Electric Machine Control

Chapter 5

Principles of Vector Control and Field Orientation

Woei-Luen Chen

5.1 Introduction

- Steady state analysis
  - Torque control
  - Field orientation
- Vector control includes
  - Amplitude control of ac excitation
  - Phase control of ac excitation
- Field orientation (Field angle control)
  - The vector control or current and voltages results in spatial orientation of the electromagnetic fields
  - Maintain a 90 degree spatial orientation between critical field components

5.2 DC Machine Torque Control

- The **orthogonality** between field flux and armature MMF
  - The action of the commutator is to reverse the direction of the armature winding currents as the coils pass the brush position such that the armature current distribution is fixed in space no matter what rotor speed exists.
- If the orthogonality were disturbed, two major complications occur:
  - The field flux is no longer independent of the armature current
  - The voltage and torque relations were be modified by addition of an angle dependent function

The electromagnetic interaction between the field flux and the armature MMF results in two basic outputs:

➢**An induced voltage: proportional to rotor speed**

$$E_a = \frac{P}{2}\lambda_{af}\omega_{rm} \qquad (5.2\text{–}1)$$

➢**An electromagnetic torque: proportional to the armature current**

$$T_e = \frac{P}{2}\lambda_{af}I_a \qquad (5.2\text{–}2)$$

➢**The flux linking the armature is related to the total field linkage λ_f**

$$\lambda_{af} = \frac{L_{af}}{L_{lf}+L_{af}}\lambda_f = \frac{L_{af}}{L_f}\lambda_f \qquad (5.2\text{–}3)$$

$$\Rightarrow \quad T_e = \frac{p}{2}\frac{L_{af}}{L_f}\lambda_f I_a \qquad (5.2\text{–}4)$$

The field flux and armature MMF are maintained in a <u>mutually perpendicular orientation</u> independent of rotor speed.

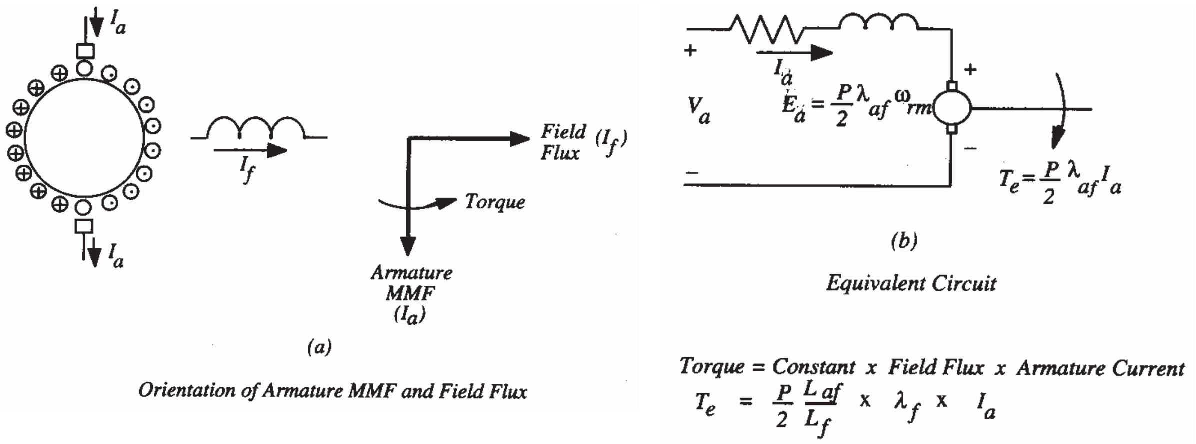


Figure 5.1 DC machine model

Adjustable speed/ torque operation

- Adjustable speed operation
  - attained by operating with a **fixed field flux** and a **varying the armature voltage**
  - **No load speed (Ia=0, Va=Ea): determined by Va**
  - **Ia≠0, speed is determined by <u>armature voltage and torque</u> required to supply the load**
    - Every armature voltage has an associated torque-speed curve
    - Current and speed are determined by the load with the torque-speed char. set by the excitation
- Adjust torque operation
  - attained by the **armature current control** instead of the voltage
  - The voltage and torque relations were be modified by addition of an angle dependent function

怎么理解？

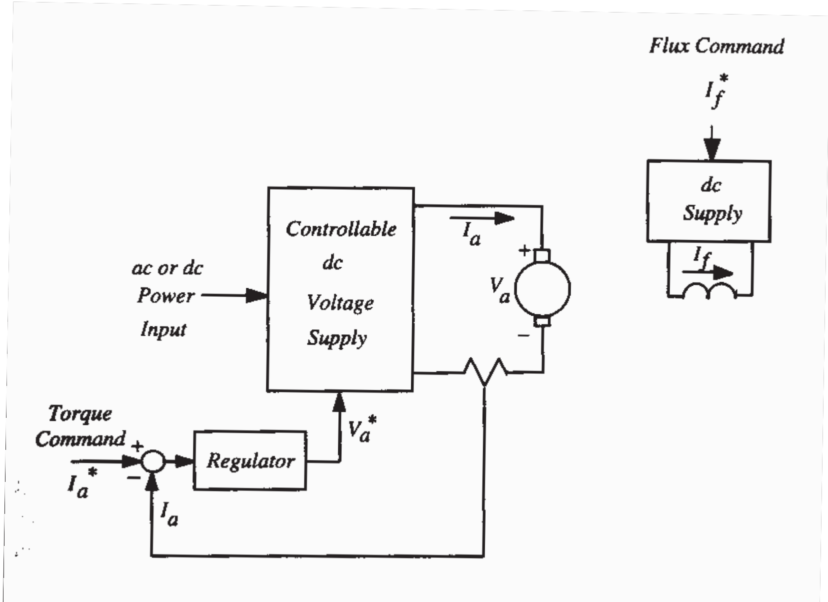


Figure 5.2 Elements of a torque controlled separately excited dc motor drive

5.3 Requirements for Torque Control

- For the dc machine, the requirements for torque control:
  - An independently controlled **armature current** to overcome the effects of armature winding resistance, leakage inductance and induced voltage
  - An independently controlled or constant value of the **field flux**
  - An independently controlled **orthogonal spatial angle** between the flux axis and the MMF axis to avoid interaction of the MMF and the flux

are assured by the commutator and the separate field excitation system for a dc machine

must be achieved by external controls for a ac machines

5.4 Synchronous Machine Vector Control

- The CSI driven synchronous machine
  - The CSI current can be controlled in both amplitude and phase
  - Field winding can be controlled as in the dc machine
  - The space position of the dc field is clearly located in space by the position of the rotor

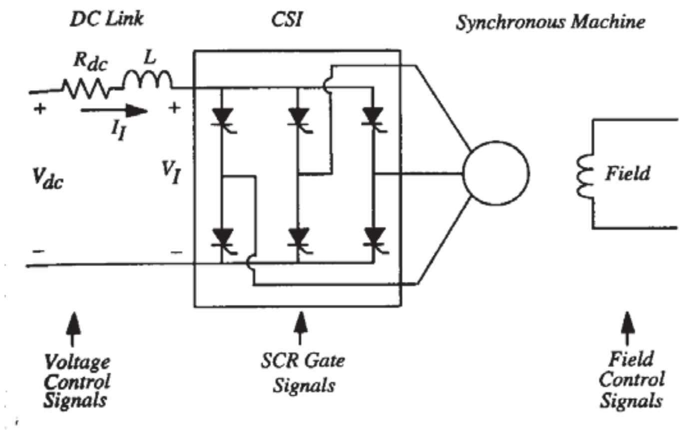


Figure 5.3 CSI–synchronous machine system

5.4.1 CSI-Synchronous Machine

- Sensing the rotor position
  - Leading current is achievable
  - Self-synchronous
  - Locate the field winding axis
  - Control the firing of the SCRs in the inverter and hence control the field angle

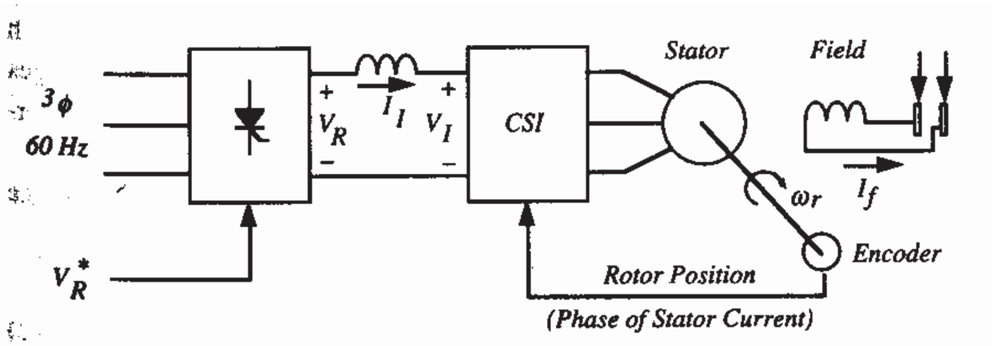


Figure 5.4 Commutatorless dc motor utilizing direct feedback of rotor position to control phase of stator current

lagging

leading

$$E_a = \omega_{re}\lambda_{af} = \frac{P}{2}\omega_{rm}\lambda_{af} \quad (5.4\text{–}1)$$

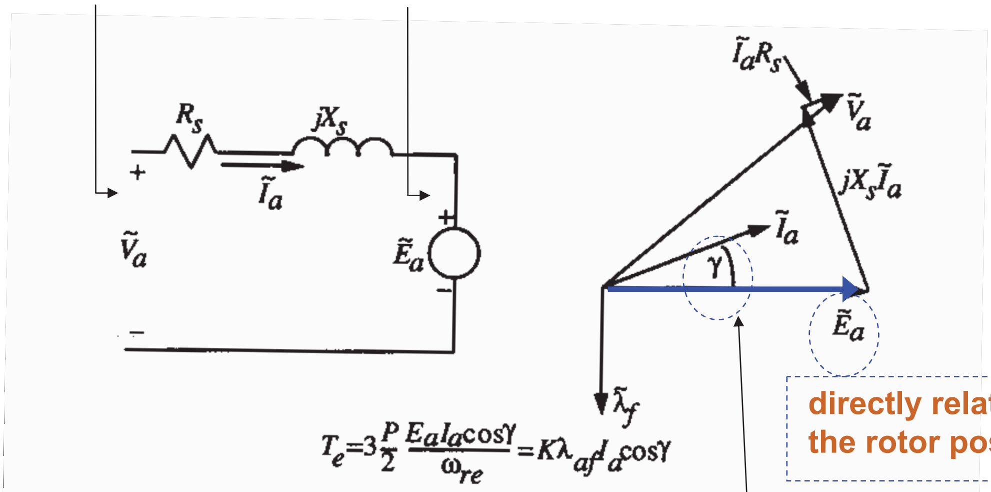


Figure 5.5 Phasor diagram and torque equation for commutatorless dc motor with positive γ

directly related to the rotor position

can be directly controlled by rotor position feedback loop

Internal voltage and machine torque

$$E_a = \omega_{re}\lambda_{af} = \frac{P}{2}\omega_{rm}\lambda_{af} \quad (5.4\text{–}1)$$

$$T_e = 3\frac{P}{2}\frac{E_aI_a\cos\gamma}{\omega_{re}} \quad (5.4\text{–}2)$$

$$T_e = 3\frac{P}{2}\lambda_{af}I_a\cos\gamma \quad (5.4\text{–}3)$$

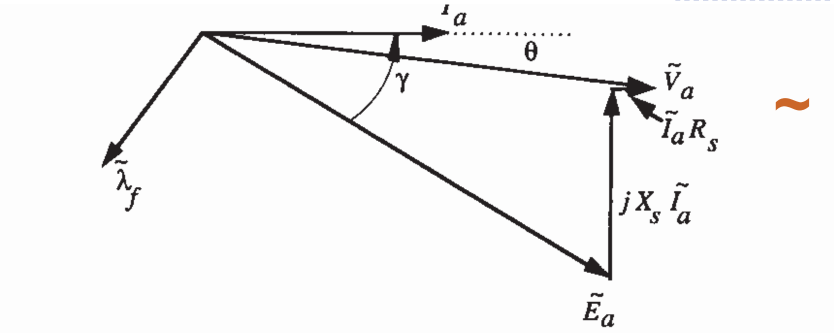
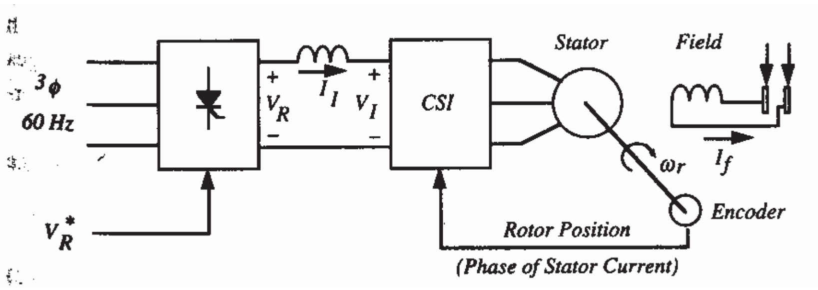


Figure 5.6 Phasor diagram for larger value of γ showing current leading voltage

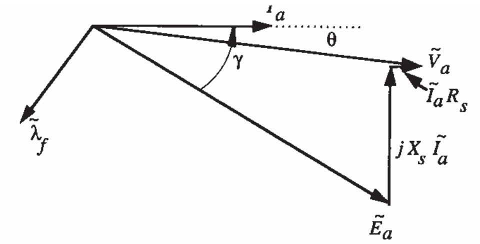
$$\sim \quad T_e = \frac{P}{2}\lambda_{af}I_a \quad (5.2\text{–}2)$$

(dc machine)



$$V_I I_I = (V_R - I_I R_{dc}) I_I = 3 V_a I_a \cos\theta \qquad (5.4\text{–}4)$$

$$I_I = \frac{\pi}{\sqrt{6}} I_a \qquad (5.4\text{–}5)$$



$$\boxed{V_a \cos\theta = E_a \cos\gamma + I_a R_s} \qquad (5.4\text{–}6)$$

$$\boxed{\left(V_a \cos\theta \right) I_a = \left(E_a \cos\gamma + I_a R_s \right) I_a}$$

$$V_R \frac{\pi}{3\sqrt{6}} = E_a \cos\gamma + \left(R_s + \frac{\pi^2}{18} R_{dc} \right) I_a \qquad (5.4\text{–}7)$$

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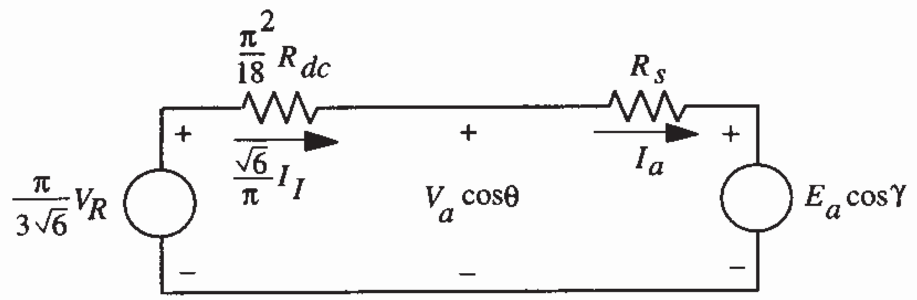
$$\boxed{V_R \frac{\pi}{3\sqrt{6}} = E_a \cos\gamma + \left(R_s + \frac{\pi^2}{18} R_{dc} \right) I_a \qquad (5.4\text{–}7)}$$



$$E_a = K \lambda_{af} \omega_{rm}$$

Figure 5.7 Equivalent circuit showing analogy to dc motor if γ = constant

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5.4.2 Torque control and choice of γ

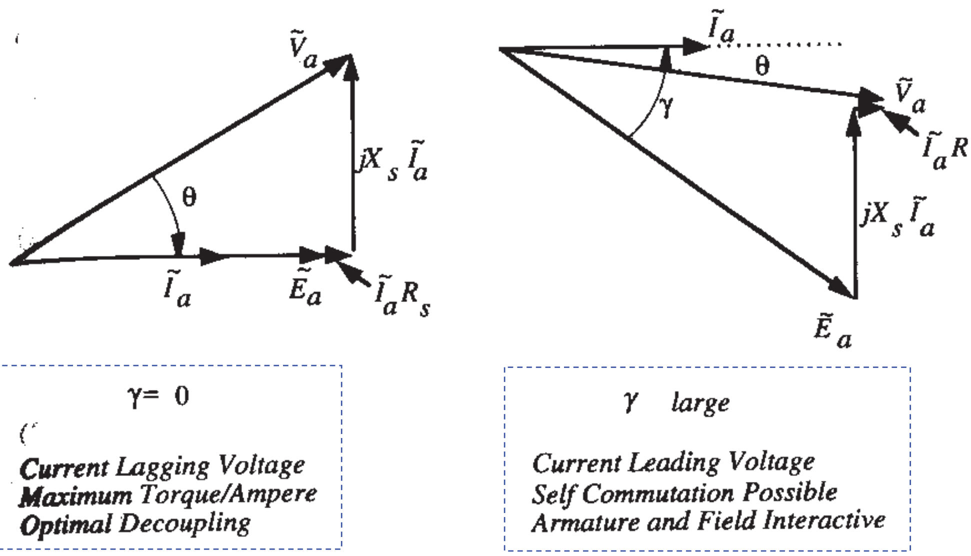


Figure 5.8 Influence of internal angle

5.5 Syn.M Steady-State d,q Model

5.5.1 steady state conditions in d,q variables

- The constraints for steady state are
  - Constant amplitude and phase of the stator current

$$i_{ds} = I_{ds} \qquad i_{qs} = I_{qs}$$

  - Constant rotor flux linkages
    - Zero currents in the damper windings

$$i_{qr} = i_{dr} = 0$$

  - Constant field current

$$i_{fr} = I_f$$

Steady-state torque equation

$$T_e = \frac{3}{2}\frac{P}{2}(\lambda_{ds} i_{qs} - \lambda_{qs} i_{ds}) \qquad (5.5\text{–}1)$$

$$T_e = \frac{3}{2}\frac{P}{2}[L_{md}(i_{fr} + \cancel{i_{dr}})\, i_{qs} - L_{mq}\cancel{i_{qr}}\, i_{ds} + (L_{ds} - L_{qs})\, i_{ds} i_{qs}] \qquad (5.5\text{–}2)$$

$$T_e = \frac{3}{2}\frac{P}{2}[L_{md} I_f I_{qs} + (L_{ds} - L_{qs}) I_{ds} I_{qs}] \qquad (5.5\text{–}3)$$

$$\boxed{\textit{Reaction Torque} = \frac{3}{2}\frac{P}{2} L_{md} I_f I_{qs} \qquad (5.5\text{–}4)}$$

$$\boxed{\textit{Reluctance Torque} = \frac{3}{2}\frac{P}{2}(L_{ds} - L_{qs}) I_{ds} I_{qs} \qquad (5.5\text{–}5)}$$

Steady-state voltage equations

$$\lambda_{qs} = L_{qs} I_{qs} \qquad (5.5\text{–}6)$$

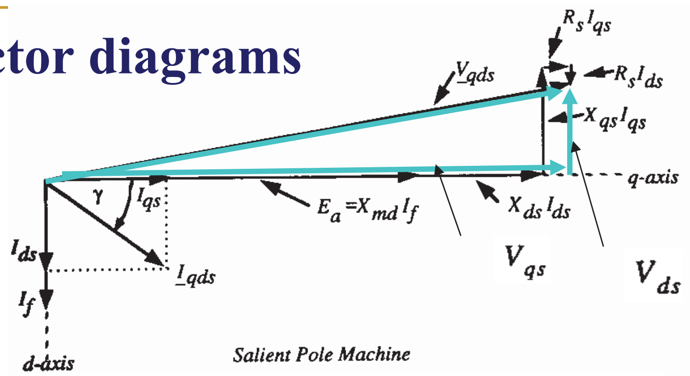
$$\lambda_{ds} = L_{ds} I_{ds} + L_{md} I_f \qquad (5.5\text{–}7)$$

$$E_a = \omega_e L_{md} I_f$$

$$V_{qs} = r_s I_{qs} + \omega_e (L_{ds} I_{ds} + L_{md} I_f) \qquad (5.5\text{–}8)$$

$$V_{ds} = r_s I_{ds} - \omega_e L_{qs} I_{qs} \qquad (5.5\text{–}9)$$

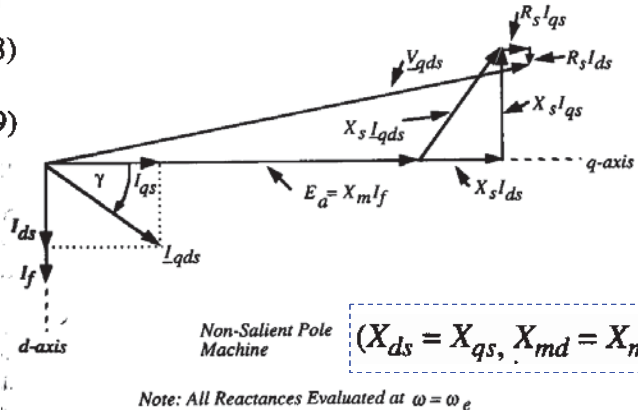
5.5.2 d,q variable vector diagrams



$$\boxed{E_a = \omega_e L_{md} I_f \qquad (5.5\text{–}10)}$$

$$V_{qs} = r_s I_{qs} + \omega_e (L_{ds} I_{ds} + L_{md} I_f) \qquad (5.5\text{–}8)$$

$$V_{ds} = r_s I_{ds} - \omega_e L_{qs} I_{qs} \qquad (5.5\text{–}9)$$



$$\boxed{(X_{ds} = X_{qs},\ X_{md} = X_{mq})}$$

Note: All Reactances Evaluated at $\omega = \omega_e$

Figure 5.9 Steady state vector diagrams showing internal voltage E_a, terminal voltage V_{qds} and the internal angle γ

Steady-state torque equation in terms of the angle γ

$$T_e = \frac{3}{2}\frac{P}{2}[L_{md}(i_{fr} + \cancel{i_{dr}})\, i_{qs} - L_{mq}\cancel{i_{qr}}\, i_{ds} + (L_{ds} - L_{qs})\, i_{ds}\, i_{qs}] \qquad (5.5\text{–}2)$$

$$T_e = \frac{3}{2}\frac{P}{2}[L_{md} I_f I_{qs} + (L_{ds} - L_{qs})\, I_{ds}\, I_{qs}] \qquad (5.5\text{–}3)$$

$$\text{Reaction Torque} = \frac{3}{2}\frac{P}{2} L_{md} I_f I_{qs} \qquad (5.5\text{–}4)$$

$$\text{Reluctance Torque} = \frac{3}{2}\frac{P}{2}(L_{ds} - L_{qs})\, I_{ds}\, I_{qs} \qquad (5.5\text{–}5)$$

$$E_a = \omega_e L_{md} I_f \qquad (5.5\text{–}10)$$

$$\text{Reaction Torque} = \frac{3}{2}\frac{P}{2}\frac{1}{\omega_e} E_a \underbrace{\boxed{I_{qds}\cos\gamma}}_{I_{qs}} \qquad (5.5\text{–}11)$$

$$\text{Reluctance Torque} = \frac{3}{2}\frac{P}{2}(L_{ds} - L_{qs})\, I_{qds}^2 \cos\gamma \sin\gamma \qquad (5.5\text{–}12)$$

Field orientation $(\gamma = 0)$

: with $(\gamma = 0)$, the stator current is entirely q-axis current and is equivalent to a torque command

$$\text{Reaction Torque} = \frac{3}{2}\frac{P}{2}\frac{1}{\omega_e} E_a \underbrace{\boxed{I_{qds}\cos\gamma}}_{I_{qs}} \qquad (5.5\text{–}11)$$

$$\text{Reluctance Torque} = \frac{3}{2}\frac{P}{2}(L_{ds} - L_{qs})\, I_{qds}^2 \cos\gamma \sin\gamma \qquad (5.5\text{–}12)$$

=0

Absence of d-axis stator current :

1.there is no reluctance torque

2.only q-axis reactance is involved in finding the terminal voltage

(no direct magnetization or demagnetization of the d-axis, only the field winding acts to produce flux in this direction)

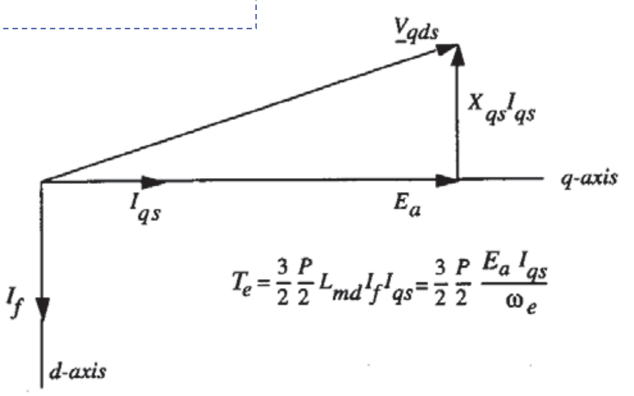


Figure 5.10 Steady state vector diagram for field orientation ($\gamma = 0$, $I_{ds} = 0$)

5.6 Torque Control Implementation-Syn.M

- Torque control
  - Angle control and field orientation concepts
    - Control of the magnitude and phase (vector control) of the stator current with respect to the location of the field winding axis
- Vector control of the stator current must be maintained for both steady-state and transient conditions

5.6.1 Torque control using field orientation with a CSI

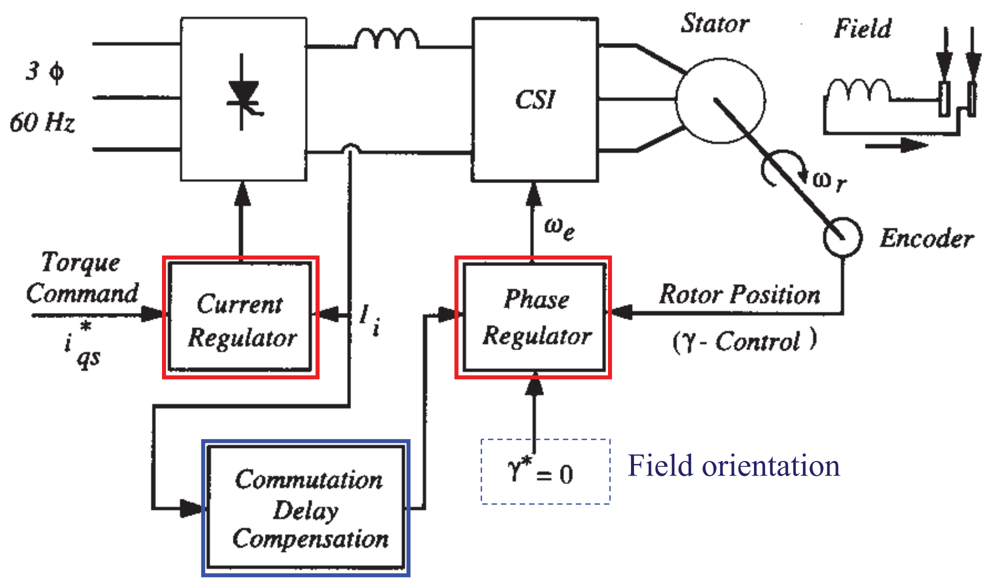


Figure 5.11 Torque control via field orientation using a current regulated CSI

5.6.2 Torque control using a CRPWM

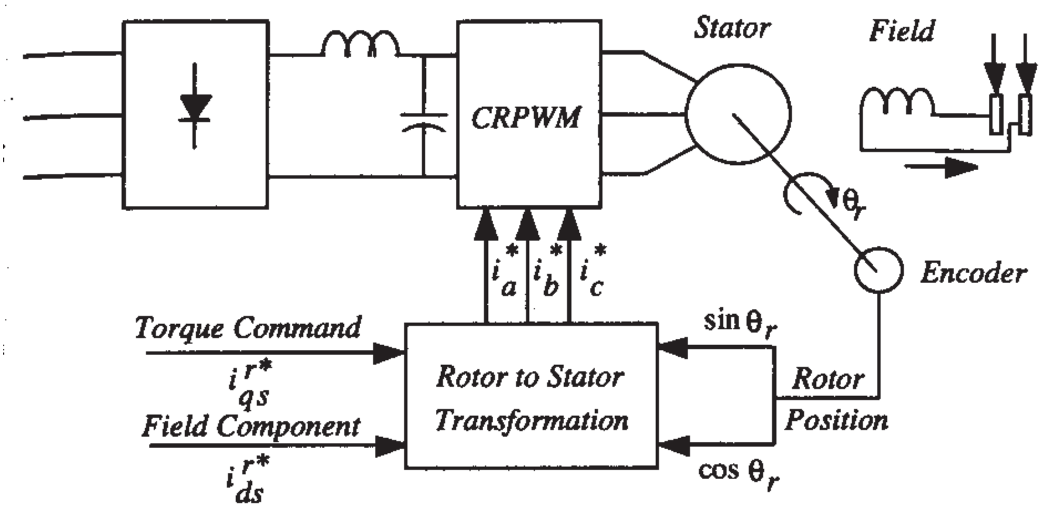


Figure 5.12 Torque control using a CPRWM. Field orientation requires $i_{ds} = 0$, $(\gamma = 0)$

Convert the dc signals (i_{ds}^* , i_{qs}^*) into ac signals (i_{as}^{s*} , i_{bs}^{s*} and i_{cs}^{s*}) for CRPWM

$$\boxed{i_{qds}^{s*} = e^{j\theta_r} i_{qds}^{r*} \quad (5.6\text{–}1)}$$

$$i_{as}^{s*} = i_{qs}^{r*} \cos\theta_r + i_{ds}^{r*} \sin\theta_r \qquad (5.6\text{–}2)$$

$$i_{bs}^{s*} = \left(-\frac{1}{2} i_{qs}^{r*} - \frac{\sqrt{3}}{2} i_{ds}^{r*}\right)\cos\theta_r + \left(\frac{\sqrt{3}}{2} i_{qs}^{r*} - \frac{1}{2} i_{ds}^{r*}\right)\sin\theta_r \qquad (5.6\text{–}3)$$

$$i_{cs}^{s*} = \left(-\frac{1}{2} i_{qs}^{r*} + \frac{\sqrt{3}}{2} i_{ds}^{r*}\right)\cos\theta_r + \left(\frac{\sqrt{3}}{2} i_{qs}^{r*} + \frac{1}{2} i_{ds}^{r*}\right)\sin\theta_r \qquad (5.6\text{–}4)$$

$$\begin{bmatrix} f_{as} \\ f_{bs} \\ f_{cs} \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta & 1 \\ \cos\left(\theta - 2\pi/3\right) & \sin\left(\theta - 2\pi/3\right) & 1 \\ \cos\left(\theta + 2\pi/3\right) & \sin\left(\theta + 2\pi/3\right) & 1 \end{bmatrix} \begin{bmatrix} f_{qs} \\ f_{ds} \\ f_{0s} \end{bmatrix}$$

5.6.3 Magnitude-angle resolver and use in CSI torque control

The magnitude output $\rightarrow$ **current command**

The angle output $\rightarrow$ γ **command**

- **Setting $i^{r*}_{ds} = 0$ results in field orientation $(\gamma = 0)$,**

which would be the preferred option for torque control unless there is a need to regulate the PF or some other terminal variable.

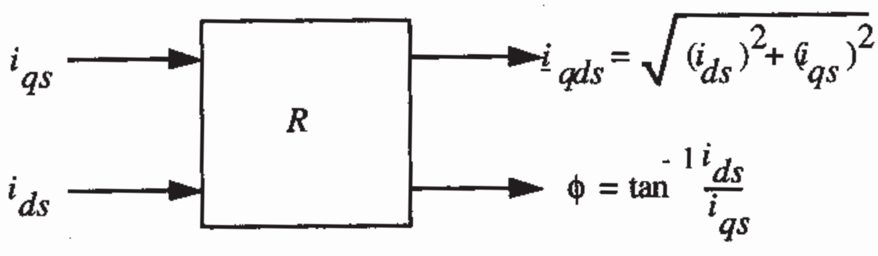
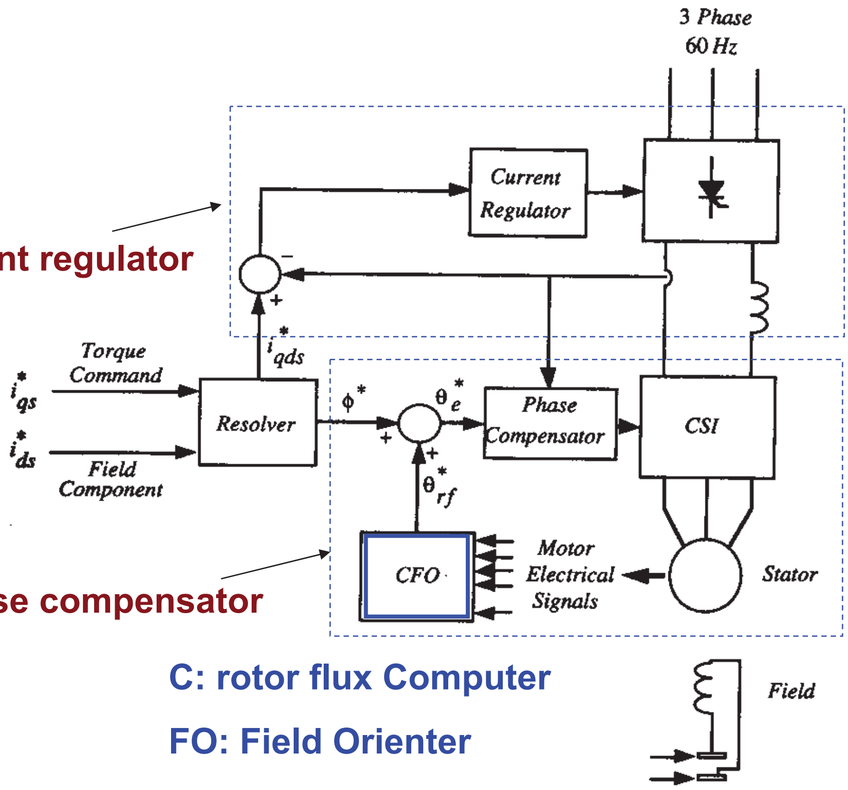


Figure 5.13 *d–q* to magnitude–angle resolver

5.7 Electrical Measurement of the Rotor Field Angle (θ_r)

- The use of an encoder or resolver (to measure the rotor flux position) on the shaft of the machine is undesirable
  - Cost
  - Reliability
- Electrical determination of rotor field angle (do not use encoder or resolver)
  - Require the knowledge of the **stator parameters**



Dc current regulator

Phase compensator

C: rotor flux Computer

FO: Field Orienter

Figure 5.14 Field orientation ($i_{ds}^* = 0$) or angle control in synchronous machine using electrical estimation of rotor flux angle

5.8 Brushless DC Machines

5.8.1 Sine wave machines with current control ---for distributed coil windings

- Resulting sinusoidal back EMF to produce high performance brushless dc machines
  - Employ a high resolution encoder or reslover and a CRPWM power supply
  - With zero value of the field component of current, the armature MMF and field flux are orthogonal and the torque is directly proportional to current

5.8.2 Trapezoidal wave machines with current control ---for concentrated coil windings

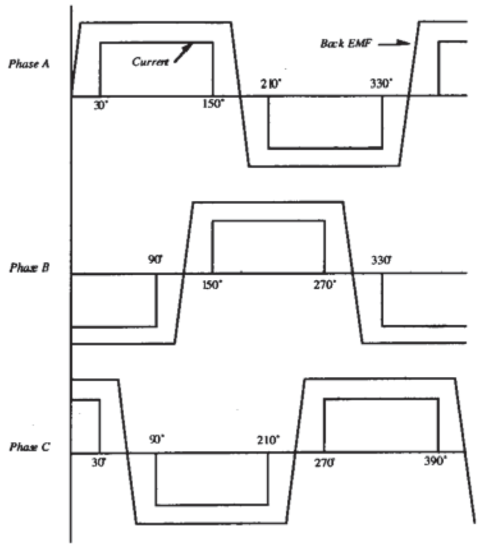


Figure 5.15 Back EMF and current in trapezoidal flux brushless dc machine

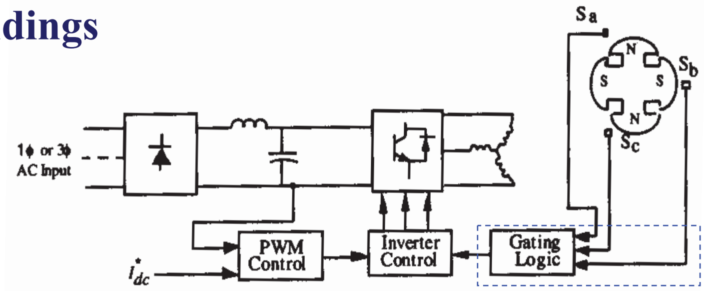


Figure 5.16 Trapezoidal EMF motor used as brushless dc machine

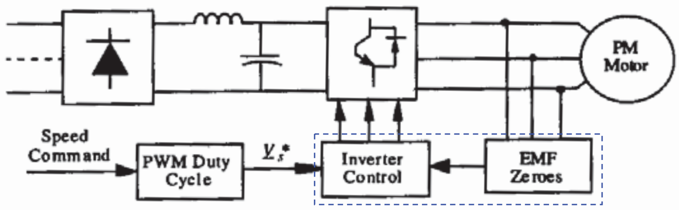


Figure 5.17 Brushless dc machine using voltage sensing to control spatial angle (no current loop)

Back EMF can be measured as there is a phase off (zero stator current)

5.9 IM Vector Control-Steady State

- How vector control of induction machine stator current can be employed to directly control torque?

5.9.1 Conventional equivalent circuit considerations

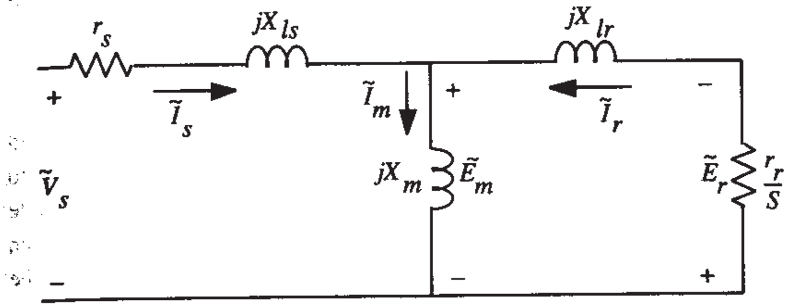
Synchronous machine

Ea was controlled directly by the field current

Induction machine

Independently controlling Er is needed

The phase angle between Er and Ir is automatically zero, corresponding to the **field oriented** synchronous machine (γ =0)



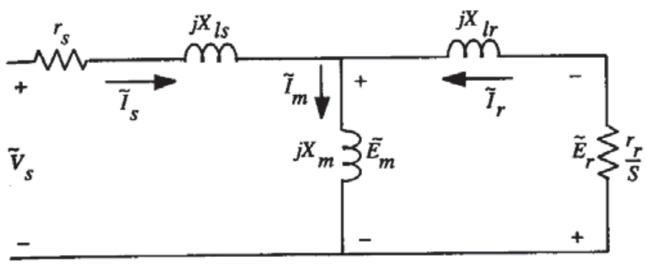
$$T = 3\frac{P}{2}\frac{I_r^2 r_r}{S\omega_e} = 3\frac{P}{2}\frac{E_r I_r}{\omega_e}$$

(5.9–1) (5.9–2)

rms

Figure 5.18 Conventional induction motor equivalent circuit showing rotor induced voltage E_r

5.9.2 Modified equivalent circuit



变换的原则和意义（理解）？

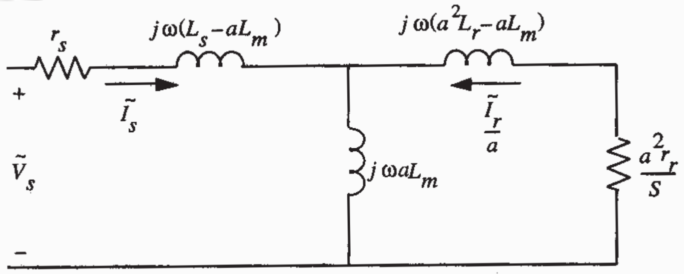


Figure 5.19 General equivalent circuit showing arbitrary value of referral ratio a ($a = N_s/N_r$ yields the conventional circuit of Figure 5.18)

$$a = \frac{L_m}{L_r} \quad (5.9\text{–}3)$$

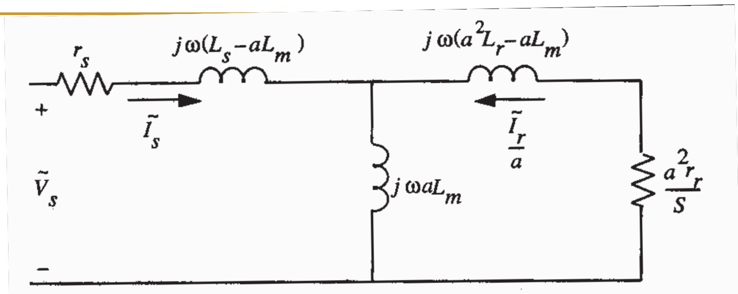
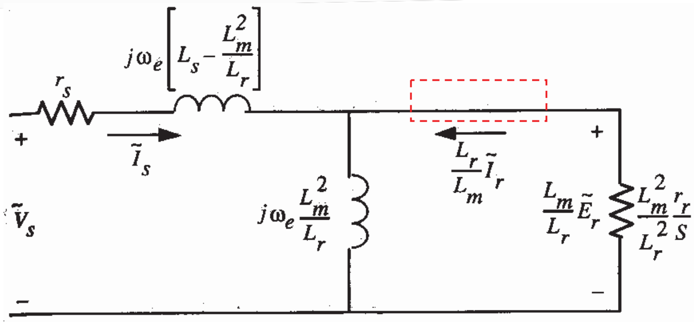


Figure 5.19 General equivalent circuit showing arbitrary value of referral ratio a ($a = N_s/N_r$ yields the conventional circuit of Figure 5.18)

The new magnetizing reactance has the same voltage across its terminals and can therefore be directly associated with the flux producing the voltage Er.

The magnetizing current responsible for the rotor flux and Er, rather than the air gap flux and Em.

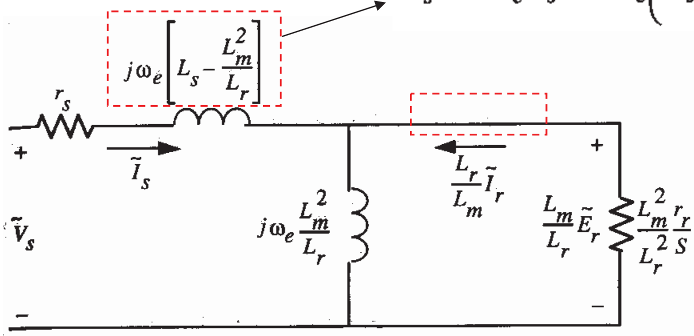


$$L_s - \frac{L_m^2}{L_r} = L_s' = \text{stator transient inductance}$$

Figure 5.20 Induction motor equivalent circuit without rotor leakage – referral ratio $a = L_m/L_r$

The magnetizing current in this new circuit is responsible for the rotor flux and Er, rather than the air gap flux and Em.

$$X_s' = \omega_e L_s' = \omega_e\left(L_s - \frac{L_m^2}{L_r}\right) \quad (5.9\text{–}4)$$



$$L_s - \frac{L_m^2}{L_r} = L_s' = \text{stator transient inductance}$$

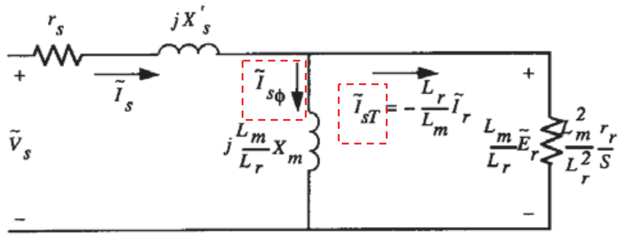
Figure 5.20 Induction motor equivalent circuit without rotor leakage – referral ratio $a = L_m/L_r$

Stator components : $I_{s\phi}$ and I_{sT}

Rotor flux control — **Torque control**

$$\tilde{I}_{s\phi} = \frac{\frac{L_m}{L_r}\tilde{E}_r}{j\frac{L_m}{L_r}X_m} = \frac{\tilde{E}_r}{jX_m} = \frac{\tilde{E}_r}{j\omega_e L_m} \quad (5.9\text{–}6)$$

$$\tilde{I}_{sT} = -\frac{L_r}{L_m}\tilde{I}_r \quad (5.9\text{–}8)$$



$$T_e = 3\frac{P}{2}\frac{L_m}{L_r}\lambda_r I_{sT} \qquad \lambda_r = L_m I_{s\phi}$$

Figure 5.21 Equivalent circuit showing torque component (I_{sT}) and rotor flux component ($I_{s\phi}$) of stator current

5.9.3 Torque control in terms of $I_{s\phi}$ and I_{sT}

$$E_r = j\omega_e\lambda_r \quad (5.9\text{–}5)$$

$$\tilde{\lambda}_r = L_m\tilde{I}_{s\phi} \quad (5.9\text{–}7)$$

$$T_e = 3\frac{P}{2}\frac{E_r I_r}{\omega_e} = 3\frac{P}{2}\frac{1}{\omega_e}(\omega_e L_m I_{s\phi})\left(\frac{L_m}{L_r}I_{sT}\right) = 3\frac{P}{2}\frac{L_m^2}{L_r}\boxed{I_{s\phi}I_{sT}} \quad (5.9\text{–}9)$$

~ similarity to the field oriented synchronous machine

- $I_{s\phi}$ **playing the role of field current control**
- I_{sT} **playing the role of stator current control**

什么意思？

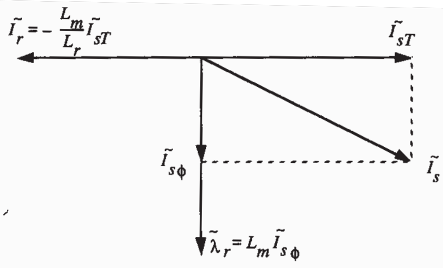


Figure 5.22 Phasor diagram showing torque and flux components of stator current

Indirect field orientation

Relation between I_{sT} and $I_{s\phi}$

$$\tilde{I}_{sT} = \frac{\dfrac{L_m}{L_r}\tilde{E}_r}{\dfrac{L_m^2 r_r}{L_r^2 S}} = \frac{L_r S\tilde{E}_r}{L_m r_r} \qquad (5.9\text{–}10)$$

$$\tilde{I}_{sT} = j\frac{L_r}{r_r}S\omega_e\tilde{I}_{s\phi} \qquad (5.9\text{–}11)$$

$$S\omega_e = \frac{r_r I_{sT}}{L_r I_{s\phi}} \qquad (5.9\text{–}12)$$

- Choose I_{sT} and $I_{s\phi}$ and compute $S\omega_e$ to attain the proper operating point.
- Stator current and slip frequency in an IM completely determines the torque.

怎么理解？

5.9.4 Terminal behavior in terms of $I_{s\phi}$ and I_{sT}

- Smaller X's → better pf and smaller terminal voltage is needed
- Torque and flux control involving $I_{s\phi}$ and I_{sT} are independent of rotor speed and frequency
- Terminal voltage and pf are obviously speed dependent

理解？

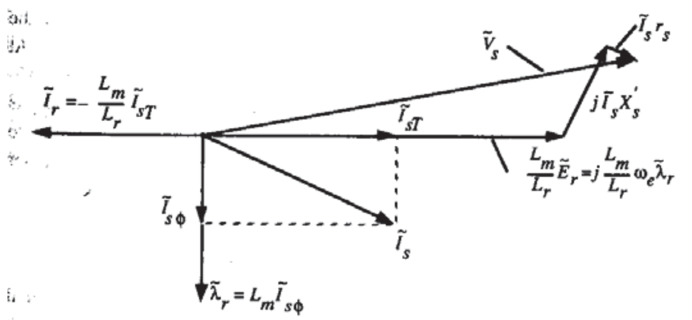
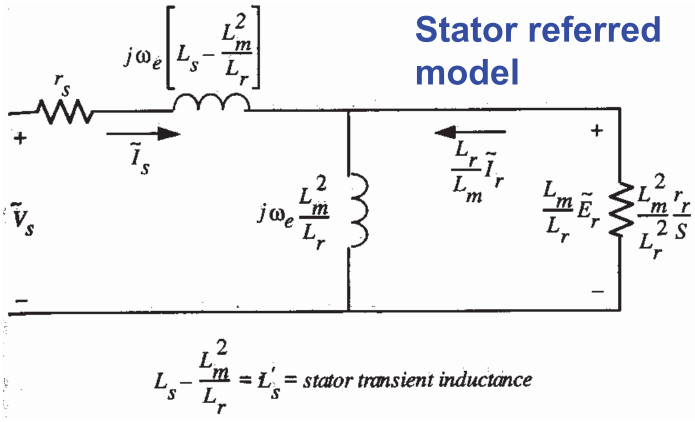


Figure 5.23 Phasor diagram showing rotor induced voltage and terminal voltage

5.10 IM Steady-State d,q Model

Stator referred model



$$I_{s\phi} = I_{ds} / \sqrt{2}$$

$$I_{sT} = I_{qs} / \sqrt{2}$$

Synchronous RF model

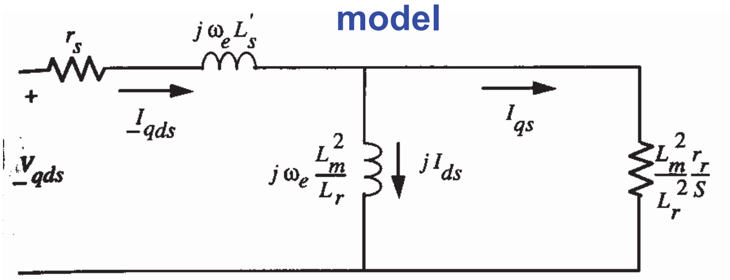
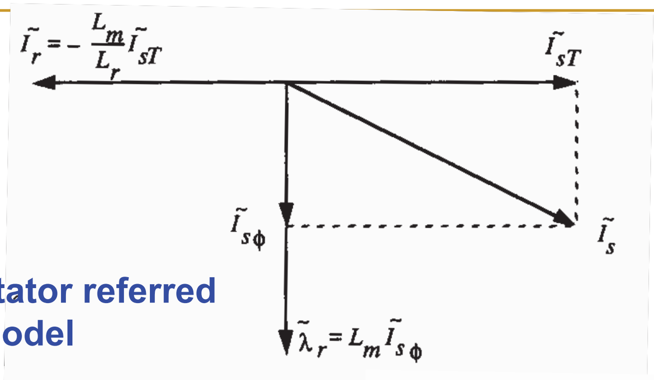
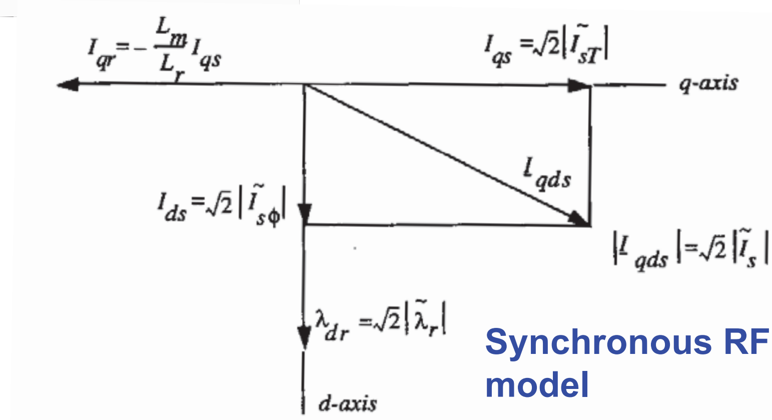


Figure 5.24 Equivalent circuit using complex steady state d–q currents – synchronously rotating reference centered on rotor flux vector



Stator referred model



Synchronous RF model

Figure 5.25 Steady state d,q currents – synchronously rotating reference centered on the rotor flux vector

5.10.1 Example- Induction machine field orientation

A 100 hp, 460 volt, induction machine is operated from an ideal controlled current electronic converter using field oriented control. The pu parameters of the machine are, in conventional per–phase symbols: (at rated frequency)

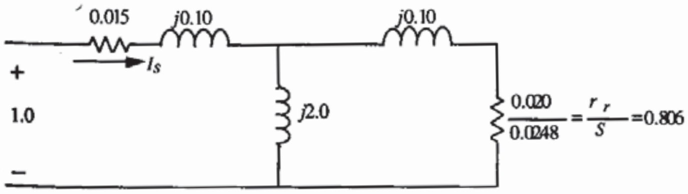
$r_s = 0.015$ pu $\quad x_{ls} = 0.10$ pu $\quad x_m = 2.0$ pu

$r_r = 0.020$ pu $\quad x_{lr} = 0.10$ pu

The rated slip is 0.0248. Express all answers in real units.

a) Find the required values of i_{qs} and i_{ds} and the slip relation relating $S\omega_e$, i_{qs} and λ_{dr} to produce operation at rated torque and rated speed if the terminal voltage and frequency are held at their rated values.

b) Find the final steady state torque and slip frequency if i_{ds} is reduced to one half its value in part a while the stator current amplitude is held constant at the value in part a. Find the terminal voltage and stator frequency if the new speed is twice that in part (a).



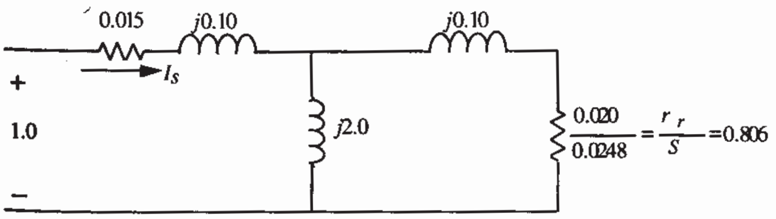
The solution assumes the following:

1) The machine has 4 poles

2) The per unit base is 100 hp, $460/\sqrt{3}$ V rms for phasors, $460\sqrt{2/3}$ V peak for d-q components.

$$I_{base} = \frac{(100\text{ hp})\ (746\text{ W/hp})}{\sqrt{3}\,(460\text{ V})} = 93.6\text{ A rms }(132\text{ A peak})$$

$$z_B = \frac{V_B^2}{P_B} = \frac{(460)^2}{(100)\ (746)} = 2.84\text{ ohms}$$

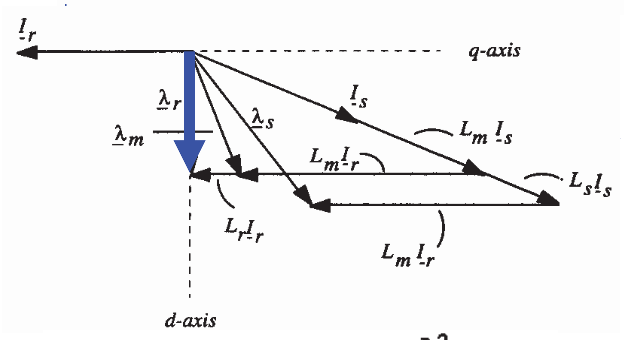


$$\tilde{I}_s = \frac{1 + j0}{(0.015 + j0.10) + [\,j2.0 \parallel (0.806 + j0.10)\,]} = 1.053 - j0.7105 \Rightarrow \left|\tilde{I}_s\right| = 1.27\text{ pu}$$

a) Find the required values of i_{qs} and i_{ds} and the slip relation relating $S\omega_e$, i_{qs} and λ_{dr} to produce operation at rated torque and rated speed if the terminal voltage and frequency are held at their rated values.

The rotor flux linkage is: $\lambda_{dr} = L_r i_{dr} + L_m i_{ds}$ ($i_{dr} = 0$ in steady state).
Hence, $\lambda_{dr} = L_m i_{ds}$. Therefore,

$$S\omega_e = \frac{r_r}{L_r}\frac{|I_{qs}|}{|I_{ds}|}$$



$$\underline{V}_s = (r_s + j\omega_e L_s')\,\underline{I}_s + j\omega_e \frac{L_m^2}{L_r}(-jI_{ds}) \quad (4.6\text{–}17)$$

$$0 = \frac{r_r}{S} I_{qr} + j\omega_e L_m(-jI_{ds}) \quad (4.6\text{–}18)$$

$$0 = -\left(\frac{L_m}{L_r}\right)^2\left(\frac{r_r}{S}\right) I_{qs} + j\omega_e\left(\frac{L_m^2}{L_r}\right)(-jI_{ds}) \quad (4.6\text{–}19)$$

(4.6–12)

a) Find the required values of i_{qs} and i_{ds} and the slip relation relating $S\omega_e$, i_{qs} and λ_{dr} to produce operation at rated torque and rated speed if the terminal voltage and frequency are held at their rated values.

$$\left(\frac{S\omega_e L_r |I_{ds}|}{r_r}\right)^2 = |I_s|^2 - |I_{ds}|^2$$

$$\left(\frac{(0.0248)\ (1.0)\ (2.0 + 0.1)\,|I_{ds}|}{0.020}\right)^2 = (1.27)^2 - |I_{ds}|^2$$

$$\Rightarrow \quad |I_{ds}| = 0.456\text{pu}$$

$$|I_{qs}| = 1.19 \text{ pu (rms)}$$

b) Find the final steady state torque and slip frequency if i_{ds} is reduced to one half its value in part (a) while the stator current amplitude is held constant at the value in part (a). Find the terminal voltage and stator frequency if the new speed is twice that in part (a).

$$|I_{ds}| = \frac{1}{2}(0.456) = 0.228 \text{ pu} \quad (30.2 \text{ A peak})$$

$$|I_{qs}| = \sqrt{|I_s|^2 - |I_{ds}|^2} = \sqrt{1.27^2 - 0.228^2} = 1.25 \text{ pu} \ (165 \text{ A peak}$$

$$T_e = \frac{3}{2}\frac{P}{2}\frac{L_m^2}{L_r} I_{qs} I_{ds} = \left(\frac{3}{2}\right)\left(\frac{4}{2}\right)\frac{(2.0)^2 (z_B/\omega_B)^2}{(2.1)(z_B/\omega_B)}(30.2)(165)$$

$$= 214.8 \text{ N-m}$$

$$(S\omega_e) = \frac{r_r |I_{qs}|}{L_r |I_{ds}|} = \left[\frac{0.020}{2.1}\frac{(z_{base})}{z_{base}/\omega_{base}}\right]\frac{165 \text{ A}}{30.2 \text{ A}} = 19.6 \text{ rad/s}$$

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b) Find the final steady state torque and slip frequency if i_{ds} is reduced to one half its value in part (a) while the stator current amplitude is held constant at the value in part (a). Find the terminal voltage and stator frequency if the new speed is twice that in part (a).

$$\omega_r = 2(\omega_e - S\omega_e) = 2\underbrace{(377 - 9.35)}_{\text{(a)}} = 735 \text{ rad/s}$$

The frequency is

$$\omega_e = \omega_r + (S\omega_e) = 735 + 19.0 = 754 \text{ rad/s}$$

$$\underline{V}_{qds} = \underline{I}_{qds}\left[r_s + j\left(X_s - \frac{X_m^2}{X_r}\right)\right] + I_{ds}\left(j\frac{X_m^2}{X_r}\right)$$

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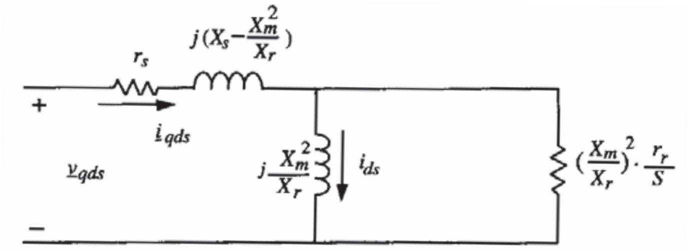
b) Find the final steady state torque and slip frequency if i_{ds} is reduced to one half its value in part (a) while the stator current amplitude is held constant at the value in part (a). Find the terminal voltage and stator frequency if the new speed is twice that in part (a).



Let $\underline{I}_{qds} = |I_{qs}| - j|I_{ds}|$ and $\underline{I}_{ds} = -j|I_{ds}|$. Remember the frequency is 754 rad/s (= 2.0 pu). This affects the reactance value proportionately. Substituting

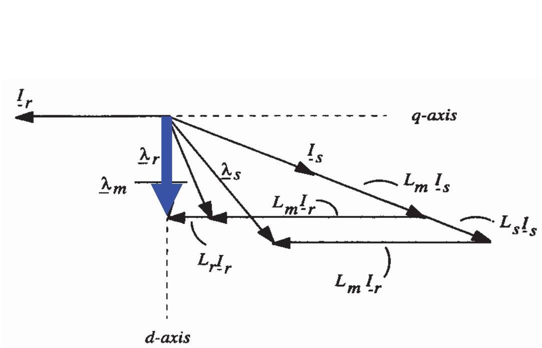
$$\underline{V}_{qds} = (1.25 - j0.228)\left[0.015 + j\frac{754}{377}\left(2.1 - \frac{2^2}{2.1}\right)\right] + (-j0.228)\left(j\frac{2^2}{2.1}\right)\left(\frac{754}{377}\right)$$

$$\underline{V}_{qds} = 1.12 - j0.0256 \text{ pu}$$

$$|\underline{V}_{qds}| = |1.12 - j0.0256|\,(460)\,\sqrt{2/3} = 420.7\,\text{V}\ (514\ \text{V}\ l\text{–}l\ \text{rms})$$

5.11 Implementation of Field Orientation in IM

- Rotor flux determination
  - Direct scheme: electrically determine the angle from flux measurements
  - Indirect scheme: measure the rotor position and utilize the slip relation to compute the angle of the rotor flux relative to the rotor



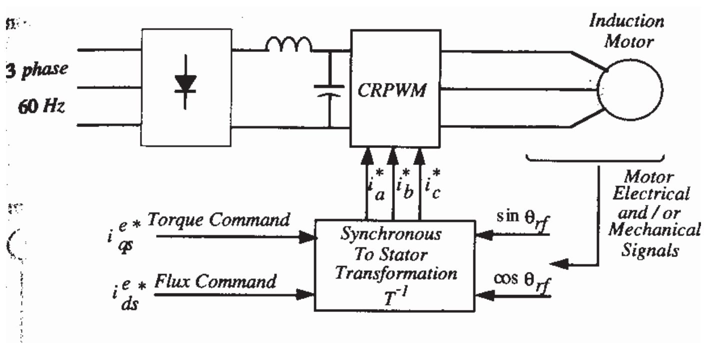


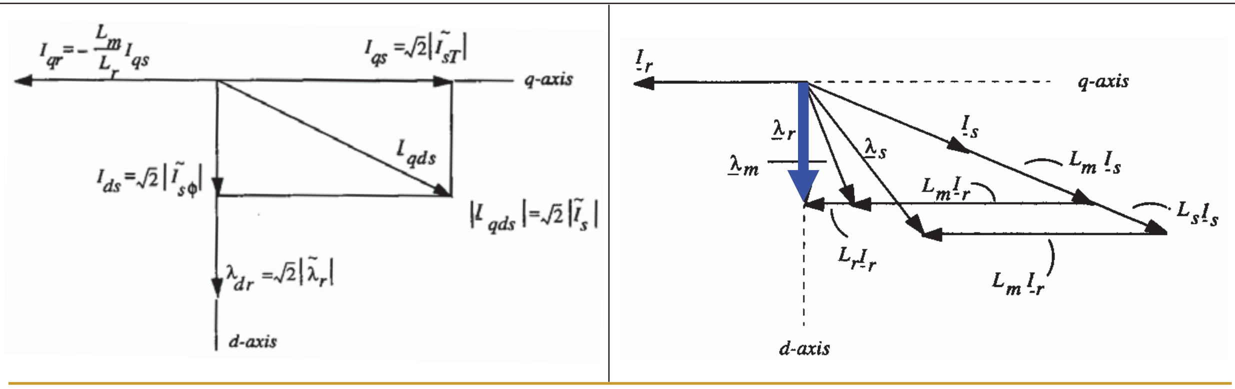
Figure 5.26 Basic induction motor field orientation system using a CPRWM

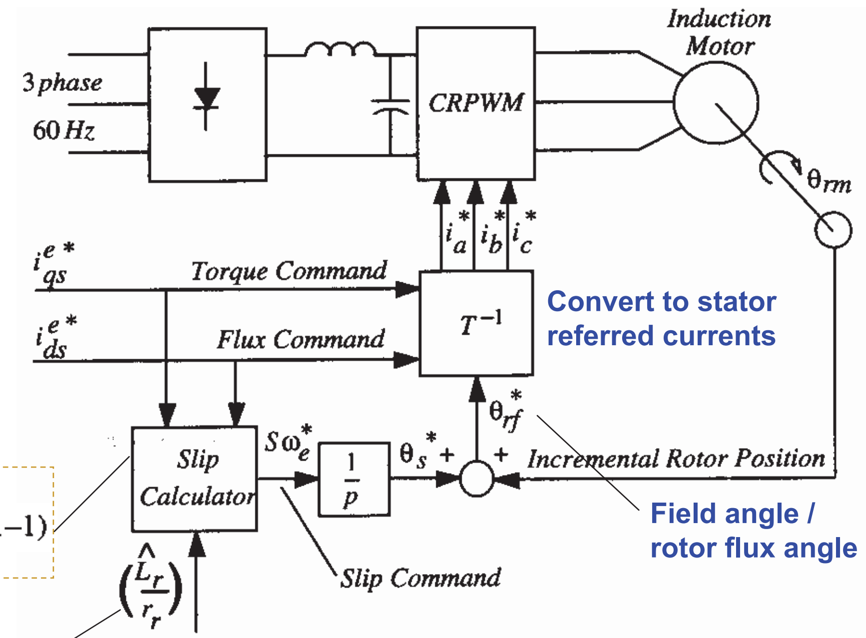
5.11.1 Indirect field orientation

- Necessary and sufficient condition to produce field orientation:

$$S\omega_e = \frac{r_r I_{qs}}{L_r I_{ds}} \qquad (5.11\text{–}1)$$

  - The I_{ds} will aligned with the rotor flux if the slip relation is satisfied.

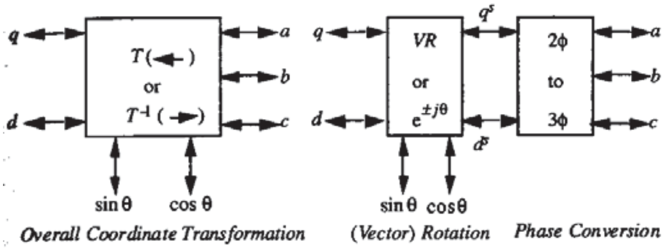




$$S\omega_e = \frac{r_r I_{qs}}{L_r I_{ds}} \qquad (5.11\text{–}1)$$

Estimated values differs from L_r / r_r

Figure 5.27 Indirect field orientation using a CRPWM



$$f_q = f_a$$

$$f_d = -\frac{1}{\sqrt{3}} f_a - \frac{2}{\sqrt{3}} f_b$$

3φ to 2φ

$$f_a = f_q$$

$$f_b = -\frac{1}{2} f_q - \frac{\sqrt{3}}{2} f_d$$

$$f_c = -\frac{1}{2} f_q + \frac{\sqrt{3}}{2} f_d = -f_a - f_b$$

2φ to 3φ

PHASE TRANSFORMATION

$$f_{qd} = e^{-j\theta} f^s_{qd} \qquad f^s_{qd} = e^{j\theta} f_{qd}$$

Stationary to Rotating — Rotating to Stationary

ROTATION TRANSFORMATION

$$\begin{bmatrix} f_q \\ f_d \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} f^s_q \\ f^s_d \end{bmatrix} \qquad \begin{bmatrix} f^s_q \\ f^s_d \end{bmatrix} = \begin{bmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} f_q \\ f_d \end{bmatrix}$$

Figure 5.28 Summary of transformations used in field orientation

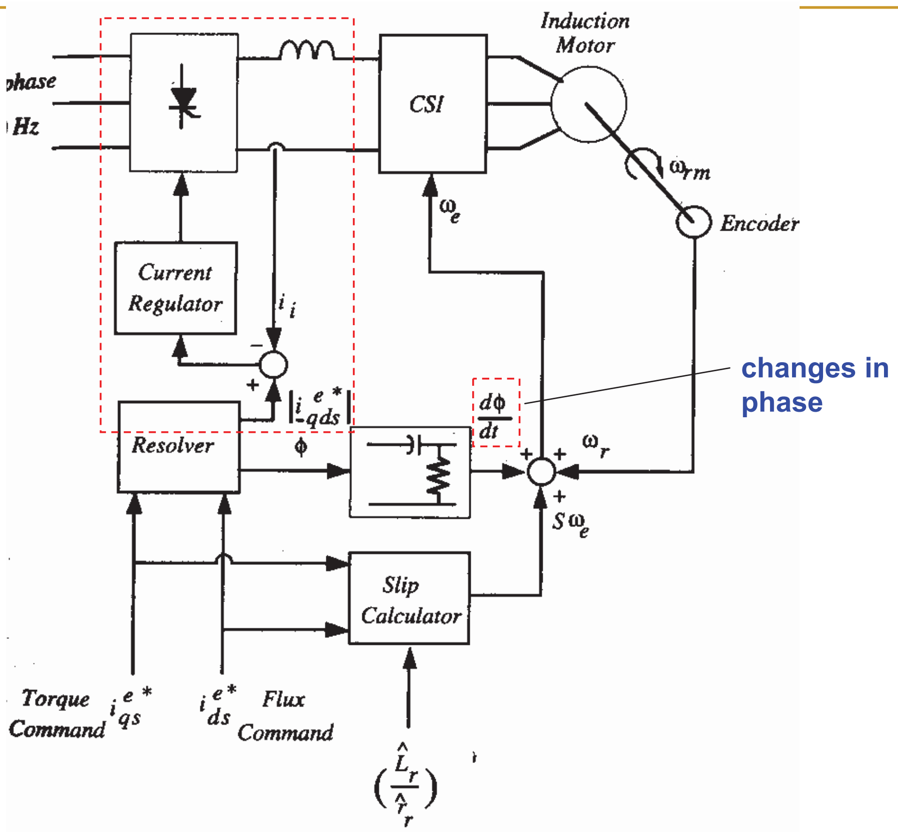
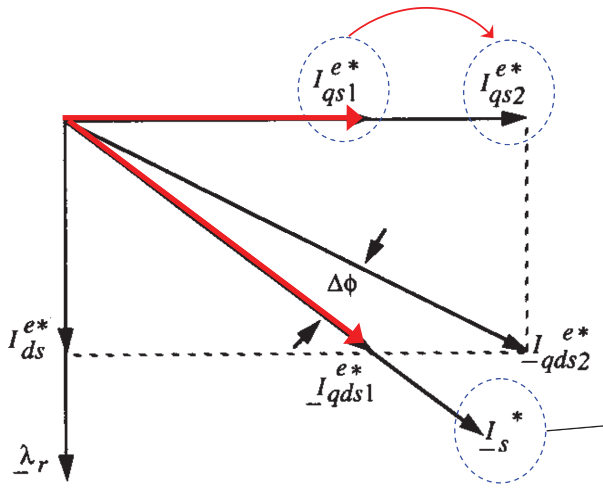


Figure 5.29 Indirect field orientation using a current regulated CSI

Phase changes compensation for a CSI



the phase changes are not contained in CSI frequency command would cause an instantaneous loss of field orientation.

Figure 5.30 Phasor diagram showing required phase correction for system of Figure 5.29

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5.11.2 Direct field orientation

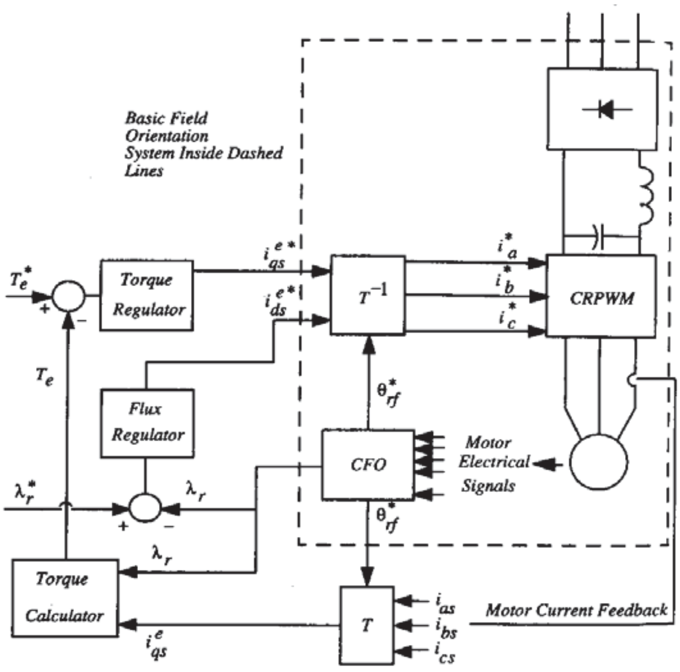

Figure 5.31 Direct implementation of induction machine field orientation using a CRPWM (torque and flux regulators optional)

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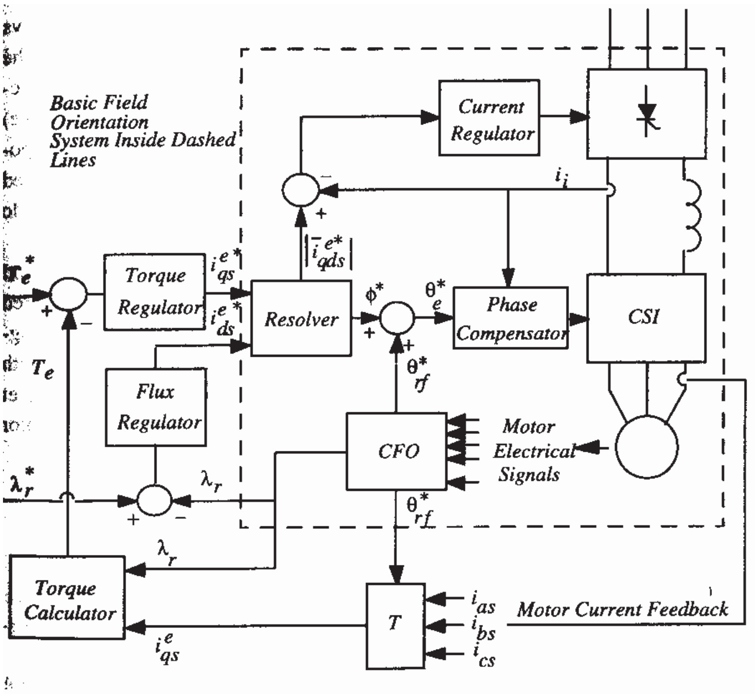

Figure 5.32 Direct implementation of induction machine field orientation using a CSI (torque and flux regulators optional)

5.11.3 Torque control requirements

- Independent current of the stator current is employed to overcome the stator resistance, stator leakage inductance and induced voltage.
- Independent control of the flux is obtained by controlling two stator components : $I_{s\phi}$ and I_{sT}.
- The spatial orientation of the rotor flux w.r.t. I_{sT} is maintained by using rotor field angle θ_{rf}