rotating magnetic field

$N = \frac{120 f_s}{P}$ rpm

$\downarrow$ ~~x~~ poles

Chapter 4

Modeling and Control of Surface Permanent Magnet Synchronous Motor; SPMSM

$\cos(\omega t - \frac{\pi}{2})$

$$\left.\begin{aligned} i_a &= I\sin(\omega t) \\ i_b &= I\sin(\omega t - \tfrac{2\pi}{3}) \\ i_c &= I\sin(\omega t - \tfrac{4\pi}{3}) \end{aligned}\right\} \quad \left.\begin{aligned} i_x &= \sqrt{\tfrac{3}{2}} I \sin(\omega t) \\ i_y &= -\sqrt{\tfrac{3}{2}} I \cos(\omega t) \end{aligned}\right\} \quad \begin{aligned} i_d &= 0 \\ i_q &= -\sqrt{\tfrac{3}{2}} I \end{aligned}$$

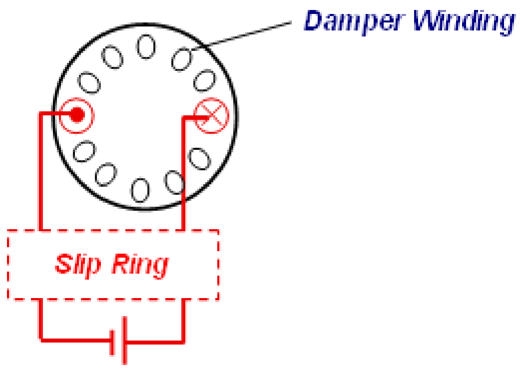
$\varepsilon = \omega t$

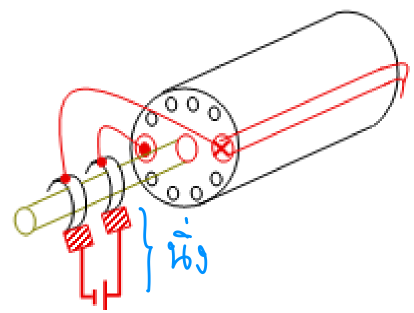
Synchronous Machines

- ชนิดของ Synchronous Motor (SM) … จำแนกตามโครงสร้างของ Rotor

  [1] Field Winding (+Damper Winding) … .ใช้กับมอเตอร์ขนาดมีพิกัดกำลังสูง (> kW)

power plant





  [2] Permanent Magnet … พิกัด ~ kW….. ใช้ในงาน Servo, High Eff. Drives

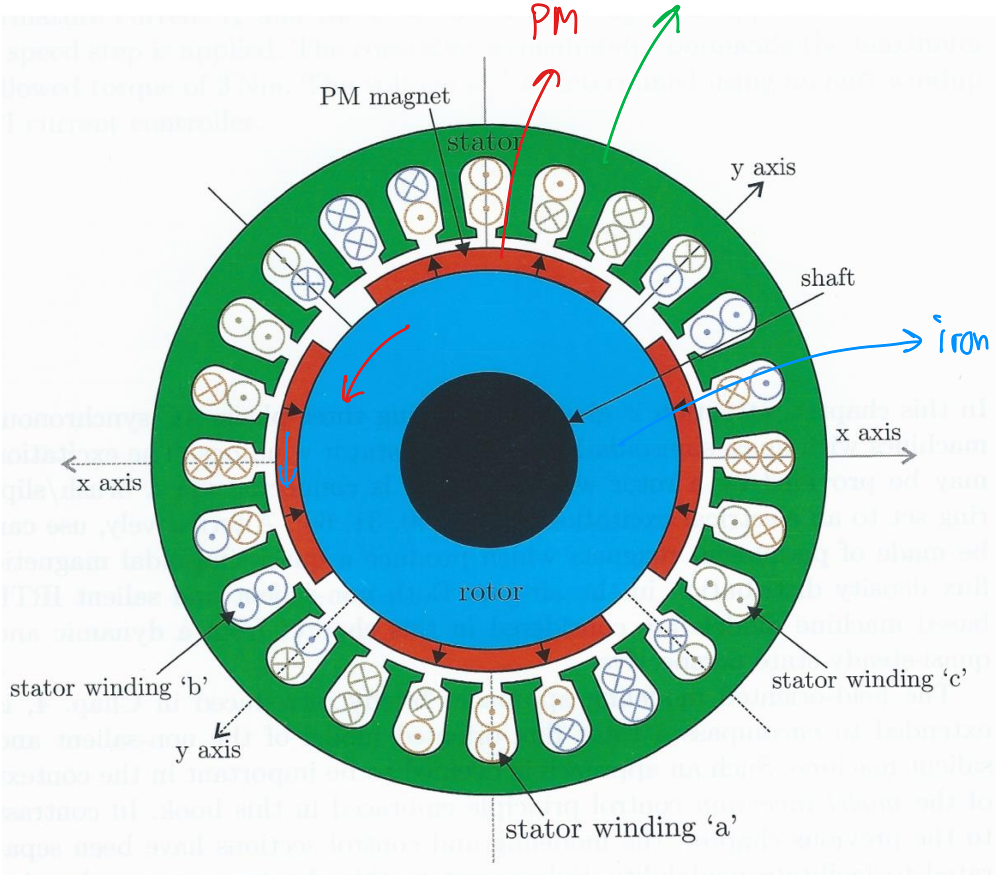
EV

  - Surface Permanent Magnet (SPM)
  - Interior Permanent Magnet (IPM)

Surface Permanent Magnet Synchronous Motor

iron core

PM



iron core

ไม่มี ข้อยื่น

-Uniform Airgap : Non salient

☒ Large Airgap

☒ High Speed

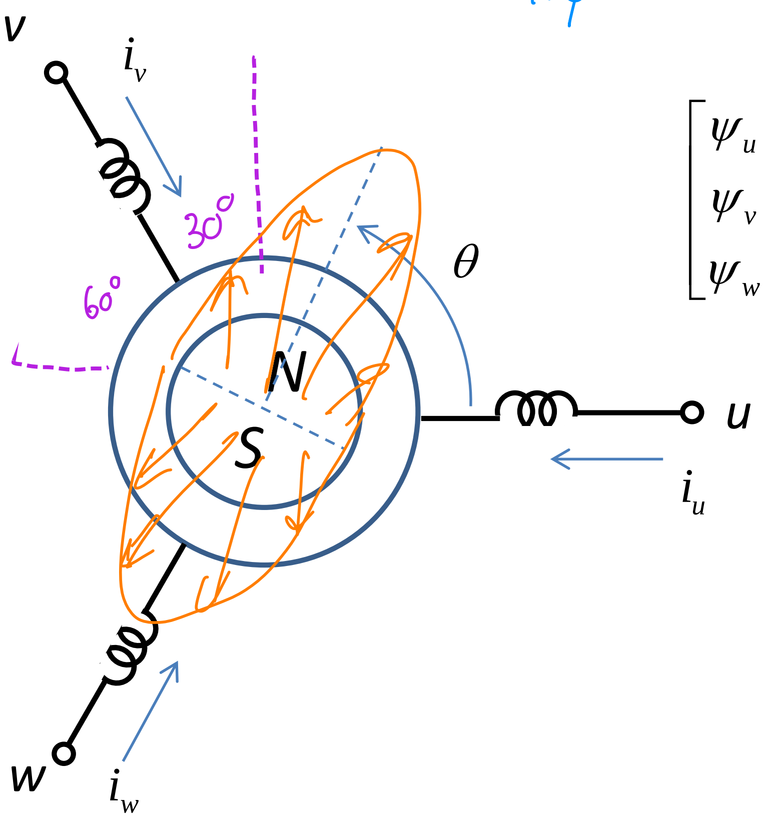
- *Cross-sectional view of 4-pole SPMSM*

stator → 3ϕ winding

Dynamic Model of SPMSM

$\psi = \lambda = Li$

$= N\phi$



Flux Linkage on Windings :

minus ∵ opposite direction

self inductance

60^o

From Rotor

$$\begin{bmatrix}\psi_u \\ \psi_v \\ \psi_w\end{bmatrix} = \begin{bmatrix} l+L & -\frac{1}{2}L & -\frac{1}{2}L \\ -\frac{1}{2}L & l+L & -\frac{1}{2}L \\ -\frac{1}{2}L & -\frac{1}{2}L & l+L \end{bmatrix}\begin{bmatrix} i_u \\ i_v \\ i_w\end{bmatrix} + \underbrace{\lambda'\begin{bmatrix}\cos\theta \\ \cos\left(\theta-120^o\right) \\ \cos\left(\theta-240^o\right)\end{bmatrix}}$$

leakage

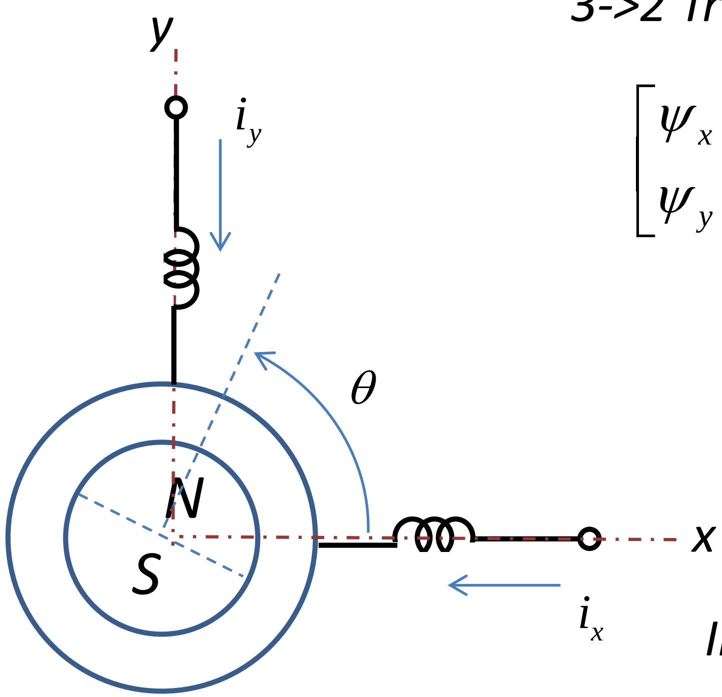
mutual

Flux Linkage from permanent magnet

Induced Voltage :

$$\begin{bmatrix} v_{un} \\ v_{vn} \\ v_{wn}\end{bmatrix} = R\begin{bmatrix} i_u \\ i_v \\ i_w\end{bmatrix} + \frac{d}{dt}\begin{bmatrix}\psi_u \\ \psi_v \\ \psi_w\end{bmatrix}$$

Dynamic Model of SPMSM



3->2 Transformation :

$$T = \sqrt{\frac{2}{3}}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}$$

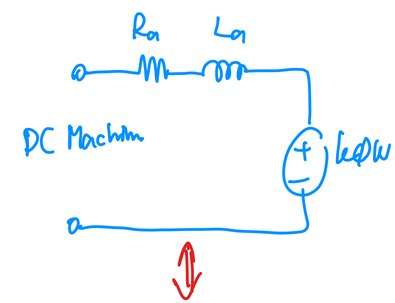
$$\begin{bmatrix} \psi_x \\ \psi_y \end{bmatrix} = T \begin{bmatrix} \psi_u \\ \psi_v \\ \psi_w \end{bmatrix} = \underbrace{\left(l + \frac{3}{2} L \right)}_{L_s} \cdot \begin{bmatrix} i_x \\ i_y \end{bmatrix} + \sqrt{\frac{3}{2}} \lambda' \begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix}$$

$$= L_s \begin{bmatrix} i_x \\ i_y \end{bmatrix} + \underbrace{\lambda \begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix}}_{\vec{\lambda}} = L_s \vec{i}_s + \lambda e^{J\theta}$$

$$\frac{d}{dt}\left(e^{J\theta}\right) = J\omega e^{J\theta} = \omega e^{J(\theta + \frac{\pi}{2})} = \omega \begin{bmatrix} \cos(\theta + \frac{\pi}{2}) \\ \sin(\theta + \frac{\pi}{2}) \end{bmatrix} = \omega \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix}$$

$$\frac{d}{dt}\left(\begin{bmatrix} \cos\theta \\ \sin\theta \end{bmatrix}\right) = \omega \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix}$$

Induced Voltage :



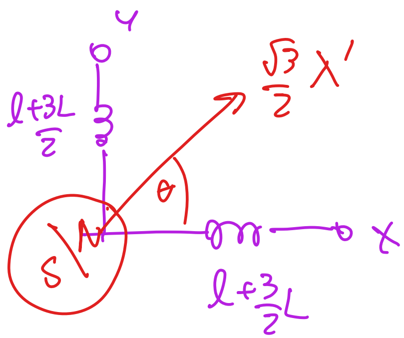
$$T \begin{bmatrix} v_{un} \\ v_{vn} \\ v_{wn} \end{bmatrix} = \begin{bmatrix} v_x \\ v_y \end{bmatrix} = R \begin{bmatrix} i_x \\ i_y \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \psi_x \\ \psi_y \end{bmatrix}$$

$$\Updownarrow$$

$$\vec{v}_s = R\vec{i}_s + \frac{d}{dt}\left(L_s \vec{i}_s + \vec{\lambda} \right) = R\vec{i}_s + L_s \frac{d\vec{i}_s}{dt} + J\omega\vec{\lambda}$$

$$T\begin{bmatrix}\psi_u\\ \psi_v\\ \psi_w\end{bmatrix} = \boxed{T\begin{bmatrix} l+L & \cdot & \cdot \\ -\frac{1}{2}L & l+L & \cdot \\ -\frac{1}{2}L & \cdot & l+L\end{bmatrix}T^{-1}}\, T\begin{bmatrix}i_u\\ i_v\\ i_w\end{bmatrix} + T\lambda'\begin{bmatrix}\cos\theta\\ \cos(\theta-120^\circ)\\ \cos(\theta-240^\circ)\end{bmatrix}$$

$$\begin{bmatrix}\psi_x\\ \psi_y\end{bmatrix} = \begin{bmatrix} l+\frac{3}{2}L & 0 \\ 0 & l+\frac{3}{2}L\end{bmatrix}\begin{bmatrix}i_x\\ i_y\end{bmatrix} + \sqrt{\frac{3}{2}}\,\lambda'\begin{bmatrix}\cos\theta\\ \sin\theta\end{bmatrix}$$



$$\vec{v}_s = R\,\vec{i}_s + L_s\frac{d\vec{i}_s}{dt} + j\omega\vec{\lambda} \Rightarrow \text{stator}$$

Power Flow

$$\left.\begin{aligned}\vec{\lambda} &= e^{j\theta}\begin{bmatrix}\lambda\\ 0\end{bmatrix}\\ \omega &= \frac{d\theta}{dt}\end{aligned}\right\}\ \text{rotor}$$

Power & Induced Torque

$$\vec{v}_s = R\vec{i}_s + L_s\frac{d\vec{i}_s}{dt} + J\omega\vec{\lambda}$$

SPMSM Model on Stator Reference Frame

Power…

power input from stator

$$\vec{i}_s \bullet \vec{v}_s = \vec{i}_s \bullet \left\{ R\vec{i}_s + L_s\frac{d\vec{i}_s}{dt} + J\omega\vec{\lambda} \right\}$$

dot product

$$\underbrace{\vec{i}_s^{\,T}\vec{v}_s}_{\text{Input Power}} = \underbrace{\vec{i}_s^{\,T}R\vec{i}_s}_{\text{Copper Loss}} + \underbrace{\vec{i}_s^{\,T}L_s\frac{d\vec{i}_s}{dt}}_{\frac{d}{dt}\underbrace{\left(\frac{1}{2}L_s\vec{i}_s^{\,T}\vec{i}_s\right)}_{\text{Magnetic Energy}}} + \underbrace{\vec{i}_s^{\,T}J\omega\vec{\lambda}}_{\text{Mechanical Power}}$$

Input Power

Copper Loss

Mechanical Power $= T_e \cdot \omega$

Magnetic Energy

Power & Induced Torque

$\omega_{elec} = P \cdot \omega_{m_{mech}}$

$\uparrow$ pole pair

2 poles $\Rightarrow P = 1$

4 poles $\Rightarrow P = 2$

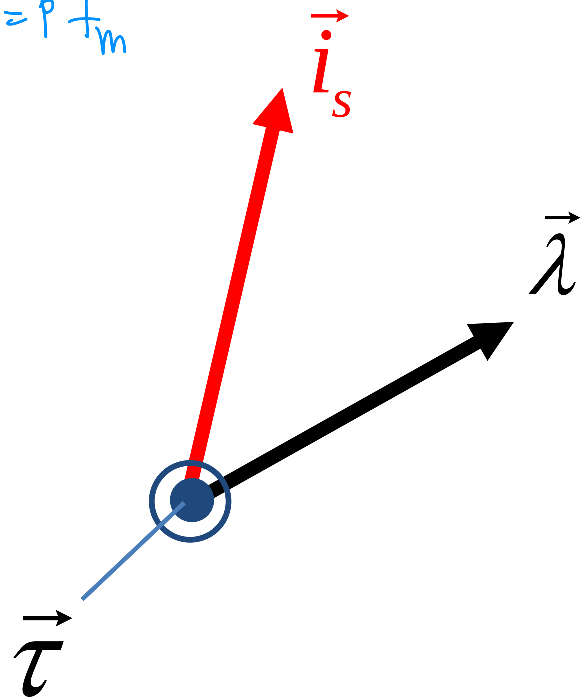
$$P_{mech} = \vec{i}_s^{\,T} J \omega \vec{\lambda} = \tau \cdot \omega_m = \tau \cdot \frac{\omega}{P}$$

$\theta_e = P\,\theta_m$

$f_e = P\,f_m$

stator current

rotor flux

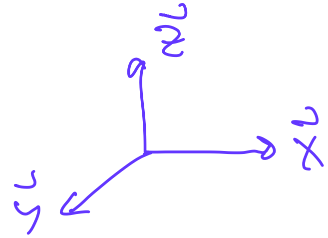


$$\tau = P \vec{i}_s^{\,T} J \vec{\lambda}$$

$$\vec{\tau} = \underline{\underline{P}}\, \vec{\lambda} \underline{\underline{\times}} \vec{i}_s$$

$\frac{\#\text{poles}}{2}$

$$\vec{a} = \begin{bmatrix} x \\ y \end{bmatrix}, \quad \vec{b} = \begin{bmatrix} m \\ n \end{bmatrix}$$



$$\vec{a} \times \vec{b} = (xn - my) \cdot z$$

$$= (\vec{b}^{T} \cdot J\vec{a})\, z \qquad J = \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}$$

$$= \left(\begin{bmatrix} m & n \end{bmatrix} \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} x \\ y \end{bmatrix} \right) z$$

$$= \left(\begin{bmatrix} m & n \end{bmatrix} \begin{bmatrix} -y \\ x \end{bmatrix} \right) z = (xn - my)\, z$$

Dynamic Model of SPMSM on Rotating Reference Frame

$$T_1(\theta) \stackrel{\Delta}{=} e^{-J\theta} \quad \times \quad \rightarrow$$

Stator ref. frame

$$\vec{v}_s = R\vec{i}_s + L_s \frac{d\vec{i}_s}{dt} + J\omega\vec{\lambda}$$

$\downarrow$ $x + jy$ or $\begin{bmatrix} x \\ y \end{bmatrix}$

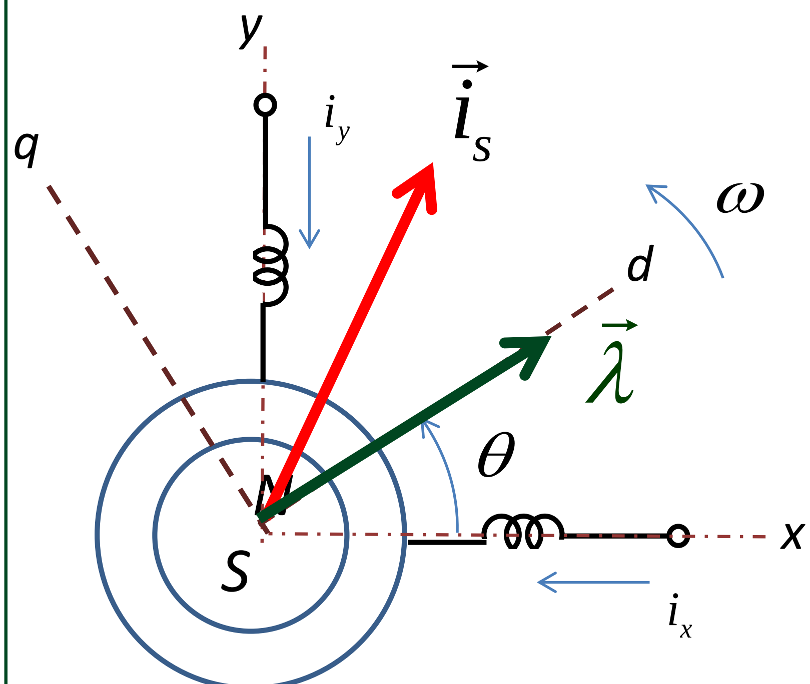
$$e^{-J\theta} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix}$$

$e^{-j\theta} = \cos\theta - j\sin\theta$

Rotor ref. frame

$$\vec{v}_s' = R\vec{i}_s' + L_s \underbrace{T_1(\theta)\frac{d\vec{i}_s}{dt}}_{} + J\omega\vec{\lambda}'$$

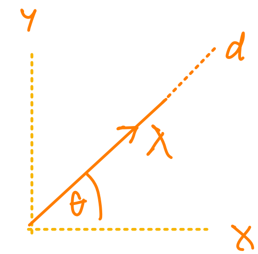
$$\frac{d}{dt}\left(T_1(\theta)\vec{i}_s\right) = \frac{d\vec{i}_s'}{dt} + J\omega\vec{i}_s'$$



Rotor ref. frame

$$\vec{v}_s' = R\vec{i}_s' + L_s \frac{d\vec{i}_s'}{dt} + J\omega L_s\vec{i}_s' + J\omega\vec{\lambda}'$$

$$\begin{bmatrix} v_{sx} \\ v_{sy} \end{bmatrix} = R \begin{bmatrix} i_{sx} \\ i_{sy} \end{bmatrix} + L_s \frac{d}{dt} \begin{bmatrix} i_{sx} \\ i_{sy} \end{bmatrix} + J\omega \begin{bmatrix} \lambda \cos\theta \\ \lambda \sin\theta \end{bmatrix}$$



$$\underset{\| \atop \vec{v}_s}{\begin{bmatrix} v_d \\ v_q \end{bmatrix}} = R \begin{bmatrix} i_d \\ i_q \end{bmatrix} + L_s \underbrace{T_1(\theta) \left(\frac{d}{dt} \begin{bmatrix} i_{sx} \\ i_{sy} \end{bmatrix} \right)} + J\omega \begin{bmatrix} \lambda \\ 0 \end{bmatrix}$$

$$\because \frac{d}{dt}\left(e^{-J\theta} \cdot \vec{i}_s\right) = e^{-J\theta} \frac{d}{dt} \vec{i}_s + \frac{d}{dt}\left(e^{-J\theta}\right) \vec{i}_s$$

$$\frac{d}{dt}\left(\vec{i}_s{}'\right) = e^{-J\theta} \frac{d}{dt} \vec{i}_s + \left(-J\omega e^{-J\theta} \vec{i}_s\right)$$

$$\therefore T_1(\theta) \frac{d}{dt} \vec{i}_s = \frac{d}{dt} \vec{i}_s{}' + J\omega \vec{i}_s{}'$$

1.96.38

$$\vec{a} \times \vec{b} = \mathrm{Im}(\vec{a}^* \cdot \vec{b})\, z$$

$$= \mathrm{Im}([x - jy] \cdot [m + jn])\, z$$

$$= \mathrm{Im}((xm + ny) + j(xn - my))\, z$$

$$= (xn - my)\, z$$

$$\vec{i}_s e^{-j\theta} = (i_{sx} + j i_{sy}) \cdot (\cos\theta - j\sin\theta) = (i_{sx}\cos\theta + i_{sy}\sin\theta) + j(-i_{sx}\sin\theta + i_{sy}\cos\theta)$$

$$e^{-j\theta}\vec{i}_s = \begin{bmatrix} \cos\theta & +\sin\theta \\ -\sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_{sx} \\ i_{sy} \end{bmatrix} = \begin{bmatrix} i_{sx}\cos\theta + i_{sy}\sin\theta \\ -i_{sx}\sin\theta + i_{sy}\cos\theta \end{bmatrix}$$

Vector Control of SPMSM

สมการแรงบิด

$|\lambda| e^{j\theta}$

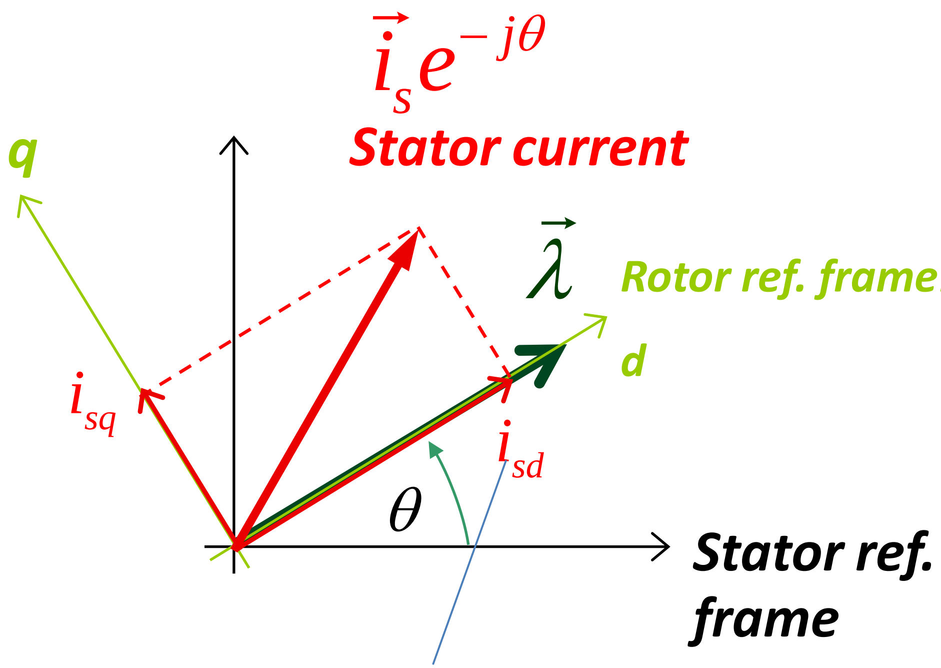
$$\vec{\tau} = P\,\vec{\lambda} \times \vec{i}_s$$

$$\tau = \mathrm{Im}\left[P|\lambda| e^{-j\theta} \cdot \vec{i}_s\right]$$

$$= P|\lambda|\,\mathrm{Im}\left[\vec{i}_s e^{-j\theta}\right]$$

$$= P|\lambda|\,\mathrm{Im}\left[i_{sd} + j i_{sq}\right]$$

$$= P|\lambda| i_{sq}$$



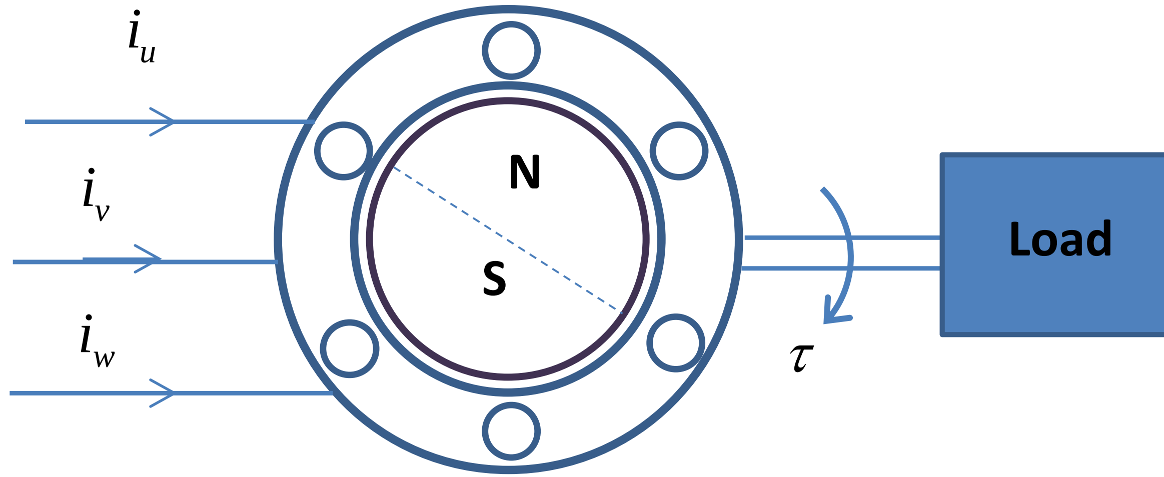
i_{sd} ไม่เกี่ยวกับการสร้างแรงบิด

↳ ใช้ทำ field-weakening

Vector Control of SPMSM

$$\tau = \underbrace{P|\lambda|}_{\text{Permanent Magnet}} i_{sq}$$

ต้องการควบคุมแรงบิด -> จะต้องจ่ายกระแสสเตเตอร์อย่างไร ?



ควบคุมแรงบิด ผ่าน...

- กระแส i_{sq}
- ให้กระแส $i_{sd} = 0$ (maximum torque per amp.)

Vector Control of SPMSM

Ex P = 2, λ = 0.1 [Wb], ต้องการ $\tau(t)$ = 1 [N.m]

$$\theta(t) = \frac{\pi}{6} + 100\pi t$$ (มุมของโรเตอร์ทางไฟฟ้า)

$$\tau(t) = P|\lambda| i_{sq} \quad \Rightarrow \quad 1 = 2\times 0.1 \times i_{sq} \quad \rightarrow \quad i_{sq} = 5[A]$$

อยากได้

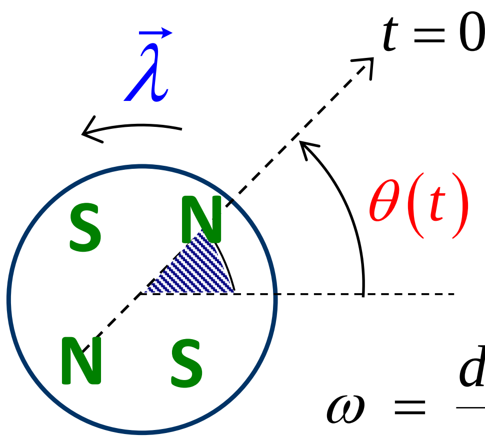
$$\left.\begin{aligned} i_{s1}(t) &= \\ i_{s2}(t) &= \\ i_{s3}(t) &= \end{aligned}\right\} \Leftrightarrow \quad \vec{i}_s \quad \Leftrightarrow \quad \vec{i}_s e^{-j\varepsilon} = i_{sd} + j i_{sq}$$

$$= 0 + j5$$

$$\theta(t) = \frac{\pi}{6} + 100\pi t$$

ถ้าต้องการ **Maximum Torque/Amp.** $\rightarrow i_{sd} = 0$

Vector Control of SPMSM



$$\omega = \frac{d\theta}{dt} = 100\pi\,[rad/s] \quad \text{(elec.)}$$

$$N = \frac{3000}{2} = 1500\,[rpm] \quad \text{(mech.)}$$

$$\vec{i}_s(t) = \left(i_{sd} + j i_{sq}\right)\cdot e^{j\theta}$$

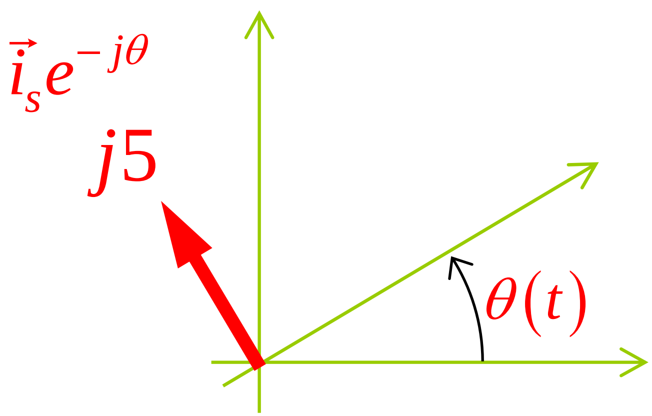
$$= j5\cdot e^{j\left(\frac{\pi}{6} + \overset{1}{\cancel{2}}00\pi t\right)}$$

$$= 5\cdot e^{j\left(\frac{2\pi}{3} + \overset{1}{\cancel{2}}00\pi t\right)}$$

$$i_u(t) = 5\sqrt{\frac{2}{3}}\cos\left(100\pi t + \frac{2\pi}{3}\right)$$

$$i_v(t) = 5\sqrt{\frac{2}{3}}\cos\left(100\pi t\right)$$

$$i_w(t) = 5\sqrt{\frac{2}{3}}\cos\left(100\pi t - \frac{2\pi}{3}\right)$$



$$\begin{bmatrix} i_{sd}^{*} \\ i_{sq}^{*} \end{bmatrix} = \begin{bmatrix} 0 \\ 5 \end{bmatrix} \Rightarrow e^{J\theta} \Rightarrow \begin{bmatrix} i_{sx}^{*} \\ i_{sy}^{*} \end{bmatrix} = 5 \begin{bmatrix} \cos\left(\frac{2\pi}{3} + 200\pi t\right) \\ \sin\left(\frac{2\pi}{3} + 200\pi t\right) \end{bmatrix}$$

2ϕ Rotating Ref frame

2ϕ stationary Ref Frame

2ϕ

$\Downarrow$

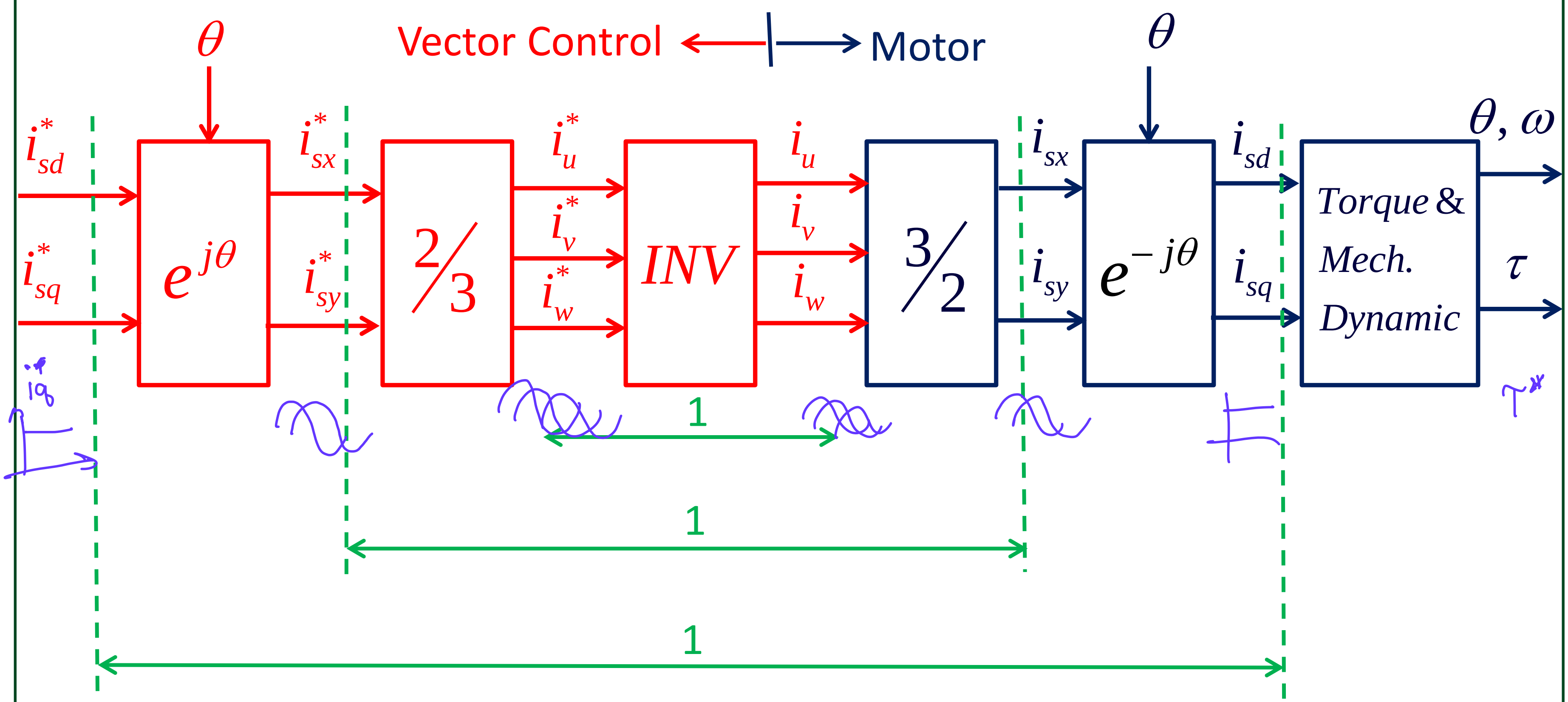
3ϕ

$$\sqrt{\frac{2}{3}} \begin{bmatrix} 1 & 0 \\ -\frac{1}{2} & \frac{\sqrt{3}}{2} \\ -\frac{1}{2} & -\frac{\sqrt{3}}{2} \end{bmatrix}$$

$\Downarrow$

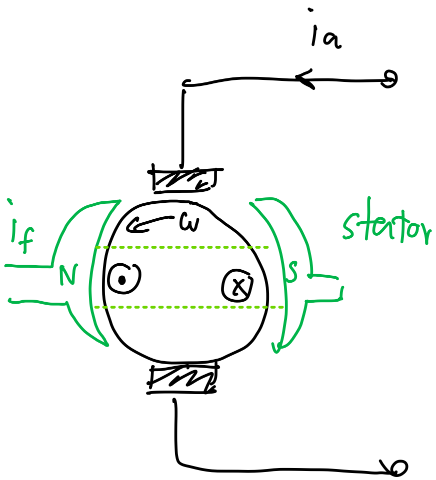
$$\begin{bmatrix} i_{s1} \\ i_{s2} \\ i_{s3} \end{bmatrix} = \begin{bmatrix} \cdot & & \\ & \cdot & \\ & & \cdot \end{bmatrix}$$

Overall Block Diagram



θ สามารถตรวจวัดได้ด้วย Position Sensor; Encoder, Resolver

DC Machine



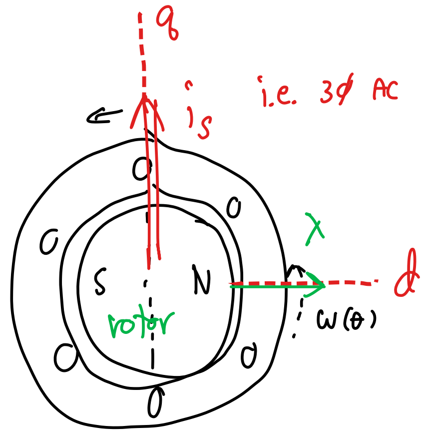
$\phi \rightarrow i_f$

stationary magnetic field

i_a

$T_{em} = K\phi i_a$

PMSM



λ, i_{sq} หมุนตามกันไป

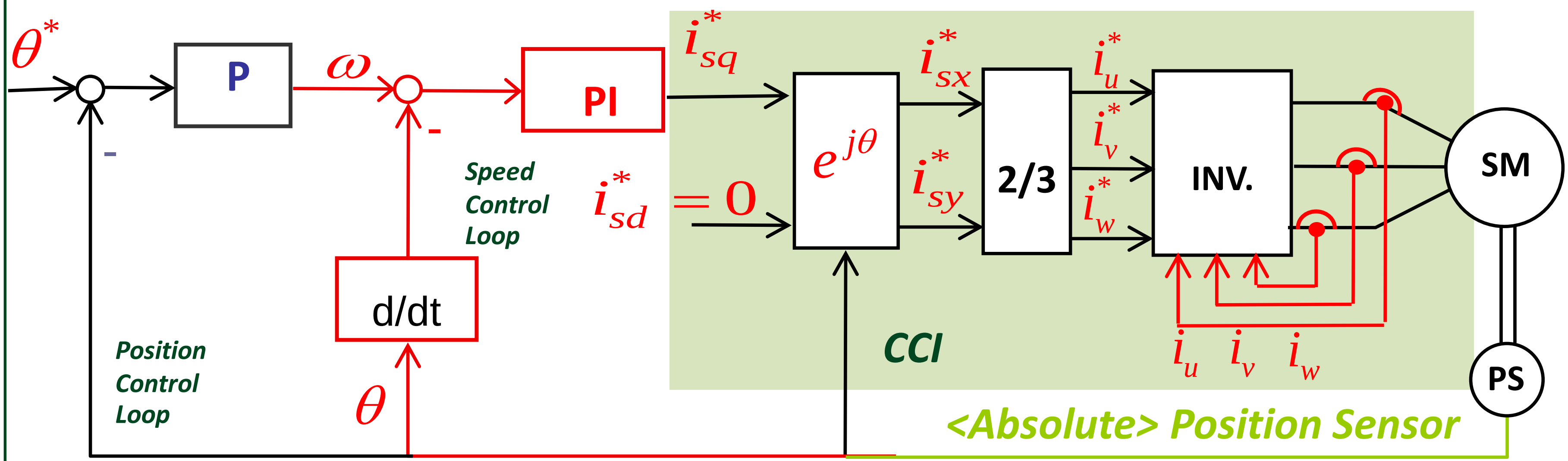
$\tilde{\lambda}$

i_{sq}

Rotating magnetic field

$T_{em} = p|\tilde{\lambda}| i_{sq}$

Vector Control with Current-Controlled Inverter



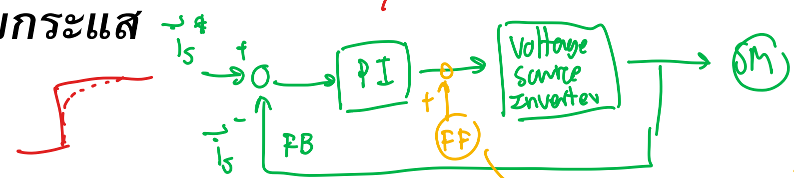
torque control $\tau^* \rightarrow \frac{1}{p|\lambda|} \rightarrow$ i_{sq}^* i_{sd}^*

☑ ***Response*** ***ไว***

☑ ไม่ต้องการค่าพารามิเตอร์มอเตอร์ R, L_s

☒ ***ใช้ Gain สูงในการควบคุมกระแส***

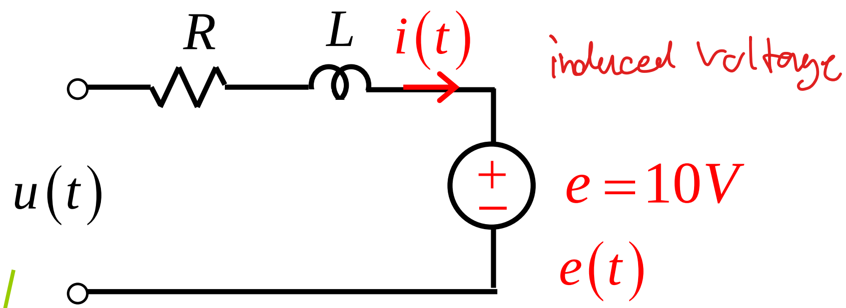
P สูง → Stability problem!



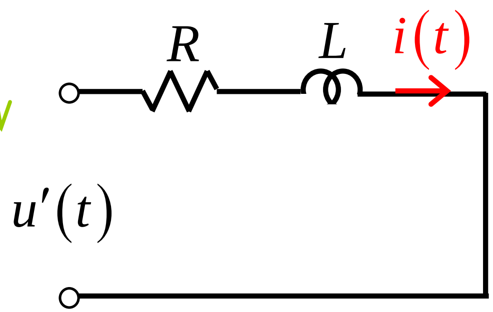
→ ช่วย P ไม่ต้องสูง

Model Machine
↳ R, Ls

Principle of Vector Control by Voltage Source Inverter



ควบคุมกระแสผ่านแหล่งจ่ายแรงดัน



- Voltage equation :

$$R i(t) + L\frac{d\,i(t)}{dt} + e(t) = u(t)$$

- Commanded voltage with induced voltage compensation:

กำหนด $$u(t) = \underbrace{10}_{e(t)} + u'(t)$$

$$R\,i(t) + L\frac{d\,i(t)}{dt} + \underbrace{\cancel{e(t)}}_{10} = u'(t) + \underbrace{\cancel{10}}_{e(t)}$$

- Decoupled current dynamic :

→ control i(t)

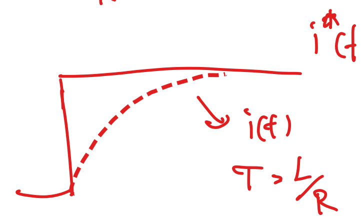
ง่าย $$R\,i(t) + L\frac{d\,i(t)}{dt} = u'(t)$$

Principle of Vector Control by Voltage Source Inverter

สมมุติว่า $R = 1\Omega, \quad L = 1\,mH$

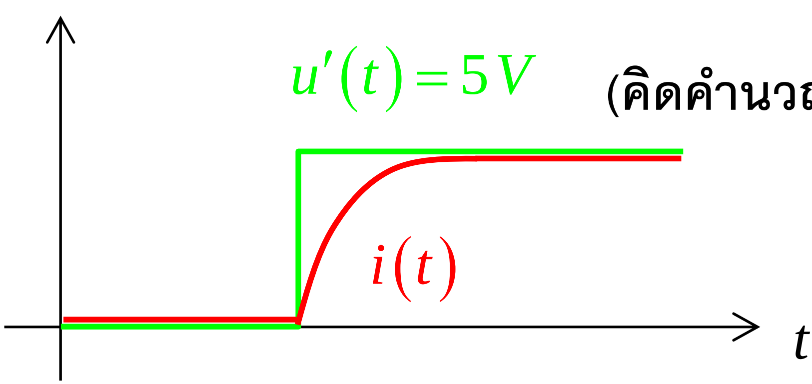
$$i(t) + \frac{L}{R}\frac{di(t)}{dt} = \frac{1}{R}u'(t) = i^*(t)$$

ต้องการให้ได้ $i(t) = 5A$



$R \times i^*(t)$

$\Rightarrow$ จ่ายแรงดัน $u'(t) = 5\times 1 = 5V$ (คงที่)



(คิดคำนวณ)

$$\therefore u(t) = 5 + e(t)$$
$$= 5 + 10 = \boxed{15V}$$

จ่ายจริง

0.43.15

$$\begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} = R \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + L_s \frac{d}{dt} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \underbrace{\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}}_{J} \omega L_s \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \underbrace{\begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix}}_{J} \omega \begin{bmatrix} \lambda \\ 0 \end{bmatrix}$$

$$\begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} = \left[\begin{array}{c:c} R & -\omega L_s \\ \hdashline \omega L_s & R \end{array}\right] \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + L_s \frac{d}{dt} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega \lambda \end{bmatrix}$$

Principle of Vector Control by Decoupling Control

$$\vec{v}_s' = R\vec{i}_s' + L_s \frac{d\vec{i}_s'}{dt} + J\omega L_s \vec{i}_s' + J\omega\vec{\lambda}'$$

$$\begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} = \begin{bmatrix} R & -\omega L_s \\ \omega L_s & R \end{bmatrix} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + L_s \frac{d}{dt} \begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \begin{bmatrix} 0 \\ \omega\lambda \end{bmatrix}$$

มีการเชื่อมโยงแรง
เคลื่อนเหนี่ยวนำ
ระหว่าง ***d-q axes !***

d-axis: $$v_{sd} = Ri_{sd} + L_s \frac{di_{sd}}{dt} - \omega L_s i_{sq}$$

q-axis: $$v_{sq} = Ri_{sq} + L_s \frac{di_{sq}}{dt} + \omega L_s i_{sd} + \omega\lambda$$

Principle of Vector Control by Decoupling Control

กำหนดให้ Decoupling Control :

$$v_{sd} = v'_{sd} - \omega L_s i_{sq}$$

$$v_{sq} = v'_{sq} + \omega L_s i_{sd} + \omega \lambda$$

ชดเชยแรงเคลื่อนเหนี่ยวนำระหว่าง d-q axes

Decoupled Stator Dynamic :

d-axis:

$$v'_{sd} = R i_{sd} + L_s \frac{di_{sd}}{dt}$$

q-axis:

$$v'_{sq} = R i_{sq} + L_s \frac{di_{sq}}{dt}$$

Principle of Vector Control by Decoupling Control

กำหนดให้ Decoupling Control :

$$v'_{sd} = R i_{sd}^{*} \longrightarrow R i_{sd}^{*} = R i_{sd} + L_s \frac{di_{sd}}{dt}$$

$$v'_{sq} = R i_{sq}^{*} \longrightarrow R i_{sq}^{*} = R i_{sq} + L_s \frac{di_{sq}}{dt}$$

Decoupled Dynamic

First-Order Response;

Time constant : L_s / R

$$v'_{sd} \longrightarrow i_{sd} \longrightarrow \lambda_s$$

Stator Flux

$$v'_{sq} \longrightarrow i_{sq} \longrightarrow \tau$$

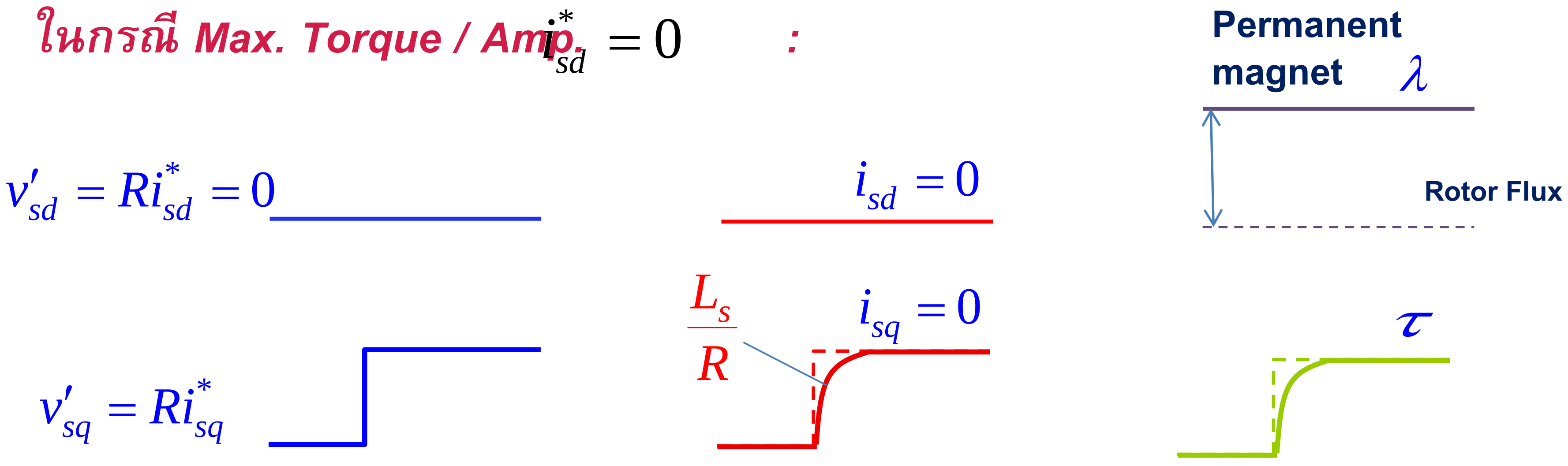
$$\frac{L_s}{R}$$

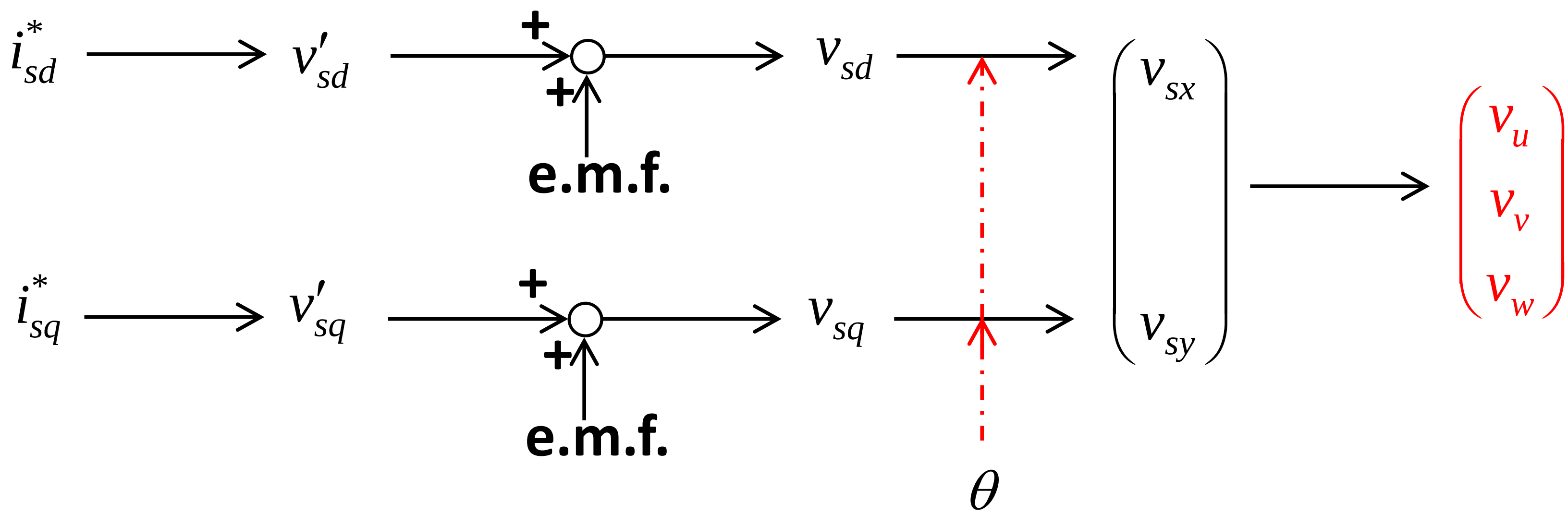
First-order lag

ไม่มี lag

Principle of Vector Control by Decoupling Control

ในกรณี ***Max. Torque / Amp.*** $i_{sd}^* = 0$:





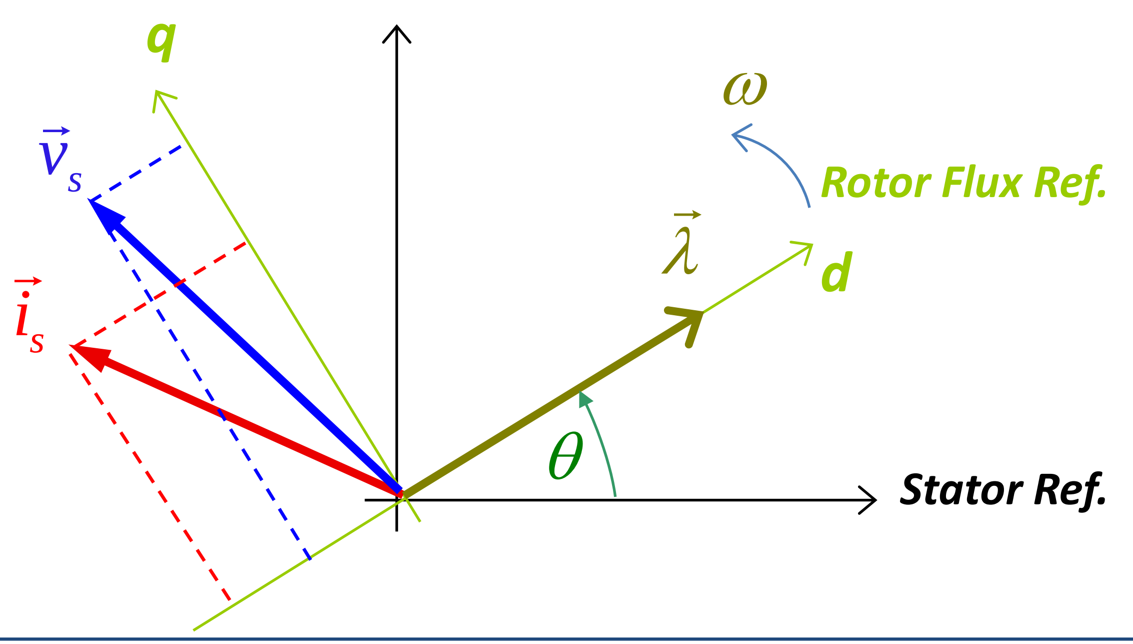
Principle of Vector Control by Decoupling Control

สรุป Decoupling Control :

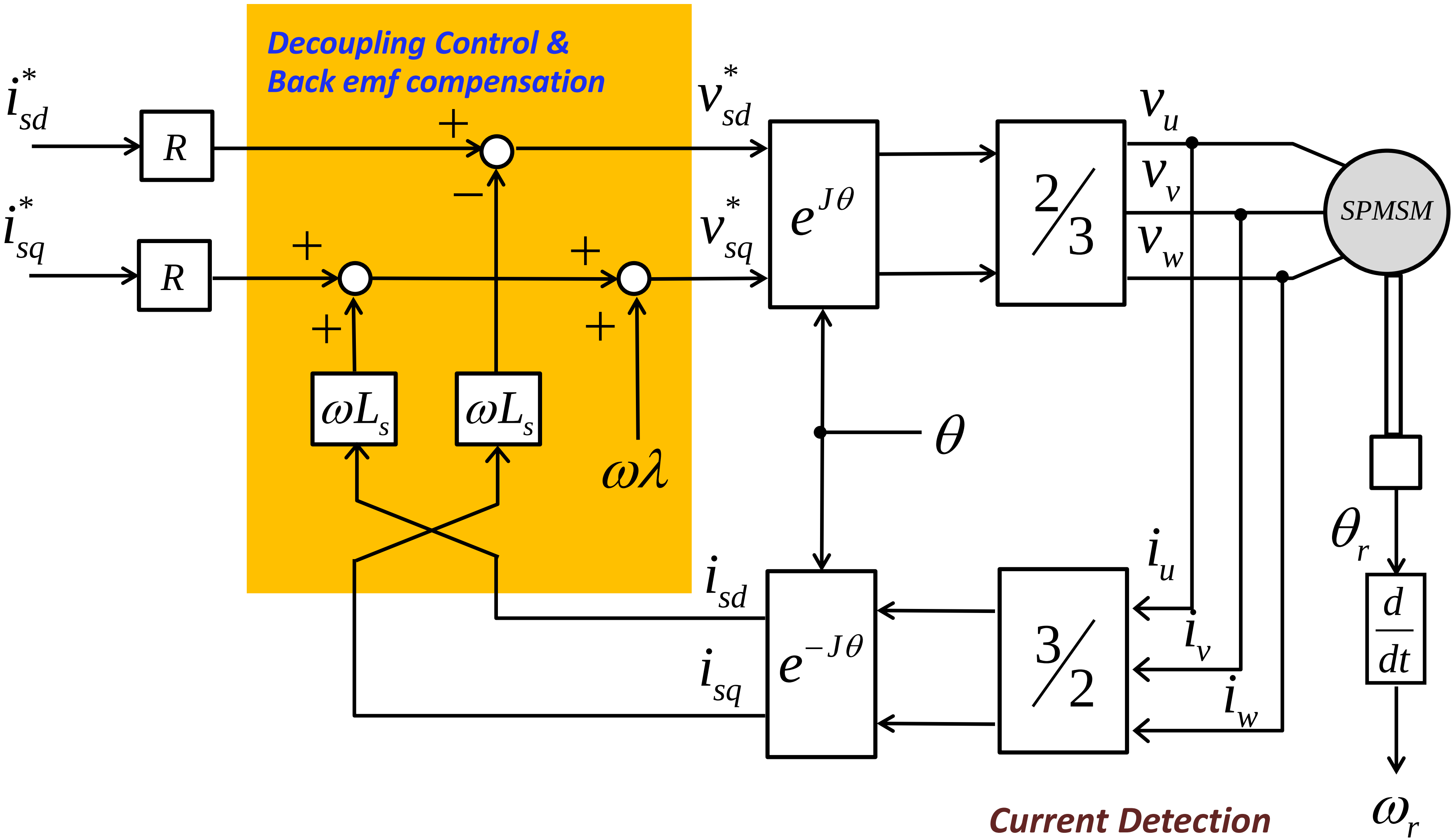
$$v_{sd}^{*} = R\,i_{sd}^{*} - \omega L_s\, i_{sq}$$

$$v_{sq}^{*} = R i_{sq}^{*} + \omega L_s\, i_{sd} + \omega\,\lambda$$

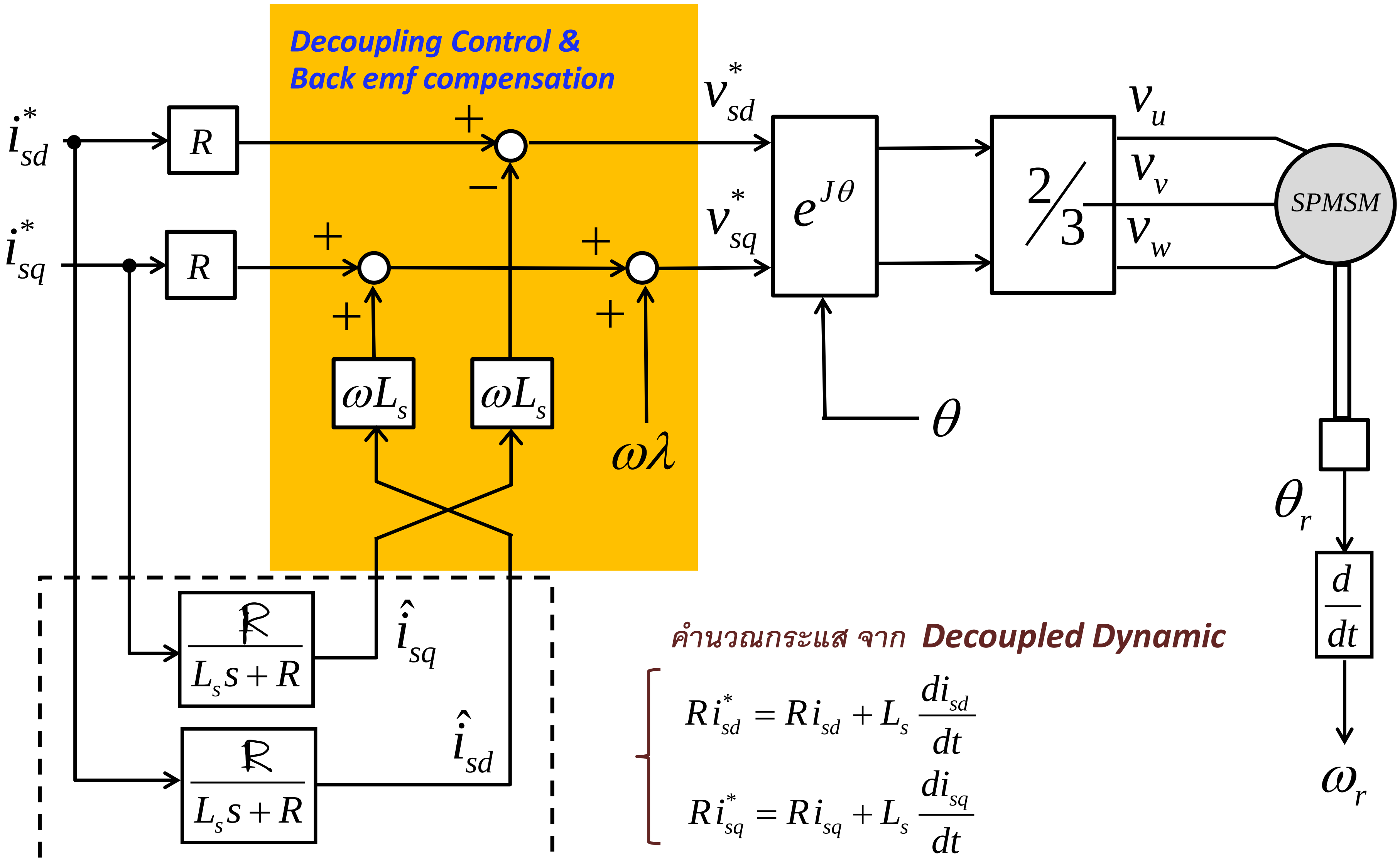
- ☑ ***Feed-Forward Control :*** *ไม่มีปัญหาเรื่องเสถียรภาพ*
- ☑ *ต้องการค่าพารามิเตอร์มอเตอร์ของมอเตอร์* ***R, Ls***



Decoupling Control Scheme #1(with current detection)



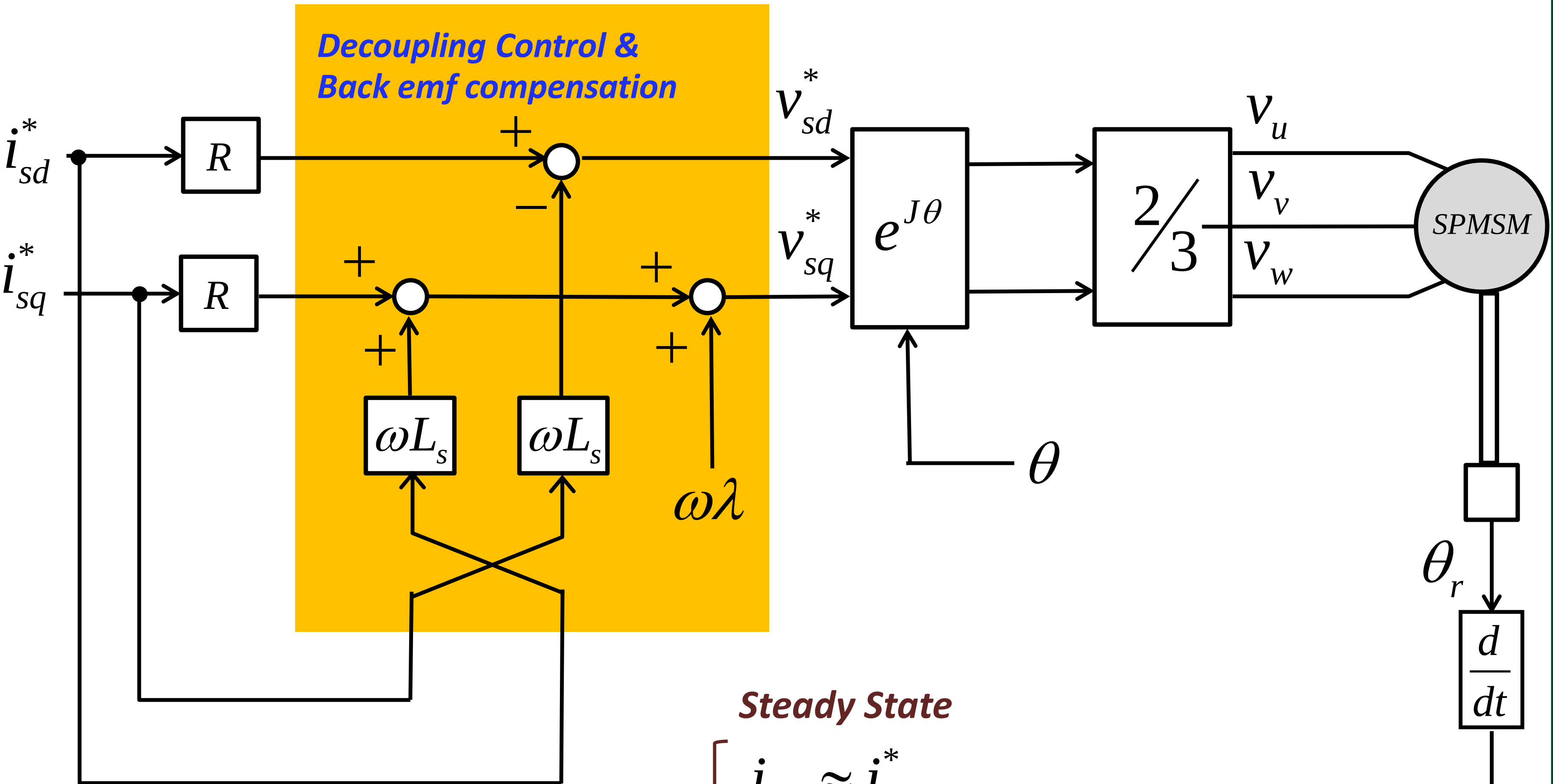
Decoupling Control Scheme #2 (with current estimation)



คำนวณกระแส จาก **Decoupled Dynamic**

$$
\begin{cases}
R i_{sd}^* = R i_{sd} + L_s \dfrac{di_{sd}}{dt} \\
R i_{sq}^* = R i_{sq} + L_s \dfrac{di_{sq}}{dt}
\end{cases}
$$

Decoupling Control Scheme #3 (simplified)



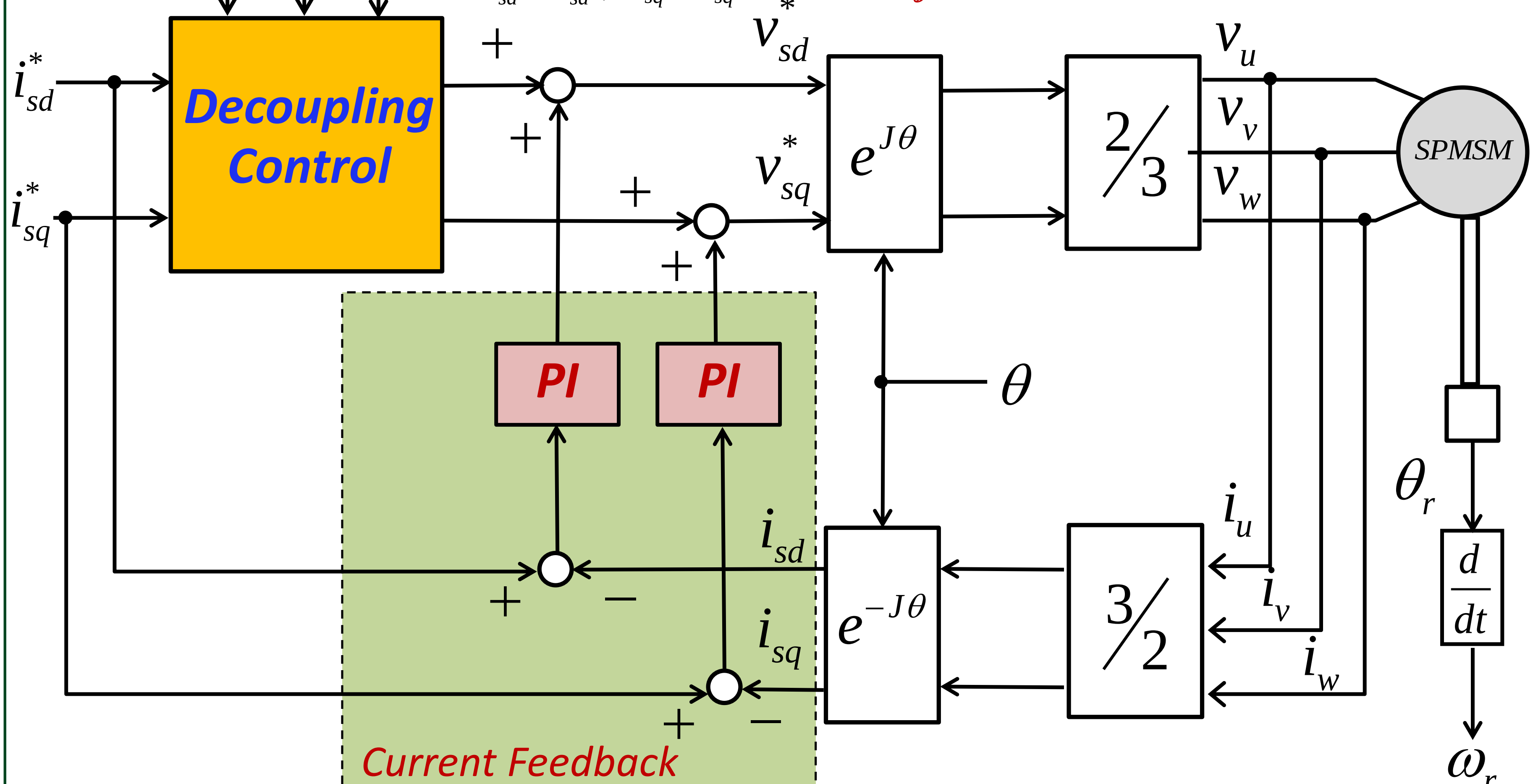
Steady State

$$\begin{cases} i_{sd} \approx i_{sd}^* \\ i_{sq} \approx i_{sq}^* \end{cases}$$

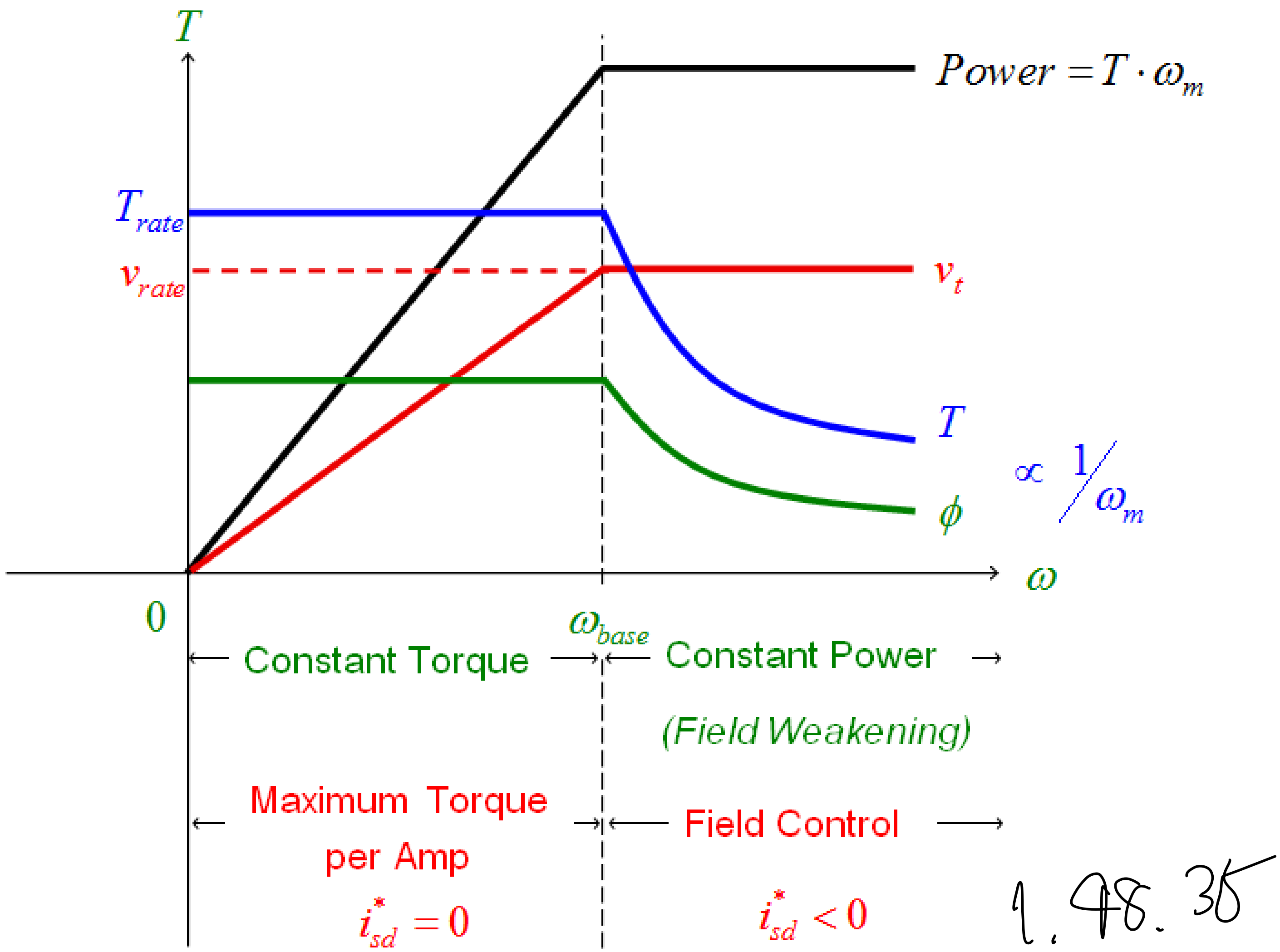
ประมาณ

Decoupling Control with Current Feedback

- *Decoupling Control เป็นการควบคุมแบบป้อนไปหน้า (feed forward)*
- *หากค่าพารามิเตอร์ไม่ถูกต้อง หรือ Inverter สร้างแรงดันผิดเพี้ยนไปจากค่าคำสั่ง จะทำให้* $i_{sd} \neq i_{sd}^*$, $i_{sq} \neq i_{sq}^*$ *สามารถแก้ปัญหานี้ด้วย Current Feedback*



Field-Weakening Operation



Field-Weakening Operation for SPMSM Drives

- *ในกรณีที่มอเตอร์ทำงานที่ความเร็วสูงกว่าพิกัด* $\omega_r > \omega_{rated}$
- *แรงเคลื่อนเหนี่ยวนำจะมีค่าสูง ⇒ แรงดันสเตเตอร์ สูงกว่าค่าพิกัด* $|\vec{v}_s| > V_{rated}$

$<<1$ $\quad <1 \quad >1 \quad >>1$

$$\vec{v}_s' = R\vec{i}_s' + L_s\frac{d\vec{i}_s'}{dt} + J\omega L_s\vec{i}_s' + \underbrace{J\omega\vec{\lambda}'}_{\text{แรงเคลื่อนเหนี่ยวนำจาก PM } \vec{e}_A}$$

$\vec{\lambda}_s' = L_s\vec{i}_s' + \lambda'$

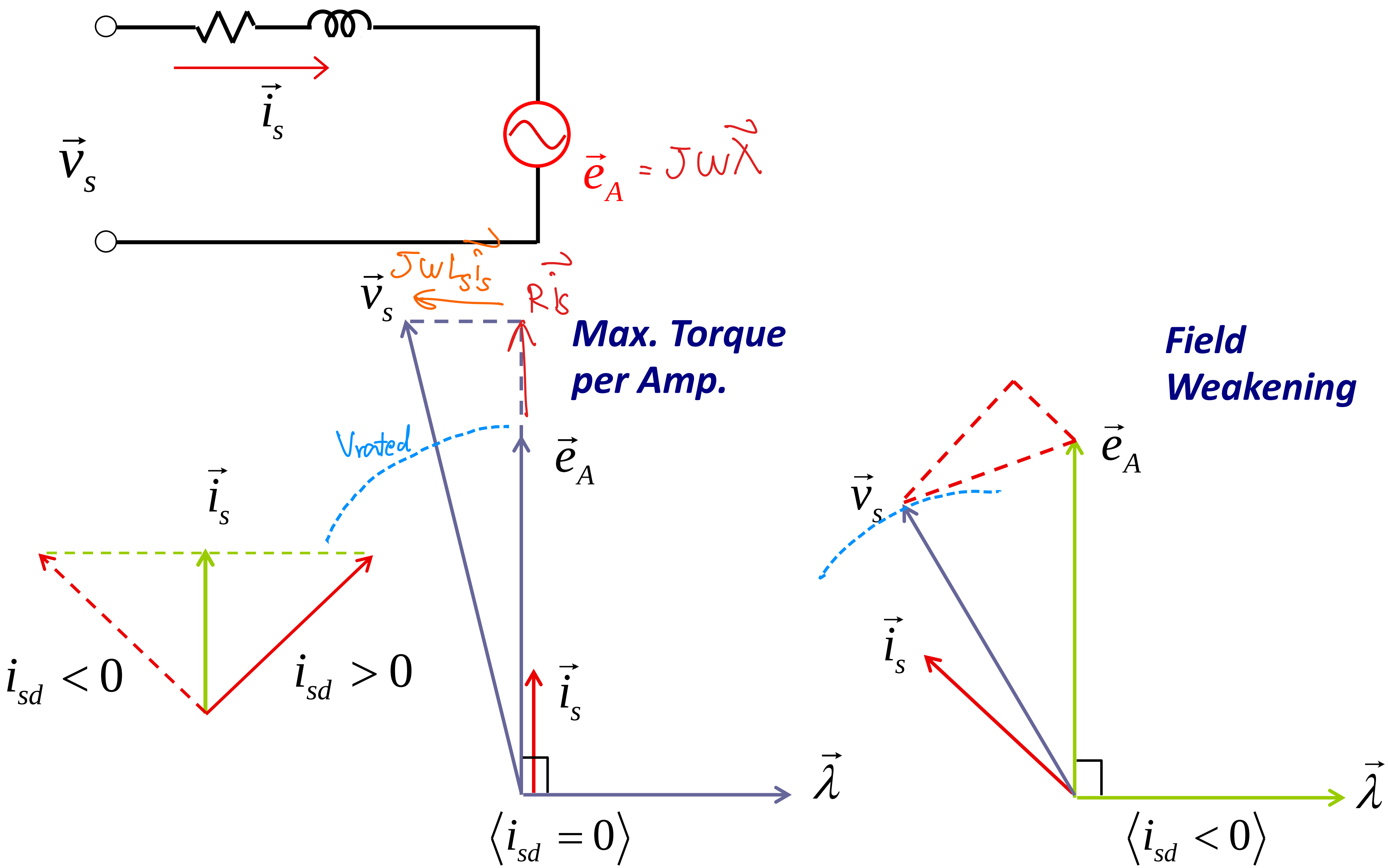
stator Flux

แรงเคลื่อนเหนี่ยวนำจากสเตเตอร์ฟลักซ์

$$\begin{bmatrix} v_{sd} \\ v_{sq} \end{bmatrix} = \begin{bmatrix} R & 0 \\ 0 & R \end{bmatrix}\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + L_s\frac{d}{dt}\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix} + \underbrace{\begin{bmatrix} 0 & -\omega L_s \\ \omega L_s & 0 \end{bmatrix}\begin{bmatrix} i_{sd} \\ i_{sq} \end{bmatrix}}_{} + \begin{bmatrix} 0 \\ \omega\lambda \end{bmatrix}$$

- ใช้กระแสในแกน **d** ลดขนาดแรงเคลื่อนเหนี่ยวนำได้ $(i_{sd} < 0)$

Field-Weakening Operation for SPMSM Drives



Field-Weakening Operation for SPMSM Drives