EMR'13
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Summer School EMR'13
"Energetic Macroscopic Representation"

Université Lille1
Sciences et Technologies

« INVERSION–BASED CONTROL »

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L2EP LILLE

- Outline -

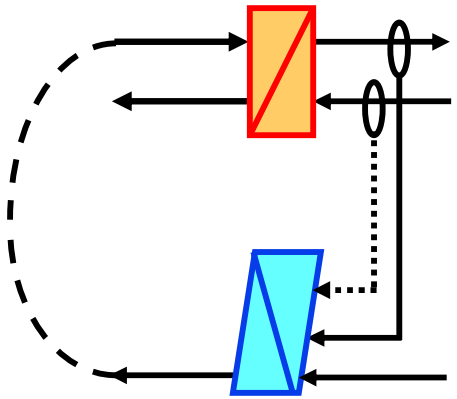
1. **Principle of model-based control**
   - Open-loop and closed-loop controls
   - Inversion-based control of complex systems

2. **Inversion of EMR elements**
   - Inversion 1: single-input time-independent relationship
   - Inversion 2: multiple-input time-independent relationship
   - Inversion 3: single-input causal relationship

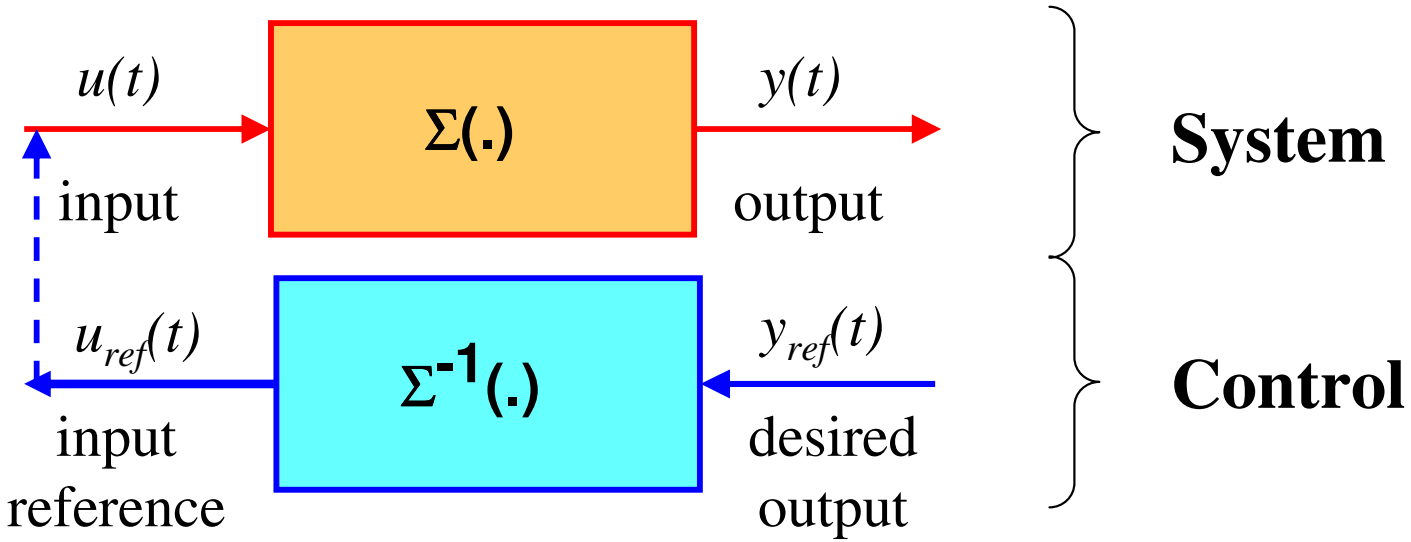
3. **Inversion-based control structures**
   - Inversion-based methodology
   - Maximum and practical control schemes

4. **Conclusion: towards energy management**

1. « Principle of model-based control »



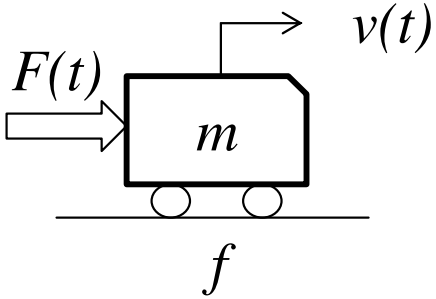
Controlling a system for output tracking can be interpreted as inverting the system

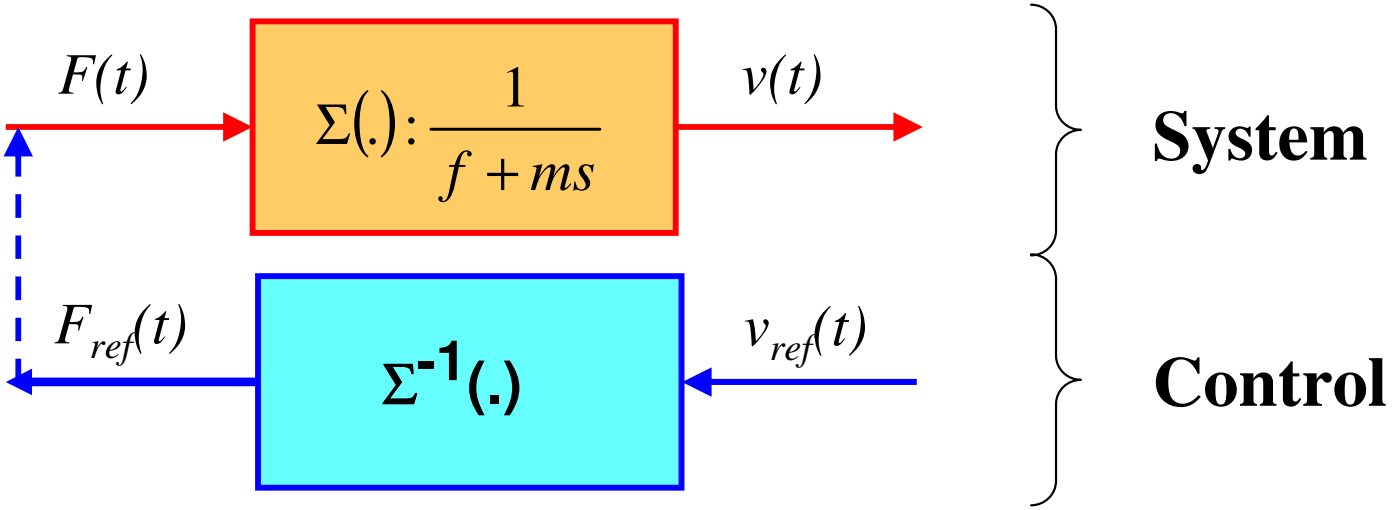


… if we can implement a good approximation of the system's inverse

- Open loop and closed-loop controls -

Let's take a simple example (a car in translation):





$$\tilde{\Sigma}^{-1}(.): \quad \frac{F_{ref}(s)}{v_{ref}(s)} = \tilde{f} + \tilde{m}s$$

No derivative in real-time

$$\tilde{\Sigma}^{-1}(.): \quad F_{ref}(t) \approx \tilde{f}\, v_{ref}(t)$$

Approximation

$$\tilde{\Sigma}^{-1}(.): \quad F_{ref}(t) = \tilde{f}\, v_{ref}(t) + \tilde{m}\, a_{ref}$$

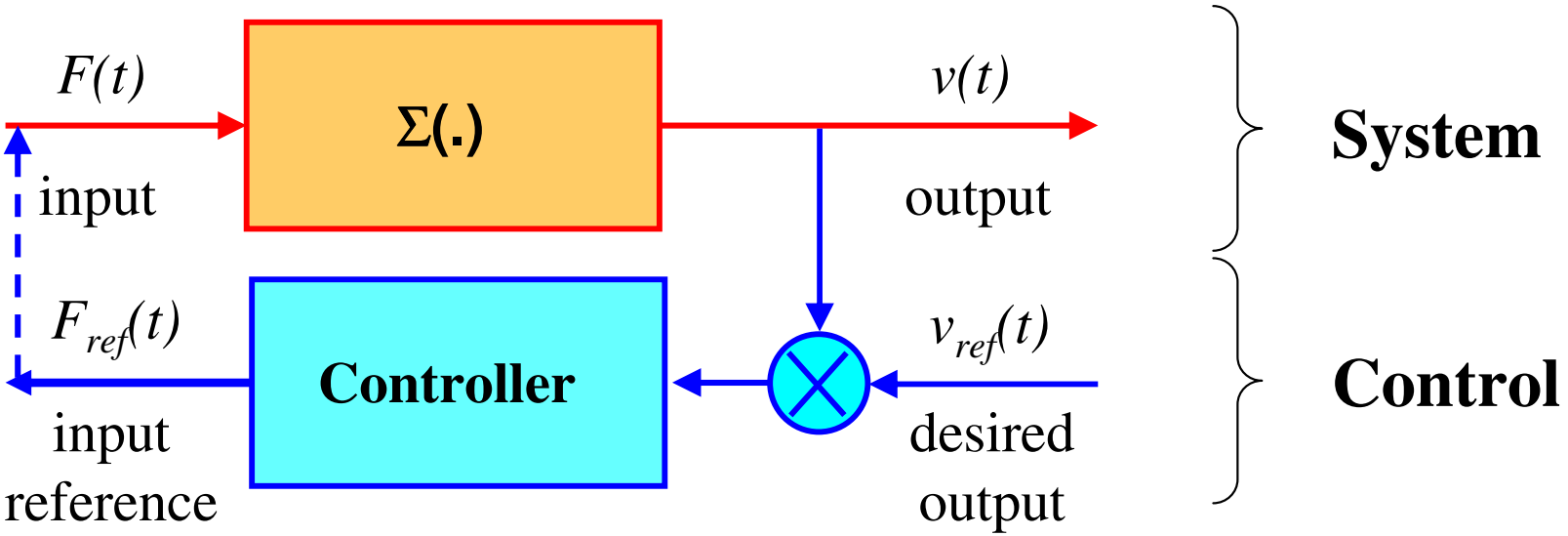
Trajectory planning

Direct inversion or Open-loop control or FeedForward control is not always the best solution!

- Open loop and closed-loop controls -

Closed-loop control is then required when:

- the model is not "directly" invertible
- the model is ill known or too complex



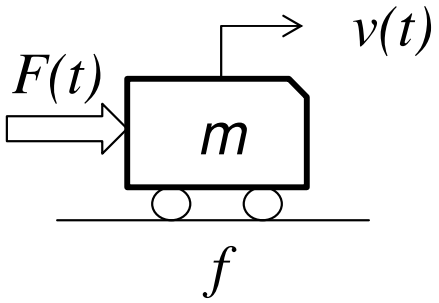
Closed-loop controllers can be used to:

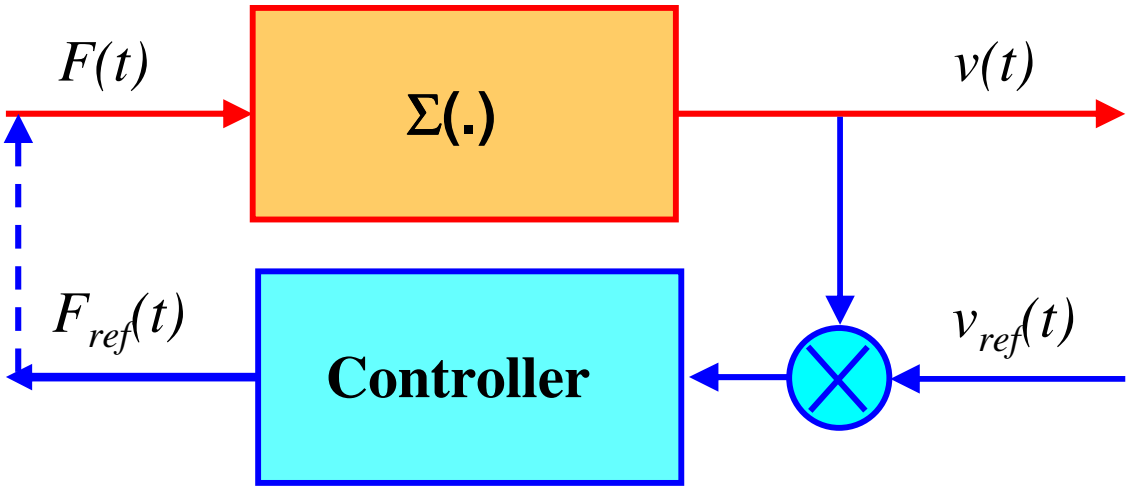
-Improve reference tracking performances, stabilize unstable processes

-Reject disturbances

-Cope with model uncertainties, reduce sensitivity to parameter variations

Let's take a simple example (a car in translation):





$$\Sigma(.): \quad \frac{v(s)}{F(s)} = \frac{1}{f + ms}$$

For example, and depending on expected performances:

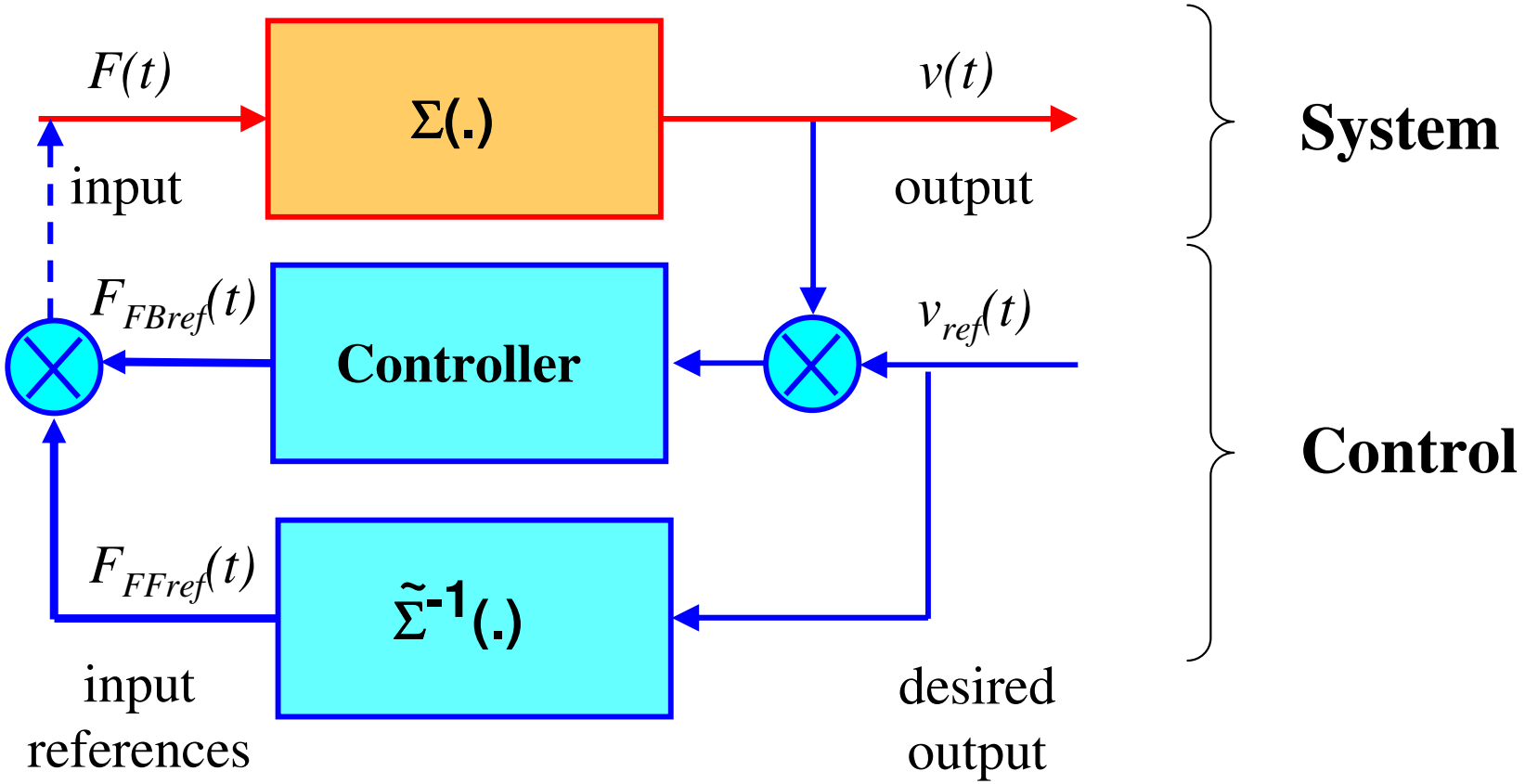
PI controller $C(s) = K_p\left(1 + \frac{1}{\tau_i s}\right)$

Closed-loop control offers many advantages !

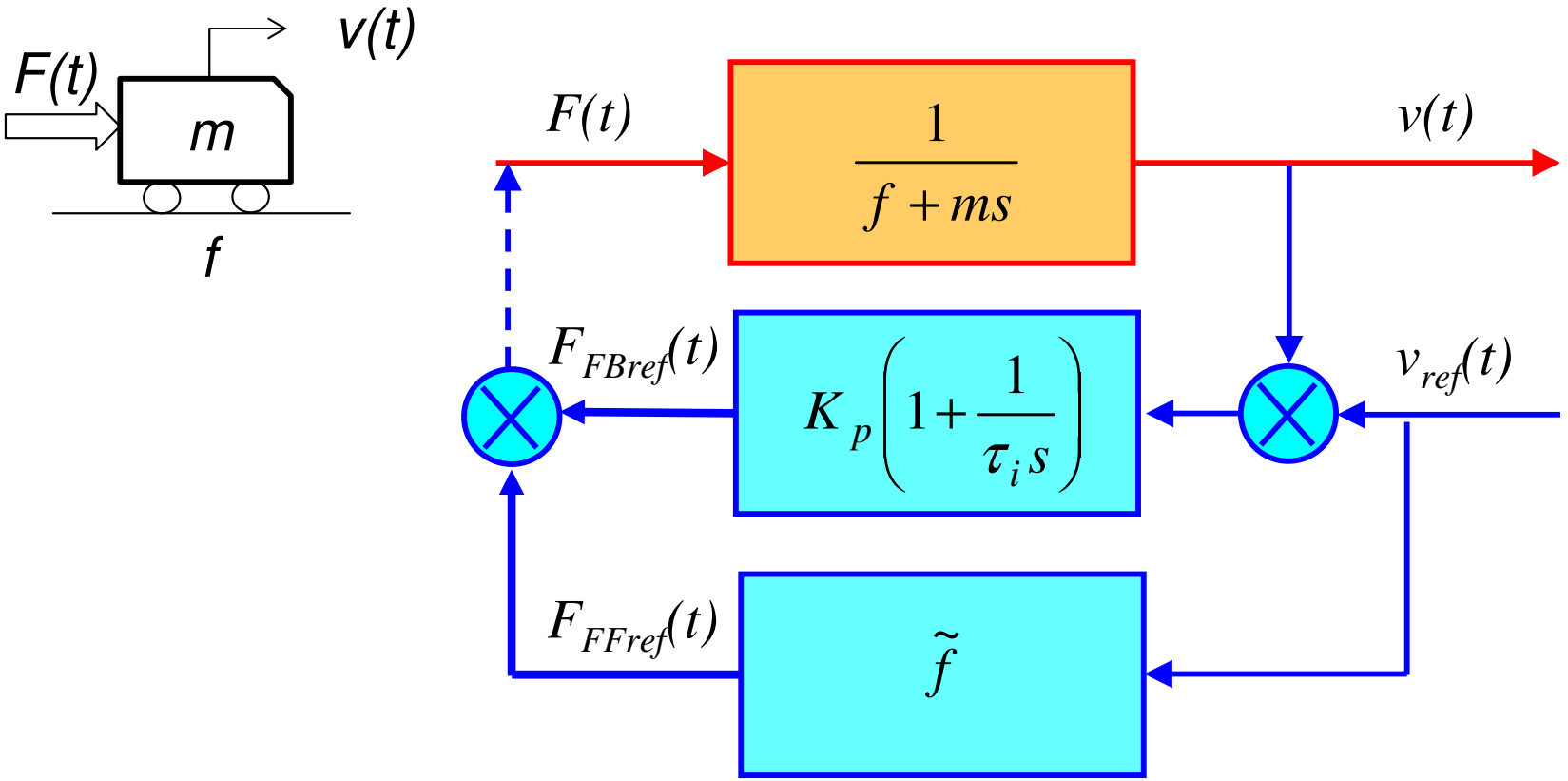
- Open loop and closed-loop controls -

Open loop and closed-loop controls can be conjointly used to take advantages of both strategies:

- FF for good dynamics with respect to intrinsic systems' properties
- FB for the "rest"

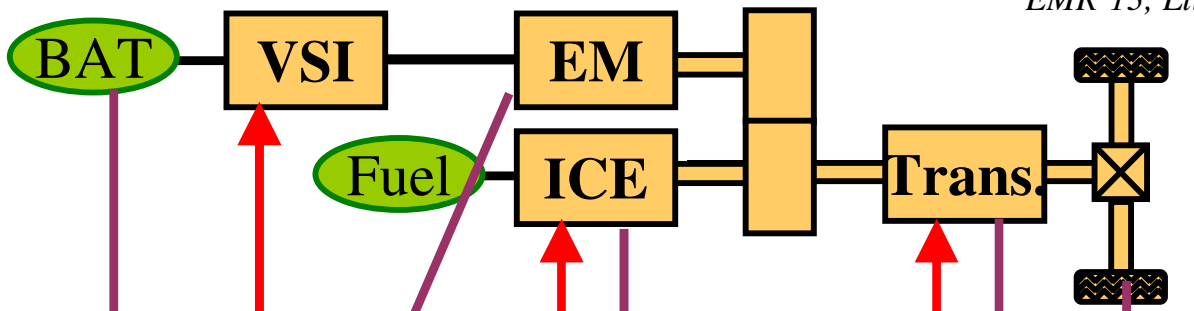


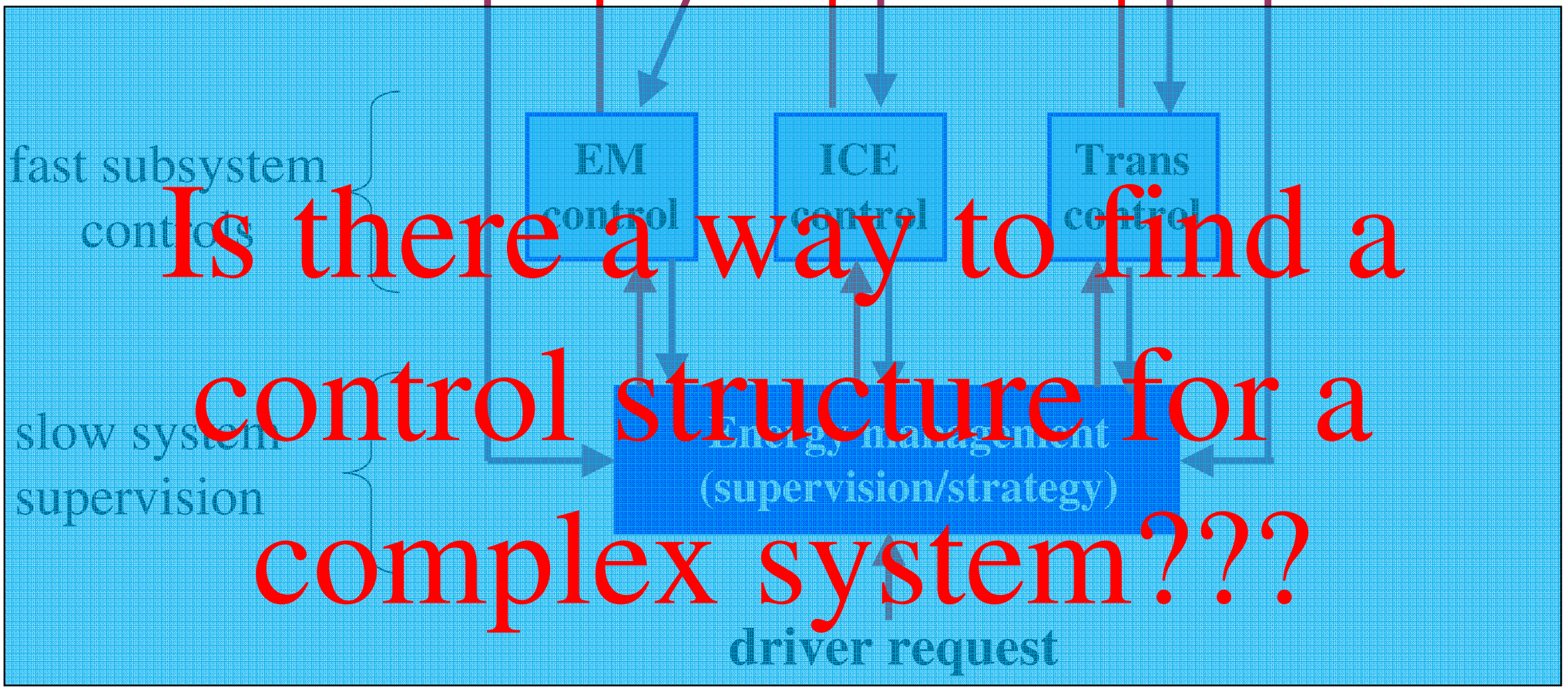
Let's take a simple example (a car in translation):



Solutions to control "simple" systems can be easily obtained thanks to existing model-based methods (FB and FF)

Parallel HEV



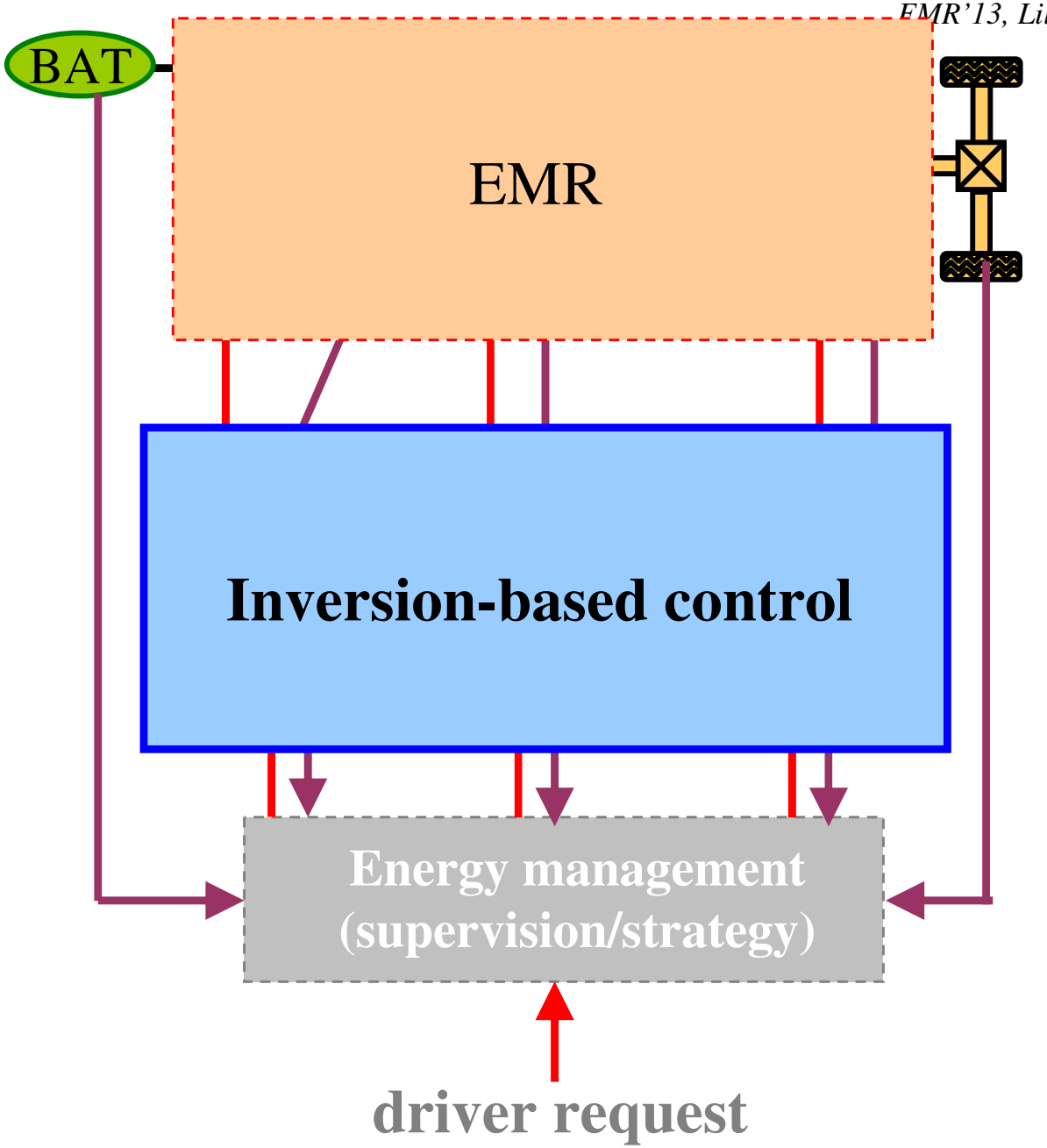


Is there a way to find a control structure for a complex system???

- Open loop and closed-loop controls -

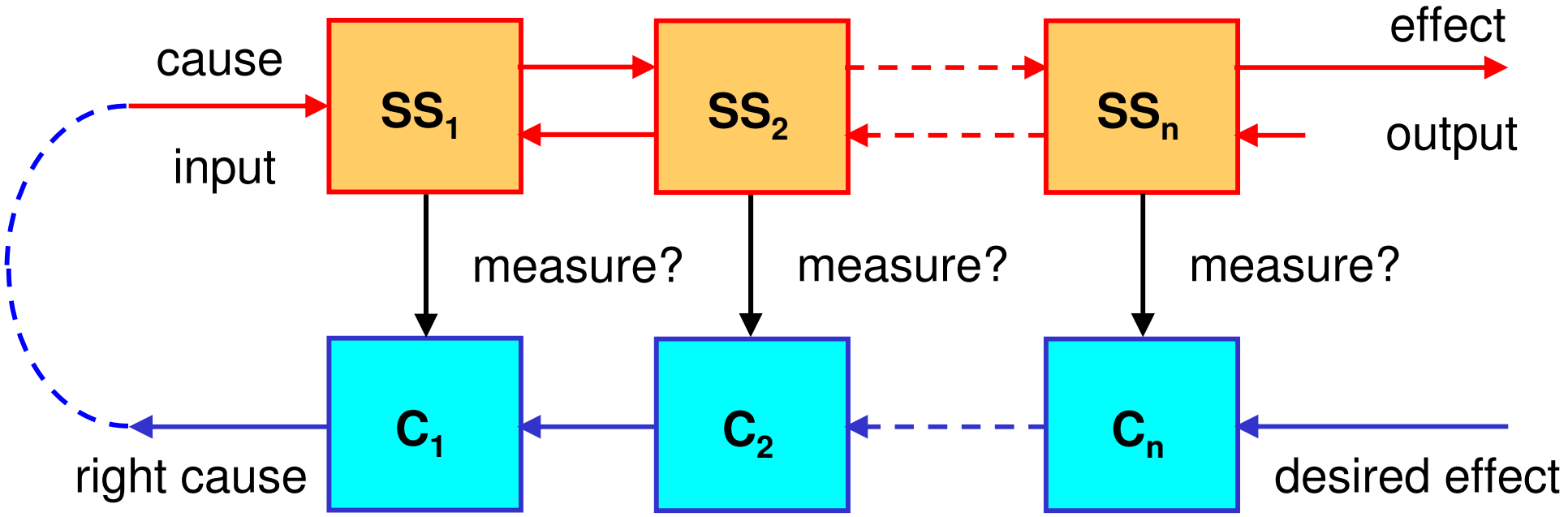
Parallel HEV

YES!



fast subsystem controls

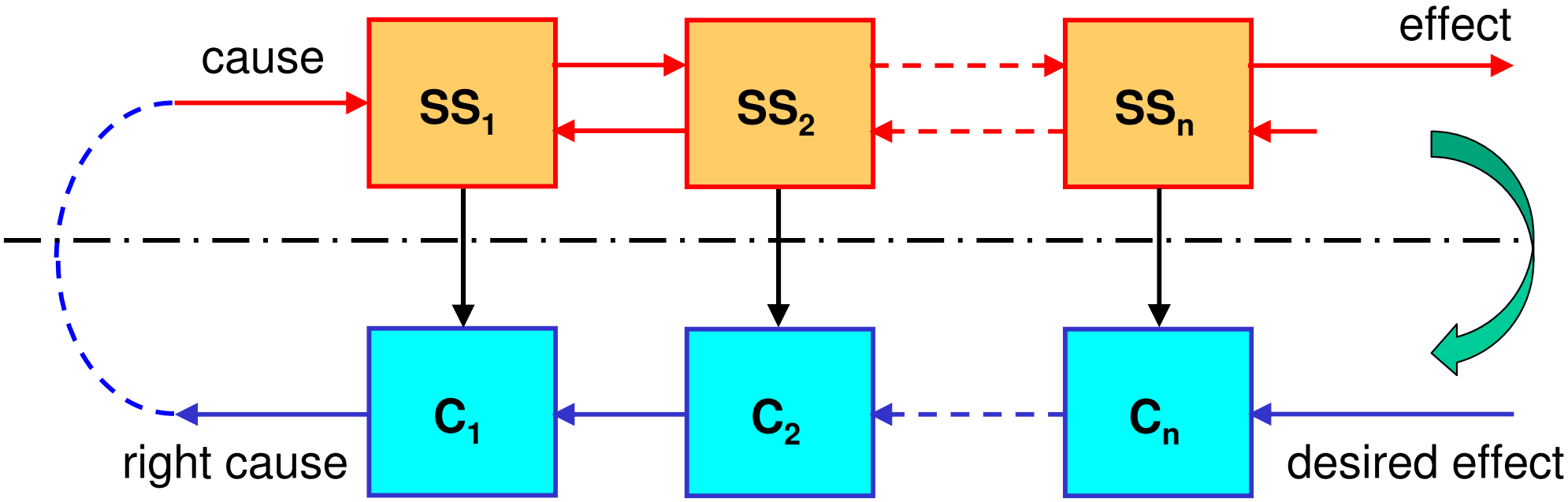
slow system supervision



EMR = system decomposition in basic energetic subsystems (SSs)

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

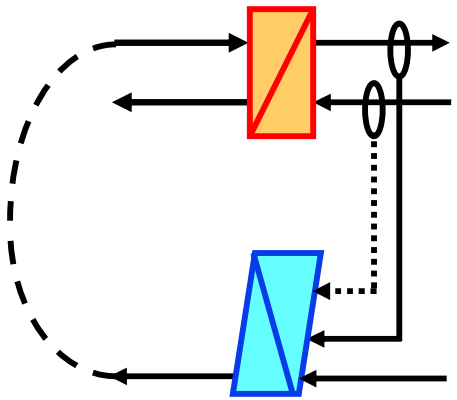
… divide and conquer …



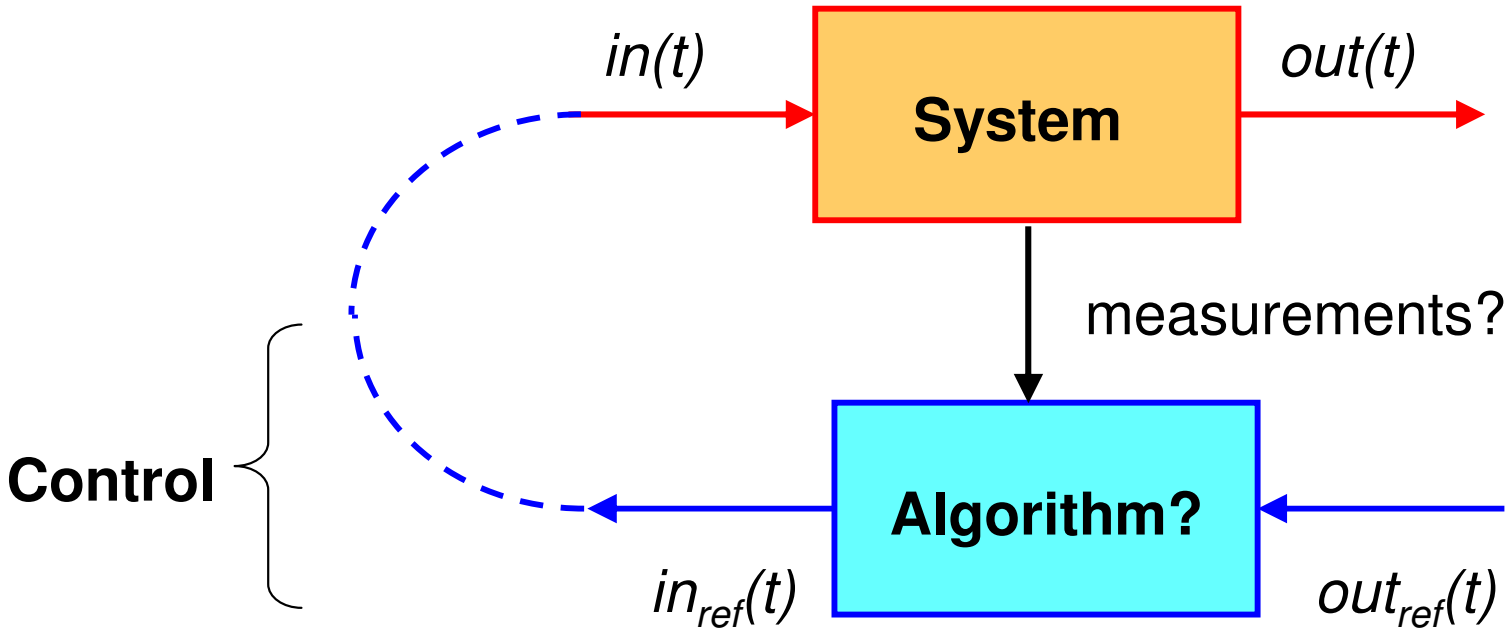
The control scheme is developed as a mirror of the model

[Hautier 96] [Bouscayrol 03]

2. « Inversion of EMR elements »



- Basic inversion of EMR elements -



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.

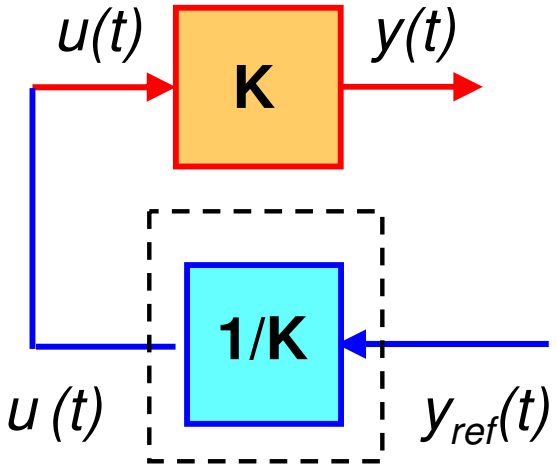
[Barre 06]

- Inversion 1: single-input time-independent relationship -

→ Output depends on a single input without delay

Example:

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

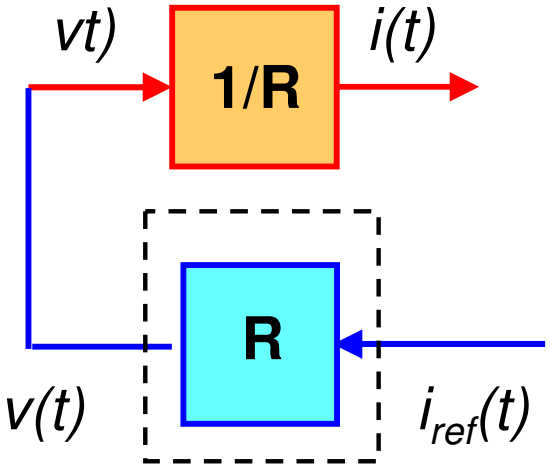


direct inversion

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

Example: Resistance

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



direct inversion

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

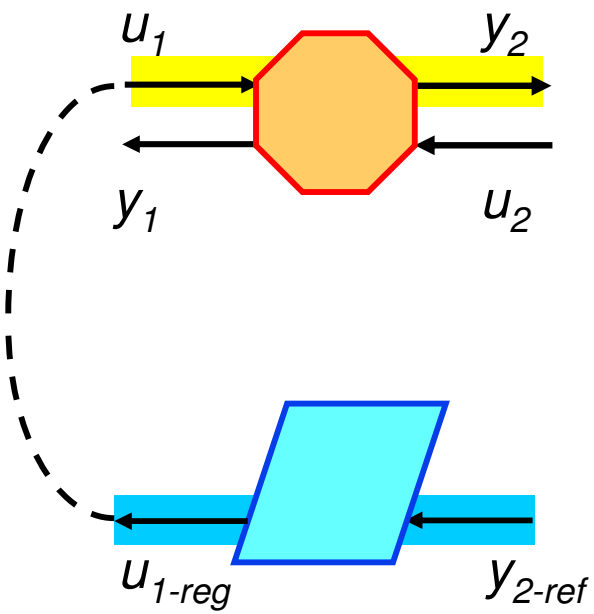
1. no measurement
2. no controller
(open-loop control)

Assumption: K well-know and constant

- Inversion 1: single-input time-independent relationship -

Inversion of a conversion element

Objective: to control y_2



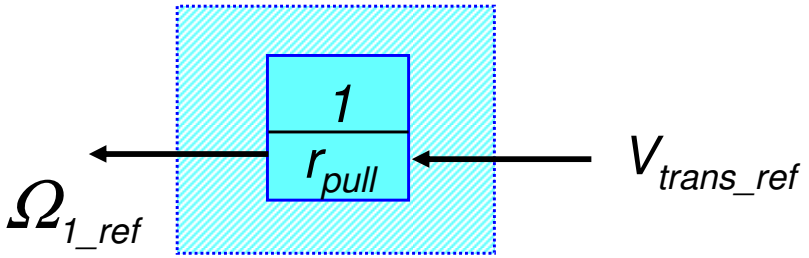
$y_2 = f(u_1)$

Manipulate u_1

Ex : pulley or roller

$$\begin{cases} V_{trans} = r_{pull}\,\Omega_1 \\ T_{trans} = r_{pull}\,F_{load} \end{cases}$$

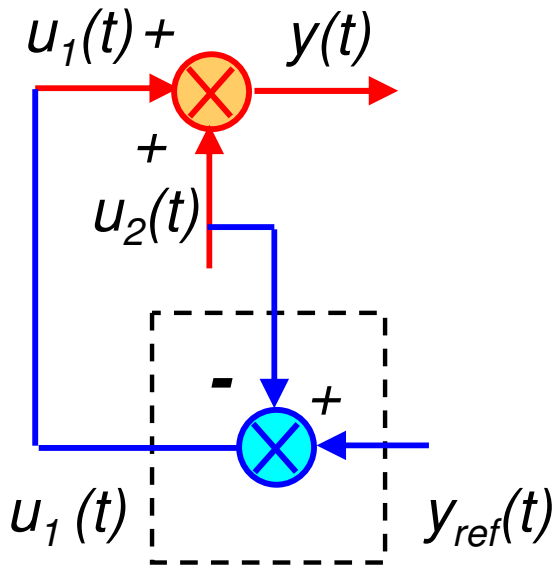
$$\Omega_{1\_ref} = V_{trans\_ref} / r_{pull}$$



- Inversion 2: multiple-input time-independent relationship -

→ 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

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

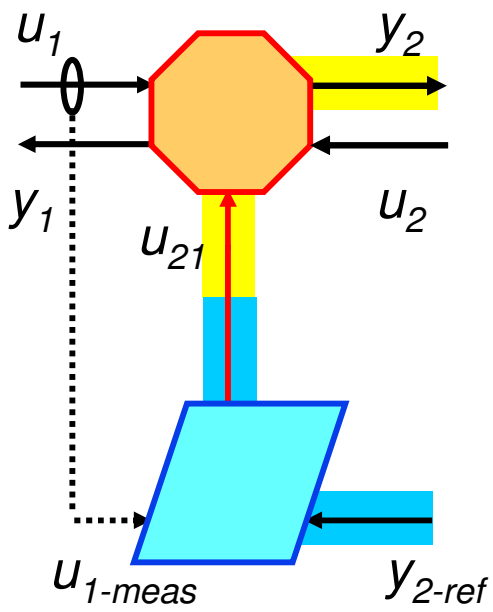
1. measurement of the disturbance input
2. no controller
(open-loop control)

Assumption: u_2 can be measured

- Inversion 2: multiple-input time-independent relationship -

Inversion of a conversion element

Objective: to control y_2



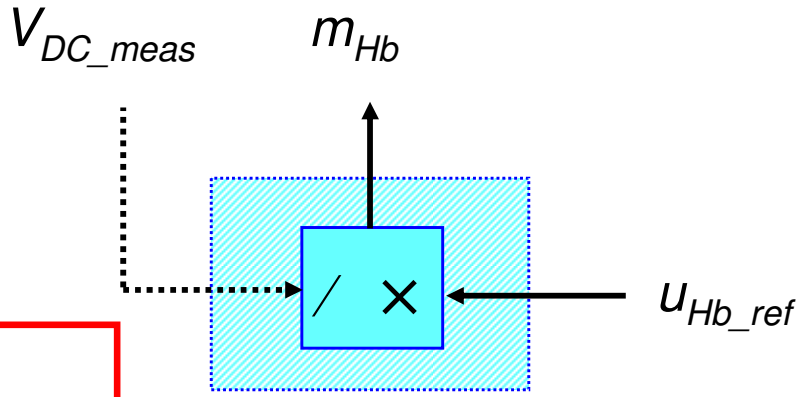
$y_2 = f(u_1, u_{21})$

Manipulate u_{21} ⇨ u_1 is a disturbance

Ex : H-bridge chopper

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

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

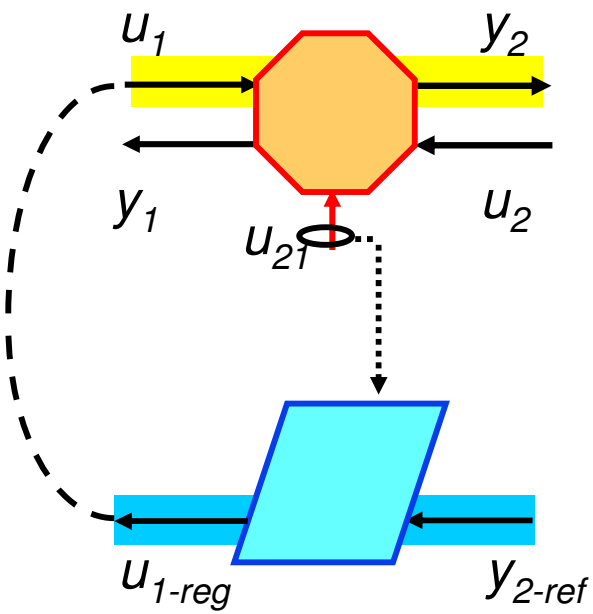


Basic rule: as a first step, compensate all disturbances assuming measurement is available.

- Inversion 2: multiple-input time-independent relationship -

Inversion of a conversion element

Objective: to control y_2



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

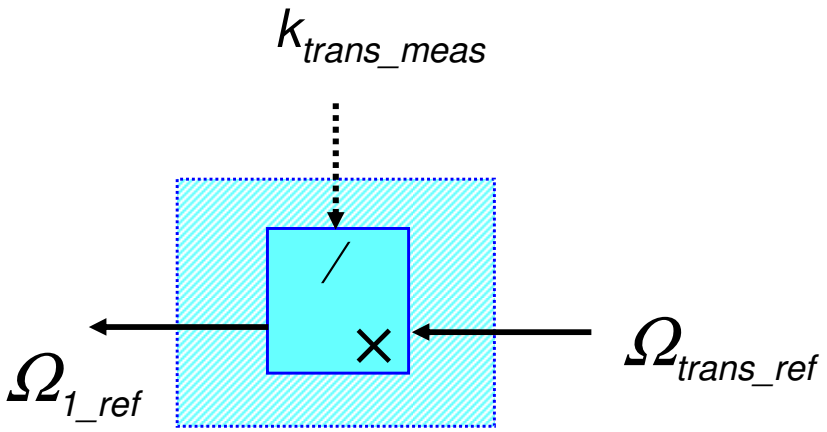
Manipulate u_1 ⇨ u_{21} is a disturbance

Ex : speed transmission

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

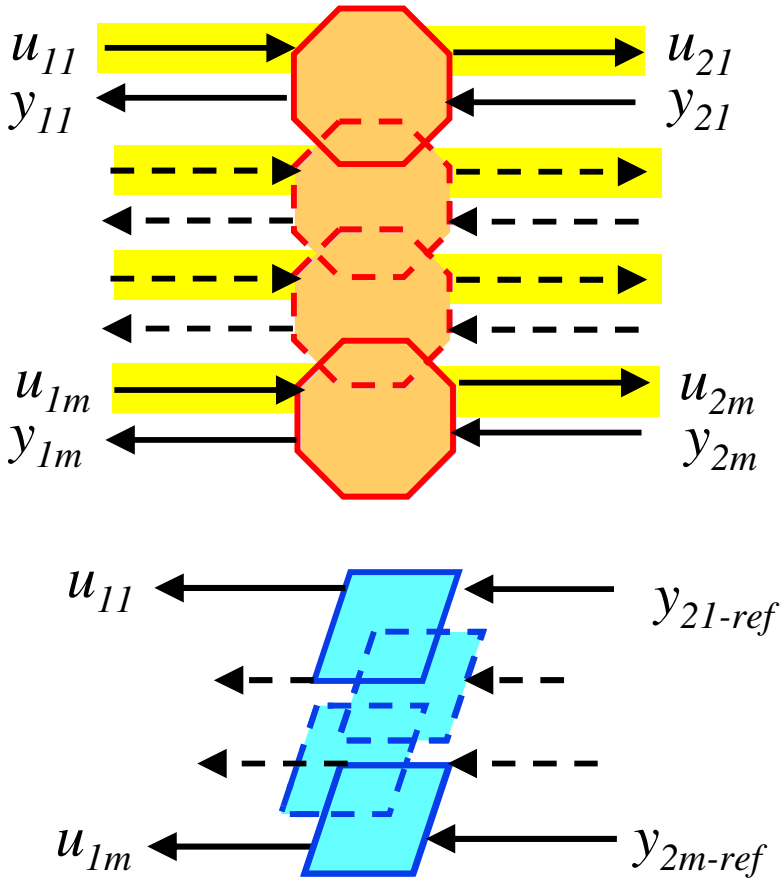
⇩

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



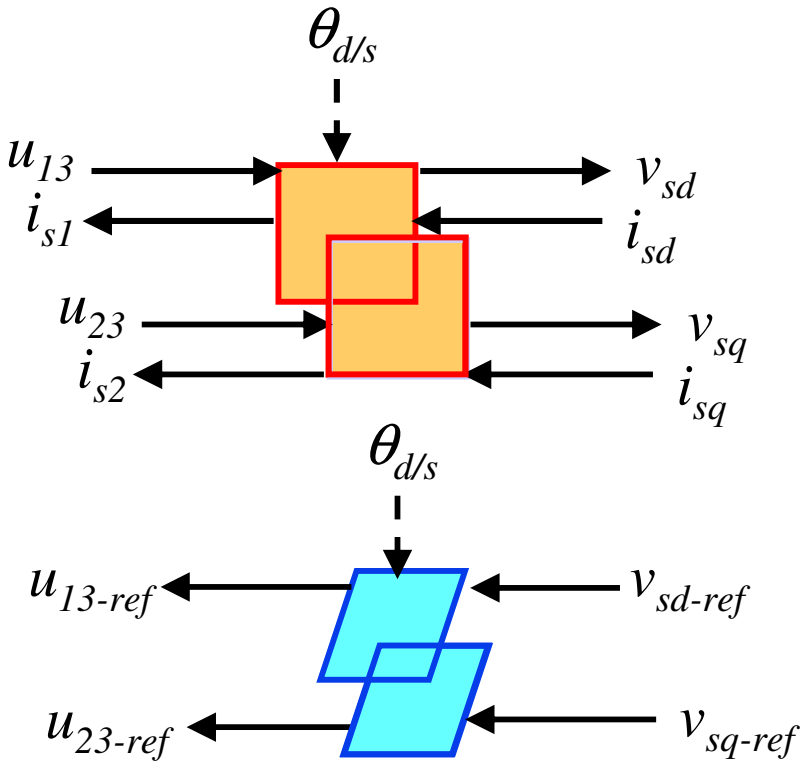
- Inversion 2: multiple-input time-independent relationship -

Inversion of a neutral coupling elements



no measurement
no controller / direct inversion

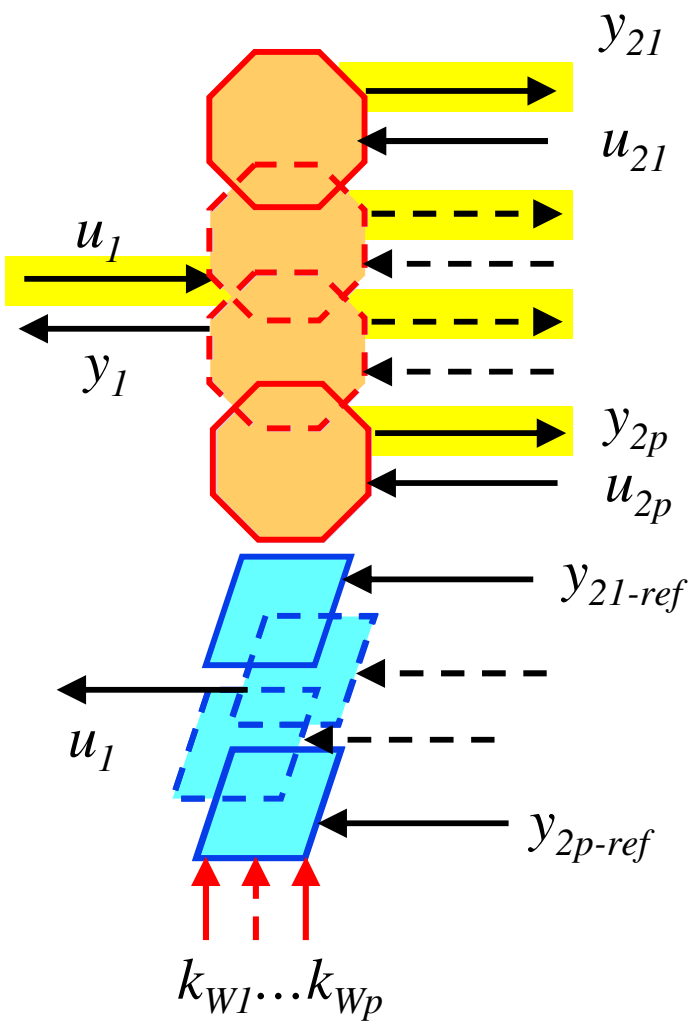
Example: Park's transformation



use of the inverse matrix

- Inversion 2: multiple-input time-independent relationship -

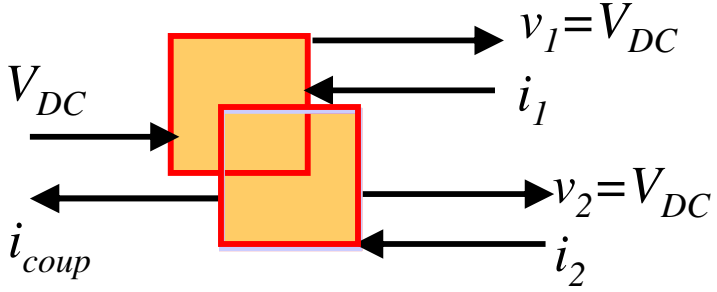
Inversion of upstream coupling elements

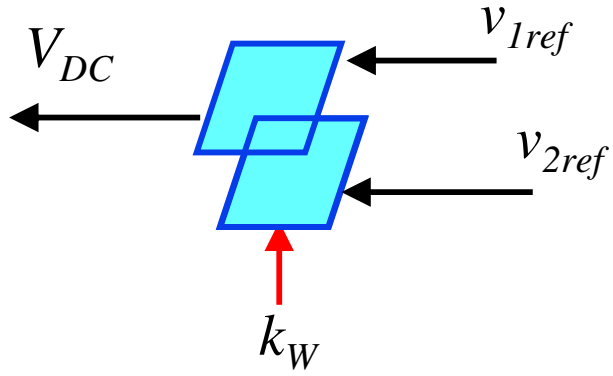


Implement a compromise or prioritize outputs.

no measurement
no controller
p weighting variables

Example: current node





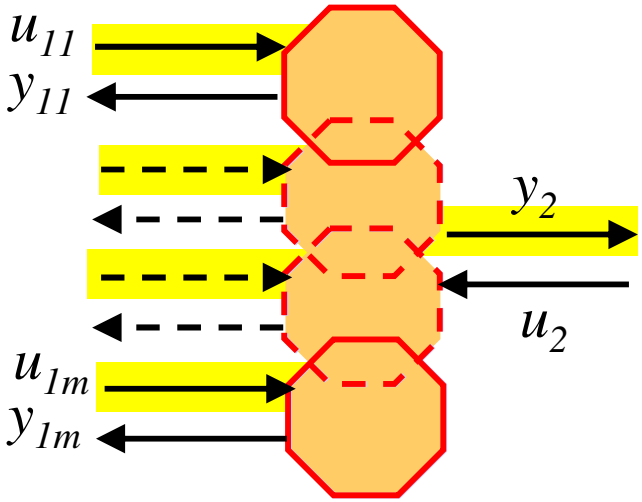
$$u_1 = k'_{W1} y_{21-ref} + \ldots + k'_{Wp} y_{2p-ref}$$

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

$$0 \leq k_W \leq 1$$

- Inversion 2: multiple-input time-independent relationship -

Inversion of downstream coupling elements



There are extra degrees of freedom!!!

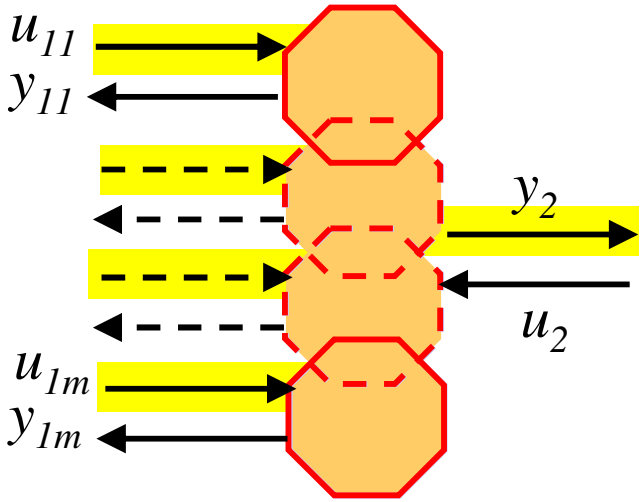
… an opportunity for energy management, efficiency optimization, load sharing …

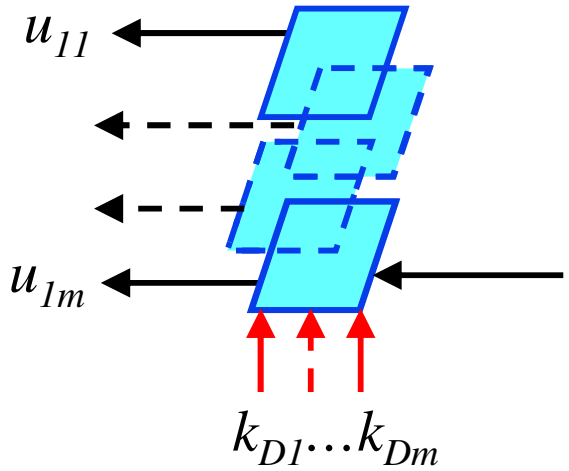
Inversion principle
Distribute the reference signal

Examples:
- ***Equal torque criteria;***
- ***Equal power criteria;***
- ***Field weakening strategy.***

- Inversion 2: multiple-input time-independent relationship -

Inversion of downstream coupling elements

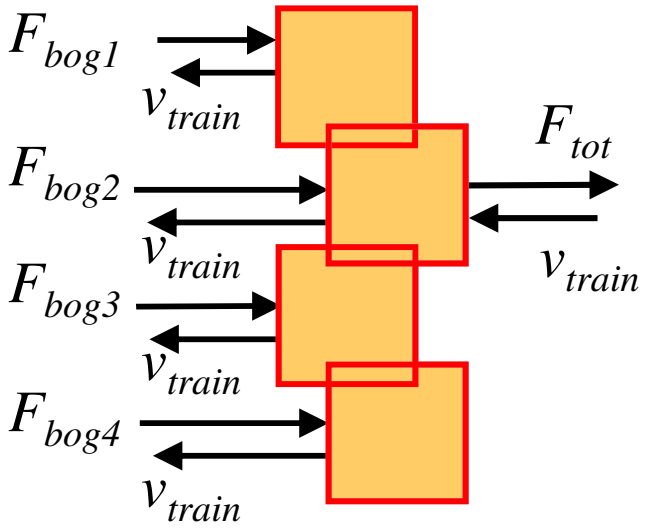


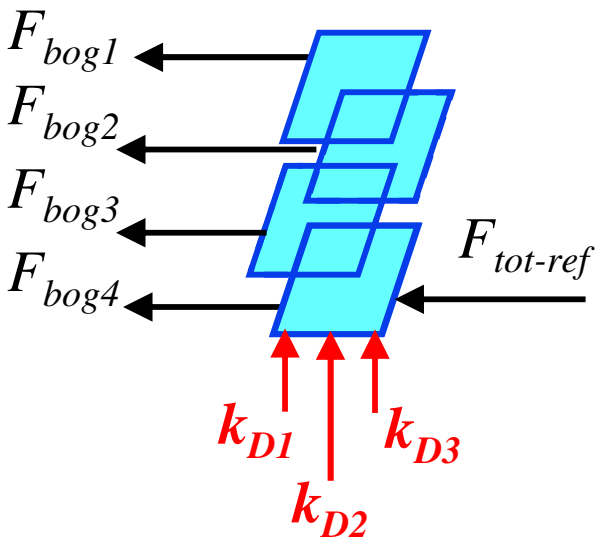


no measurement
no controller
m distribution
variables

$$\begin{cases} u_{11} = k'_{D1}\, y_{2ref} \\ \ldots \\ u_{1m} = k'_{Dm}\, y_{2ref} \end{cases}$$

<u>Example</u>: chassis of a train

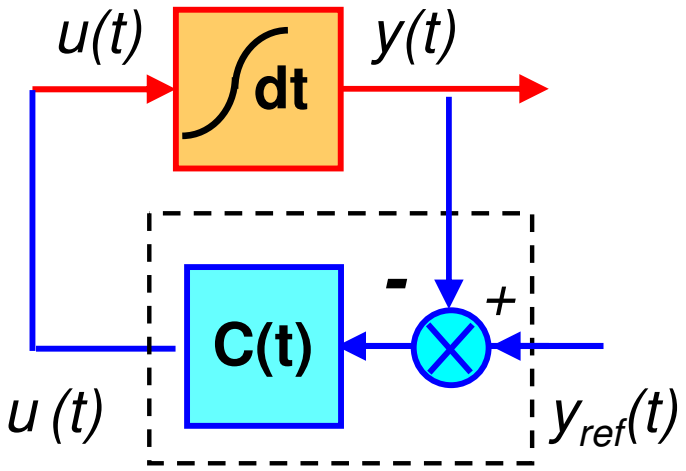




Output depends on a single input and time (delay) ⇨ causality principle

Example:

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



direct inversion

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

not possible in real-time

indirect inversion

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

closed loop controller

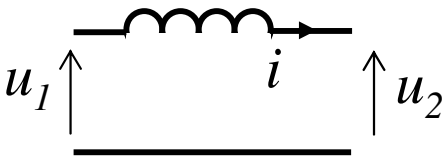
Path-planning sometimes possible

Out of the scope

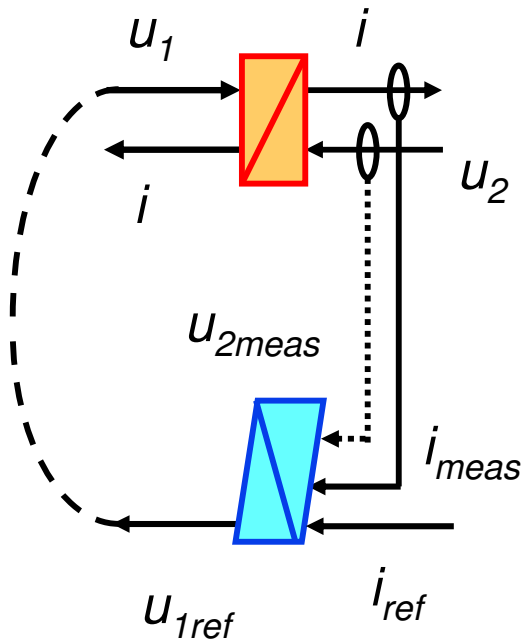
1. measurement of output
2. a controller is required
(closed-loop control)

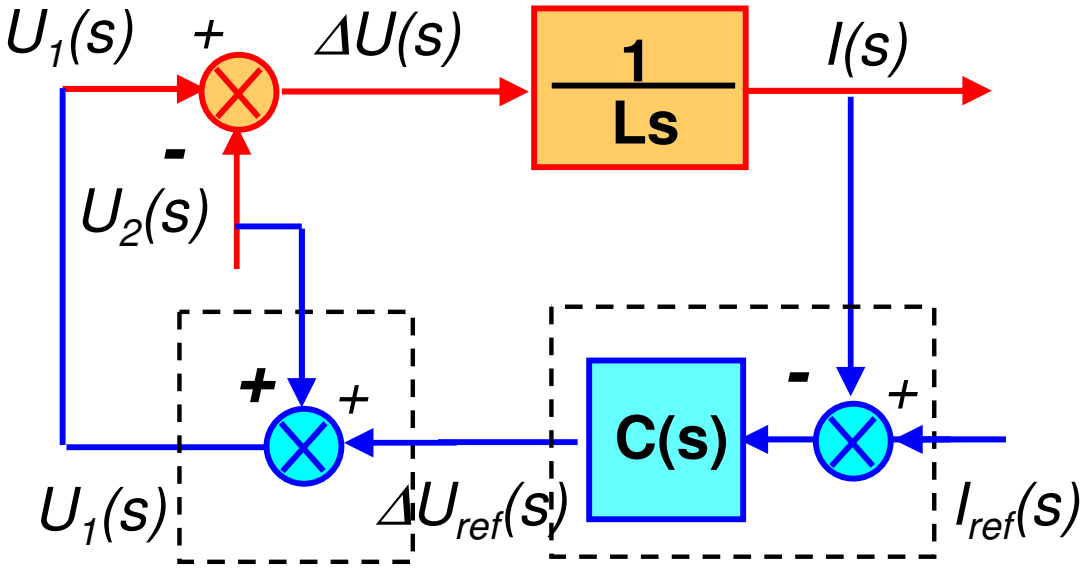
- Inversion 3: single-input causal relationship -

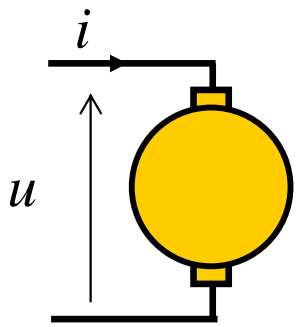
Output depends on a single input and time (delay) ⇨ causality principle

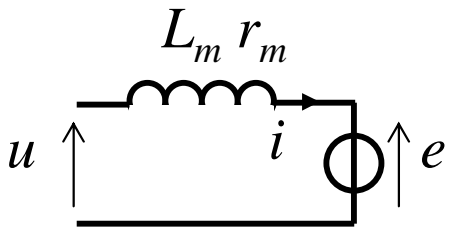


$$L\frac{di}{dt} = u_1 - u_2$$









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

multi-input causal relationship

⇩

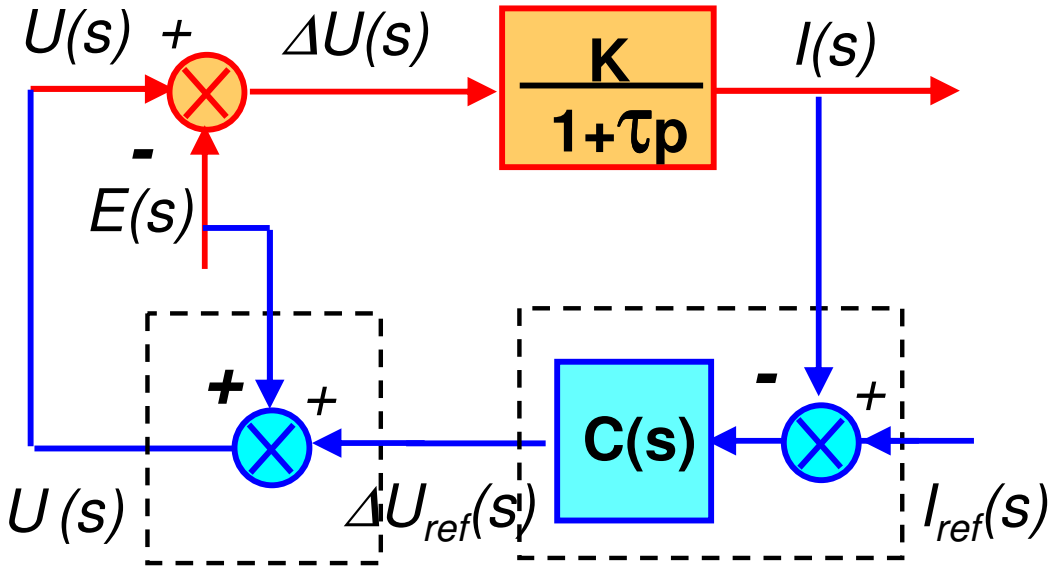
decomposition

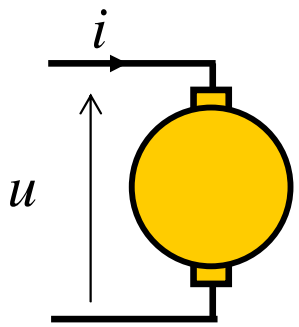
$$\Delta u = u - e$$

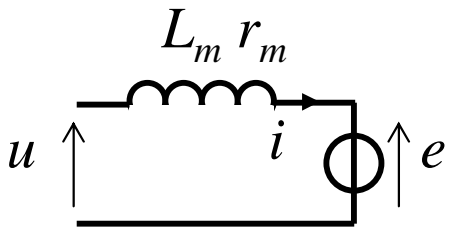
$$L_m \frac{di}{dt} = \Delta u - r_m i$$

direct inversion

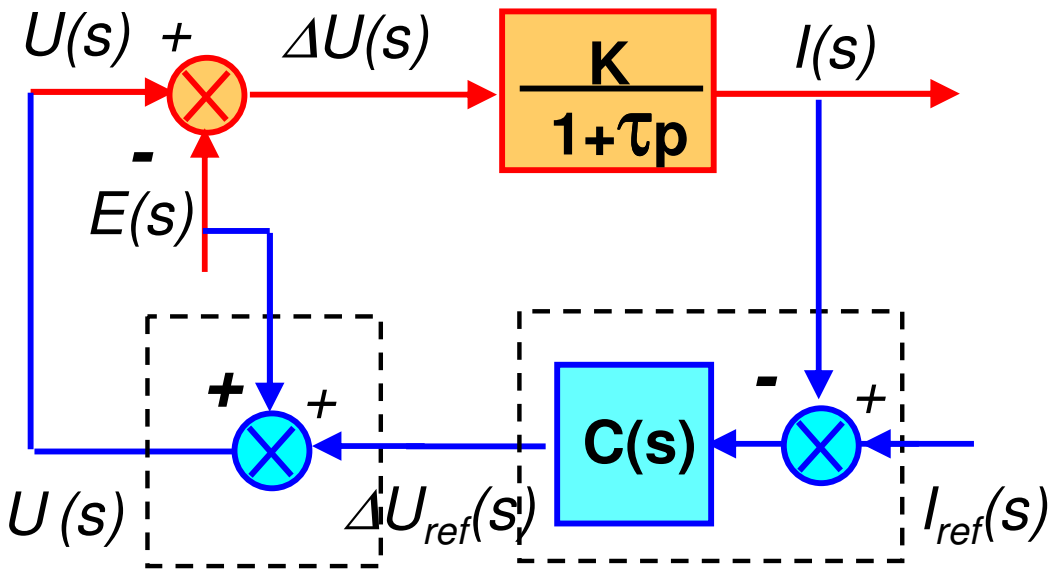
closed-loop controller

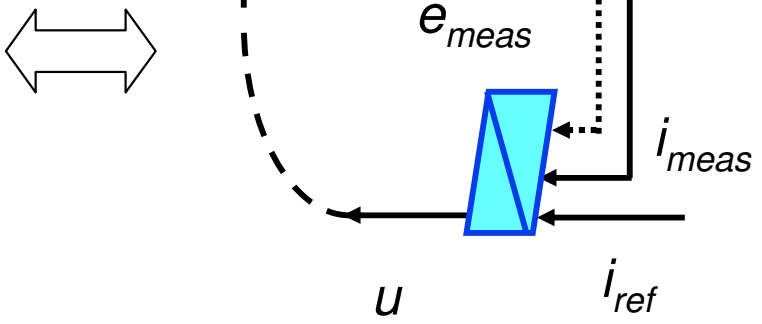






$$L_m \frac{di}{dt} = u - e - r_m i$$





- Inversion of EMR elements -

Legend

Control = light blue parallelogram with dark blue contour

direct inversion

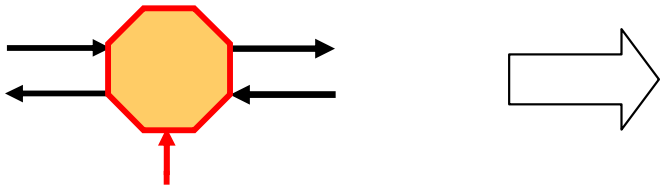
indirect inversion

sensor

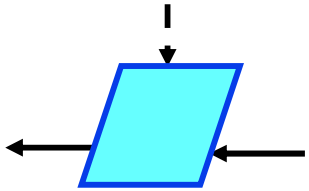
mandatory link

optional link

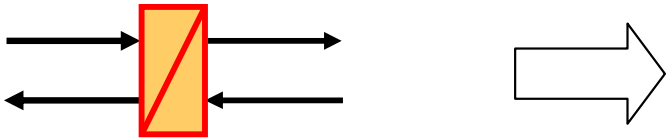
conversion element



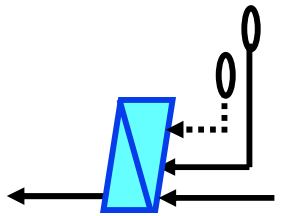
direct inversion + disturbance rejection



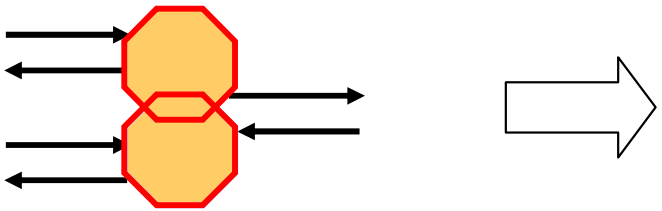
accumulation element



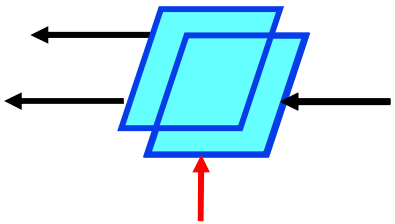
controller + disturbance rejection



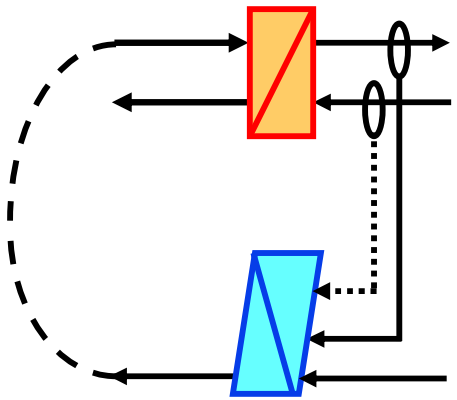
coupling element



distribution criteria

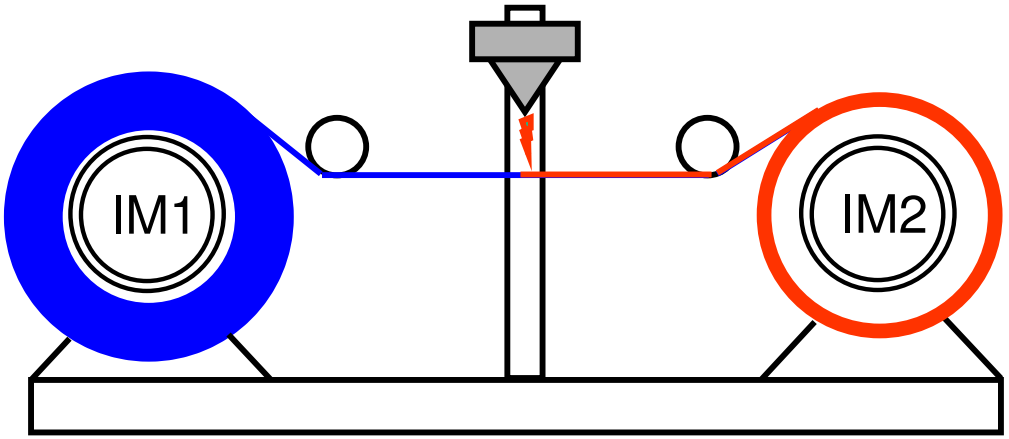


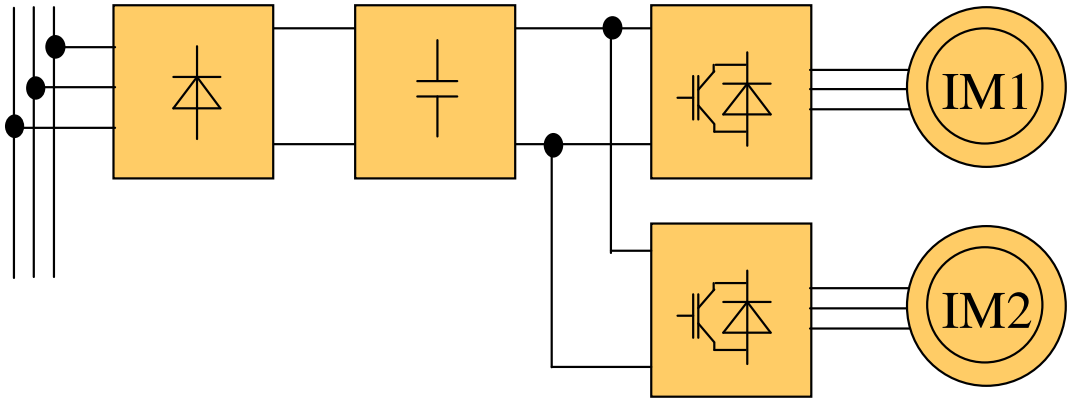
3. « Inversion-based control structures »



- Paper processing system as an example -

Paper processing
using 2 induction machines

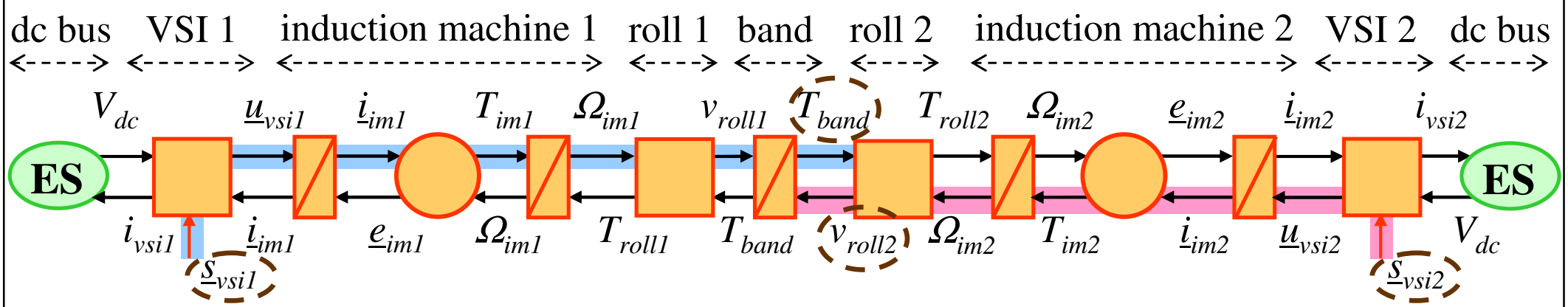




Technical requirements:
- paper tension control for high quality of paper roll
- winding velocity control for high quality of processing

[Djani 06]

- Maximum control structure -

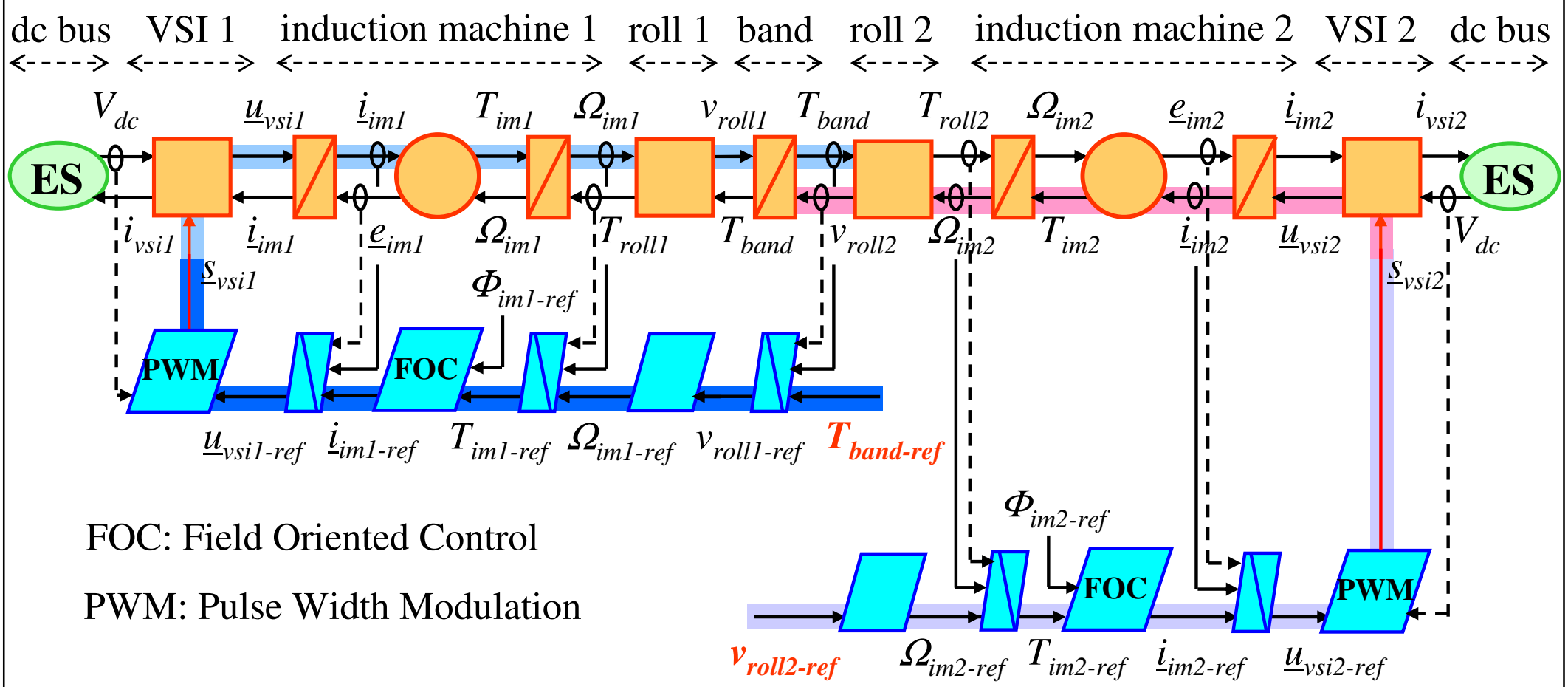


Step 1: Develop the EMR of the system

Step 2a: Identify all control variables (outputs) and control inputs

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

- Maximum control structure -



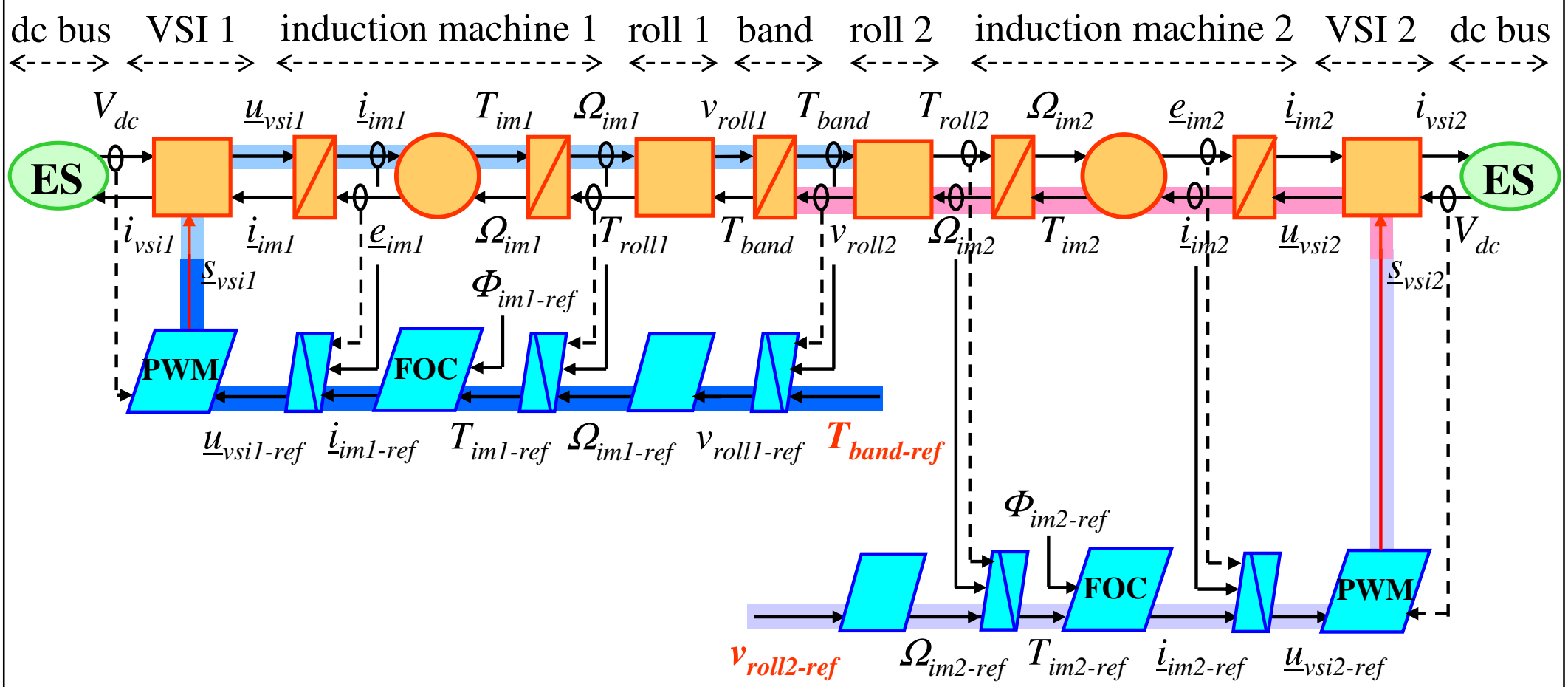
FOC: Field Oriented Control

PWM: Pulse Width Modulation

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

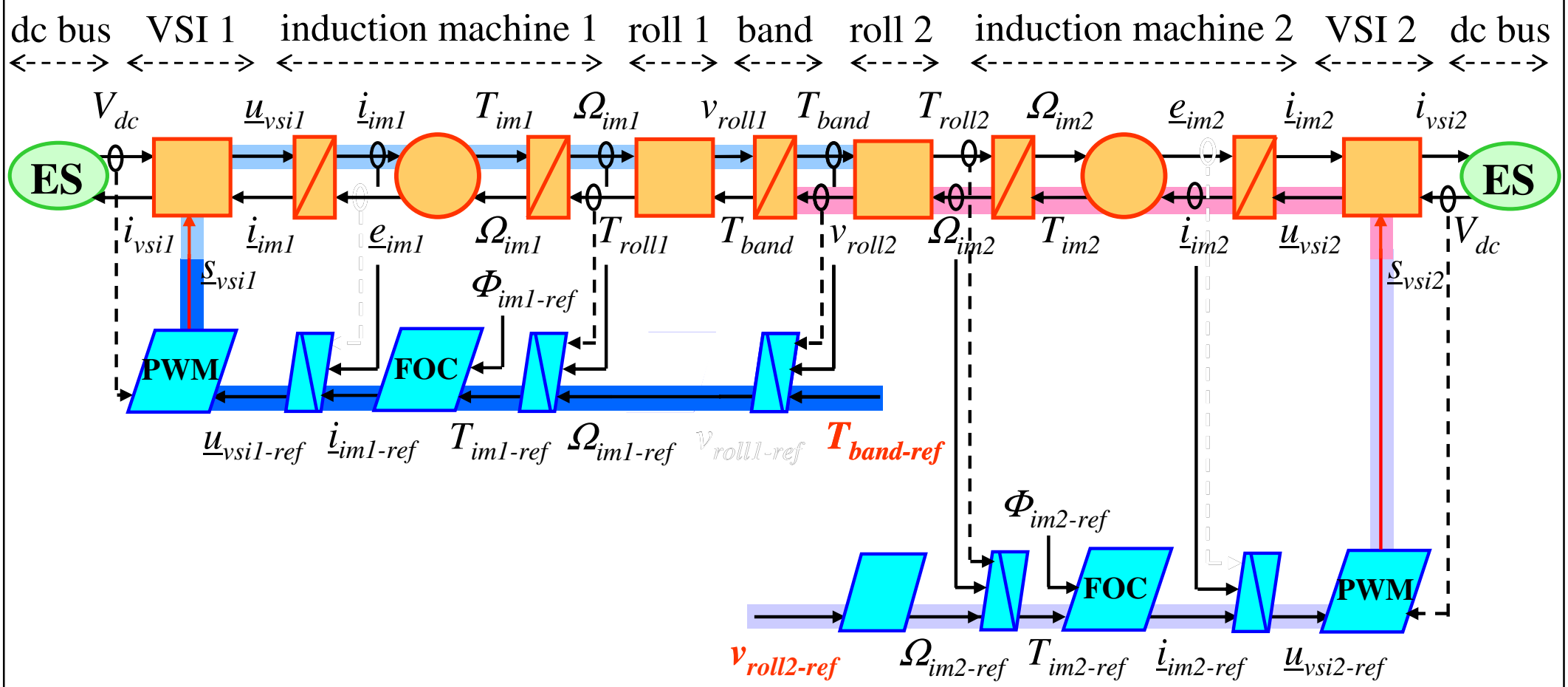
- assume that all the signals are measurable;
- compensate for all disturbances.

- Maximum control structure -

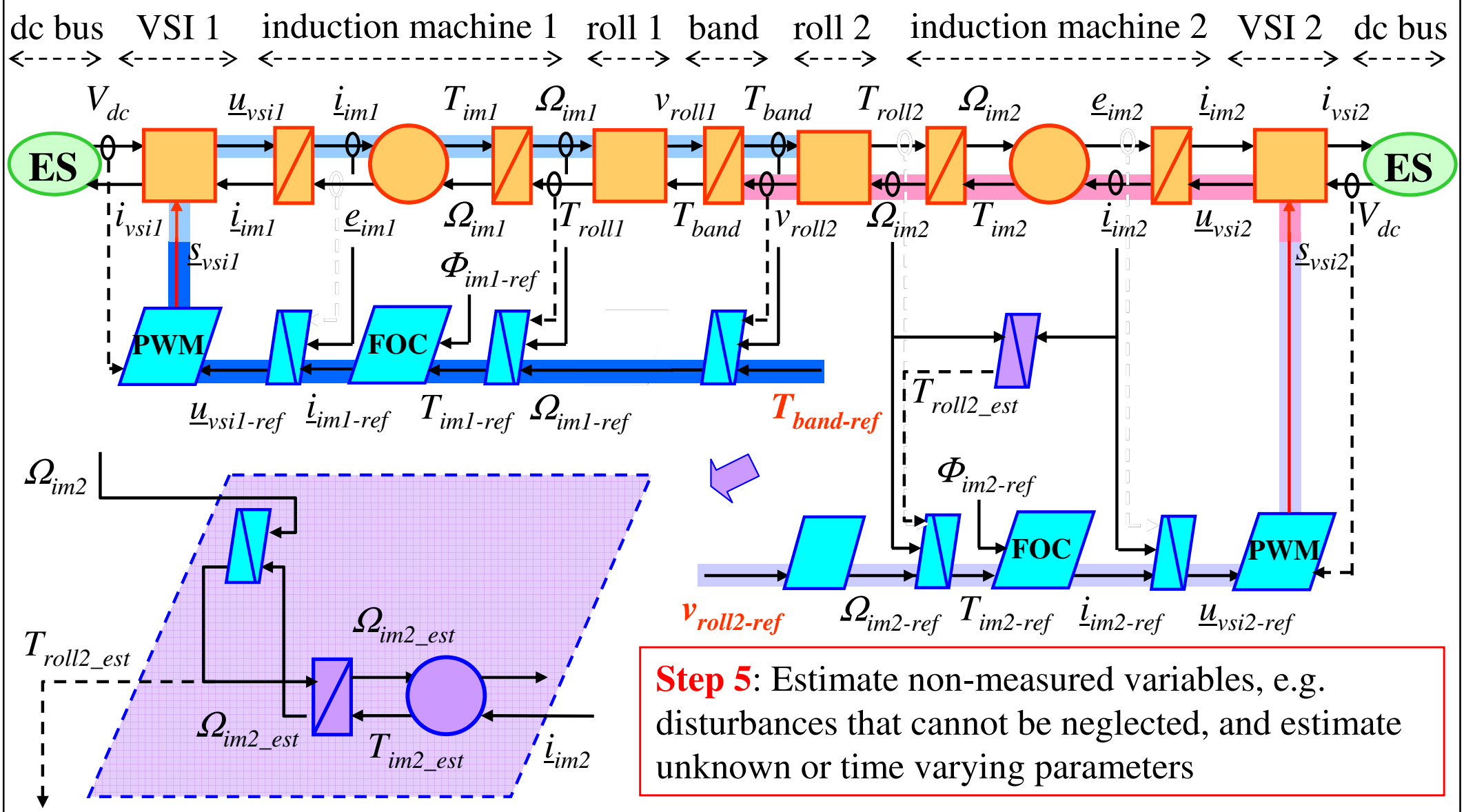


Maximum control structure:

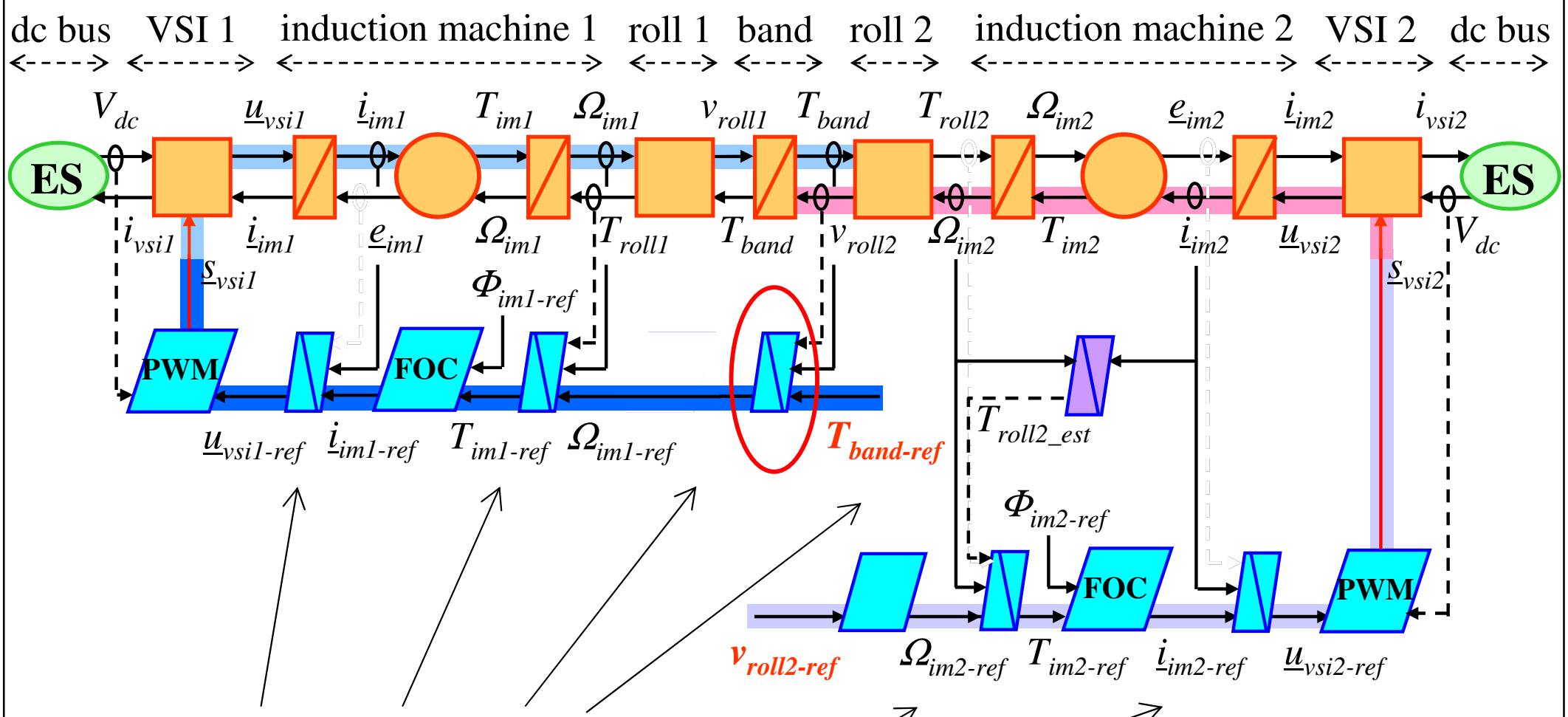
- one elementary feedback controller per accumulator
- simple tuning is possible by time coordination/separation of the control loops



Step 4: Simplify the MCS: group operations, do not reject disturbances explicitly.
— Impact will be on cost, on processing time and on performance

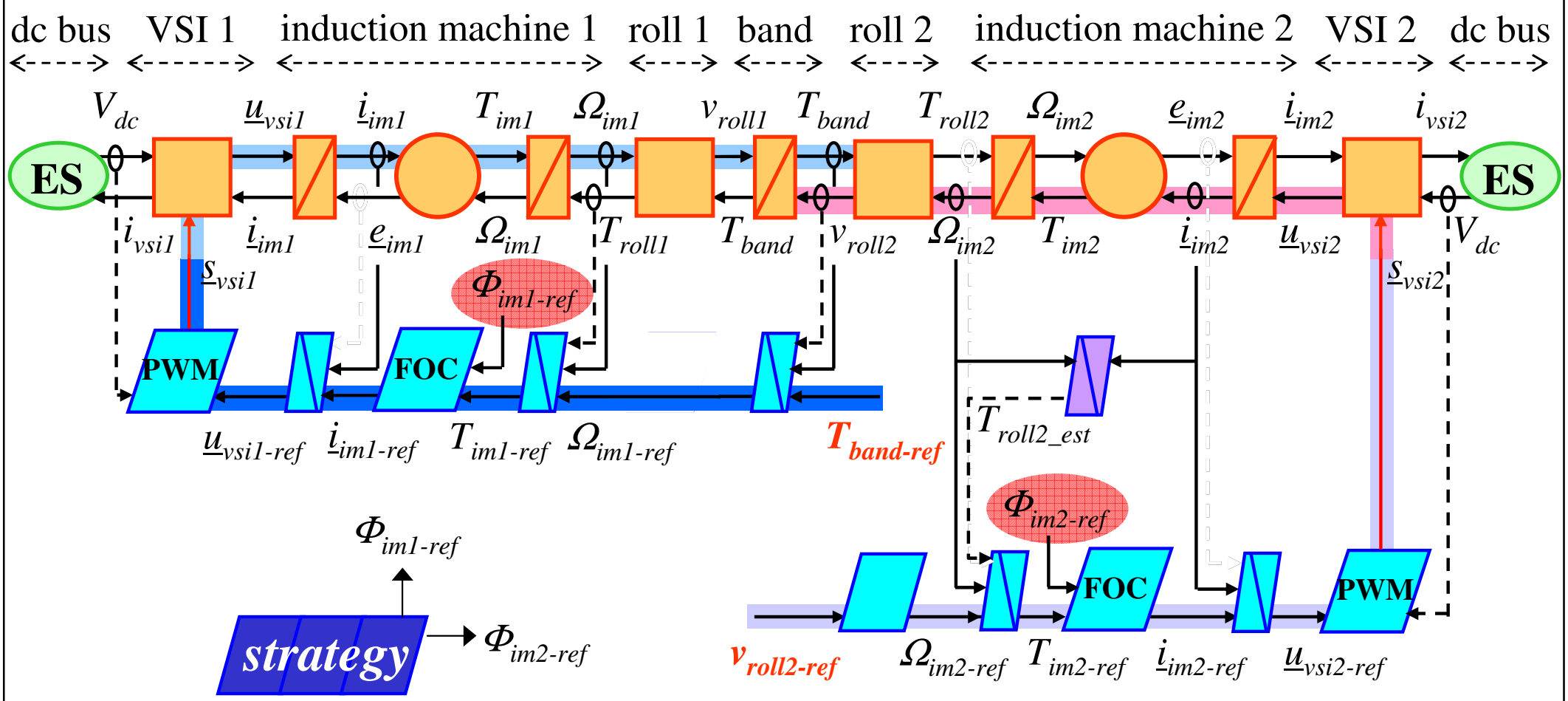


Step 5: Estimate non-measured variables, e.g. disturbances that cannot be neglected, and estimate unknown or time varying parameters



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

PI controllers OK except



3b: Exploit degrees of freedom to implement advanced strategies

« Conclusion »

Inversion based control = inversion of EMR

based on the cognitive systemic
and the causality principle (energy)

Inversion rules for control scheme

closed-loop control to invert accumulation elements,
direct inversion for conversion elements,
degrees of freedom to invert coupling elements

Different steps in defining the control scheme

From Maximum Control Scheme….
… to Practical Control Scheme….
… to the strategy level

« BIOGRAPHIES AND REFERENCES »

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