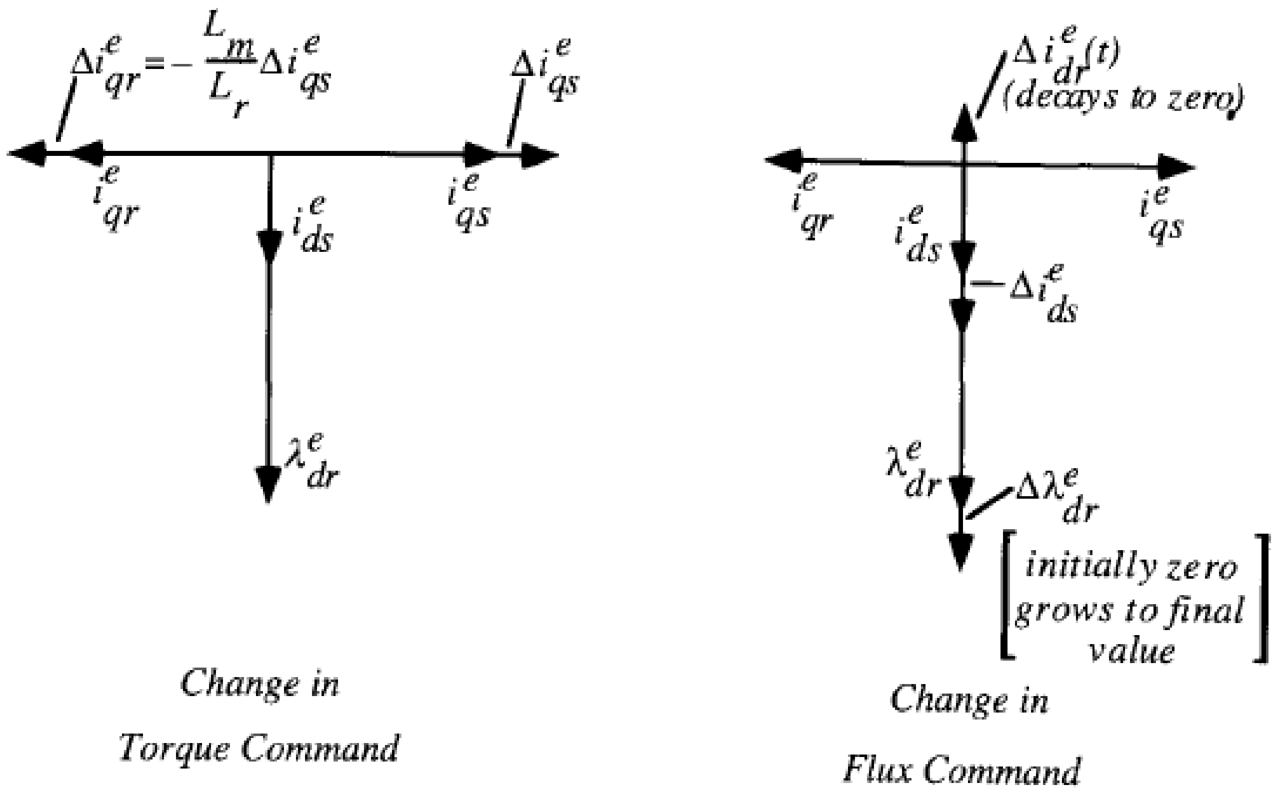


Figure 6.4 Illustration of response to step changes in torque command and flux command

$i_{dr} = 0$ In steady state

Direct field oriented controller

Overall strategy

- Knowledge of both the rotor flux and the developed torque are required

- The torque may be estimated directly in rotor-flux coordinates:

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m}{L_r}(\lambda^e_{dr} i^e_{qs})$$

or in stationary coordinates:

$$T_e = \frac{3}{2}\frac{P}{2}\mathrm{Im}\{\underline{\lambda}^*_{qds}\underline{i}_{qds}\}$$

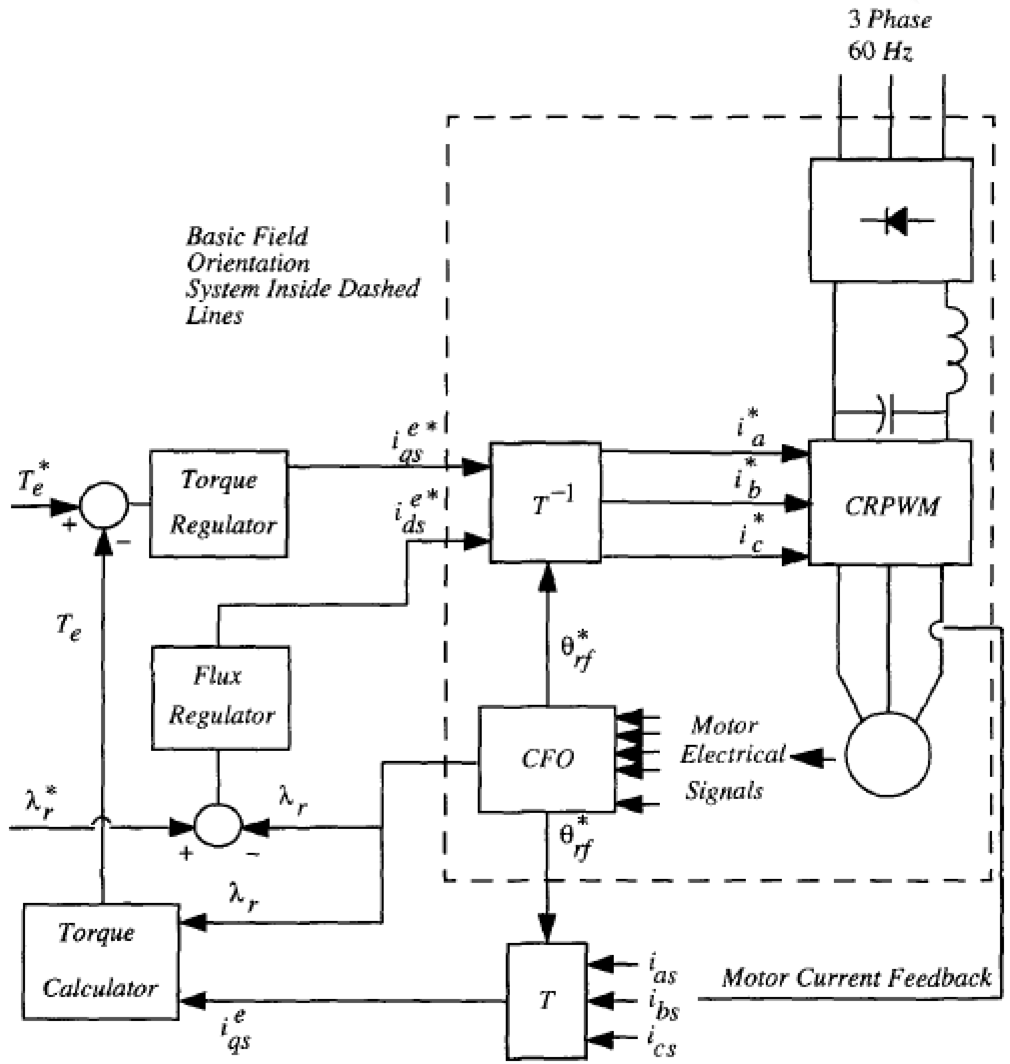


Figure 5.31 Direct implementation of induction machine field orientation using a CRPWM (torque and flux regulators optional)

Measurement of air gap flux

- Flux sensing coils or Hall elements detect

$$\underline{\lambda}_{qdm} = L_m(\underline{i}^s_{qds} + \underline{i}^s_{qdr})$$

- The rotor flux is

$$\underline{\lambda}^s_{qdr} = L_m\underline{i}^s_{qds} + L_r\underline{i}^s_{qdr}$$

- Eliminating the rotor current gives

$$\underline{\lambda}^s_{qdr} = \frac{L_r}{L_m}\underline{\lambda}^s_{qdm} - (L_r - L_m)\,\underline{i}^s_{qds} = \frac{L_r}{L_m}\underline{\lambda}^s_{qdm} - L_{lr}\underline{i}^s_{qds}$$

Properties:

1. Independent of the rotor position
2. Good accuracy except in the low-speed region
3. Fragile sensors are needed in the air gap
4. Depends on two motor parameters

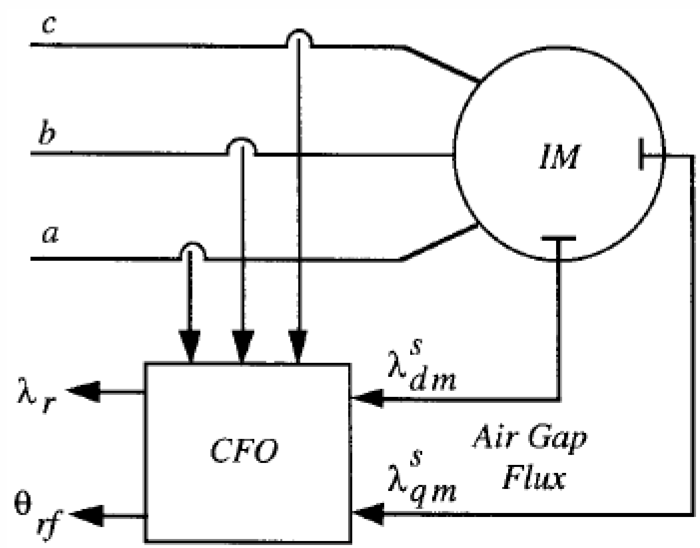
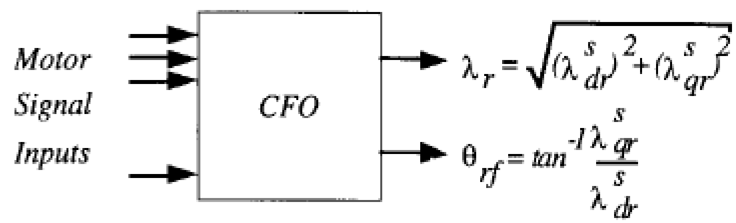


Figure 6.15 Field angle determination using flux sensors



Flux Computer & Field Orienter

Figure 6.14 Rotor flux computer and field orientation

Methods to estimation of rotor flux

- In practice the rotor flux is estimated from measurements of two or more of the following signals:
  1. The stator current
  2. The stator voltage (difficult to measure – may be estimated from the PWM and the VSI.)
  3. The rotor speed
  4. The rotor position

- A large number of methods (estimators/observers) exist (see next transparency)

Note:

1. All analyses are made in the continuous time domain despite that the implementation is often made in a sampled-data system
2. Other practical problems such as measurement offset, initial values for integrators, etc. are disregarded also

Exercise:

Finish the provided Simulink model to realize a in-direct rotor field oriented controller for induction machine. To have a simple implementation, the relationship between stator d-axis current and rotor flux, slip estimation, may only be considered in steady state.