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

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1. What is HIL Simulation?

2. Which Models for HIL Simulation?

3. Different types of HIL Simulation?
Graphical rules

Physical power system (orange)

process control (blue)

mathematical model (purple)

SIMULATION SOFTWARE

REAL-TIME CONTROLLER

SUBSYSTEM UNDER TEST

power variables

signal variables
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

Coordination: Prof. A. Bouscayrol

- 6 projects
- 4 PhDs in progress
- 11 PhDs defended
- 8 industrial partners
- 10 academic Labs

(Energy management of Hybrid and Electric Vehicles)

http://www.megevh.org/
MEGEVH philosophy

theoretical developments

- MEGEVH-macro
- MEGEVH-strategy
- MEGEVH-optim
- MEGEVH-FC
- MEGEVH-store

Development of modeling and energy management methods

- independently of the kind of vehicle

experimental plate-forms

Reference vehicles

- 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 – 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

- Technical requirements
- System specifications
- Component design
- Component tests
- Integration tests
- Prototype
- Component tests
- component realization

Accuracy level:
Development
Validation
HIL simulation approach

**Example of an EV**

- Component design
- Component tests
- Component realization
- Simulation
- HIL platform
- Prototype
- Production

http://www.renault.com

The more tests are made at HIL, the less prototypes are developed.
Example of an electric drive for traction

How to develop the system?

Software simulation
Example of an EV traction

Traction of an EV:
- Battery + chopper
- DC machine
- Differential
- 2 driven wheels

Switching order $s_{ij}$

Drive control

Battery + chopper

DC machine

Mechanical power train

$V_{bat}$

$u_{chop}$

$T_{dcm}$

$V_{bat_meas}$

$i_{dcm}$

$i_{dcm_meas}$

$\Omega_{gear}$

$\Omega_{gear_meas}$

$V_{ev_meas}$

$T_{im}$

$T_{diff1}$

$T_{diff2}$

$W_{gear}$

$W_{gear_meas}$

$W_{wh1}$

$W_{wh2}$

$T_{wh1}$

$T_{wh2}$
simulation of the system and the control in a simulation software: development / safety / gain of time ...
Example of an EV traction system

\[
\begin{align*}
  u_{chop} &= m_{chop} V_{bat} \\
  i_{chop} &= m'_{chop} i_{dcm}
\end{align*}
\] (1)

**Assumptions:** 1 single equivalent wheel

\[
\begin{align*}
  u_{chop} &= L \frac{d}{dt} i_{dcm} + R_i_{dcm} + e_{dcm} \\
  T_{dc} &= k_\phi i_{dcm} \\
  e_{dcm} &= k_\phi \Omega_{gear}
\end{align*}
\] (2) (3)

\[
\begin{align*}
  F_{tract} &= \frac{m_{gear}}{R_{wh}} T_{dc} \\
  F_{res} &= F_0 + A v_{ev}^2 + M g \sin \alpha
\end{align*}
\] (4) (5) (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”

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

- **real system**
- **system model**
- **system representation**
- **system simulation**

**smoothing inductor**

\[ v_L = L \frac{d}{dt} i_L + R i_L \]

**(low frequency dynamical model)**

**smoothing inductor**

\[ V_L = \frac{I}{R + Ls} \]

**(bloc diagram + Laplace)**

**smoothing inductor**

\[ \text{Step} \rightarrow \frac{1}{Ls+R} \rightarrow \text{scope} \]

**Simulink © + Runge Kutta**
Different categories

real system

- dynamic / quasi-static / static
- structural/functional
- causal/non-causal
- backward / forward

Different possibilities at each step in function of the objective
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
Example of electrical machine

**Static efficiency map**

\[ i_{DC} = \frac{T_{em} \Omega + P_t(T_{em} \cdot \Omega)}{U_{DC}} \]

**Dynamic model**

\[
\begin{align*}
V_{sd} &= R_s i_{sd} + \frac{d \phi_{sd}}{dt} - \omega_s \phi_{sq} \\
V_{sq} &= R_s i_{sq} + \frac{d \phi_{sq}}{dt} + \omega_s \phi_{sd} \\
0 &= R_R i_{rd} + \frac{d \phi_{rd}}{dt} - \omega_R \phi_{rq} \\
0 &= R_R i_{rq} + \frac{d \phi_{rq}}{dt} + \omega_R \phi_{rd}
\end{align*}
\]

\[ T_{em} = p \frac{L_m}{L_R} \cdot (\phi_{rd} \cdot i_{sq} - \phi_{rq} \cdot i_{sd}) \]

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

**Example**

3D Finite Element Model

Mathematic model
- Assumption: Ideal transformer

\[
\begin{align*}
\nu_2 &= m \nu_1 \\
\iota_1 &= m \iota_2
\end{align*}
\]
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)
Causal vs. non-causal description

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

How to connect subsystem?

\[ J \frac{d}{dt} \Omega = T_1 - T_2 \]
Subsystem interconnexion

Example

ICE

\[ J_1 \frac{d}{dt} \Omega = T_1 - T_2 \]

\[ J_2 \frac{d}{dt} \Omega = T_2 - T_3 \]

causal description

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

derivative relationship

specific solver

electrical machine

acausal description

\[ J_{equ} \]

HIL’16, Lille Sept. 2016
Principle of causality
physical causality is integral

\[ \int x \, dt \rightarrow \text{area} \]

OK in real-time

knowledge of past evolution

\[ \frac{dx}{dt} \rightarrow \text{slope} \]

impossible in real-time

knowledge of future evolution

\[ ? \rightarrow \text{cause} \]

input

cause

\[ \text{s} \rightarrow \text{output} \]

effect

Causality principle
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

He, guy! A new energy converter!

Don’t forget to respect causality!

I will press on the neck to model it

When you discover a new process (!)

You should apply the right Input...
If not...

It was not a good idea!
Systemic approach
Study of subsystems and their interactions
Holistic property: associations of subsystems induce new global properties.

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

Systemic vs. Cartesian approach

System = interconnected subsystems

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

System 1 vs. System 2

Group made of individualists

Team made of partners

Cartesian approach

Systemic approach

Brazil 1 – 7 Germany
**Interaction principle**
Each action induces a reaction

**Example**

$$V_{bat}$$

$$i_{load}$$

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

Power exchanged by S1 and S2 = action x réaction
If the interaction principle is not respected for 1 subsystem

Error in the energy analysis for the whole system

\[ \text{Power} = 0 \]
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
- ...

CONTROLLER BOARD (ECU)

signal HIL simulation
Signal HIL simulation

CONTROL BOARD (ECU)

SYSTEM UNDER TEST

SIMULATION ENVIRONMENT

power electronics

mechanical power train

Interface System:
- only signals
- equivalent measurements
- equivalent control signals

process control

control signals

measurements
Signal HIL simulation

- **CONTROL BOARD (ECU)**
  - **process control**

- **SYSTEM UNDER TEST**
  - **EMULATION CONTROLLER**
  - **power electronics**
  - **electric machine**
  - **mechanical power train**

- **control signals**

- **Fast dynamic: FPGA?**

- **measurements**

- **Second controller board with its own interface**
Remark: dynamic causal models

\[ u_{\text{chop}} \longrightarrow L \frac{d}{dt} i_{\text{dcm}} = u_{\text{chop}} - R i_{\text{dcm}} - e_{\text{dcm}} \]

\[ i_{\text{dcm}} \approx \int u_{\text{chop}} \, dt \]
The actual controller board and a power subsystem are tested.

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

[Diagram showing control signals and measurements between power electronics, electric machine, and mechanical power train.]
Power HIL simulation

Interface System:
- control and power signals
- equivalent measurements
- power action and reaction

SYSTEM UNDER TEST

POWER TRAIN

CONTROL BOARD (ECU)

SIMULATION ENVIRONMENT

process control

power electronics

electric machine
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)

Battery + chopper → DC machine (2) (3)

Battery + chopper → Emulation system

Battery + chopper → Emulation system

Example of emulation system

Battery + chopper → Emulation system

Battery + chopper → Emulation system

Subsystem to test

Must impose the same current

Example of power HIL simulation (1)
Example of power HIL simulation (1)

- fast current loop
- small sampling period

Real battery and chopper

Emulation system

Drive control

ECU

Emulation controller

DC machine (2) (3)

Mechanical trans. (4)-(6)
Mechanical power HIL simulation

subsystem to test

example of emulation system

ECU

DC machine

mechanical trans. (4)-(6)

must impose the same speed

$T_{dcm}$

$\Omega_{gear}$

speed / current loops

$\Omega_{gear\_ref}$
Example of mechanical power HIL simulation

- real bat. & chopper
- real machine
- emulation system

Drive control

ECU

Emulation controller

Mechanical trans. (4)-(6)

\[ T_{dc\text{m}} \]

\[ \Omega_{gear} \]

\[ \Omega_{\text{gear_ref}} \]

\[ T_{dc\text{m_est}} \]
3b. Full-scaled and reduced-scale HIL simulation

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

Full-power subsystems are tested

- 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

real bat. & chopper

real machine

emulation system

\[ T_{dcm} \]

\[ \Omega_{gear} \]

\[ \Omega_{gear_{ref}} \]

speed / current loops

mechanical trans. (4)-(6)

\[ T_{dcm_{est}} \]

drive control

ECU

EMULATION CONTROLLER

\[ (T_{es})_{max} > (T_{real})_{max} \]

\[ (\Omega_{es})_{max} > (\Omega_{real})_{max} \]

\[ (P_{es})_{max} > (P_{real})_{max} \]

\[ J_{es} < J_{mech-trans} \]

\[ (dynamics)_{es} \text{ faster than } (dynamics)_{mech \text{-} trans} \]
Reduced-power subsystems are tested

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

real bat. & chopper

real machine

emulation system

reduced-power experimental set-up

speed / current loops

drive control

ECU

EMULATION CONTROLLER

mechanical trans. (4)-(6)
Example of power adaptation

\[
\begin{align*}
T_{\text{dcm-mod}} &= k_T T_{\text{dcm-est}} \\
\Omega_{\text{gear-mod}} &= k_\Omega \Omega_{\text{gear-ref}} \\
\end{align*}
\]

\[P_{\text{mt}} = k_T k_\Omega P_{\text{em}}\]

PA = power amplification
Conclusion

• Full-scale HIL simulation
• Reduced-scale HIL simulation
Conclusion

HIL simulation =

Hardware (energy conversion) + Models computed in real-time in dynamic interactions

energetic model
causal model
dynamical model

Don’t forget the coffee break!

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


Other references


