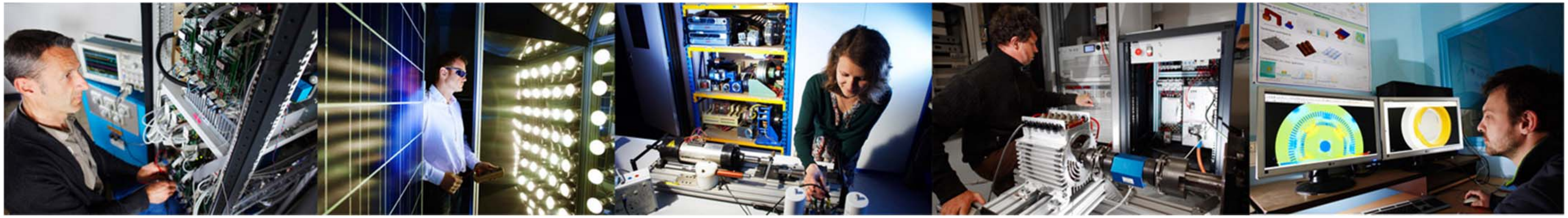

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Laboratoire d'électrotechnique et d'électronique de puissance de Lille

Introduction to Vector Control of Permanent Magnet Synchronous Machines using Energetic Macroscopic Representation

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Introduction to Vector Control of Permanent Magnet Synchronous Machines using Energetic Macroscopic Representation

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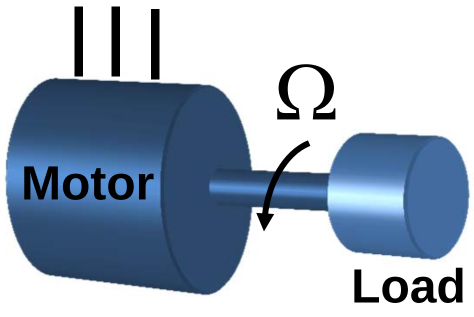
At the end of the lecture, students have to be able to:

- Use a methodological approach to represent models of electrical systems in order to help the deduction of dedicated control schemes
- Understand what are the variables of a Permanent Magnet Synchronous Machine (PMSM) to be controlled
- Know, with the help of SIMULINK simulations, how to control a PMSM in the *abc* reference frame and what are the inherent limitations
- Know, with the help of SIMULINK simulations, how to control a PMSM in the *dq* reference frame and what are the necessary mathematical transformations to implement

- Models and Representations for the control of electrical systems
- Modelling and **Energetic Macroscopic Representation** (EMR) of Permanent Magnet Synchronous Machines (PMSM)
- Principles of **Inversion Based Control**
- Inversion Based Control of Permanent Magnet Synchronous Machines (PMSM) – ***abc*** **reference frame**
  - Simulation with SIMULINK
- Inversion Based Control of Permanent Magnet Synchronous Machines (PMSM) – ***dq*** **reference frame**
  - Simulation with SIMULINK

What are the quantities to be controlled ?

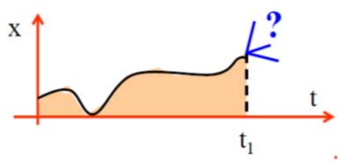


$$T_{motor} - T_{res} = J\frac{d\Omega}{dt} + f\Omega$$

$$\Omega = \frac{d\theta}{dt}$$

- Equations are usually written with differential operators, however:

$$\left(\frac{d\Omega(t)}{dt}\right) = \lim_{\Delta t \to 0}\left(\frac{\Omega(t+\Delta t) - \Omega(\Delta t)}{\Delta t}\right)$$



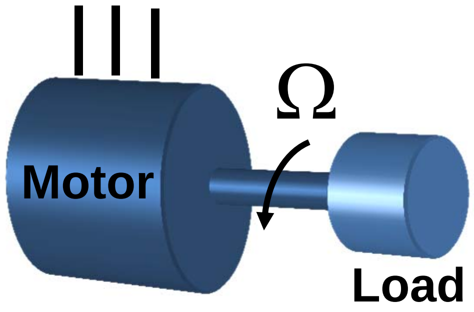
The torque at time *t* cannot depend on the speed at time *t+Δt*

→ *Physically impossible!*

→ Physical causality is integral

What are the quantities to be controlled ?

- If equations are written in integral form, then:



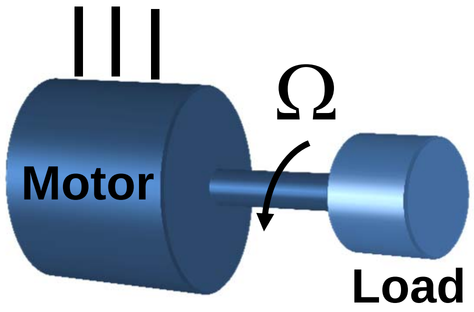
$$\Omega = \frac{d\theta}{dt} \Rightarrow \theta(t) = \int_0^t \Omega(\alpha)\, d\alpha \Rightarrow \boxed{\theta = \frac{\Omega}{s}}$$

$$T_{motor} - T_{res} = J\frac{d\Omega}{dt} + f\Omega \Rightarrow \boxed{\Omega = \frac{T_{motor} - T_{res}}{f + Js}}$$

- The position at time *t* depends on the speed up to *t*
- The speed at time *t* depends on the torque up to *t*

→ There are natural (physical) causalities

What are the quantities to be controlled ?



$$\theta = \frac{\Omega}{s}$$

$$\Omega = \frac{T_{motor} - T_{res}}{f + Js}$$

- Motor Torque (T_{motor}) -> Rotation of the load (Ω)

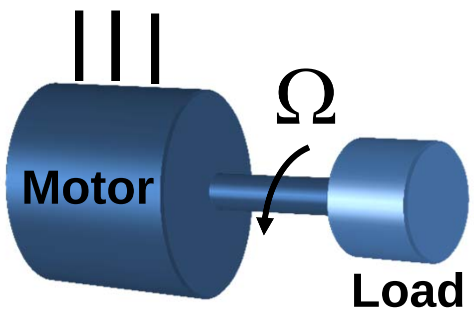
  → **Action implies Reaction**

- Motor Torque (T_{motor}) x Rotation of the load (Ω) = Power

  → **Action x Reaction = Power**

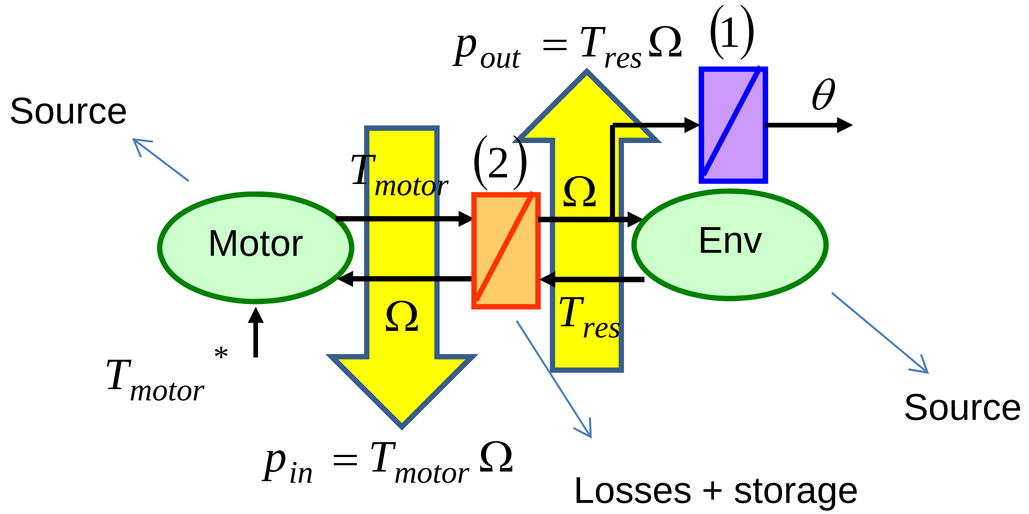
Energetic Macroscopic Representation makes possible to represent a model in order to:

- To respect the natural (integral) causality
- To highlight actions and reactions and power flows



$$\theta = \frac{\Omega}{s} \quad (1)$$

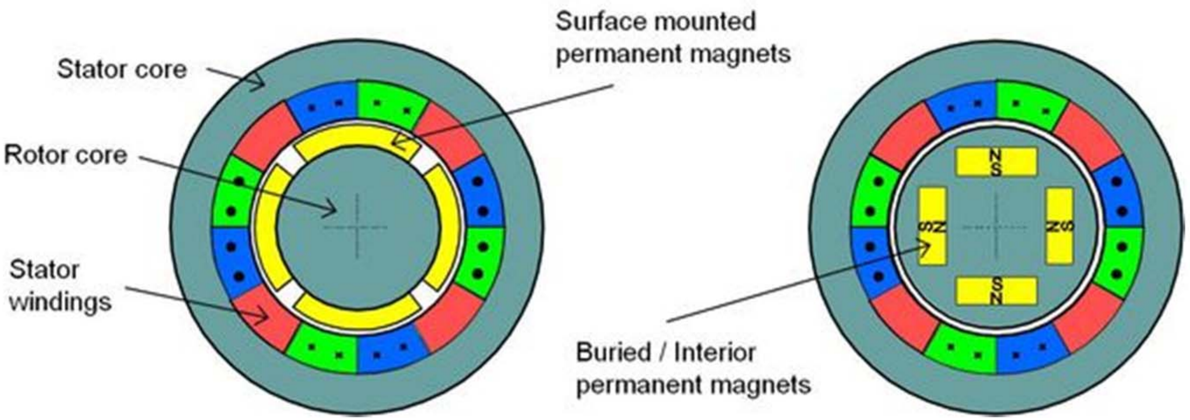
$$\Omega = \frac{T_{motor} - T_{res}}{f + Js} \quad (2)$$



$$p_{in} - p_{out} = p_{losses} + p_{"stored"}$$

Constitution of a PMSM

- Stator composed of three windings
- Rotor composed of surface mounted or buried magnets



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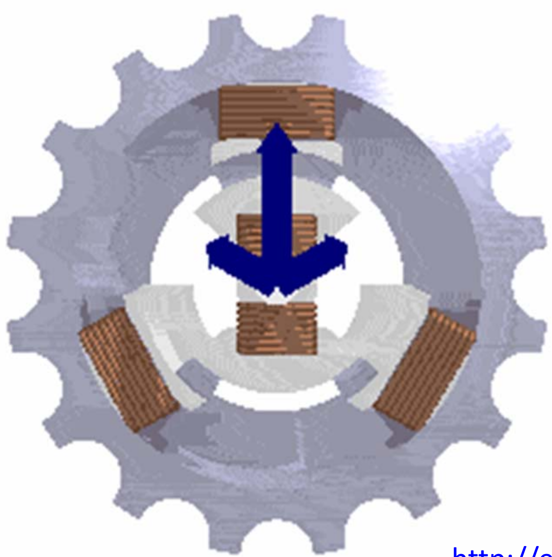
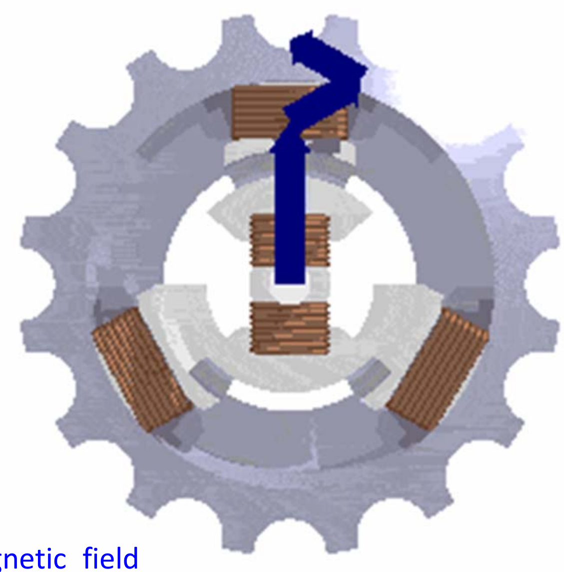
Principle of functioning of a PMSM

- Stator creates a rotating magnetic field (equivalent to a rotating magnet although stator windings are at stand still)

→ Each winding produces a magnetic field with a magnitude proportional to the coil current and a direction corresponding to the coil axis

→ If the three coils are supplied with a 3-phase AC sine current system, the resultant magnetic field is rotating

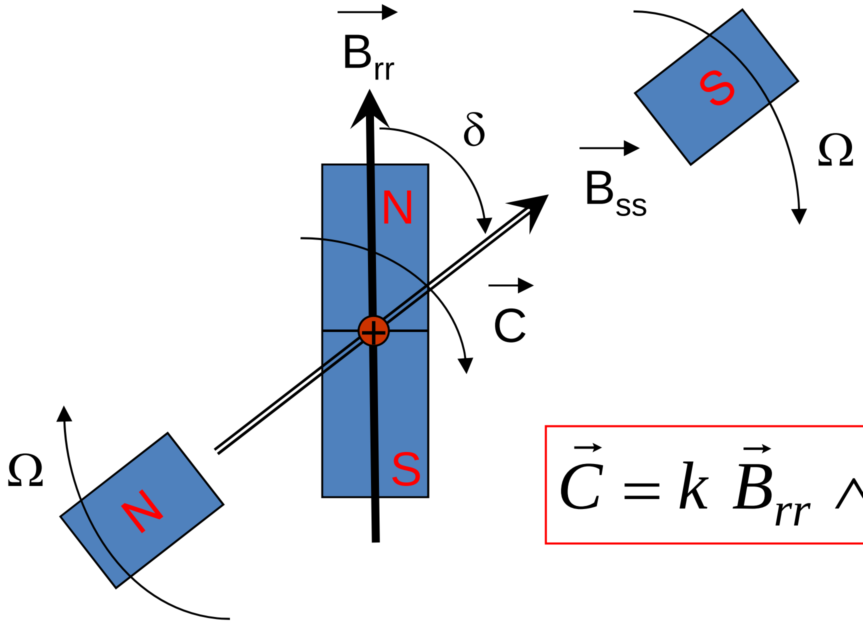




http://en.wikipedia.org/wiki/Rotating_magnetic_field

Principle of functioning of a PMSM

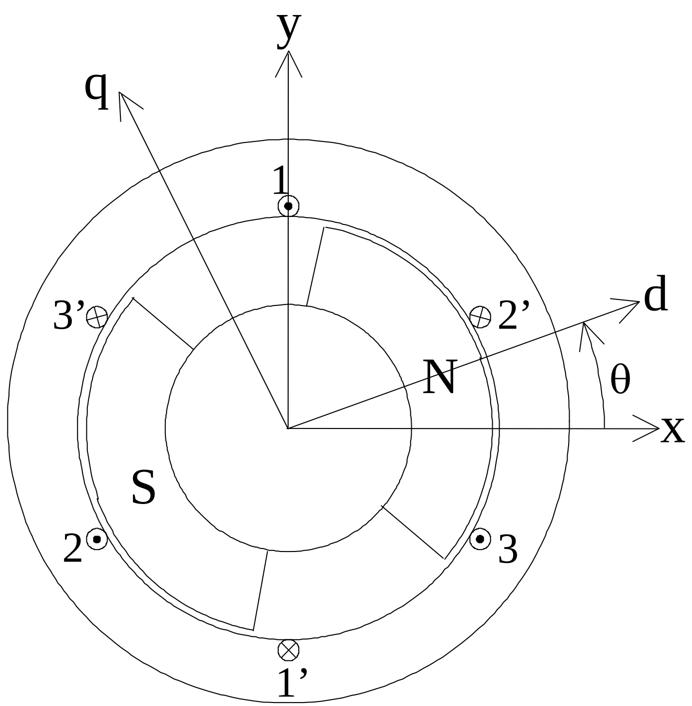
- Stator creates a rotating magnetic field (equivalent to a rotating magnet although stator windings are at stand still)
- Rotor magnets are attracted by the rotating field and rotate at the same speed (in steady state)

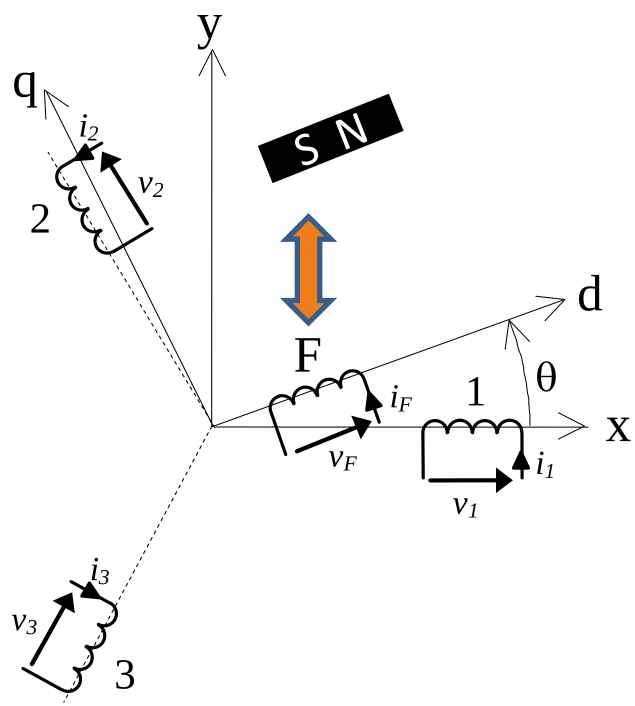


$$\vec{C} = k\ \vec{B}_{rr} \wedge \vec{B}_{ss}$$

Torque Control requires a VECTOR CONTROL

Modelling of a PMSM





Only one pole pair for the sake of simplicity.

The permanent magnet is equivalent to a winding supplied with a DC current

Modelling of a PMSM

Stator flux linkage equations are

$$\begin{pmatrix}\lambda_1\\ \lambda_2\\ \lambda_3\end{pmatrix}=\begin{pmatrix}\lambda_{1s}\\ \lambda_{2s}\\ \lambda_{3s}\end{pmatrix}+\begin{pmatrix}\lambda_{1r}\\ \lambda_{2r}\\ \lambda_{3r}\end{pmatrix}$$

with

$$\begin{pmatrix}\lambda_{1s}\\ \lambda_{2s}\\ \lambda_{3s}\end{pmatrix}=\begin{pmatrix}L_s & M_s & M_s\\ M_s & L_s & M_s\\ M_s & M_s & L_s\end{pmatrix}\begin{pmatrix}i_1\\ i_2\\ i_3\end{pmatrix}$$

and

$$\begin{pmatrix}\lambda_{1r}\\ \lambda_{2r}\\ \lambda_{3r}\end{pmatrix}=\lambda_{\max}\begin{pmatrix}\cos\theta\\ \cos(\theta-2\pi/3)\\ \cos(\theta-4\pi/3)\end{pmatrix}$$

$\lambda_{\max}=cste$ in case of rotor with permanent magnets

$\lambda_{\max}=M_F\ i_F$ in case of wound-rotor

Modelling of a PMSM

Stator voltage equations are then

$$\begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix} = R_s \begin{pmatrix} i_1 \\ i_2 \\ i_3 \end{pmatrix} + \frac{d}{dt}\begin{pmatrix} \lambda_1 \\ \lambda_2 \\ \lambda_3 \end{pmatrix} = R_s \begin{pmatrix} i_1 \\ i_2 \\ i_3 \end{pmatrix} + \frac{d}{dt}\begin{pmatrix} \lambda_{1s} \\ \lambda_{2s} \\ \lambda_{3s} \end{pmatrix} + \frac{d}{dt}\begin{pmatrix} \lambda_{1r} \\ \lambda_{2r} \\ \lambda_{3r} \end{pmatrix}$$

$$\begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix} = R_s \begin{pmatrix} i_1 \\ i_2 \\ i_3 \end{pmatrix} + \begin{pmatrix} L_s & M_s & M_s \\ M_s & L_s & M_s \\ M_s & M_s & L_s \end{pmatrix} \frac{d}{dt}\begin{pmatrix} i_1 \\ i_2 \\ i_3 \end{pmatrix} + \begin{pmatrix} e_1 \\ e_2 \\ e_3 \end{pmatrix}$$

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Modelling of a PMSM

Or in a more concise way (matrix notation)

$$[v] = R_s[i] + [L_s]\frac{d[i]}{dt} + [e]$$

with $[v] = \begin{bmatrix} v_1 \\ v_2 \\ v_3 \end{bmatrix}$ Voltage vector

$[e] = \begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix}$ EMF vector

$[i] = \begin{bmatrix} i_1 \\ i_2 \\ i_3 \end{bmatrix}$ Current vector

R_s Stator resistance

$[L_s]$ Stator inductance matrix

Modelling of a PMSM

The power balance is

$$p_{in} = p_{losses} + p_{mag} + p_{em}$$

With

$$p_{in} = [v]_t . [i] = v_1 i_1 + v_2 i_2 + v_3 i_3$$

$$p_{losses} = R_s . \|[i]\|^2 = R_s i_1{}^2 + R_s i_2{}^2 + R_s i_3{}^2$$

$$p_{mag} = [L_s] \frac{d[i]_t}{dt} [i] = \frac{d}{dt}\left(\frac{1}{2} [i]_t [L_s] . [i] \right)$$

Modelling of a PMSM

and

$$p_{em} = [e]_t [i] = e_1 i_1 + e_2 i_2 + e_3 i_3 = T_{em}\Omega$$

then

$$T_{em} = \frac{p_{em}}{\Omega} = \frac{[e]_t [i]}{\Omega} = \frac{e_1 i_1 + e_2 i_2 + e_3 i_3}{\Omega}$$

As

$$[e] = \frac{d[\lambda_r]}{dt} = \frac{d\theta}{dt}\frac{d[\lambda_r]}{d\theta} = \Omega \frac{d[\lambda_r]}{d\theta}$$

then

$$\boxed{T_{em} = \frac{d[\lambda_r]_t}{d\theta}[i]}$$

Torque Control requires a VECTOR CONTROL

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Modelling of a PMSM

If

$$\begin{pmatrix} \lambda_{1r} \\ \lambda_{2r} \\ \lambda_{3r} \end{pmatrix} = \lambda_{\max} \begin{pmatrix} \cos\theta \\ \cos(\theta - 2\pi/3) \\ \cos(\theta - 4\pi/3) \end{pmatrix}$$

and

$$\begin{pmatrix} e_1 \\ e_2 \\ e_3 \end{pmatrix} = \Omega \frac{d}{d\theta} \begin{pmatrix} \lambda_{1r} \\ \lambda_{2r} \\ \lambda_{3r} \end{pmatrix} = -\Omega \lambda_{\max} \begin{pmatrix} \sin\theta \\ \sin(\theta - 2\pi/3) \\ \sin(\theta - 4\pi/3) \end{pmatrix}$$

then

$$T_{em} = -\lambda_{\max} \left(i_1 \sin\theta + i_2 \sin(\theta - 2\pi/3) + i_3 \sin(\theta - 4\pi/3) \right)$$

Modelling of a PMSM

Question: Find the current references that lead to a constant torque under minimum copper losses

Modelling of a PMSM

Solution:

$p_{losses} = R_s . \left\| [i] \right\|^2$ is minimum if $\left\| [i] \right\|$ is minimum

For a given T_{em}^* $\left\| [i] \right\|$ is minimum if $[i]$ is collinear to $\frac{d[\lambda_r]}{d\theta}$

i.e. $[i^*] = [i] = k \frac{d[\lambda_r]}{d\theta}$

Then $T_{em}^* = \frac{d[\lambda_r]_t}{d\theta} k \frac{d[\lambda_r]}{d\theta} = k \left\| \frac{d[\lambda_r]}{d\theta} \right\|^2$

$$\Rightarrow [i^*] = \frac{T_{em}^*}{\left\| \frac{d[\lambda_r]}{d\theta} \right\|^2} \frac{d[\lambda_r]}{d\theta} = \frac{T_{em}^*}{\left(\frac{3}{2}\right) \lambda_{max}^{\ 2}} \frac{d[\lambda_r]}{d\theta}$$

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Modelling of a PMSM

Solution:

Finally

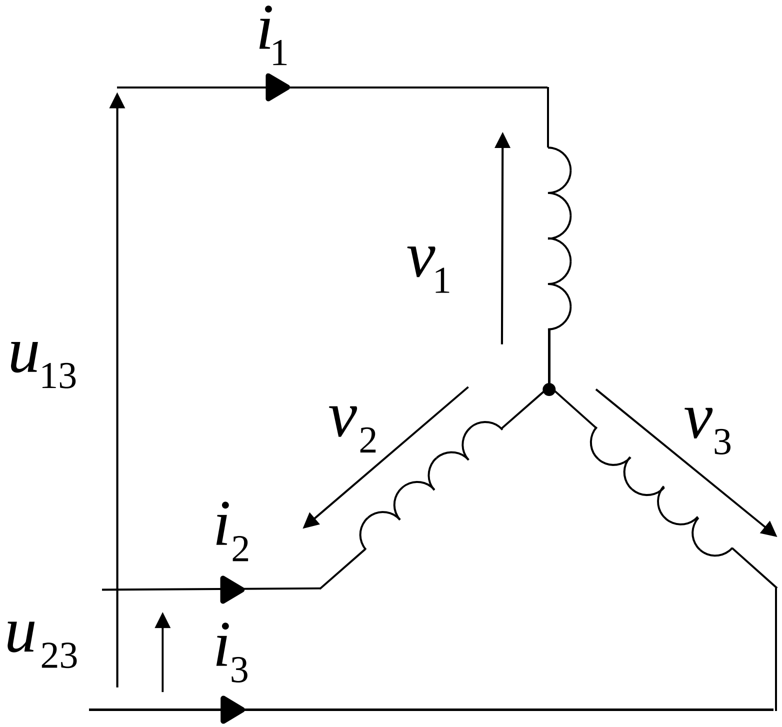
$$\left[i^*\right] = -\frac{2T_{em}}{3\lambda_{\max}} \begin{bmatrix} \sin\theta \\ \sin\left(\theta - 2\pi/3\right) \\ \sin\left(\theta - 4\pi/3\right) \end{bmatrix}$$

Current vector is collinear to EMF vector

Modelling of a PMSM

If the stator windings are star coupled: $i_1 + i_2 + i_3 = 0$

Only two voltages and two currents are sufficient to model the machine:



Question: Rewrite the voltage equation with i_1, i_2, u_{13}, u_{23} as variables

$$\begin{pmatrix} v_1 \\ v_2 \\ v_3 \end{pmatrix} = R_s \begin{pmatrix} i_1 \\ i_2 \\ i_3 \end{pmatrix} + \begin{pmatrix} L_s & M_s & M_s \\ M_s & L_s & M_s \\ M_s & M_s & L_s \end{pmatrix} \frac{d}{dt} \begin{pmatrix} i_1 \\ i_2 \\ i_3 \end{pmatrix} + \begin{pmatrix} e_1 \\ e_2 \\ e_3 \end{pmatrix}$$

Modelling of a PMSM

Solution:

$$\begin{bmatrix} u_{13} \\ u_{23} \end{bmatrix} = \begin{bmatrix} v_1 - v_3 \\ v_2 - v_3 \end{bmatrix} = \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} R_s \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} + \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} L_c \frac{d}{dt} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} + \begin{bmatrix} e_1 - e_3 \\ e_2 - e_3 \end{bmatrix}$$

$L_c = (L_s - M_s)$ is called the stator cyclic inductance

Remark: if we add the same quantity v_Z (Zero-sequence) to v_1, v_2 and v_3, u_{13} and u_{23} remain the same.

EMR of a PMSM

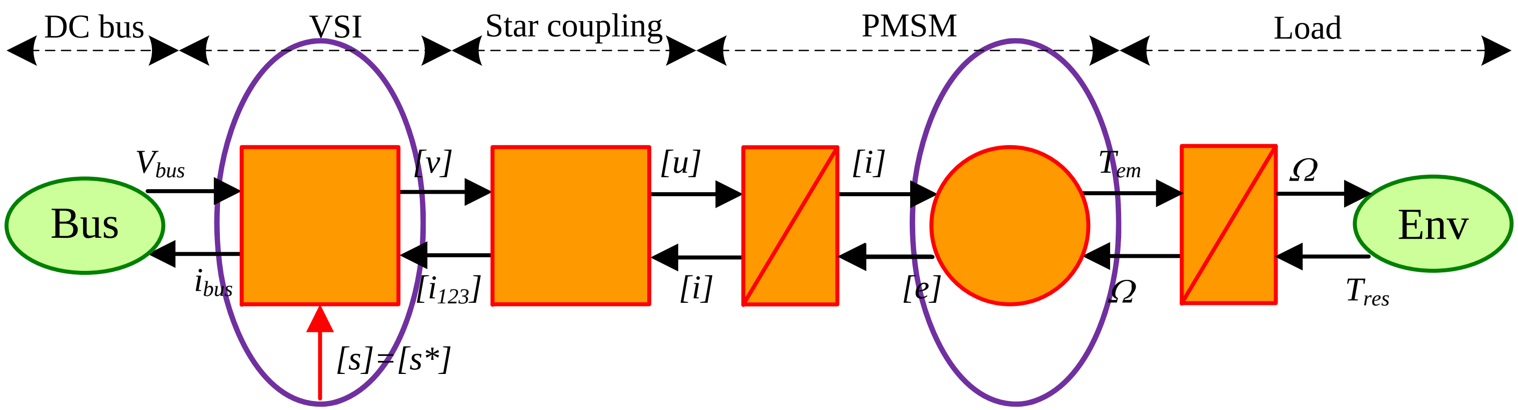
The VSI (Voltage Source Inverter) is considered as an amplifier:

VSI: $v_k = s_k V_{bus}, \quad -1 \le s_k \le 1$

Star coupling: $i_1 + i_2 + i_3 = 0 \qquad v_1 + v_2 + v_3 = 0$

PMSM:
$$\begin{bmatrix} u_{13} \\ u_{23} \end{bmatrix} = \begin{bmatrix} v_1 - v_3 \\ v_2 - v_3 \end{bmatrix} = \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} R_s \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} + \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} L_c \frac{d}{dt} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} + \begin{bmatrix} e_1 - e_3 \\ e_2 - e_3 \end{bmatrix}$$
$$(e_1 - e_3) i_1 + (e_2 - e_3) i_2 = T_{em} \Omega$$

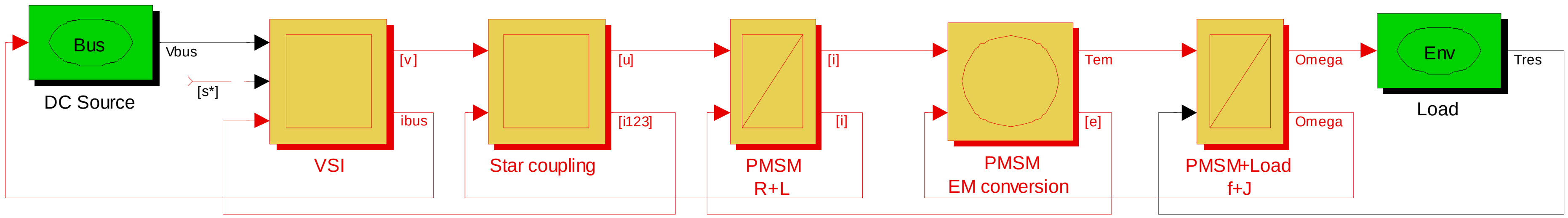
Load: $T_{em} - T_{res} = J \dfrac{d\Omega}{dt} + f\Omega$

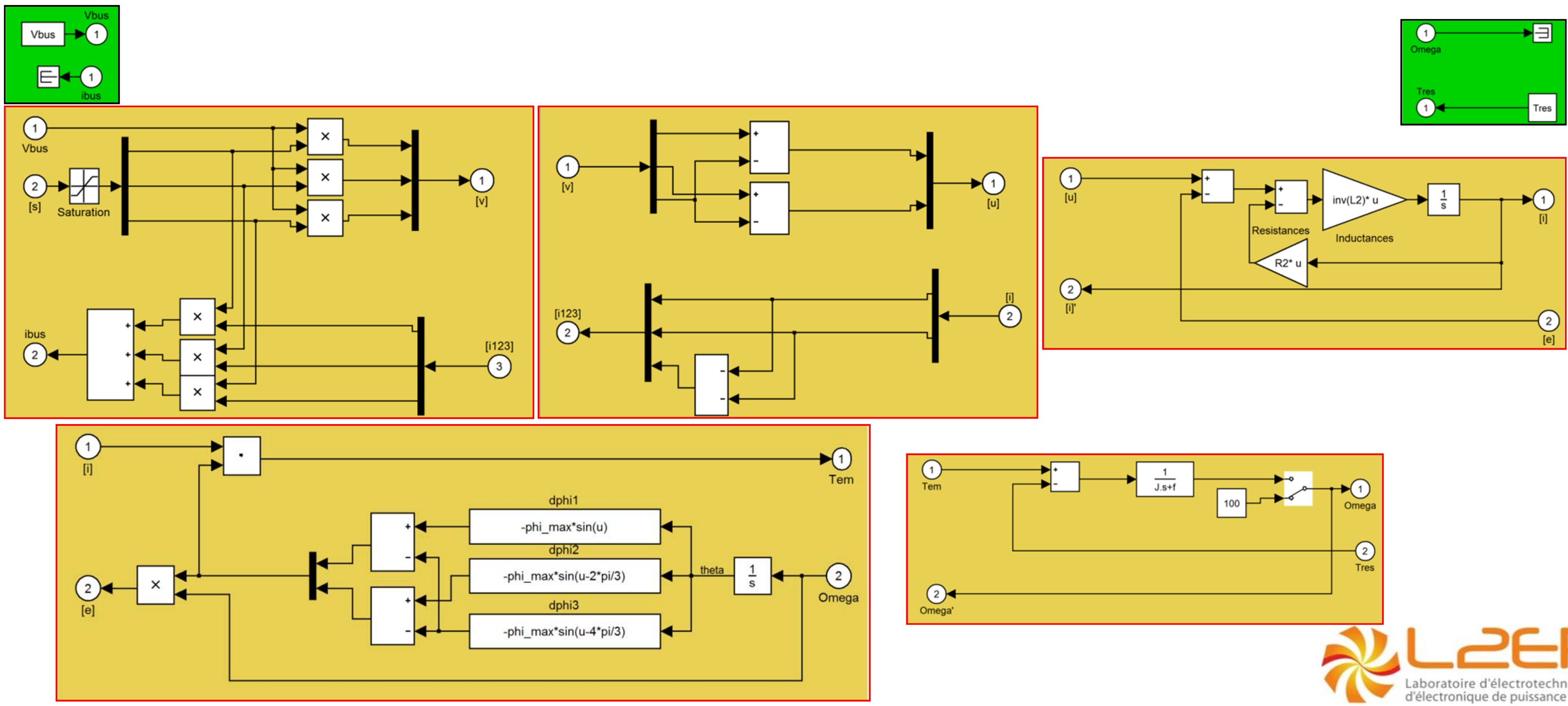


Mono-physical conversion (elec→elec)

Multi-physical conversion (elec→méca)

From EMR to Simulink…





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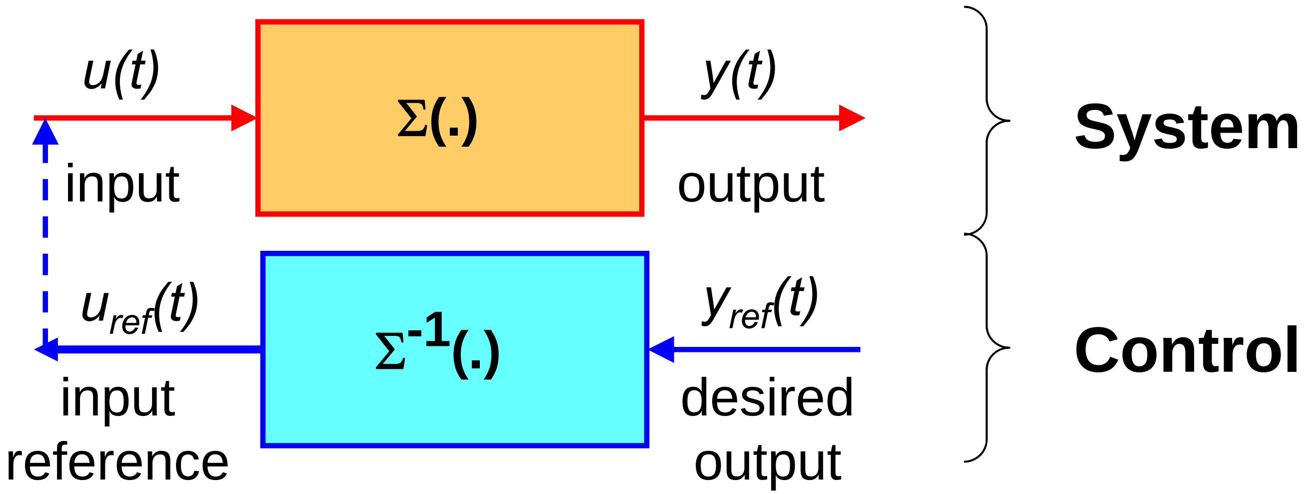
Open loop and closed-loop controls

Controlling a system for output tracking can be interpreted as inverting the system

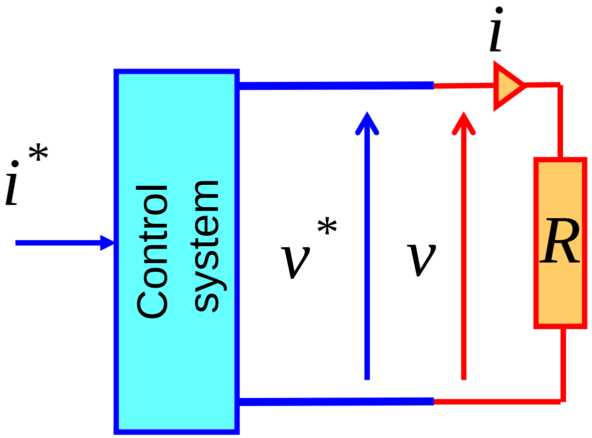


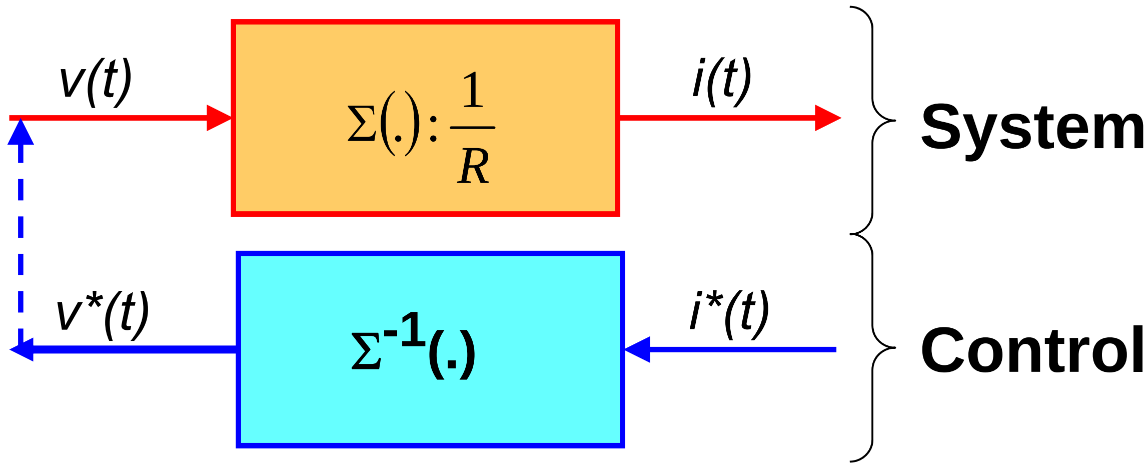
… if we can implement a good approximation of the system's inverse

Principles of Inversion Based Control

Open loop controls

Let’s take a simple example: current control of a resistance





$$\tilde{\Sigma}^{-1}(.): \quad v^*(t) = \tilde{R}\, i^*(t)$$

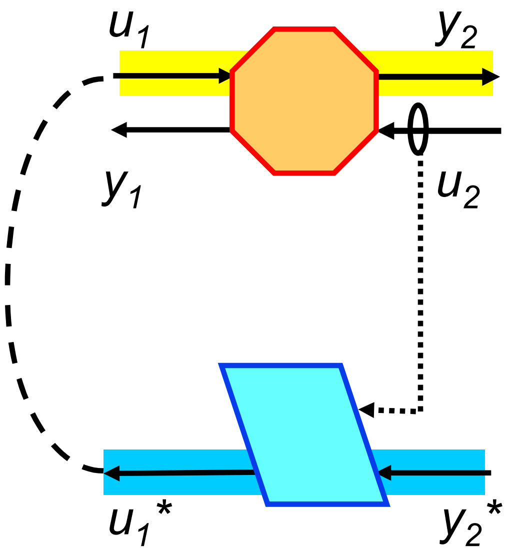
In case of acausal relationship (no accumulation), open loop control is possible (No need of controllers).

The inversion of the element is said “direct”.

Open loop controls

Direct Control with EMR formalism

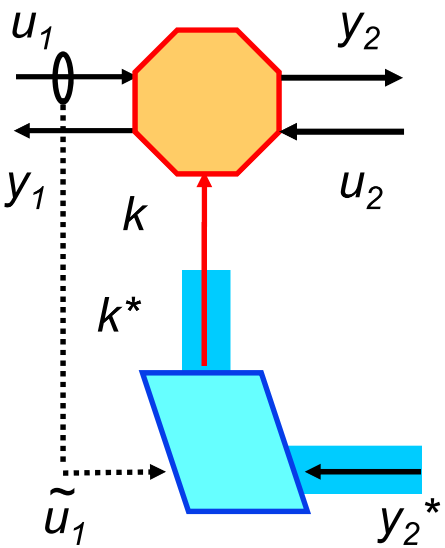
Objective: to control y_2



$y_2 = f(u_1) + g(u_2)$

$u_1^* = f^{-1}(y_2^*) + \tilde{g}(u_2)$

Compensate u_2
Manipulate u_1



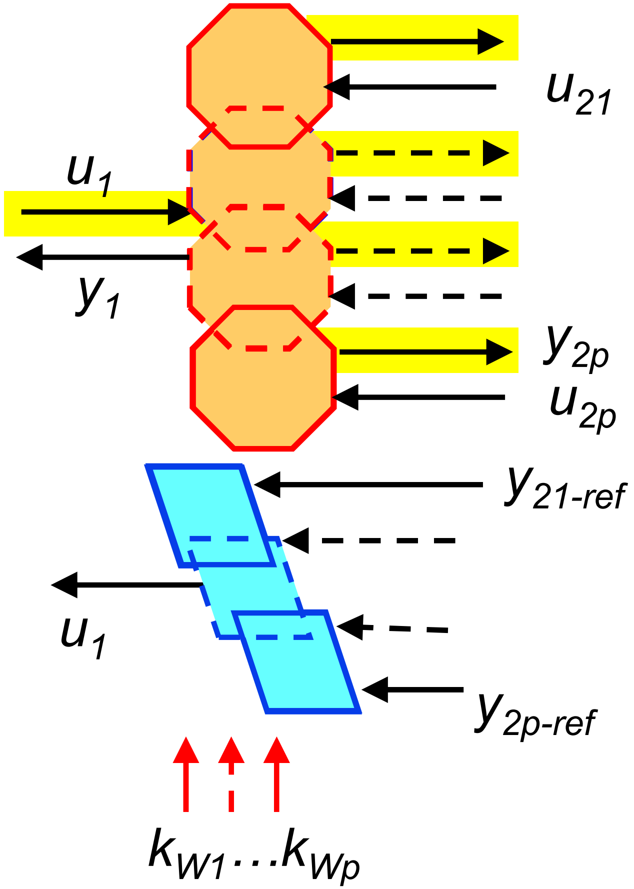
$y_2 = k \, x \, u_1$

$y_1 = (1/k) x \, u_2$

$k^* = y_2^* / \tilde{u}_1$

Open loop controls

Direct Control with EMR formalism

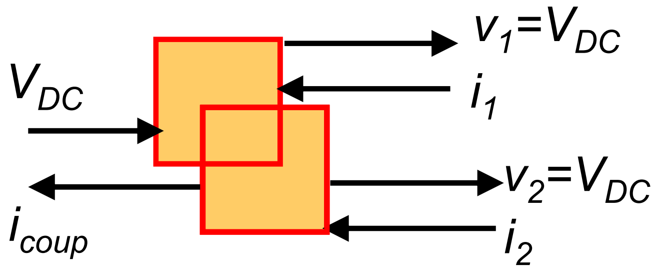


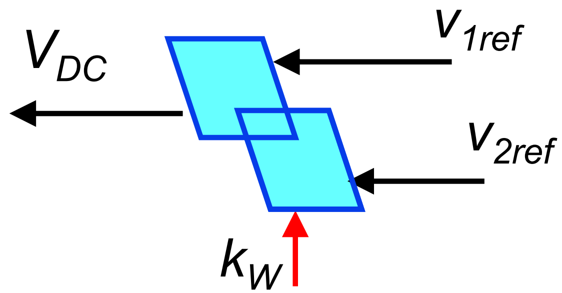
Implement a compromise or prioritize outputs.

no measurement
no controller
p weighting variables

$$u_1 = k'_{W1} y_{21-ref} + \ldots + k'_{Wp} y_{2p-ref}$$

<u>Example</u>: current node



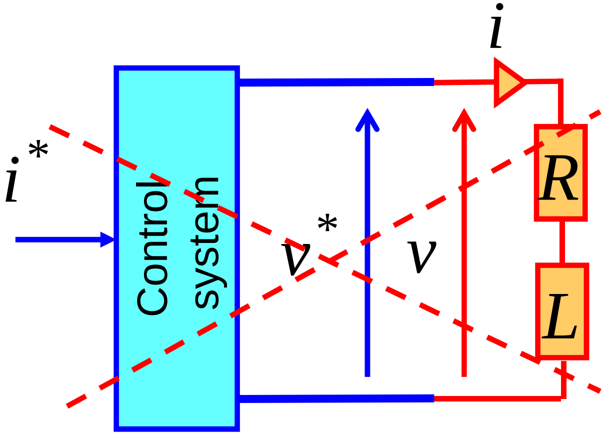


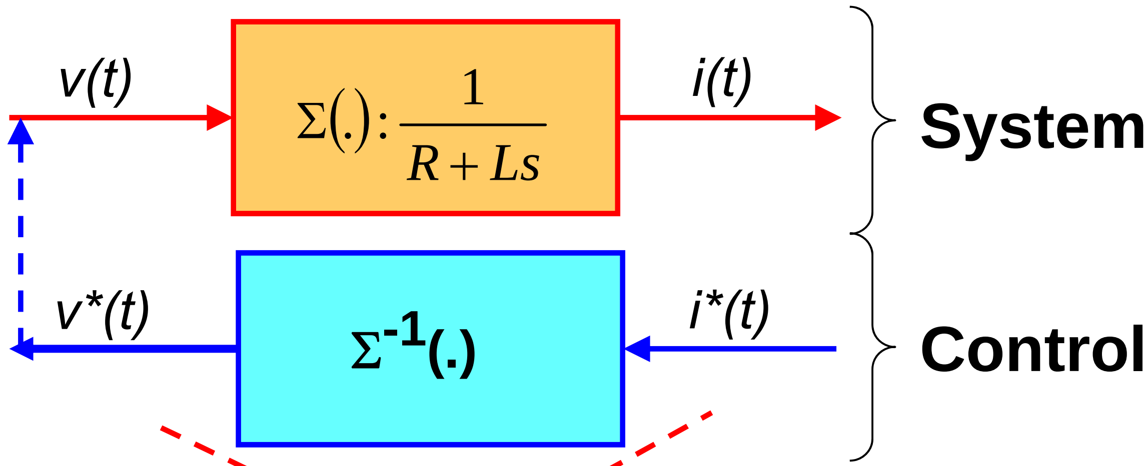
$$V_{DC} = \left[k_W v_{1ref} + (1 - k_W) v_{2ref} \right]$$

$$0 \leq k_W \leq 1$$

Closed-loop controls

Let's take a simple example: current control of a R+L circuit





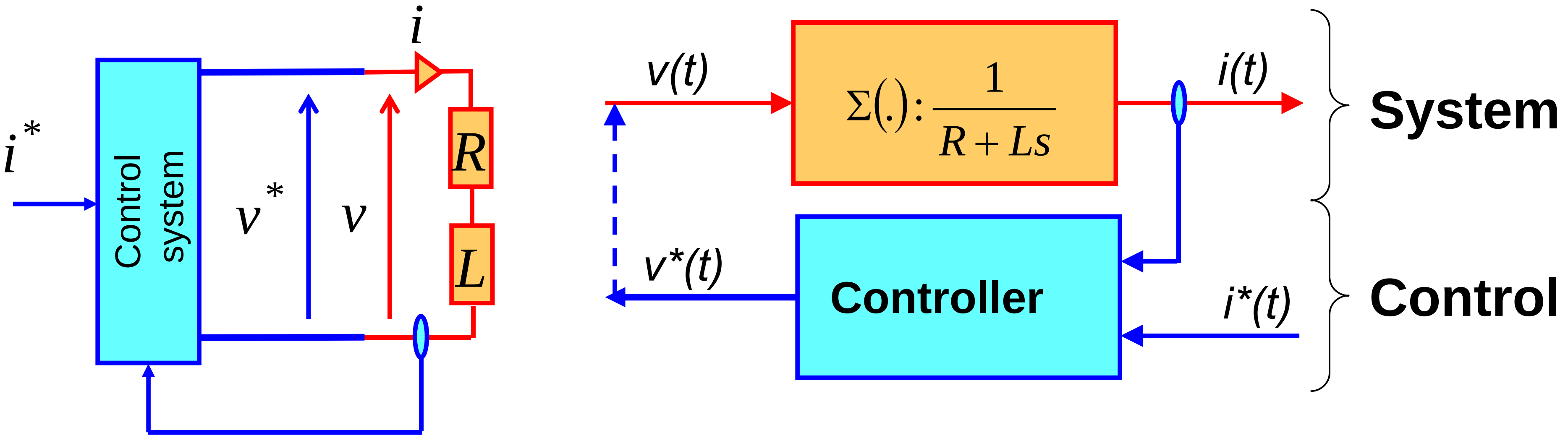
No derivative in real-time

$$\tilde{\Sigma}^{-1}(.): \quad v^*(s) = \left(\tilde{R} + \tilde{L}s\right) i^*(s)$$

In case of causal relationship (accumulation of energy), open loop control is not possible ➔ Need of controllers

Closed-loop controls

Let's take a simple example: current control of a R+L circuit



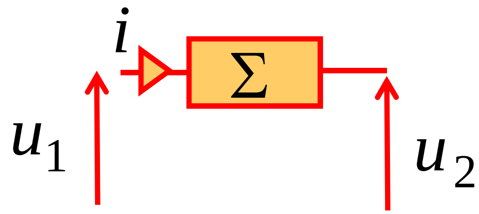
$$Controller: \quad v^*(s) = C(s)\left(i^*(s) - i(s)\right)$$

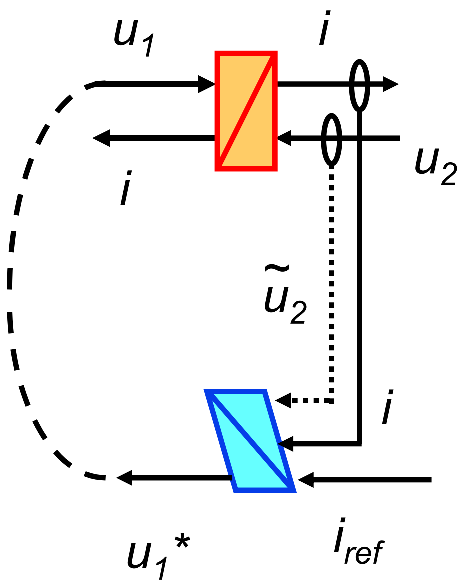
In case of causal relationship (accumulation of energy), closed-loop control is mandatory

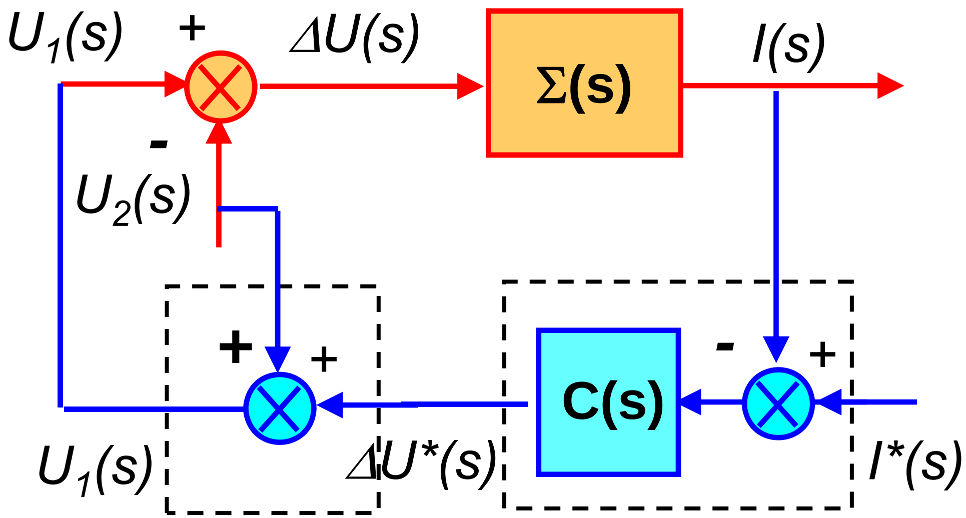
➔ Need of measurements and controllers (Indirect control)

Closed-loop controls

Indirect Control with EMR formalism
(System with accumulation of energy)







Inversion Based Control of PMSM (*abc frame*)

Inversion based-control of the PMSM in the *abc* reference frame

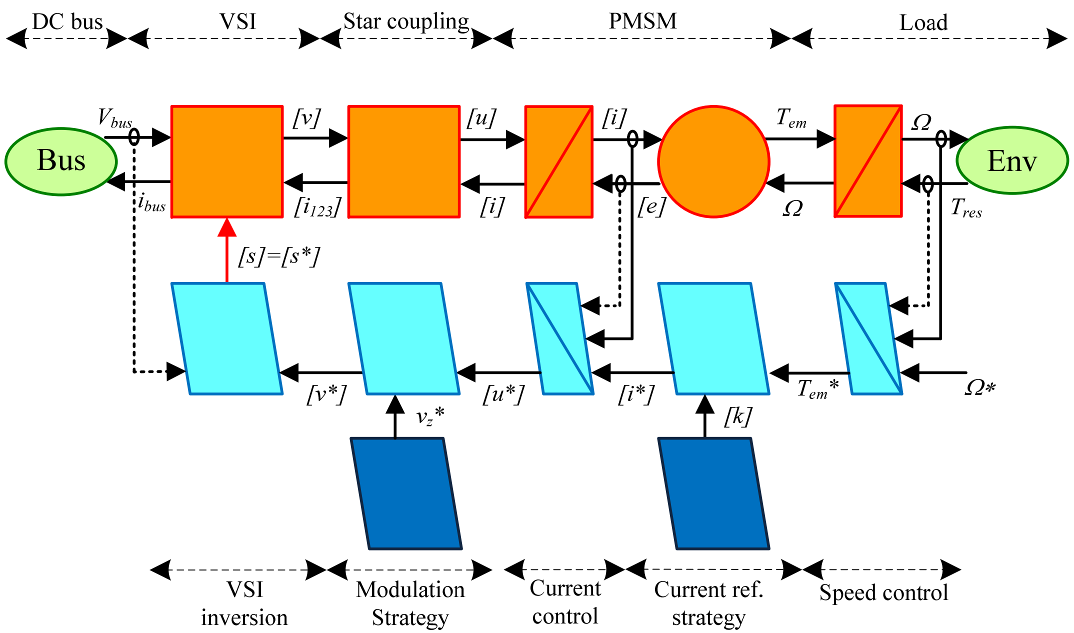
The VSI (Voltage Source Inverter) is considered as an amplifier:

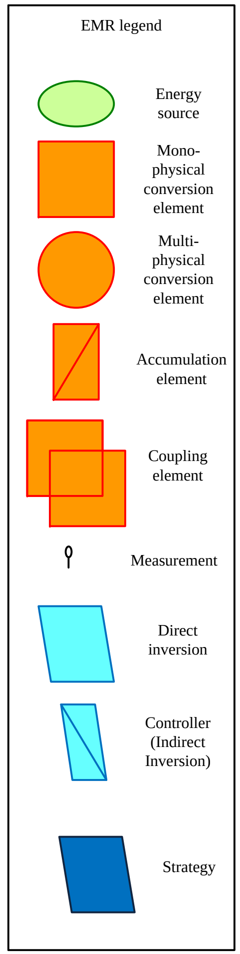
$$v_k = s_k V_{bus}, \quad -1 \le s_k \le 1$$

$$i_1 + i_2 + i_3 = 0 \qquad v_1 + v_2 + v_3 = 0$$

$$\begin{bmatrix} u_{13} \\ u_{23} \end{bmatrix} = \begin{bmatrix} v_1 - v_3 \\ v_2 - v_3 \end{bmatrix} = \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} R_s \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} + \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} L_c \frac{d}{dt} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} + \begin{bmatrix} e_1 - e_3 \\ e_2 - e_3 \end{bmatrix}$$

$$(e_1 - e_3) i_1 + (e_2 - e_3) i_2 = T_{em} \Omega \qquad T_{em} - T_{res} = J \frac{d\Omega}{dt} + f\Omega$$





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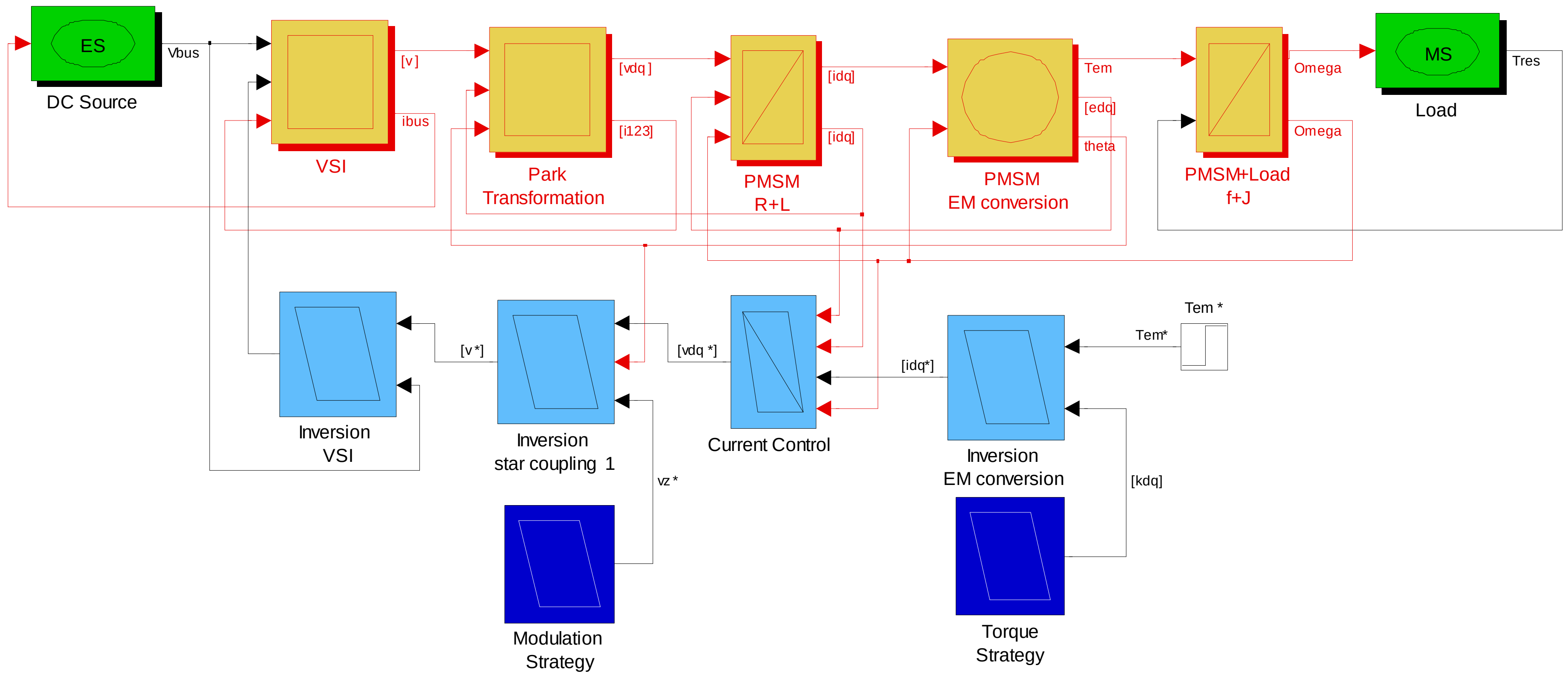
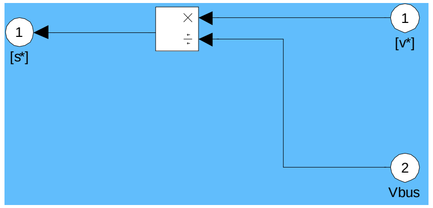
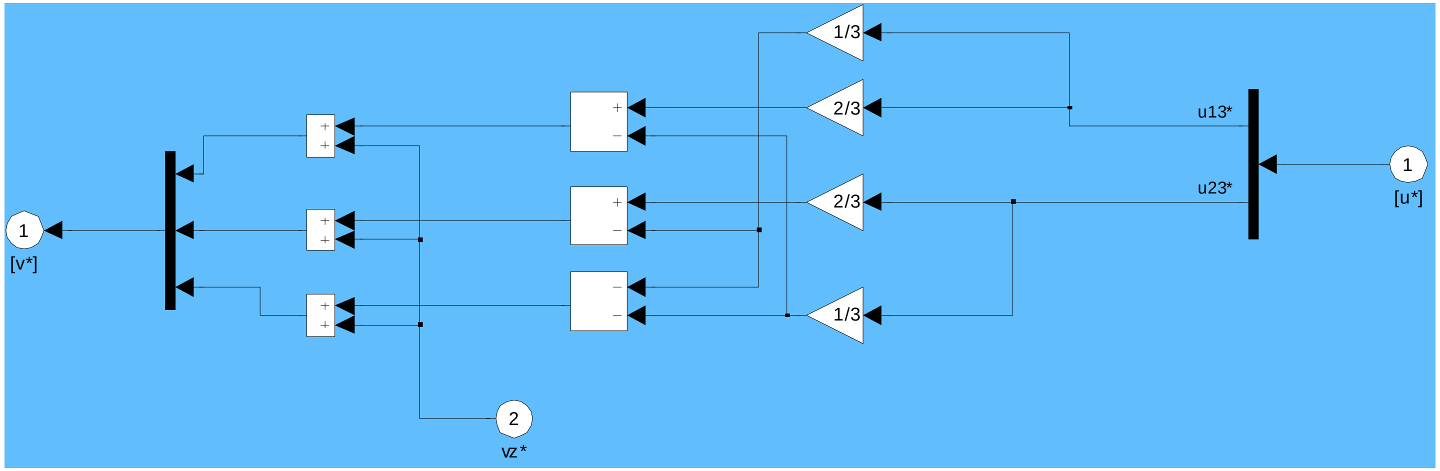
From EMR and IBC to Simulink…

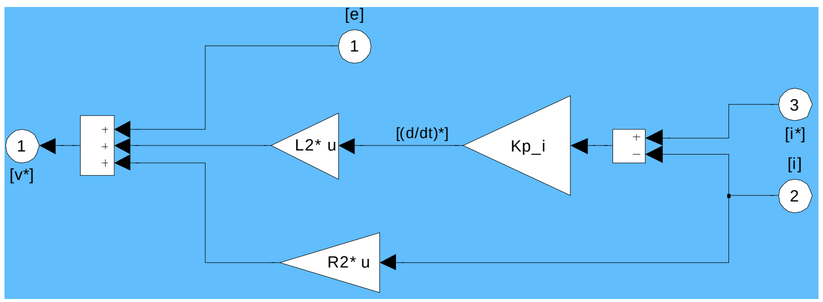


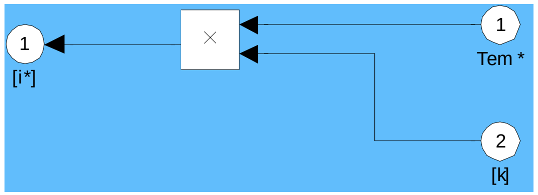
Inversion Based Control of PMSM (*abc frame*)

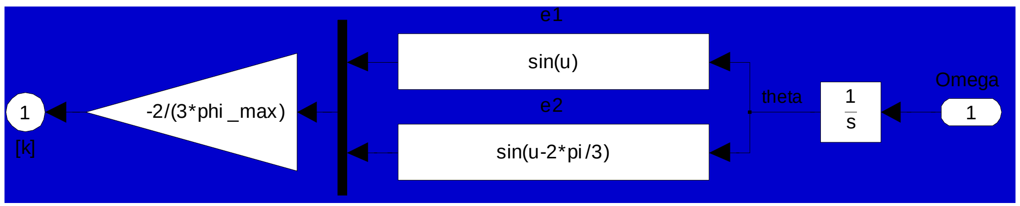
From EMR and IBC to Simulink…

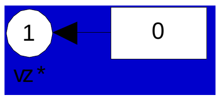












From EMR and IBC to Simulink…

Questions: Using the Simulink file PMSM_abc

- Analyse the simulation (Model-Control-Strategy)
- Comment the effect of the knowledge of the system's parameters and the gain Kp_i on the overall performances
- Conclude

Solution:

To attain good performances, very good knowledge of the system's parameters is necessary (which is difficult) and a high value for Kp_i gain is required to perfectly track the references (which can lead to instability)

→ Another type of control is required

Modelling of a PMSM in the *dq* reference frame

The control of the currents is difficult because the system in the *abc* reference frame is highly coupled

$$\begin{bmatrix} u_{13} \\ u_{23} \end{bmatrix} = \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} R_s \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} + \begin{bmatrix} 2 & 1 \\ 1 & 2 \end{bmatrix} \lambda_s \frac{d}{dt} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix} + \begin{bmatrix} e_1 - e_3 \\ e_2 - e_3 \end{bmatrix}$$

By using the following change of variables (called Concordia transformation):

$$\begin{bmatrix} i_1 \\ i_2 \end{bmatrix} = [C] \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = \begin{bmatrix} \sqrt{\frac{2}{3}} & 0 \\ -\frac{1}{\sqrt{6}} & \frac{1}{\sqrt{2}} \end{bmatrix} \begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix}$$

Modelling of a PMSM in the *dq* reference frame

The system becomes :

$$[C]^t\begin{bmatrix}u_{13}\\u_{23}\end{bmatrix}=[C]^t\begin{bmatrix}2&1\\1&2\end{bmatrix}R_s[C]\begin{bmatrix}i_\alpha\\i_\beta\end{bmatrix}+[C]^t\begin{bmatrix}2&1\\1&2\end{bmatrix}[C]L_c\frac{d}{dt}\begin{bmatrix}i_\alpha\\i_\beta\end{bmatrix}+[C]^t\begin{bmatrix}e_1-e_3\\e_2-e_3\end{bmatrix}$$

Considering:

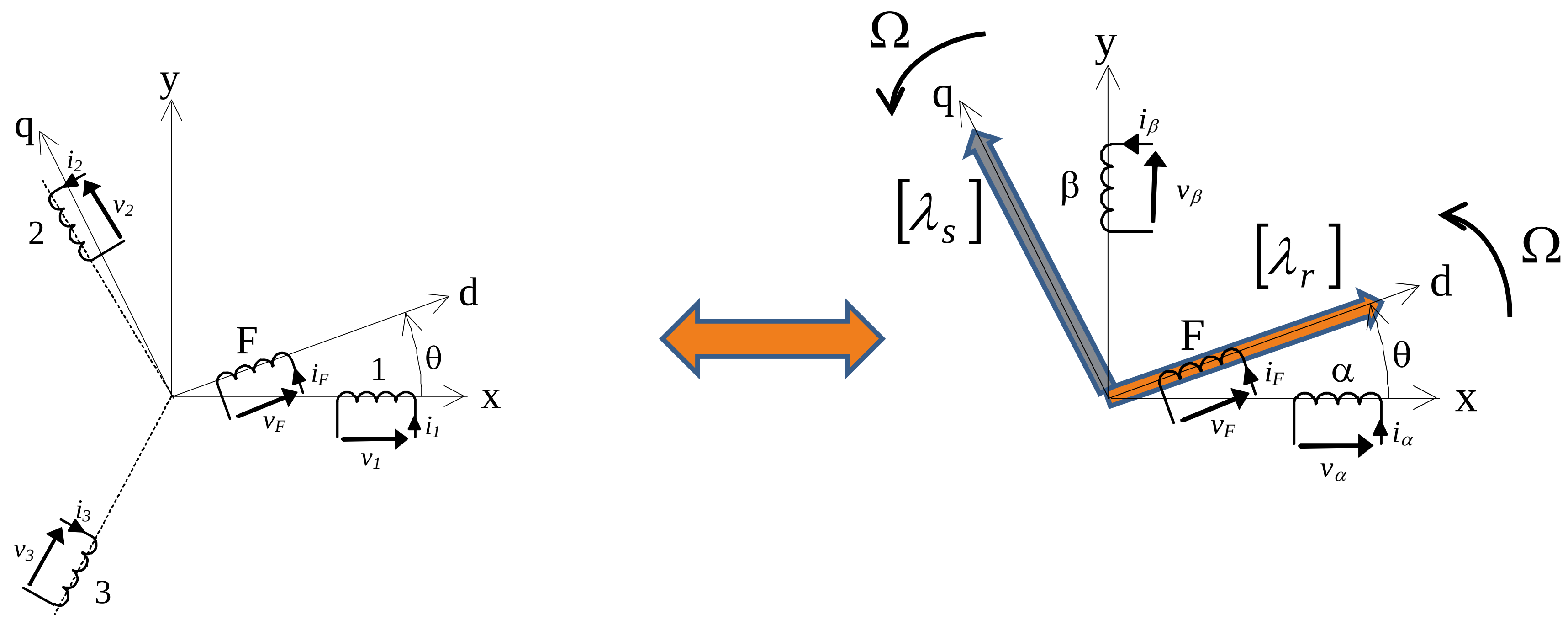
$$\begin{bmatrix}v_\alpha\\v_\beta\end{bmatrix}=[C]^t\begin{bmatrix}u_{13}\\u_{23}\end{bmatrix}\qquad\begin{bmatrix}e_\alpha\\e_\beta\end{bmatrix}=[C]^t\begin{bmatrix}e_{13}\\e_{23}\end{bmatrix}$$

It comes:

$$\begin{bmatrix}v_\alpha\\v_\beta\end{bmatrix}=\begin{bmatrix}R_s&0\\0&R_s\end{bmatrix}\begin{bmatrix}i_\alpha\\i_\beta\end{bmatrix}+\begin{bmatrix}L_c&0\\0&L_c\end{bmatrix}\frac{d}{dt}\begin{bmatrix}i_\alpha\\i_\beta\end{bmatrix}+\begin{bmatrix}e_\alpha\\e_\beta\end{bmatrix}$$

The real three phase machine is equivalent to a fictitious two independent phase machine (All matrices are diagonal).

Modelling of a PMSM in the *dq* reference frame



However, to obtain a constant torque, stator currents have still to be sinusoidal (since the rotor rotates!) and then difficult to track.

Modelling of a PMSM in the *dq* reference frame

If the stator windings rotate at the same speed as the rotor, stator currents will become constant!

By using the following change of variables (called Rotation):

$$\begin{bmatrix} i_\alpha \\ i_\beta \end{bmatrix} = [R(-\theta)] \begin{bmatrix} i_d \\ i_q \end{bmatrix} = \begin{bmatrix} \cos\theta & -\sin\theta \\ \sin\theta & \cos\theta \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix}$$

It comes:

$$\begin{bmatrix} v_d \\ v_q \end{bmatrix} = R_s \begin{bmatrix} i_d \\ i_q \end{bmatrix} + L_c \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + L_c \Omega \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \begin{bmatrix} e_d \\ e_q \end{bmatrix}$$

Although the system is (weakly) recoupled, currents in steady state are constant and then easy to control.

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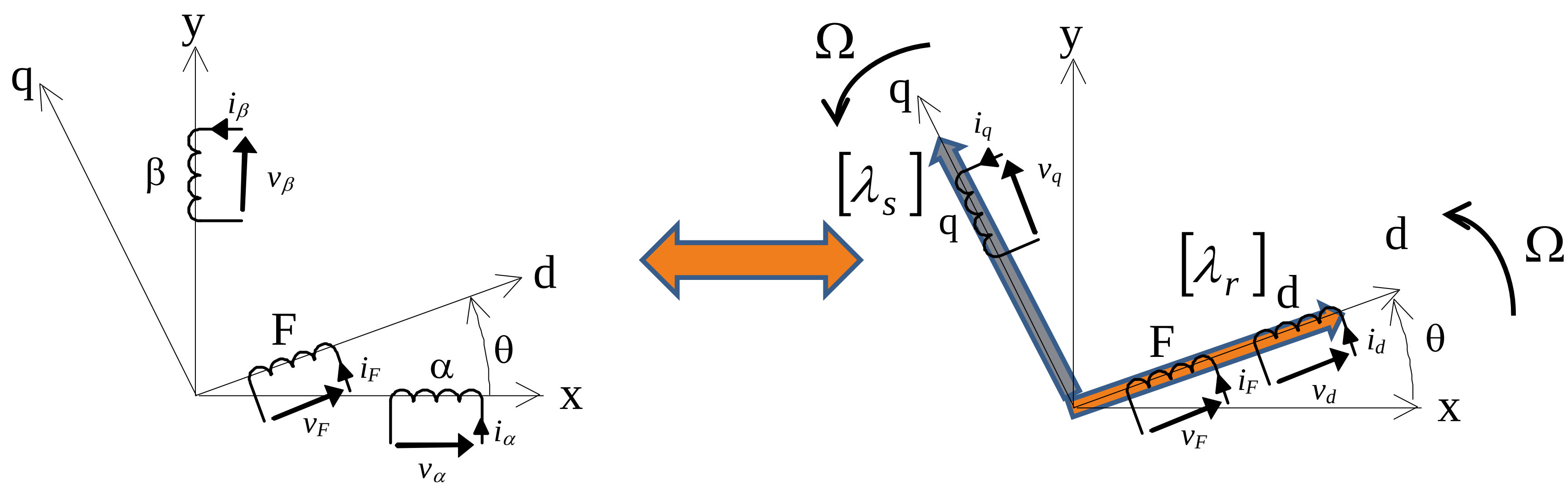
Modelling of a PMSM in the *dq* reference frame

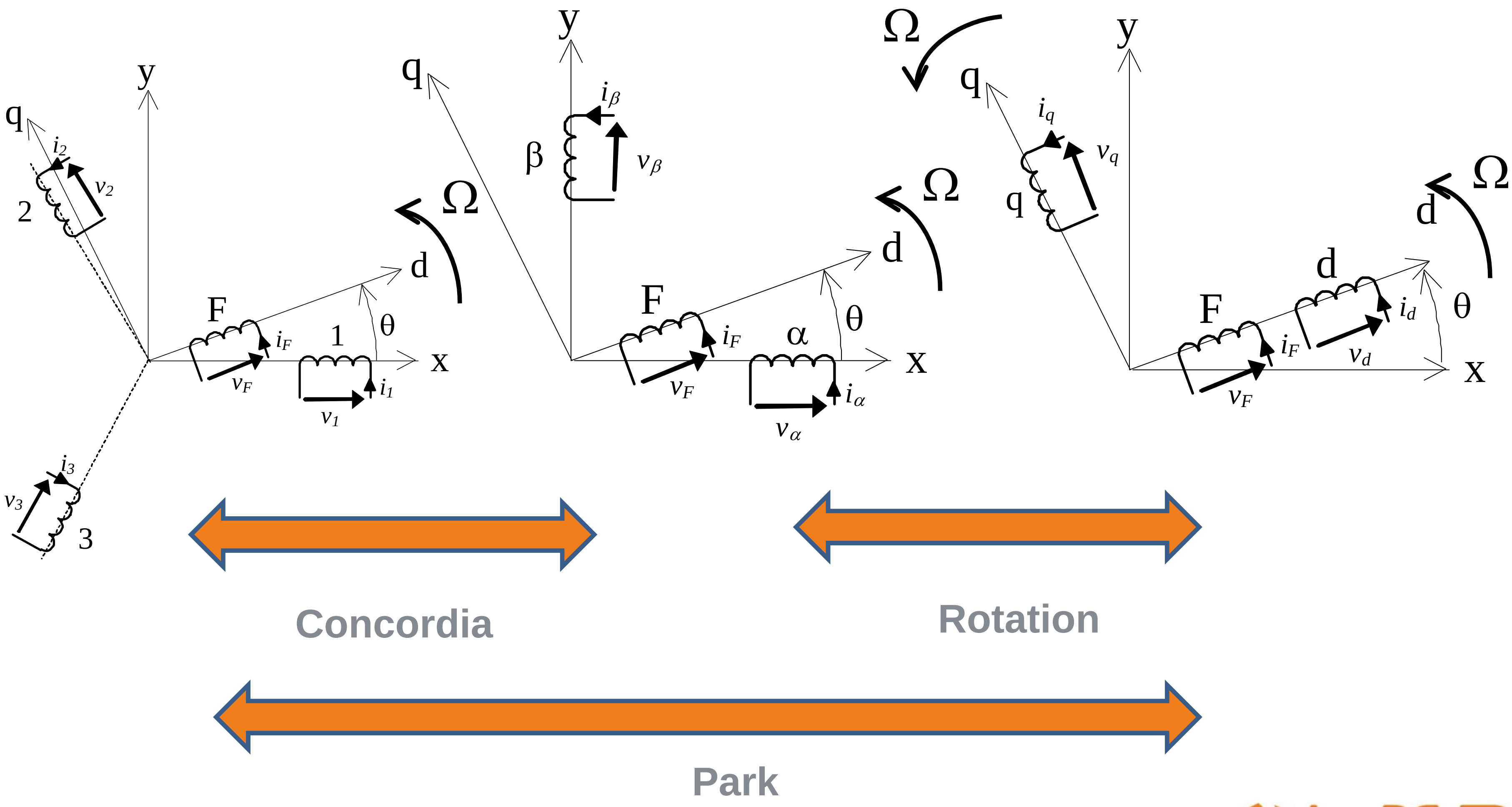


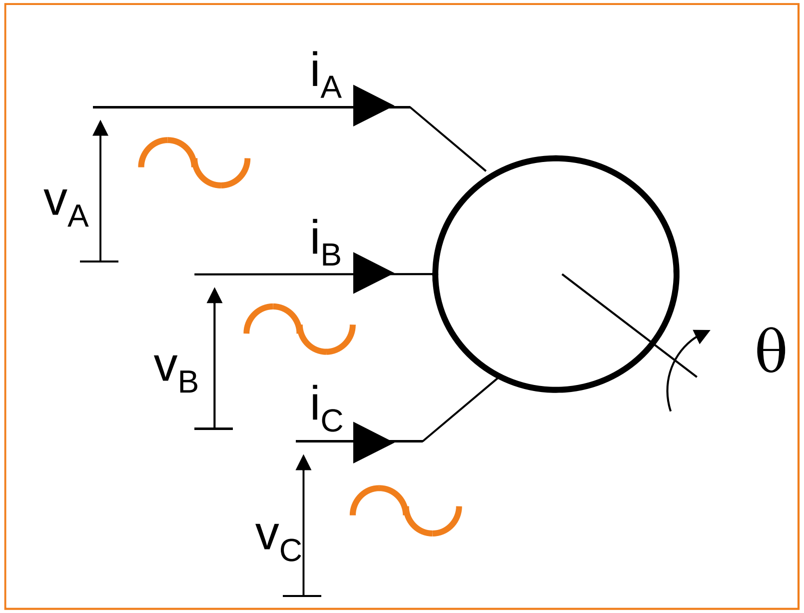
Moreover, flux vector $[\lambda_s]$ depends only on i_q. Then i_d can be kept equal to zero (e_d=0).

→ Equivalence with a DC Brushless machine

Vector control is easy to implement in *dq* reference frame.

Modelling of a PMSM in the *dq* reference frame

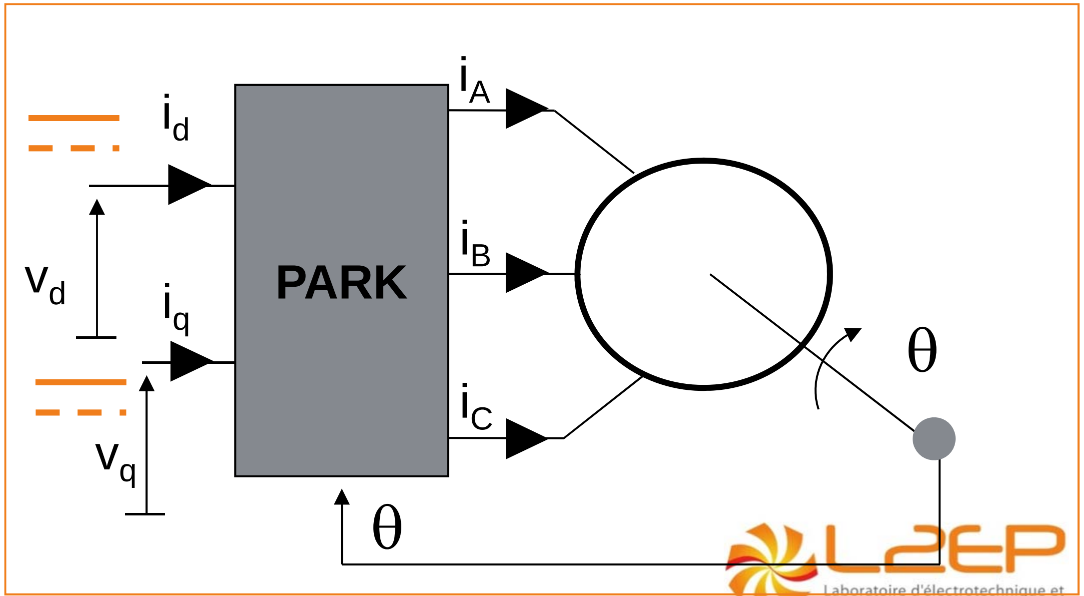




Modelling of a PMSM in the *dq* reference frame

Park-1

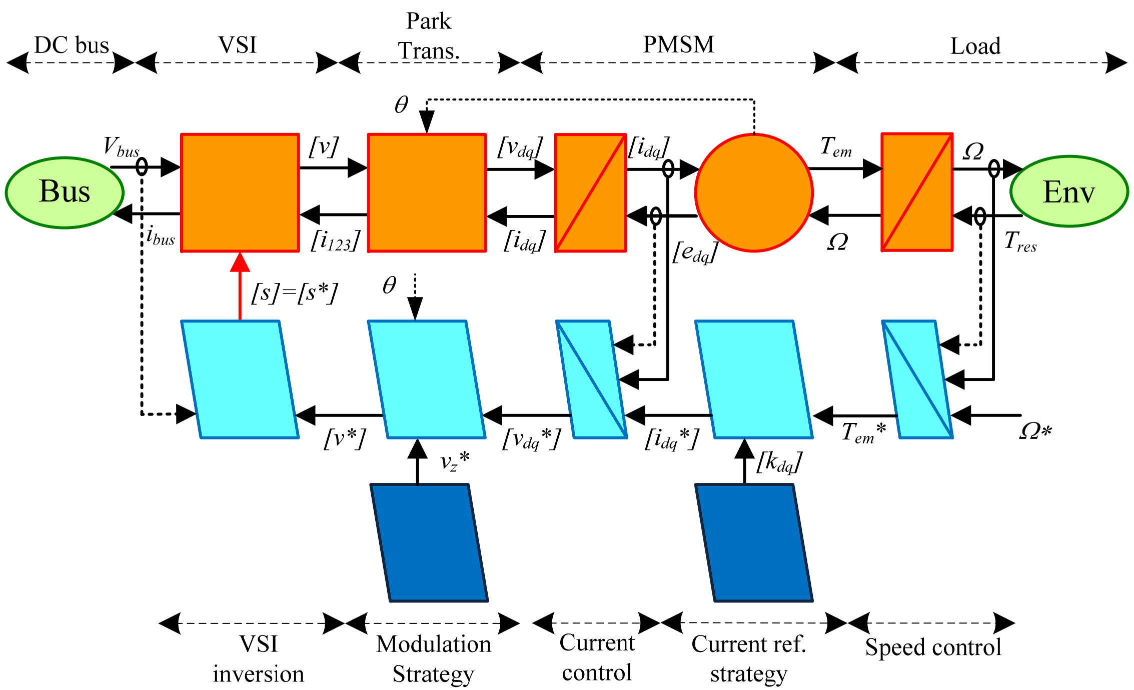
Park



EMR of a PMSM in the *dq* reference frame

$$[v_{dq}] = [R(\theta)][v_{\alpha\beta}] = [R(\theta)][C]^t \begin{bmatrix} u_{13} \\ u_{23} \end{bmatrix} \qquad [i_{dq}] = [R(\theta)][i_{\alpha\beta}] = [R(\theta)][C]^{-1} \begin{bmatrix} i_1 \\ i_2 \end{bmatrix}$$

$$[v_{dq}] = R_s [i_{dq}] + L_c \frac{d[i_{dq}]}{dt} + L_c \Omega \begin{bmatrix} 0 & -1 \\ 1 & 0 \end{bmatrix} [i_{dq}] + [e_{dq}]$$



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From EMR and IBC to Simulink…

Questions: Using the Simulink file PMSM_dq_students

- Simulate the control system using the EMR
- Conclude

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Thanks for your attention

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