Real-Time and Hardware-In-The-Loop Simulation of Electric Drives and Power Electronics: Process, problems and solutions

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Abstract – This paper discusses Real-Time and Hardware-In-The Loop simulation used for the design and testing of electric drives and power electronic systems. A thorough overview of the design process involving the approach of real-time simulation and rapid prototyping is given along with an explanation of the difficulties and pitfalls encountered, and the solutions available and implemented in RT-LAB real-time electrical simulator.

The paper summarizes the general design and architecture of the RT-LAB simulator with particular emphasis on hardware and software components that address the difficulties on the HIL simulation of power electronic systems.

Keywords: Electric drives, power electronics, real-time, simulation, hardware-in-the-loop, rapid prototyping, HIL, RT-LAB, motor drive.

1. Introduction

Today, electric drives, power electronic systems and their controls are getting more and more complex, and their use is widely increasing in all sectors: power systems, traction, hybrid vehicles, industrial and home electronics, automotive, naval and aerospace systems, etc.

But the complexity and costs of projects are increasing, and at the same time, there is a growing pressure to reduce the time-to-market. As a consequence, testing and validation of these complex systems has become more and more important in the design and engineering process.

Traditionally, validation of the system was done by non-real-time simulation of the concept at early stage in the design, and by testing the system once the design is implemented; but this method has two major drawbacks: first, the leap in the design process, from off-line simulation to real prototype is so wide that it is prone to many troubles and problems related to the integration at once of different modules; second, the off-line, non-real-time, simulation may become tediously long for any moderately complex system, especially for AC motor drives with switching power electronics.

In a separate stream of design logic, it is often necessary to change and improve a part of an existing system, like the controller or simply the control algorithm. However, it may be difficult to have access to the complete system for testing the new controller, the system being already in use and its operation cannot be easily interrupted; or it may be simply too risky to test a new control scheme in an expensive system, or to directly move from off-line simulation to implementing the new scheme in the final system.

For these reasons, it has become necessary over the past years to use a gradual approach in designing the system, integrating its modules or simply upgrading one of its modules or experimenting with it. This approach, involving the Real-Time (RT) digital simulation, has been traditionally reserved to very large and complex projects (mainly in power systems & aeronautics).

For power electronics and motor drives, RT simulation is used as a step in the engineering process, either to simulate the complete system in RT, or to connect a part of the system to a RT digital model of the remaining part, in what it is commonly called Hardware-in-the-Loop (HIL) application.

The present work will explain this gradual engineering approach and process, heavily involving HIL simulation and rapid prototyping of power electronics and motor drives. The hardware and software components of the HIL system will be thoroughly discussed and the specific needs, constraints and problems related to RT simulation of electric drives and power electronic systems will be enumerated and discussed. The paper also discusses available solutions and techniques and comprehensively explains the implementations of these methods in the RT-LAB (1) real-time electrical simulator, both from the hardware and software point of view.

2. The Process of HIL Simulation

2.1 Overview of Power Electronics System

A power electronics system, similar to any control system, is usually made of a controller and a plant (Fig. 1); this latter is the power circuit (power source, power electronics converter and load). These are usually connected in closed loop by the means of sensors sending feedback signals from the plant to the controller and an interface (actuators) to level the signals sent from the controller to the power switches (Firing pulse unit, gate drives, etc).

Multiple such sub-systems (power converters and drives), each with its load and controller, may be inter-connected to form a single complex system; examples are: a typical AC motor drive using two converters to connect it to the power grid; a hybrid electric vehicle power drive, using inverter, traction motor, DC-DC converters and AC-DC converters for auxiliary loads; etc.

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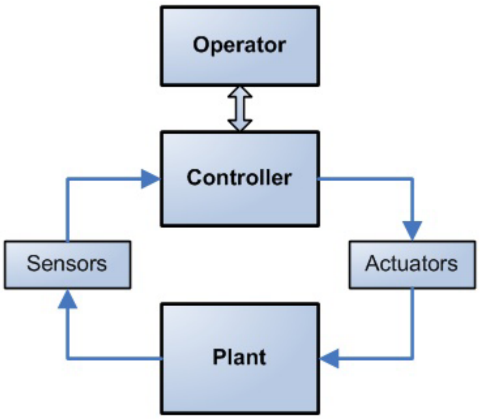


Fig. 1. Block diagram of a control system

2.2 Traditional Design Process

The design process of most engineering projects, including the development of power electronics based system, consists of the following four fundamental consecutive steps: requirements and specifications, design, implementation, and testing.

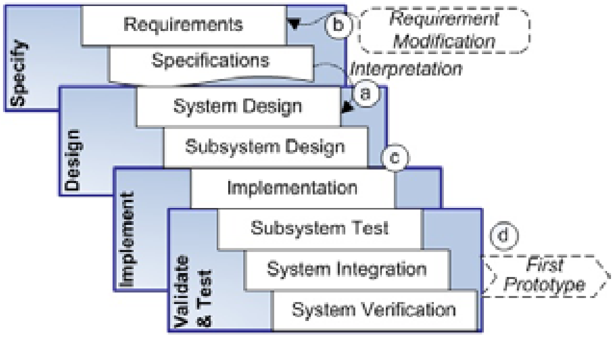


Fig. 2. Traditional Design Process

This design workflow has few limitations embedded in it. First, design information is communicated and managed by the means of text based documentation. But text based documentation is usually difficult to comprehend or subject to interpretation errors (Fig. 2-a).

On other hand, in a typical project, the design requirements may change due to addition or modification of a requirement (Fig. 2-b). This requirement change necessitates new development and verification, and the resulting iterative loop (requirement change, development and testing) is inefficient and often has a significant impact on the development and testing times.

Another major limitation is caused by the fact that code is created manually from specification and requirements documents; this hand coding is both time-consuming, and prone to implementation errors (Fig. 2-c); and there is little tracking to ensure that changes are correctly implemented.

Finally, in this conventional 'manual' design approach, obtaining a prototype of the system during the early developmental phase is very difficult and costly (Fig. 2-d).

As a consequence, design and requirements errors are discovered late in the design cycle resulting in expensive delays and even jeopardizing the entire project.

2.3 Model Based Design Process

Model-Based Design process addresses the difficulties and shortcomings of traditional development method and aims at overcoming them. In this design method, the ambiguous specifications documents are replaced by mathematical models made of system-level, graphical block diagrams (data flow, state flow, etc).

By using these model-based block and state diagrams, the design can be simulated and refined iteratively until it meets the requirements. Once the design is refined and validated, designers can automatically generate code from the model, eliminating the need for hand coding and the errors that manual coding can introduce.

Verification and validation are conducted throughout the development process by integrating tests into the models at any stage. This continuous verification and simulation helps identify errors early, when they are easier and less expensive to fix.

This method is commonly illustrated by the V shaped design process of Fig. 3.

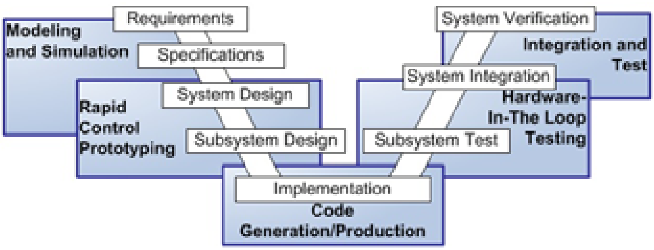


Fig. 3. The V-Cycle of Model-Based Design Process involving RCP and HIL

The main characteristic of this V-cycle, model-based design process is the use of simulation through all the stages of the design: from off-line simulation at the specification and concept design phases, to RT simulation for rapid control prototyping and design, and for testing and validation through hardware-in-the loop simulation. The iterative loop (specify, design, implement and test) is, therefore, greatly accelerated.

2.4 Model Based Design Process Applied to Power Electronic Systems

This model based design process, using rapid control prototyping and hardware-in-the loop simulation, is being more and more used in the development of a power electronics system. This process, based on the V-cycle and illustrated in Fig. 3, consists of the following major steps:

- ***Concept design of the system***: this involves analysis of the requirements of the system and their translation into a list of specifications. Even at this early stage, non-real-time simulation can be used to help define the specifications.

- ***Design of the system***, its subsystems and their interconnections. During this phase, modeling of the system and off-line simulation is conducted.
- ***Real-time digital simulation*** of the complete system; the offline simulation model is converted, at this phase, to a real-time digital model, to accelerate the simulation, interact with the simulated system and to prepare the following phase that involves actual hardware; moreover, the controller of any converter or drive is nowadays most probably digital, underlining the need and importance for this phase of discretizing the design model.
- ***Hardware-in-the-loop simulation*** of either the controller (rapid control prototyping, RCP) or the plant (plant-in-the-loop, or generally called hardware-in-the-loop). At this stage, a part of the designed system is built and available to be integrated to the other part that is being simulated in real-time. This phase may constitute for some projects the only phase that is used (i.e. when the project consist on improving an existing system, or upgrading a new design, or correcting a bug in one of its modules). If the hardware (controlled equipment) is available, rapid control prototyping and testing is done with the real hardware. But, for complex systems, like a hybrid car power drive, or a complex industrial drive, in most cases, the controller will be ready before the hardware it controls; so, HIL testing, where the real hardware is replaced by its RT digital model is used to debug and refine the controller. This is done with a key characteristic of this design process: code generation. The block diagram based model is automatically implemented in real-time through fast and automatic code generation; the long, error prone hand coding is avoided; prototyping and iterative testing is therefore greatly accelerated.
- ***Integration and testing***: this is the final stage where all the modules of the system are integrated together to build the final prototype or the final product.

In this design process, minor and major feedback loops exist between these phases; they allow fast and cyclic correction of design flaws. But most importantly, the system is debugged and verified at early stage of the design process reducing, the cost and time of any possible correction.

Hardware-in-the-Loop simulation permits repetition and variation of tests on the actual or prototyped hardware without any risk for people or system. Tests can be performed under realistic and reproducible conditions. They can also be programmed and automatically executed.

2.5. The RT-LAB Platform for Rapid Prototyping and HIL Simulation of power electronics and Drives

RT-LAB is an integrated real-time software platform that enables model-based design by the use of rapid prototyping and HIL simulation and testing of control systems, according to the V-cycle design process.

It is based on the PC commercial-off-the-shelf technology, and uses the MATLAB/Simulink environment as a front-end for designing system-level, block diagram models and simulating them off-line. The block-diagram models become the source from which code can be automatically generated, and downloaded onto target Pentium-based PC's, for real-time simulation ([2], [3]). It consists of a host PC (development and user interface) and a target PC (or many target PCs in parallel), as shown in Fig. 4.

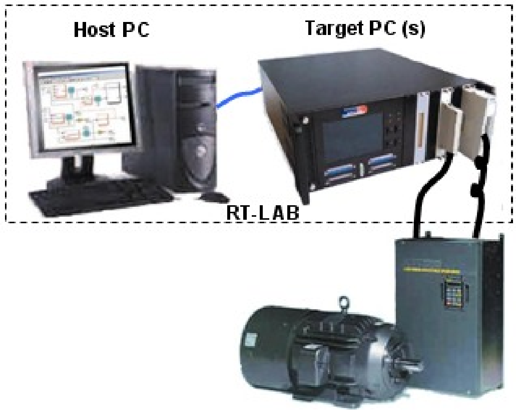


Fig. 4. General configuration of RT-LAB simulator

But, as will be explained in the following sections, *rapid control prototyping and HIL testing of power electronic systems necessitates more than the RT simulation platform*; their simulation accuracy and speed constraints are so high that special modeling and solving methods are needed in order to be able to simulate them in real-time. RT-LAB Electrical Engineering Simulators builds on the RT-LAB software platform and integrates special methods and techniques for the control and simulation of complex power electronics and drives as will be detailed in the following sections.

3. The Challenges of RT and HIL Simulation

The most critical criterion in conducting HIL simulation is: how to attain acceptable model accuracy with an achievable digital simulation time-step. This is especially a challenging task for the simulation of switching power electronics and motor drives. These highly non-linear systems need very tiny time-steps to reach acceptable accuracy, and a processing power that can handle their complexities, especially for multi-converter systems, or converters with large number of power switches.

Fig. 5 shows the need in terms of processing power and sampling speed for the RT simulation of electric applications. For electric systems involving switching power electronics, the sampling time step ranges from about 50 μs for naturally switching converters to few μs and lower for converters with high frequency switching. It is clear that there is a direct proportional relation between the sampling frequency and the switching frequency.

This puts a great pressure on the hardware performance on one hand, and on the other hand, it solicits the implementation of different and ingenious software techniques both at the real-time software level and at the level of the solving methods.

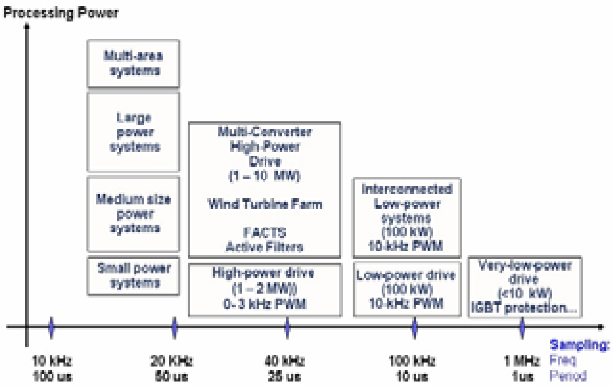


Fig. 5. Needs of processing power and sampling speed for RT simulation of electric systems

The problem of simulating electrical systems becomes harder when simulating switching power converters because of their high switching frequencies.

Because real-time (and HIL) simulations use discrete step solvers, the switching of the power devices will often occur between time steps. The error in capturing the exact switching times, if not corrected, produces such problems as jitter, non-characteristic harmonics, spurious voltage spikes and non-linearity of the control characteristics (example: ladder-like waveform of the current or voltage as a function of the modulation index, or the firing angle).

The following two sections will address this accuracy problem where the third one will deal with the speed issues.

3.1. Interpolation of Device Switching

One method to accurately simulate the firing gate generation and to remove the effects of inter-time step switching is to decrease the time step itself. However, very small time-steps may not be achievable with even the most advanced digital simulator available.

RT-LAB solves this problem by applying an interpolation algorithm to determine the exact instant of the switching event. This is faster and more accurate than reducing the time step. The use of the interpolation algorithm allows the simulator to accurately simulate switching events, while maintaining real-time operation.

In RT-LAB simulator, this is accomplished by two means: (1) interpolation applied to generation of switch signals accomplished by the RT-Events [(4)] toolbox for Simulink for precise simulation of gate firing (and pulse encoders); (2) interpolation applied to switching converters; this is done by implementing a real-time compensation scheme in the state-space solving method of ARTEMIS [(5)], applied to the SimPowerSystems [(6)] circuits; or by voltage compensation of voltage-source inverters, with the time-stamping technique of RT-Events [(8)].

3.2. Time-Stamping of Captured Gate Signals

In HIL application where the plant is interacting with an external (to the simulator) controller, the PWM signals, with a switching frequency of several kHz, cannot be sampled by the simulator at the simulation frequency; this is because achieving the necessary resolution for gate signals would need a sampling time that is in the sub-µs range, and this is inaccessible with the current state of technology. Therefore, the gate signals of the switching devices must be sampled by high frequency timer boards and the resulting time stamps incorporated into the simulation process.

This is accomplished, in RT-LAB simulator, by the use of a Xilinx FPGA board, with high-frequency clock (100 MHz), capturing the PWM signals with a resolution of 10 ns (Fig. 6).

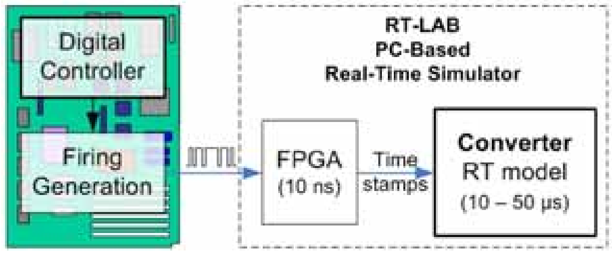


Fig. 6. Capturing gate signals in the simulator with FPGA board

By capturing the PWM signals with the fast timer board, the times of rising and falling transitions are recorded; then these time-stamps are forwarded to the switch model, as shown in Fig. 6.

3.3. Processing and communication power

Because the RT simulation of power electronics is very demanding on computing resources, and because there may be multiple converters and drives in the simulated system, it is necessary with today's technology, to use parallel computing in order to be able to handle the calculation load of these complex systems. Parallel processing, with very low communication latency is implemented in RT-LAB as well as the following characteristics, necessary for the HIL simulation of power electronics:

- Support at the simulator hardware and software level, for parallel processing suitable for distributed simulation of large systems.
- Exploitation of system topology to reduce matrices' size and number by splitting the equations of separated systems.
- Implementation of advanced techniques for constant computation time, avoiding peaks.
- Strictly non-iterative operation.
- Very fast analog and digital inputs/outputs.

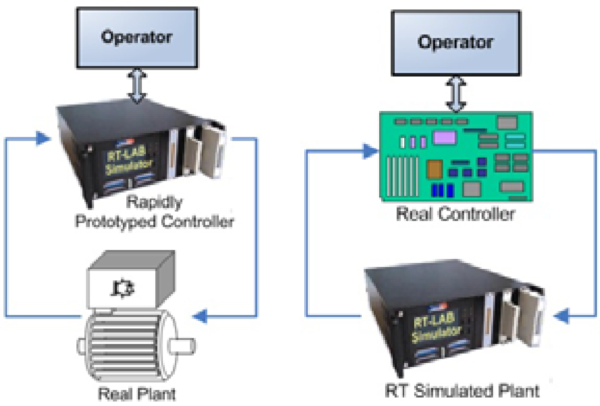
4. Applications

There are many applications of the RT-LAB simulator in power electronics systems and drives, where the HIL approach is used ([(7)] - [(10)]).

The two major applications of rapid control prototyping and hardware-in-the-loop testing of motor drives are briefly described hereafter for typical projects.

- ***Rapid control prototyping***: (Fig. 7-a) in this application, the controller of an ac motor for vehicle power steering was designed in Simulink, then automatically implemented in embedded RT-LAB system for on-road testing and tuning. This type of application is also widely used in university labs to teach control theories, and for research, development and rapid testing of new control algorithms for motor drives and power converters.

- ***Hardware-In-The-Loop Testing***: (Fig. 7-b) in order to test a new controller board for industrial power drive, it may be sometimes very difficult to get access to actual drive; also, it is too risky to test the new board directly on the large power equipment; for these reasons, RT-LAB simulator is used to simulate the ac motor drive. This type of application can be used for teaching courses on electric drives, converters and their controls, where different types of drives can be simulated on the same RT-LAB system.



(a) Rapid Control Prototyping (b) HIL Testing

Fig. 7. Typical applications of RT-LAB Simulator

Some examples are given hereafter (details are given in [8] and [9]):

- Real-time simulator of ***wind turbine generator system*** for controller design and test (Fig.8): with doubly fed induction machine with vector controlled back-to-back PWM voltage source inverter at the rotor. Real-time step size with (RT-LAB) was 25 μs including both the circuit and the controller.

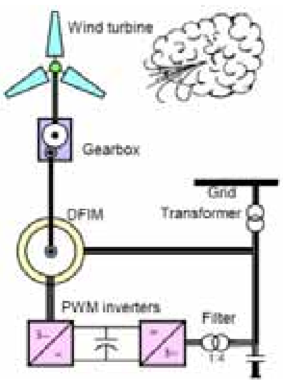


Fig. 8. Wind turbine generation system

- Real-time simulation of ***fuel-cell hybrid vehicle drive*** with multiple dc-dc converters and ac converters (Fig. 9).

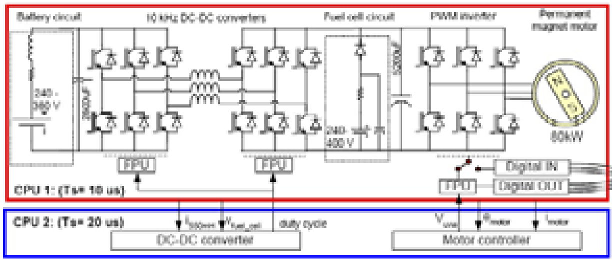


Fig. 9. RT model of fuel-cell hybrid vehicle drive

- Real-time simulation and HIL testing of ***multi-level inverter drive*** for steel lamination application (Fig. 10).

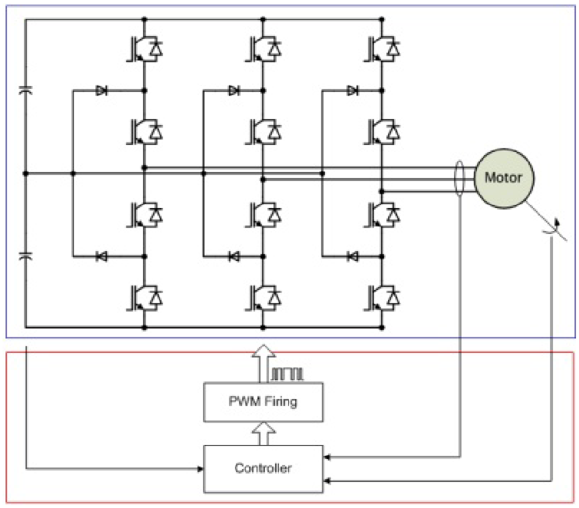


Fig. 10. Multi-Level inverter drive

5. Conclusions

The hardware-in-the-loop method for testing and validating electric systems was explained, with a special focus on the specific challenges and problems related to electric drives and power electronic systems. An overview of the design process based on model-based approach and real-time simulation was described along with an explanation of the difficulties and the solutions available. An overview of RT-LAB simulation platform and its applications were given.

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