# Different types of Hardware-In-the-Loop simulation for electric drives

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***Abstract* — Hardware-In-the-Loop (HIL) simulations are more and more used to assess performances of electric drives. Software simulations lead to develop control of the studied system. In this case generally a lot of simplifications are assumed to reduce the computation time. Before a real-time implementation of the control, HIL simulations could be a very useful intermediary step. Thus a hardware device is introduced in the loop in order to take its real constraints into account. In this paper, three different kinds of HIL simulation are suggested: signal level, power level, and mechanical level. A example is given for the traction system of an electric scooter.**

***Keywords* — Hardware-in-the-loop simulation, electric drive, drive control, real-time simulation.**

## I. Introduction

Electric drives are more and more used in industrial applications. In order to achieve the required performances of the drive and its control, software simulation becomes an essential preliminary step. The power system is then replaced by simple models to define and tune the control algorithm. Hardware-In-the-Loop (HIL) simulations are some times used for validation tests before implementation on actual processes. On the contrary of software simulation, HIL simulation uses one or several actual devices instead of their simulation models. The other parts of the process are simulated in a controller board or in parallel computers [1]. If a lot of HIL simulations are dedicated to assess controller boards, drive validations are nowadays more and more developed using this methodology. HIL simulation enables thus to check availability and reliability of drives (machines, power electronics and control) before their insertion on a whole system. Indeed, implementation constraints are taken into account such as sensor accuracy, sampling period, modulation frequency, active limitations and so on. Moreover, fault operations can easily be tested in various cases.

HIL simulation has been intensively used for controller assessment for a long time. The aerospace industry has used this technique since flight control systems is a safety-critical aspect [1]-[3]. This methodology yields exhaustive testing of a control system to prevent costly and damageable failures. Moreover, HIL simulations reduce development time and can enable more tests than on the actual system.

From 90's, many groups in automotive industry have employed HIL simulation for testing embedded Electronic Control Units (ECU) [4]-[7]. Indeed, this methodology avoids intense and complex integration tests on the actual vehicle. Thus, the time development can be reduced and a high quality assurance can be obtained. HIL simulation is becoming a standard for ECU development in the automotive industry [4].

HIL simulation is nowadays more and more used to develop new components and actuators in many fields. Vehicle component evaluation [8]-[11], assessment of drive controls [12]-[26], power electronics and electric grid [27]-[33], servo control and robotics [34]-[39], railway traction systems for trains and subways [40]-[43], education applications [44][45] can be cited. More recently, electrical generators of wind energy conversion systems are tested using HIL simulation [46]-[53]. In this case, sometimes small-rate power systems are firstly used to validate control algorithms and Maximum Power Point Tracking (MPPT) strategies before implementation on a full-rate power system. Power propulsion systems for electric vehicles (EVs) and hybrid electric vehicle (HEVs) [54]-[67] are also new applications for HIL simulation. In these cases, actual drives can be tested before integration on the vehicle chassis.

The aim of this paper is to define different kinds of HIL simulation for electric drives. Section II is devoted to a non-exhaustive classification of HIL simulation for electric drives. Section III will present an example of the different kind of HIL simulation for an electrical scooter.

## II. Different HIL simulations concepts for electric drives

An electrical drive can be decomposed into several subsystems (Fig. 1): the process control, the power electronics set, the electrical machine and the mechanical load to move (the mechanical power train of a vehicle for example). Power devices are connected according to the action and reaction principle [68]. A controller board contains the process control and yields the switching orders of the power electronics converter. Measurements of all power parts are inputs for this controller board. In some cases, several controller boards are used. In other case analog devices as FPGA are used to control the faster dynamics and to achieve high-frequency modulations of power electronics.

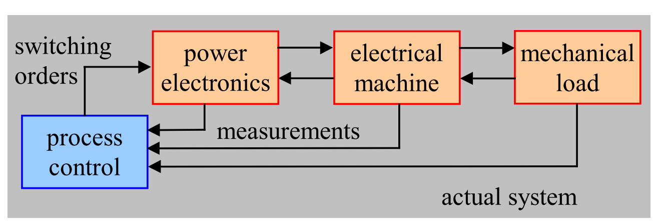


*Fig. 1: Subsystems of an electric drive*

*Limitation of software simulation*

The first step of the study is the simulation of the whole system including its control. All parts are simulated in the same simulation environment (software). In order to reduce the computation time, simple models and other simplifications are considered. For instance, the sampling period of the control is often neglected. For these reasons, simulation is not always accurate enough to enable a direct real-time implementation of the control.

Before implementation on the actual system (a vehicle for instance), different validations have to be made. HIL simulation could be a very useful intermediary step. One of the simulated parts can be replaced by its hardware device. By this way, the real constraints of this hardware subsystem are taken into account in the simulation loop. Three kinds of HIL simulation can be considered [21].

*Signal level HIL simulation*

In the first case, only the controller board (which contains the process control) is tested (Fig. 2). The other parts (power electronics, machine and mechanical load) are simulated in real-time. The simulation system must manage inputs and outputs of the controller board under test. A second controller board is thus used to simulate in real-time the power parts of the system. A specific signal conditioning is required to impose the same inputs and outputs as imposed by the power parts. This method can be called "signal level HIL simulation" because only signals are used at the interface between the system under test and the simulation environment. This kind of HIL has been very often employed in aerospace and automotive applications for assessment of controller boards.

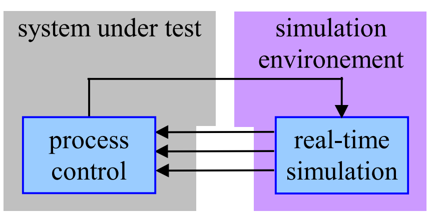


*Fig. 2: Signal level HIL simulation*

*Power level HIL simulation*

In the second case, the actual controller board and the power electronics converter are evaluated. The other parts (electrical machine and mechanical load) are simulated. The simulation system must impose inputs and outputs for the power electronics and the controller board under test. The simulation environment is generally composed of a second power electronics set (electric load) and a second controller board (real-time simulation) (Fig. 3). This method can be called "power level HIL simulation". Indeed the interface between the system under test and the simulation environment require signal and power variables.

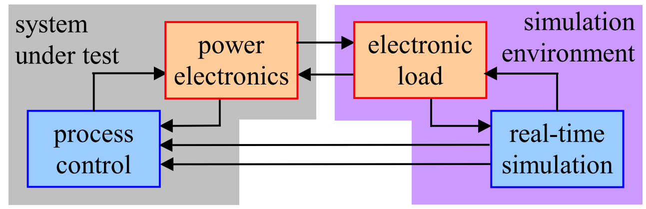


*Fig. 3: Power level HIL simulation*

*Mechanical level HIL simulation*

In the last case, the whole drive (control, power electronics and electric machine) is tested and the mechanical part is simulated. The simulation system must impose mechanical inputs and outputs to the electrical machine under test. Moreover, measurements on the mechanical part have to be sent to the controller board under test. Another electrical machine (load machine) is often used as controlled mechanical load. It is supplied by a second power electronics set (load supply). A second controller board (real-time simulation) is required to control the load machine and to send fictitious mechanical "measurements" to the controller board under test (Fig. 4). This method can be called "mechanical level HIL simulation". Indeed the interface between the system under test and the simulation environment correspond to mechanical variables.

## III. Example of Different HIL Simulations for the Same Electric Drive

In this section, a very simple example is taken in order to present the different kinds of HIL simulation. The studied system is an electric scooter using a battery, a chopper, a DC machine, a gearbox and a wheel [69] (Fig. 5). We consider that the drive and the control units have to be tested before their insertion on the actual vehicle.

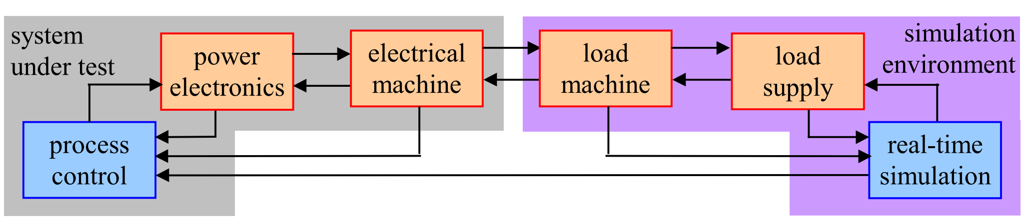


*Fig. 4: Mechanical level HIL simulation*

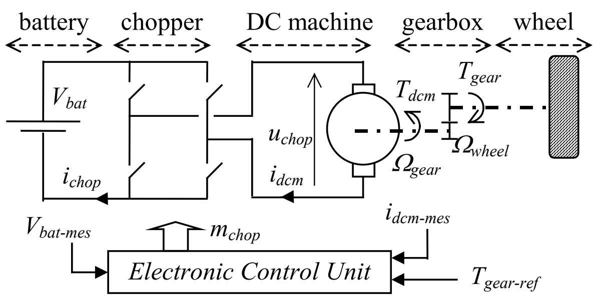


*Fig. 5: Scheme of the electric drive of the studied scooter*

### *A. Model of the studied traction system*

The chopper leads to the chopper voltage $u_{chop}$ from the battery voltage $V_{bat}$, and the current $i_{chop}$ from the machine current $i_{dcm}$:

$$\begin{cases} u_{chop} = m_{chop}\, V_{bat} \\ i_{chop} = m_{chop}\, i_{dcm} \end{cases} \tag{1}$$

with $m_{chop}$ the modulation ratio of the chopper. The DC machine is described in three parts. The armature winding leads to the armature current $i_{dcm}$ as state variable from the e.m.f.$e_{dcm}$ and the chopper voltage $u_{chop}$:

$$L_{arm}\frac{d}{dt}i_{dcm} = u_{chop} - e_{dcm} - R_{arm}i_{dcm} \tag{2}$$

where $L_{arm}$ and $R_{arm}$ are the inductance and resistance of the windings. The torque of the DC machine $T_{dcm}$ is obtained from its machine current $i_{dcm}$, and its e.m.f. $e_{dcm}$ is linked to the rotation speed $\Omega_{gear}$:

$$\begin{cases} T_{dcm} = k_{dcm}i_{dcm} \\ e_{dcm} = k_{dcm}\Omega_{gear} \end{cases} \tag{3}$$

where $k_{dcm}$ is the torque coefficient. The gearbox leads to the gearbox torque $T_{gear}$ and the rotation speed $\Omega_{gear}$ respectively from the machine torque and the rotation speed of the wheel $\Omega_{wheel}$ using the gearbox ratio $k_{gear}$:

$$\begin{cases} T_{gear} = k_{gear}\, T_{dcm} \\ \Omega_{gear} = k_{gear}\, \Omega_{wheel} \end{cases} \tag{4}$$

The wheel converts the rotational motion in a linear motion according to obtain the traction force $F_{tract}$:

$$\begin{cases} F_{tract} = \dfrac{1}{k_{wheel}}T_{gear} \\ \Omega_{wheel} = \dfrac{1}{k_{wheel}}v_{ev} \end{cases} \tag{5}$$

where $R_{wheel}$ is the wheel radius. The scooter velocity $v_{ev}$ is obtained using the classical dynamics relationship with the traction and resistant forces, $F_{tract}$ and $F_{res}$:

$$M\,\frac{d}{dt}v_{ev} = F_{tract} - F_{res} \tag{6}$$

with $M$ the equivalent mass of the vehicle including the rotating masses. The environment leads to the resistive force $F_{res}$ from the vehicle velocity and characteristics of environment:

$$F_{res} = F_0 + a\, v_{ev} + bv_{ev}^2 + Mg\sin\alpha \tag{7}$$

with $F_o$ the initial rolling force, $a$ the rolling coefficient, $b$ the drag coefficient, $\alpha$ the slope rate and $g$ the gravity.

The electronic control unit (ECU) contains the control algorithm which delivers the modulation ration $m_{chop}$ to the chopper from the reference torque $T_{gear-ref}$ deduce from the acceleration demand.

### *Signal HIL simulation of the studied drive*

In this case, the ECU is tested. All power components are then simulated in real-time using another controller board (DSP for example) and relationships (1) to (6) are sampled (Fig. 6). Because this real-time simulation has to generate pseudo continuous variable ($V_{bat-mes}$ and $i_{dcm-mes}$), and also it has to simulate the modulation effects of the chopper, its sampling period $T_{samp-dsp}$ is very small in comparison with the sampling period of the control unit $T_{samp-ecu}$. For instance, a sampling period 20 times lower than the modulation period $T_{mod}$, enables a sufficient accuracy to take into account the modulation effect of the power electronics. A powerful and fast DSP is thus required.

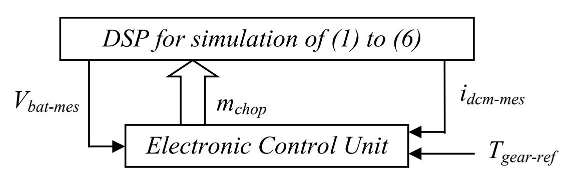


*Fig. 6: Hardware configuration of the signal HIL simulation*

### *Power HIL simulation of the studied drive*

In this case, the ECU, and also the battery and the chopper are tested. In order to simulate the behaviour of the DC machine the chopper can be connected to an inductor and another chopper (Fig. 7). A controller board (DSP) simulates in real-time the relationships (2) to (6) and the chopper modulation ratio $m_{emul}$ is calculated to impose the same current $i_{dcm}$ in the inductor as imposed by the machine model (2). A control loop of the current in the inductor is thus required.

An important inductance and/or a high chopper frequency of the emulation part would be useful to impose a continuous current $i_{dcm}$, as imposed by an actual dc machine. Moreover, the time constant of the inductor must be lower than the time constant of the dc machine, to be able to reproduce the same evolution of the dc machine current thanks to the current loop. Moreover, the sampling period of the emulation controller board is chosen to ensure good performances to this emulation control loop. But generally this sampling period is lower than the sampling period requires by the signal HIL simulation.

This HIL simulation enables to check the electronic control unit, but also the chopper, and the battery that will be integrated on the final system. The chopper influence (EMC on the control for instance) and reliability can be tested. The actual battery can also be tested (state-of-charge, current limitations), and its influence on the vehicle behaviour can be studied (limitation of regenerative braking for example). But this power HIL simulation requires other power components to impose a correct behaviour of the DC machine. If more experimental results can be achieved than the signal HIL simulation, the cost of this kind of HIL is generally higher.

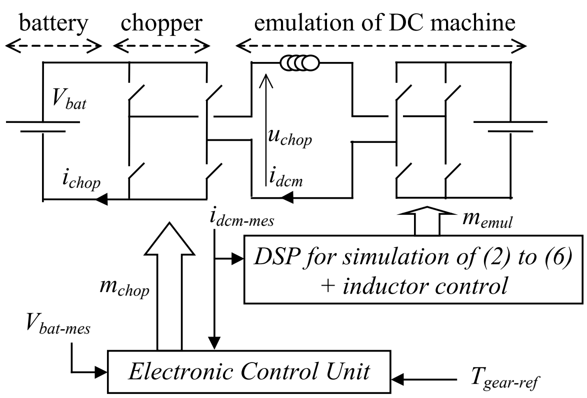


*Fig. 7: Hardware configuration of the power HIL simulation*

*Mechanical HIL simulation of the studied drive*

In this case, all the drive, including the actual electric motor is tested. This HIL simulation enables intensive tests on a static experimental bench, because the machine is not connected to the wheel. In order to simulate the behaviour of the mechanical power train, the shaft of the dc machine can be connected to another electric machine supplied by a power converter (e.g. an induction machine and an inverter as in Fig. 4). A controller board (DSP) simulates in real-time the relationships (4) to (6) and the inverter modulation vector $\underline{m}_{emul}$ is calculated to impose the same rotation speed $\Omega_{gear}$ to the DC machine as imposed by the mechanical power train (4). A speed control loop is thus required (and a field oriented control for example, for the control of the induction machine).

In this case, the time constant of the IM shaft must be lower than the equivalent time constant of the rotation speed of the DC machine, in order to be able to follow the dynamics of the mechanical power train. The sampling period of the emulation controller board is fixed in function of the lower time constant of the emulation part (i.e. the time constant of the IM current).

This HIL simulation enables to check the control unit, but also the chopper, the battery, and the electric machine that will be integrated on the final system. The effect of power electronics on torque, the machine limitation (saturation for example) can be tested. The drive performance and reliability can be tested without the mechanical parts without being embedded on the vehicle. But this mechanical HIL simulation requires more power components than the other and its cost is more important.

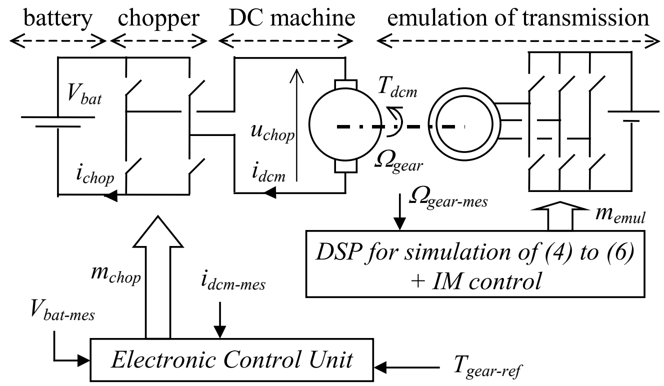


*Fig. 8: Hardware configuration of the mechanical HIL simulation*

This last HIL simulation has been validated on an experimental set-up using a DC machine of 1.5 kW, an induction machine of 1.5 kW, a chopper and an inverter (Fig. 9). A dSPACE 1103 is used both for the control unit of the electrical scooter and for the emulation of the mechanical power train. The modulation period of the chopper is set to $f_{mod}$ = *1 kHz* as in the actual system. The sampling period of the control unit and the emulation is set to $T_{samp\text{-}cu} = T_{samp\text{-}simul} = 100$ $\mu s$. A classical field oriented control and a standard Puse Width Modulation are used for the induction machine.

*Fig. 9: Experimental set-up of the mechanical HIL simulation*

Experimental results are provide for a trapezoidal reference of velocity with a sharp slope from t=18s to t=24 s (Fig. 10). The rotation speed is close the rotation speed imposed by the mechanical power train, except during the fast transient of the slope steps (Fig. 11). Other experimental results can be found in [58].

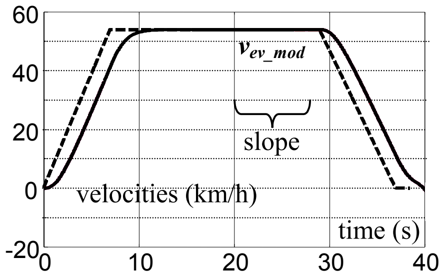


*Fig. 10: Emulated vehicle velocity*

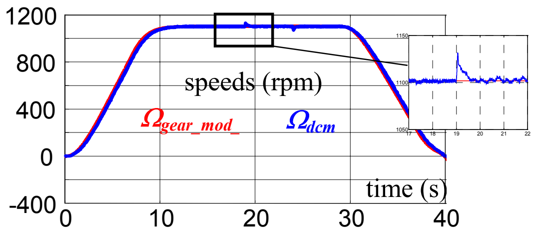


*Fig. 11: Experimental rotation speed*

## IV. Conclusion

HIL simulation reduces development time and enables various tests that cannot be achieved on the actual system for cost or security reasons (fault operation for instance). "Signal level HIL simulation" is very often used in industry to check controller boards and process controls. Its "power level" and "mechanical level" extensions are growing because they are a promising intermediary step before integration of electric drives in actual systems. Because of the increasing complexity of the systems under test, the organization of the HIL simulator is of prime importance to assess the best performance.

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