Tallinn University of Technology, May 2025

Estonian Doctoral School

“Inversion-based control”

……………..

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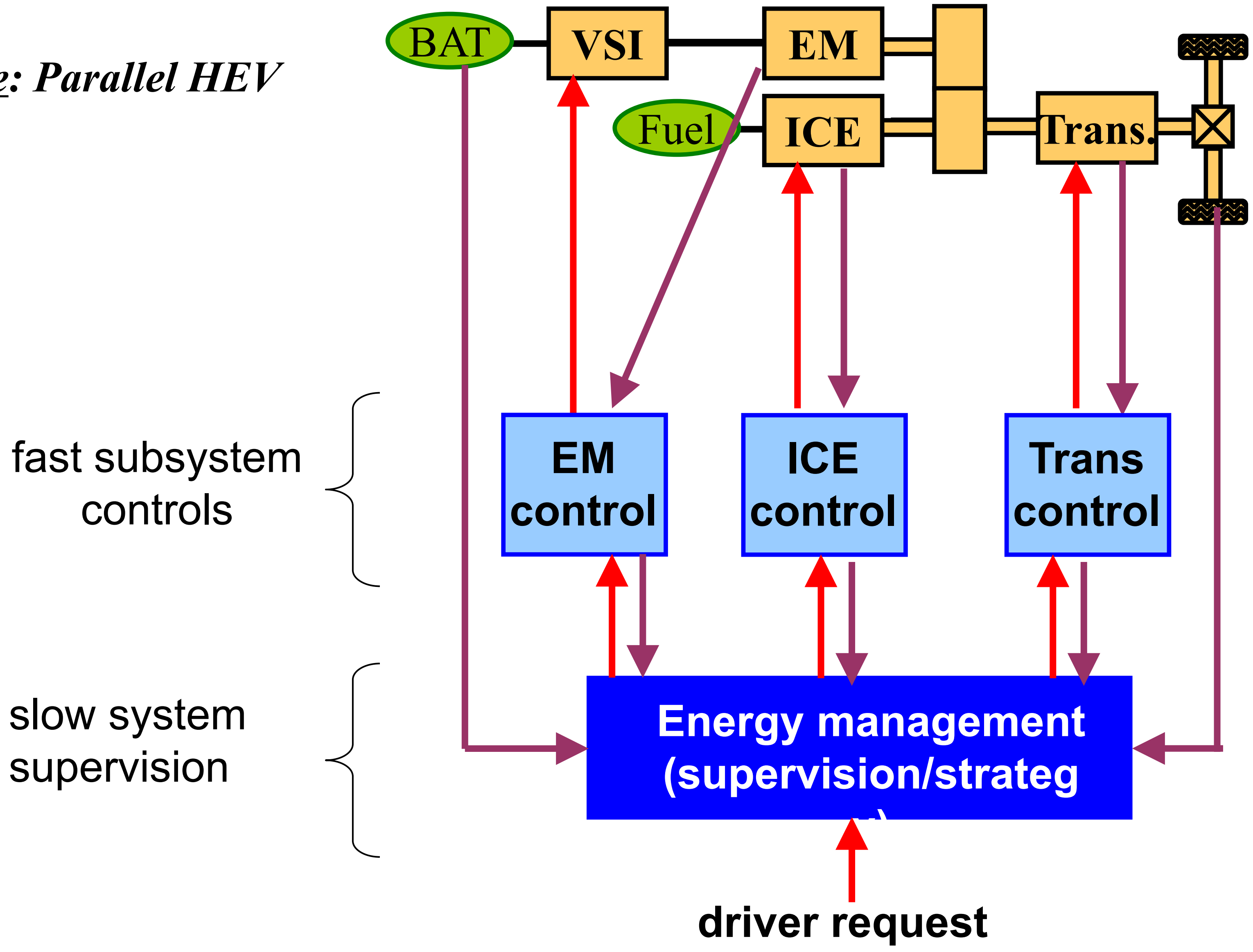
Based on the EMR summer school
and Master “Electrical Engineering for
sustainable development” course at Univ. Lille

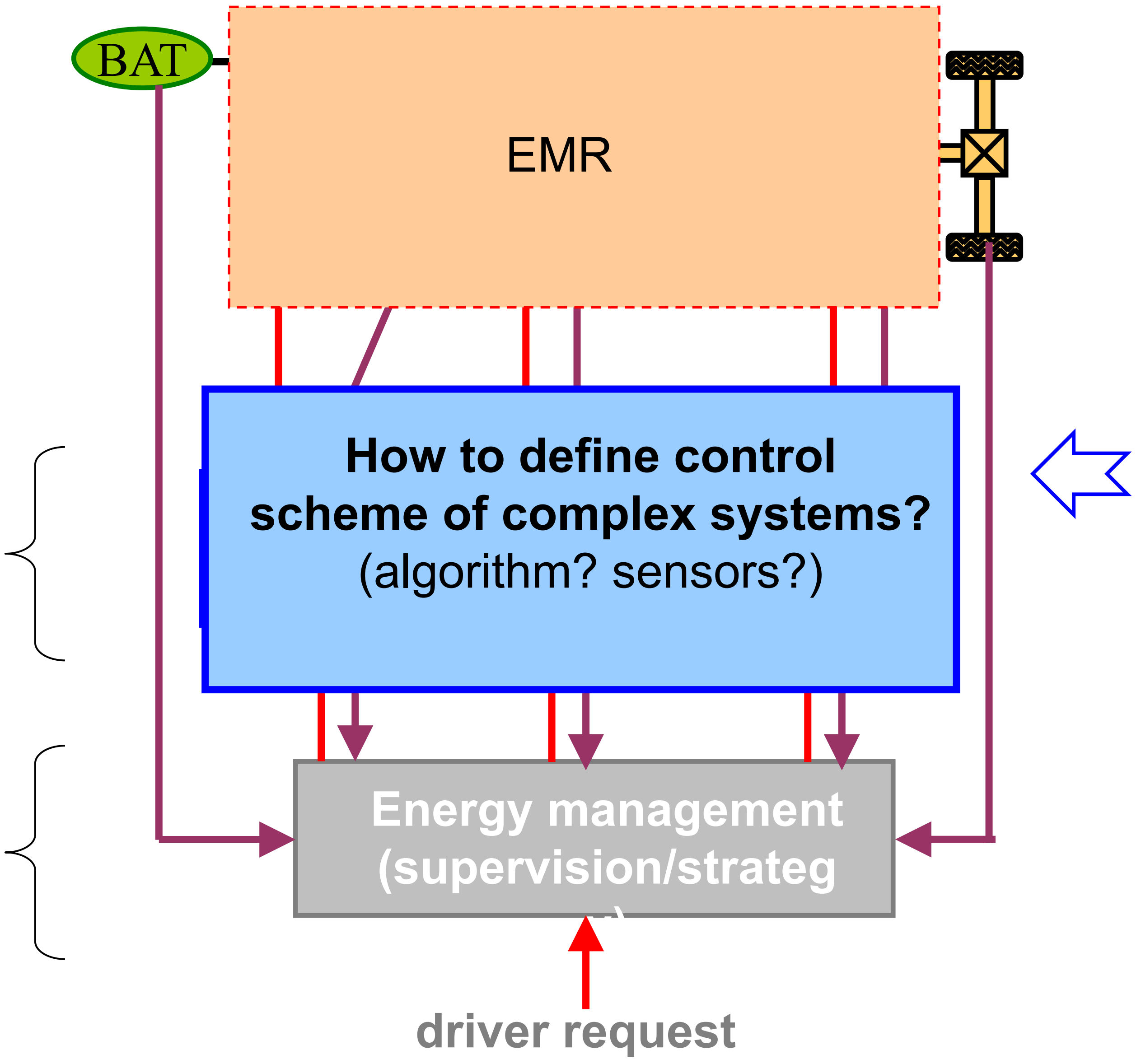
__Example__: Parallel HEV



***Example*: Parallel HEV**

fast **subsystem** controls

slow system supervision



Objective of this section

1 Control principle

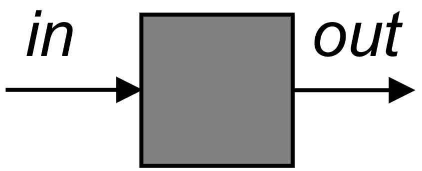
2 Inversion of EMR elements

3 Inversion-based control scheme

4 Example

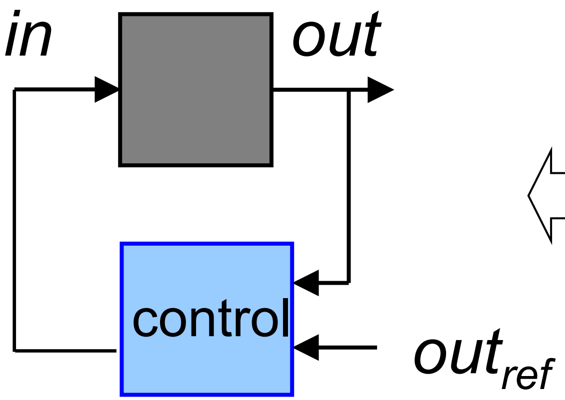
1. **Control principle**
2. Inversion of EMR elements
3. Inversion-based control scheme
4. Example

or “Black box” approach: no internal knowledge



identification test:
observation of *out(t)* from selected *in(t)*

Behavior model:
out(t) = f(t) *in(t)*



closed-loop control of *out*:
for uncertainty compensations

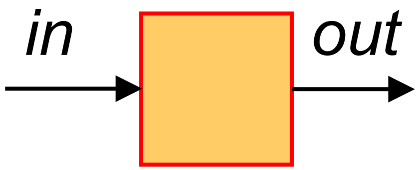
Limitations:
- limited validity range of the model
- risk of physical “mistake”
- non-optimal management of internal energy

multi-physical complex **energetic** systems?

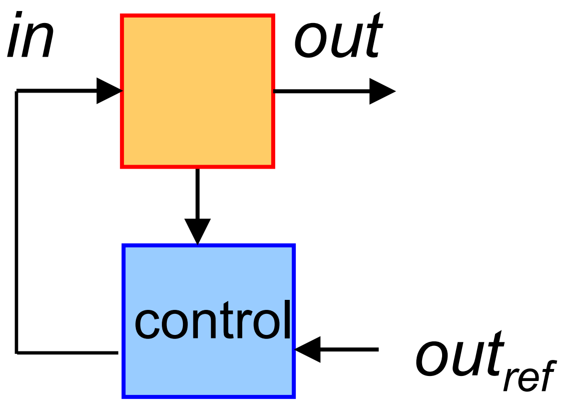
or “White box” approach: prior internal knowledge

Physical laws of
system components

Knowledge model:
out(t) = f(t) *in(t)*



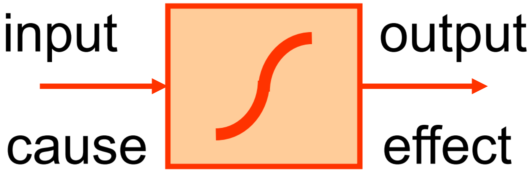
control = inversion of model:
(closed loop = an inversion way)



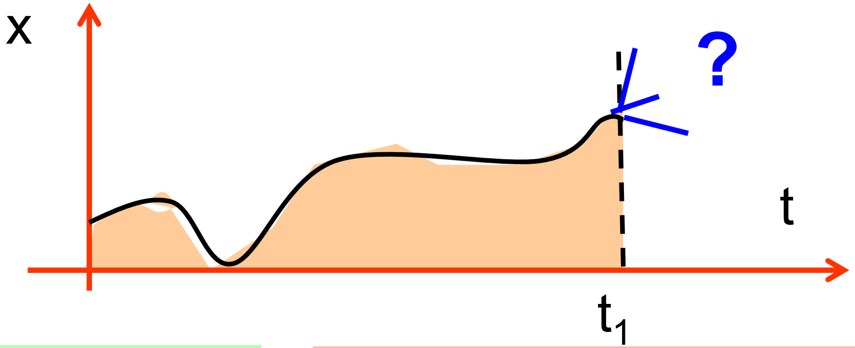
Limitations:
- physical knowledge of each subsystem
- not all functions are invertible

multi-physical complex
energetic systems?

Principle of causality
i.e. output is always delayed from input
i.e. output is an integral function of input



CONTROL =
real-time process management



$\int x\,dt$ ⇨ area

⇩

knowledge of past evolution

OK in real-time

slope ⇦ $\dfrac{dx}{dt}$

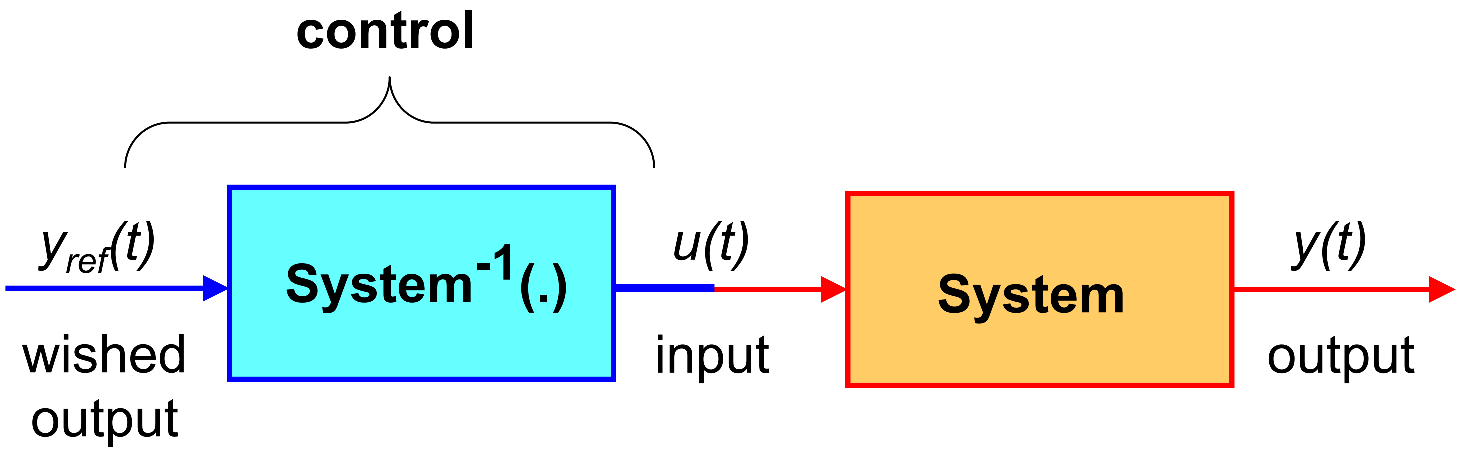
⇩

knowledge of future evolution

impossible in real-time

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

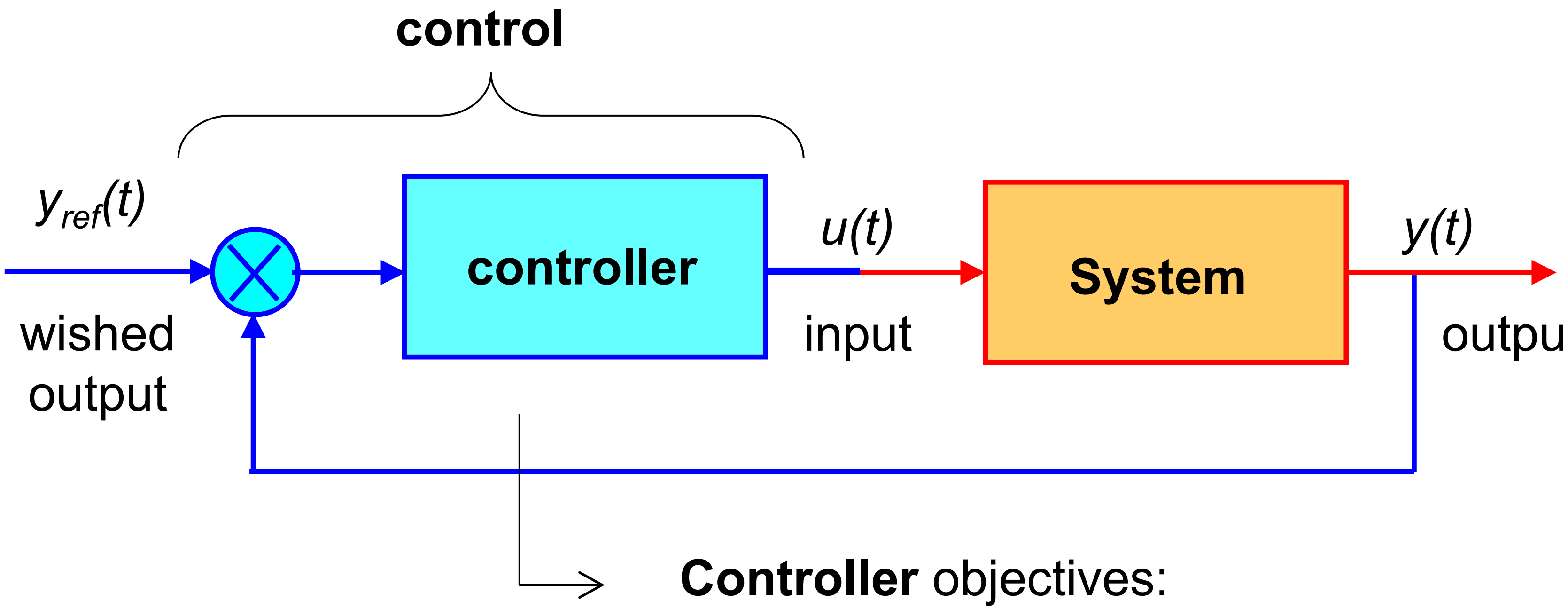
… if we can implement a good approximation of the system's inverse.



Limitations:
- the model is not always invertible,
- the model is well-defined or too complex,
- the system parameter are varying
- some unknown disturbance impact the system

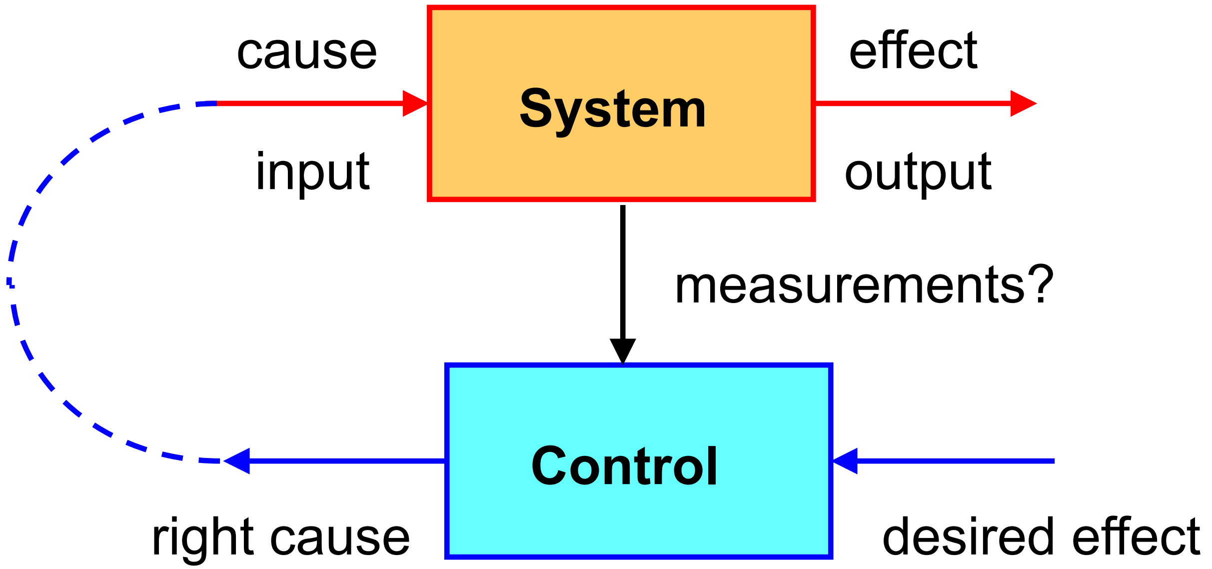
[Sicard 09]

objective:
- solve problems of open loop control



Controller objectives:
- tracking of reference changes
- rejection of disturbances and uncertainties

[Hautier 96]



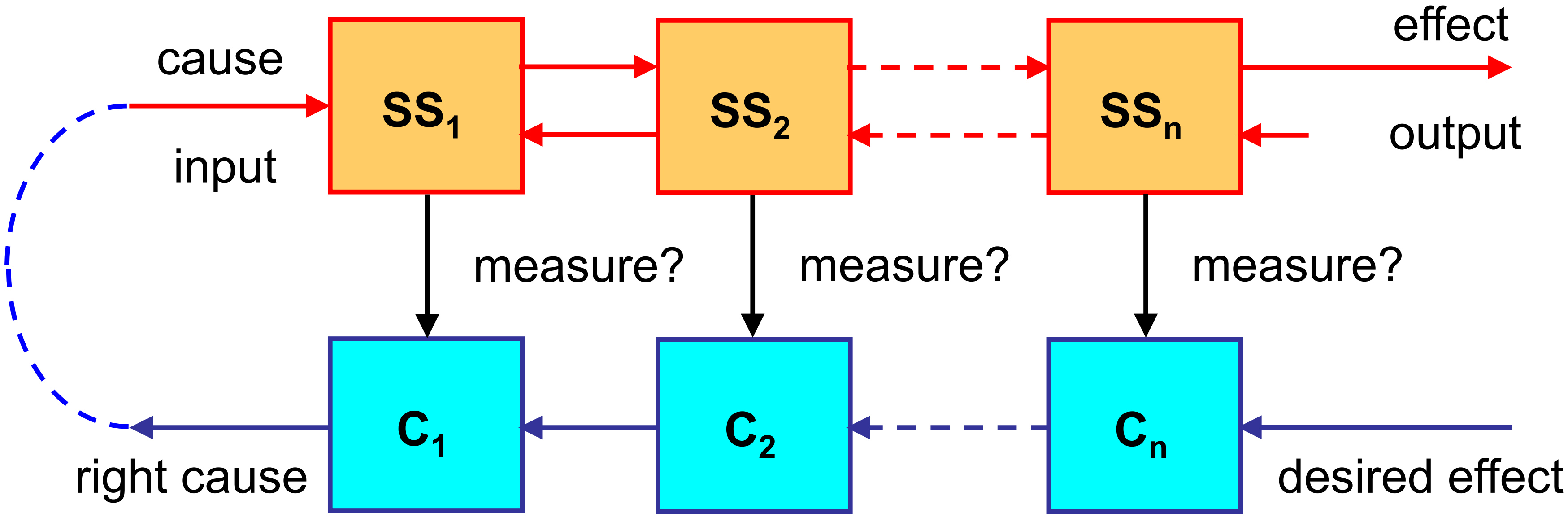
control = inversion of the causal path

1. Which kind of algorithm? (how many controllers)
2. Which variables to measure?
3. How to tune controllers?
4. How to implement the control?

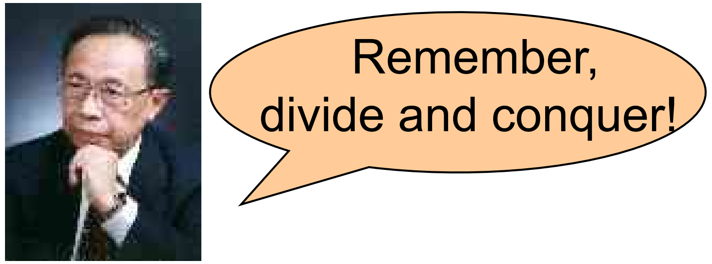
1–2 → **Inversion-based methodology**

3 → automatic control

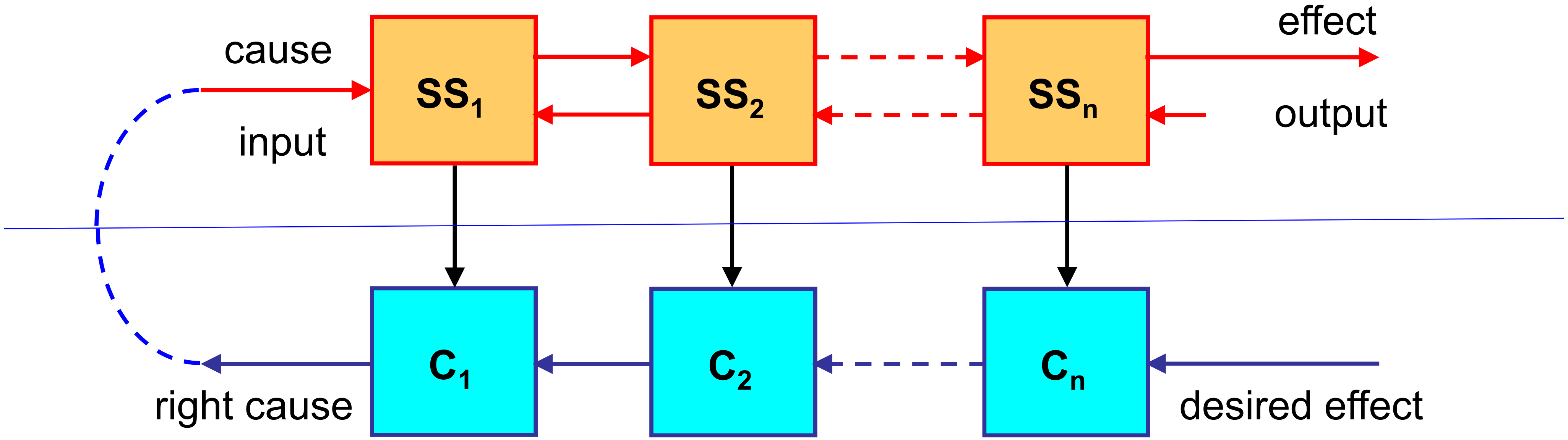
4 → industrial electronics



EMR = system decomposition in basic energetic subsystems (SSs)



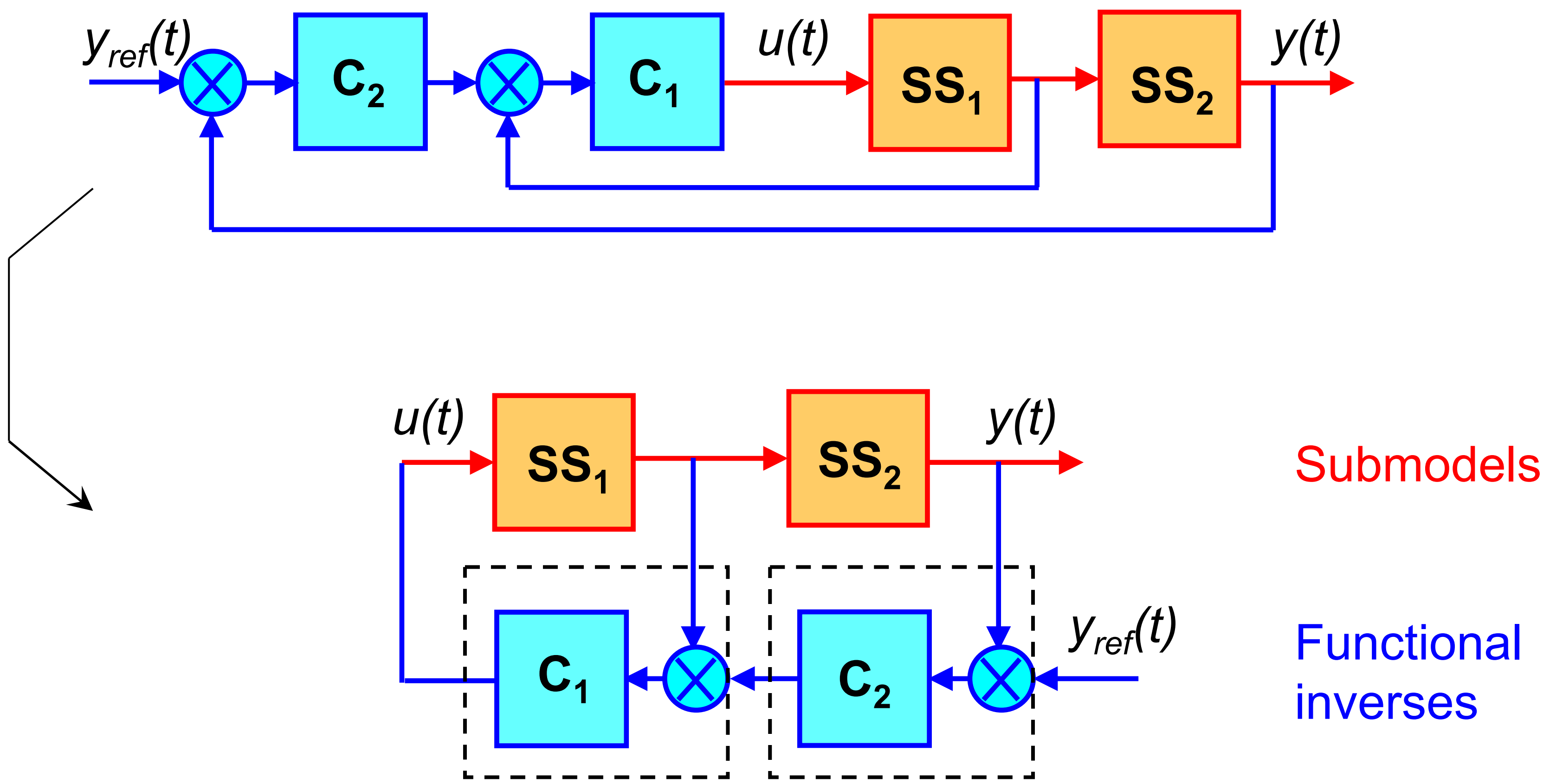
Inversion-based control: systematic inversion of each subsystems using open-loop or closed-loop control

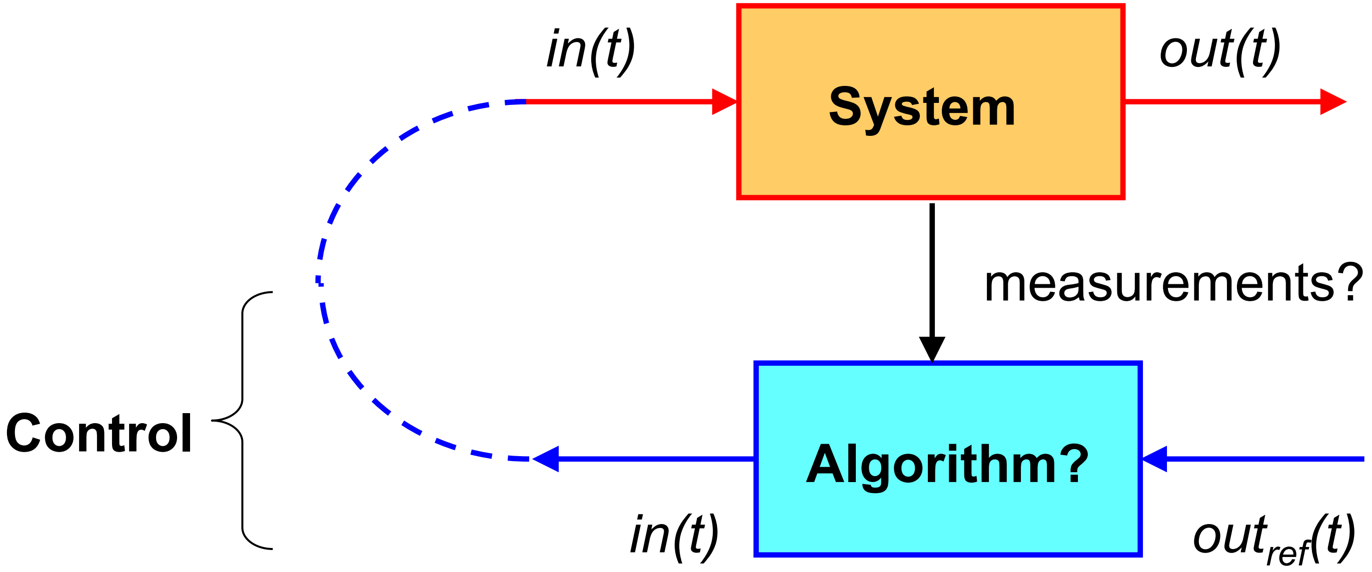


The control scheme is developed as a mirror of the model

[Hautier 2004] [Bouscayrol 2012]

Well-known cascaded control loops can be described in the same may





There are **3 basic inversion categories**:

1. Single-input time independent relationships (incl. conversion elements)
2. Multiple-input time independent relationships (incl. coupled conversion elements)
3. Single-input causal relationships (accumulation elements)

Other inversion schemes can be deduced from these basic inversions.

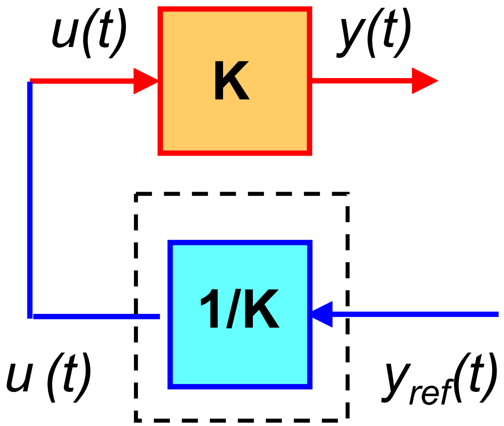
[Bouscayrol 12]

1. Inversion of mono-input rigid relation

Output depends on a unique inputs without delay

Example:

$$y(t) = K\,u(t)$$

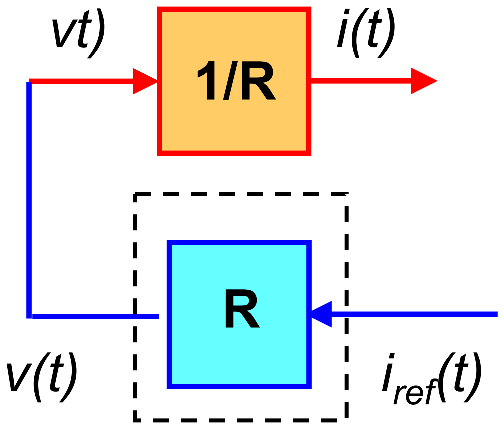


direct inversion

$$u(t) = \frac{1}{K}\,y_{ref}(t)$$

Example: Resistance

$$i(t) = \frac{1}{R}\,v(t)$$



direct inversion

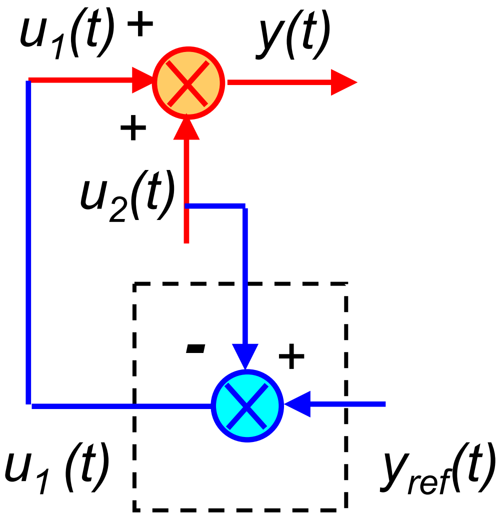
$$v(t) = R\,i_{ref}(t)$$

1. no measurement
2. no controller
(open-loop control)

<u>Assumption</u>: *K* well-know and constant

Output depends on several inputs
without delay

Example:



$$y(t) = u_1(t) + u_2(t)$$

u_1 is chosen to act on the output y

⇨ u_2 becomes a **disturbance** input

direct inversion

$$u_1(t) = y_{ref}(t) - u_{2meas}(t)$$

1. measurement of the disturbance input
2. no controller
(open-loop control)

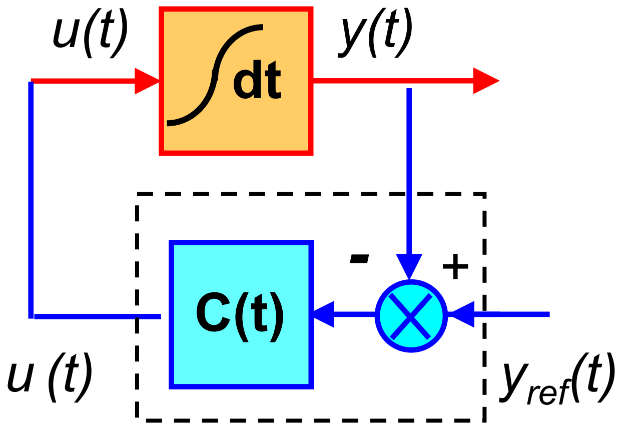
Assumption: u_2 well-know and can be measured

3. Inversion of mono-input causal relation

output depends on a single input and time (delay) $\Rightarrow$ causality principle

Example:

$$y(t) = \int u(t)\mathrm{dt}$$



direct inversion

$$\cancel{u(t) = \frac{d}{dt} y_{ref}(t)}$$

not possible in real-time

indirect inversion

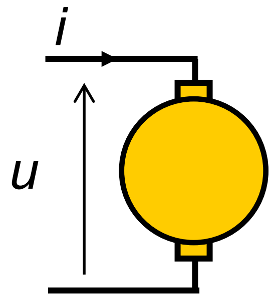
$$u(t) = C(t)\left[y_{ref}(t) - y_{meas}(t)\right]$$

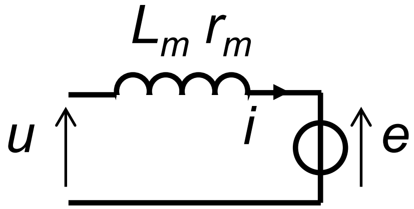
closed loop controller

1. measurement of output
2. a controller is required
(closed-loop control)

Other I/O relations:

Decomposition in elementary relations





$$L_m \frac{di}{dt} = u - e - r_m i$$

multi-input causal relationship

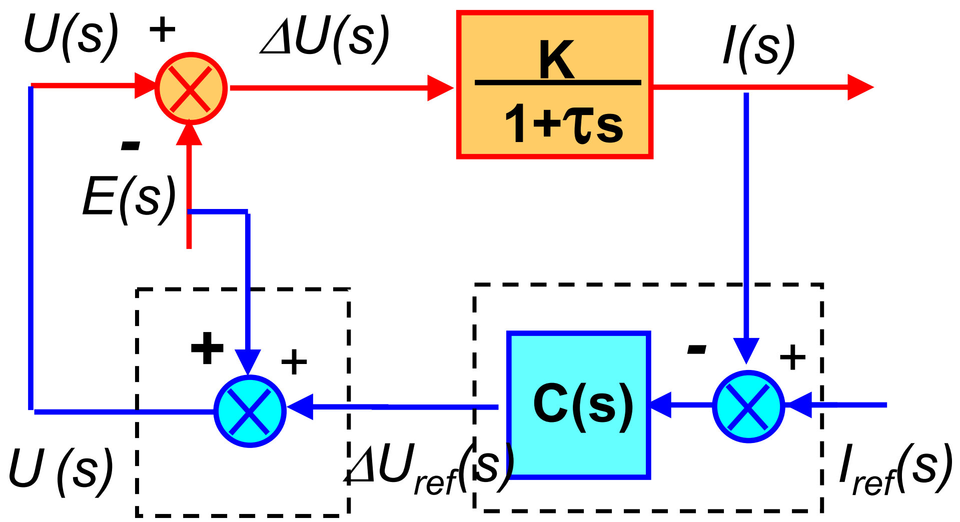
decomposition

$$\Delta u = u - e$$

direct inversion

$$L_m \frac{di}{dt} = \Delta u - r_m i$$

closed-loop



divide and conquer!

Prof. C.C. Chan

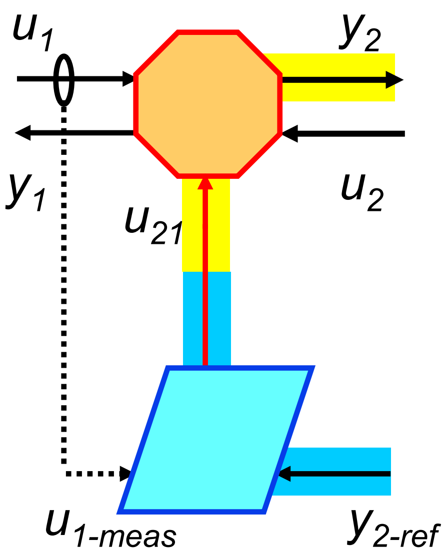
1 Control principle

2 Inversion of EMR elements

3 Inversion-based control scheme

4 Example

Conversion element: no delay



$y_2 = f(u_1, u_{21})$

Modelling equation

↓

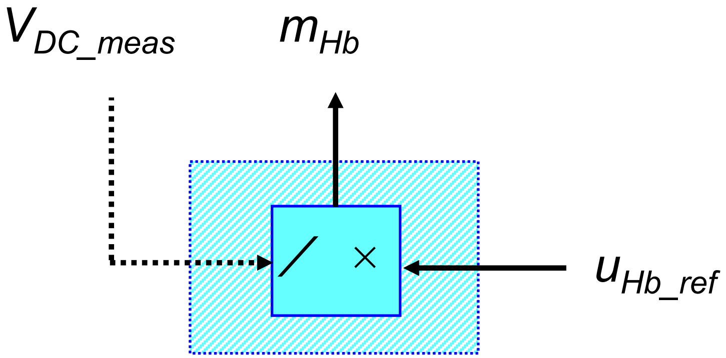
Control equation
(inverse equation)

Ex : H-bridge chopper

$$\begin{cases} u_{Hb} = m_{Hb} V_{DC} \\ i_{Hb} = m_{Hb}\, i_{dcm} \end{cases}$$

↓

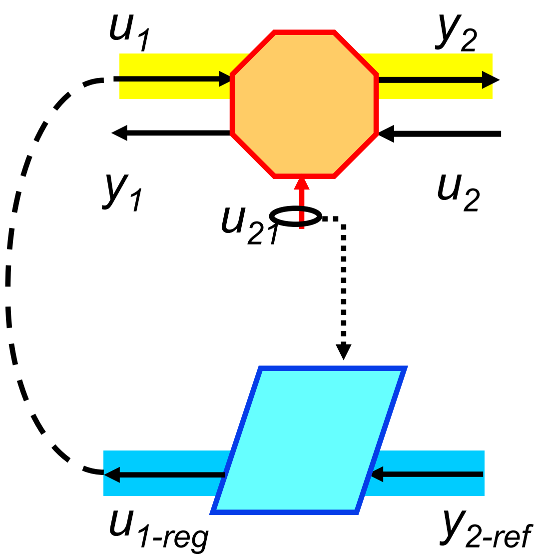
$m_{Hb} = u_{Hb\_ref} / V_{DC\_meas}$



acting ing on u_{21} ⇨ u_1 disturbance

1. Which measure? only the disturbance (not the output)
2. Which algorithm? direct inversion (no need of control loop)

Conversion element without tuning input



$y_2 = f(u_1, u_{21})$

<u>Ex</u> : speed transmission

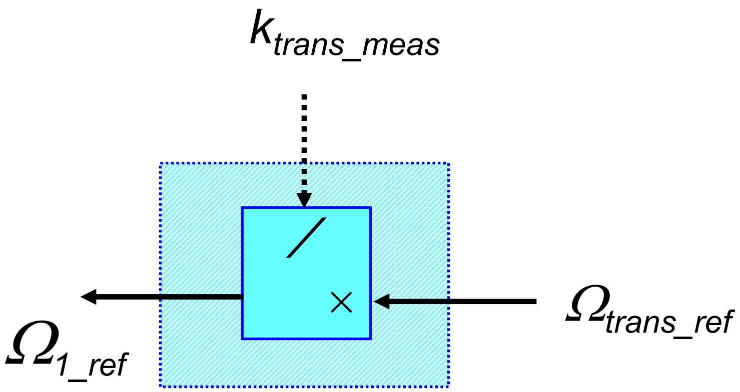
Modelling equation

$$\begin{cases} \Omega_{trans} = k_{trans}\, \Omega_1 \\ T_{trans} = k_{trans}\, T_{load} \end{cases}$$

↓

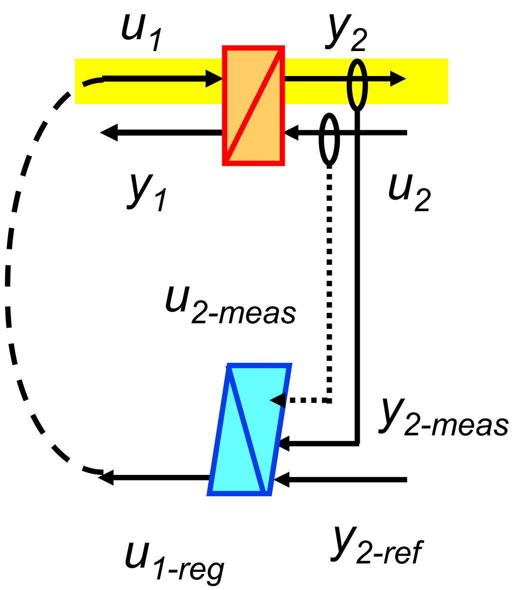
Control equation
(inverse equation)

$$\Omega_{1\_ref} = \Omega_{trans\_ref} / k_{trans\_meas}$$



1. Which measure? none (not the output)
2. Which algorithm? Direct inversion (no need of control loop)

Accumulation element: delay



$y_2 = f(u_1, u_2)$

f is in integral form

⇩

~~Direct inversion is in derivative form~~

⇩

Approximate inversion by closed loop control

Ex : rotating shaft

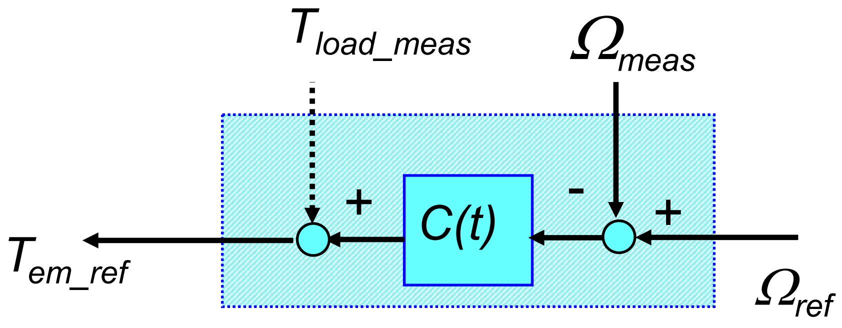
Modelling equation

$$J\frac{d}{dt}\Omega + f\Omega = T_{em} - T_{load}$$

↓

Control equation (closed-loop)

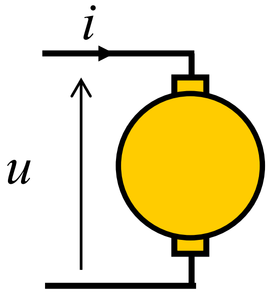
$$T_{em\_ref} = C(t)(\Omega_{ref} - \Omega_{meas}) + T_{load\_meas}$$

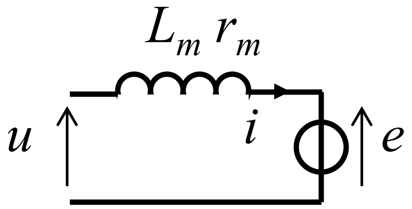


C(t) controller (e.g. PI)

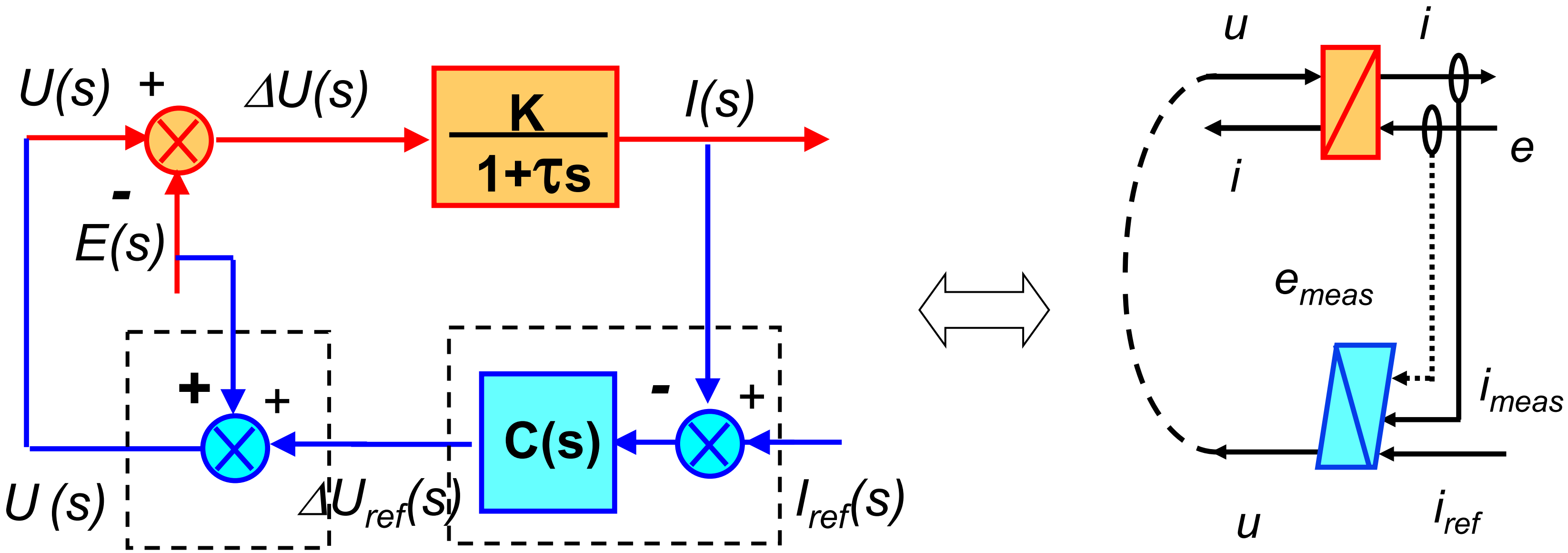
1. Which measure? output and disturbance
2. Which algorithm? indirect inversion (controller to define)

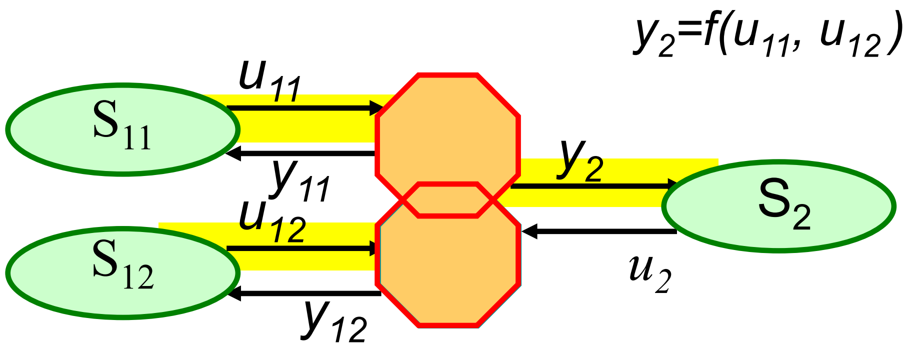
Example of a DC machine





$$L_m \frac{di}{dt} = u - e - r_m i$$

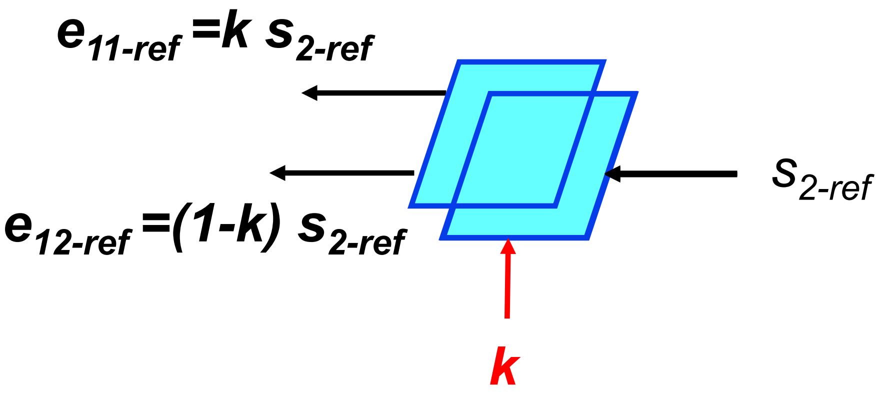




2 inputs to impose 1 output

⇩

non-bijective inversion
(different solutions)



Inversion criteria
Distribute the reference signals

$k=1/2$ equi-distribution

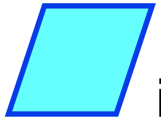
1. Which measure? none
2. Which algorithm? direct inversion (but criteria to define)

Other solutions
(see [Bouscayrol 12])

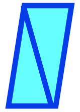
Summary of the inversions of EMR elements

Legend

Control = light blue Parallelograms with dark blue contour



direct inversion



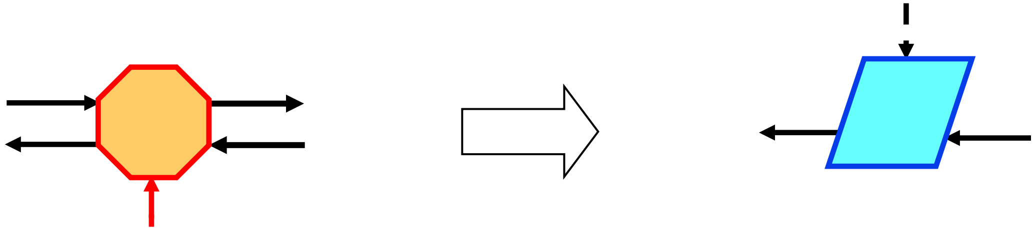
indirect inversion

sensor

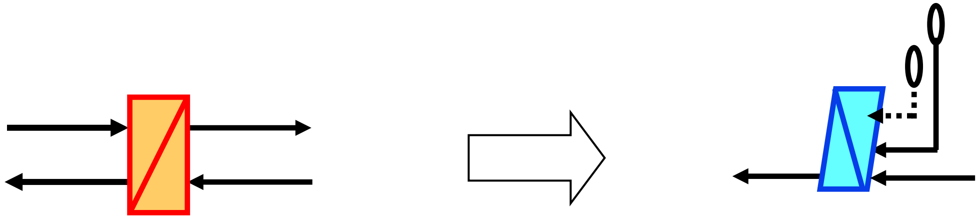
mandatory link

facultative link

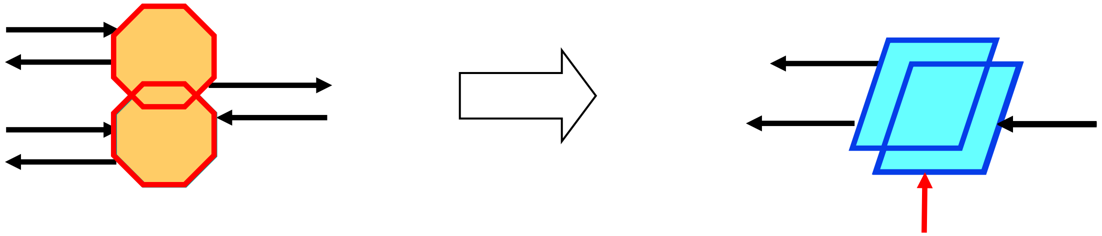
conversion element → direct inversion + disturbance rejection



accumulation element → controller + disturbance rejection



coupling element → distribution criteria



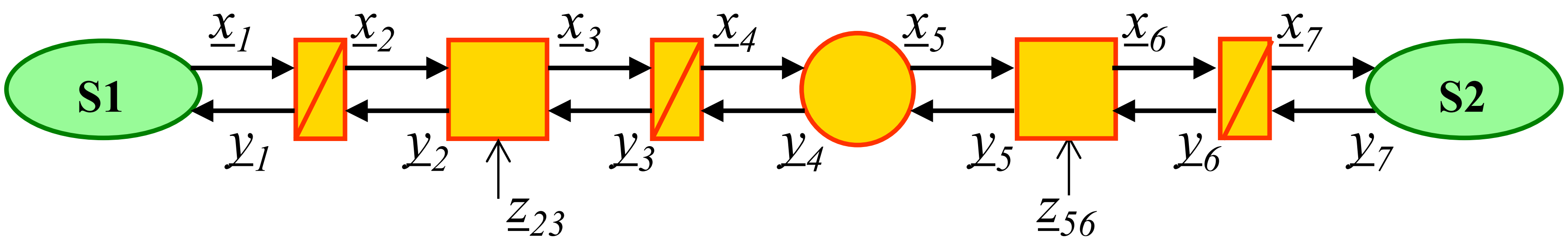
1 Control principle

2 Inversion of EMR elements

3 Inversion-based control scheme

4 Example

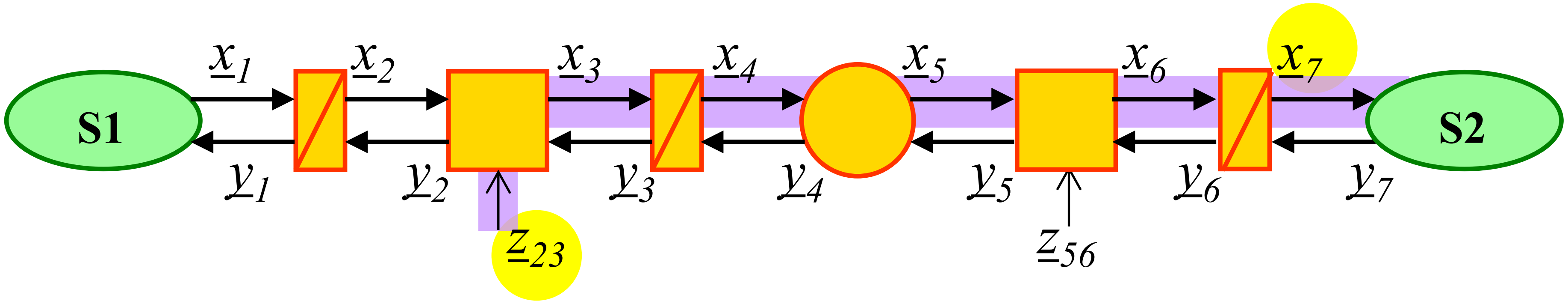
1. EMR of the system



EMR depends on:
- the study objective (limits between system and sources)
- the physical laws of subsystems (physical causality)
- the association of subsystems (systemic approach)

1. EMR of the system

2. Tuning path



The tuning path is:

- dependent on the technical requirements (chosen tuning input / output to control)

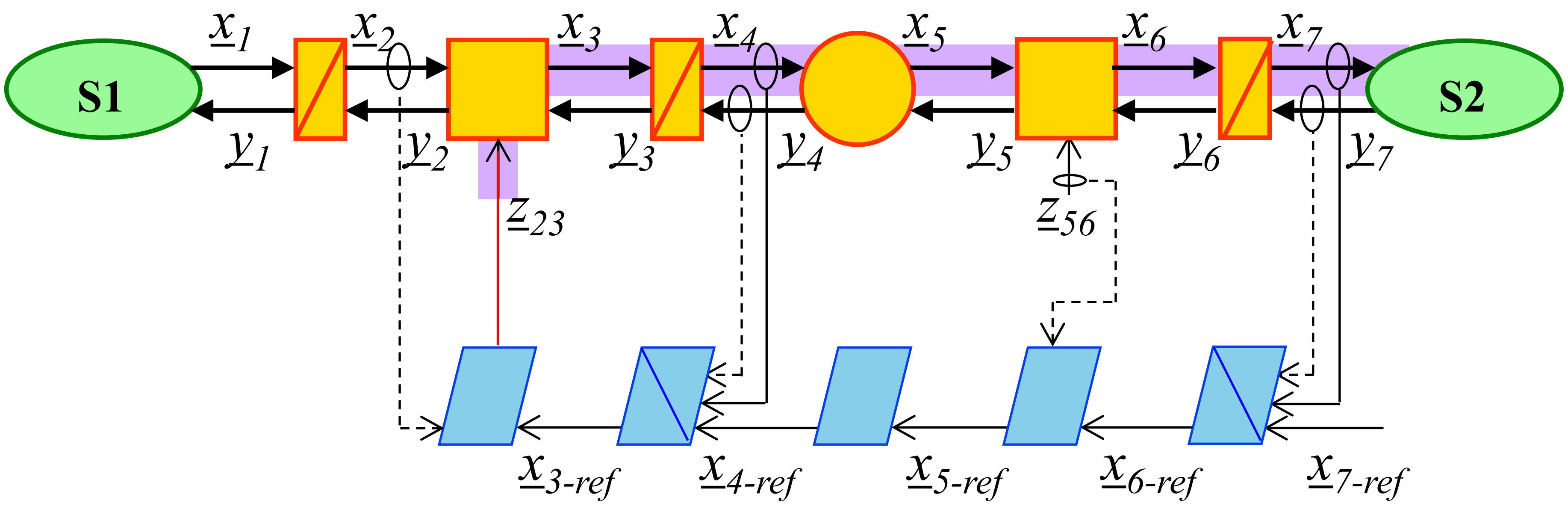
- **independent of the power flow direction**

1. EMR of the system

2. Tuning path

3. Inversion step-by-step

Strong assumption: all variables can be measured!



Maximal Control Structure (or scheme):
- maximum of sensors
- maximum of operations

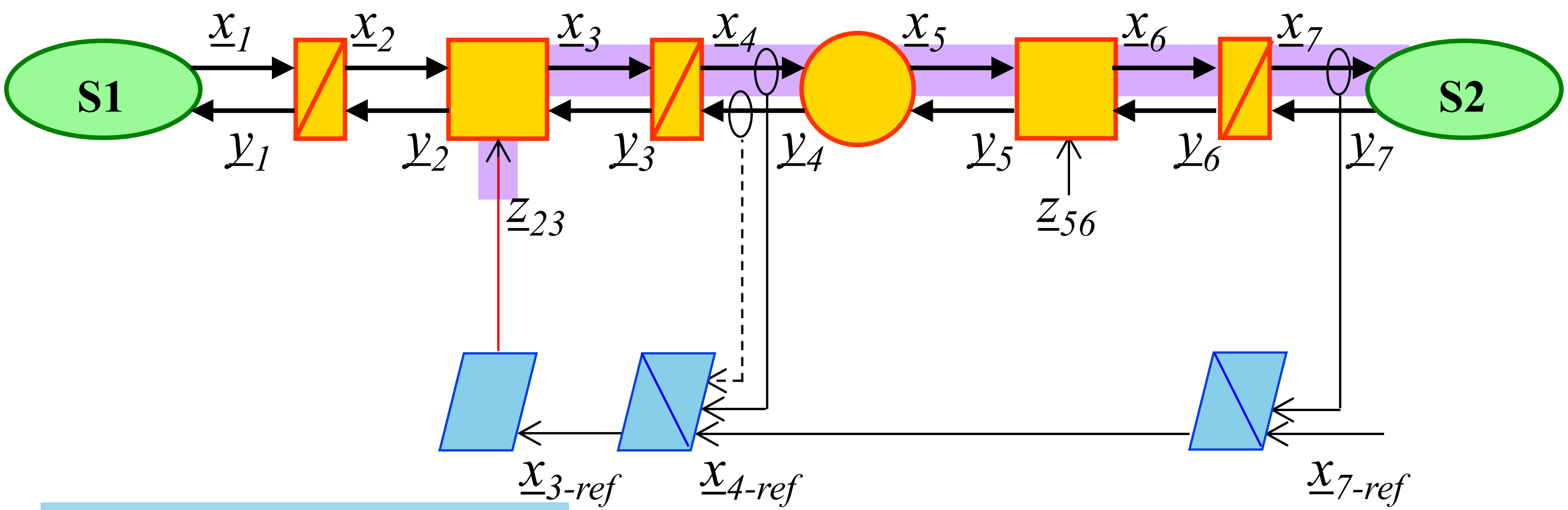
Example:
- 7 sensors
- 2 closed-loop controllers

1. EMR of the system

2. Tuning path

3. Inversion step-by-step

Strong assumption: all variables can be measured!



4. Simplification of control

Simplifications:

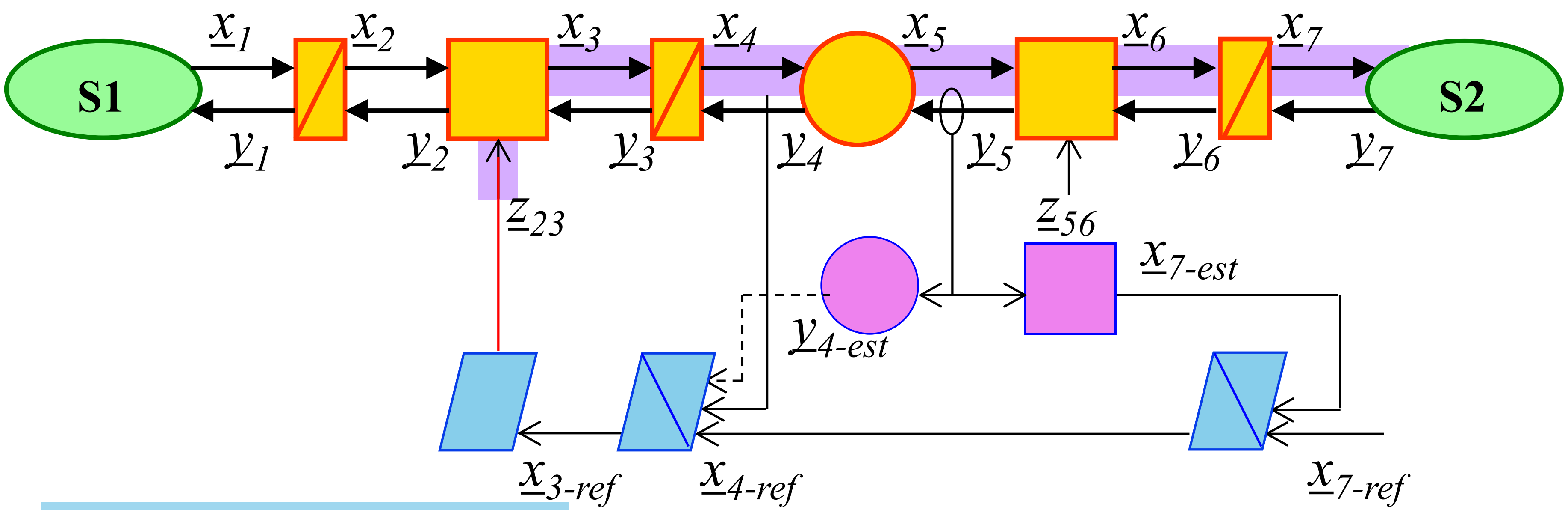
- non-consideration of disturbances ⇨ impact on the tuning and on the performances
- merging control blocks…

1. EMR of the system

2. Tuning path

3. Inversion step-by-step

Strong assumption: all variables can be measured!



4. Simplification of control

5. Estimation of non-measured variables

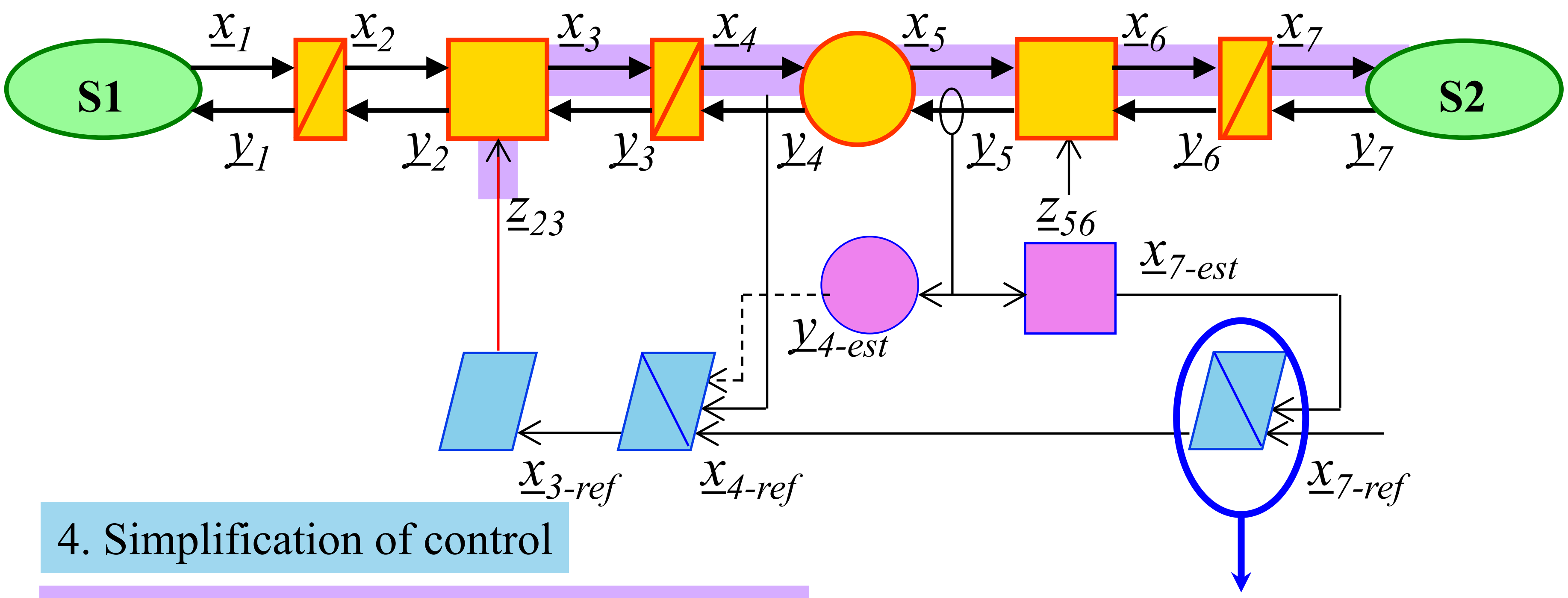
from measured variables

1. EMR of the system

2. Tuning path

3. Inversion step-by-step

Strong assumption: all variables can be measured!



4. Simplification of control

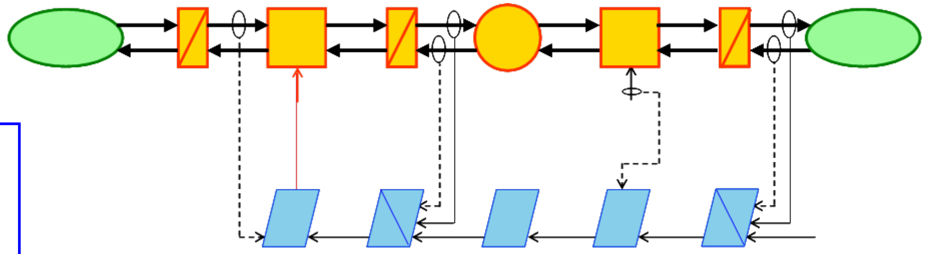
5. Estimation of non-measured variables

6. Tuning of controllers

PI / PID / fuzzy controller?

Calculation of parameters?

1. EMR of the system
2. Tuning path
3. Inversion step-by-step



Maximal Control Scheme
- mirror of the EMR (systematic)
- unique and theoretical solution

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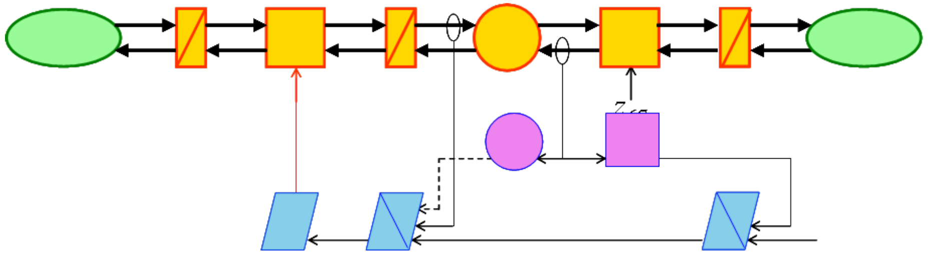
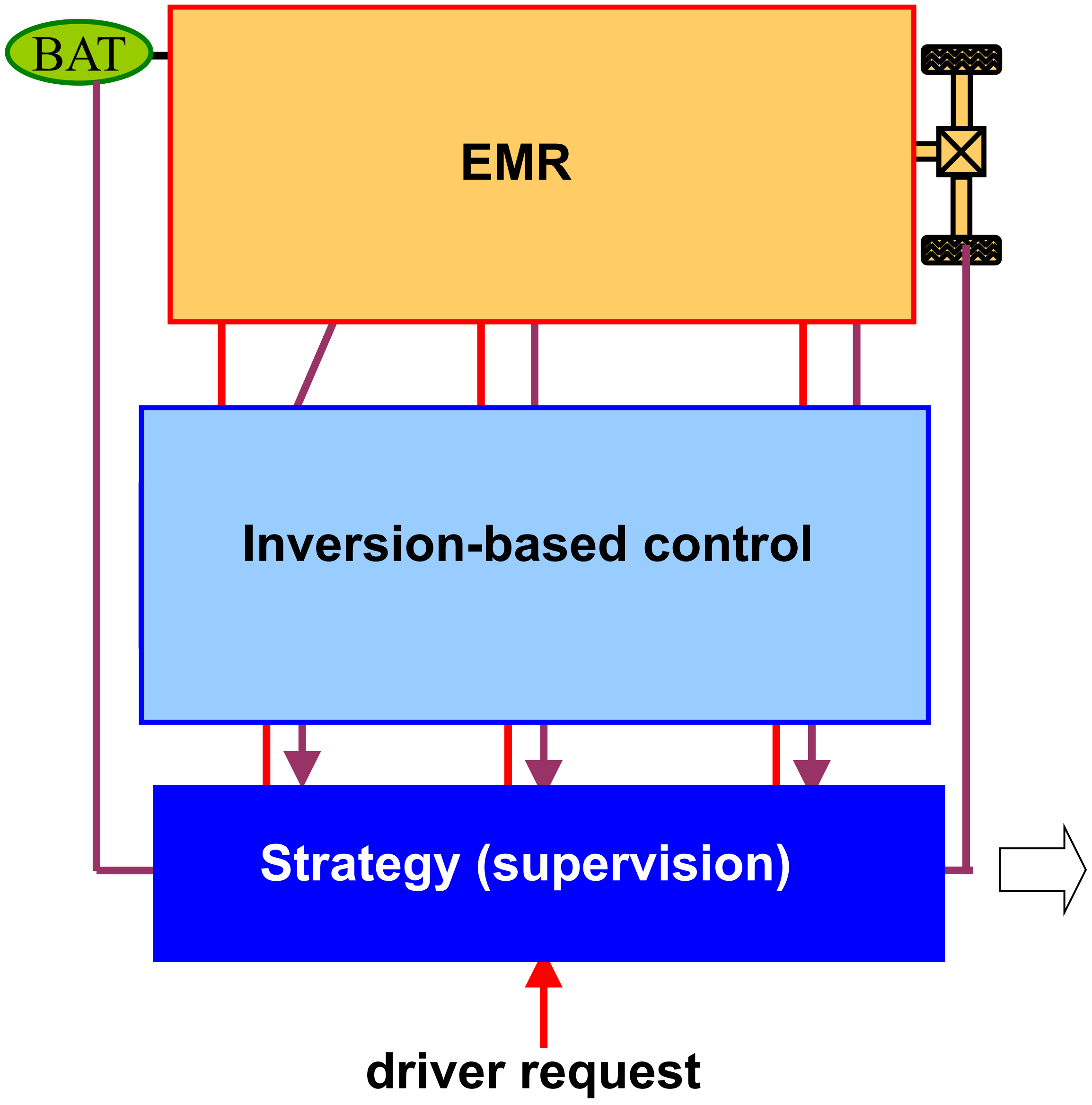
4. Simplification of control
5. Estimation of variables
6. Tuning of controllers



Practical Control Schemes
- several solutions (expertise)
- reduced performances

Parallel HEV



fast subsystem controls

slow system supervision

Definition of the reference (translation from user request)

Definition of the criteria (optimization or priority Management)

Slow dynamics

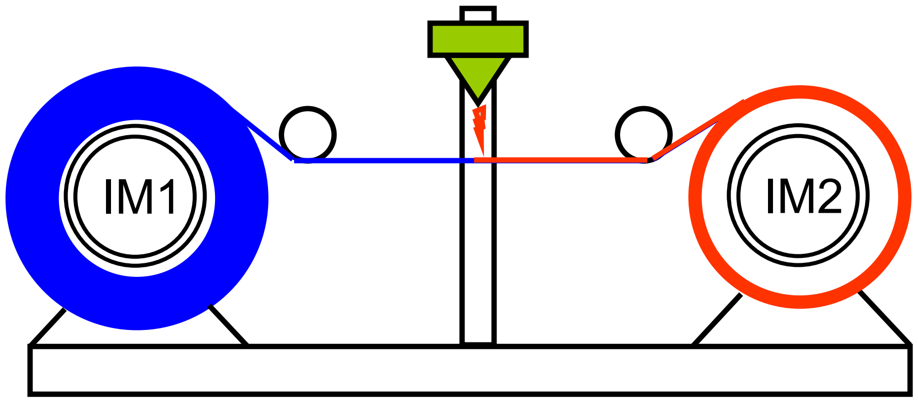
1 Control principle

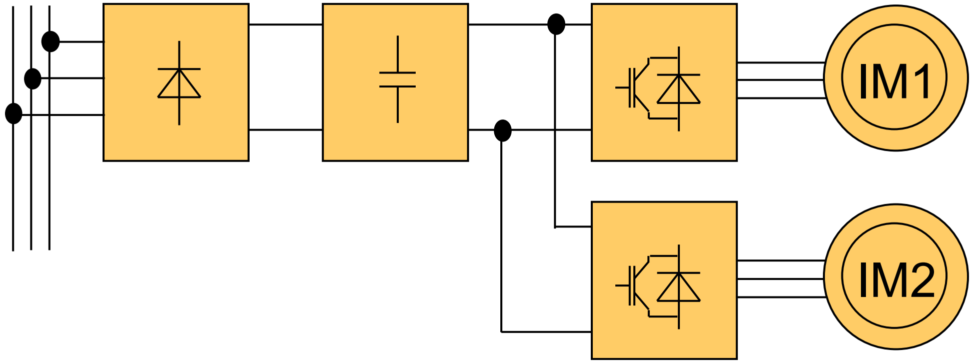
2 Inversion of EMR elements

3 Inversion-based control scheme

4 Example

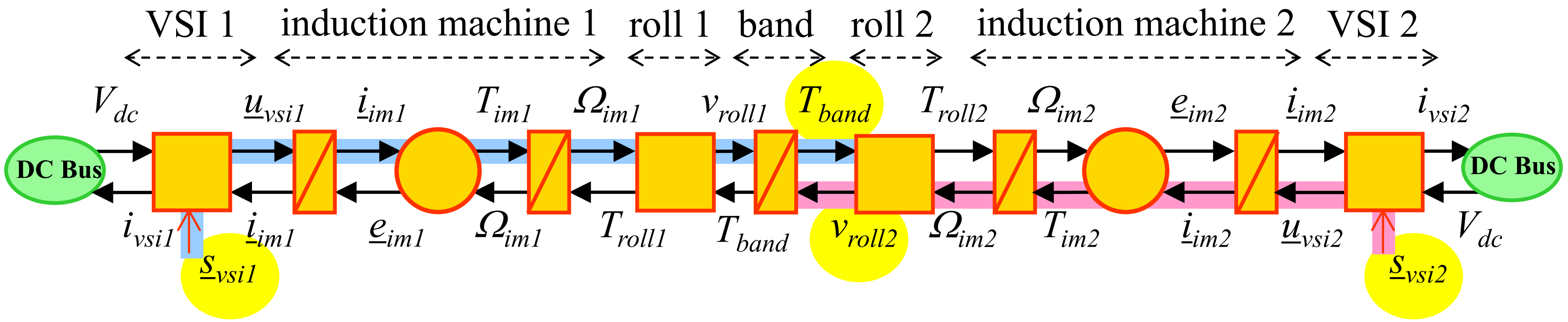
Paper processing
using 2 induction machines





Technical requirements:
- paper tension control for high quality of paper roll
- winding velocity control for high quality of processing

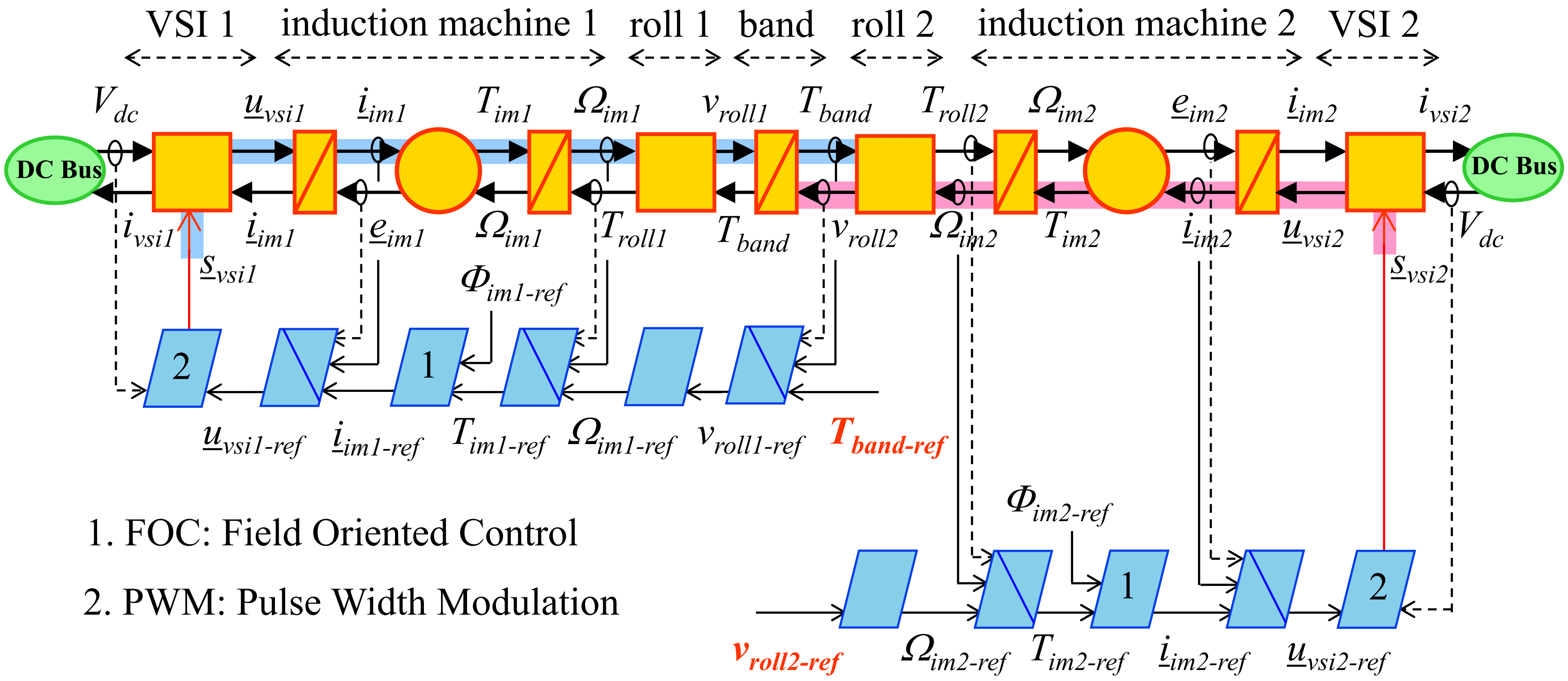
[Djani 06]



Step 1: develop the EMR of the system

Step 2a: identify all variables to be controlled (outputs) and control inputs

Step 2b: identify tuning paths from inputs to outputs, avoiding crossing the paths

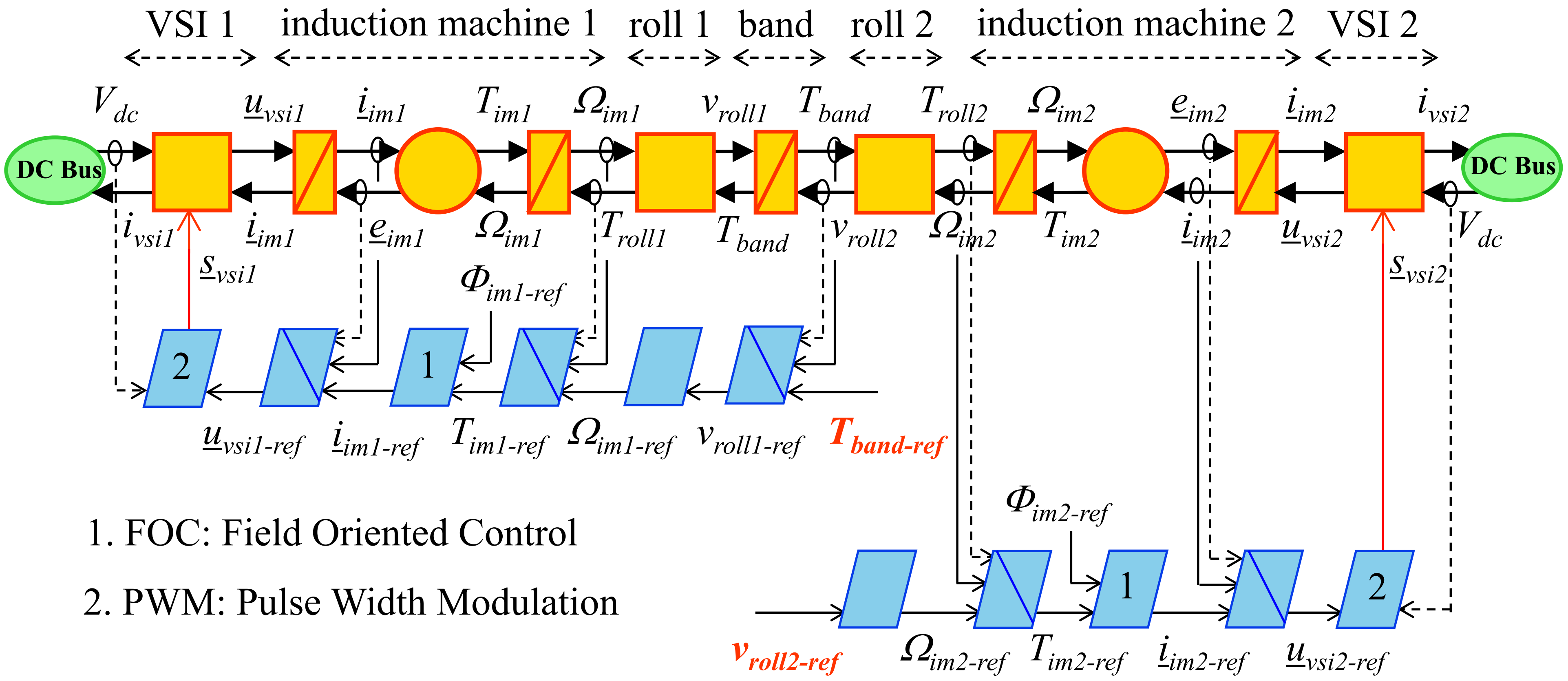


1. FOC: Field Oriented Control

2. PWM: Pulse Width Modulation

Step 3: invert each element of the tuning paths by applying inversion rules

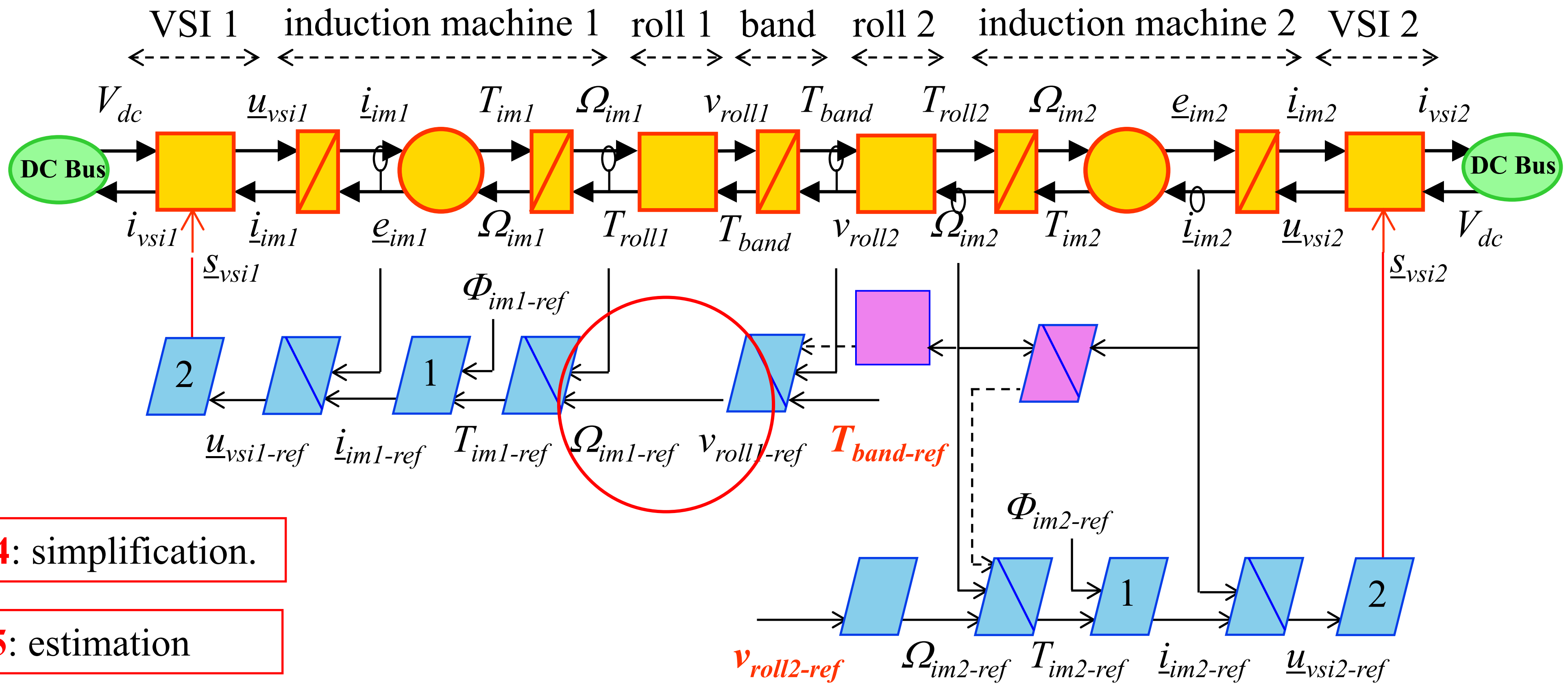
- assume that all the signals are measurable;
- compensate for all disturbances.



1. FOC: Field Oriented Control
2. PWM: Pulse Width Modulation

Maximal Control Structure

- 16 sensors (including 2 ac components for currents and voltages)
- 5 closed-loop controls (including 2 controllers of dimension 2 for currents)

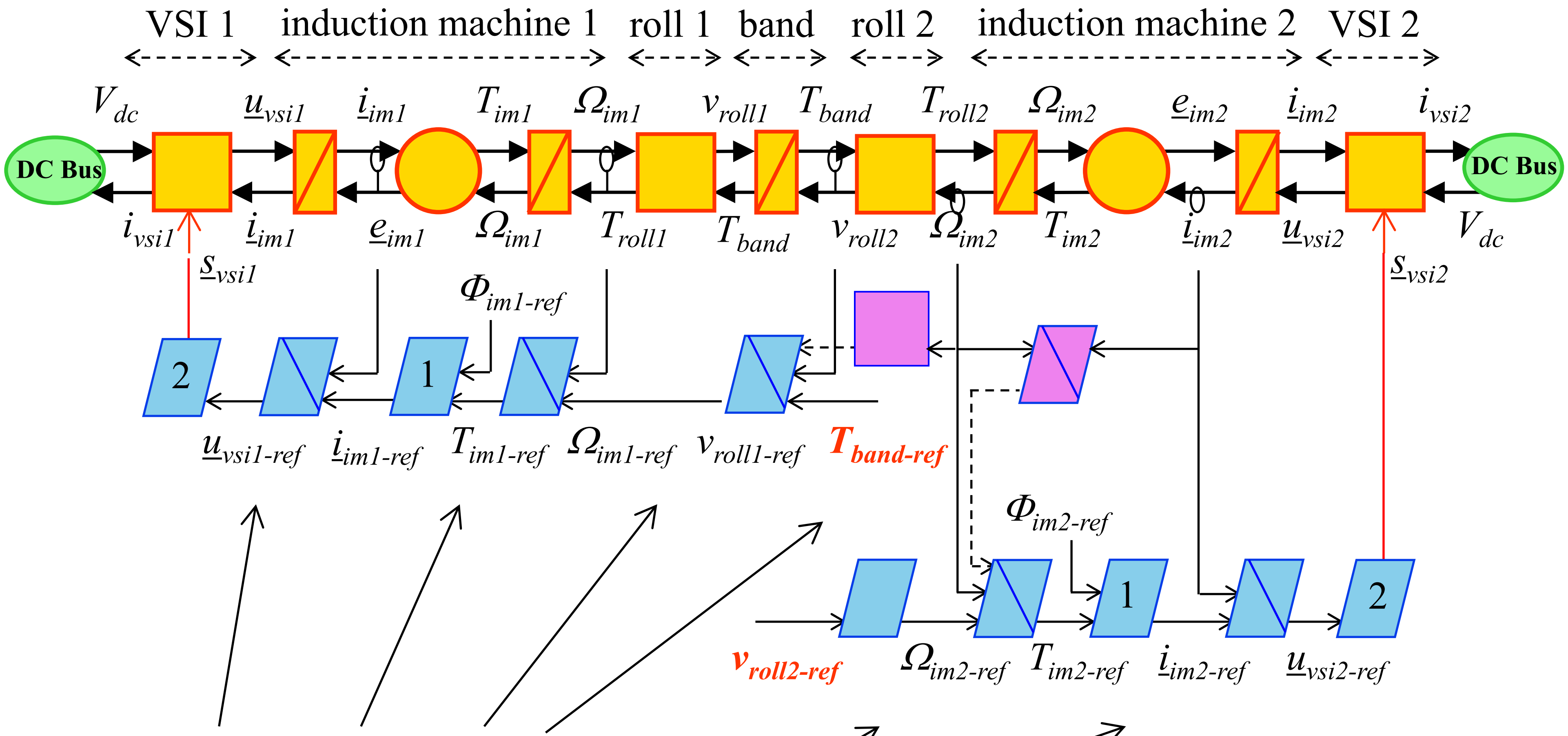


Step 4: simplification.

Step 5: estimation

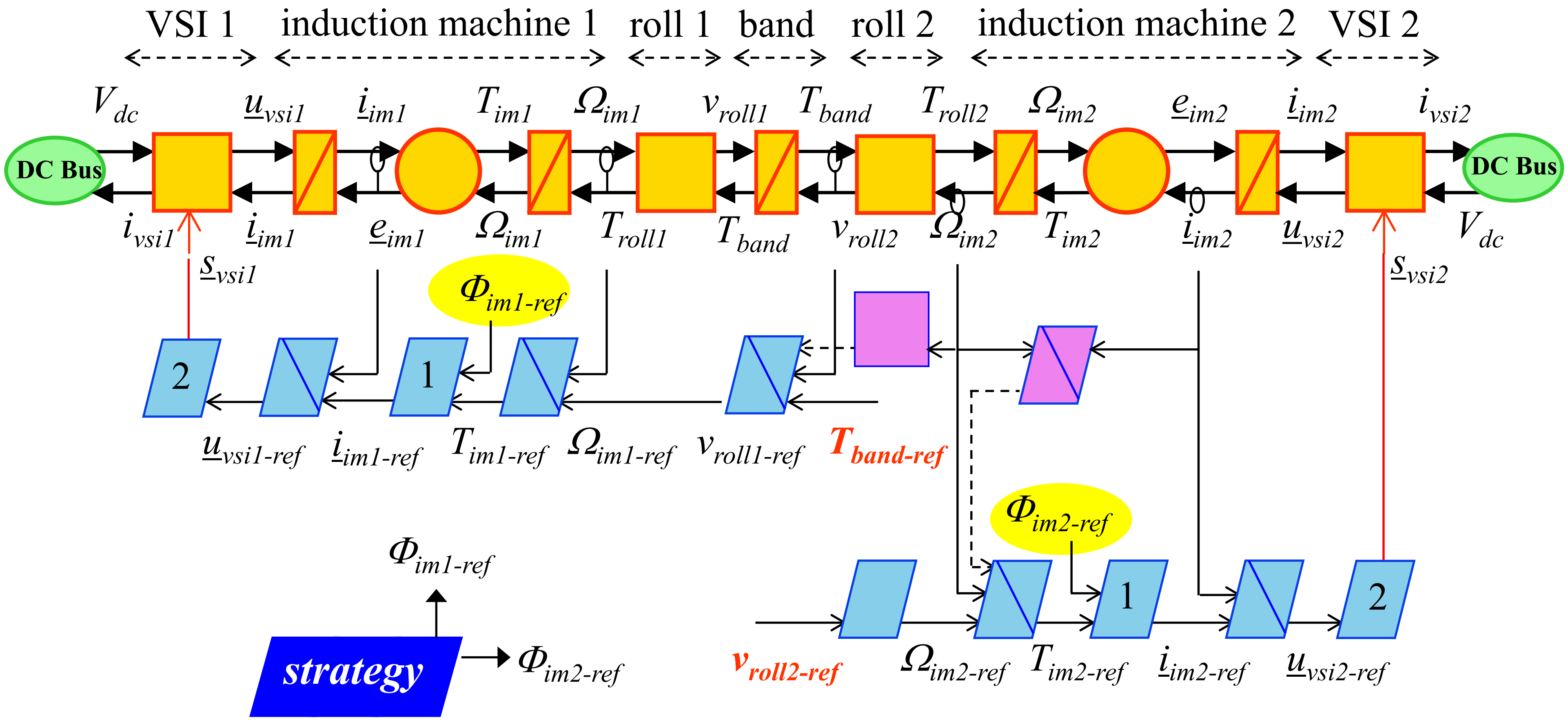
Practical Control Structure

- 6 sensors
- 5 closed-loop controls (including 2 controllers of dimension 2 for currents)



Step 6: choose and tune all controllers (dynamic decoupling), and estimators

PI controllers OK except



Step 7: Exploit degrees of freedom to implement advanced strategies
(e.g. MPTA – Maximal Torque per Ampere)

Conclusion

Inversion based control = inversion of EMR

systematic control organization

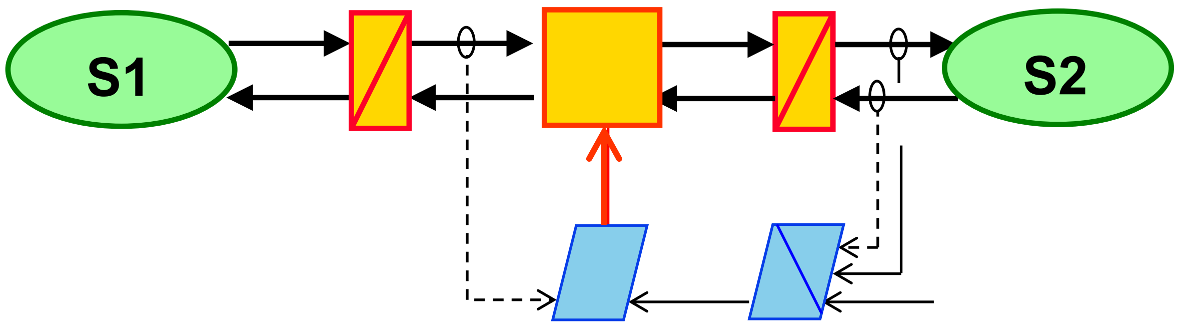
Inversion rules for control scheme

closed-loop control but also direct inversion

Different steps on the control scheme

From Maximal Control Scheme….

… to Practical Control Schemes….



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Thanks for your attention!

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