Scalar control of PM machines

1. Why V/f control cannot be used for PM machine?
2. I/f controller proposed
3. Identification of machine parameters in practice
4. Practice

Basic considerations

We need to place the current vector correctly with respect to the rotor position, in order to produce torque.

$$u_q = Ri_q + p\lambda_q + \omega_r\lambda_d \qquad \lambda_q = (L_{ls} + L_{mq})i_q = L_q i_q$$

$$u_d = Ri_d + p\lambda_d - \omega_r\lambda_q \qquad \lambda_d = (L_{ls} + L_{md})i_d + \lambda_{mpm} = L_d i_d + \lambda_{mpm}$$

Mech. rotor speed x number of pole pairs

Peak value

Torque

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

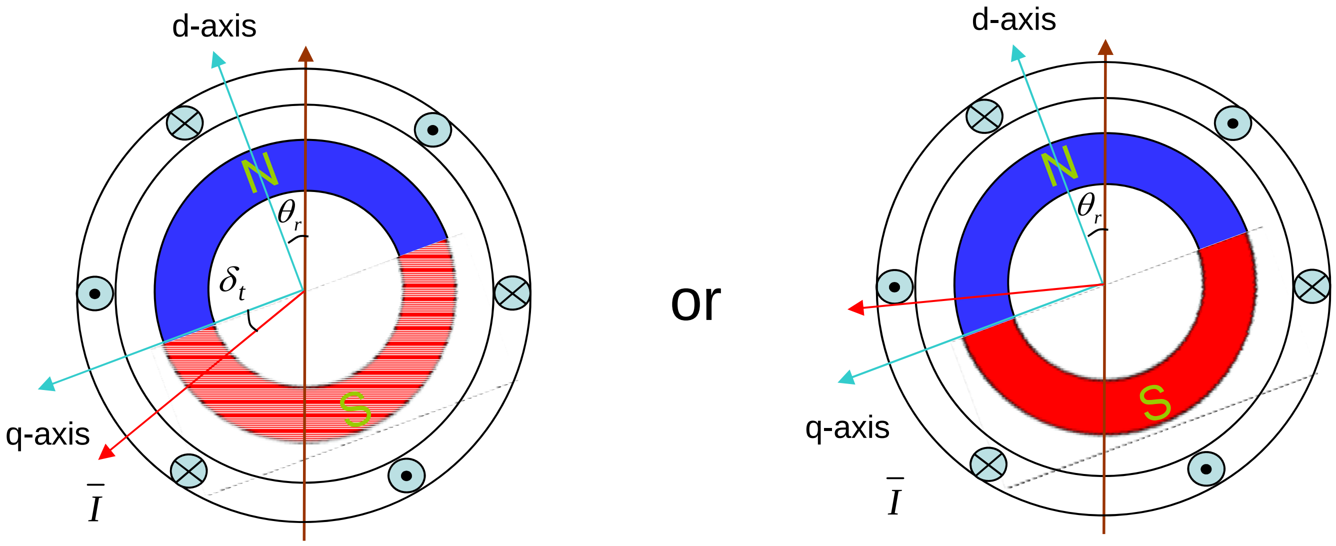
If d and q axes inductances are equal

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

Basic considerations

The desired current vector will be

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



Basic considerations

When use V/f control the, the resultant current vector location is depending on the machine parameters and the speed.

Situation will be worse when considering load torque change!

$$\boxed{\begin{aligned} u_q &= Ri_q + p\lambda_q + \omega_r\lambda_d \\ u_d &= Ri_d + p\lambda_d - \omega_r\lambda_q \end{aligned}}$$

$$\lambda_q = \left(L_{ls} + L_{mq}\right)i_q = L_q i_q$$

$$\lambda_d = \left(L_{ls} + L_{md}\right)i_d + \lambda_{mpm} = L_d i_d + \lambda_{mpm}$$

⇓ In S. S.

$$\boxed{\begin{aligned} u_q &= Ri_q + \omega_r\lambda_d \\ u_d &= Ri_d - \omega_r\lambda_q \end{aligned}}$$

⇓ In S. S.

Current and flux linkage will be DC

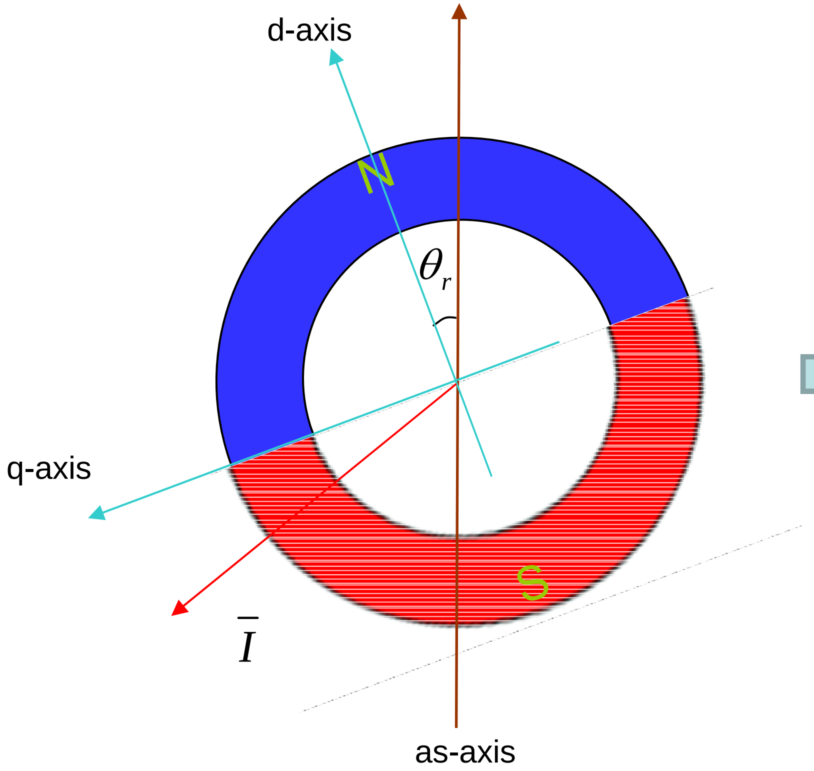
⇓ In vector form $\bar{u}_{dq} = u_d + ju_q$

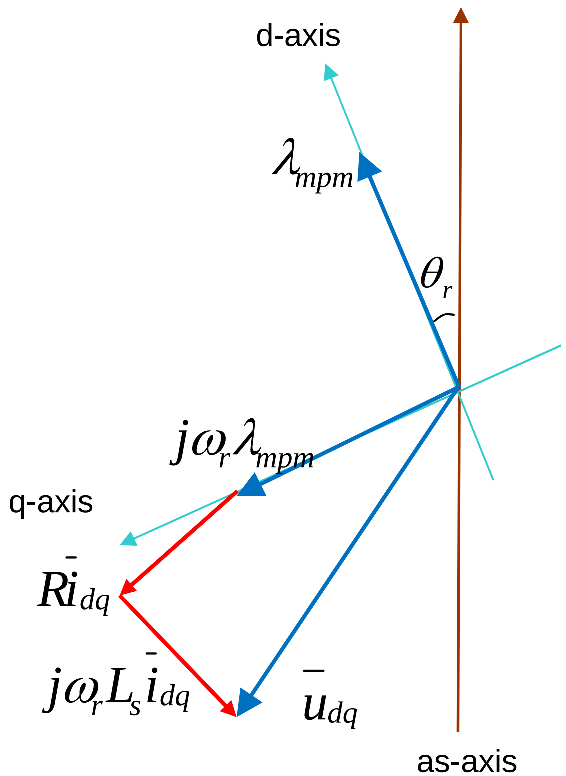
$$\bar{u}_{dq} = R\bar{i}_{dq} + j\omega_r\bar{\lambda}_{dq}$$

Basic considerations

Consider $L_d = L_q \hat{=} L_s$, we have

$$\bar{u}_{dq} = R\bar{i}_{dq} + j\omega_r \bar{\lambda}_{dq} \Rightarrow \bar{u}_{dq} = R\bar{i}_{dq} + j\omega_r L_s \bar{i}_{dq} + j\omega_r \lambda_{mpm}$$



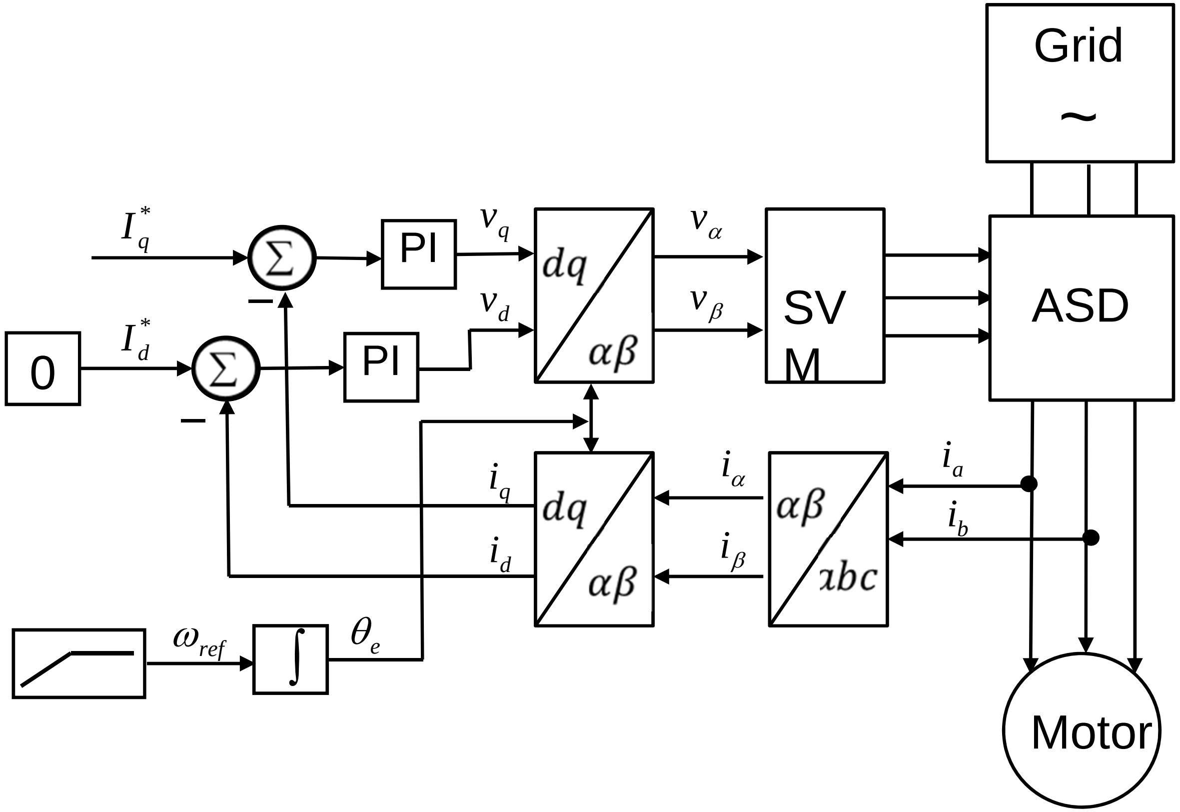


So we may use I/f control

Similar to V/f control for IM, now

- The frequency command is still ramping up (to change the speed)
- In the meantime, we keep the **amplitude** of machine current vector to be **CONSTANT**.
- Use PI controllers to make sure the real machine current follows the reference current.

I/f control structure

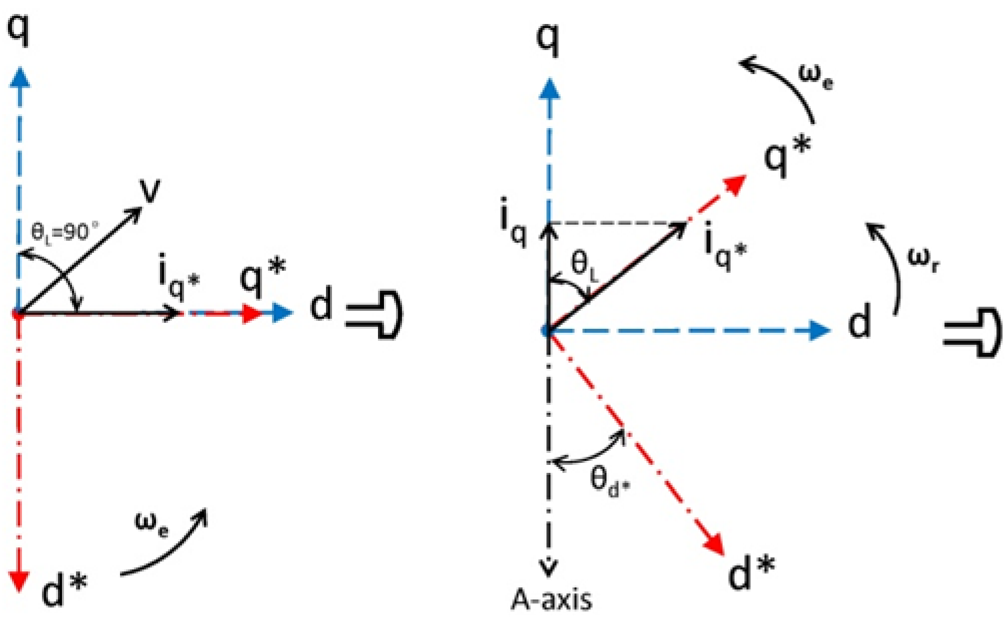


I/f control – during startup

- The useful torque production q-axis current will be determined automatically by the load.
- Self-stabilization mechanism may be observed

$$T_e - T_{load} = J\frac{d\omega_{r,mec}}{dt}$$

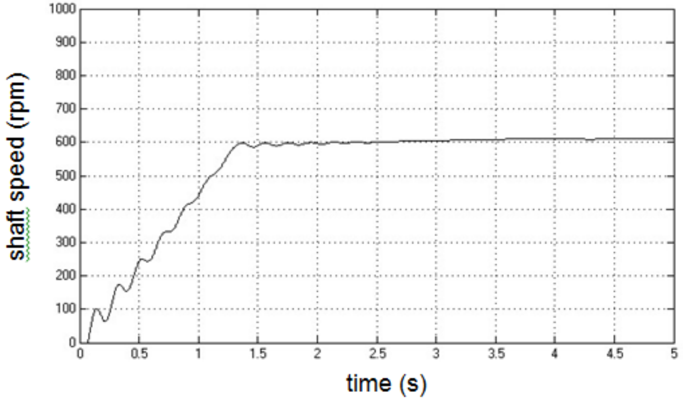
$$\boxed{T_{load}\uparrow \;\Rightarrow\; \omega_{r,mec}\downarrow \;\Rightarrow\; \theta_L\uparrow \;\Rightarrow\; i_q\uparrow \;\Rightarrow\; T_e\uparrow}$$



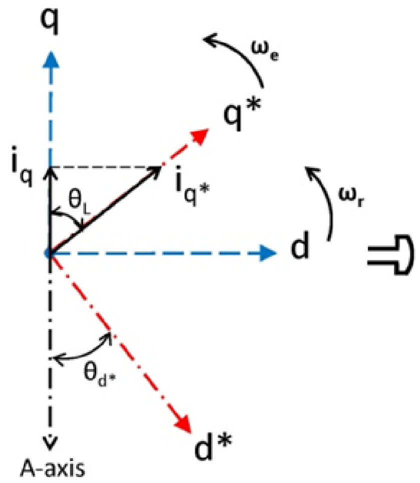
Some observations

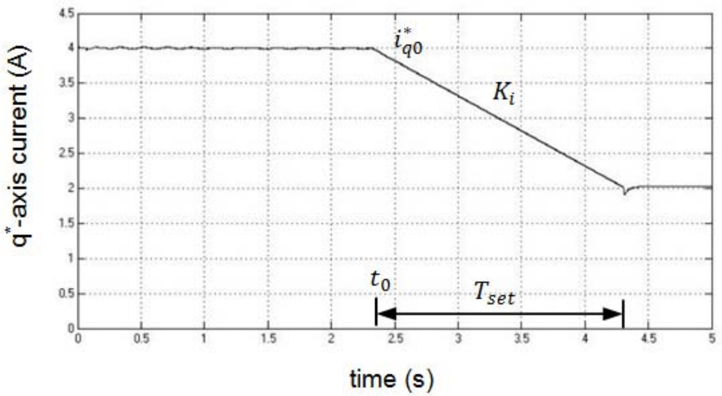
- It has self-stabilization mechanism.
- Large positive d-axis current may be present – causing the d, q-axes inductance to vary and estimated rotor position may be affected.
- Due to this large positive d-axis current, estimated rotor position may have a large error (e.g. 25 degrees position error for the test motor) even at a medium speed.
- When switched to sensorless FOC, large transient current may occur.

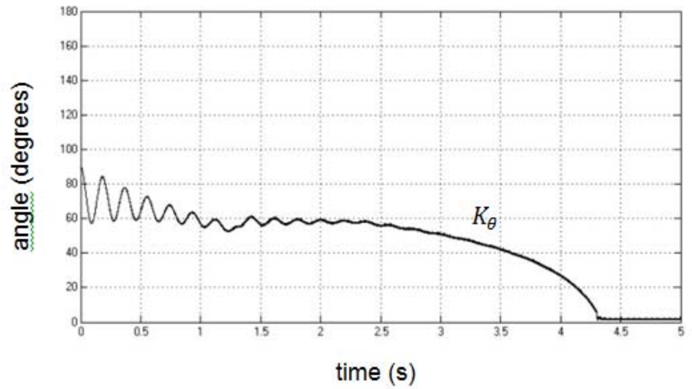
Regulate the transient current



(a) Motor shaft speed during startup







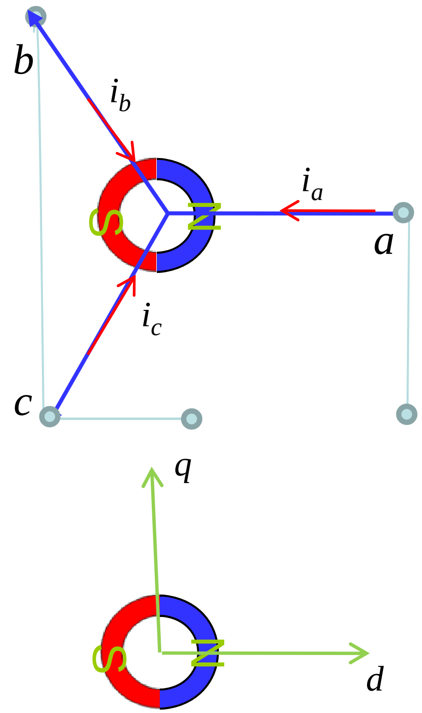
(b) Transient behavior of angle θ_L .

Measure machine parameters in practice

d-axis inductance

$$i = i_a = -2i_b = -2i_c$$

$$V = V_a = -2V_b = -2V_c \Rightarrow V_{ab} = V_a - V_b = \frac{3}{2}V$$



At rotor position angle $\theta_r = 0$

$$\begin{bmatrix} f_d \\ f_q \\ f_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \cdot \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix}$$

$$\Downarrow$$

$i_d = i$ $\quad V_d = V = \frac{2}{3}V_{ab}$ q component is zero

$$\Downarrow$$

$$V_{ab} = \frac{3}{2}V_d = (\frac{3}{2}r)i_d + \left(\frac{3}{2}L_d\right)\frac{di_d}{dt} = (\frac{3}{2}r)i + \left(\frac{3}{2}L_d\right)\frac{di}{dt}$$

Measure machine parameters in practice

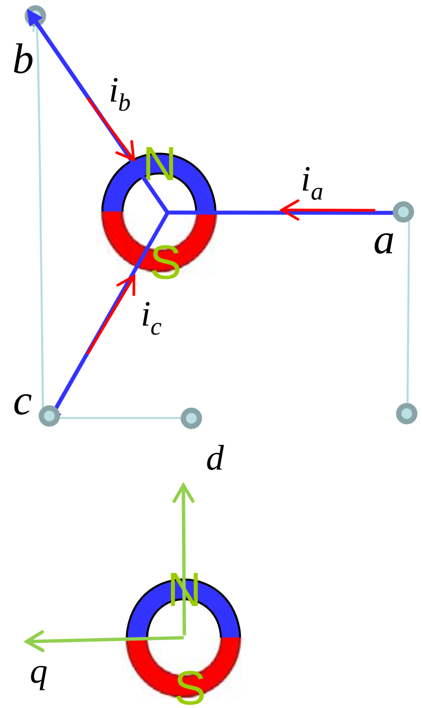
q-axis inductance

$$i = i_a = -2i_b = -2i_c$$

$$V = V_a = -2V_b = -2V_c \Rightarrow V_{ab} = V_a - V_b = \frac{3}{2}V$$

At rotor position angle $\theta_r = 90^o$

$$\begin{bmatrix} f_d \\ f_q \\ f_0 \end{bmatrix} = \frac{2}{3}\begin{bmatrix} 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ -1 & \frac{1}{2} & \frac{1}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \cdot \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix}$$



$$i_q = -i \qquad V_q = -V = -\frac{2}{3}V_{ab}$$

d component is zero

$$V_{ab} = \left(-\frac{3}{2}\right)V_q = \left(-\frac{3}{2}r\right)i_q + \left(-\frac{3}{2}L_q\right)\frac{di_q}{dt} = (\frac{3}{2}r)i + \left(\frac{3}{2}L_q\right)\frac{di}{dt}$$

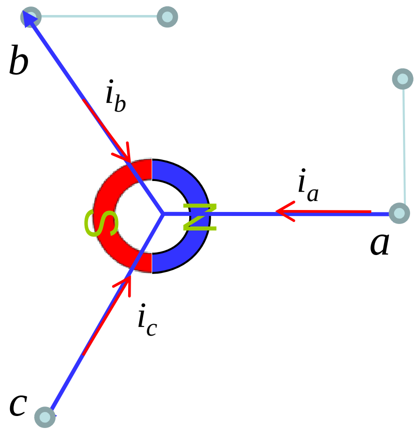
Measure machine parameters in practice

If Ld=Lq

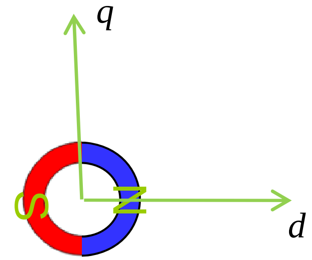
$$i = i_a = -i_b, \quad i_c = 0$$

$$V = V_a = -V_b, \quad V_c = 0 \Rightarrow V_{ab} = V_a - V_b = 2V$$

At rotor position angle $\theta_r = 0^o$



$$\begin{bmatrix} f_d \\ f_q \\ f_0 \end{bmatrix} = \frac{2}{3} \begin{bmatrix} 1 & -\frac{1}{2} & -\frac{1}{2} \\ 0 & \frac{\sqrt{3}}{2} & -\frac{\sqrt{3}}{2} \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \cdot \begin{bmatrix} f_a \\ f_b \\ f_c \end{bmatrix}$$



$$i_d = i \qquad V_d = V$$

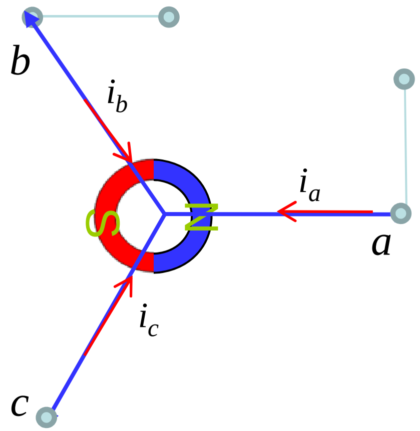
$$i_q = -\frac{\sqrt{3}}{3} i \qquad V_q = -\frac{\sqrt{3}}{3} V$$

Measure machine parameters in practice

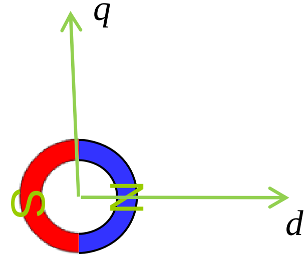
If Ld=Lq

$$i_d = i \qquad V_d = V$$

$$i_q = -\frac{\sqrt{3}}{3} i \qquad V_q = -\frac{\sqrt{3}}{3} V$$



$$V_d = V = ri + L\frac{di}{dt}$$



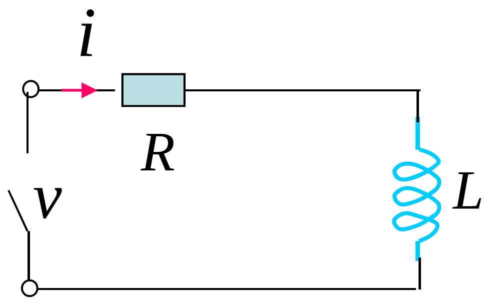
$$V_q = \left(-\frac{\sqrt{3}}{3}\right)V = ri_q + L\frac{di_q}{dt} = \left(-\frac{\sqrt{3}}{3}r\right)i + \left(-\frac{\sqrt{3}}{3}L\right)\frac{di}{dt}$$

$$V_{ab} = 2V = (2r)i + (2L)\frac{di}{dt}$$

Measure machine parameters in practice

How the inductance is determined?

- Step voltage injection – measuring the transient current response
- Sinusoidal voltage injection – measuring the static reactance
- The equivalent circuit is always:



Measure machine parameters in practice

When it is not easy to lock the rotor position,

Another method → ‘quasi-static’ measurement

i.e. rotor rotates at e.g. 1000 rpm (in electrical meaning), the stator synchronous frequency rotates at 1006 rpm, then what happens?

Mathematics behind this

The machine equation may finally be expressed as

$$\boxed{\bar{v}_{\alpha\beta} = R\bar{i}_{\alpha\beta} + L_1 \frac{d\bar{i}_{\alpha\beta}}{dt} + L_2 \frac{d\bar{i}^*_{\alpha\beta}}{dt} \cdot e^{j2\theta_r} + j2\omega_r L_2 \bar{i}^*_{\alpha\beta} e^{j2\theta_r} + j\omega_r \lambda_{mpm} e^{j\theta_r}}$$

$$\bar{v}_{\alpha\beta} = V_m e^{j\theta_e}, \qquad \theta_e = \omega_e t$$

$$\bar{i}_{\alpha\beta} = I_m e^{j\theta_e} e^{-j\varphi}$$

Valid in a small time period

$$\lambda_{mpm} = 0$$

$$L_1 = \frac{L_d + L_q}{2}$$

$$L_2 = \frac{L_d - L_q}{2}$$

$$L_d = L_1 + L_2$$

$$L_q = L_1 - L_2$$

$$\boxed{V_m e^{j\theta_e} = RI_m e^{j\theta_e} e^{-j\varphi} + j\omega_e L_1 I_m e^{j\theta_e} e^{-j\varphi} - j\omega_e L_2 I_m e^{j(2\theta_r - \theta_e + \varphi)} + 2j\omega_r L_2 I_m e^{j(2\theta_r - \theta_e + \varphi)}}$$

Continuous …

$$\boxed{V_m e^{j\theta_e} = RI_m e^{j\theta_e} e^{-j\varphi} + j\omega_e L_1 I_m e^{j\theta_e} e^{-j\varphi} - j\omega_e L_2 I_m e^{j(2\theta_r - \theta_e + \varphi)} + 2j\omega_r L_2 I_m e^{j(2\theta_r - \theta_e + \varphi)}}$$

$$\Downarrow$$

$$\boxed{V_m e^{j\varphi} = RI_m + j\omega_e L_1 I_m - j\omega_e L_2 I_m e^{2j(\theta_r - \theta_e + \varphi)} + 2j\omega_r L_2 I_m e^{2j(\theta_r - \theta_e + \varphi)}}$$

$$\Downarrow \quad \omega_e \approx \omega_r$$

$$\boxed{V_m e^{j\varphi} = RI_m + j\omega_e L_1 I_m + j\omega_e L_2 I_m e^{2j(\theta_r - \theta_e + \varphi)}}$$

Now we have the equations in ‘phasors’ → taking the current phasor as the reference.

Finally

$$\boxed{V_m e^{j\varphi} = RI_m + j\omega_e L_1 I_m + j\omega_e L_2 I_m e^{2j(\theta_r - \theta_e + \varphi)}}$$

$$\boxed{\begin{aligned} L_d &= L_1 + L_2 \\ L_q &= L_1 - L_2 \end{aligned}}$$

When $\boxed{2(\theta_r - \theta_e + \varphi) = 0}$ $\Rightarrow$ $\boxed{V_m e^{j\varphi} = RI_m + j\omega_e (L_1 + L_2) I_m}$ $\Rightarrow$ $\boxed{I_m = \max}$

When $\boxed{2(\theta_r - \theta_e + \varphi) = \pi}$ $\Rightarrow$ $\boxed{V_m e^{j\varphi} = RI_m + j\omega_e (L_1 - L_2) I_m}$ $\Rightarrow$ $\boxed{I_m = \min}$

Constant

This may be observed from the Simulink model.