UPC

PMSM Control (FOC & DTC) for WECS & Drives

- Introduction. Classification. Motor Types
- Permanent Magnet Synchronous Machine (PMSM) Modeling
- Control Strategies
  - –Field Oriented Control (FOC)
    - •Current Loop
    - •Speed Loop
    - •PI tuning
  - –Direct Torque Control (DTC)
    - •Flux Loop
    - •Torque Loop
    - •Hysteresis Comparators

Direct Torque Control

- the world's most advanced AC drive technology

ABB

Classification

- Types of electrical machines
  - DC
  - Universal
  - AC
    - Single-phase AC Induction Motors
    - Single-phase AC Synchronous Motors
    - Three-phase AC Induction Motors
    - Three-phase AC Synchronous Motors
  - Stepper
  - Permanent Magnet
    - PMDC – Brushless
    - PMAC – SMPM, IPM
  - Linear
  - Nano

Most important and used

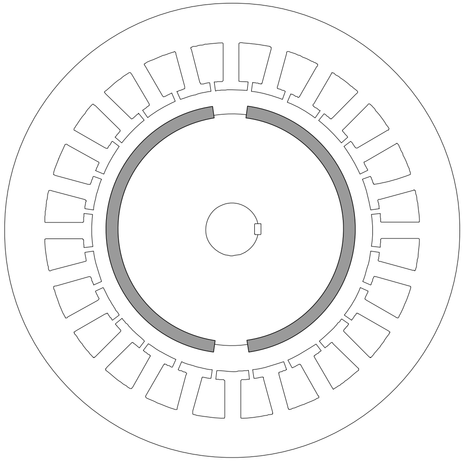
Permanent Magnet Machines

- Magnetic material to establish the rotor flux.
  - Most common magnetic material are samarium-cobalt (SmCo) and neodymium-iron-boron (NdFeB) introduced in 1983 having superior magnetic characteristics at room temperature.
- Advantages:
  - No rotor currents => no rotor losses.
  - Higher efficiency => energy saving capability. Attractive for Wind applications.
  - Smaller rotor diameters, higher power density and lower rotor inertia.
  - Higher torque per ampere constant.
  - Weight and volume less than other type of machine for the same power. Attractive for aerospace applications such as aircraft actuators.
  - Other applications: machine tools, position servomotors (replacing the DC motors).
- Inconvenience:
  - synchronous machines => need for rotor position.
  - Price

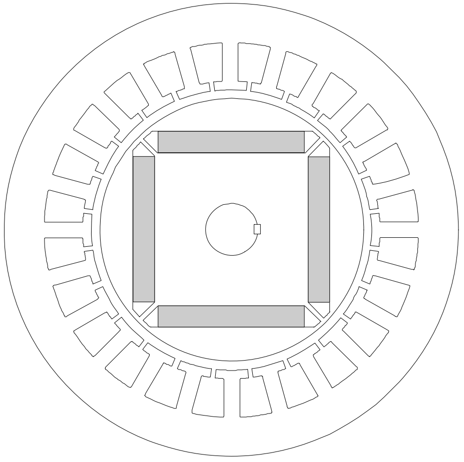
PM Motor Types

- Considering the shape of the back EMF
  - PMDC – brushless - trapezoidal
  - PMAC – sinusoidal
    - Surface Mount PM
    - Interior Mount PM

SMPM



IPM

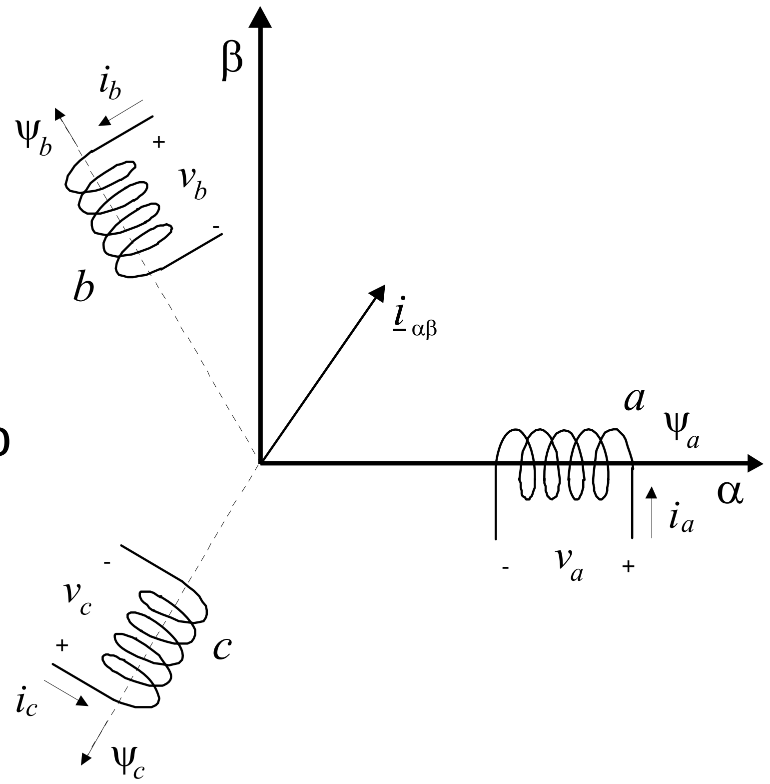


PMSM Dynamic Equations

- Space vector transformation
  - combines the individual phase quantities in to a single vector in the complex plane

$$\underline{i}_{\alpha\beta} = \frac{2}{3}\left(i_a(t) + i_b(t)e^{j\frac{2\pi}{3}} + i_c(t)e^{j\frac{4\pi}{3}} \right)$$

$$i_\alpha = i_a(t) \quad ; \quad i_\beta = \frac{\sqrt{3}}{2}\left(i_b(t) - i_c(t)\right)$$



  - Similar transformation are applied to
    - Stator voltages $\underline{v}_s$
    - Stator flux linkage $\underline{\psi}_s$

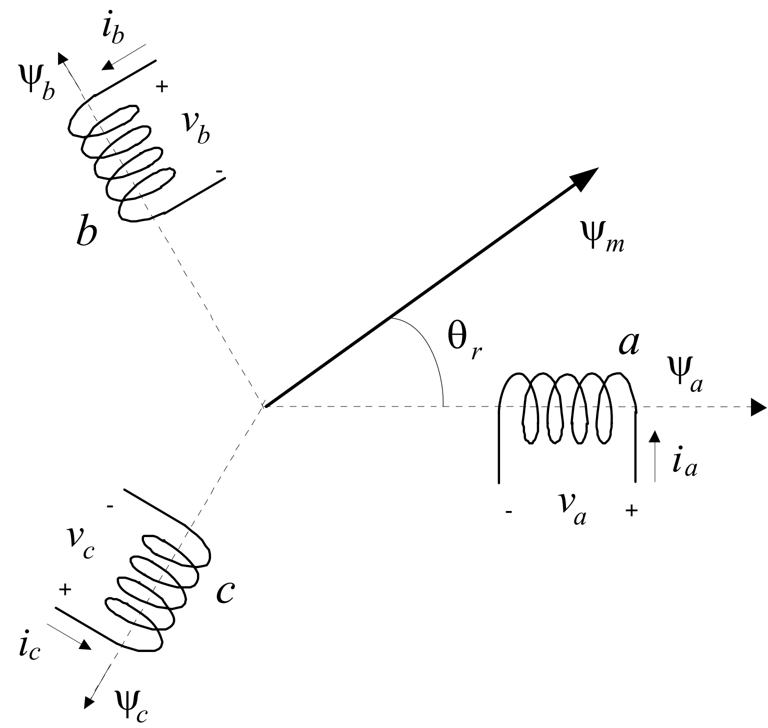
PMSM Dynamic Equations

- Basic equation for phase windings voltages

$$\begin{bmatrix} v_a \\ v_b \\ v_c \end{bmatrix} = r_s \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \end{bmatrix}$$

- Total flux linkage

$$\begin{bmatrix} \psi_a \\ \psi_b \\ \psi_c \end{bmatrix} = \begin{bmatrix} L_a & M_{ab} & M_{ac} \\ M_{ba} & L_b & M_{bc} \\ M_{ca} & M_{cb} & L_c \end{bmatrix} \cdot \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \psi_m \begin{bmatrix} \cos(\theta_r) \\ \cos(\theta_r - \frac{2\pi}{3}) \\ \cos(\theta_r - \frac{4\pi}{3}) \end{bmatrix}$$



flux produced by the rotor magnet ψ_m

Leakage inductance L_l

Magnetising inductance L_m

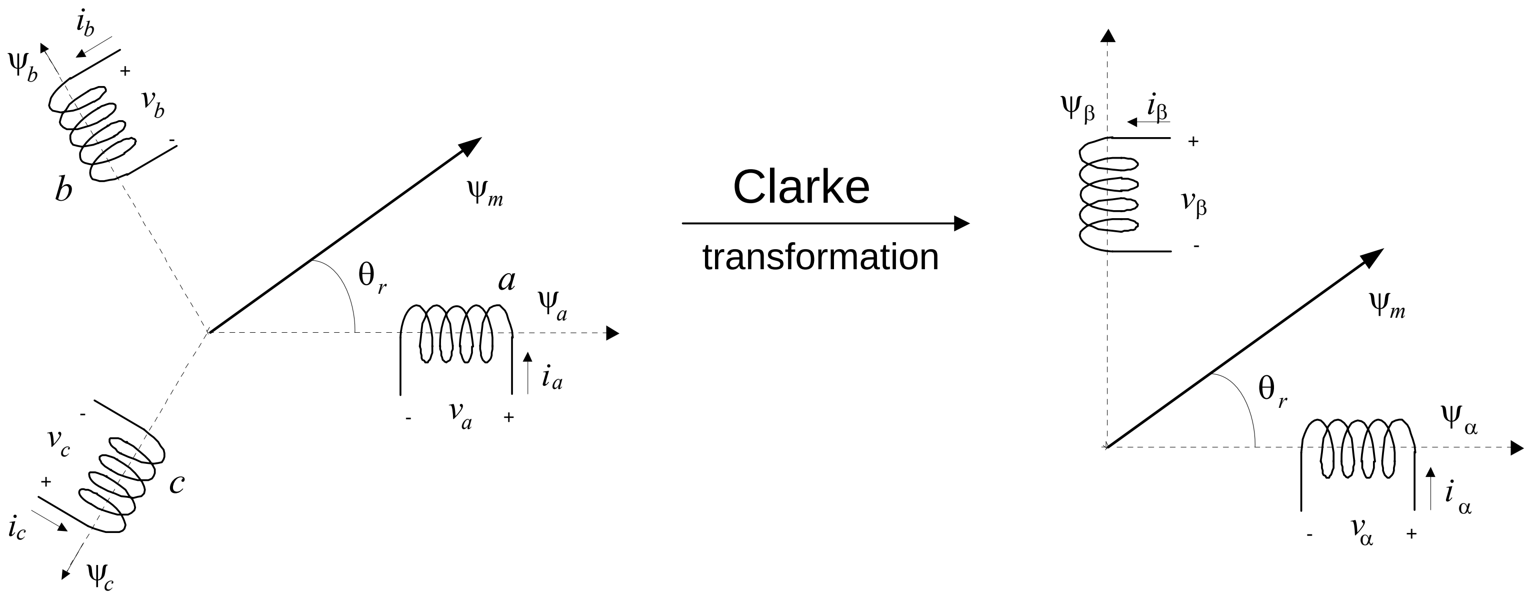
Self inductance $L_a = L_b = L_c = L_l + L_m$

Mutual inductance $M_{ab} = M_{bc} = M_{ca} = -\frac{L_m}{2}$; $M_{ab} = M_{ba}$; $M_{bc} = M_{cb}$; $M_{ca} = M_{ac}$

PMSM Dynamic Equations

- voltage vector equation in the stationary α-β frame
  - Replacing the inductances values and applying the space vector transformation

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = r_s \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \left(L_l + \frac{3}{2} L_m \right) \frac{d}{dt} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \psi_m \frac{d}{dt} \begin{bmatrix} \cos(\theta_r) \\ \cos(\theta_r - \frac{\pi}{2}) \end{bmatrix}$$



PMSM Dynamic Equations

- Saliency
  - Variation of the stator phase inductance as function of the rotor position.

$$L_a = L_l + \overline{L}_m - \Delta L_m \cos(2\theta_r)$$

$$L_b = L_l + \overline{L}_m - \Delta L_m \cos(2\theta_r - \tfrac{4\pi}{3})$$

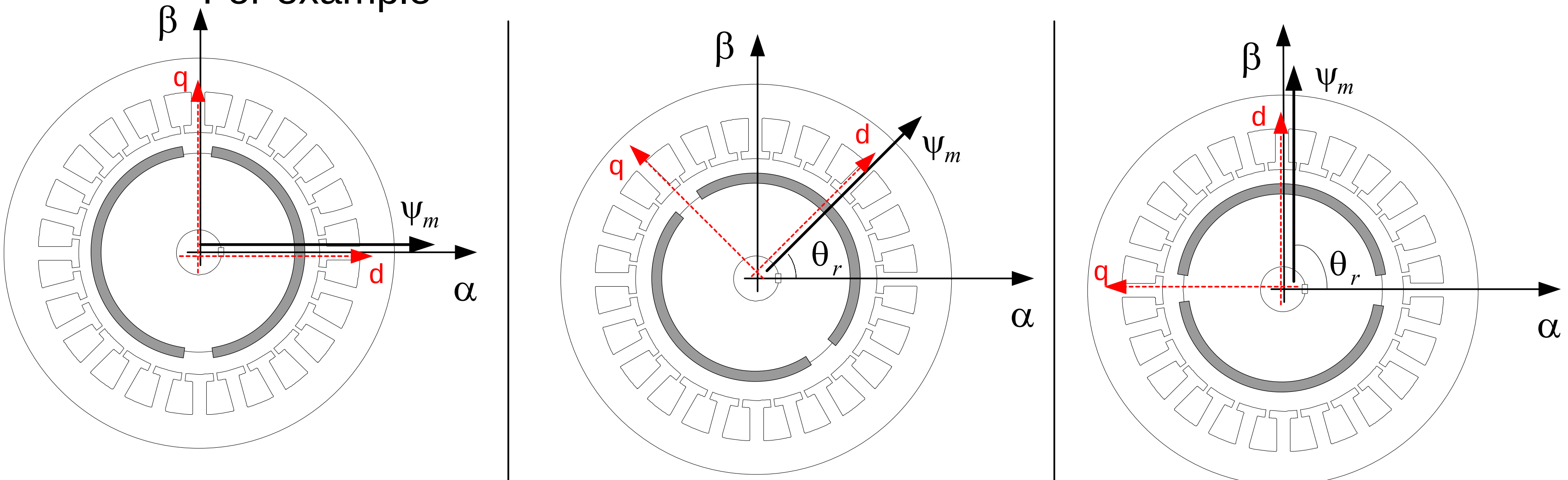
$$L_a = L_l + \overline{L}_m - \Delta L_m \cos(2\theta_r - \tfrac{2\pi}{3})$$

$$M_{ab} = -\frac{\overline{L}_m}{2} - \Delta L_m \cos(2\theta_r - \tfrac{2\pi}{3})$$

$$M_{bc} = -\frac{\overline{L}_m}{2} - \Delta L_m \cos(2\theta_r)$$

$$M_{ca} = -\frac{\overline{L}_m}{2} - \Delta L_m \cos(2\theta_r - \tfrac{4\pi}{3})$$

  - For example



$$L_a = L_l + \overline{L}_m - \Delta L_m \cos(2\theta_r) = L_l + \overline{L}_m - \Delta L_m$$

$$L_a = L_l + \overline{L}_m - \Delta L_m \cos(2\theta_r) = L_l + \overline{L}_m$$

$$L_a = L_l + \overline{L}_m - \Delta L_m \cos(2\theta_r) = L_l + \overline{L}_m + \Delta L_m$$

PMSM Dynamic Equations

- voltage vector equation in the stationary α-β frame considering saliency

$$\begin{bmatrix} v_\alpha \\ v_\beta \end{bmatrix} = r_s \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} + \frac{d}{dt}\begin{bmatrix} L_s - \Delta L_s \cos(2\theta_r) & \Delta L_s \sin(2\theta_r) \\ \Delta L_s \sin(2\theta_r) & L_s + \Delta L_s \cos(2\theta_r) \end{bmatrix} \cdot \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

$$+ \psi_m \frac{d}{dt}\begin{bmatrix} \cos(\theta_r) \\ \cos(\theta_r - \frac{\pi}{2}) \end{bmatrix}$$

- Where $L_s = L_l + \frac{3}{2}\bar{L}_m$

  $\Delta L_s = \frac{3}{2}\Delta L_m$

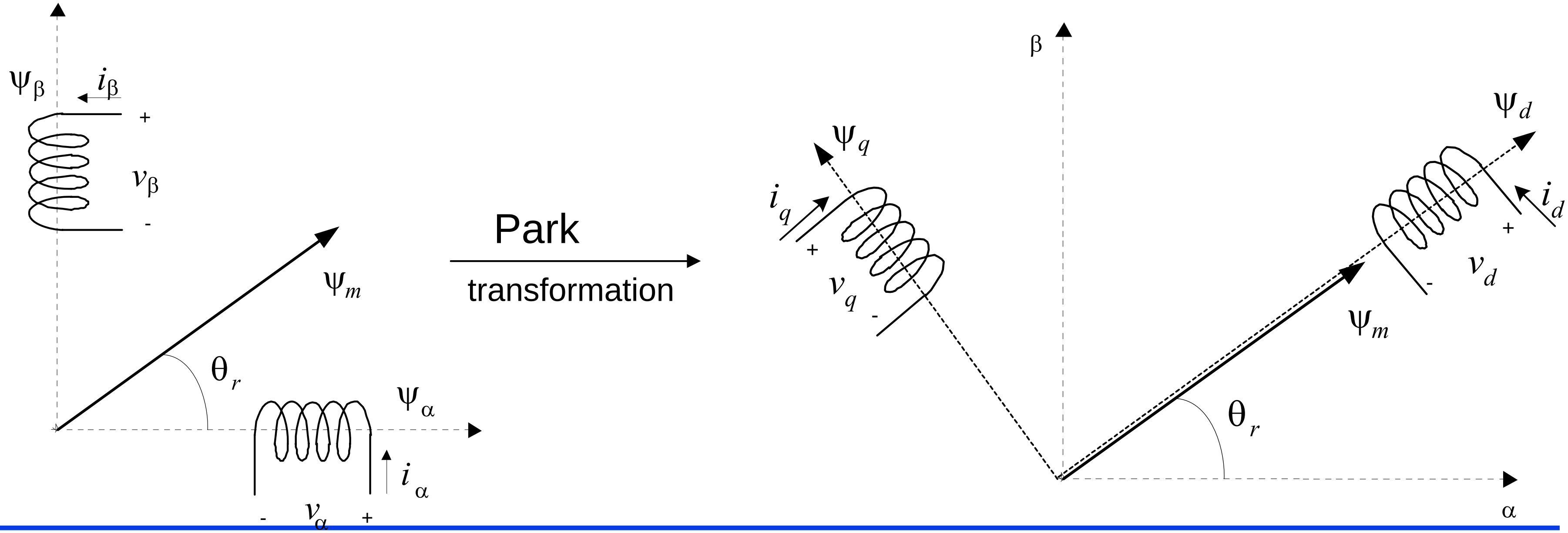
- If $\Delta L_m = 0$ there is no saliency and it is obtained the previous equation.

PMSM Dynamic Equations

- voltage vector equation in the synchronous reference d/q frame fixed on the rotor
  - Angle chosen equal to the PM position

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = r_s \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} L_d p & -L_q \omega_r \\ L_d \omega_r & L_q p \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \psi_m \omega_r \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

differential operator p ; direct axis $L_d = L_s - \Delta L_s$ and quadrature axis inductances $L_q = L_s + \Delta L_s$



PMSM Dynamic Equations

- expression for the instantaneous torque for the PM synchronous machine

$$T_e = \frac{3P}{2}\left\{\psi_m i_q + i_d i_q (L_d - L_q)\right\}$$

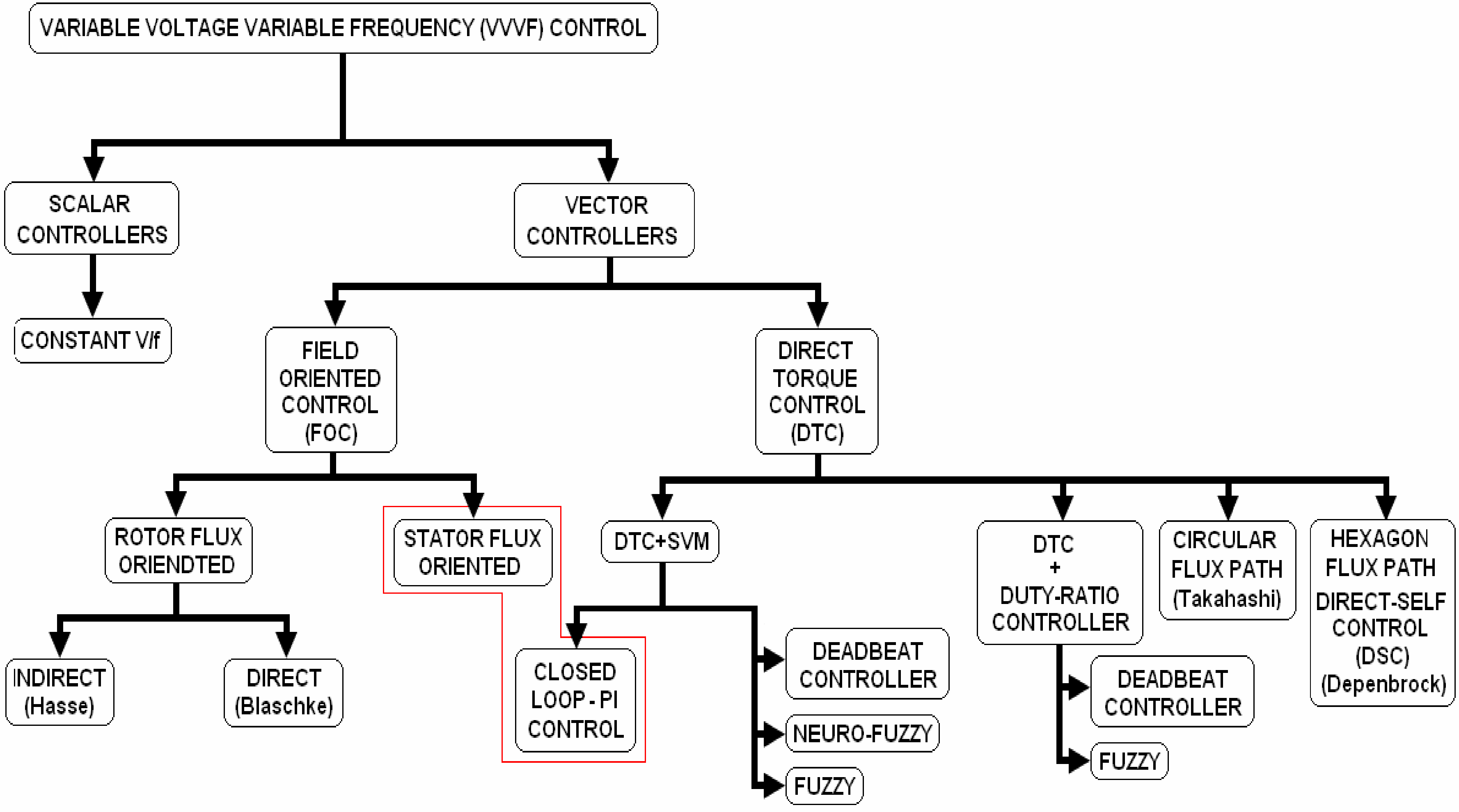
  - first term, usually called as magnet torque, is directly proportional to i_q and independent of i_d .
  - second term, or reluctance torque, is only present in salient machines where $L_d - L_q \neq 0$ and is proportional to the current product $i_d i_q$.

– Motion equation:

  - J rotor inertia
  - D friction

UPC

Types of Controllers

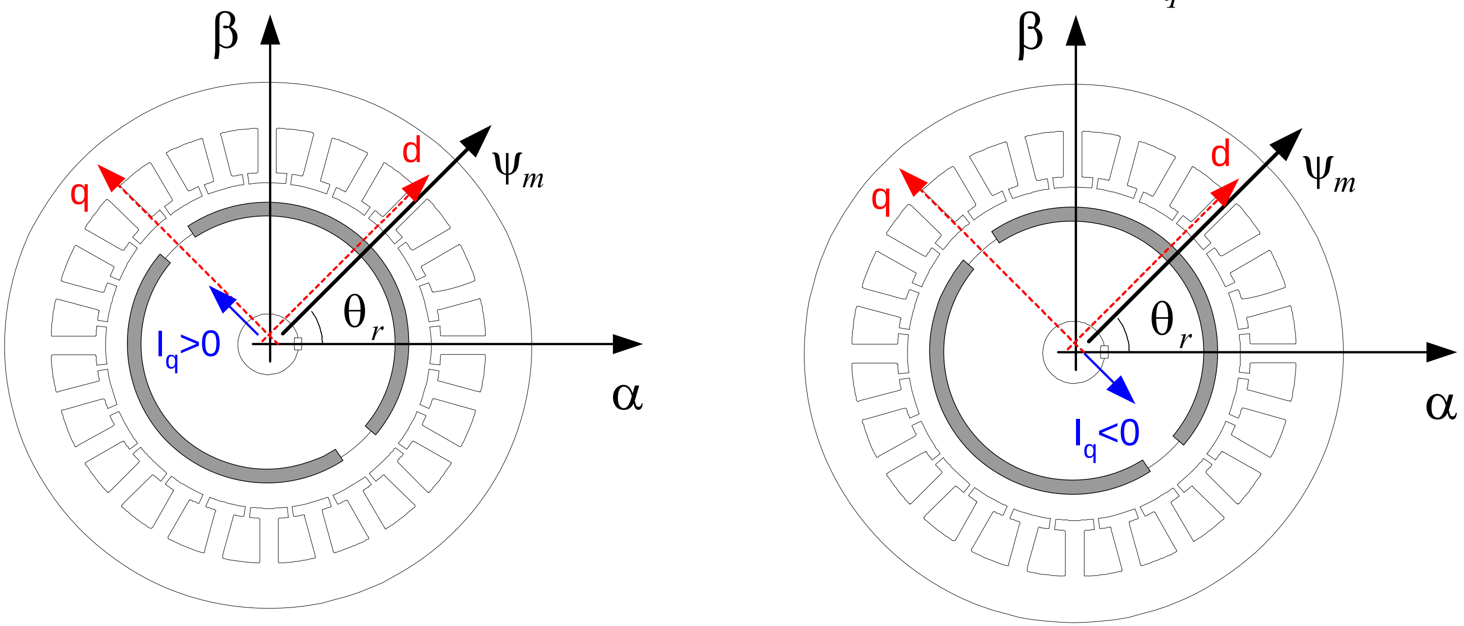


Field Oriented Control (FOC) for PMSM

- Instantaneous torque for the PM synchronous machine

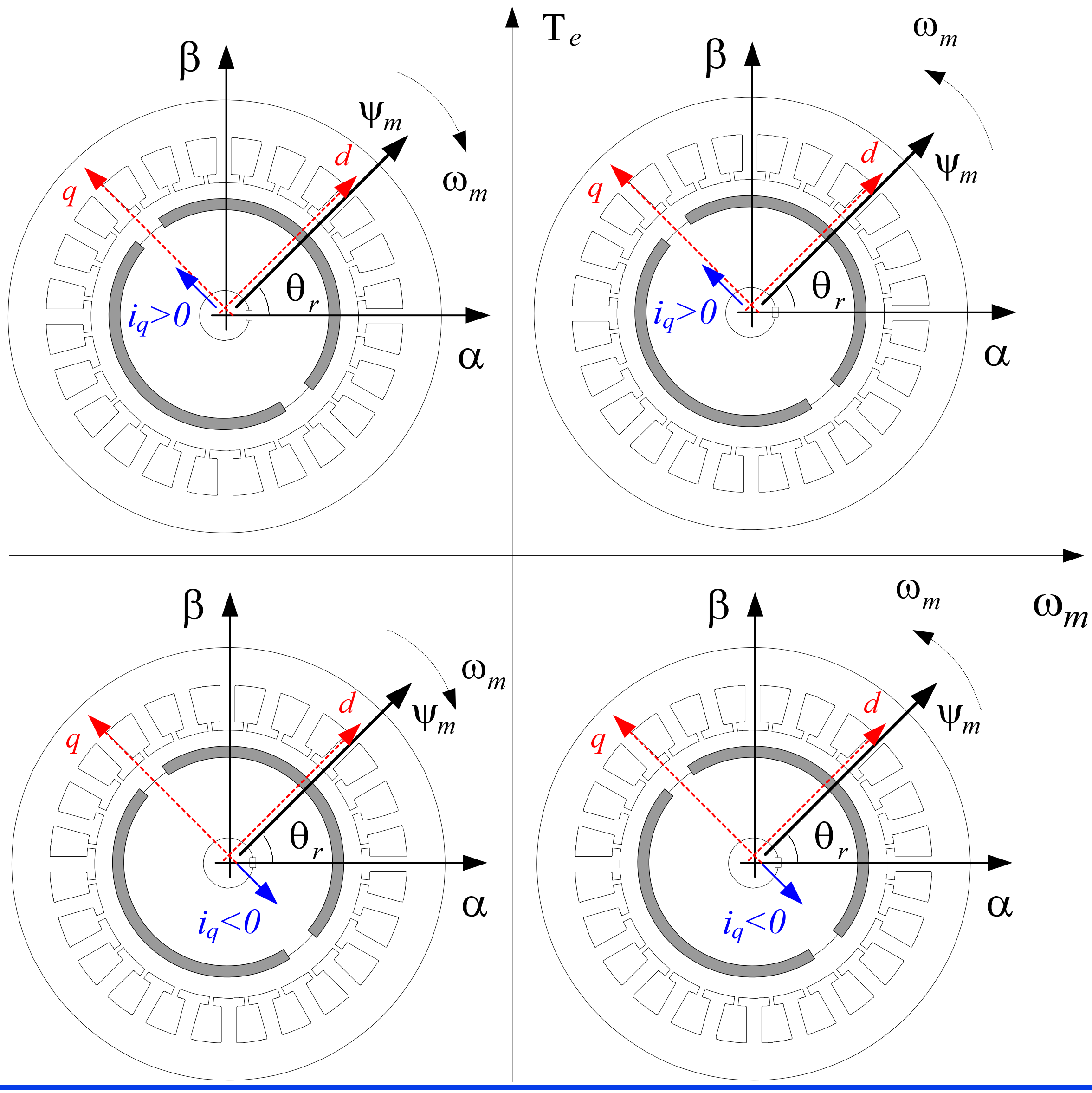
$$T_e = \frac{3P}{2}\left\{\psi_m i_q + i_d i_q (L_d - L_q)\right\}$$

  - i_d is kept to zero, for not demagnetizing the PM machine. Therefore, the reluctance torque will be zero.
  - Electromagnetic torque will be regulated with i_q .



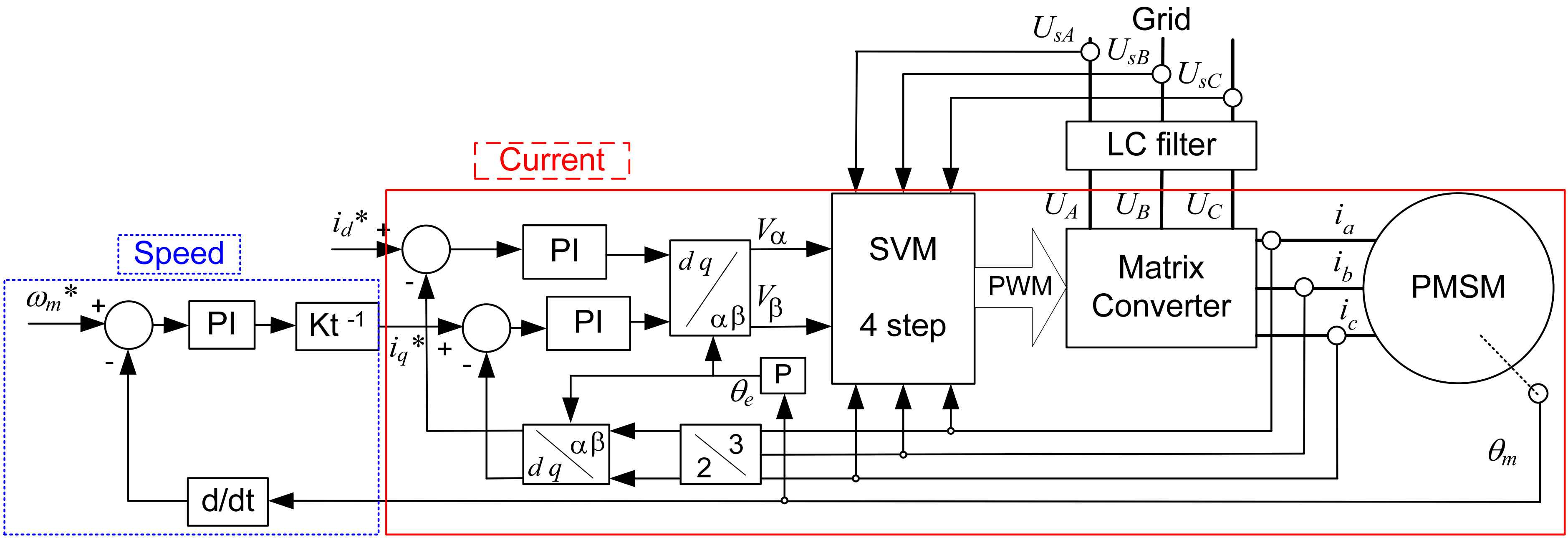
$T_e > 0$ $T_e < 0$

FOC in PMSM



Four quadrant Motor (Q1 & Q3) Generator (Q2 & Q4)

FOC Scheme



- 3 PI control loops
  - 2 identical inner (and faster) current loops, d & q axis.
  - 1 outer (and slower) speed loop.

- *Typical dynamic values (for a PMSM 3.8kW)*
  - *Current PI loop band width: 100 µs – 10kHz*
  - *Speed PI loop band width: 5ms – 200Hz*

Current PI Controller loop

- Inner faster loop.
- D and Q current loops are closed by identical PI.
- From PMSM model

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = R_s \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} L_d p & -L_q \omega_e \\ L_d \omega_e & L_q p \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \psi_m \omega_e \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

- If d-q coupling terms are eliminated a first order system is obtained.

$$\frac{\underline{i}_{dq}(s)}{\underline{v}_{dq}(s)} = \frac{1}{L_{dq}\, s + R_s} = \frac{1/R_s}{L_{dq}/R_s\, s + 1}; \qquad \tau = L_{dq}/R_s$$

Current PI Controller loop

Manufacturer's data for the PM machine from Control Techniques under the commercial name UNIMOTOR.

$$\frac{i_{dq}(s)}{v_{dq}(s)} = \frac{1}{L_{dq}\, s + r_s}$$

Model:	142UMC30
Number of poles:	6
Rated speed:	3000 (rpm)
Rated torque:	12.2 (Nm)
Rated power	3.82 (kW)
Kt:	1.6 (Nm/Arms)
Ke:	98.0 (Vrms/krpm):
Inertia:	20.5 (kgcm²)
R (ph-ph):	0.94 (Ohms)
L (ph-ph):	8.3 (mH)
Continuous stall:	15.3 (Nm)
Peak:	45.9 (Nm)

$$\frac{i_{dq}(s)}{v_{dq}(s)} = \frac{1}{4.15\cdot 10^{-3} s + 0.47} = \frac{1/0.47}{4.15\cdot 10^{-3}/0.47 \cdot s + 1}$$

$$\tau = 4.15\cdot 10^{-3}/0.47 = 8.83(ms)$$

Step input time open loop response

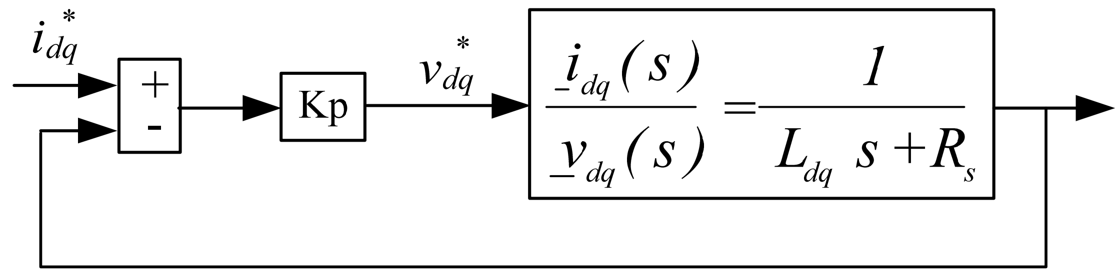
$$i_{dq}(t) = 1/R_s\,(1 - e^{-t/\tau})v_{dq}; \quad \tau = L/R$$

$$t = \tau; \quad i(t) = 1/R_s\, 0.632 \cdot v_{dq}$$

$$t = 3\tau; \quad i(t) = 1/R_s\, 0.95 \cdot v_{dq}$$

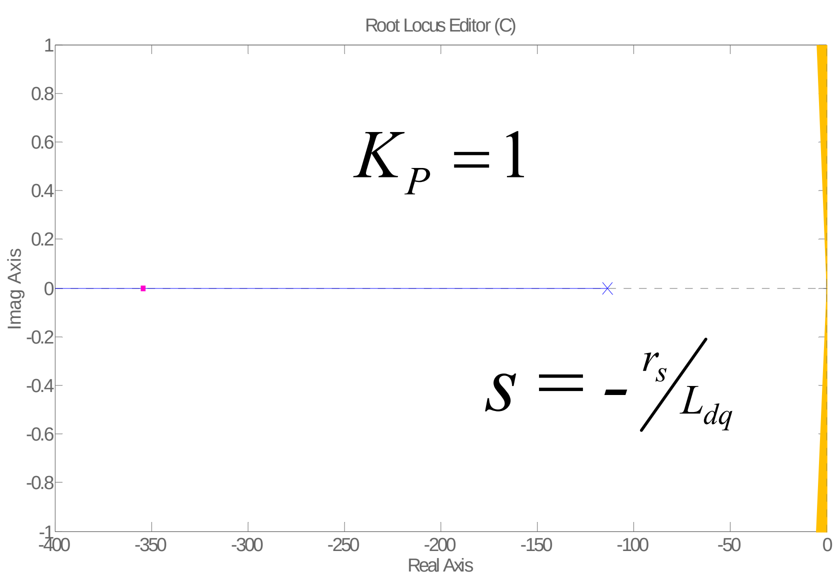
$$t = 5\tau; \quad i(t) = 1/R_s\, 0.993 \cdot v_{dq}$$

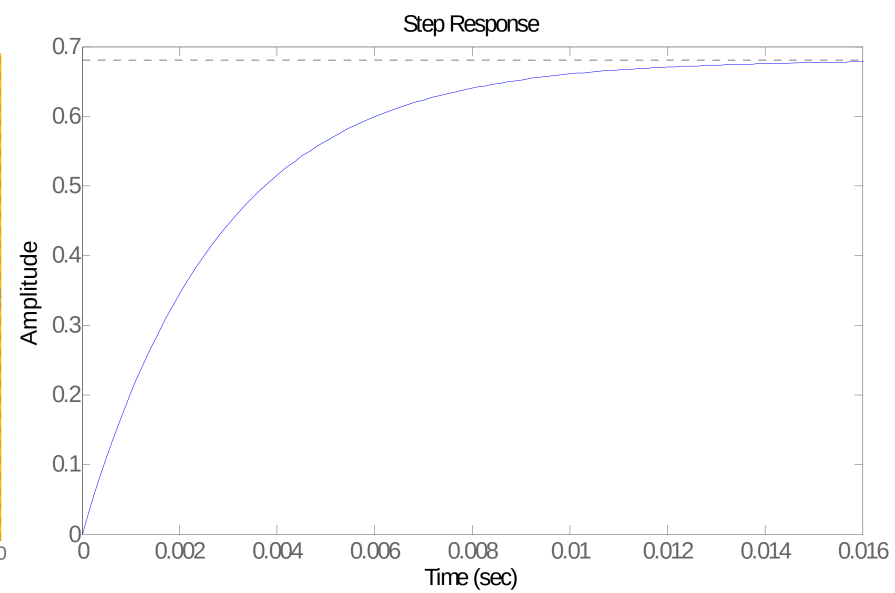
Current PI Controller loop



- Root locus and step response with a P controller
  - Slow dynamics
  - E_0. Position Error

$$E_0 = \frac{1}{1 + K_p / R_s} = \frac{R_s}{R_s + K_p}$$





- Solution: add a PI controller

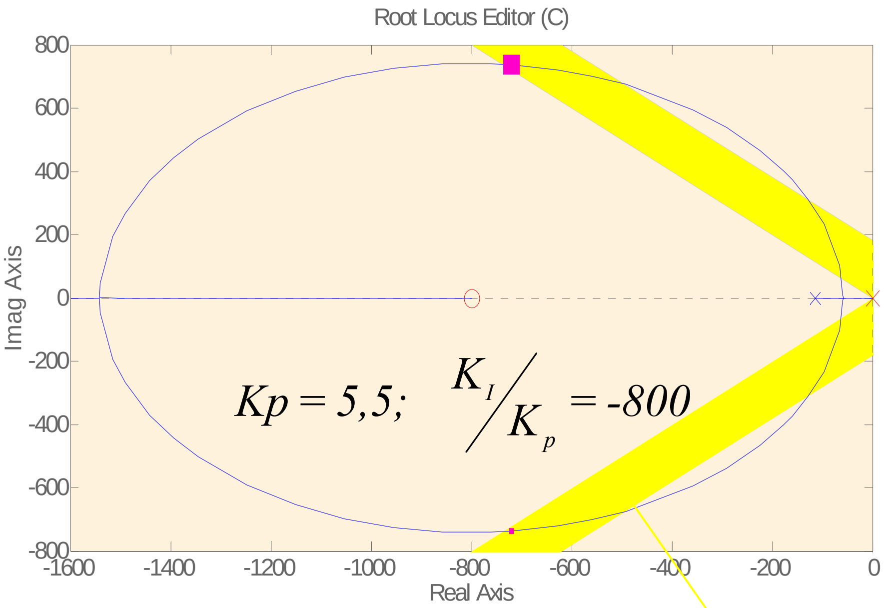
Current PI Controller loop

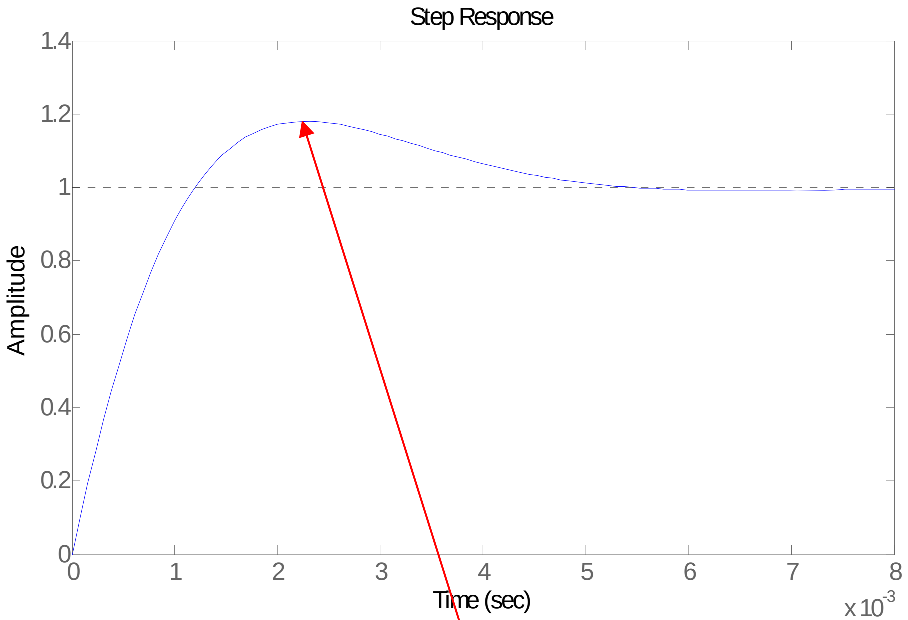
$$PI(s) = K_P + {K_I}/{s} = \frac{K_P s + K_I}{s} = K_I \frac{{K_P}/{K_I}\, s + 1}{s}$$

$\Rightarrow$ $pole: s = 0$; $zero: s = -{K_I}/{K_P}$

Because of the K_I $E_0=0$

2nd order system and response



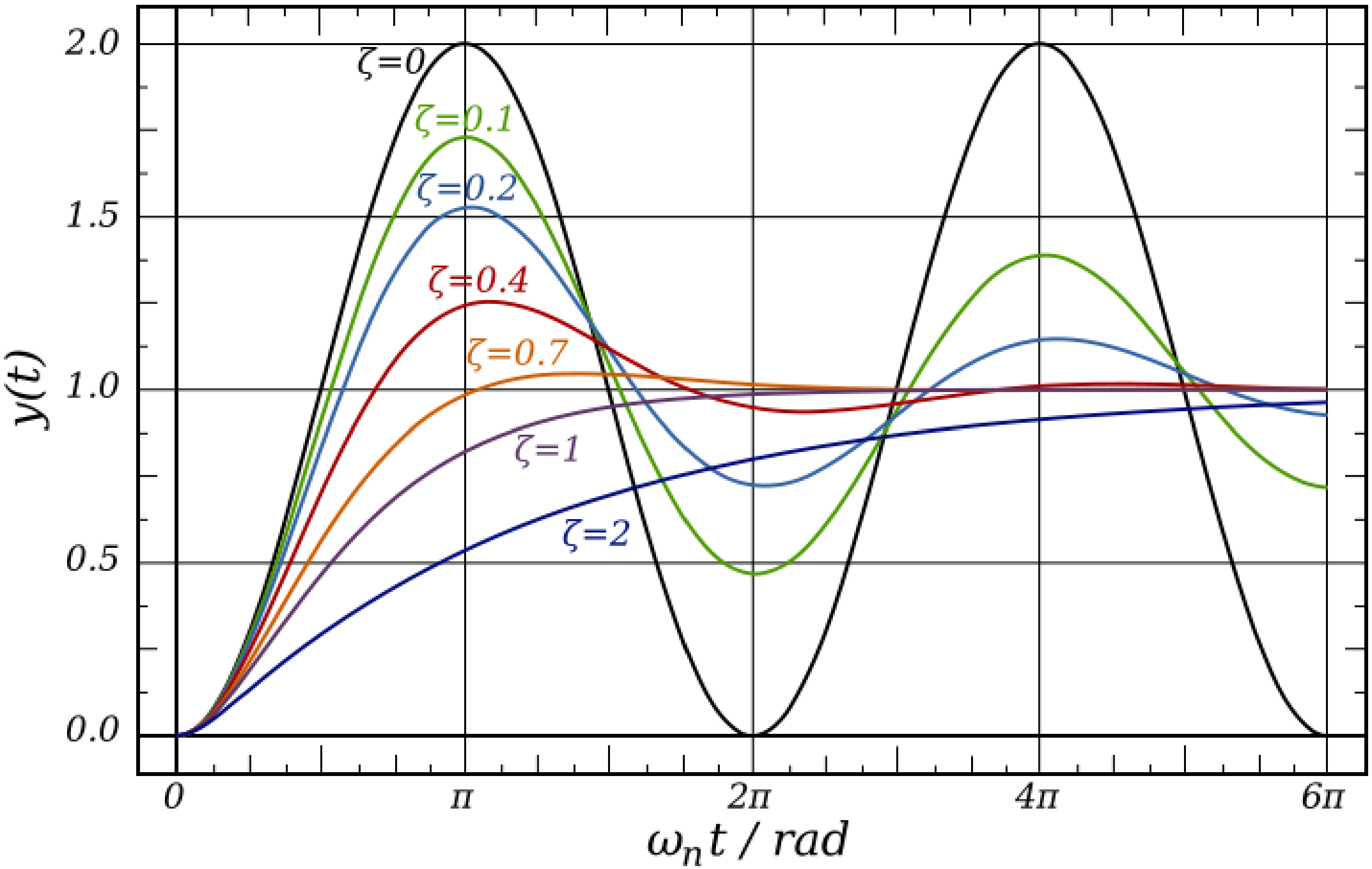


Damping factor equal to 0,707

The overshoot is too large !

Current PI Controller loop

2nd order system and response depending on the damping factor value



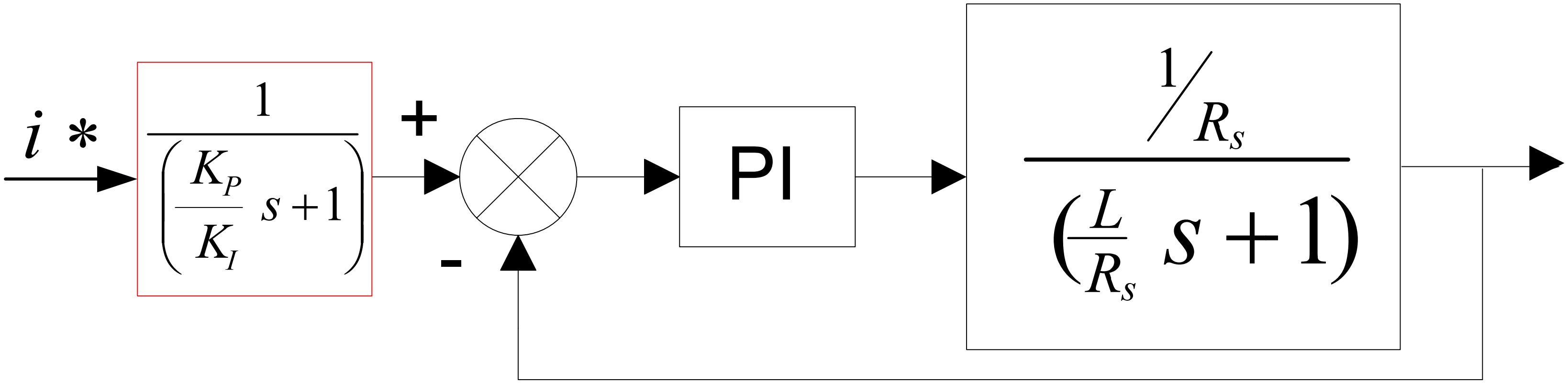
Current PI Controller loop

- Second order transfer function: $\dfrac{\omega_n^2}{s^2 + 2\xi\omega_n \cdot s + \omega_n^2}$

- The closed loop transfer function gives an unwanted zero

$$W(s) = \frac{G}{1+GH} = \frac{\frac{K_I}{L}\left(\frac{K_P}{K_I}s+1\right)}{s^2 + s\left(\frac{R_s}{L} + \frac{K_P}{L}\right) + \frac{K_I}{L}}$$

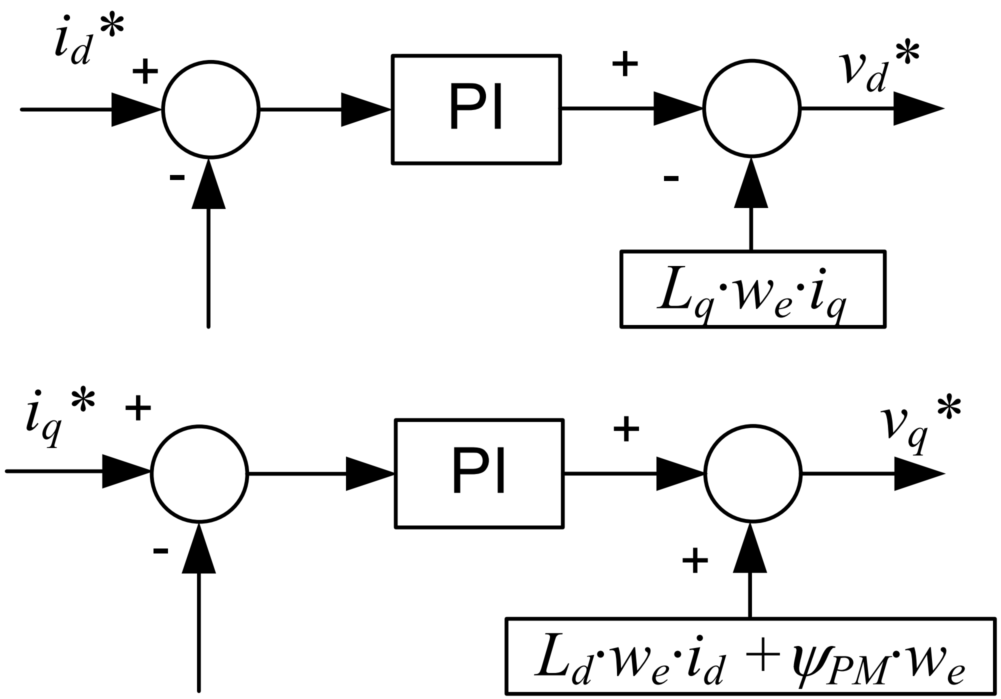
- A pre filter is used to get rid of the unwanted zero



Current PI Controller loop

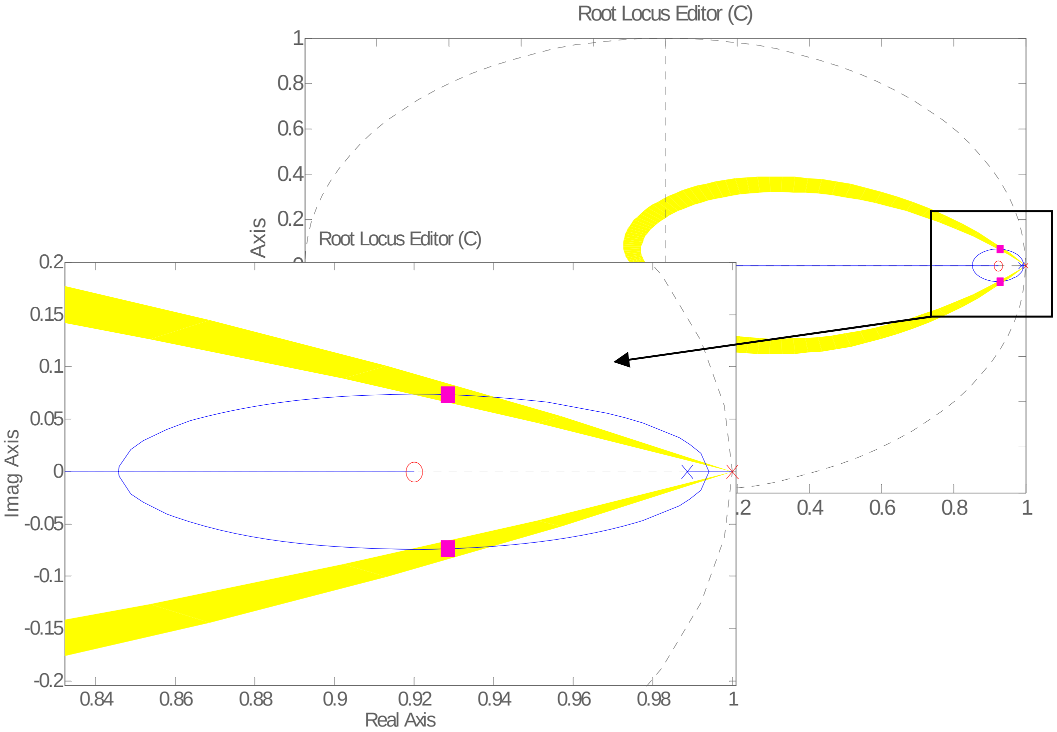
- Feed forward crossed terms

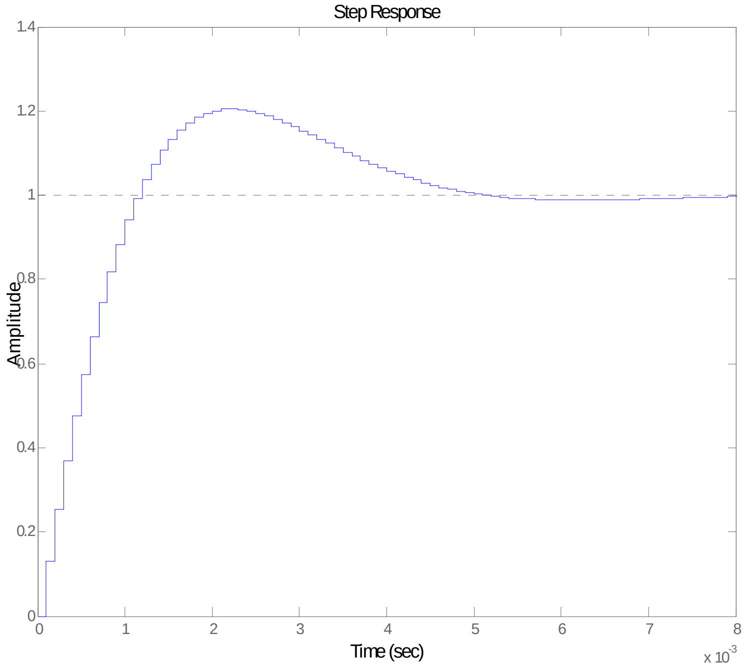
$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = R_s \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} L_d p & -L_q \omega_e \\ L_d \omega_e & L_q p \end{bmatrix} \cdot \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \psi_m \omega_e \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$



Current PI Controller loop

- Implementing PI in a DSP
  - From S to Z domain $$PI(s) = K_P \frac{s + {}^{K_I}\!/_{K_P}}{s} \rightarrow PI(z) = K_P \frac{z - (1 - {}^{K_I}\!/_{K_P} Ts)}{z - 1}$$
  - Ts=100us $$PI(s) = 5{,}5 \frac{s + 800}{s} \rightarrow PI(z) = 5{,}5 \frac{z - 0{,}92}{z - 1}$$





Current PI Controller loop

- Implementing a PI Controller in a DSP
  - From Z to discrete time domain $PI(z)=\frac{vq\_ref(z)}{iq\_error(z)}=K_P\frac{z-(1-{}^{K_I}\!/_{K_P}Ts)}{z-1}$

$$vq\_ref(z)(z-1)=iq\_error(z)[K_P(z-(1-{}^{K_I}\!/_{K_P}Ts))]$$

$$vq\_ref(z)(1-z^{-1})=iq\_error(z)[K_P(1-z^{-1}(c\_K_i\_K_p))]$$

$$vq\_ref=vq\_ref\_last+K_P(iq\_error-iq\_error\_last(c\_K_i\_K_p))$$

  - C code for the TI DSP 6711

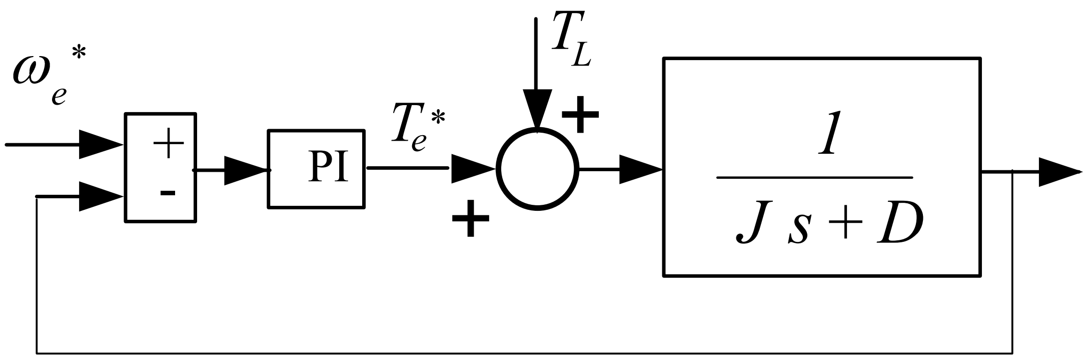
```
// start iq PI controller
iq_error = iq_ref-iq;

vq_ref = vq_ref_last+c_Kp*(iq_error-c_Ki_Kp*iq_error_last);
iq_error_last = iq_error;

if (vq_ref > VPI_MAX) vq_ref = VPI_MAX;
if (vq_ref < -VPI_MAX) vq_ref = -VPI_MAX;
vq_ref_last = vq_ref;
// end iq PI controller
```

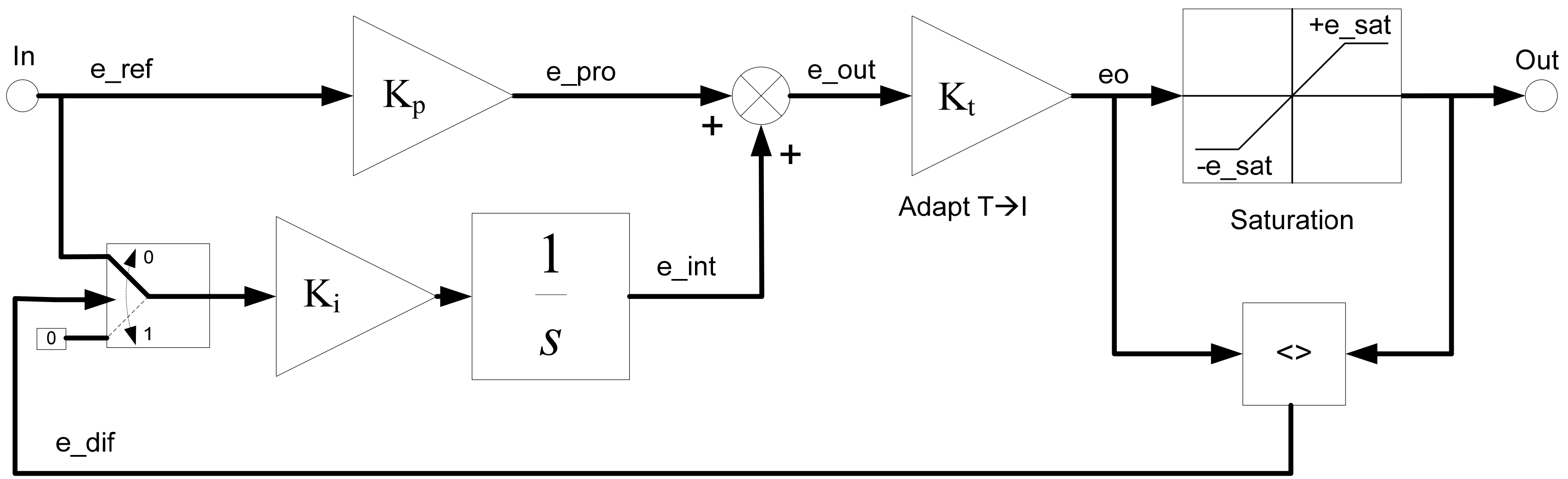
Speed PI Controller loop

- The plant can be simplified as follows
  - First order with one pole $s = -D/J$
  - Mechanical time constant might be 50 times slower than the electrical one. Current loop is neglected.
  - Typical sampling time 5ms.



Speed PI Controller loop

- Windup phenomenon
  - Limits of the real plant (currents and voltages)
  - Might end up with instability
- Anti Windup PI



UPC

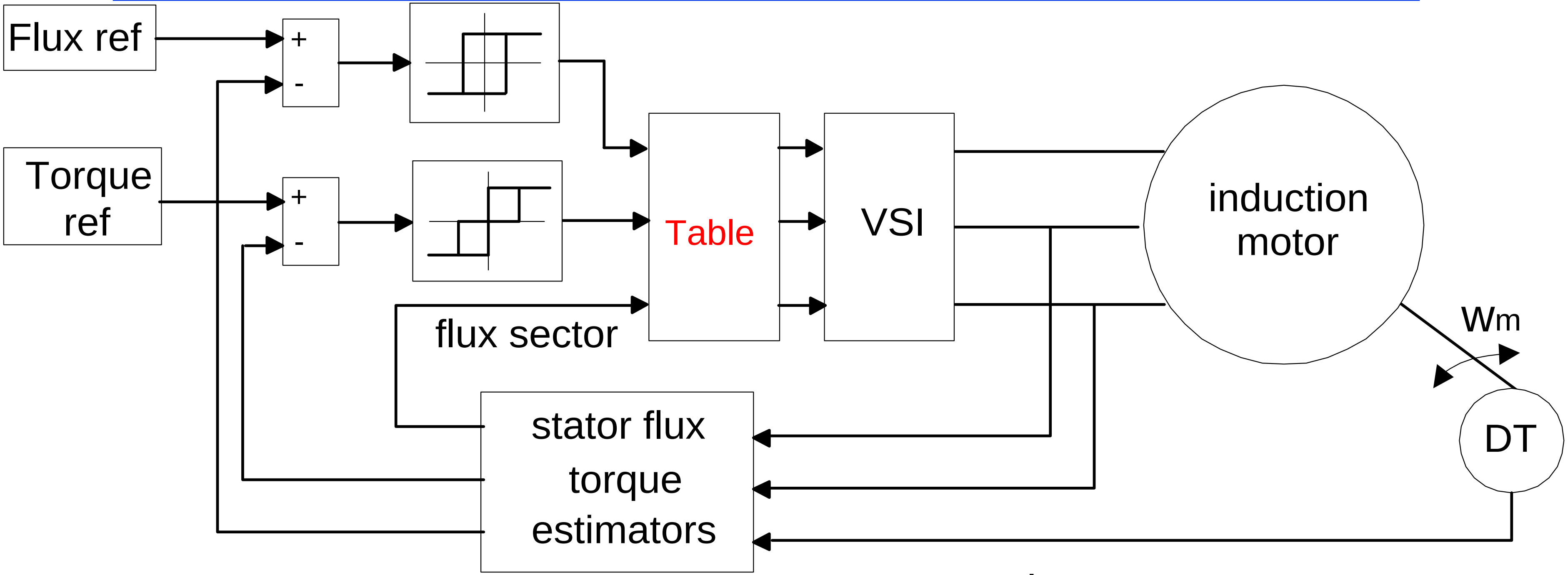
Direct Torque Control

- Direct Torque Control (DTC) was firstly introduced by Takahashi in 1986 [Ref 1]. It was an important new method becoming very popular.
- Depenbrock in 1988 [Ref 2] introduced a similar idea under the name Direct Self Control.
- However, just ABB company has got a popular commercial drive based on DTC, the ASC600.
  - Great number of applications such as: pumps, conveyors, lifts…from 2.2kW until 630kW.
  - Thanks to its 40MHz Toshiba processor plus ASIC, ASC600/800 closes the entire control loop every 25us.

Takahashi, I and Nogushi, T. “A New Quick-Response and High-Efficiency Control Strategy of an Induction Motor”, IEEE Trans. Industry Appl., Vol. 1A-22, pages 820-827, October 1986.

Depenbrock, M. "Direct Self Control of Inverter-Fed Induction Machines". IEEE Trans. on Power Electronics. vol: PE-3, no:4 October 1988. pp: 420-429.

Classical DTC schematic



Features

– Direct torque and stator flux control
– Indirect control of stator currents and voltages
– Approximately sinusoidal stator fluxes and currents

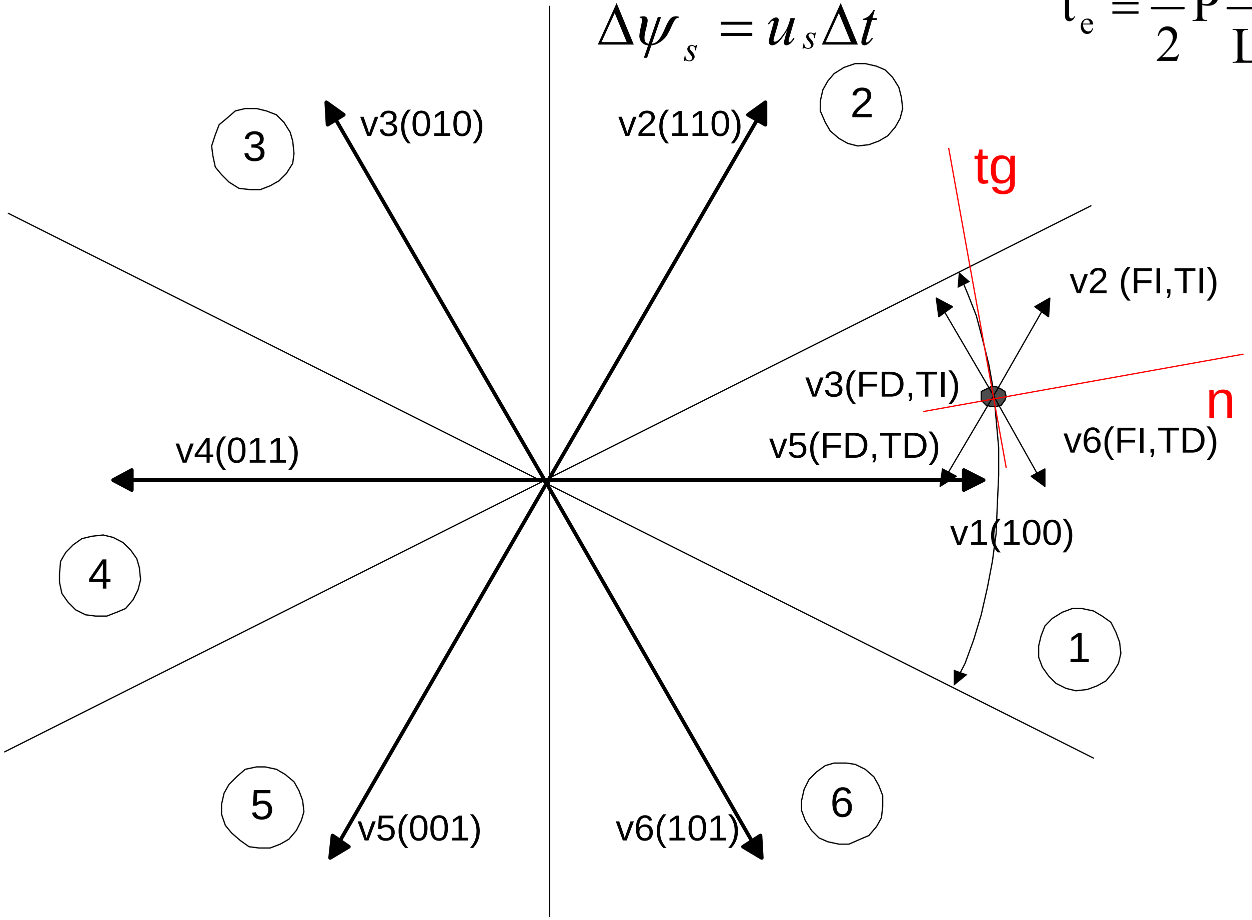
Advantages

– Absence of co-ordinate transform.
– Absence of voltage modulator block, as well as other controllers such as PID for flux and torque.
– Fast torque response.
– Robustness for parameters variation.

DTC Principles

$$\Delta\overline{\psi}_s = \overline{u}_s \Delta t$$

$$t_e = \frac{3}{2} P \frac{L_m}{L_s L_r - L_m^2} \left|\overline{\psi}'_r\right| \times \left|\overline{\psi}_s\right| \cdot \sin(\rho_s - \rho_r)$$



Φ	τ	S_1
FI	TI	V_2
	T=	V_0
	TD	V_6
FD	TI	V_3
	T=	V_7
	TD	V_5

Tangential component - torque *Normal component - modulus flux*

Classical Look up Table

Φ	τ	S_1	S_2	S_3	S_4	S_5	S_6
FI	TI	V_2	V_3	V_4	V_5	V_6	V_1
	T=	V_0	V_7	V_0	V_7	V_0	V_7
	TD	V_6	V_1	V_2	V_3	V_4	V_5
FD	TI	V_3	V_4	V_5	V_6	V_1	V_2
	T=	V_7	V_0	V_7	V_0	V_7	V_0
	TD	V_5	V_6	V_1	V_2	V_3	V_4

Conclusions

- Permanent Magnet Synchronous Machines
  - Advantages:
    - No rotor currents => no rotor losses.
    - Higher efficiency => energy saving capability.
    - Smaller rotor diameters, higher power density and lower rotor inertia.
    - Attractive for **Wind** applications, **Aerospace** applications such as **aircraft** actuators, Machine tools, position servomotors (replacing the DC motors).
  - Inconvenience:
    - Synchronous machines => need for rotor position.
    - Price

Conclusions

- PMSM dynamic Modelling
- FOC for PMSM has been introduced
  - Principles
  - Scheme
  - PI Controller design
- Classical DTC
  - Principles & features
  - Scheme
- *Research: Sensorless Control of PMSM*