Chapter 5

Modeling and Control of Interior Permanent Magnet Synchronous Motor; IPMSM

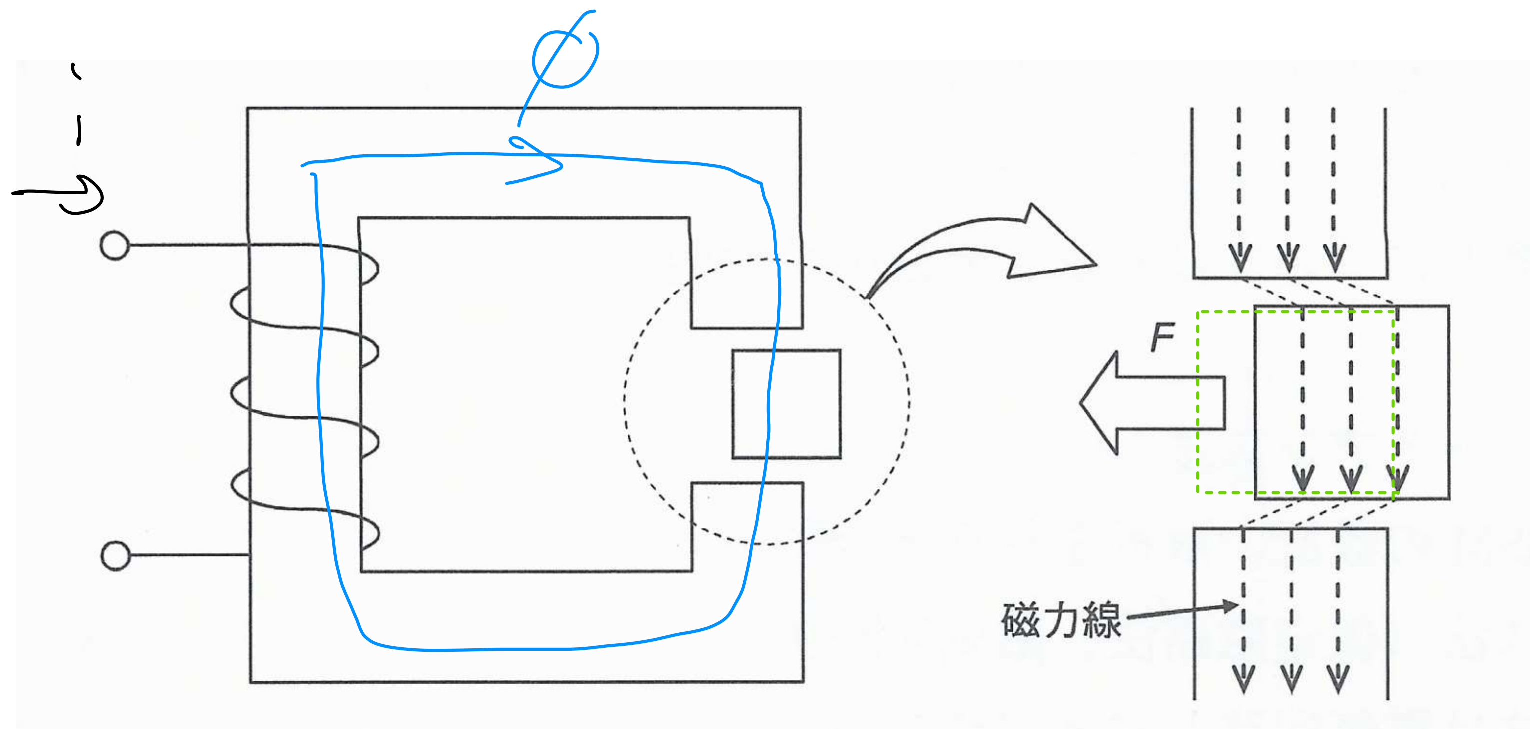
$R = \frac{l}{\mu A}$ $L = \frac{N^2}{R}$

$i \rightarrow H \rightarrow B \rightarrow \phi \rightarrow \lambda$

Ni $B = \mu H$ $\phi = BA$ $\lambda = N\phi$

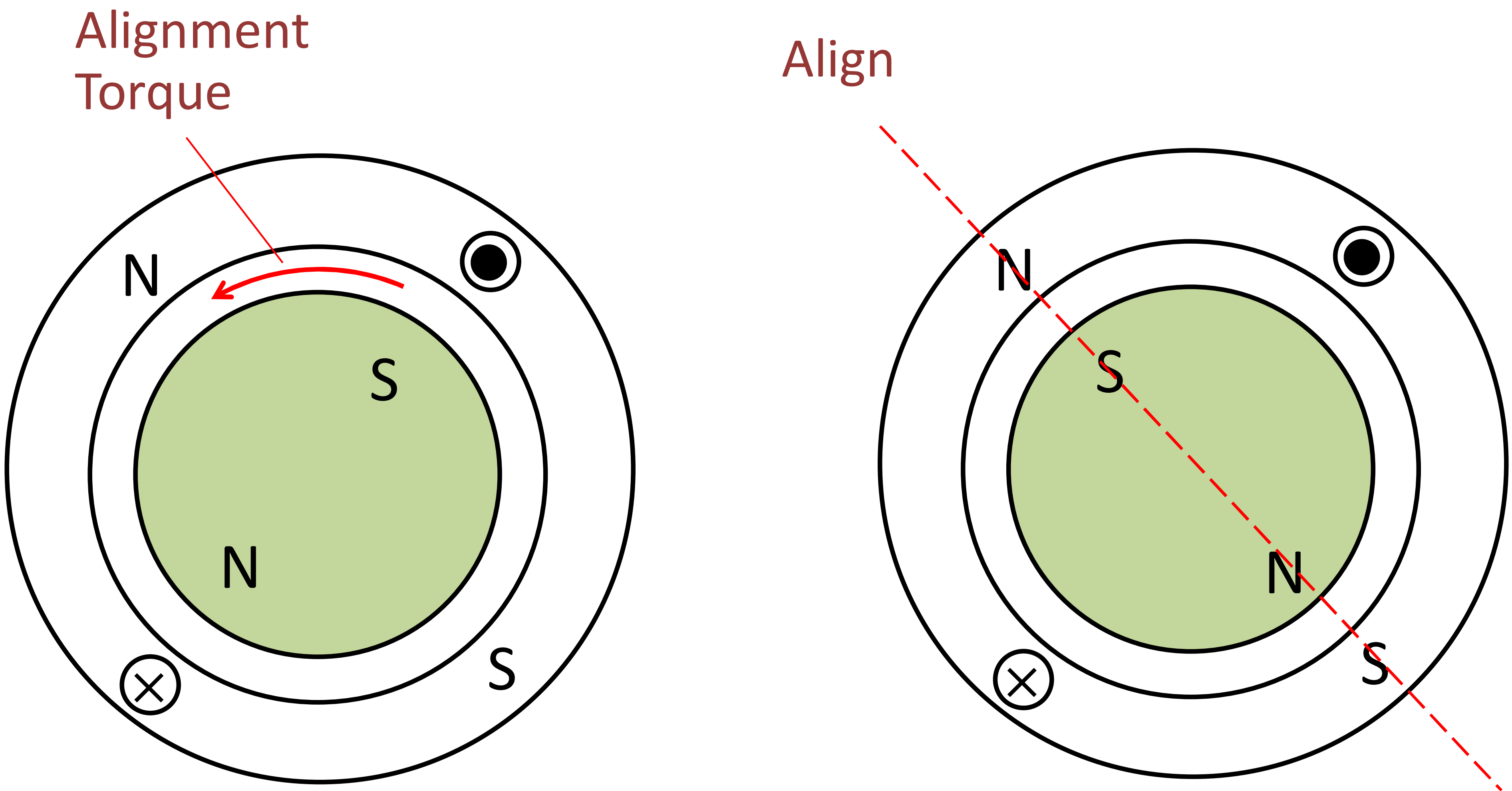
MMF

Reluctance Force



เป็นแรงที่เกิดขึ้นในทิศทางที่พยายามทำให้ Reluctance ในวงจรแม่เหล็กมีค่าน้อยที่สุด
(พิจารณาจากเส้นแรงของสนามแม่เหล็ก)

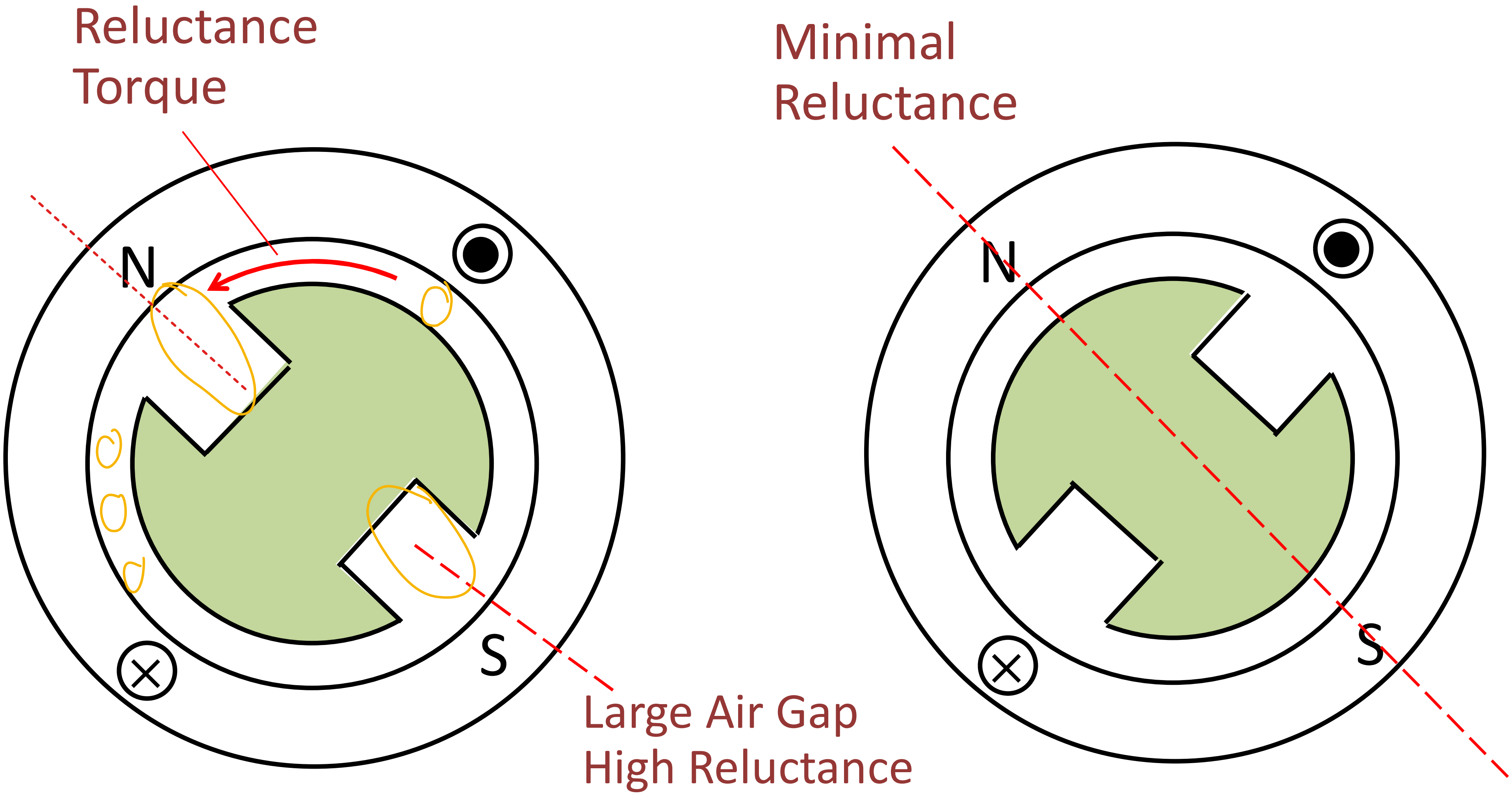
Alignment Torque



-Alignment Torque จะออกแรงในทิศทางที่พยายามทำให้สนามแม่เหล็กจากโรเตอร์เรียงตัวในแนวเดียวกันกับสนามแม่เหล็กจากสเตเตอร์

- ต้องมีสนามแม่เหล็กทั้ง 2 ด้าน (สเตเตอร์ และ โรเตอร์)

Reluctance Torque



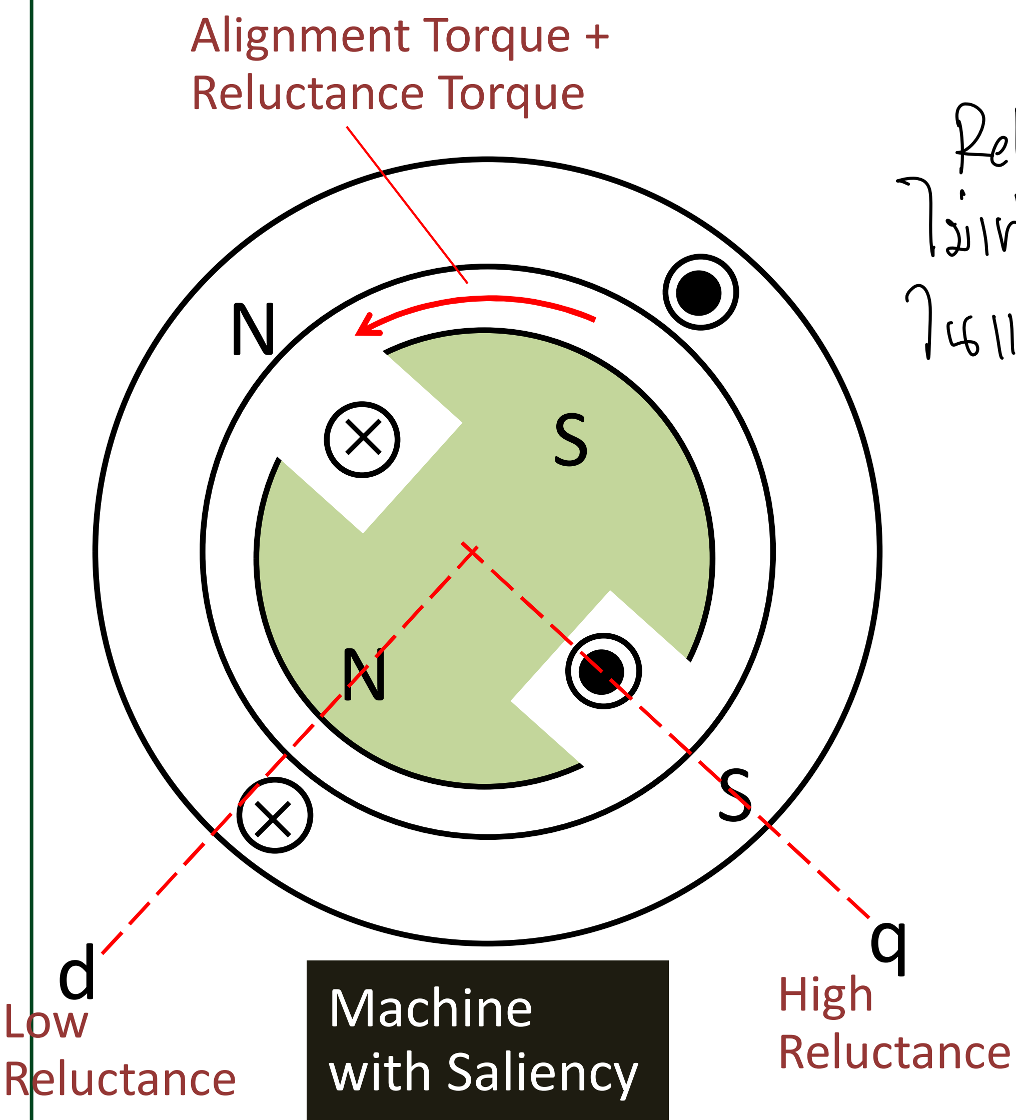
-Reluctance Torque จะออกแรงในทิศทางที่พยายามทำให้ Reluctance มีค่าน้อยที่สุด

- มีเพียงสนามแม่เหล็กด้านใดด้านหนึ่งเท่านั้น

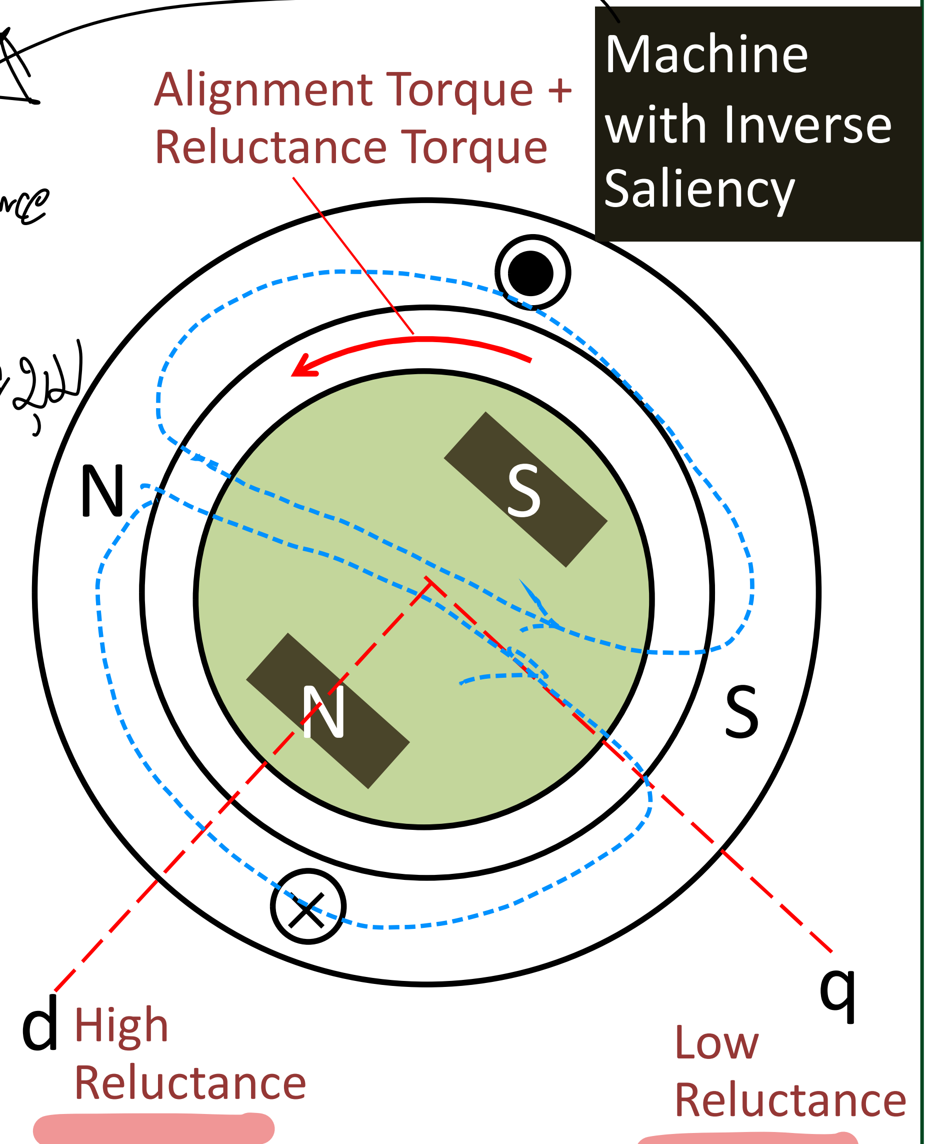
→ non uniform air gap

- Reluctance ที่ตำแหน่งต่าง ๆของโรเตอร์ ต้องไม่เท่ากัน : Saliency

Alignment Torque & Reluctance Torque

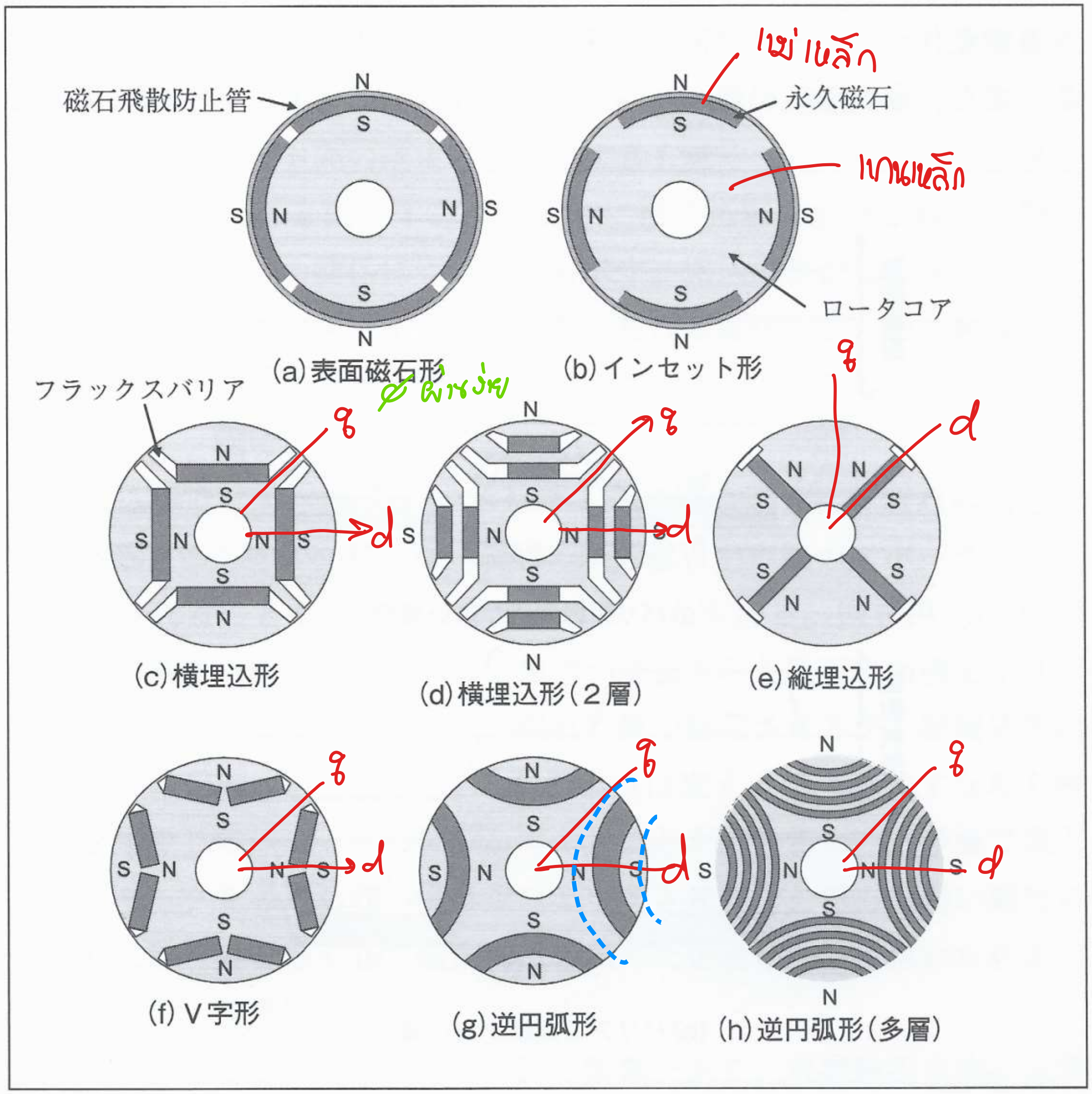


Reluctance
ไม่เท่ากัน
ในแต่ละมุม



พิจารณา Permanent Magnet เป็น Air gap (มี $\mu r \approx 1$)

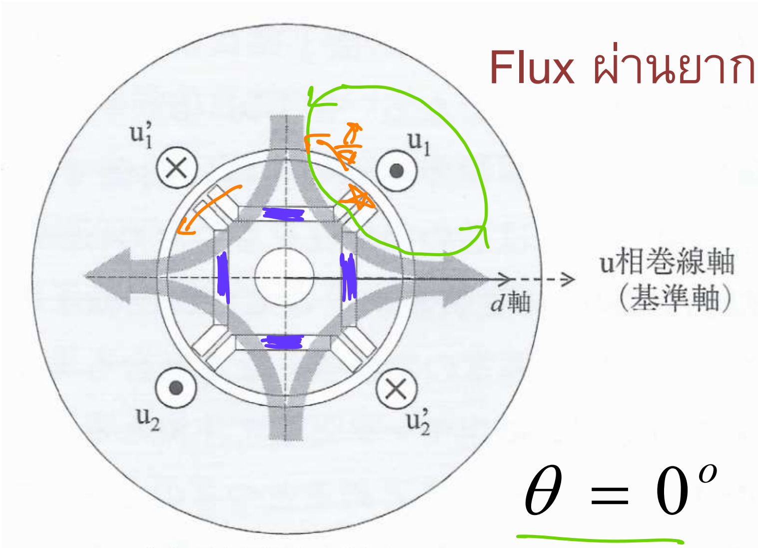
Rotor Structure of Synchronous Machine



〔図 5-16〕代表的な永久磁石配置

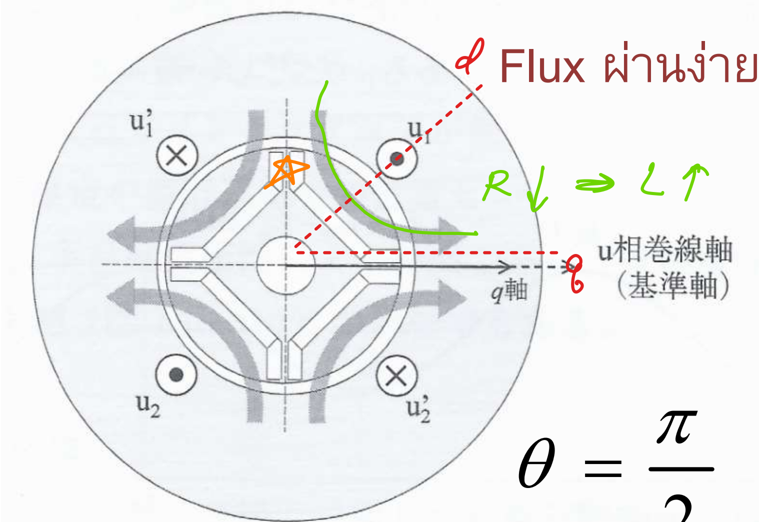
Reluctance & Inductance of IPMSM

$L \propto \frac{1}{R}$



$\theta = 0^o$

(a) d軸方向の磁束

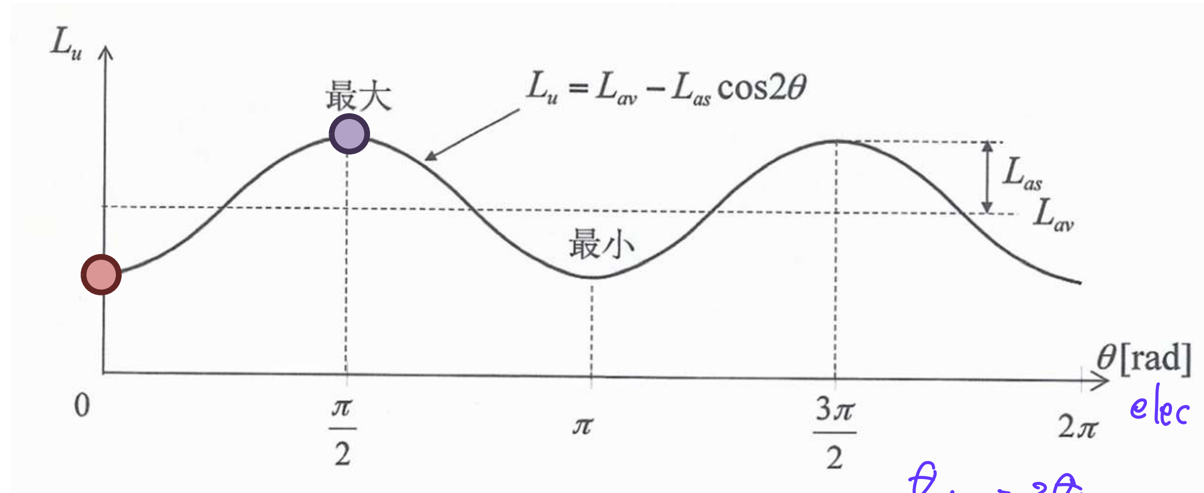


$R \downarrow \Rightarrow L \uparrow$

$\theta = \frac{\pi}{2}$

(b) q軸方向の磁束

$\theta_m = \pi/4$



$\theta_{elec} = 2\theta_m$
(4 poles)

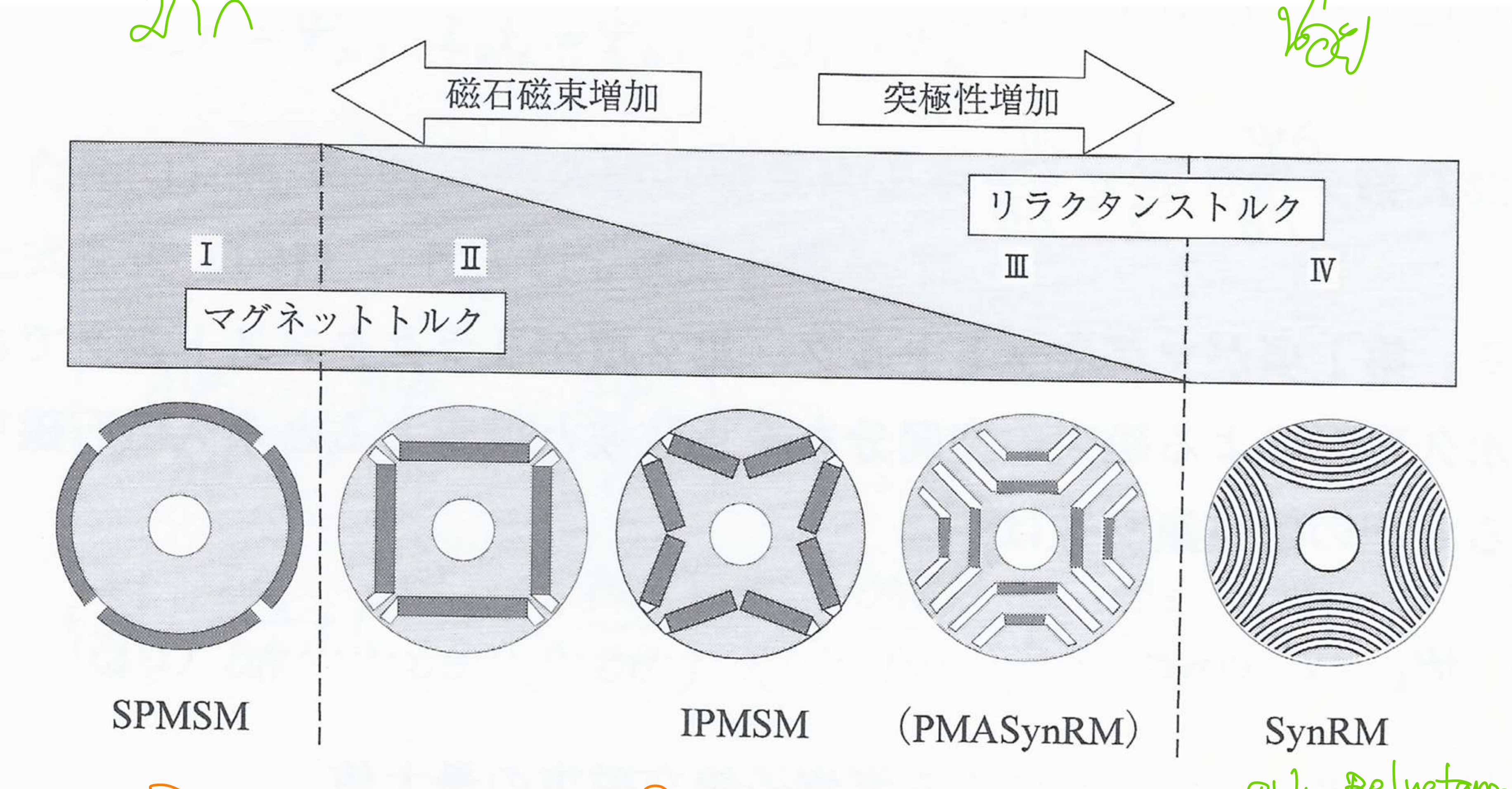
ค่า Inductance เปลี่ยนแปลงตามตำแหน่งของโรเตอร์

1.00.28

Synchronous Machine & Usage of Permanent Magnet

มาก

น้อย

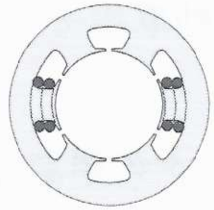
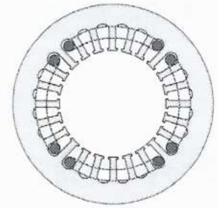
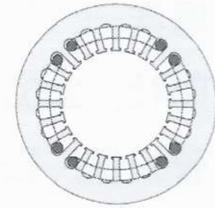
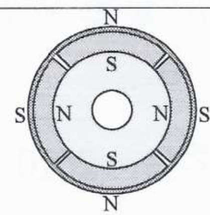
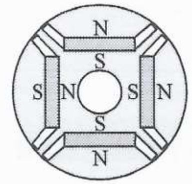
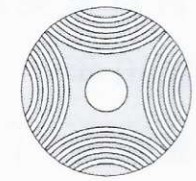
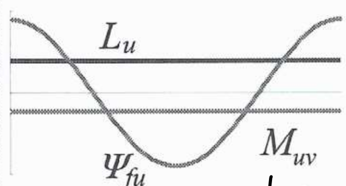
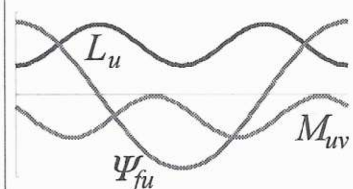
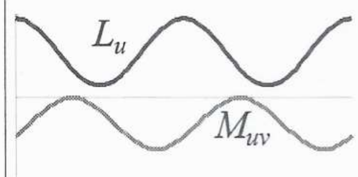


แรงบิดเท่ากัน ใครใช้ PM มากกว่า

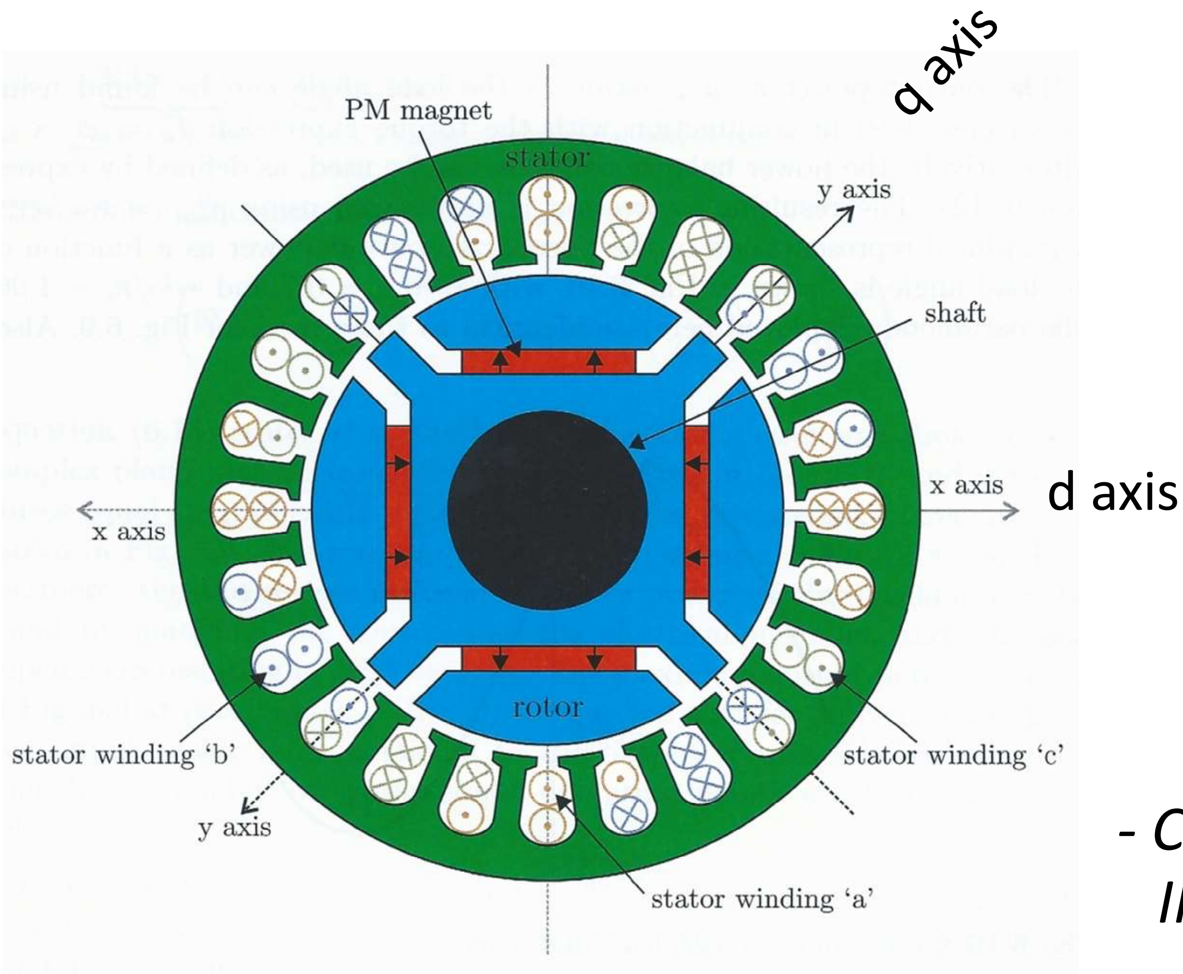
only Reluctance force
no PM!

Comparison of Synchronous Machines

〔表 1-4〕同期モータの構造とトルク発生メカニズムによる分類

項 目	SPMSM	IPMSM	SynRM
stator 固定子構造			
rotor 回転子構造			
インダクタンス・永久磁石磁束の位置による変化			
トルク発生メカニズム	PM mutual Inductance 永久磁石による電機子鎖交磁束の変化（マグネットトルク）	永久磁石による電機子鎖交磁束の変化（マグネットトルク）＋自己インダクタンスと相互インダクタンスの変化（リラクタンストルク）	自己インダクタンスと相互インダクタンスの変化（リラクタンストルク）

Interior Permanent Magnet Synchronous Motor



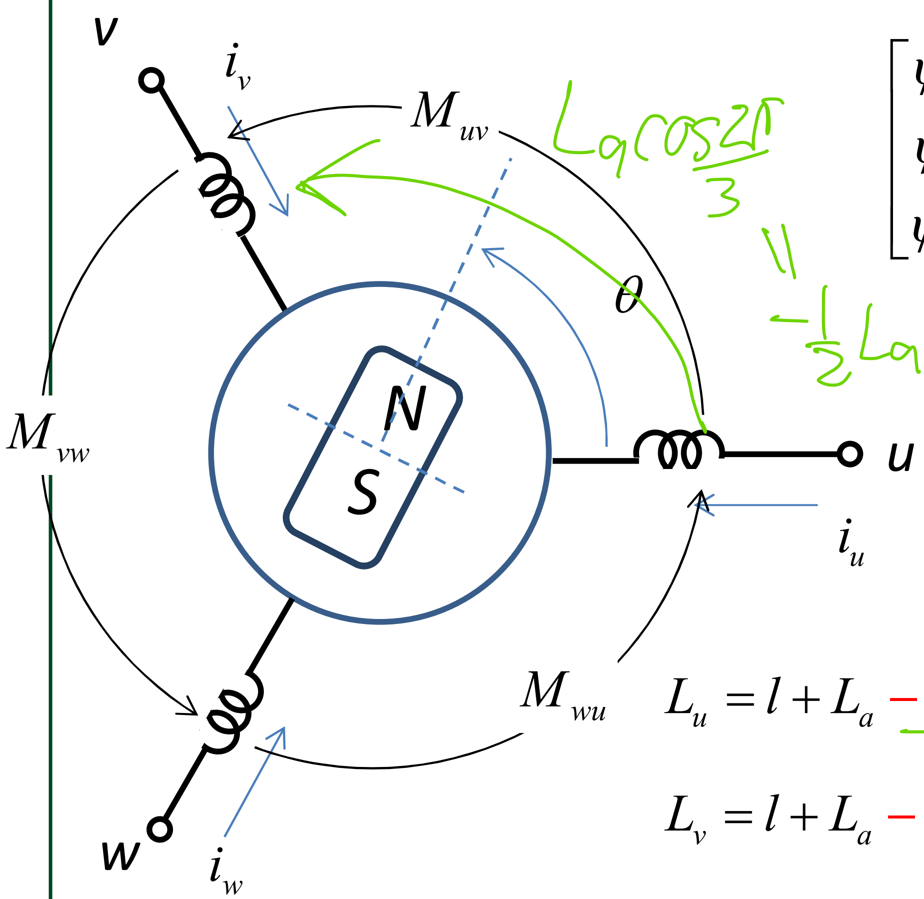
-Inverse saliency

- ✓ High Speed
- ✓ High Efficiency
- ✓ High Power Density

- Cross-sectional view of 4-pole IPMSM

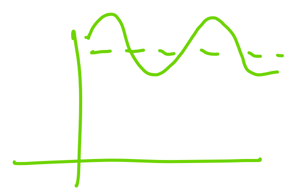
Dynamic Model of IPMSM

Flux Linkage on Windings :



$$\begin{bmatrix} \psi_u \\ \psi_v \\ \psi_w \end{bmatrix} = \begin{bmatrix} L_u & M_{uv} & M_{wu} \\ M_{uv} & L_v & M_{vw} \\ M_{wu} & M_{vw} & L_w \end{bmatrix} \begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix} + \lambda' \underbrace{\begin{bmatrix} \cos\theta \\ \cos\left(\theta - 120^o\right) \\ \cos\left(\theta - 240^o\right) \end{bmatrix}}_{\text{Flux Linkage from permanent magnet}}$$

Flux Linkage from permanent magnet



$L_a \cos\frac{2\pi}{3}$

$$L_u = l + L_a - L_{as}\cos 2\theta$$

$$L_v = l + L_a - L_{as}\cos\left(2\theta + \frac{2\pi}{3}\right)$$

$$L_w = l + L_a - L_{as}\cos\left(2\theta - \frac{2\pi}{3}\right)$$

$$M_{uv} = -\frac{1}{2}L_a - L_{as}\cos\left(2\theta - \frac{2\pi}{3}\right)$$

$$M_{vw} = -\frac{1}{2}L_a - L_{as}\cos 2\theta \quad \left(2\theta - \frac{2\pi}{3} + \frac{2\pi}{3}\right)$$

$$M_{wu} = -\frac{1}{2}L_a - L_{as}\cos\left(2\theta + \frac{2\pi}{3}\right)$$

$$L_u = l + L_a - L_{as}\cos 2\theta$$

$$M_{uv} = \underbrace{L_a \cos\frac{2\pi}{3}}_{-\frac{1}{2}L_a} - L_{as}\cos\left(2\theta - \frac{2\pi}{3}\right)$$

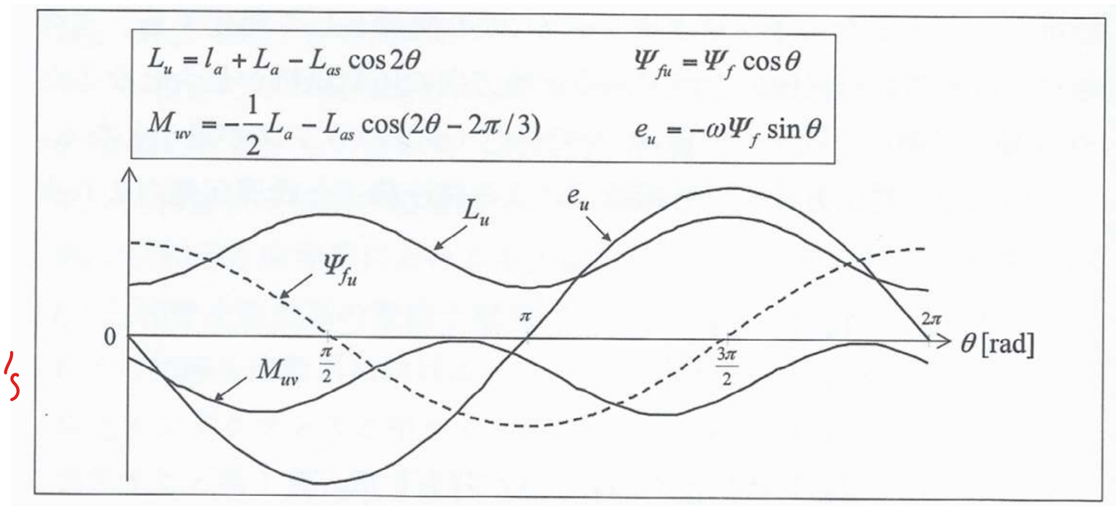
Dynamic Model of IPMSM

Induced Voltage :

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

Faraday's

$$\boxed{e = \frac{d\psi}{dt}}$$



$$= \underbrace{\begin{bmatrix} R+pL_u & pM_{uv} & pM_{wu} \\ pM_{uv} & R+pL_v & pM_{vw} \\ pM_{wu} & pM_{vw} & R+pL_w \end{bmatrix}}_{Z_s} \underbrace{\begin{bmatrix} i_u \\ i_v \\ i_w \end{bmatrix}}_{\mathbb{I}} + \underbrace{\begin{bmatrix} -\omega\lambda'\sin\theta \\ -\omega\lambda'\sin\left(\theta - \frac{2\pi}{3}\right) \\ -\omega\lambda'\sin\left(\theta + \frac{2\pi}{3}\right) \end{bmatrix}}_{\mathbb{E}}$$

$$\left(p = \frac{d}{dt}\right)$$

vector

$$\mathbb{V} = Z_s\,\mathbb{I} + \mathbb{E}$$

Dynamic Model of IPMSM

(transpose)

$T^T = T^{-1}$

3->2 Transformation :

$$T\,\mathbb{V} = T\,Z_s\,\mathbb{I} + T\,\mathbb{E}$$

$$= \left(T\,Z_s\,T^T\right)\left(T\,\mathbb{I}\right) + T\,\mathbb{E}$$

$$\begin{bmatrix} v_x \\ v_y \end{bmatrix} = \begin{bmatrix} R + p\left(L_0 + L_1\cos 2\theta\right) & pL_1 \sin 2\theta \\ pL_1 \sin 2\theta & R + p\left(L_0 + L_1\cos 2\theta\right) \end{bmatrix} \begin{bmatrix} i_x \\ i_y \end{bmatrix} + \omega\lambda \begin{bmatrix} -\sin\theta \\ \cos\theta \end{bmatrix}$$

$$L_0 = l + \frac{3}{2}L_a \qquad L_1 = -\frac{3}{2}L_{as} \qquad \lambda' = \sqrt{\frac{3}{2}}\,\lambda$$

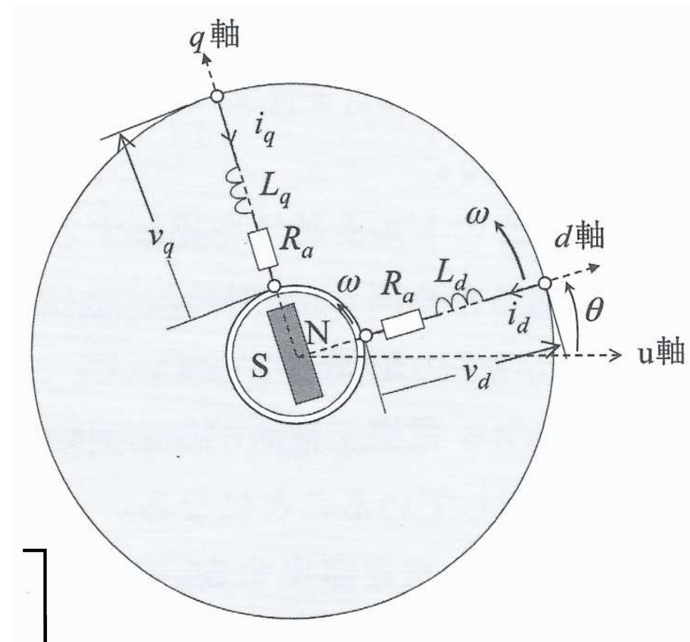
Dynamic Model of IPMSM on Rotor Reference Frame

Axis Transformation :

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} R + pL_d & -\omega L_q \\ \omega L_d & R + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} 0 \\ \omega\lambda \end{bmatrix}$$

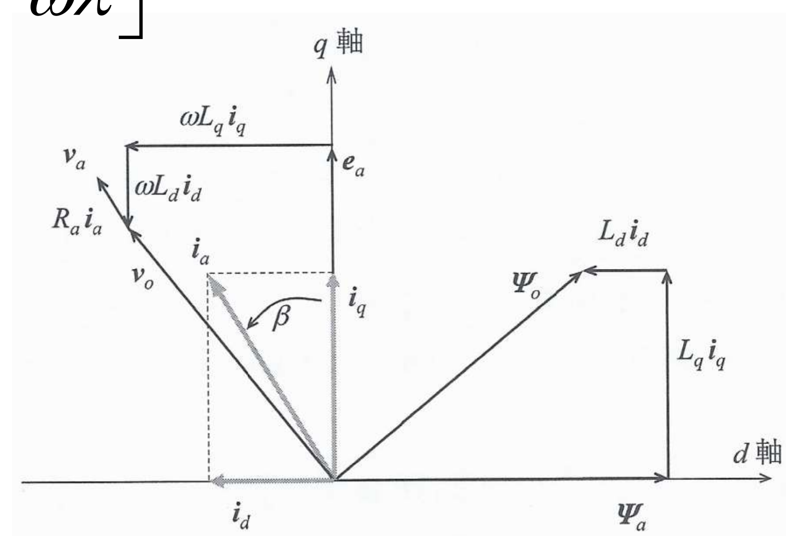
(ในกรณี SPMSM $L_d = L_q$ *)*

$$\begin{bmatrix} 0 & -\omega L_q \\ \omega L_d & 0 \end{bmatrix}$$



$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = R \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} -\omega L_q i_q \\ \omega L_d i_d + \omega\lambda \end{bmatrix}$$

$$\left.\begin{aligned} L_d &= l + \frac{3}{2}(L_a - L_{as}) \\ L_q &= l + \frac{3}{2}(L_a + L_{as}) \end{aligned}\right\} \quad \boxed{L_q > L_d}$$



Power & Torque

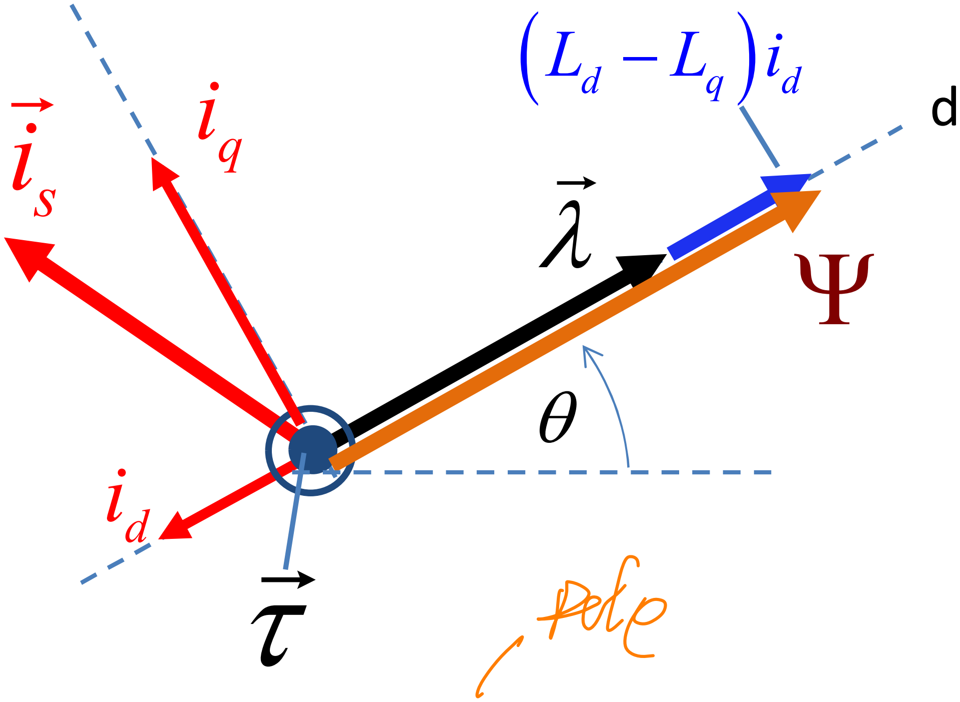
Power…

$$P_{in} = \begin{bmatrix} i_d \\ i_q \end{bmatrix}^T \begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} i_d \\ i_q \end{bmatrix}^T \begin{bmatrix} R + pL_d & -\omega L_q \\ \omega L_d & R + pL_q \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} i_d \\ i_q \end{bmatrix}^T \begin{bmatrix} 0 \\ \omega\lambda \end{bmatrix}$$

$$P_{in} = \underbrace{R\left(i_d^2 + i_q^2\right)}_{\text{Copper Loss}} + \underbrace{\frac{d}{dt}\left\{\frac{1}{2}\left(L_d\, i_d^2 + L_q\, i_q^2\right)\right\}}_{\text{Magnetic Energy}} + \underbrace{\omega\left\{\underbrace{\lambda\, i_q}_{\text{stator}} + \overbrace{\underbrace{\left(L_d - L_q\right) i_d\, i_q}_{\text{rotor}}}^{\text{Reluctance torque}}\right\}}_{\text{Mechanical Power}}$$

$$\tau = \frac{P_{mech}}{\omega_m} = \frac{P_{mech}}{\omega / P}$$

Torque



$$\tau = P \Psi \, i_q$$

$$\tau = P\left\{ \underbrace{\lambda i_q}_{\text{Alignment Torque}} + \underbrace{\left(L_d - L_q\right) i_d \, i_q}_{\text{Reluctance Torque}} \right\}$$

$$\tau = P\left\{ \underbrace{\lambda}_{\text{Permanent Magnet}} + \underbrace{\left(L_d - L_q\right)}_{\text{Saliency}} i_d \right\} i_q$$

$$\Psi \triangleq \lambda + \left(L_d - L_q\right) i_d$$

Fictitious Flux

Vector Control of IPMSM

$$\begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} v_d \\ v_q \end{bmatrix} - R \begin{bmatrix} i_d \\ i_q \end{bmatrix} - \begin{bmatrix} -\omega L_q i_q \\ \omega L_d i_d + \omega \lambda \end{bmatrix}$$

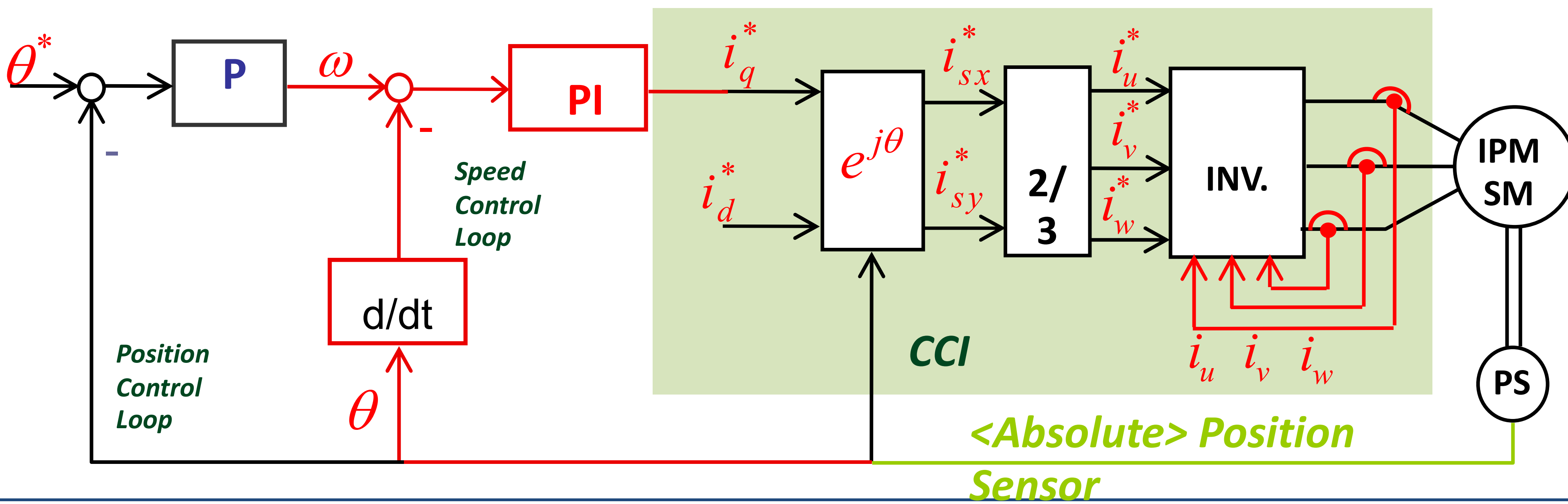
$$\Psi = \lambda + \left(L_d - L_q\right) i_d$$

$$\frac{d\theta}{dt} = \omega \qquad \tau = P \Psi \, i_q$$

-ควบคุมแรงบิดผ่านการควบคุมกระแส...

$i_d^* = 0, i_q^*$ Alignment Torque

i_d^*, i_q^* Reluctance Torque



Decoupling Control

$$\begin{bmatrix} L_d & 0 \\ 0 & L_q \end{bmatrix} \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} v_d \\ v_q \end{bmatrix} - R \begin{bmatrix} i_d \\ i_q \end{bmatrix} - \underbrace{\begin{bmatrix} -\omega L_q i_q \\ \omega L_d i_d \end{bmatrix}}_{\text{Crossing Coupling EMF}} - \underbrace{\begin{bmatrix} 0 \\ \omega\lambda \end{bmatrix}}_{\text{Back EMF}}$$

กำหนดให้ Decoupling Control :

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = \begin{bmatrix} v'_d \\ v'_q \end{bmatrix} + \begin{bmatrix} -\omega L_q i_q \\ \omega L_d i_d \end{bmatrix} + \begin{bmatrix} 0 \\ \omega\lambda \end{bmatrix}$$

$$\begin{bmatrix} v'_d \\ v'_q \end{bmatrix} = R \begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix}$$

Decoupling Control

Resultant Dynamic :

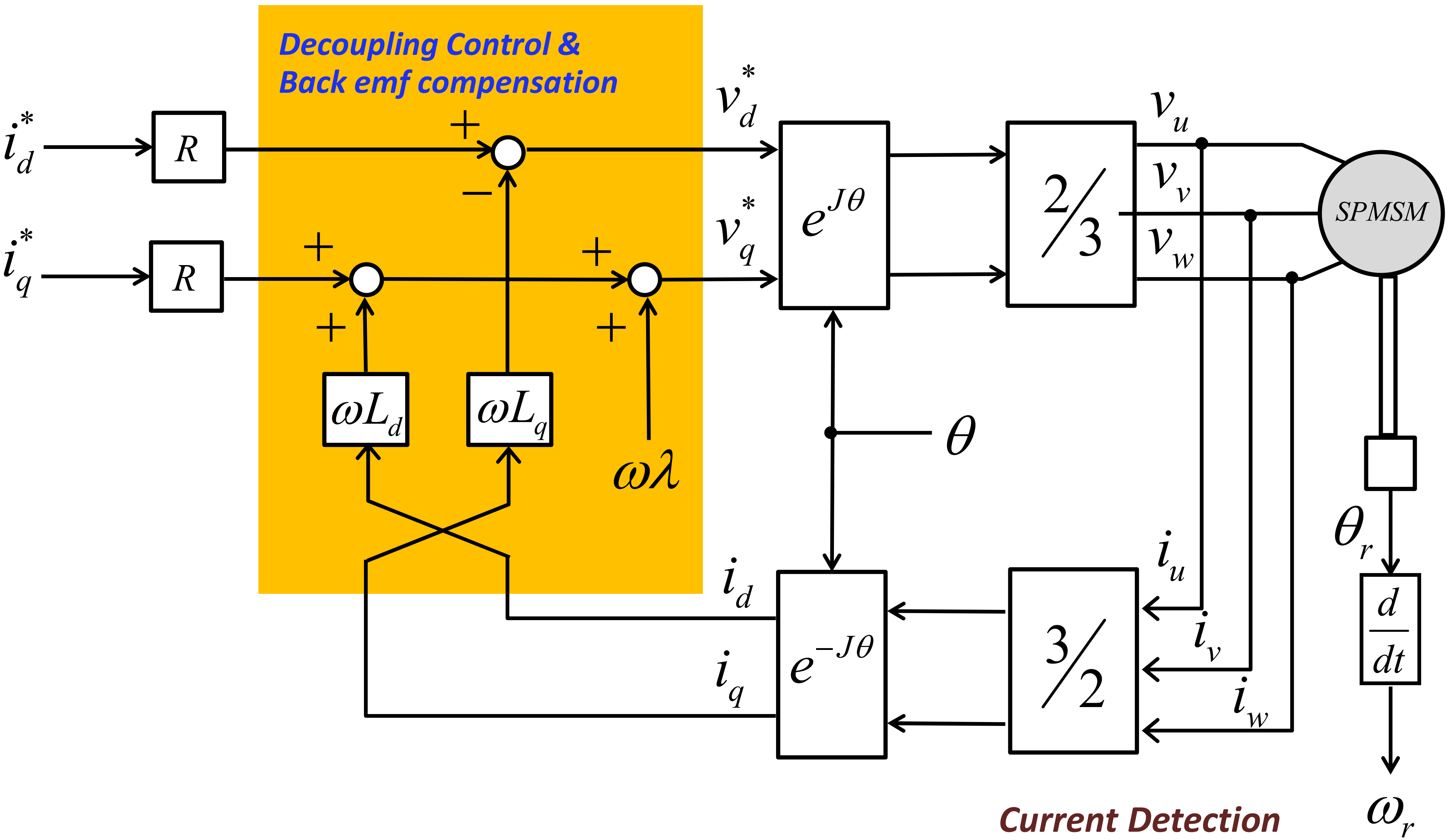
$$\begin{bmatrix} L_d \dfrac{di_d}{dt} \\ L_q \dfrac{di_q}{dt} \end{bmatrix} = -R \begin{bmatrix} i_d \\ i_q \end{bmatrix} + R \begin{bmatrix} i_d^* \\ i_q^* \end{bmatrix}$$

$$i_d = \frac{1}{L_d\, s/R + 1}\, i_d^*$$

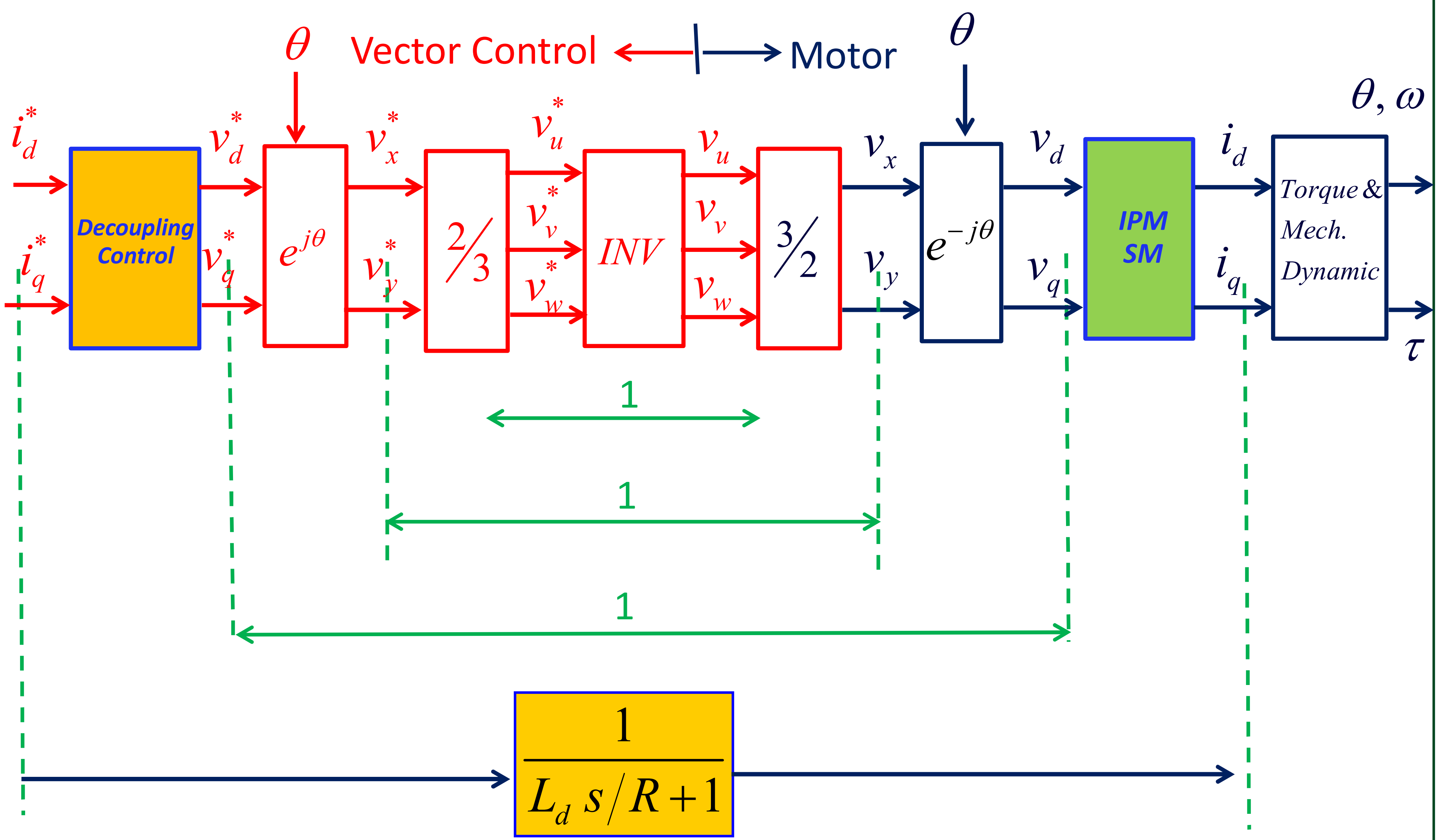
$$i_q = \frac{1}{L_q\, s/R + 1}\, i_q^*$$

First-Order Response

Vector Control with Decoupling Control Scheme



Overall Block Diagram of Decoupling Control



Decoupling Control with Current Feedback