HIL'16 summer school
Lille, 1-2 September 2016
http://l2ep.univ-lille1.fr/hil2016/

« Different concepts for Hardware-In-the-Loop simulation »

Prof. Alain BOUSCAYROL

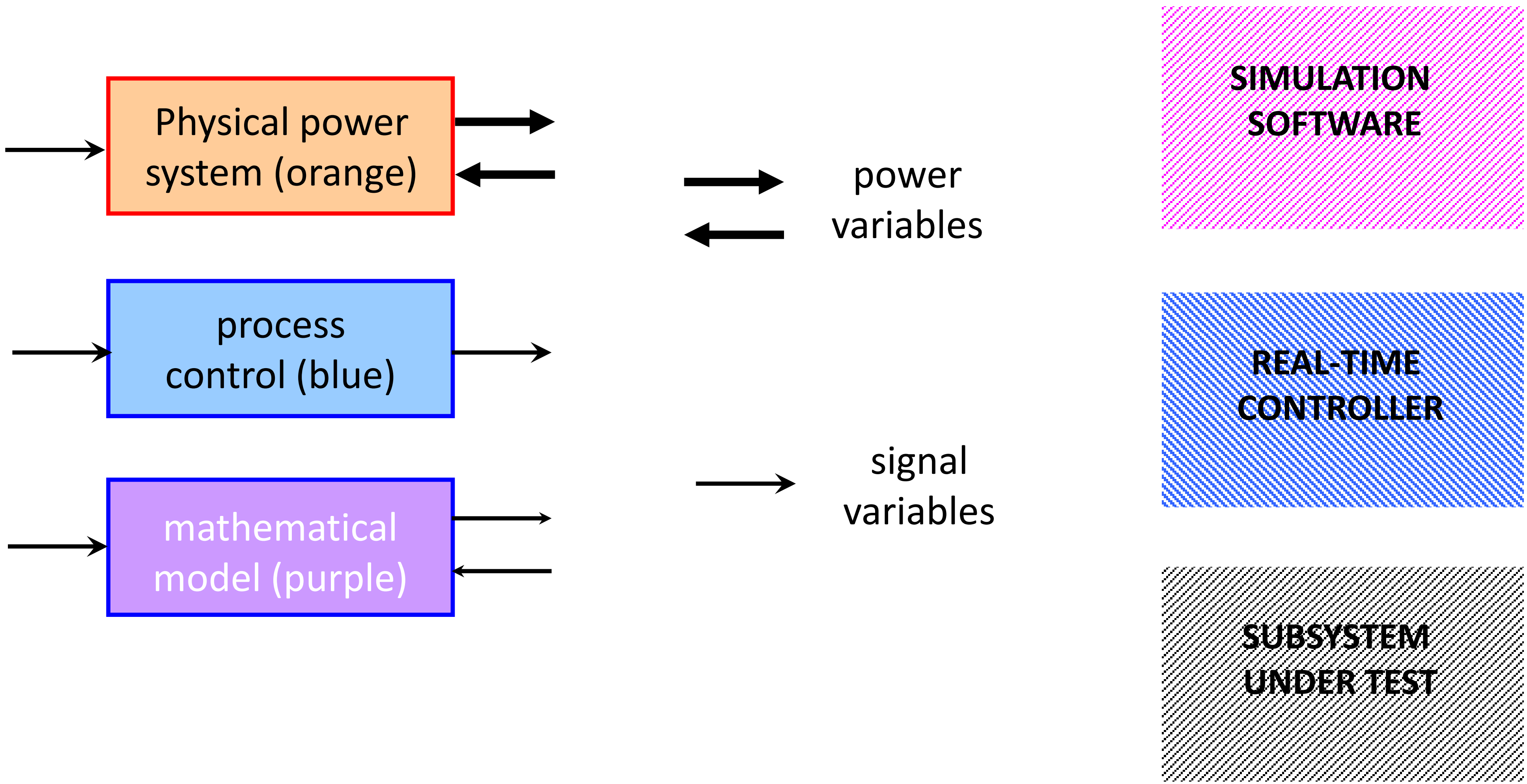
L2EP, University Lille1,
MEGEVH network, IEEE-VTS DL

1. WHAT IS HIL SIMULATION ?

2. WHICH MODELS FOR HIL SIMULATION ?

3. Different types of HIL SIMULATION ?

Graphical rules



Scientific context

....

- **L2EP Lille**
- **MEGEVH Network**
- **IEEE VTS DL program**

Laboratory of Electrical Engineering and Power electronics (L2EP)

http://l2ep.univ-lille1.fr/

100 members : 30 professors and associate professors,
40 PhD students, 12 lab's staff, Post-doctoral positions, Master students, etc.

MEGEVH Network

MEGEVH
French network on HEV's

(Energy management of Hybrid and Electric Vehicles)

Coordination:
Prof. A. Bouscayrol

6 projects
4 PhDs in progress
11 PhDs defended

8 industrial partners
10 academic Labs

http://www.megevh.org/

MEGEVH philosophy

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theoretical developments

MEGEVH-macro

MEGEVH-strategy

MEGEVH-optim

MEGEVH-FC **MEGEVH-store**

experimental plate-forms


L2EP


femto-st


IFSTTAR

Reference vehicles


L2EP


PSA PEUGEOT CITROËN


IFSTTAR


nexter


femto-st


SNCF

Development of modeling and energy management methods

independently of the kind of vehicle

Paper Prize Award of IEEE-VPPC'08

Paper Prize Award of IEEE-VPPC'12

Paper Award EPE'14 ECCE Europe

Best paper Award IET-EST journal 2015

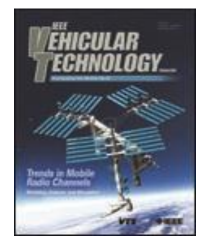
IEEE - Institute of Electrical & Electronics Engineers




- **Non-profit professional organization**
  for advancing technological innovation and excellence
- **400,000 members from 160 countries** (30 % students)
- **38 societies on technical interest**
- **Activities**
  - scientific workshop, conferences, publications, standards
  - database ***IEEE Xplore***, 3.5 millions documents, etc

IEEE Advancing Technology for Humanity

IEEE – Vehicular Technology Society (VTS)



- **Technical topics**
  - land, airborne and maritime services
  - mobile communication, vehicle electro-technology
- **2 publications and 4 annual conferences**
- **Distinguished Lecturer Program**

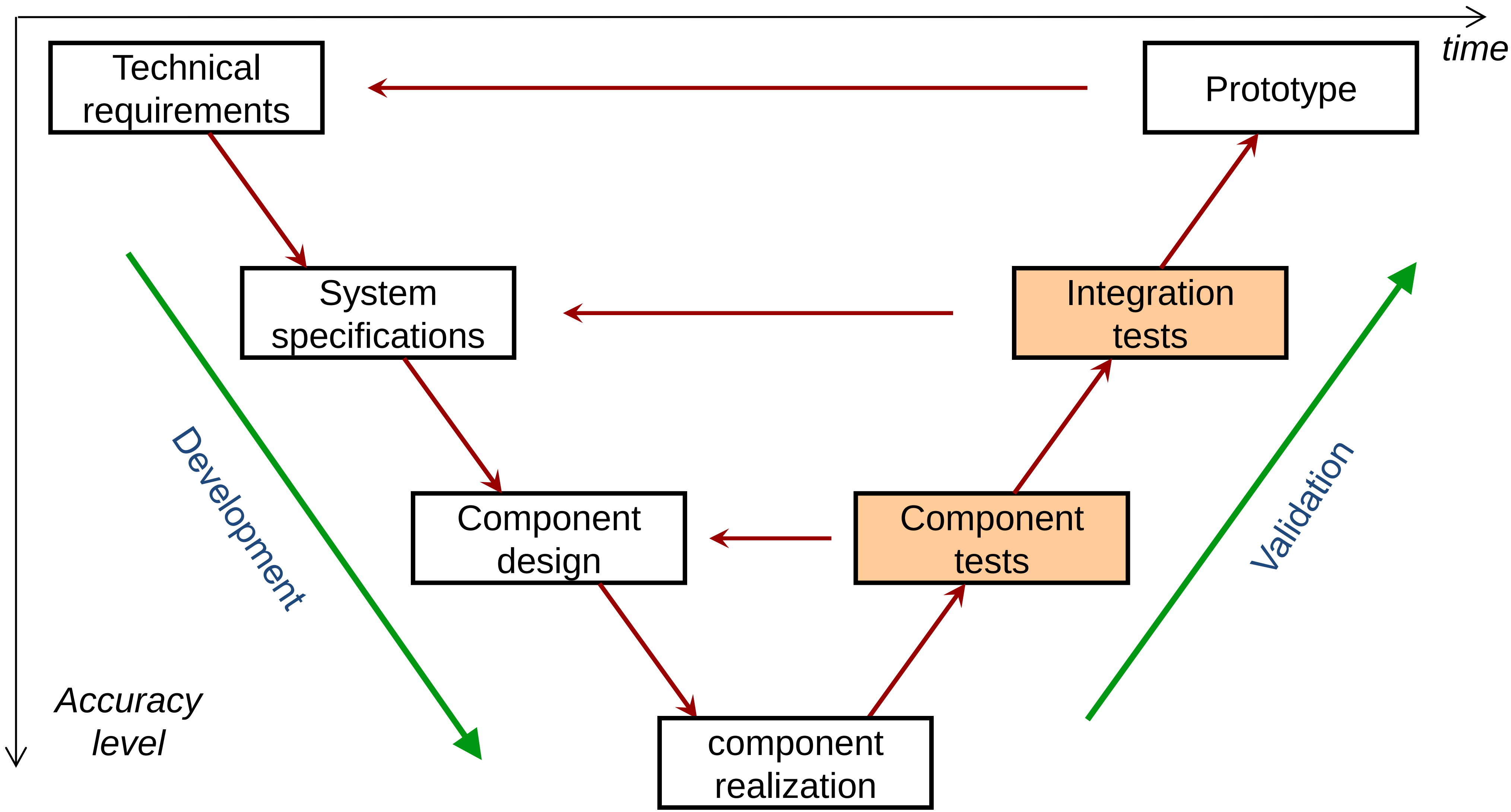
Prof. A. Bouscayrol
- HIL simulation
- EMR formalism
- EVs and HEVs

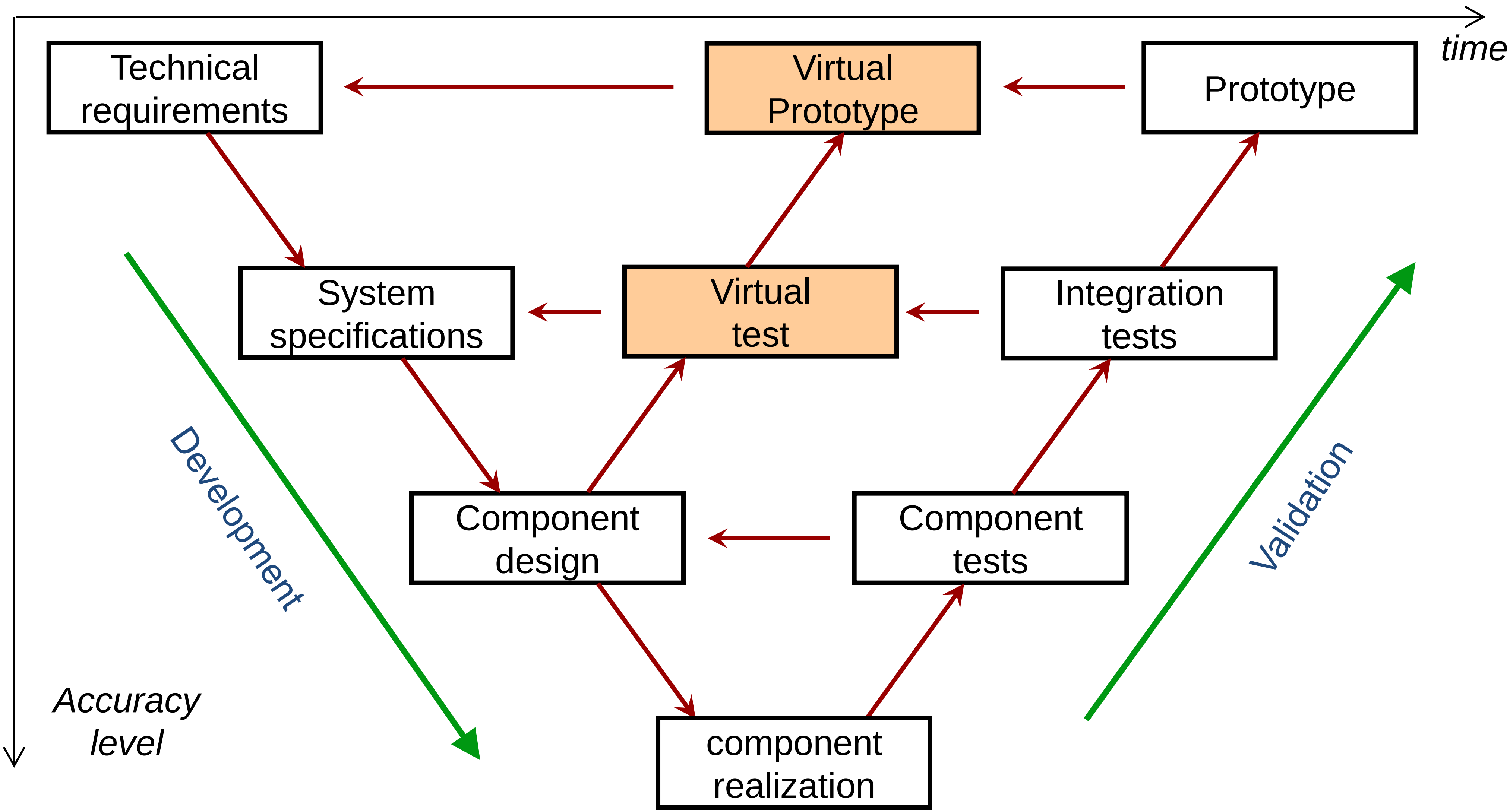
1. What is of HIL simulation?

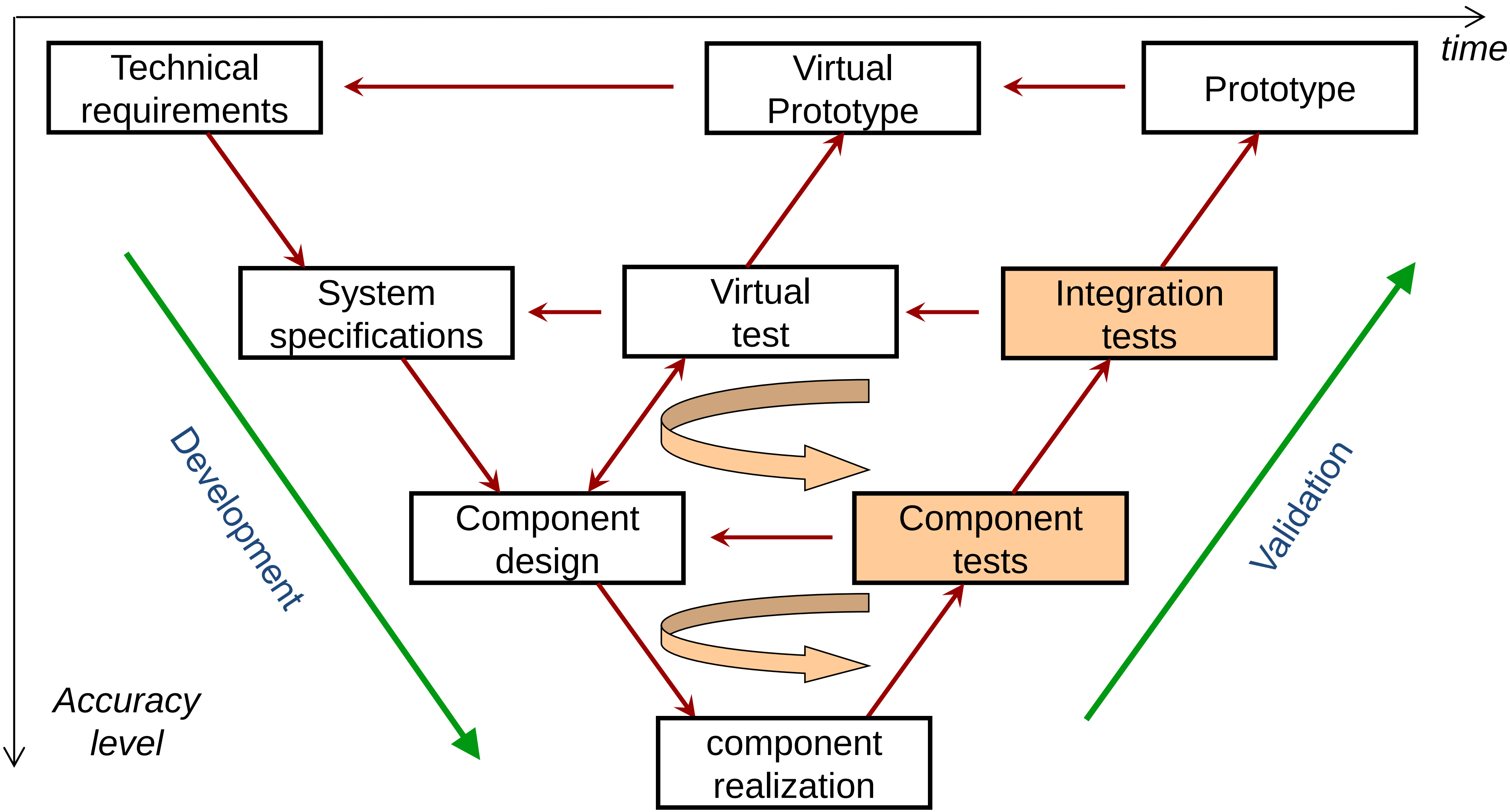
…………………

- Software simulation
- HIL simulation
- Models for HIL simulation

Industrial V-cycle




time
Technical requirements
Virtual Prototype
Prototype
System specifications
Virtual test
Integration tests
Component design
Component tests
component realization
Development
Validation
Accuracy level



time
Technical requirements
Virtual Prototype
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Virtual test
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component realization
Development
Validation
Accuracy level

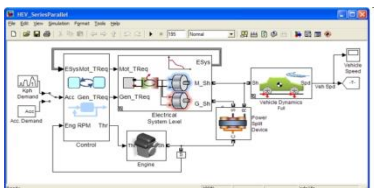
Example of an EV

prototype

production

http://www.renault.com

simulation



HIL platform

Component design

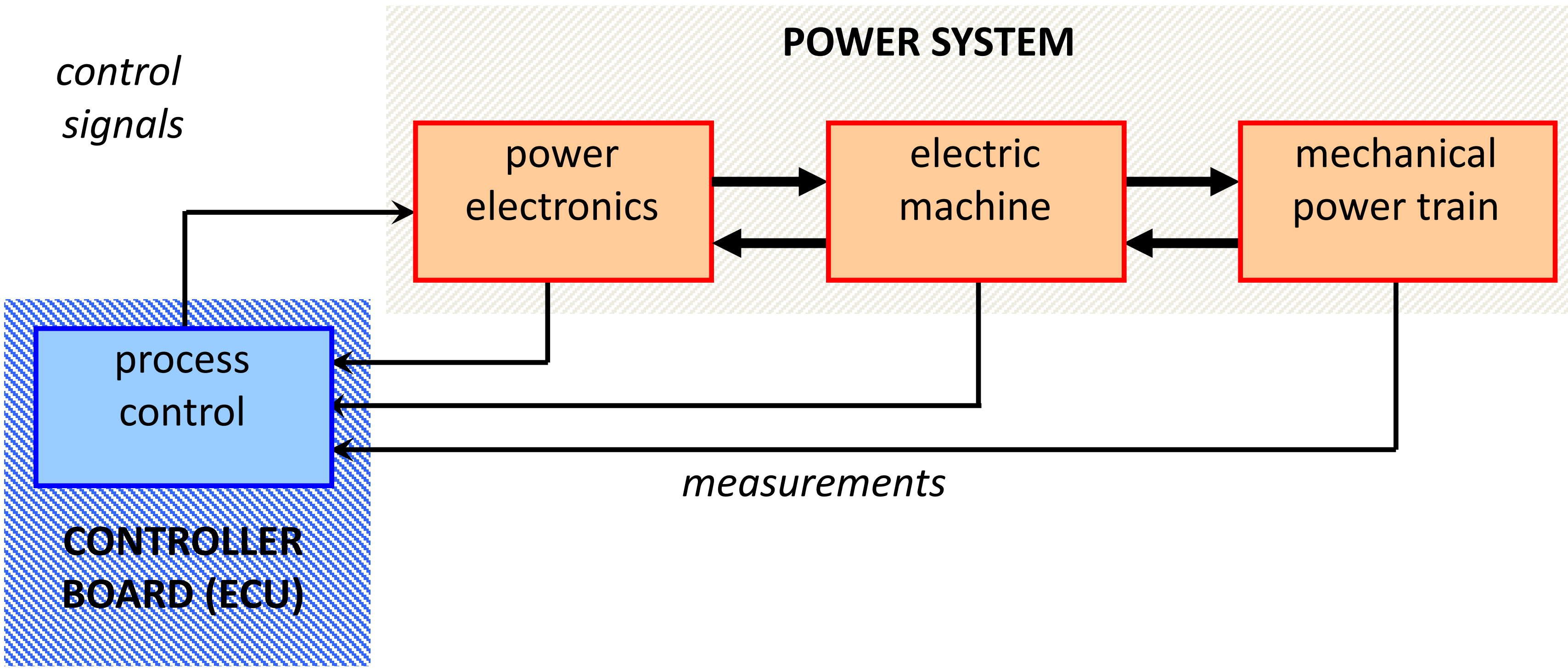
Component tests

component realization

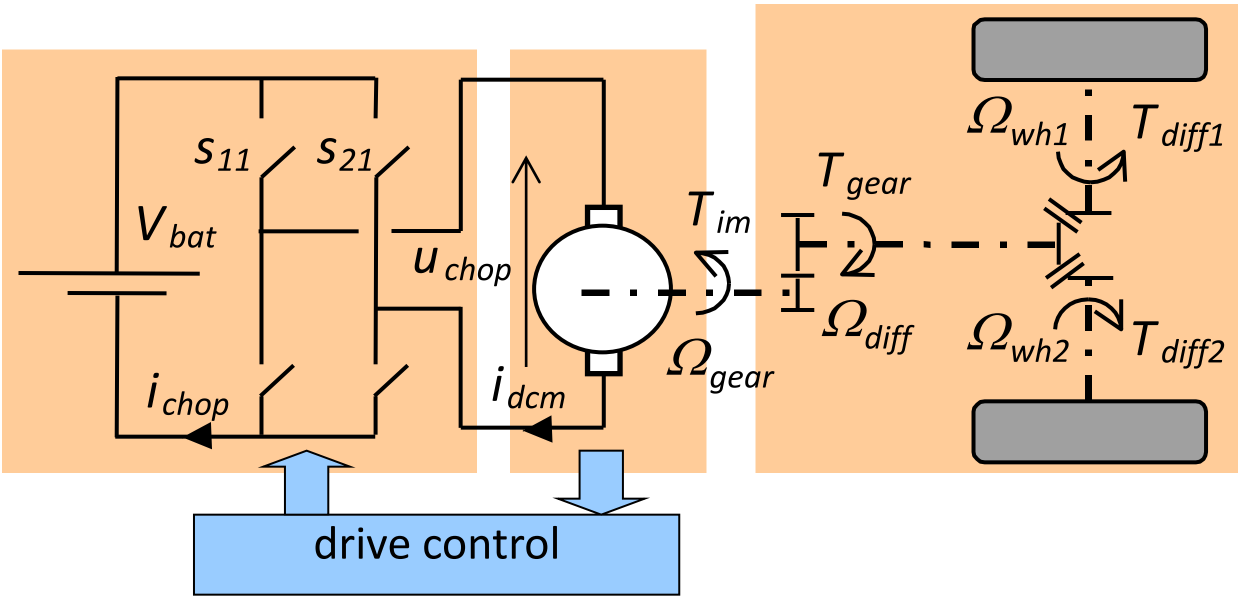
the more test are made at HIL
the less prototypes are developed

System & control

Example of an electric drive for traction



How to develop the system? ⇨ Software simulation



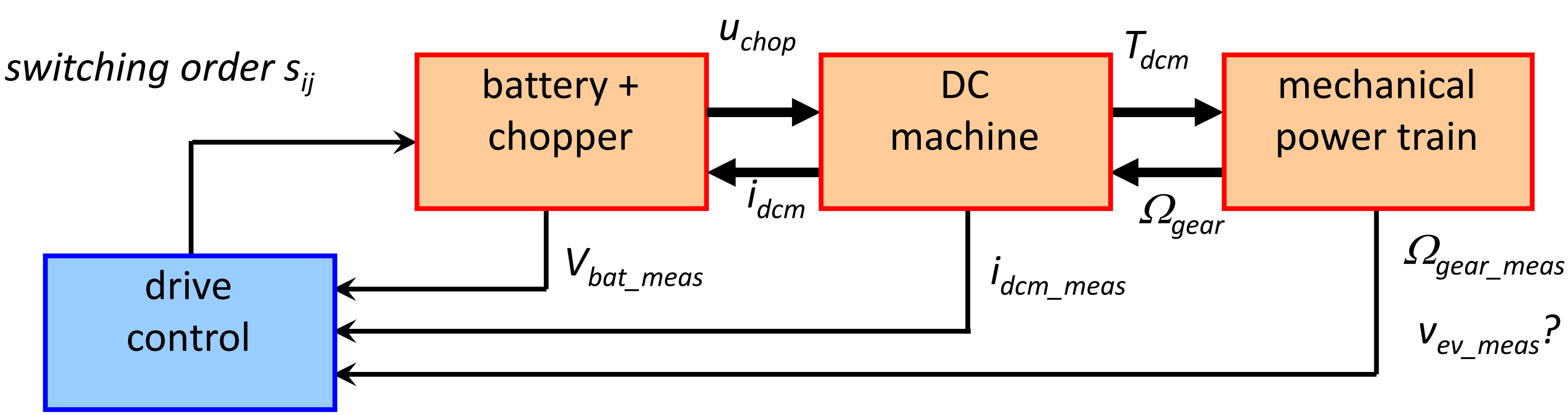
Traction of an EV:

Battery + chopper

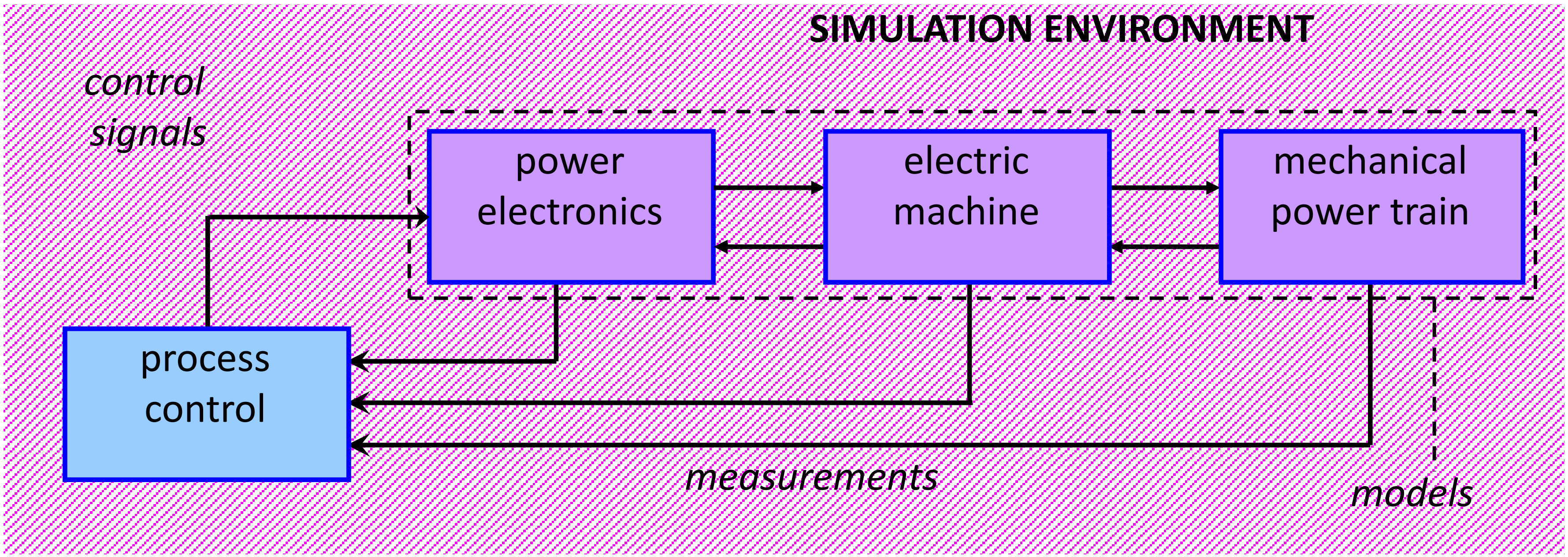
+ DC machine

+ differential

+ 2 driven wheels



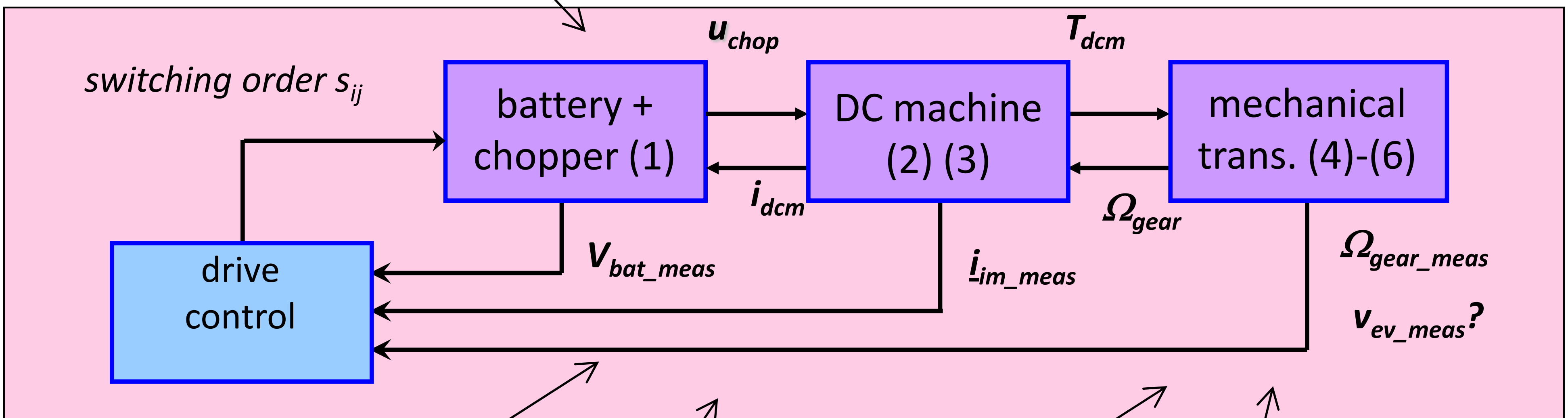
simulation of the system and the control in a simulation software:
development / safety / gain of time ...



Example of an EV traction system

$$\begin{cases} u_{chop} = m_{chop} V_{bat} \\ i_{chop} = m^{t}_{chop} i_{dcm} \end{cases} \quad (1)$$

Assumptions: 1 single equivalent wheel



$$u_{chop} = L \frac{d}{dt} i_{dcm} + R i_{dcm} + e_{dcm} \quad (2)$$

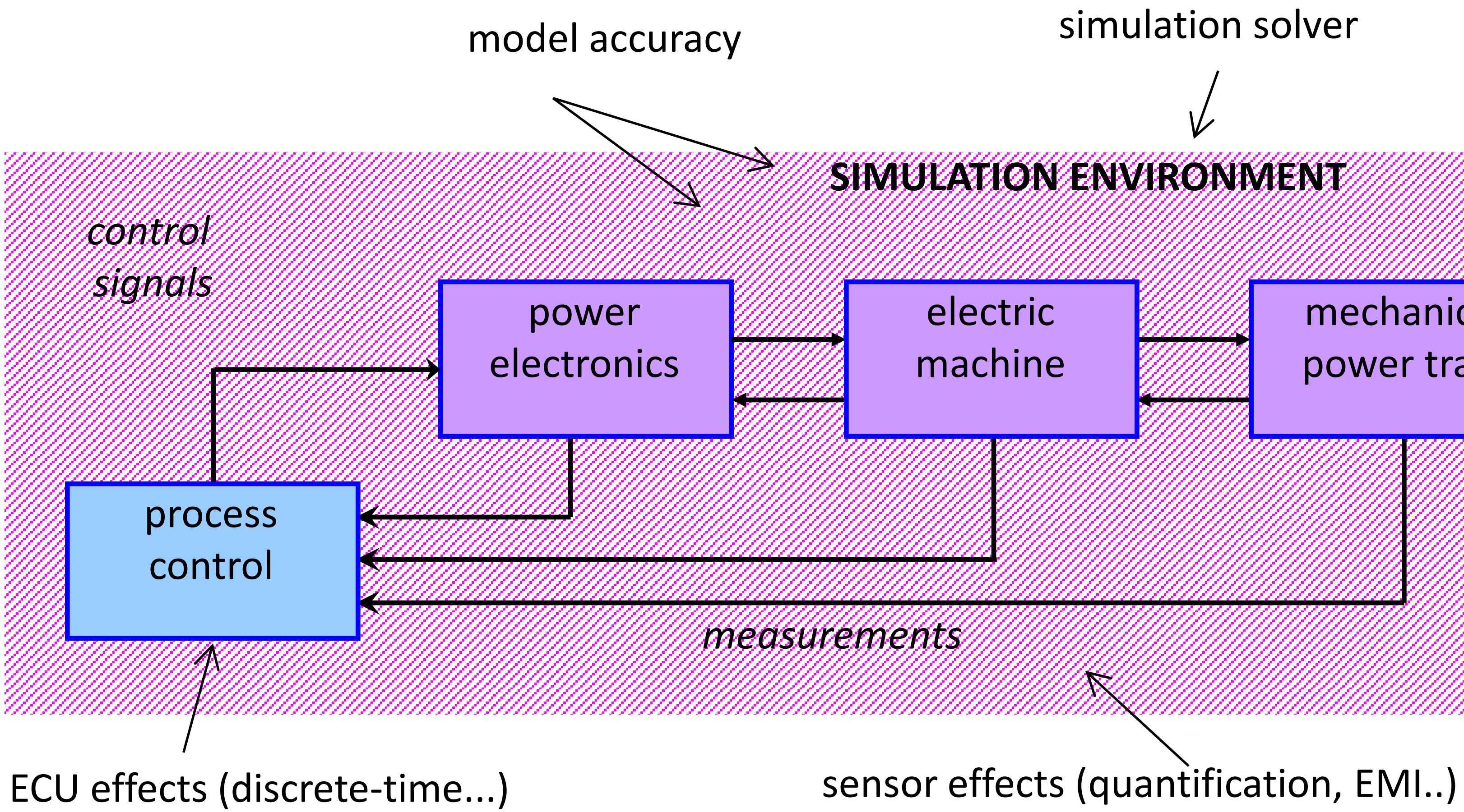
$$\begin{cases} T_{dc} = k_{\Phi} i_{dcm} \\ e_{dcm} = k_{\Phi} \Omega_{gear} \end{cases} \quad (3)$$

$$\begin{cases} F_{tract} = \dfrac{m_{gear}}{R_{wh}} T_{dcm} \\ \Omega_{gear} = \dfrac{m_{gear}}{R_{wh}} v_{ev} \end{cases} \quad (4)$$

$$F_{tract} - F_{res} = M \frac{d}{dt} v_{ev} \quad (5)$$

$$F_{res} = F_0 + A v_{ev}^2 + Mg \sin\alpha \quad (6)$$

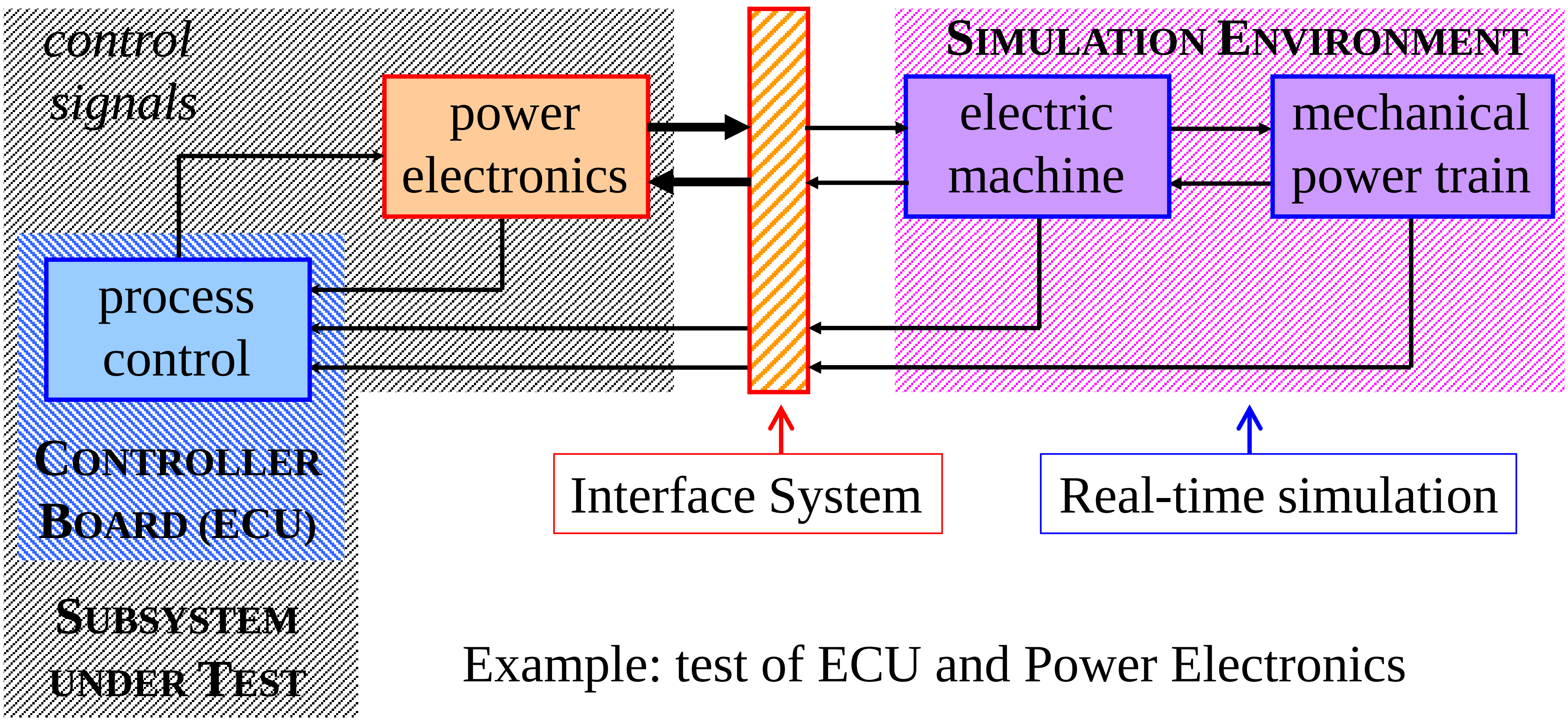
Limitation of software simulation



How to check subsystems before real-time implementation?

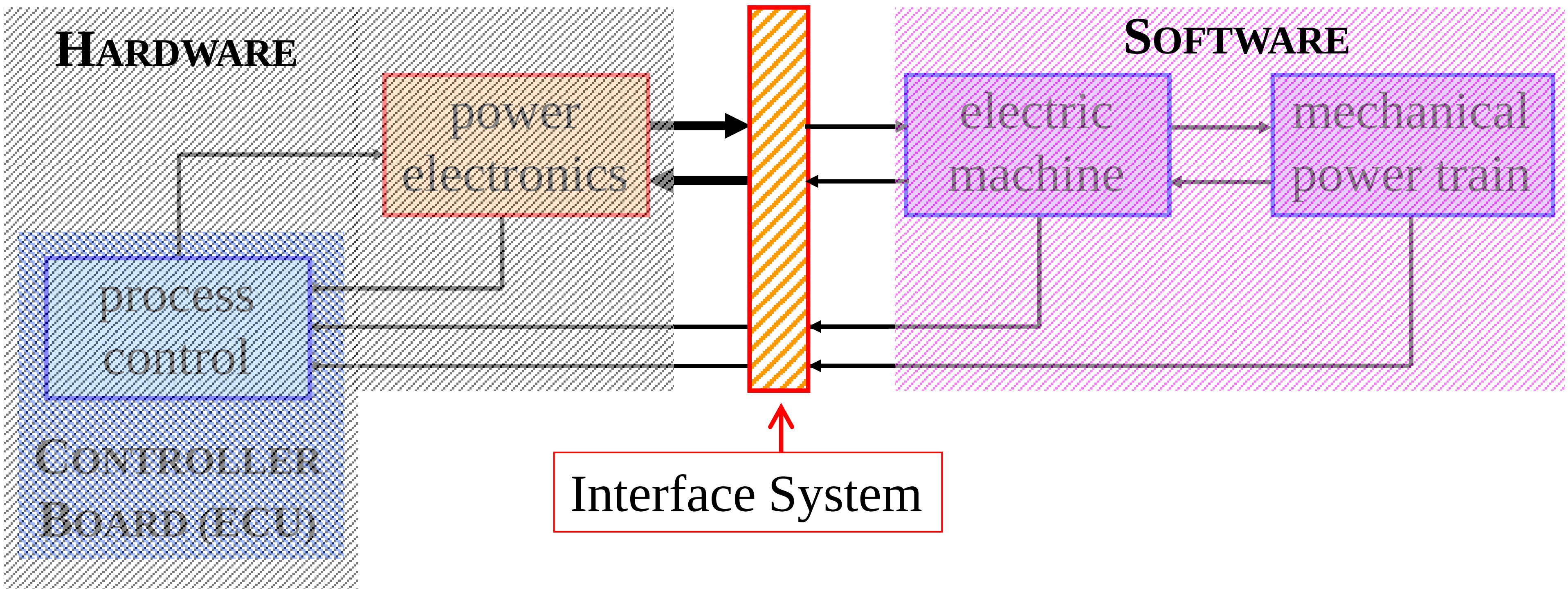
⇨ HIL simulation?

Hardware-In-the-Loop (HIL) simulation:
one simulation part is replaced by an actual part



Example: test of ECU and Power Electronics

HIL simulation:
Includes a hardware part, a software part and **a specific interface**



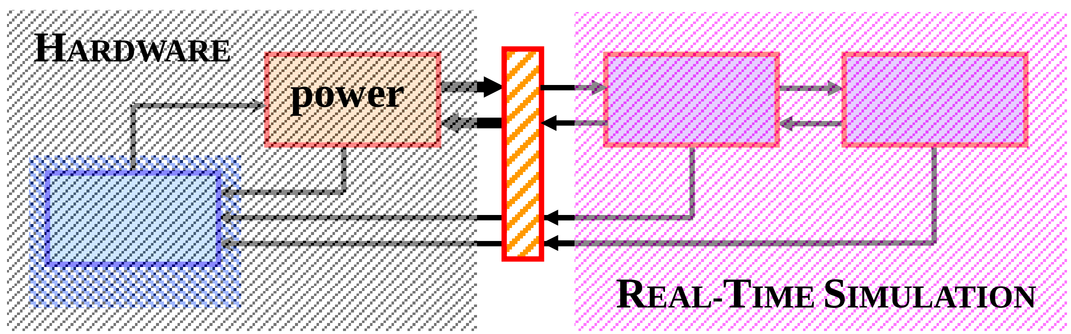
HIL simulation = Real-time simulation (but including a hardware part)
= Emulation

HIL simulation =

Hardware (energy conversion) → energetic model

+ Models computed in real-time → causal model

in dynamic interactions → dynamical model



efficient results require:

- an accurate model!
- an ideal interface system

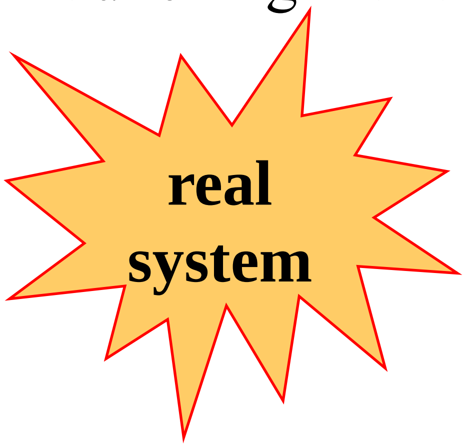
2. Which models for HIL simulation?

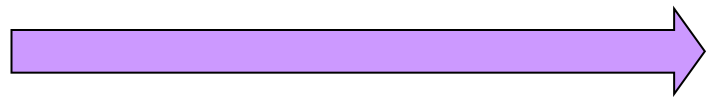
…………………

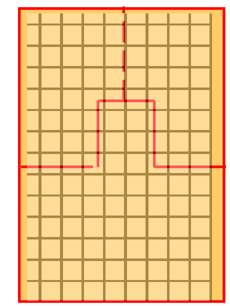
- **Models and organization**
- **Systemics and interaction**

Simulation for ever!

Launching Matlab/Simulink is more and more a "Pavlov reflex"







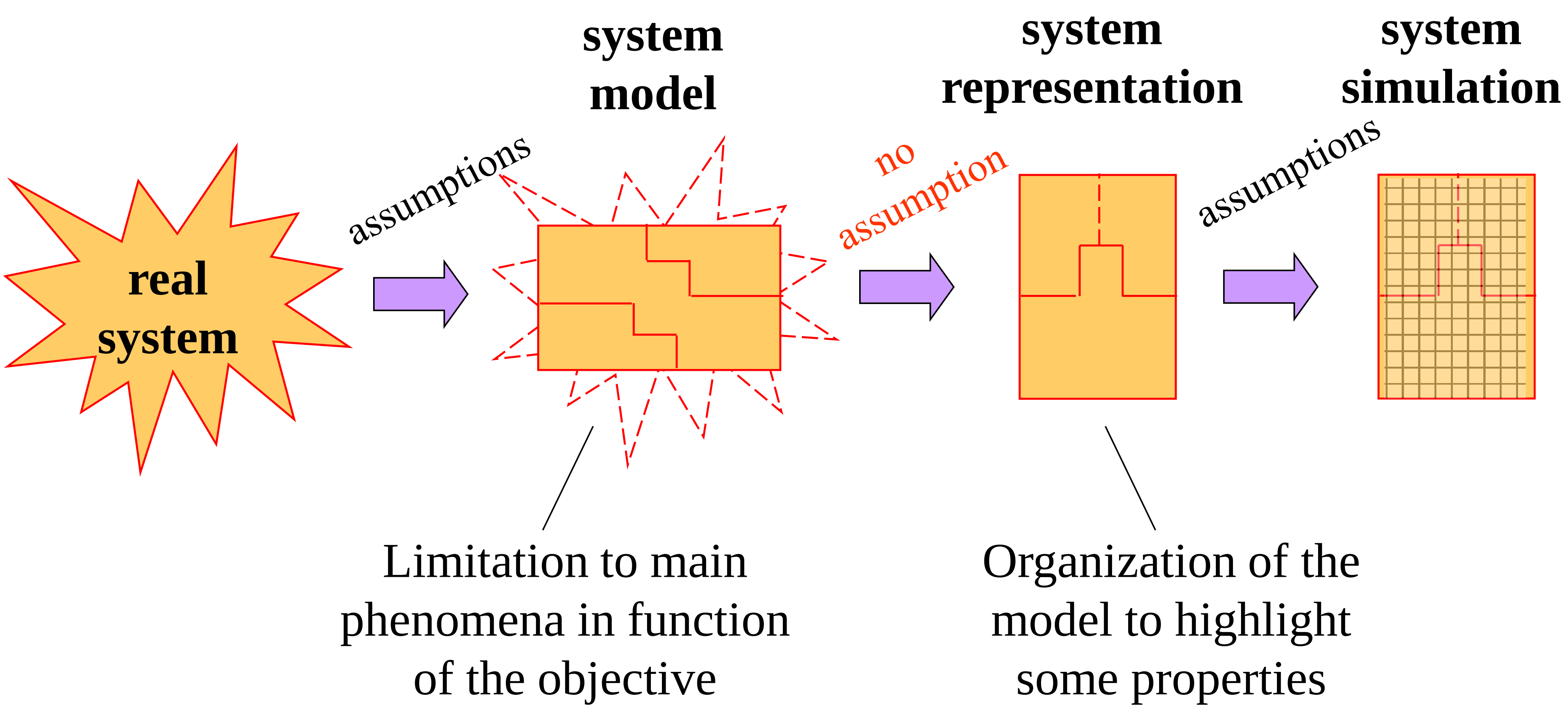
system simulation

↓

behavior study

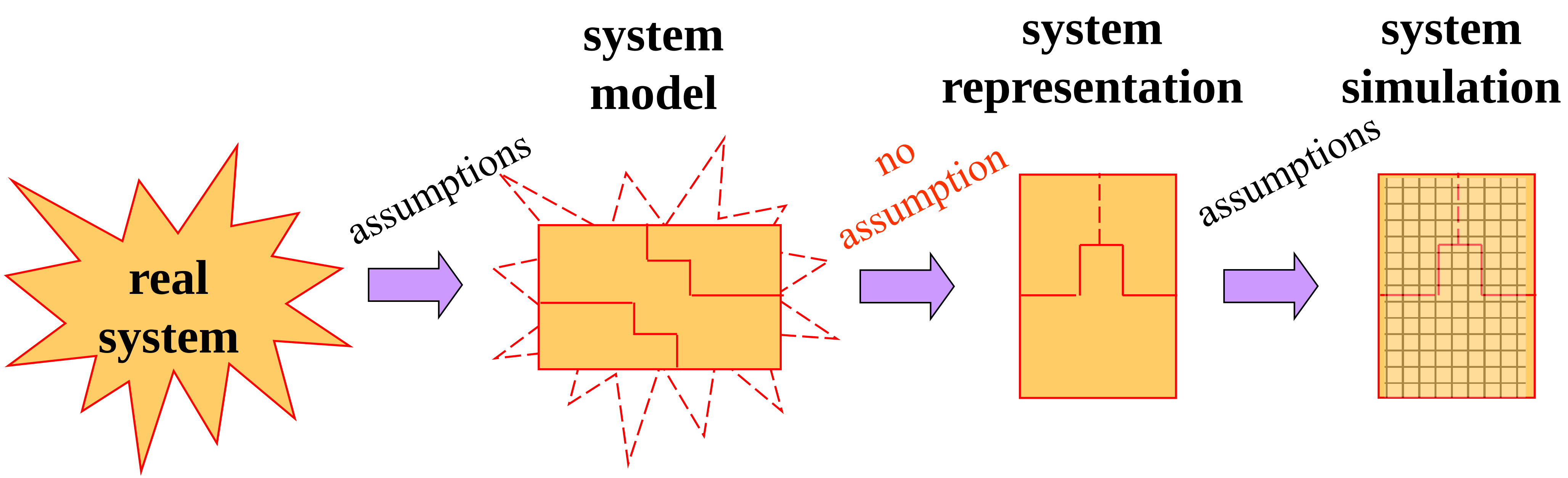
But:

- Why simulation?
- Which constraints and objectives?
- Which level of accuracy?
- How to be sure of the results?



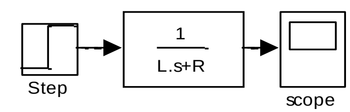
Intermediary steps are required for complex systems

Basic example



$$v_l = L\frac{d}{dt}i_L + Ri_L$$

$$V_L \rightarrow \boxed{\frac{1}{R+Ls}} \rightarrow I_L$$



smoothing inductor

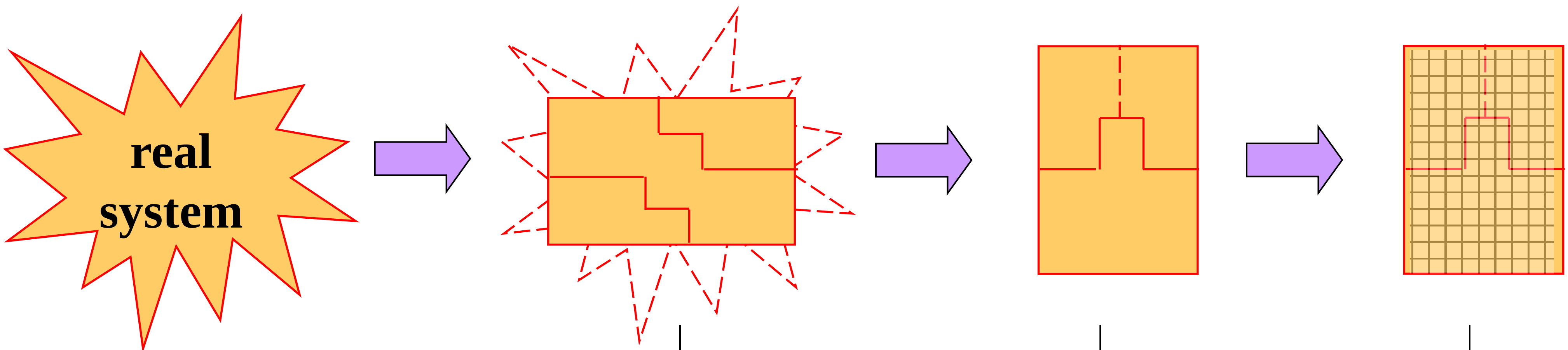
(low frequency dynamical model)

(bloc diagram +Laplace)

(Simulink © +Runge Kutta)

Different categories

system model | **system representation** | **system simulation**



- **system model**
  - dynamic / quasi-static / static
- **system representation**
  - structural/functional
  - causal/non-causal
- **system simulation**
  - backward / forward

Different possibilities at each step in function of the objective

Static vs. dynamical models

Which model subsystem?

Static model

- steady state operations
- no transient states
- fast computation time
- global behavior

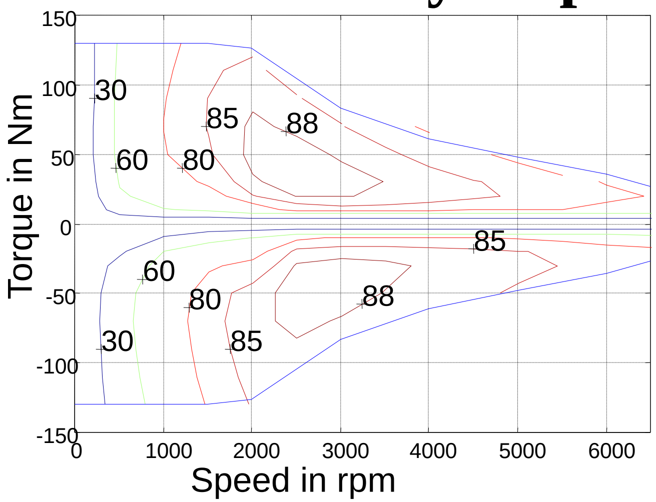
Dynamical model

- transient state operations
- but also steady state operations
- long computation time
- detailed behavior

Quasi-static model

- static model + main time constant
- intermediary computation time
- intermediary behavior

static efficiency map



$$i_{DC} = \frac{T_{em}\Omega + P_t(T_{em},\Omega)}{U_{DC}}$$

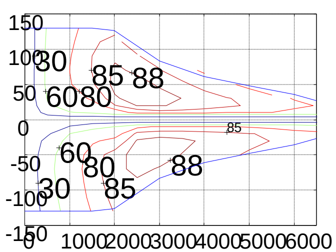
dynamic model

$$\begin{cases} V_{Sd} = R_S i_{Sd} + \frac{d\phi_{Sd}}{dt} - \omega_S \phi_{Sq} \\ V_{Sq} = R_S i_{Sq} + \frac{d\phi_{Sq}}{dt} + \omega_S \phi_{Sd} \\ 0 = R_R i_{Rd} + \frac{d\phi_{Rd}}{dt} - \omega_R \phi_{Rq} \\ 0 = R_R i_{Rq} + \frac{d\phi_{Rq}}{dt} + \omega_R \phi_{Rd} \end{cases}$$

$$T_{em} = p\frac{L_m}{L_R} \cdot (\phi_{Rd} \cdot i_{Sq} - \phi_{Rq} \cdot i_{Sd})$$

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

quasi-static model



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

How to describe a system?

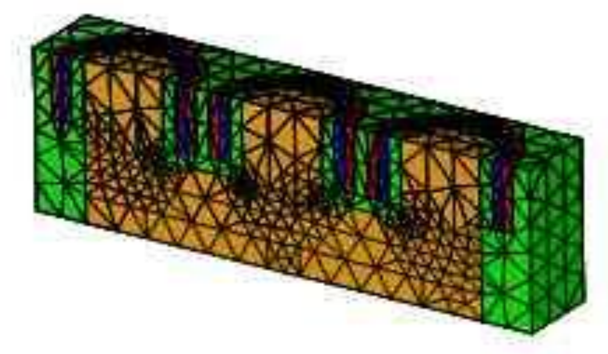
Structural description

- Physical structure in priority
- Physical links between subsystems
- Design application

Functional description

- function priority
- Virtual links between subsystems
- Analysis and control application

<u>*Example*</u>



3D Finite Element Model

$$\begin{cases} \underline{v}_2 = m\,\underline{v}_1 \\ \underline{i}_1 = m\,\underline{i}_2 \end{cases}$$

Mathematic model

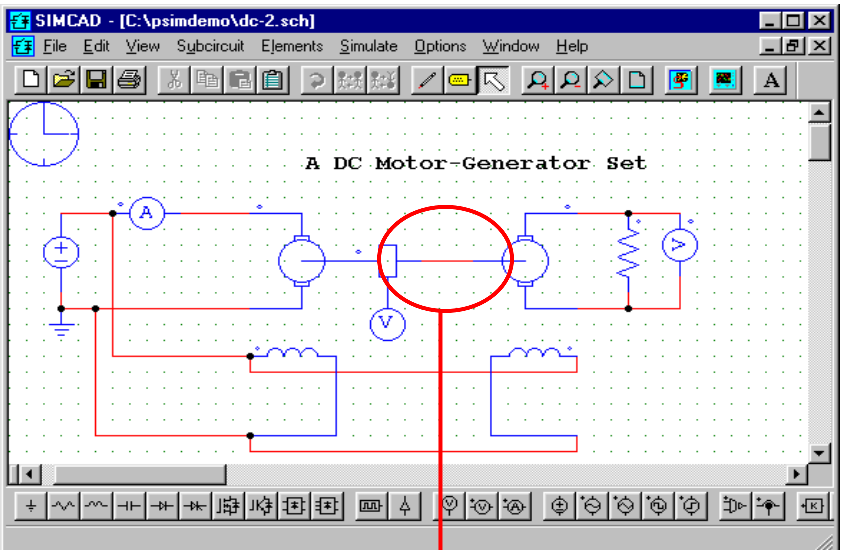
Assumption:

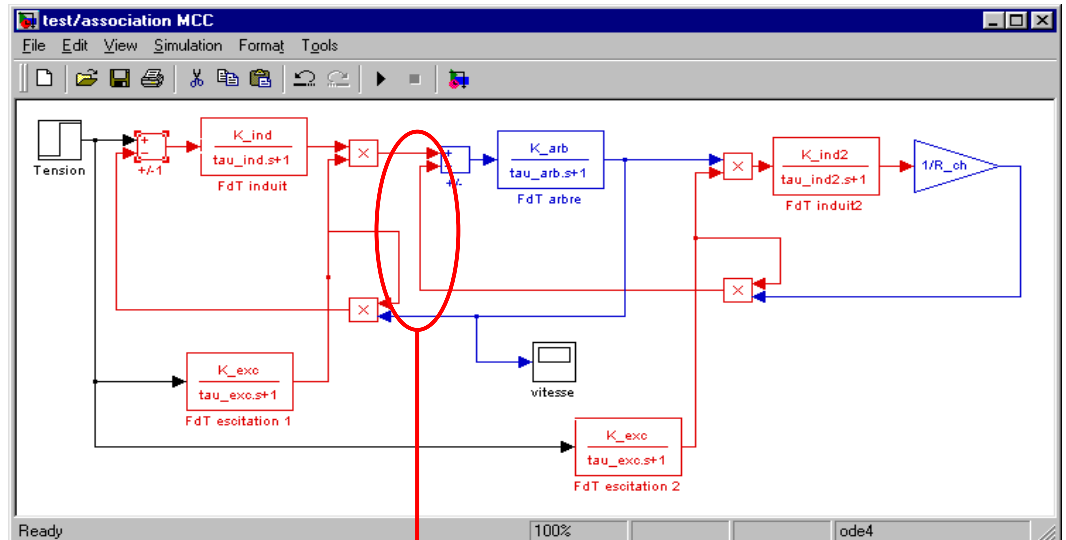
Ideal transformer

two DC machine system

PSIM (structural)

Matlab-Simulink (functionnal)

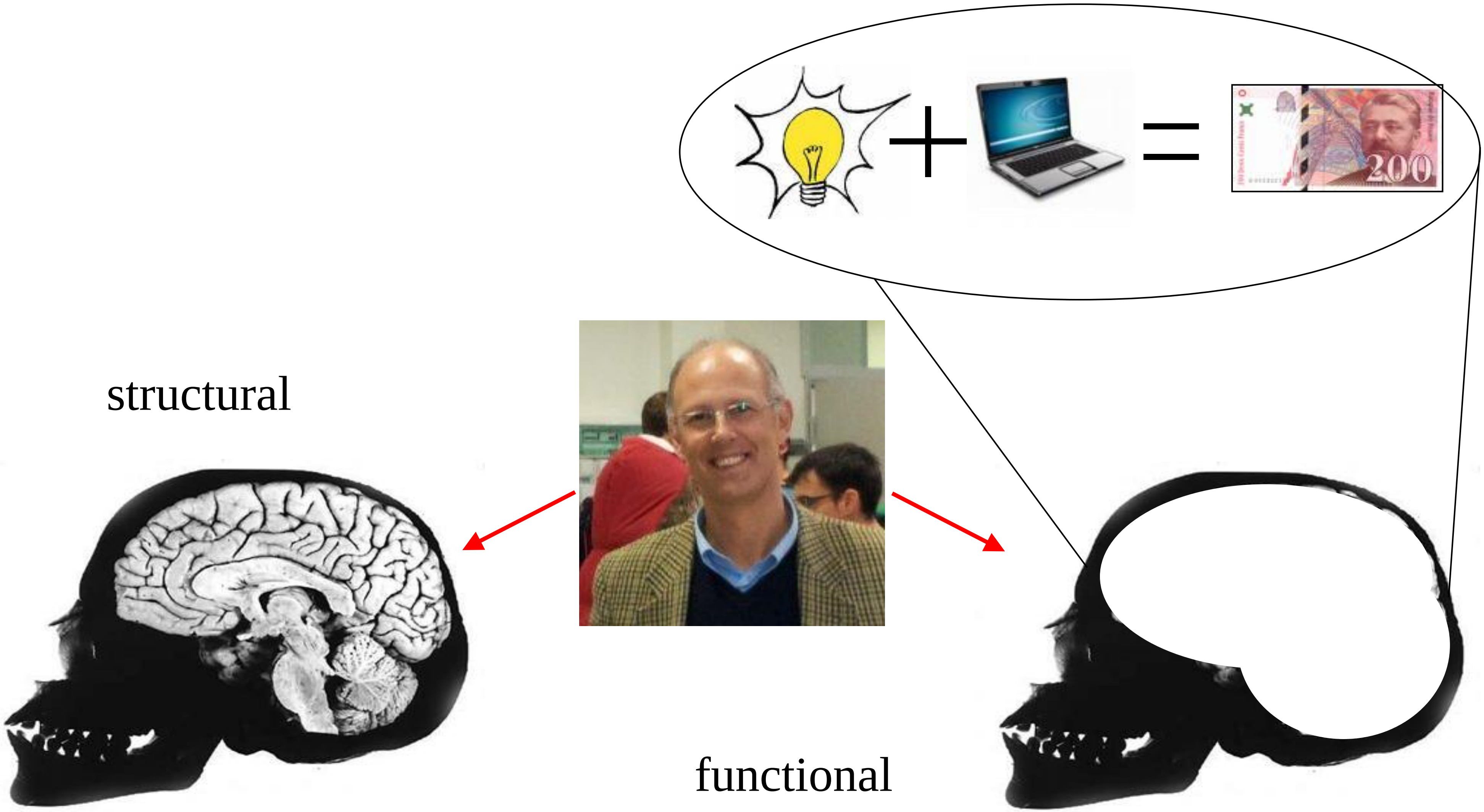




machines connected by
a unique link (shaft)

machines connected by
two links (torque/speed)

Structural vs. functional description (example)



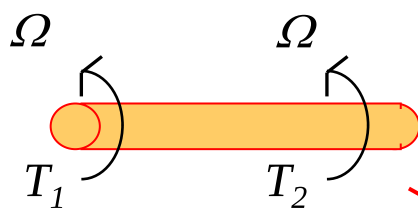
How to connect subsystem?

Causal description

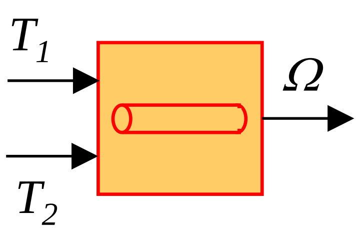
- fixed input and output
- output = integral function of inputs
- difficult interconnection subsystems
- basic solver

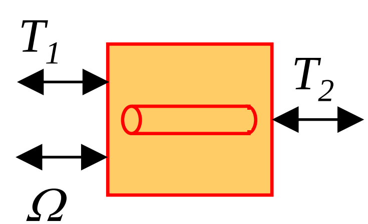
Non-causal (acausal) description

- non-fixed inputs and outputs
- different relationships
- easy subsystem interconnection
- specific solver required
- simulation library

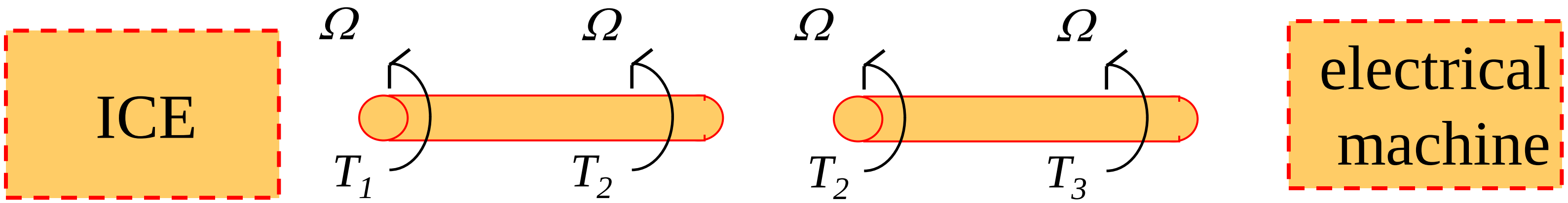


$$J\frac{d}{dt}\Omega = T_1 - T_2$$



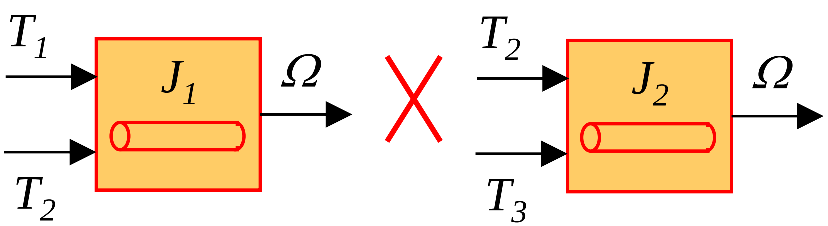


Example

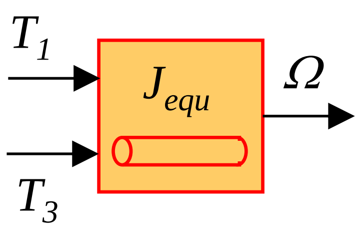


$$J_1 \frac{d}{dt}\Omega = T_1 - T_2 \qquad J_2 \frac{d}{dt}\Omega = T_2 - T_3$$

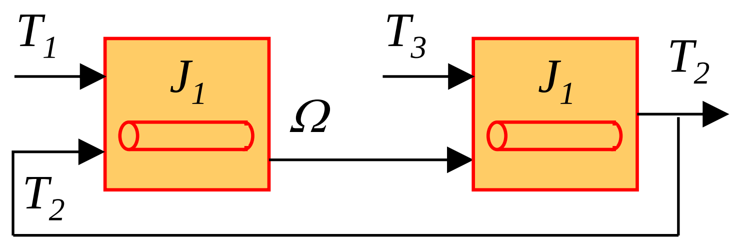
causal description



$$(J_1 + J_2)\frac{d}{dt}\Omega = T_1 - T_3$$



acausal description



derivative relationship

specific solver

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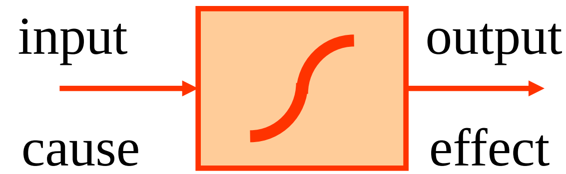
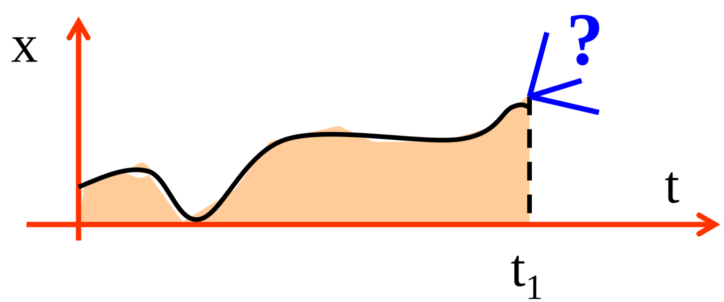
Principle of causality
physical causality is integral





$\int xdt$ ⇨ area ⇩ knowledge of past evolution

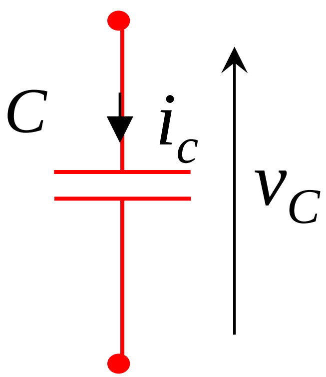
OK in real-time

~~slope~~ ⇦ ~~$\frac{dx}{dt}$~~ ⇩ ~~knowledge of future evolution~~

impossible in real-time

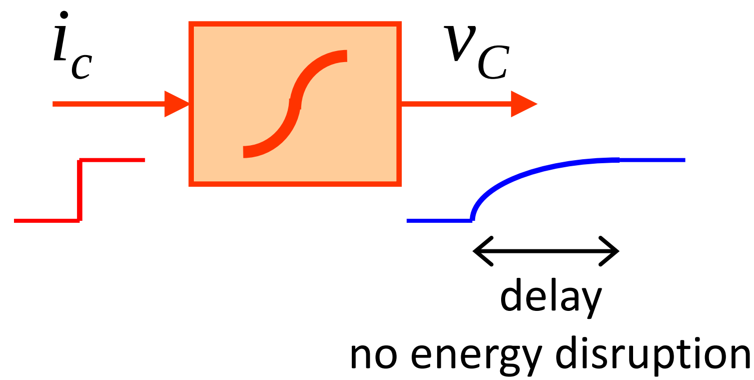
Causality principle

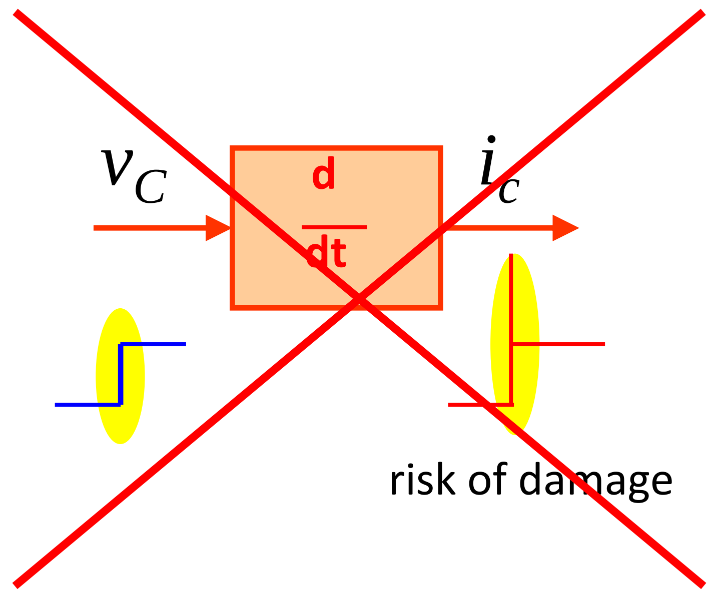
Example



$$i_c = C\frac{d}{dt}v_c$$

$$E_c = \frac{1}{2}v_c^{\;2}$$

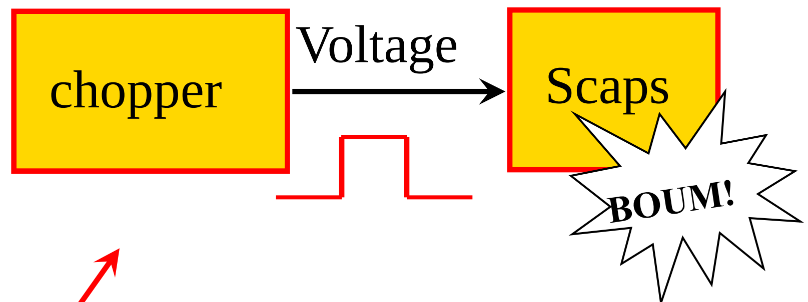


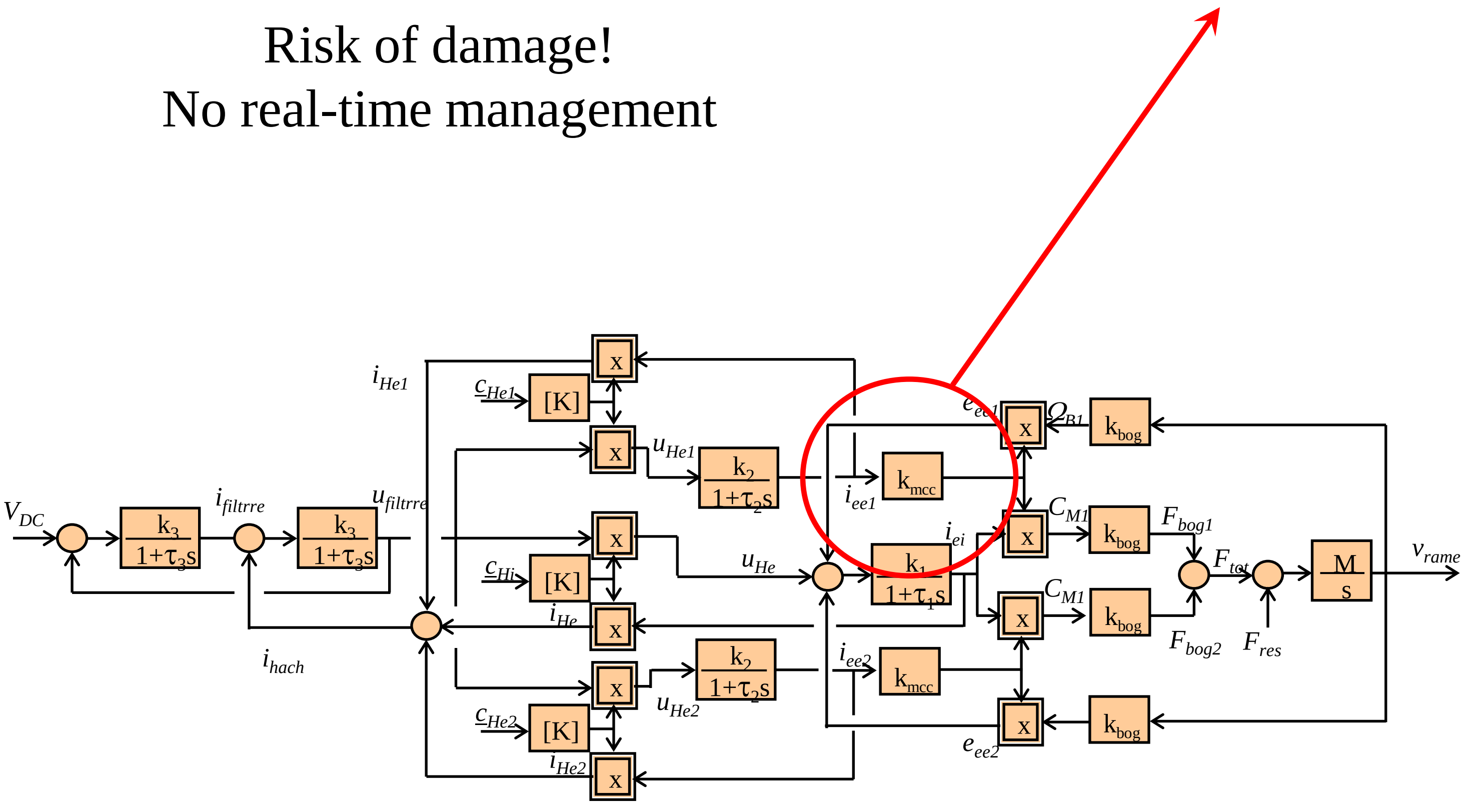


For energetic systems
physical causality is VITAL

If the causality principle is not respected for 1 subsystem

Risk of damage!
No real-time management





Causality mistake

When you discover a new process (!)

You should apply the right Input…
If not…

Don't forget to respect causality!

Systemic vs. Cartesian approach

System = interconnected subsystems

Systemic approach
Study of subsystems and their interactions
Holistic property: associations of subsystem induce new global properties.

Cartesian approach
The study of subsystems is sufficient to know the system behaviour.

Cybernetic systemic
black box approach.
behaviour model

Cognitive systemic
physical laws
knowledge model

For better performances of a system
Interactions and physical laws must be considered!

Expected results

System 1 vs. System 2

Group made of individualists

↓

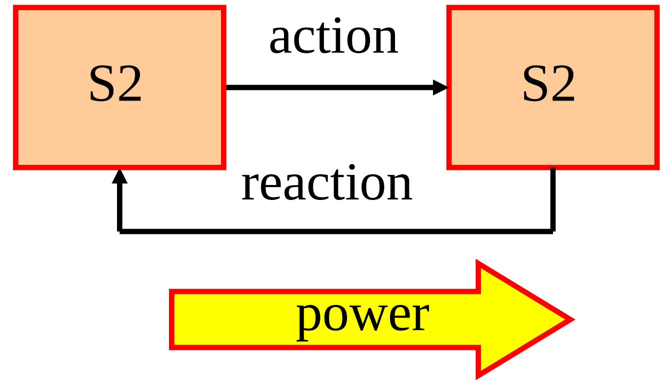
Cartesian approach

Team made of partners

↓

Systemic approach

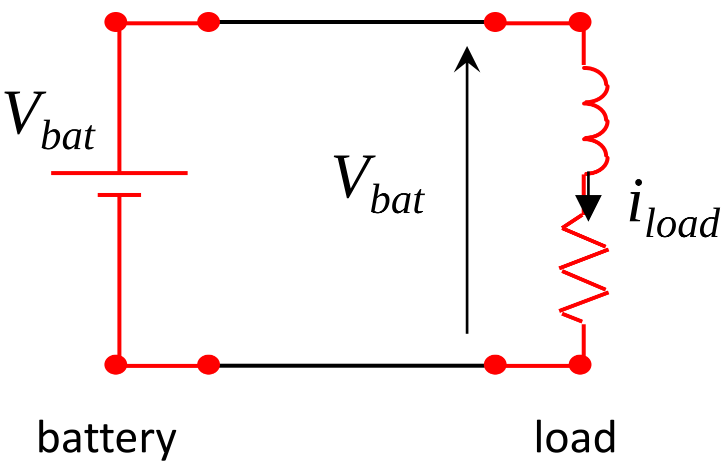
Brazil 1 – 7 Germany

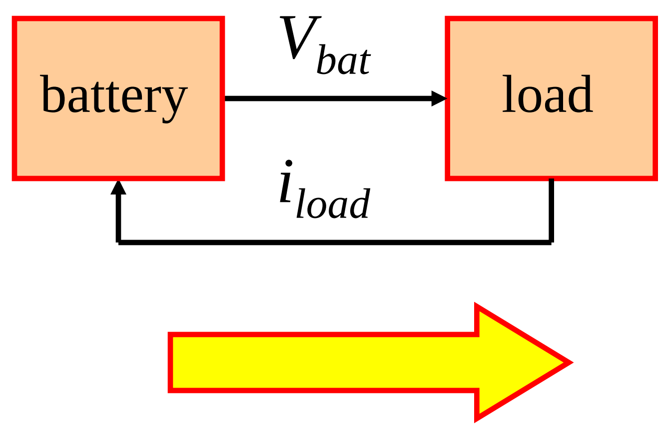


Interaction principle
Each action induces a reaction

Power exchanged by S1and S2 = action x réaction

Example

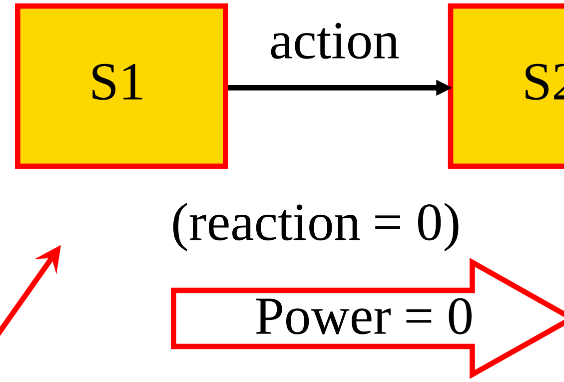


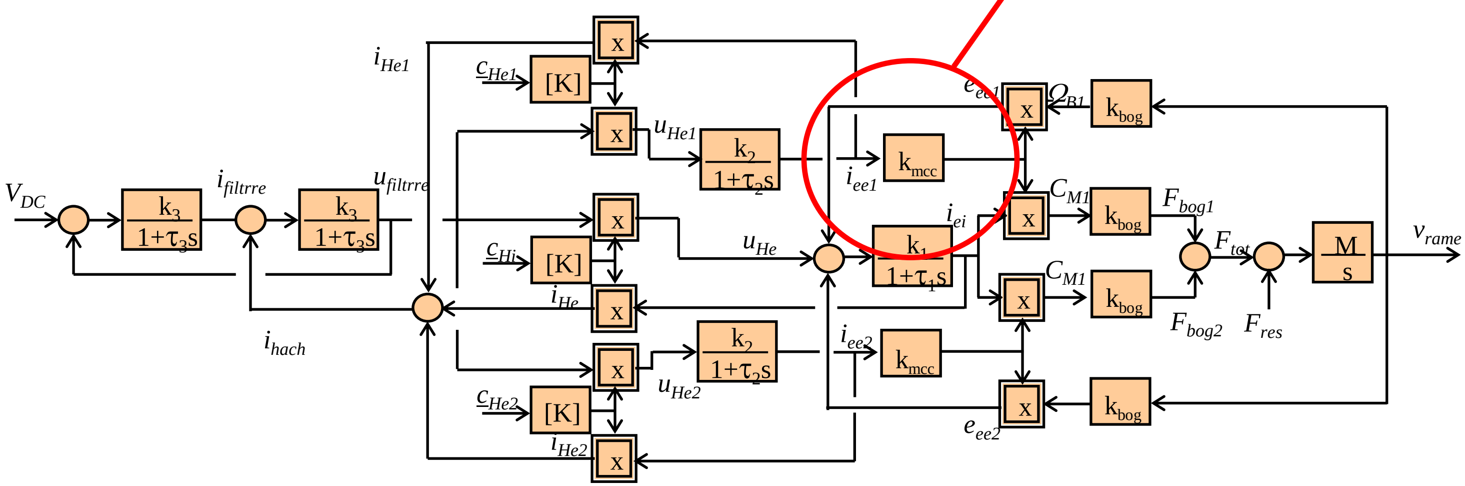


$$P = V_{bat}\, i_{load}$$

If the interaction principle is not respected for 1 subsystem

Error in the energy analysis for the whole system



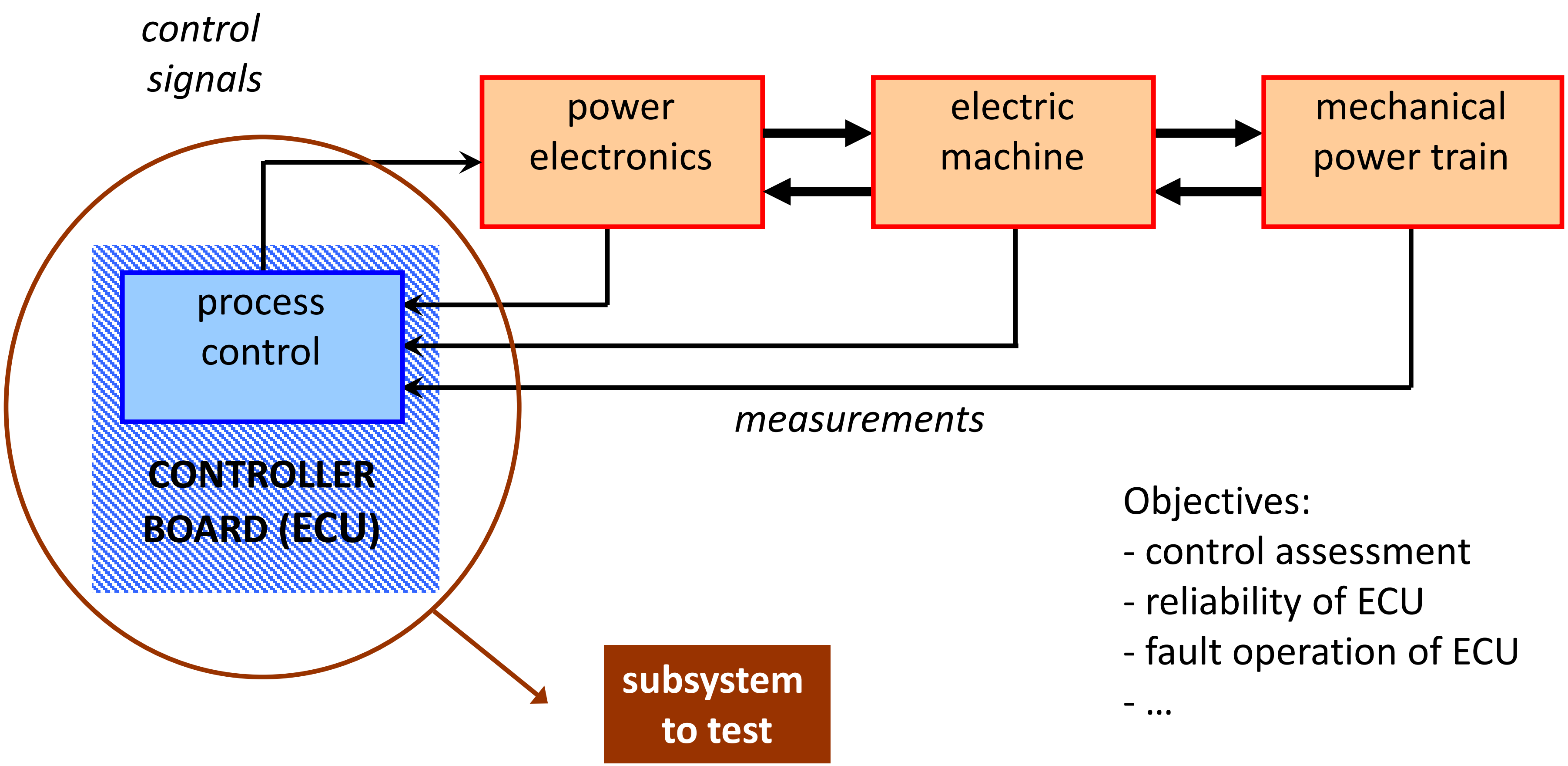


3. Different types of HIL simulation

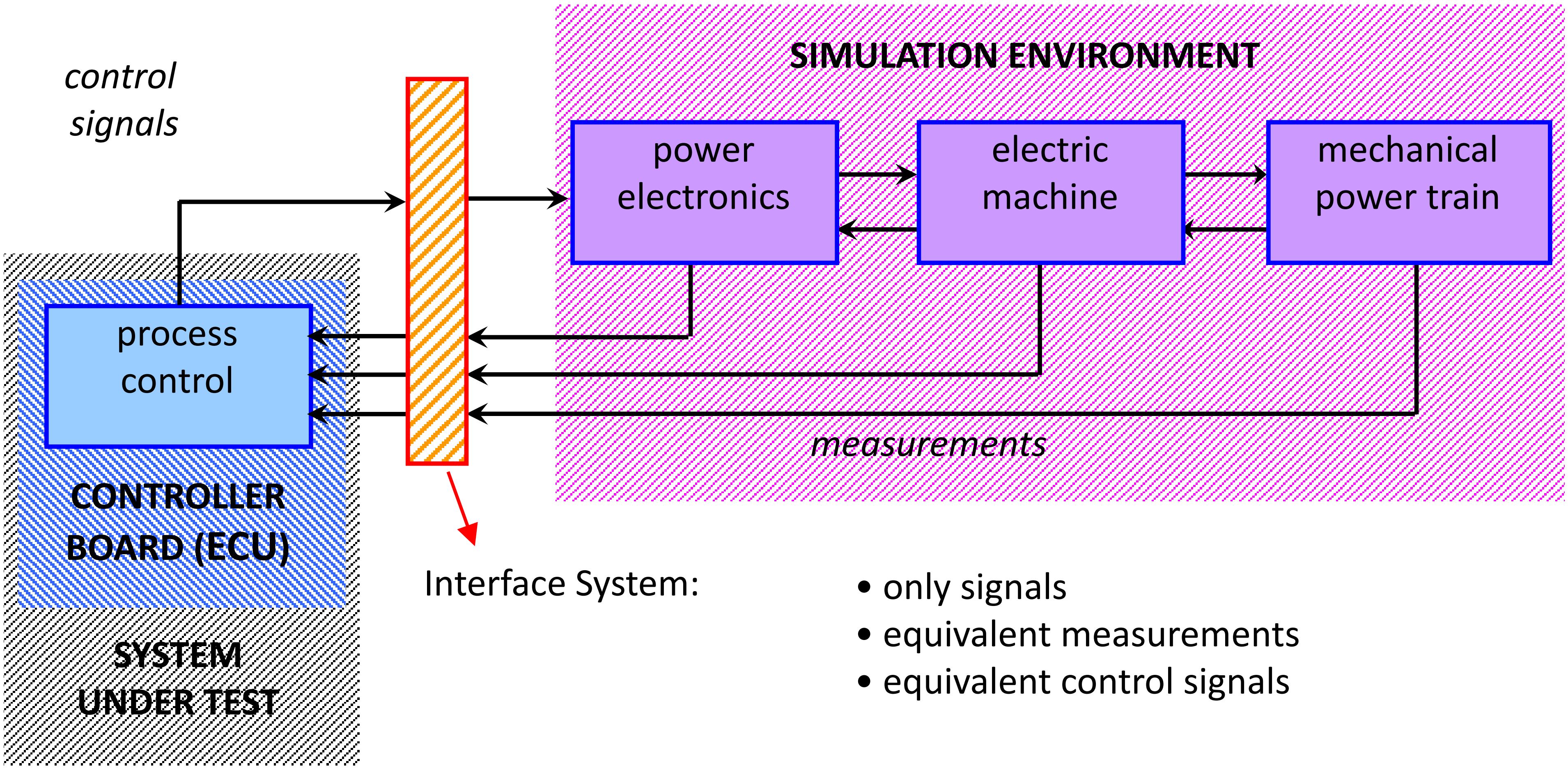
…………………

- **Signal HIL simulation**
- **Power HIL simulation**

The actual controller board containing the process control is tested.



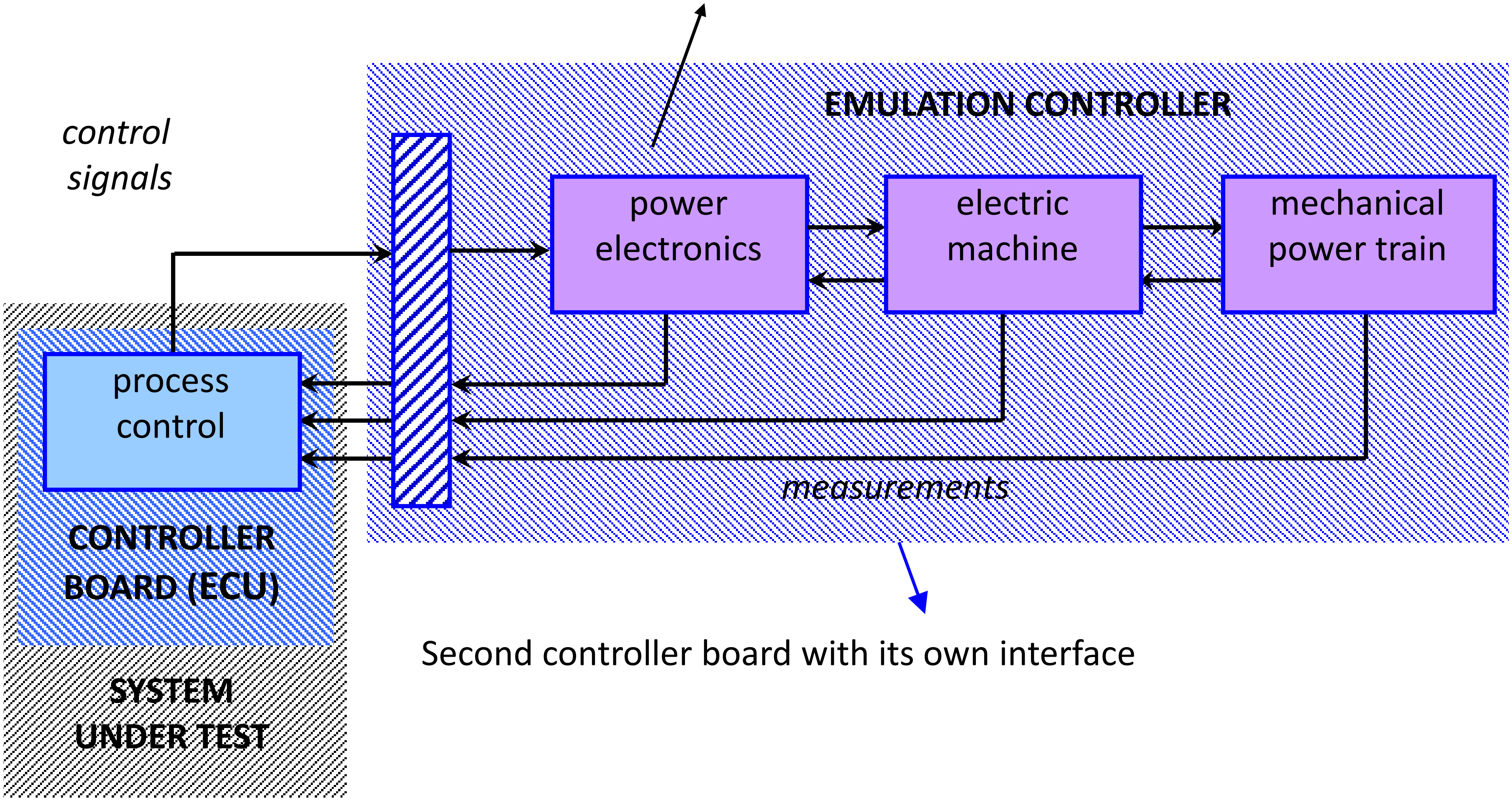
Objectives:
- control assessment
- reliability of ECU
- fault operation of ECU
- …



Interface System:

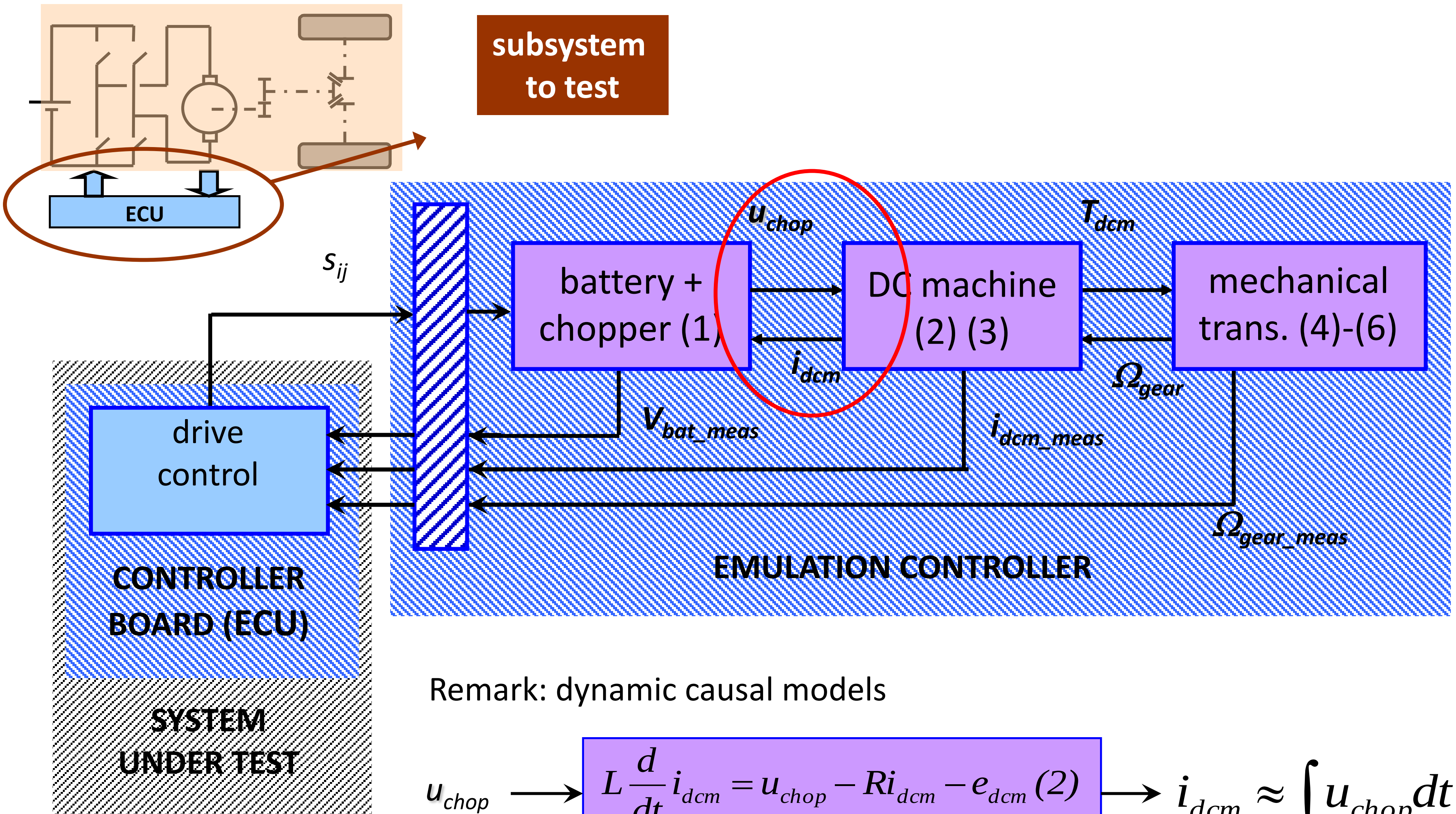
- only signals
- equivalent measurements
- equivalent control signals

Fast dynamic: FPGA?



Second controller board with its own interface

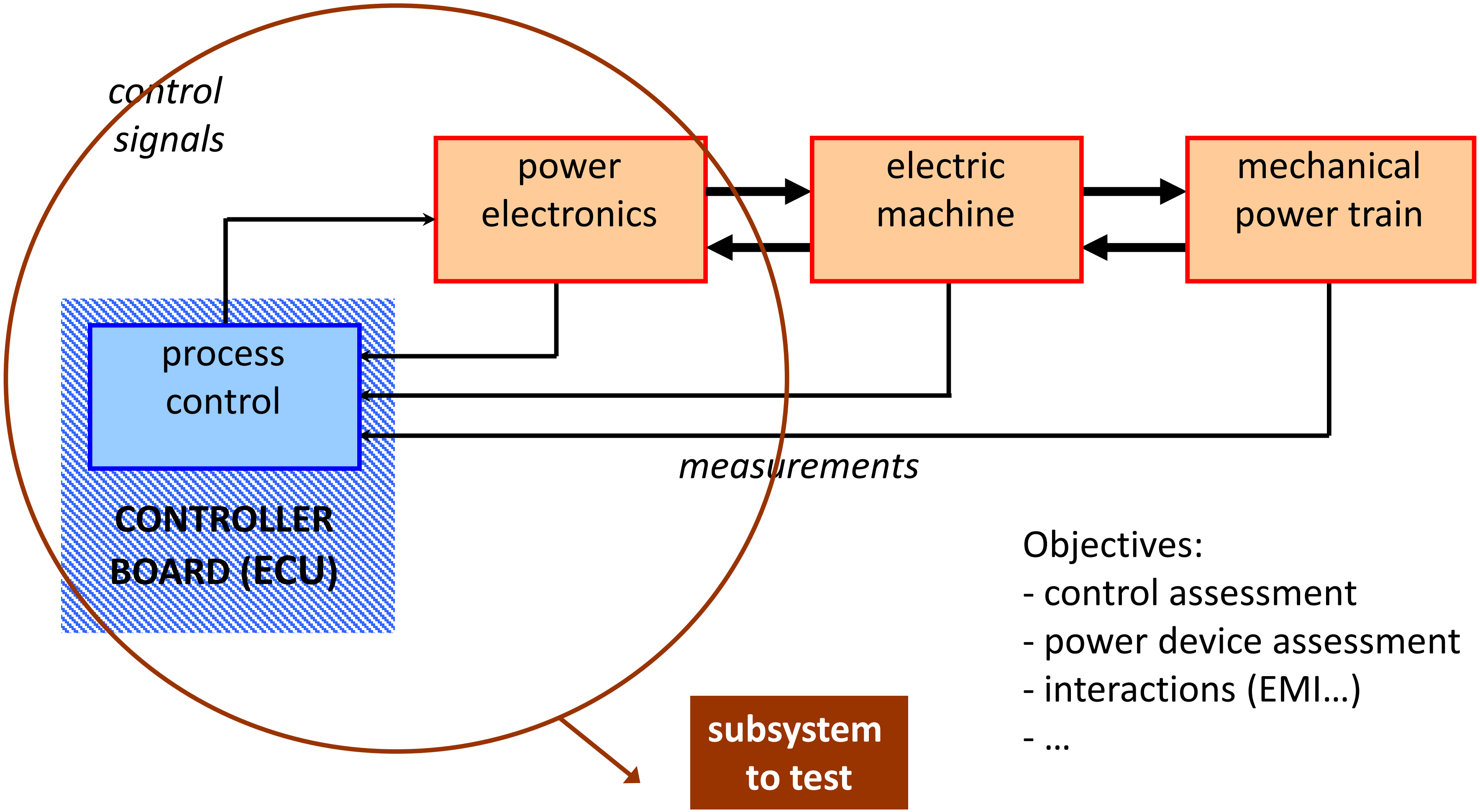
Example of signal HIL simulation



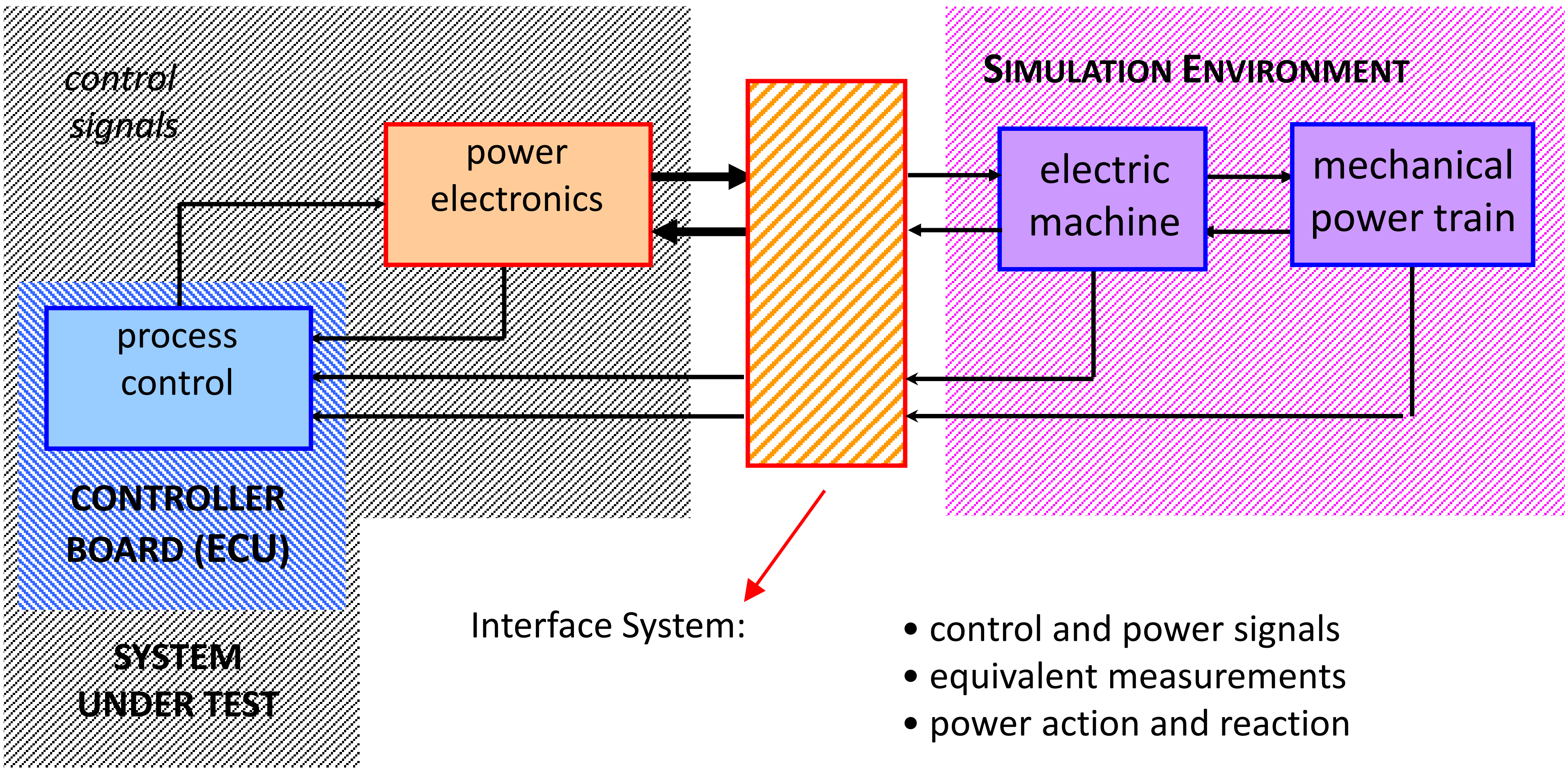
Remark: dynamic causal models

$$u_{chop} \longrightarrow \boxed{L\frac{d}{dt}i_{dcm} = u_{chop} - Ri_{dcm} - e_{dcm} \ (2)} \longrightarrow i_{dcm} \approx \int u_{chop} dt$$

The actual controller board and a power subsystem are tested.

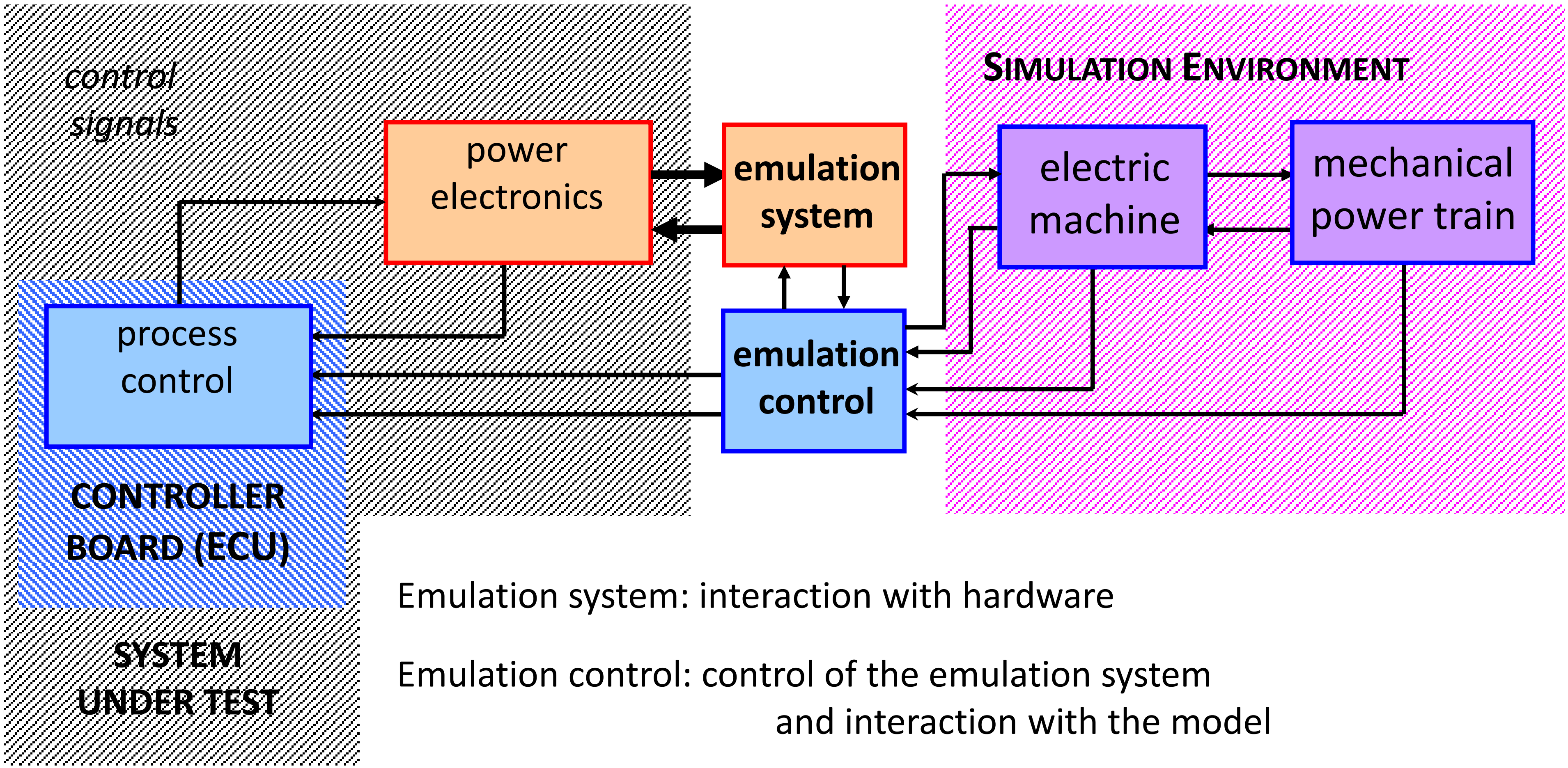


Objectives:
- control assessment
- power device assessment
- interactions (EMI…)
- …



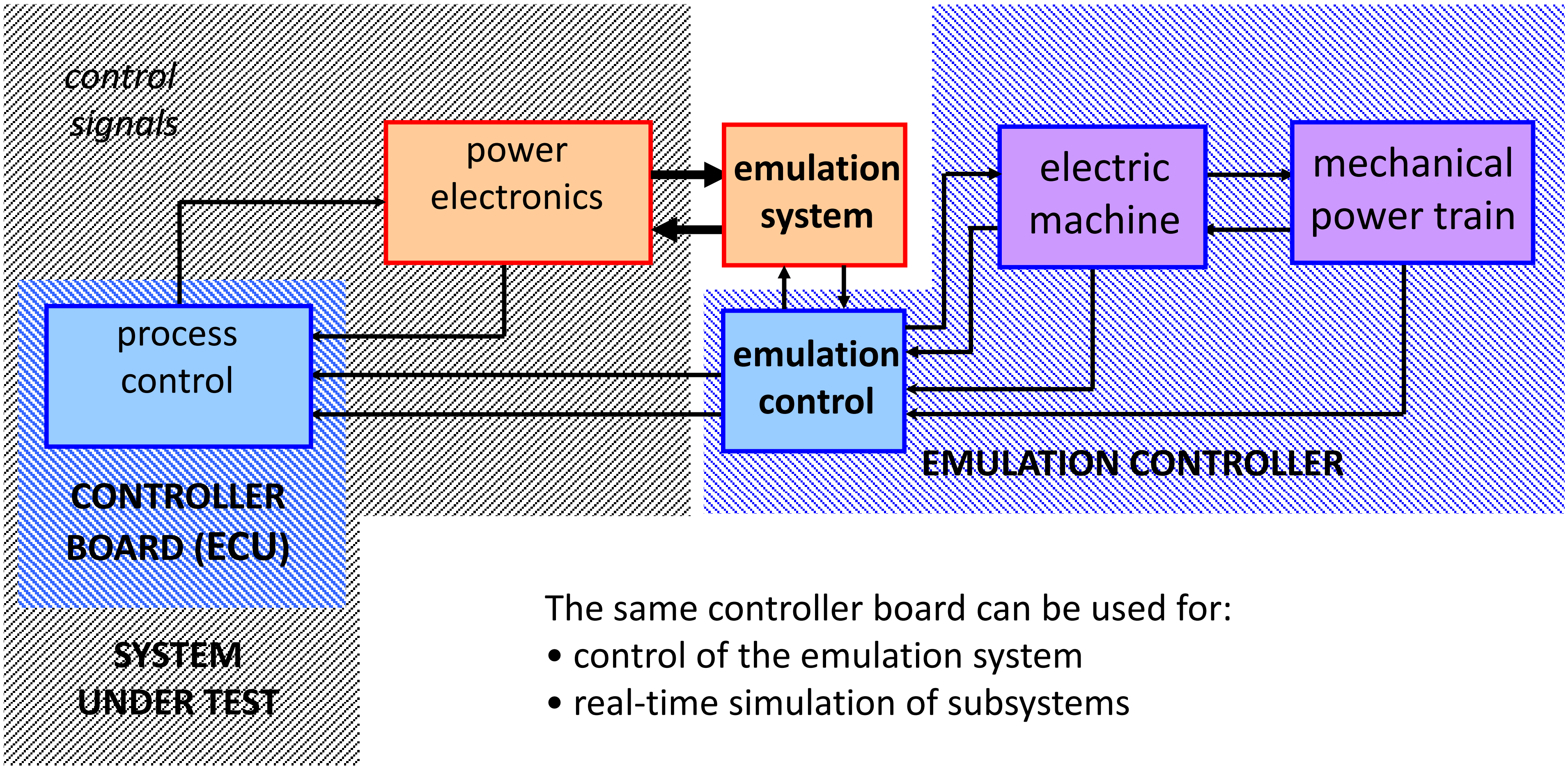
Interface System:

- control and power signals
- equivalent measurements
- power action and reaction



Emulation system: interaction with hardware

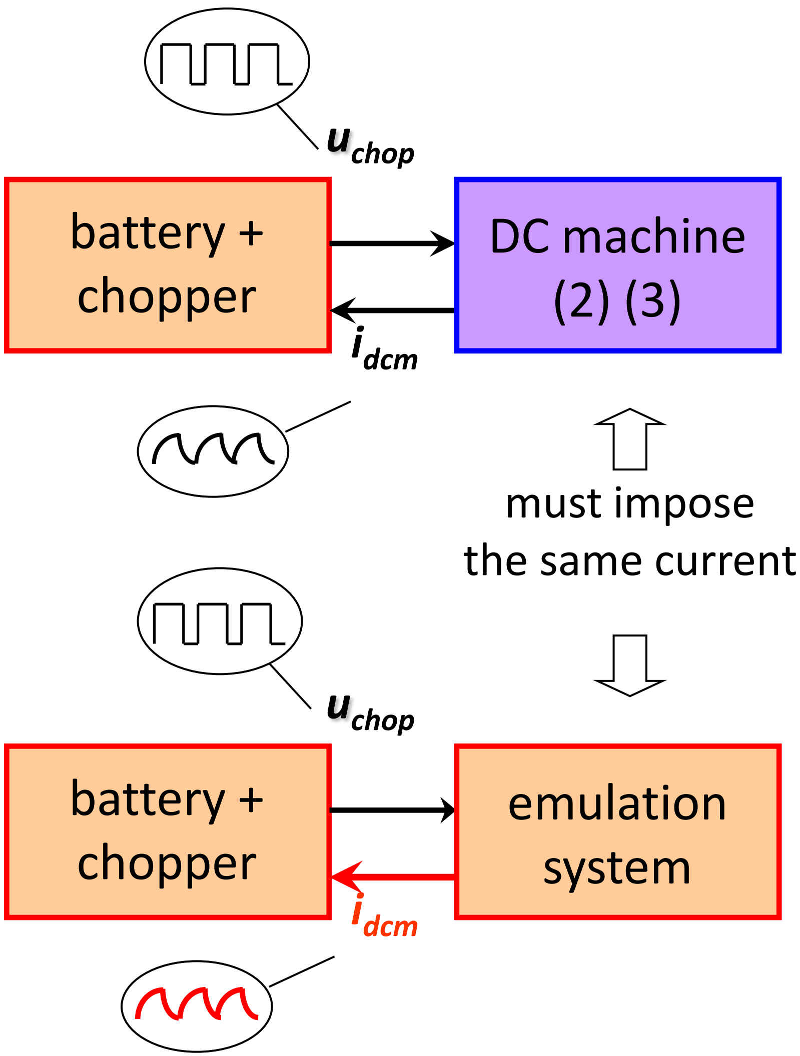
Emulation control: control of the emulation system and interaction with the model

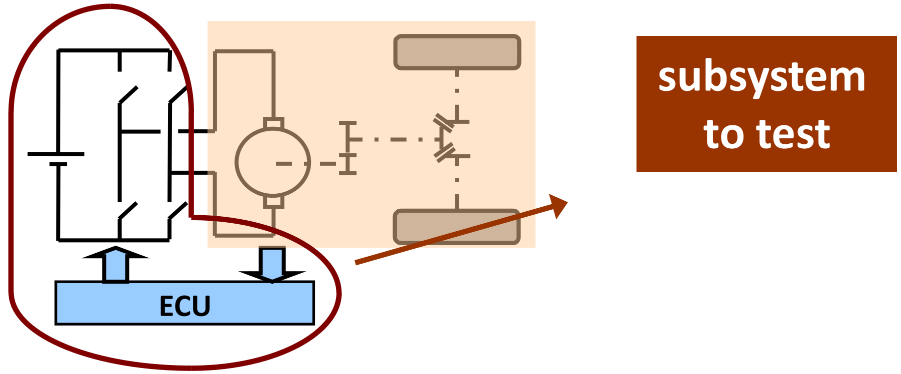


The same controller board can be used for:

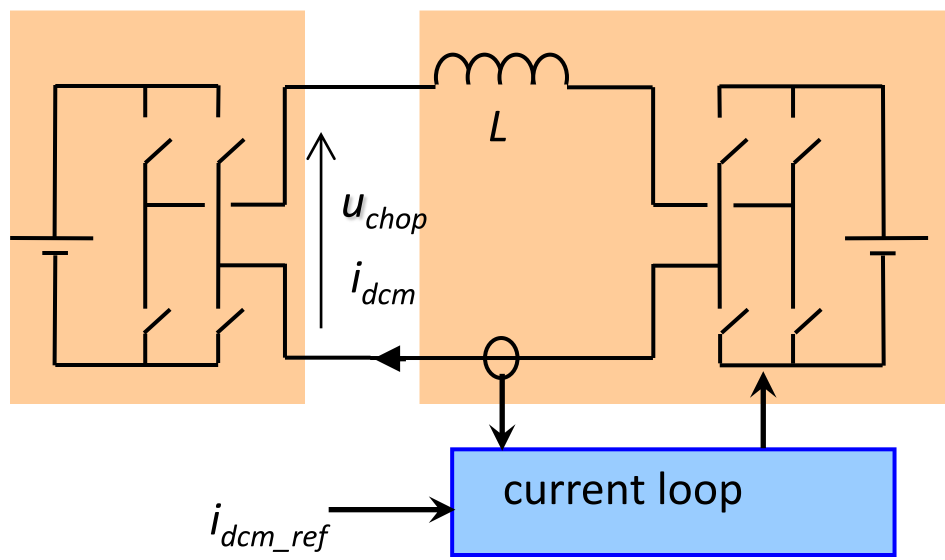
- control of the emulation system
- real-time simulation of subsystems

Example of power HIL simulation (1)

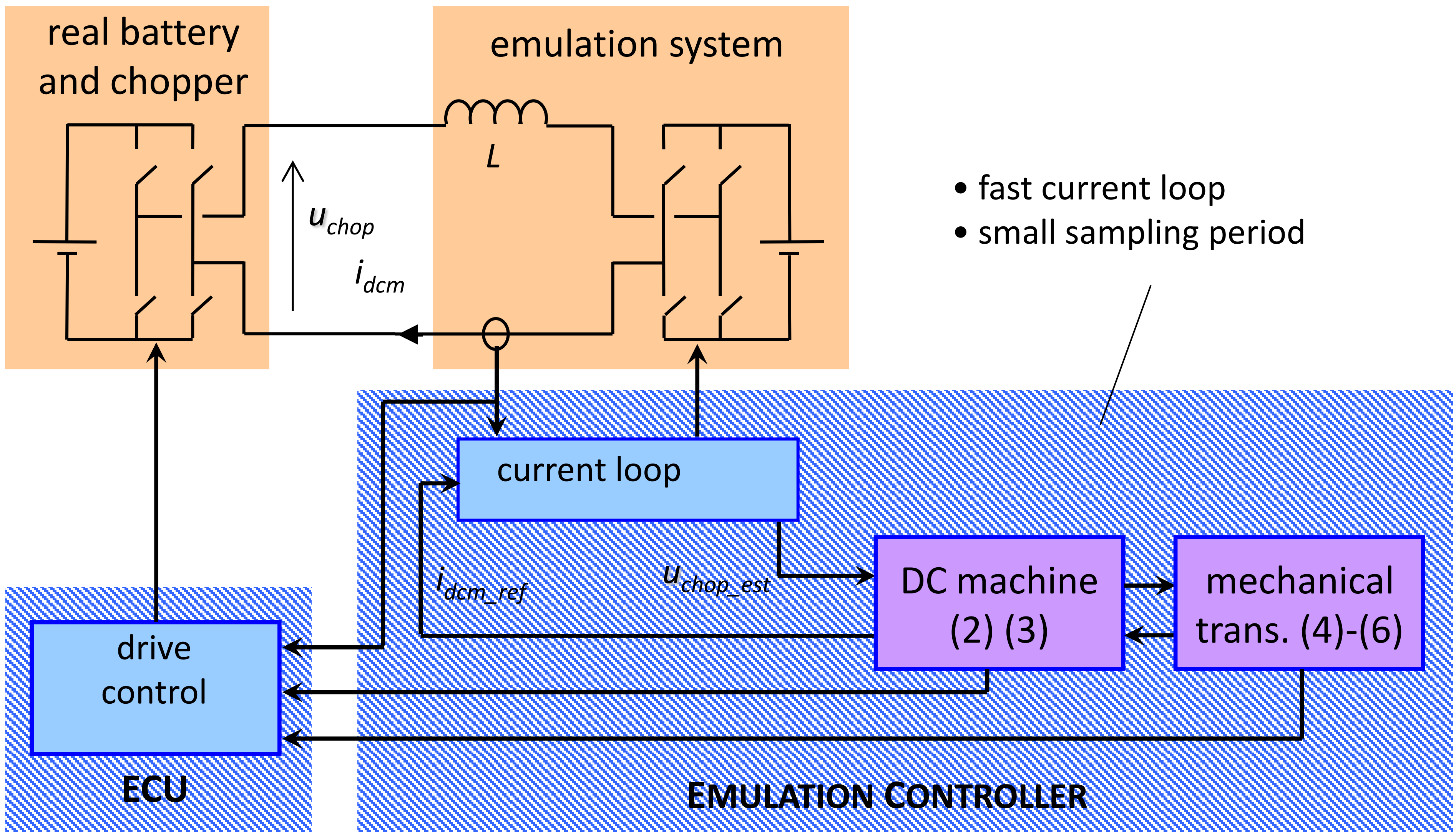




example of emulation system

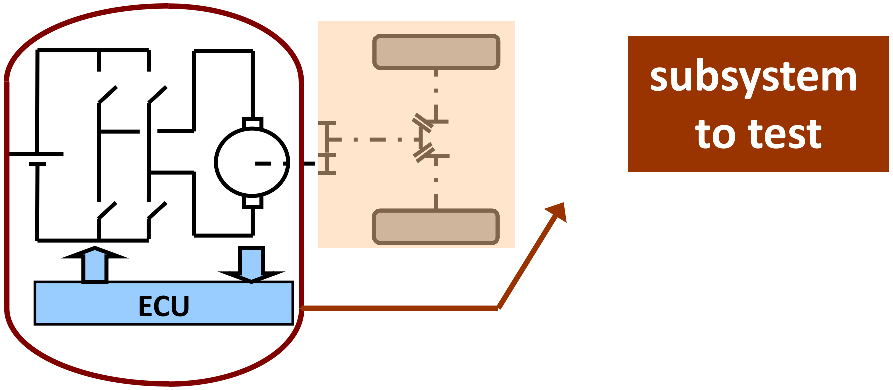


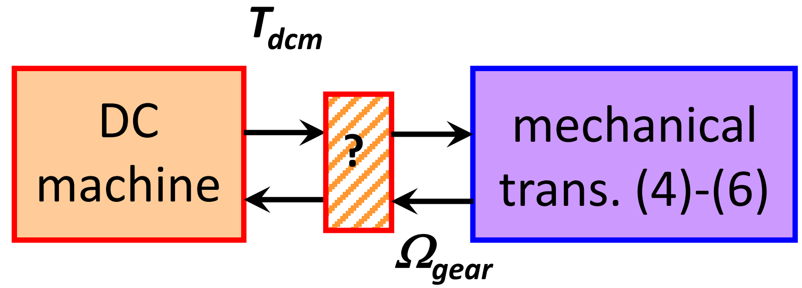
Example of power HIL simulation (1)



- fast current loop
- small sampling period

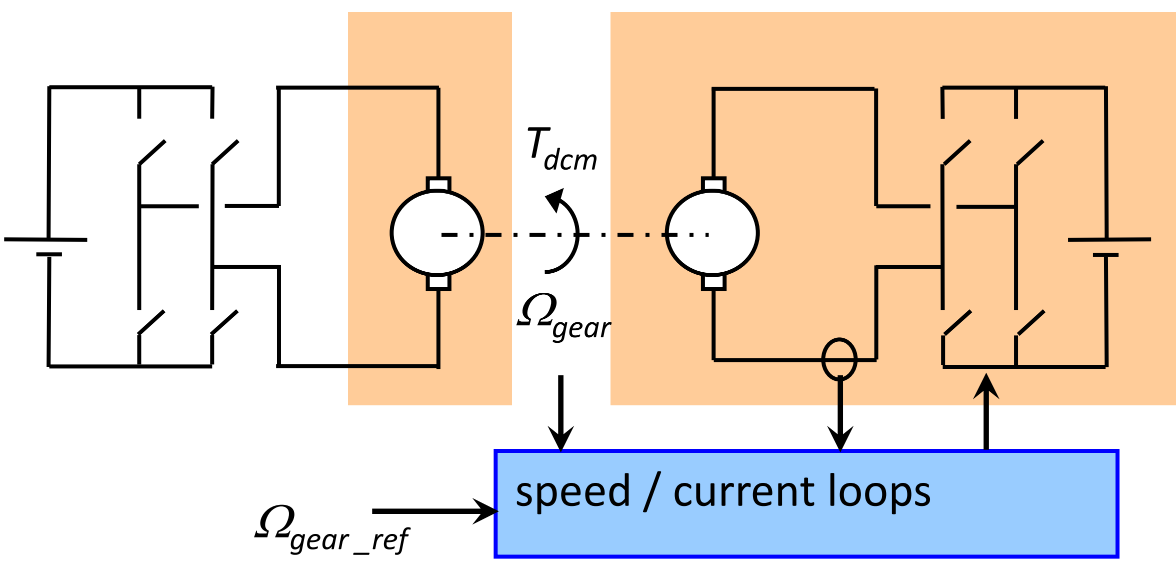
Mechanical power HIL simulation



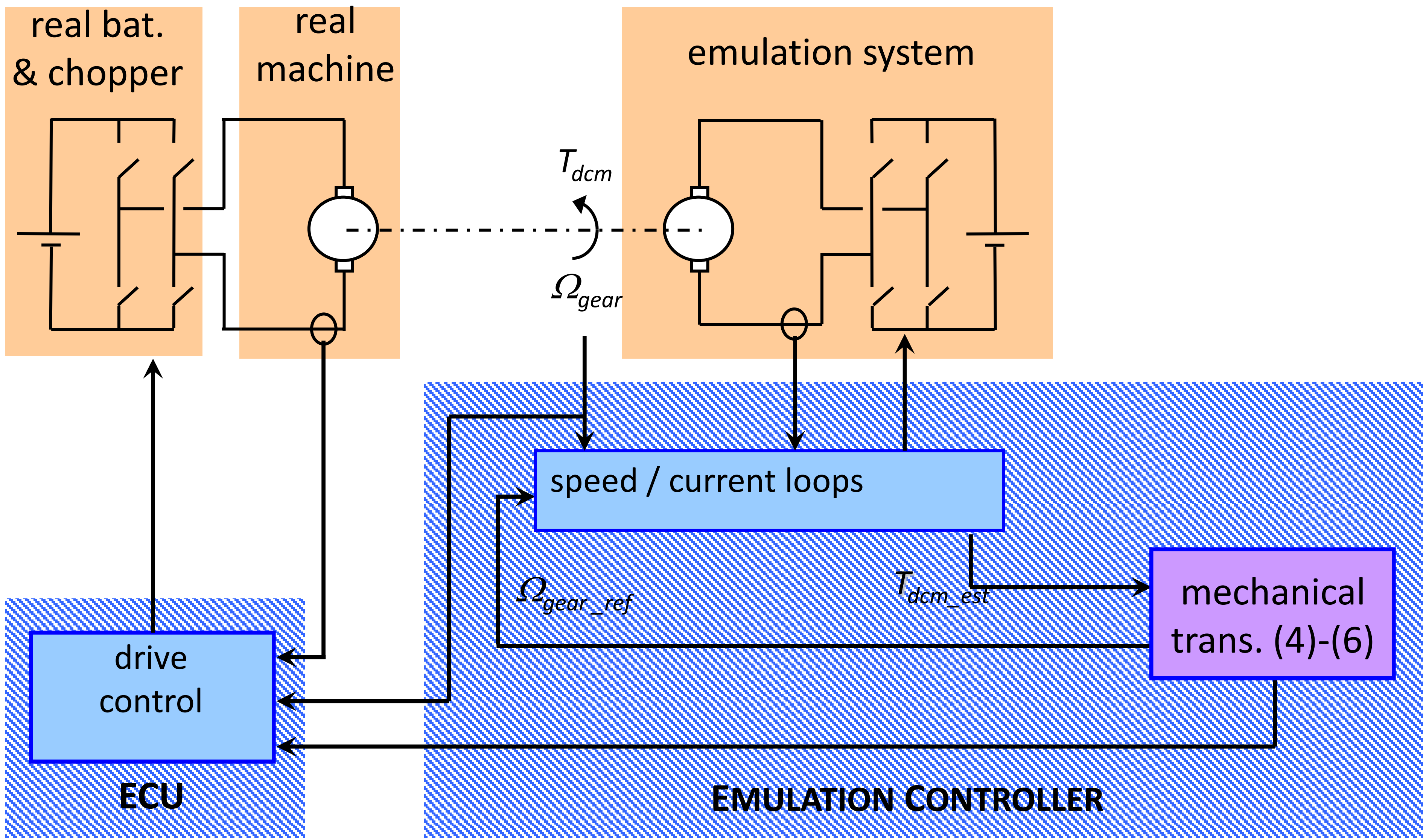


must impose the same speed

example of emulation system



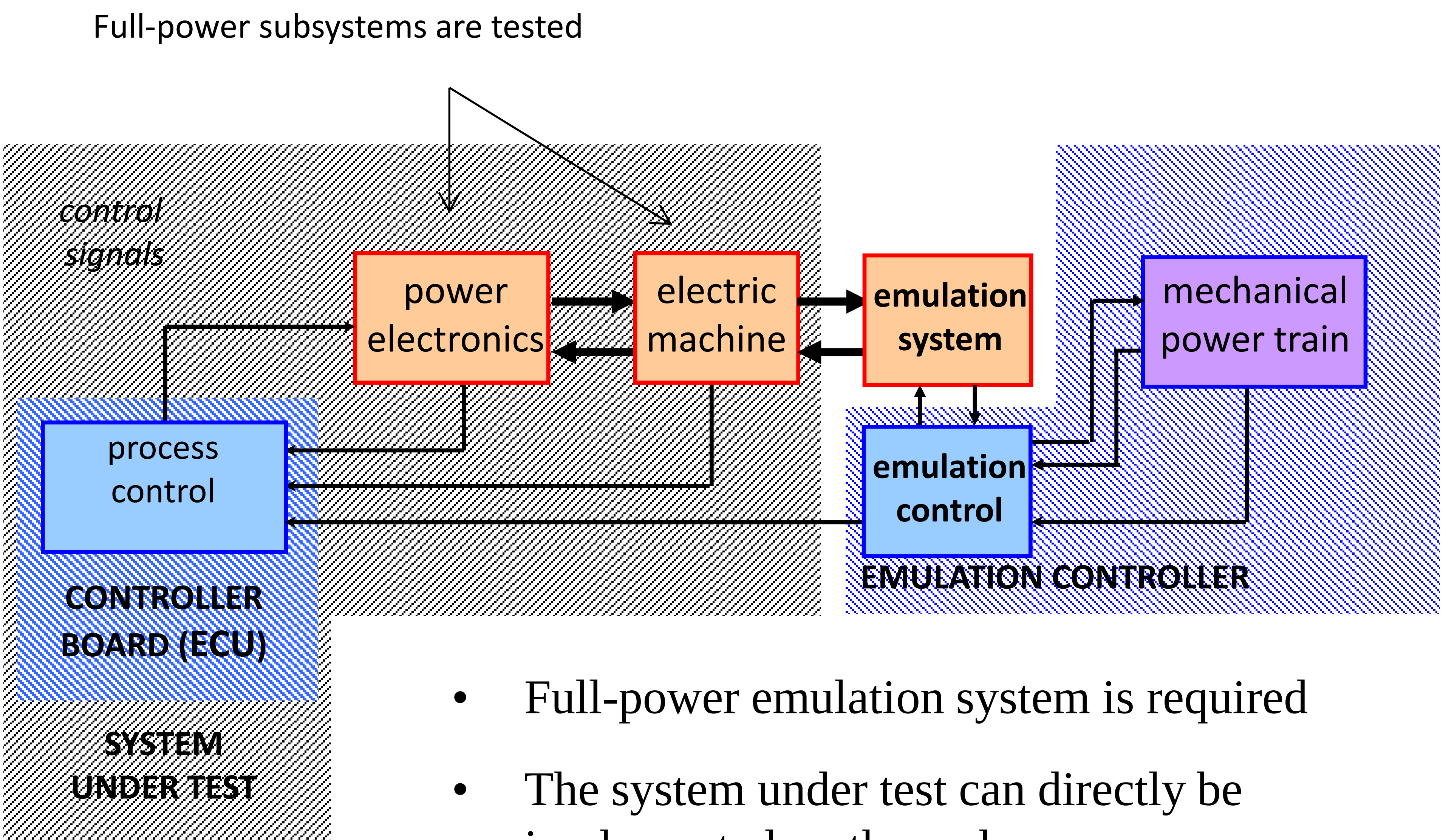
Example of mechanical power HIL simulation



3b. Full-scaled and reduced-scale HIL simulation

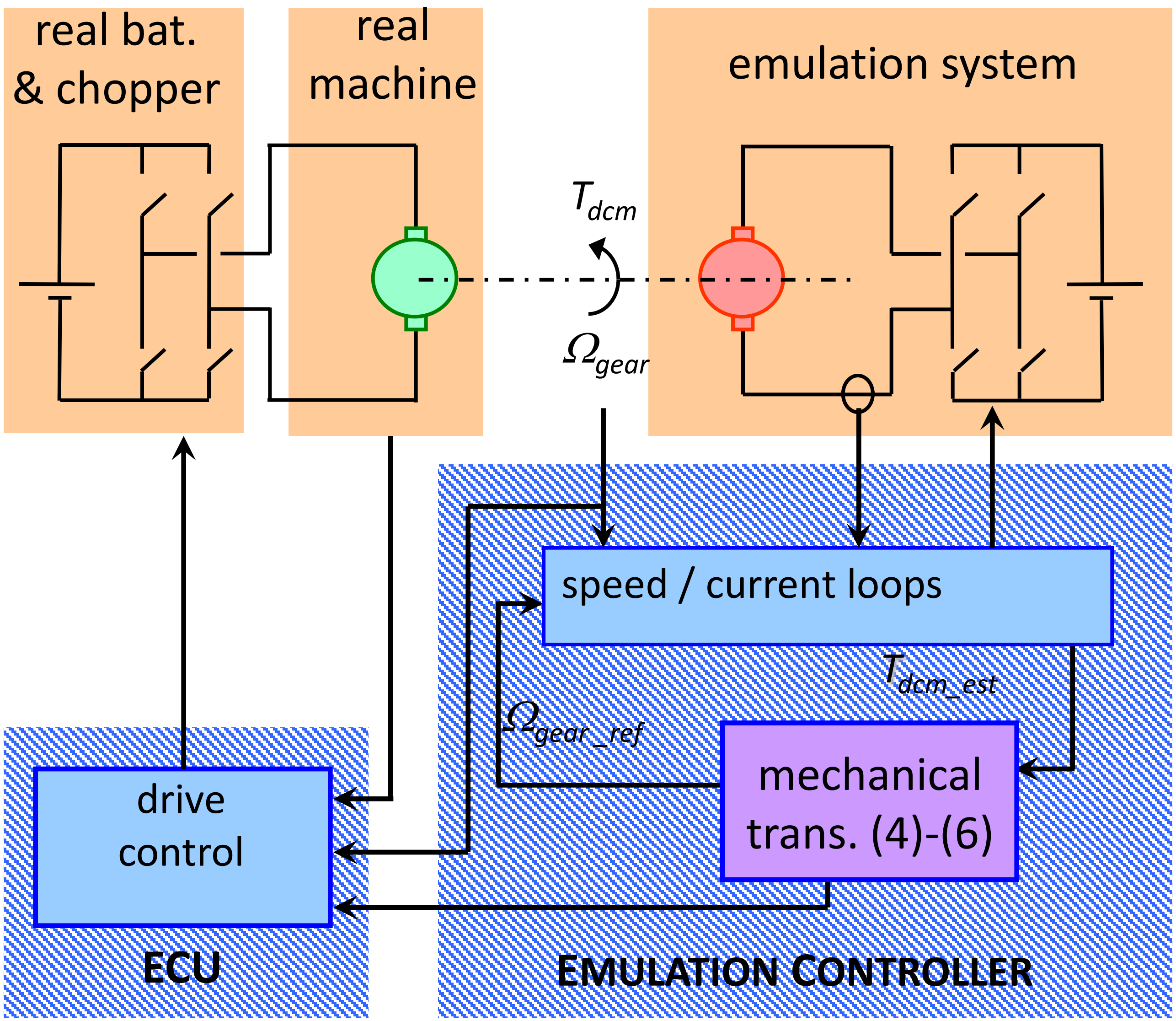
………………….

- Full-scale HIL simulation
- Reduced-scale HIL simulation



- Full-power emulation system is required
- The system under test can directly be implemented on the real process

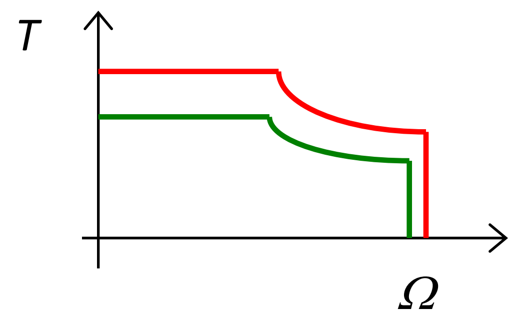
Example of full-scale power HIL simulation



$(T_{es})_{max} > (T_{real})_{max}$

$(\Omega_{es})_{max} > (\Omega_{real})_{max}$

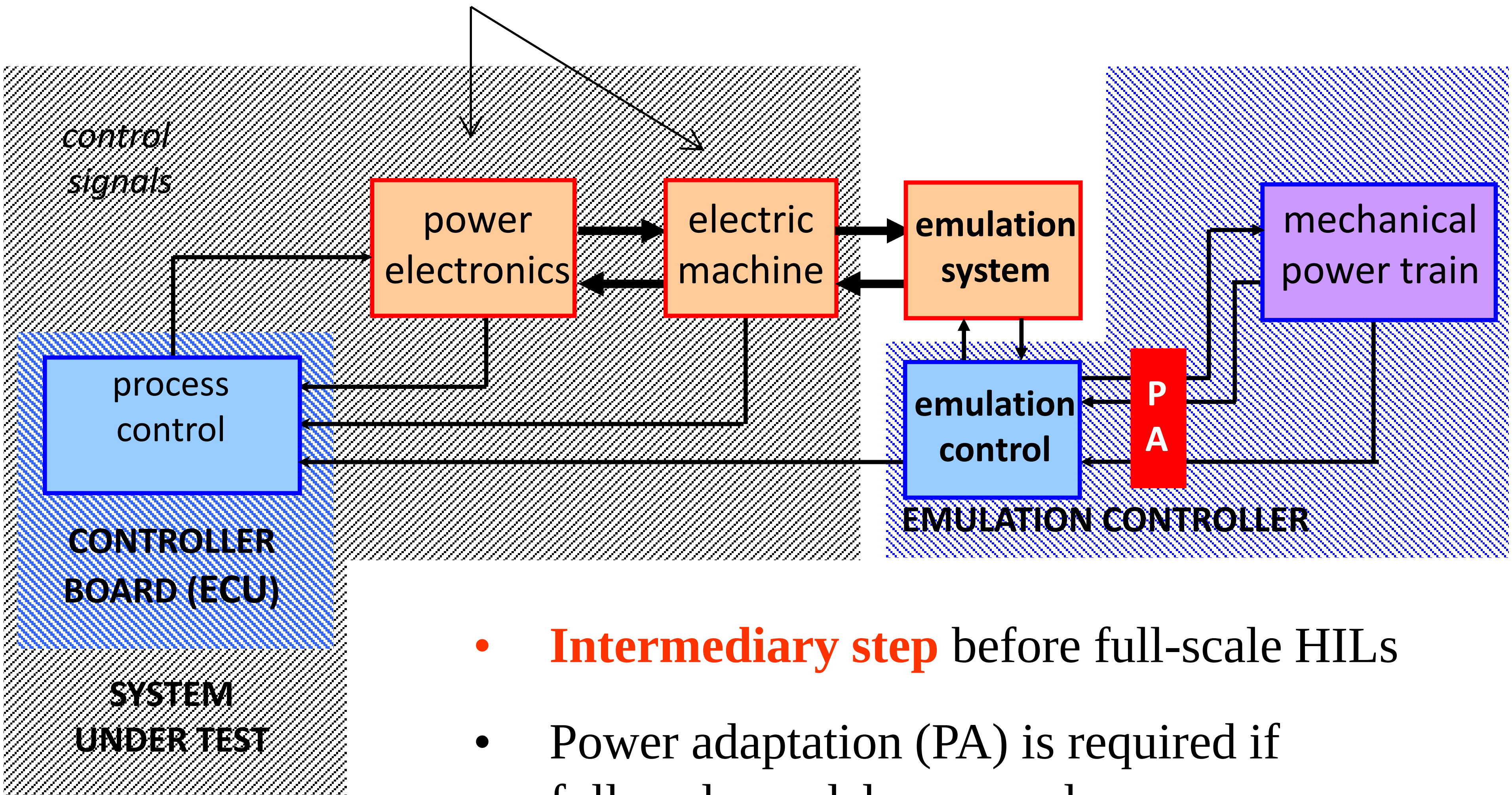
$(P_{es})_{max} > (P_{real})_{max}$



$(\text{dynamics})_{es}$ ***faster than*** $(\text{dynamics})_{mech\ trans}$

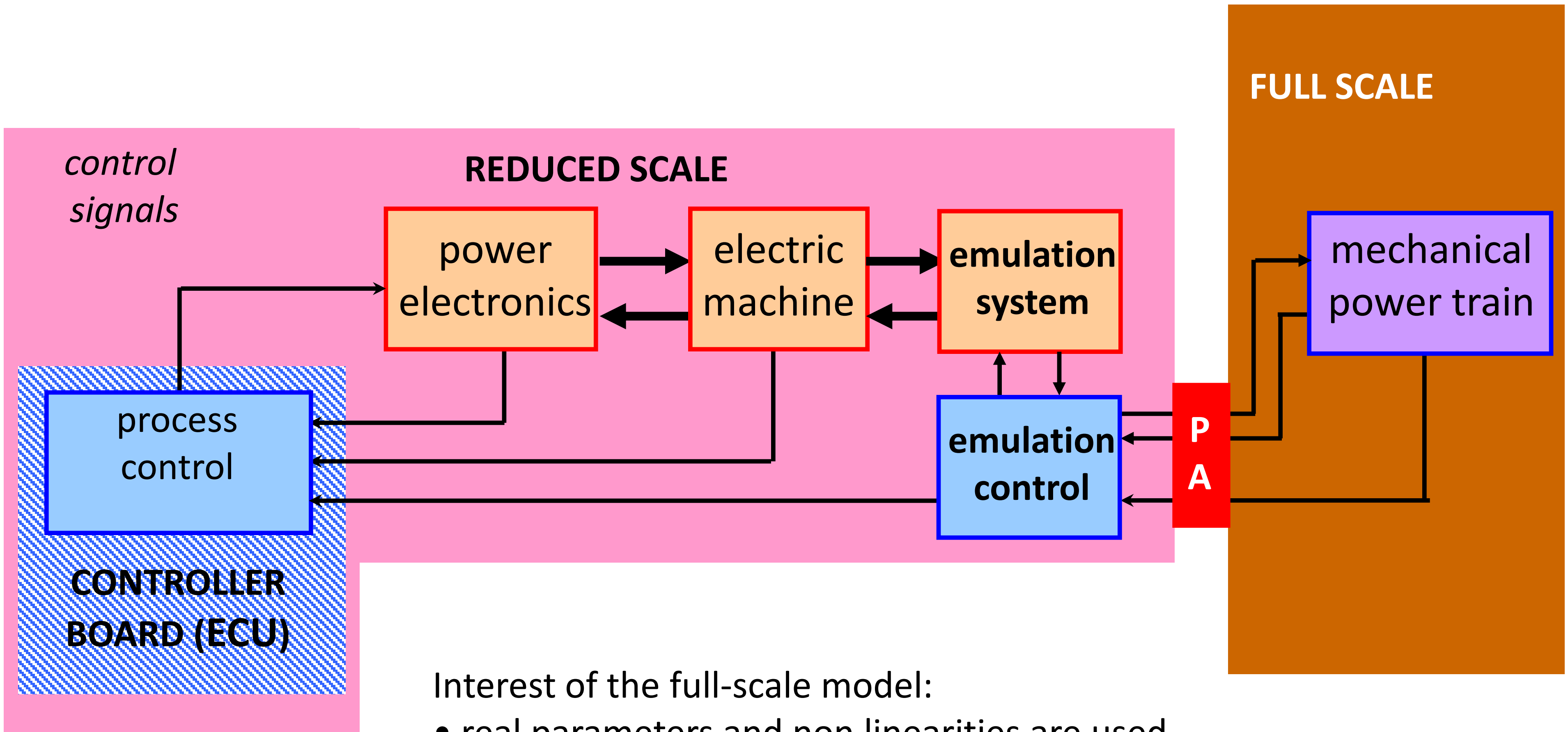
$J_{es} < J_{mech\text{-}trans}$

Reduced-power subsystems are tested



- **Intermediary step** before full-scale HILs
- Power adaptation (PA) is required if full-scale models are used

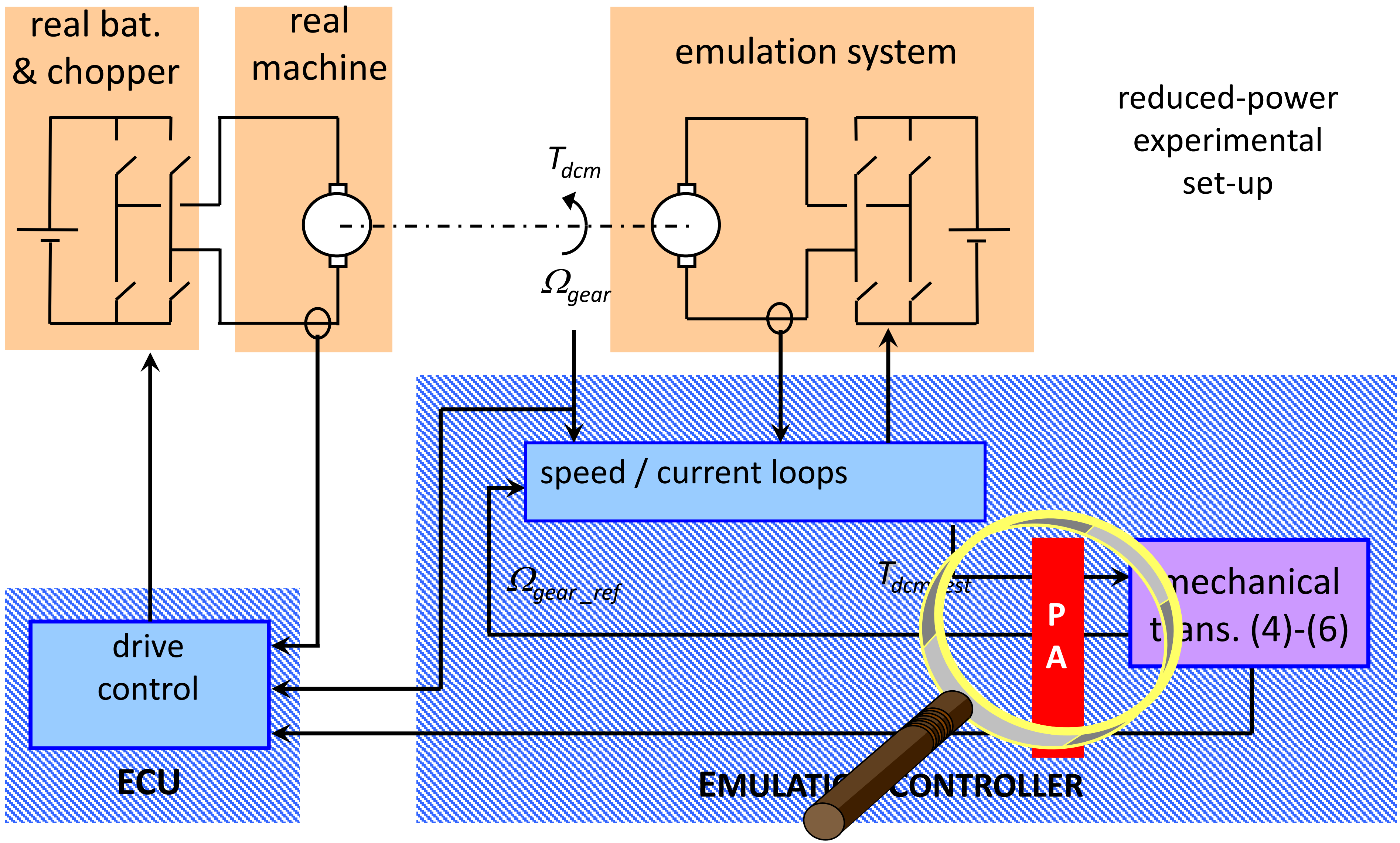
Reduced-scale power HIL simulation



Interest of the full-scale model:

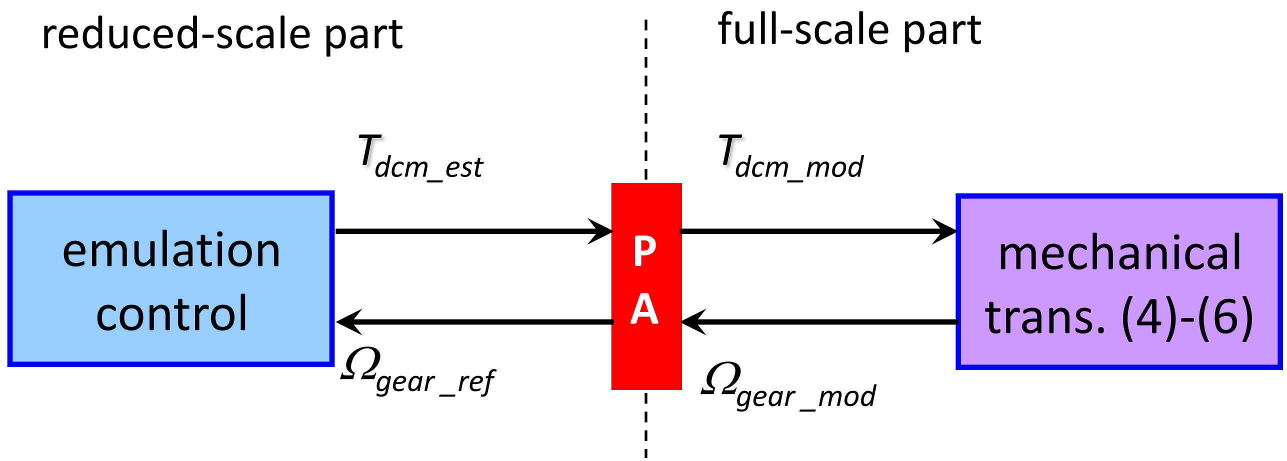
- real parameters and non linearities are used
- can be used for full-scale HIL extension

Example of reduced-scale power HIL simulation



reduced-power experimental set-up

Example of power adaptation



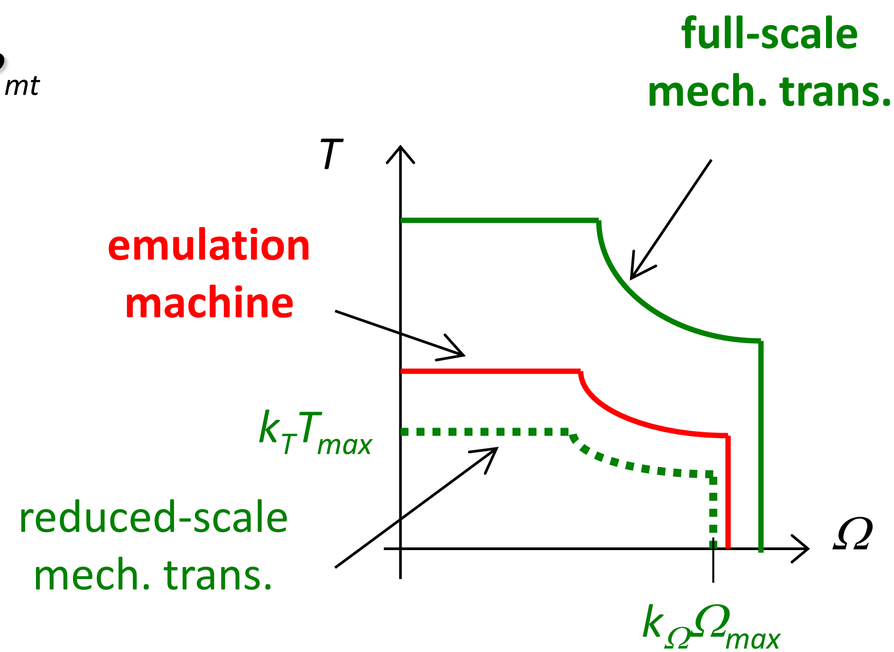
$P_{em} < P_{mt}$

$$\begin{cases} T_{dcm-mod} = k_T T_{dcm-est} \\ \Omega_{gear-mod} = k_\Omega \Omega_{gear-ref} \end{cases}$$

$$\Downarrow$$

$$P_{mt} = k_T k_\Omega P_{em}$$

PA = power amplification



Conclusion

…………………

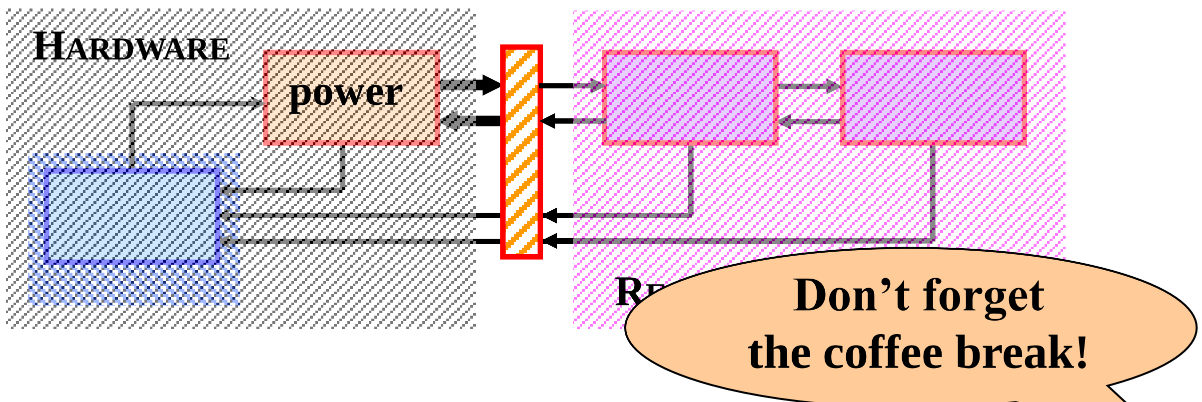
- **Full-scale HIL simulation**
- **Reduced-scale HIL simulation**

HIL simulation =

Hardware (energy conversion) → energetic model

\+ Models computed in real-time → causal model

in dynamic interactions → dynamical model



- an accurate and adapted model!
- an ideal interface system

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