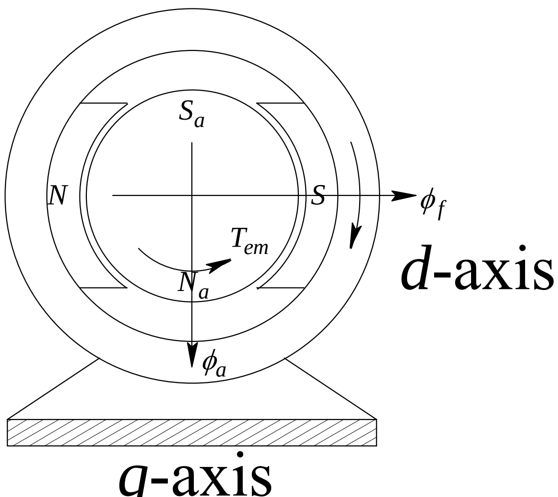
Chapter 13

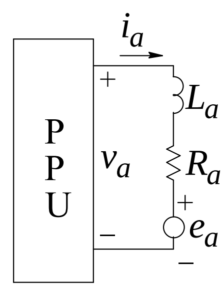
Vector Control of Induction-Motor Drives: A Qualitative Examination

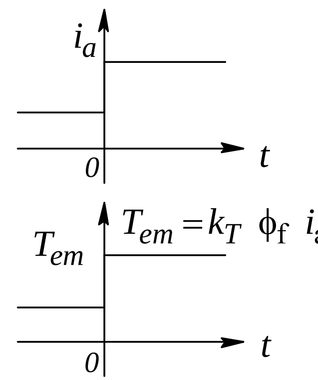
Objective:- For induction motor to emulate the superior dynamic performance of dc and pmac motors

DC Motor Drive

The field (or direct) *d*-axis is from the North to South pole. The armature (or quadrature) *q*-axis is at 90° or in quadrature with the d-axis.





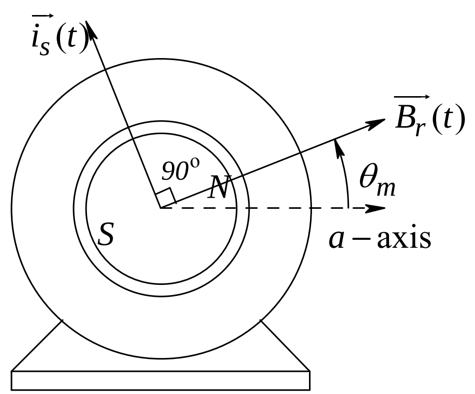


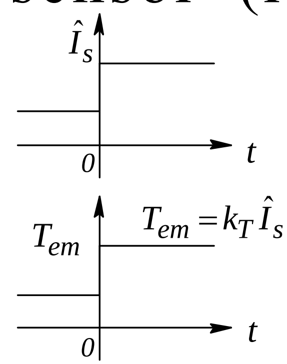
$$T_{em} = k_T \ \phi_f \ i_a$$

In a separately-excited machine electromagnetic torque can be controlled precisely and dynamically by controlling the field and armature currents separately.

Brushless DC Motor Drive

Also known as the permanent magnet ac machine. See Chapter 10 of ED. Characterized by (i) sinusoidally wound stator, (ii) permanent magnets on rotor, (iii) necessity for power electronics and position sensor (resolver).

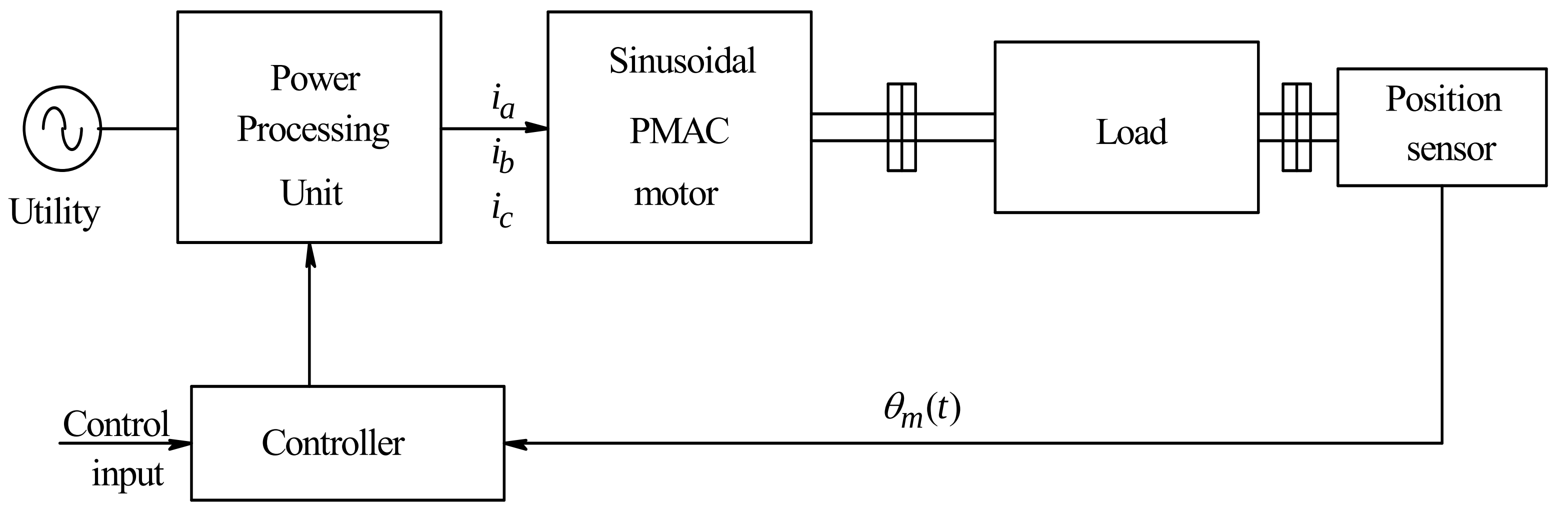




$$T_{em} = k_t \; \hat{B}_r \; \hat{I}_S$$

In a pmac drive, the power converter controls the stator current space vector to be 90° ahead of the permanent magnet field space vector. The resolver tracks the magnet position.

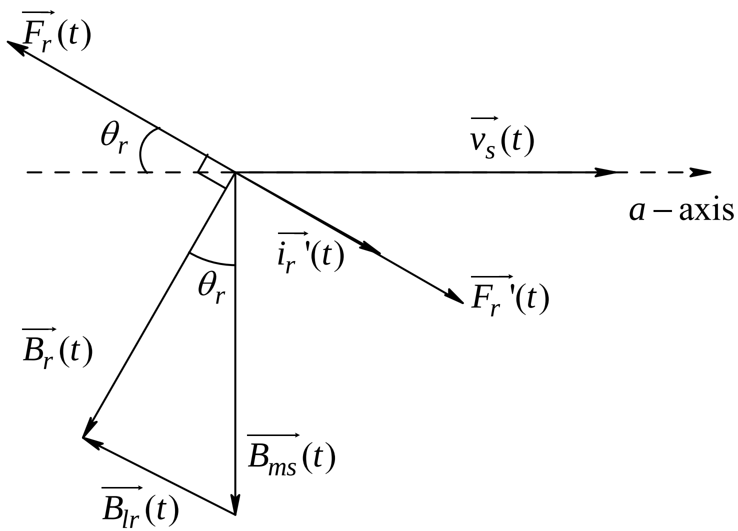
Controller and Power Processing Unit for Brushless DC Motor Drive (See Chapter 10 of ED)

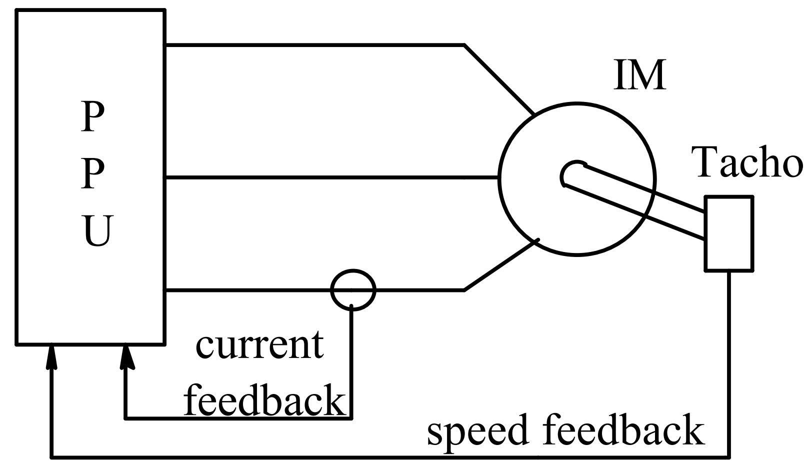


- Controller determines desired phase currents based on desired torque and motor position
- *Proposed Moog project – to eliminate the position sensor*

Vector-Controlled Induction Motor Drive

Using vector control, the induction motor can emulate the superior dynamic response of the brushed and brushless dc motors.

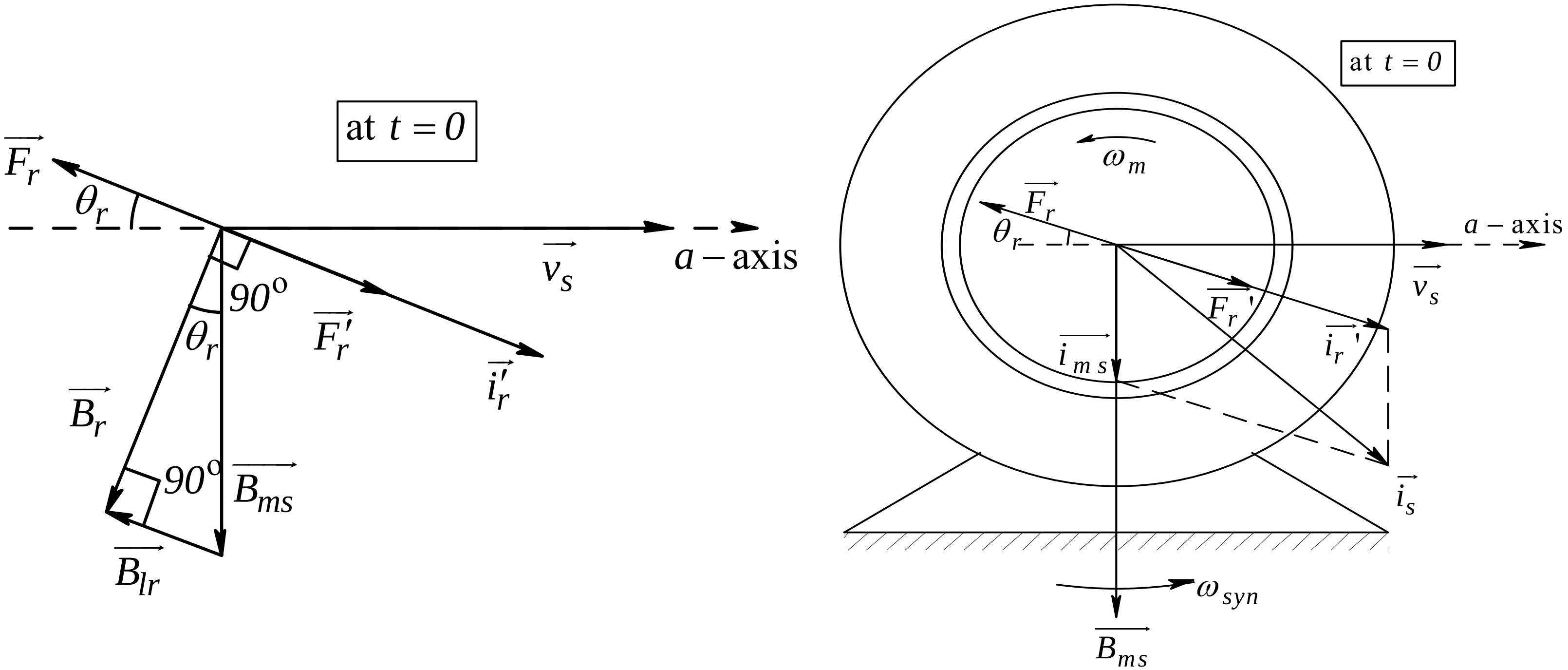




$$T_{em} = k_t \; \hat{B}_r \; \hat{I}_r$$

In vector control, the components of the stator current space vector controlling the rotor flux and rotor current are controlled to produce the desired torque

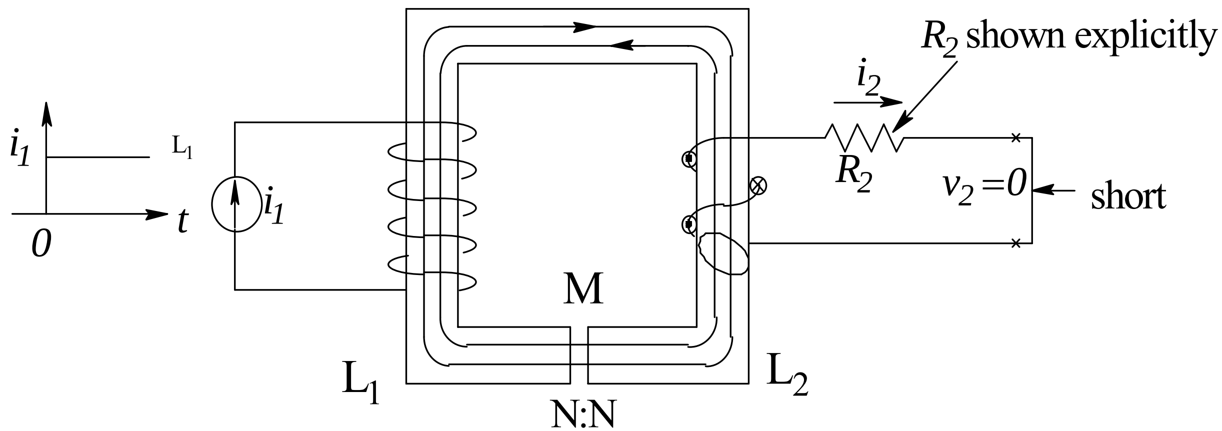
Vector Control – Space Vectors



Space Vectors

$$T_{em} = k\,\hat{B}_r \hat{I}'_r = k\,\hat{B}_{ms} \hat{I}'_r \sin\left(\pi/2 - \theta_r\right)$$

Analogy to a Current-Excited Transformer With a Shorted Secondary



Back emf equation:

$$e_2 = -L_2 \frac{di_2}{dt} + M\frac{di_1}{dt} = 0 \quad \Rightarrow \frac{di_2}{dt} = \frac{M}{L_2}\frac{di_1}{dt} \Rightarrow \frac{di_2'}{dt} = \frac{L_m}{L_2}\frac{di_1}{dt}$$

Therefore, a step change in stator current will force a step change in rotor current and not affect the magnetizing current

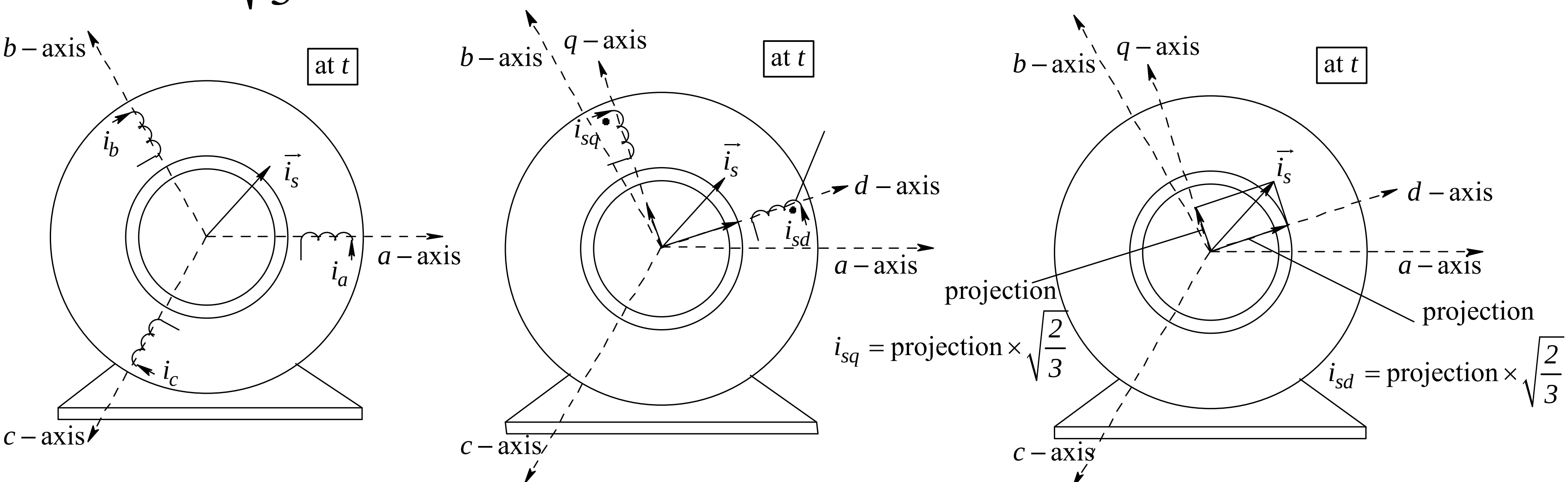
$$i_2(0^+) = \frac{L_m}{L_2} i_1(0^+)$$

d- and q- Axis Winding Representation

To emulate the dc machines, let's define an orthogonal rotating set of d- and q- axis windings producing the same mmf as the three phase currents.

$$i_{sd} = \sqrt{\frac{2}{3}} \text{ the projection of } \vec{i}_s(t) \text{ vector along the d-axis to emulate field}$$

$$i_{sq} = \sqrt{\frac{2}{3}} \text{ the projection of } \vec{i}_s(t) \text{ vector along the q-axis to emulate armature}$$



Space Vector Current

$$\vec{i_s}(t) = \hat{I}_s(t)\angle\theta_{i_s}(t)$$

$$= i_a(t)\angle 0^0 + i_b(t)\angle 120^0 + i_c(t)\angle 240^0$$

$$= \sqrt{\frac{3}{2}}\left(i_{sd}(t) + j \cdot i_{sq}(t)\right)$$

Transformation I

Let $$\vec{i_s^d}(t) = \sqrt{\frac{3}{2}}\left(i_{sd}(t) + j \cdot i_{sq}(t)\right)$$

Where $\vec{i_s^d}(t)$ is the space vector current defined with respect to the rotating d-axis.

Let $$\vec{i_s^a}(t) = i_a(t)\angle 0^0 + i_b(t)\angle 120^0 + i_c(t)\angle 240^0$$

$$= i_a(t)e^{j0^o} + i_b(t)e^{j120^o} + i_c(t)e^{j240^o}$$

Where $\vec{i_s^a}(t)$ is the space vector current defined with respect to the stationary phase *a* magnetic axis.

Exit

Transformation II

Therefore $\vec{i_s^d}(t) = \vec{i_s^a} e^{-j\theta_{da}}$

Where θ_{da} is the angle of the rotating *d*-axis w.r.t. the stator *a*-axis.

Thus $\vec{i_s^d}(t) = i_a(t)e^{j(-\theta_{da})} + i_b(t)e^{j\left(120^o - \theta_{da}\right)} + i_c(t)e^{j\left(240^o - \theta_{da}\right)}$

$$= i_a(t)\left[\cos\theta_{da} - j\sin\theta_{da}\right]$$

$$+ i_b(t)\left[\cos\left(\theta_{da} - 120^o\right) - j\sin\left(\theta_{da} - 120^o\right)\right]$$

$$+ i_c(t)\left[\cos\left(\theta_{da} - 240^o\right) - j\sin\left(\theta_{da} - 240^o\right)\right]$$

$$= \sqrt{\frac{3}{2}}\left(i_{sd} + j \cdot i_{sq}\right)$$

Exit

Transformation III

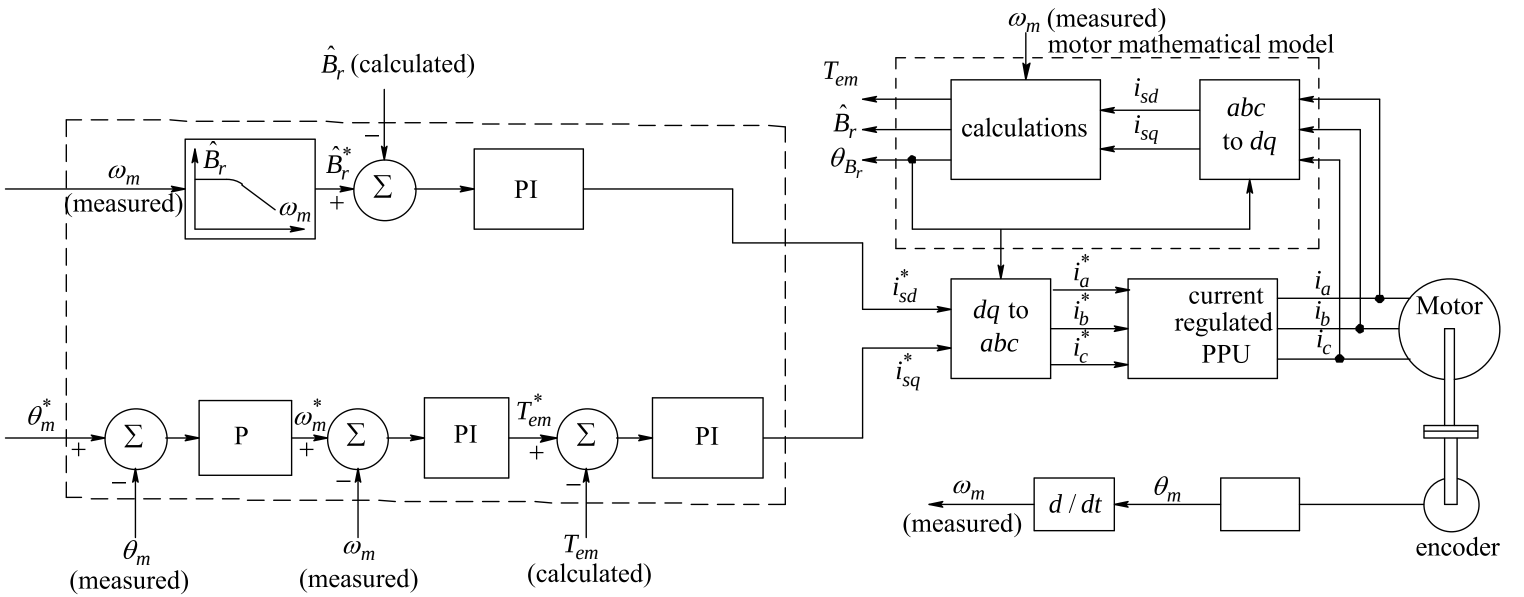
Thus, the tranformation matrix, *T*, from the stator currents to the *dq* axes is given by

$$\begin{pmatrix} i_{sd} \\ i_{sd} \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \cos\theta_{da} & \cos\left(\theta_{da} - 120^o\right) & \cos\left(\theta_{da} - 240^o\right) \\ -\sin\theta_{da} & \sin\left(\theta_{da} - 120^o\right) & -\sin\left(\theta_{da} - 240^o\right) \end{pmatrix} \begin{pmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{pmatrix}$$

The inverse tranformation matrix, *T*, from the *dq* axes currents to the stator can be shown to be

$$\begin{pmatrix} i_a(t) \\ i_b(t) \\ i_c(t) \end{pmatrix} = \sqrt{\frac{2}{3}} \begin{pmatrix} \cos\theta_{da} & -\sin\theta_{da} \\ \cos\left(\theta_{da} + 240^o\right) & -\sin\left(\theta_{da} + 240^o\right) \\ \cos\left(\theta_{da} + 120^o\right) & -\sin\left(\theta_{da} + 120^o\right) \end{pmatrix} \begin{pmatrix} i_{sd} \\ i_{sq} \end{pmatrix}$$

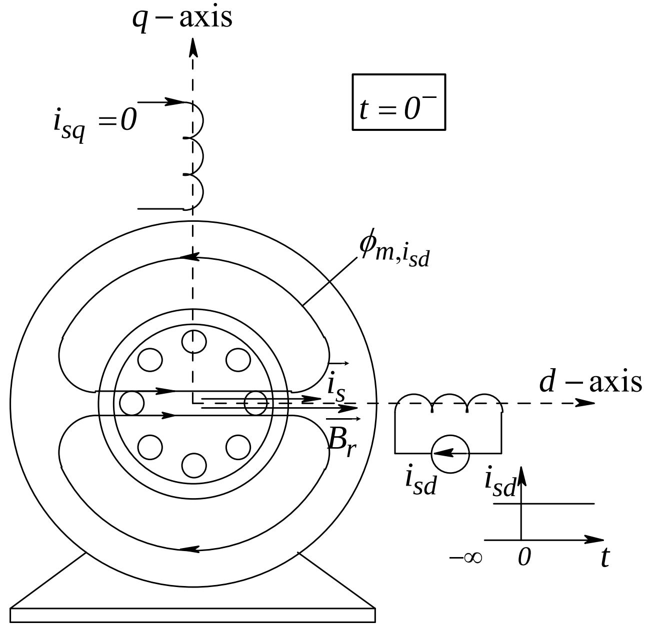
Torque, Speed, and Position Control



$$\omega_{syn}(t) = \omega_m(t) + \omega_{slip}(t)$$

$$\theta_{B_r}(t) = 0 + \int_0^t \omega_{syn}(\tau) \cdot d\tau$$

Initial Flux Buildup Prior to $t = 0^-$

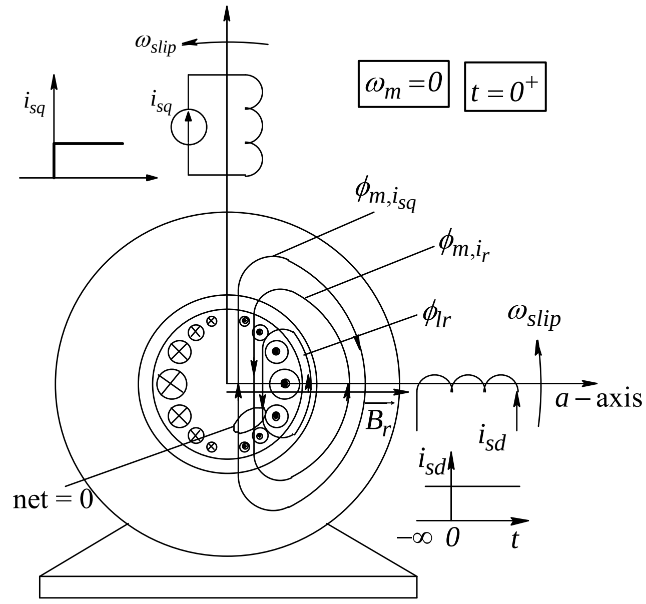


$$i_a(0^-) = \hat{I}_{m,rated} \text{ and } i_b(0^-) = i_c(0^-) = -\frac{1}{2}\hat{I}_{m,rated}$$

$$i_{sd}(0^-) = \sqrt{\frac{2}{3}}\hat{I}ms,rated = \sqrt{\frac{2}{3}}\left(\frac{3}{2}\hat{I}_{m,rated}\right) = \sqrt{\frac{3}{2}}\hat{I}_{m,rated}$$

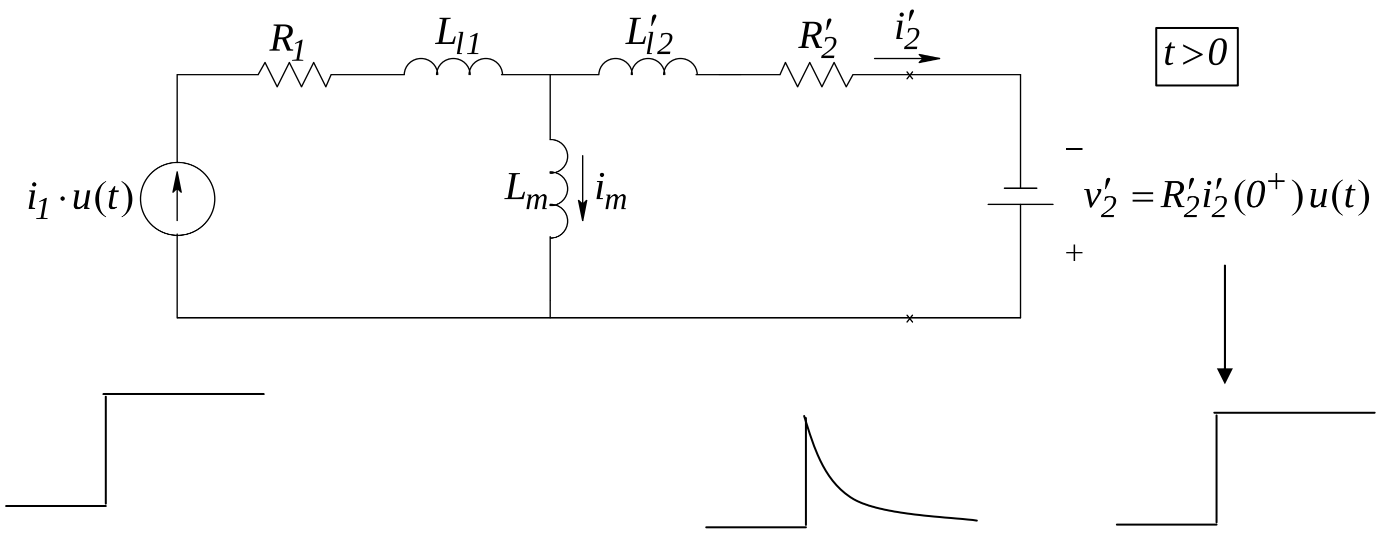
$$i_{sq} = 0$$

Step Change in Torque at $t = 0^+$



- $\omega_m = 0$
- I_{sd} unchanged
- Step-change in i_{sq} will result in step torque
  - $T_{em} \; \alpha \; \hat{B}_r, \dfrac{L_m}{L_r} \, i_{sq}$

Transformer Analogy – Voltage Needed to Prevent the Decay of Secondary Current

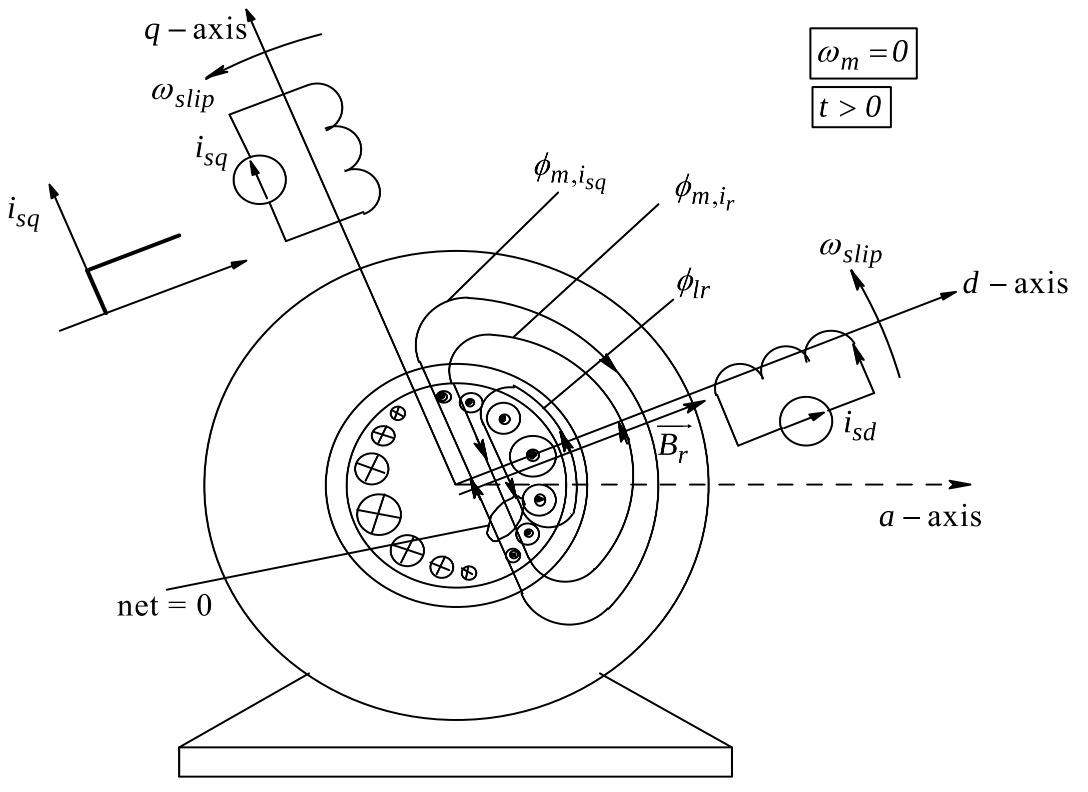


Step current

Impulse torque

Step torque

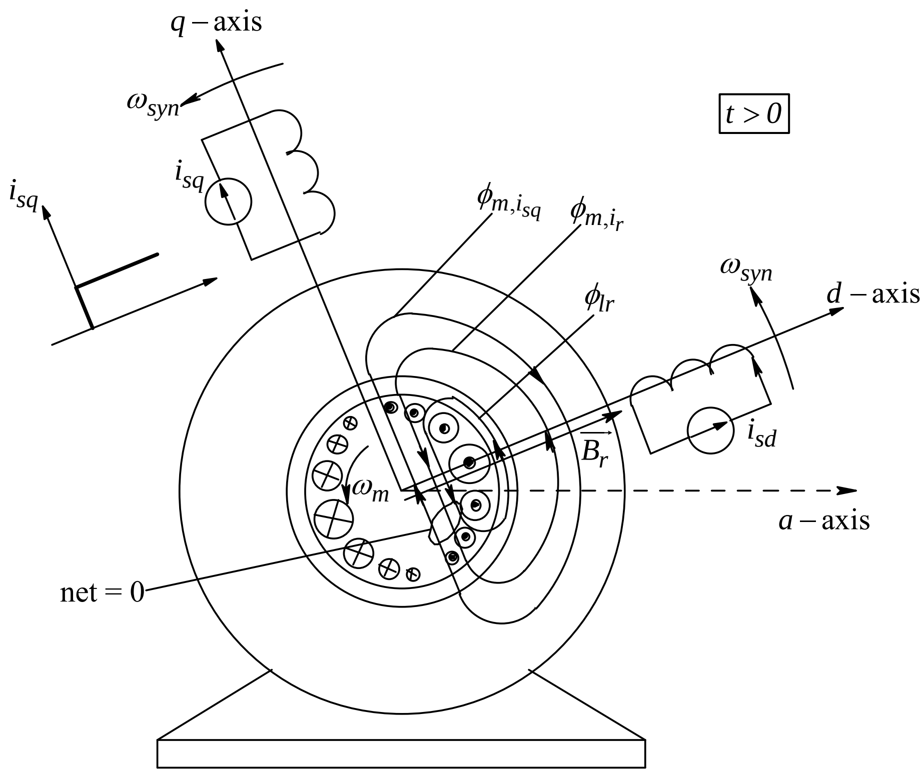
Currents and Fluxes at Sometime Later t > 0, Blocked Rotor



Supplying an electrical frequency with slip will maintain the torque.

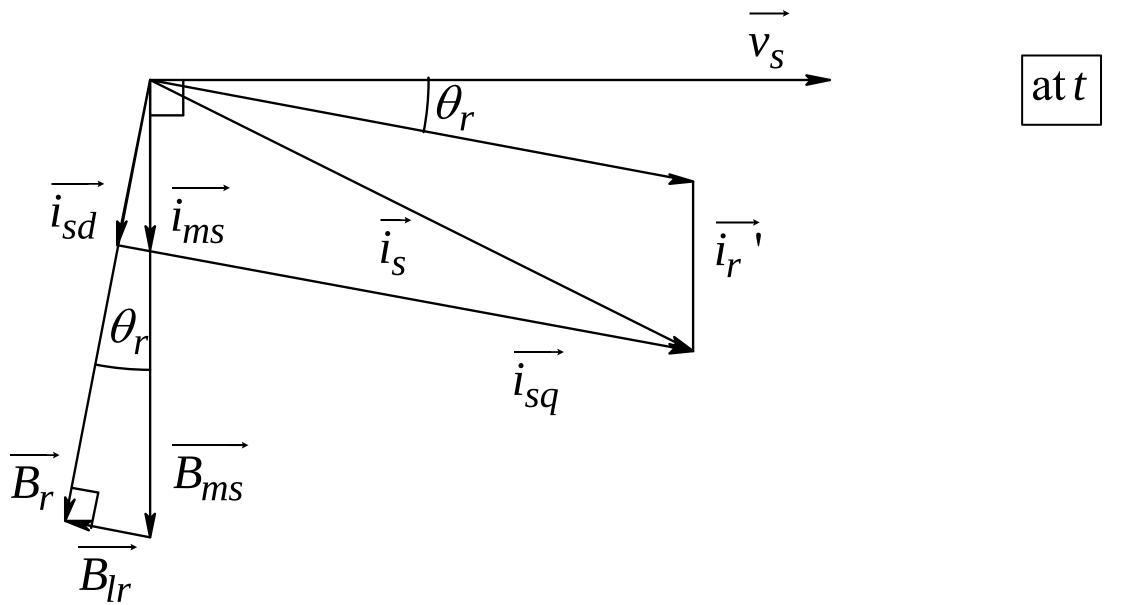
$$f_e = \frac{p}{2} f_{syn} = \frac{p}{2}\left(f_m + f_{slip}\right)$$

Vector-Controlled Condition With a Rotor Speed ω_m



$$\omega_{syn} = \omega_m + \omega_{slip}$$

Similarity Between Voltage-Fed and Vector-Controlled Induction Machines in Steady State



Sensor-Less Drives

- DTC

Reference 4: M. Depenbrock, “Direct Self Control (DSC) of Inverter-Fed Induction Machines,” IEEE Transactions on Power Electronics, Vol. 3, 1988, pp. 420-429

Reference 5: I. Takahashi and Y. Ohmori, “High Performance Direct Torque Control of an Induction Motor,” IEEE/IAS Annual Meeting, 1987, pp. 163-169

Summary/Review

- How is torque controlled in brush-type dc drives and brushless-dc drives?
- In a sentence, describe the vector control of induction-motor drives that emulates the performance of dc drives. Why is it more challenging?
- What does the Theorem of Constant Flux Linkage state?
- In words, what does the analogy of a transformer with the short-circuited secondary, and excited by a step-current conclude?
- What is the reason for introducing the d-axis and the q-axis windings?
- Without the details, state the reason for choosing $\sqrt{3/2}\,N_s/2$ as the number of turns in the d-axis and q-axis windings.

Summary/Review

- How are i_{sd} and i_{sq} obtained from the $\vec{i}_s$ space vector?
- At the end of the initial flux build-up process at $t = 0^-$, are there any currents in the rotor bar?
- How are the currents induced in the rotor bars at $t = 0^+$?
- What needs to be done to maintain the torque produced at $t = 0^+$?
- Why does the slip speed at which the d-axis and q-axis windings need to be rotated, to maintain the torque produced beyond $t = 0^+$, depend on various quantities as given in Eq. 13-12?
- Describe the similarity between voltage-fed induction machines and vector-controlled induction machines.
- Describe the control block diagram of vector control.
- Describe DTC and its objectives.

Flux Densities at $t = 0^+$