Real-Time, PC-Based Simulator of Electric Systems and Drives

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***Abstract* – This paper presents a fully digital, real-time transient simulator on PC-cluster, of self-contained electric systems and drives.**

This simulator was developed with the aim of meeting the transient simulation needs of electromechanical drives and electric systems while solving the limitations of traditional real-time simulators. It is based on a central principle: the use of widely available, user-friendly, highly competitive commercial products (PC platform, Simulink ™). It consists of a real-time distributed simulation platform (RT-LAB) for the execution of a Simulink block diagram and circuits over a cluster of PCs, and innovative algorithmic software for the fixed-time-step simulation of stiff electric circuits and their firing pulse units.

It is intended for real-time simulation and rapid control prototyping of power electronic systems and drives.

Keywords – Real-time, digital simulation, transient simulation, PC, Cluster, Simulink, Drive, RT-LAB.

I. Introduction

With the ever evolving use and complexity of power electronic systems, and with increased pressure for reduced time-to-market and costs, the need for extensive simulation is becoming more and more inevitable; real-time simulation of electric systems and drives becomes an increasingly important requirement for the rapid prototyping and testing of new circuit topologies and control strategies.

Digital real-time simulation has been used for years in the high-voltage power system sector; and many commercial products have been developed based on Dommel's algorithm including RTDS and Hypersim. However, these tools have few drawbacks related to their being expensive and highly complex proprietary hardware, and to the numerical oscillations that arise from their use of the Tustin integration algorithm.

The real-time simulator presented in this paper consists of two main tools: a real-time distributed simulation package (RT-LAB) for the execution of Simulink block diagrams on a PC-cluster, and algorithmic toolboxes designed for the fixed-time-step simulation of stiff electric circuits and their controllers.

This paper describes the RT-LAB Electric Simulator, and explains its software and hardware configuration. Examples of implementation are discussed; and their results show the main features of this simulator: 1) highly stable solvers suitable for stiff power electronics systems and drives; 2) advanced computational techniques adapted to the technical needs of the real-time simulation of such systems; 3) open architecture with a user-friendly interface; 4) interface to external hardware; 5) non-proprietary hardware; and 6) scalability.

II. Simulator Architecture

A. Commercial-off-the-shelf PC equipment

Real-time simulation and Hardware-In-the-Loop (HIL) applications are increasingly recognized as essential tools for engineering design and especially in power electronics and electrical systems. These real-time simulation systems have very tight constraints regarding such technical issues as: very small simulation step size, high processing power, high throughput communication links, fast I/O's, etc. For this reason, they have been using proprietary, expensive, high-end technology to meet their requirements

As Commercial-Off-The-Shelf (COTS) equipment performance has been evolving at a very fast rate, PC systems have now supplanted proprietary designs for many simulation and control applications. With the fast evolving PC technology and with the advent of embedded PCs, low-cost fast communication links, and other PC technologies, the range of applications that can benefit from the low cost of COTS hardware has grown.

Today, true COTS hardware such as PC, Ethernet and IEEE 1394 (FireWire) allow large savings in cost and engineering effort. Similarly, commercial simulation software such as MATLAB™/Simulink is now widely used in engineering simulation.

B .Block Diagram and Schematic Interface

The present real-time electric simulator is based on RT-LAB real-time, distributed simulation platform; it is optimized to run Simulink and SimPowerSystems™ Blockset (previously known as the Power Systems Blockset™ or PSB) in real-time, with efficient fixed-step solvers, on PC-Cluster.

Based on COTS non-proprietary PC components, RT-LAB is a modular real-time simulation platform, for the automatic implementation of system-level, block diagram models, on standard PC's ([1], [2]). It uses the popular MATLAB/Simulink as a front-end for editing and viewing graphic models in block-diagram format. The block-diagram models become the source from which code can be automatically generated, manipulated and downloaded onto target processors (Pentium and Pentium-compatible) for real-time or distributed simulation.

C. Inputs and Outputs (I/O)

A requirement for real-time HIL applications is interfacing with real world hardware devices, controller or physical plant alike. In the RT-LAB real-time simulator, I/O interfaces are configured through custom blocks, supplied as a Simulink toolbox. The engineer merely needs to drag and drop the blocks to the graphic model and connect the inputs and outputs to these blocks, without worrying about low-level driver programming. RT-LAB manages the automatic generation of I/O drivers and model's code so to direct the model's data flow onto the physical I/O cards.

D. Simulator Configuration

In a typical configuration (Figure 1), the RT-LAB simulator consists of:

- One or more target PC's (computation nodes); one of the PCs (Master) manages the communication between the hosts and the targets and the communication between all other target PC's. The targets use the QNX real-time operating system;
- One or more host PC's allowing multiple users to access the targets; one of the hosts has the full control of the simulator, while other hosts, in read-only mode, can receive and display signals from the real-time simulator;
- I/O's of various types (analog in and out, digital in and out, PWM in and out, timers, encoders, etc). I/O's can be managed by dedicated processors distributed over several nodes.

The simulator uses the following communication links:

- Ethernet connection (100 Mb/s) between the hosts and target PC's;
- Ethernet connection between target nodes allowing parallel computation of models with low and medium step size (in the millisecond range), or for free-running, non real-time simulation;
- Fast IEEE 1394 (FireWire) communication links (400 Mb/s) between target PC's for parallel simulation of models with small step sizes (down to 20 μs) and tight communication constraints (power systems, electric drive control, etc);
- Fast shared-memory communication between processors on the same motherboard (dual, quad or 8 processors).

The target PC's may be in different form factors: desktop, laptop, rack mount, industrial, embedded PC/104, VME or Compact PCI. They use Pentium or AMD processors, with different processing speeds (from x86 in the megahertz range to Intel Pentium and AMD Athlon in the gigahertz) and various processor configurations (from single and dual Pentium microprocessor motherboards to quad-processor Xeon motherboards); the system is scalable so that additional nodes may be added as needed.

An example of a rack mount simulator layout is given on figure 2.

III. SIMULATOR SOLVERS

The RT-LAB electrical simulator uses advanced fixed-time-step solvers and computational techniques designed for the strict constraints of real-time simulation of stiff systems. They are implemented as a Simulink toolbox called ARTEMIS [3], which is used with the simPowerSystems (PSB). PSB is a Simulink toolbox that enables the simulation of electric circuits and drives within the Simulink environment. While PSB now supports a fixed-time-step solver based on the Tustin method, PSB alone is not suitable for real-time simulation due to many serious limitations, including iterative calculations to solve algebraic loops, dynamic computation of circuit matrices, undamped switching oscillations, and the need for a very small step size which greatly slows down the simulation.

The ARTEMIS solver uses a high-order fixed-time-step

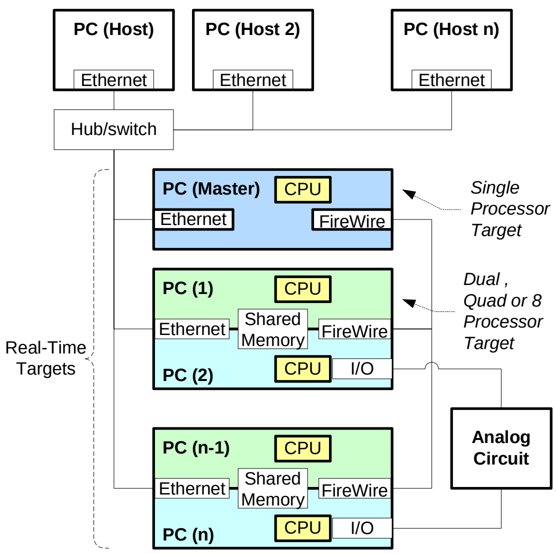


Fig. 1 RT-LAB Simulator Architecture

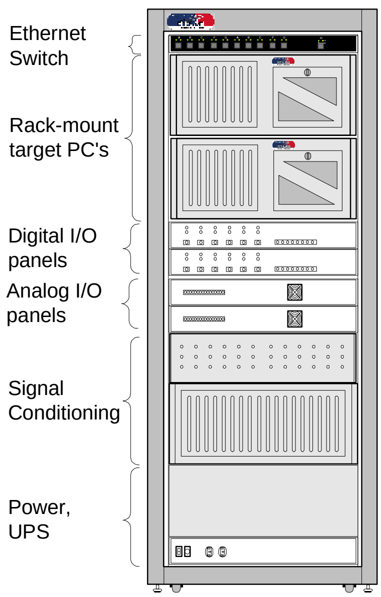


Fig. 2 Typical simulator layout

integration algorithm that is not prone to numerical oscillations, and advanced computational techniques necessary for the real-time simulation of power electronic systems and drives such as:

- Exploitation of system topology to reduce matrices' size and number by splitting the equations of separated systems [4];
- Support for parallel processing suitable for distributed simulation of large systems;
- Implementation of advanced techniques for constant computation time;
- Strictly-non-iterative integration;
- Real-time compensation of switching events occurring anywhere inside the time step, enabling the use of realistic simulation step sizes while ensuring a good precision of circuits with switches (GTO, IGBT, etc) ([5], [6] and [7]).

IV. RT Simulation Development Process

Electric and power electronic systems are created on the host personal computer by interconnecting:

- *Electrical components* from component model libraries available in the Power System Blockset;
- *Controller components* and other components from Simulink and its toolboxes that are supported by Real-Time-Workshop;
- *I/O blocks* from the simulator I/O toolboxes.

The easy-to-use drag-and-drop Simulink interface is used at all stages of the process.

These systems are then simulated and tuned off-line in the MATLAB/Simulink environment. ARTEMIS fixed-step solvers are used for the electric part and Simulink native solvers for the controller and other block-diagram parts.

Finally, the model is automatically compiled and loaded to the PC-Cluster with RT-LAB simulation interface.

The simulator software converts Simulink and SimPowerSystems non-real-time models to real-time simulation by providing support for:

- *Model Distribution*: If a model is too complex to be computed within the time step, the simulator allows the model to be distributed over several processors, automatically handling the inter-processor communication through TCP/IP, FireWire or Shared Memory. Electric systems can be separated by using "natural" delay in the system (Analog-to-Digital conversion delays, filtering delays, transmission lines, etc);
- *Multi-rate Computation*: Not all the components in a system need to be executed at very small time steps. If the system can be separated into subsystems and executed at different update rates, cycles can be freed up for executing the subsystem(s) that need to be updated faster;
- *Specialized Solvers*: The simulator uses libraries of specialized solvers (ARTEMIS) and blocks that address many of the mathematical problems that arise when taking a model to real-time, such as new fixed-step integrators that reduce the errors introduced when replacing a variable step integrator, and special toolbox that compensate for errors introduced when events occur between time steps (RT-Events);
- *Software and Hardware Interfaces*: In addition to wide range of I/O types and boards, the simulator includes a comprehensive application program interface (API) that allows signals in the model to be used in other on-line software for visualization and interaction (i.e. LabVIEW™).

V. Application Examples

A. Testing Real Controller with Real-Time Plant Model

In this hardware-in-the-loop application, the real controller under development is connected to the simulator where the electric plant model runs in real-time. In this application, the real controller board and algorithms are tested with a simulated plant of a drive, a conversion system, etc, in order to eliminate the risks of damaging the real plant or prior to building it.

B. Testing Real Plant with Rapidly Prototyped Controller

This is another hardware-in-the-loop application. But, it is the real electric plant (drive, FACTS, etc) that is connected to the controller, rapidly prototyped with RT-LAB simulator. In this way, engineering efforts and concentration or dedicated to the development and validation of the controller algorithms and protection schemes and implementing and them graphically with Simulink model-based, system-level approach, without worrying about the technical intricacies met when migrating from the off-line block diagram to its real-time implementation; when this is done manually, it requires hand-coding the controller with all the difficult and multi-disciplinary tasks involved, such as the real-time scheduling, I/O drivers, interrupt handling, etc.

C. Fully-Digital Simulation

In fully digital simulation, both the controller and electric plant are modeled and tested off-line in Simulink and then migrated automatically to the PC-Cluster with RT-LAB.

The complete system may be run in a free-run mode, as fast as possible or in real-time, for external verification with external equipment as oscilloscopes and analyzers or for interactivity and operator training.

It is also possible to switch quickly back and forth from real-time fully digital simulation to hardware-in-the-loop simulation, for example, to switch between a rapidly prototyped controller and the real controller.

VI. Examples

A. DC Motor Drive

The DC motor drive of figure 3 is simulated with Simulink/PSB; the circuit consists of a three-phase, 6-pulse, thyristor AC-DC converter, operating in closed-loop, with two PI regulators to adjust the motor current and speed.

Simulation results at 100 µs from the fixed-step Tustin and fixed-step ARTEMIS solver are compared to reference results from variable-step solver with tight-tolerance.

When simulating switching circuits like this thyristor converter with fixed-step solver, switching events (thyristor opens or closes) occurring anywhere inside the simulation fixed time step can only take effect at the following time step. This discrete switching latency distorts the output spectrum of the simulation by introducing low frequency jitter; this is clearly shown by the oscillation of DC current simulated with Tustin at 100 µs (Figure 4).

This oscillation is introduced by the discrete simulation method and is not a real phenomenon. In some feedback systems, the jitter may even lead to instability. On the other hand, the simulation of the same circuit with ARTEMIS solver and RT-Events ([5], [8]) fixed-step control toolbox shows no such oscillation because of its switching event interpolation algorithm.

The advantages of fixed-step ARTEMIS solver is that the same precision may be reached at a higher step size that is affordable and suitable for real-time simulation.

Finally, the model has been implemented on an RT-LAB PC-cluster of 3 Pentium III, 1 GHz processors, one processor for the drive circuit, one for the firing and a third one for the controller. The calculation and the sampling times

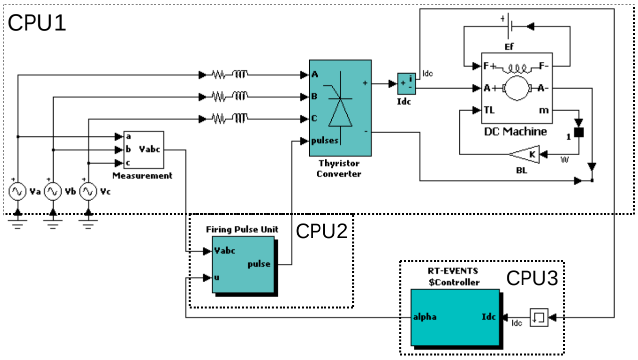
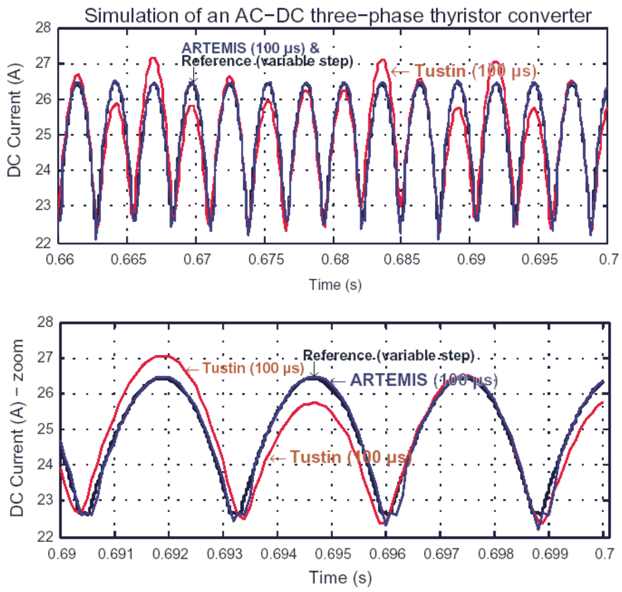


Fig. 3 DC motor drive model in Simulink



are given in table 1. The computation of the circuit needed 12 µs and the firing logic needed also 12 µs; the controller computation time was 8 µs.

It can be seen that the computational load was distributed between the three PC nodes so that a sampling time as low as 35 µs has been achieved. The minimum sampling time of the real-time simulation is dictated by the complexity of the simulated system and its computational load, but also by the latencies associated with inter-processor communication.

Table 1. Simulation times of the dc motor drive (P3, 1 GHz)

	Circuit	**Firing**	**Control**
CPU	CPU1	CPU2	CPU3
Calculation Time (µs)	12	12	8
Sampling Time (µs)	35	35	70

B. Induction Motor Drive

An induction motor IGBT drive (Figure 5) with Pulse Width Modulation (PWM) firing has been simulated with both Tustin and ARTEMIS solvers. The induction machine is operating at fixed rotor speed; the modulation index is varied and the machine electric torque is recorded; Figure 6 displays the machine torque as a function of the modulation index.

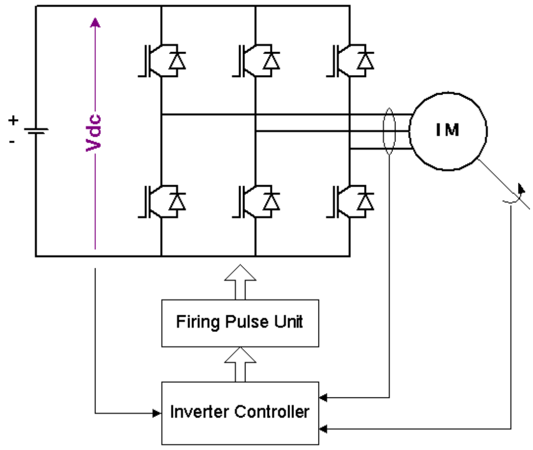


Fig. 5 Three-phase DC-AC PWM converter

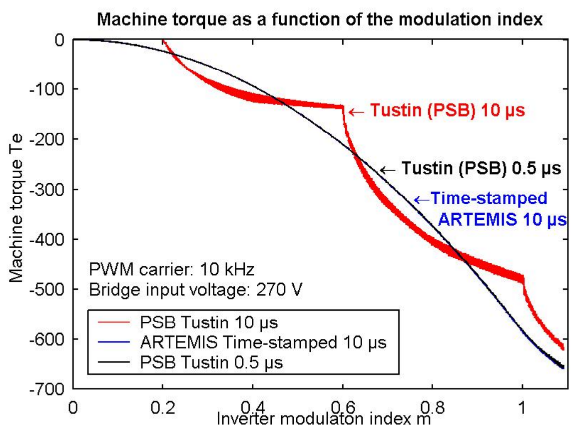


Fig. 6 Machine torque as a function of the modulation index

It can be seen that the simulation at 50 µs with the RT-LAB simulator solver gives a regulation characteristic of Te=f(m) that is very close to the reference, taken as being the result of the simulation with the Tustin solver at very small time step (0.5 µs); this precision is obtained due to the real-time interpolation algorithm implemented with the RT-LAB electric simulator that applies the necessary compensation of IGBT switching transitions occurring asynchronously to the fixed simulation clock.

On other hand, the standard Tustin solver causes important distortion that can be illustrated with a non linear torque-versus-modulation characteristic; this latter varies by threshold that are smoothed on figure 6 by the low-pass filter applied to the measured torque. This distortion can be eliminated only by reducing the integration step size down to 1 or 2 µs. Unfortunately, at these step sizes, the simulation of power converters becomes very slow; and their real-time simulation becomes impossible with today's technology.

The ac drive is simulated in real-time with the RT-LAB real-time simulator. It was implemented on a 3-node PC-cluster of 3 Pentium III, 1 GHz processors, one processor for the drive circuit, one for the firing and a third one for the controller. The calculation and the sampling times are given in table 2. The computation of the circuit needed 13 µs and the firing logic needed also 5 µs; the controller computation time was 8 µs.

It can be seen that a sampling time of 35 µs has been achieved for the power circuit and its firing logic; the controller sampling time was 70 µs.

Table 2. Simulation times of the ac motor drive (P3, 1 GHz)

	Circuit	**Firing**	**Control**
CPU	CPU1	CPU2	CPU3
Calculation Time (µs)	13	5	8
Sampling Time (µs)	35	35	70

B. Multi-Level AC-DC-AC Drive

An induction motor multi-level IGBT drive (Figure 5) with PWM firing is simulated on a PC-cluster of 3 Pentium III, 1 GHz processors: one processor for the acquisition and master control, one for the AC-DC converter circuit and a third one for the three-level 12-IGBT converter and the induction motor. The PWM frequency is 1,6 kHz.

This circuit presents the following challenges:

- The 6-pulse diode rectifier connected to the transformer, creates a stiff system that has more inductances than the number of independent state variables.
- Inductive circuit switching *usually* create voltage spikes due to current chopping or numerical instability.
- Simulation precision must be maintained for duty factor varying by 1% increments.
- Complex three-level DC-AC converters with 12 IGBT with PWM frequency of 1,6 kHz, present a particular problem due to the high number of possible topologies and to the small switching period (625 µs).
- Complex controls, with precise Firing Pulse Unit (FPU) simulation, is required for full numerical simulation mode or for control prototyping.

These challenges are solved by RT-LAB simulator by applying the following solutions:

- Use SimPowerSystem and ARTEMIS solvers to simulate the AC system
- Use of Time Stamped Bridge method for the IGBT converter, to increase precision with a practical time step and to accelerate the simulation in order to achieve a small time step.
- Use RT-EVENTS to simulate the control and FPU for precise generation of firing pulses

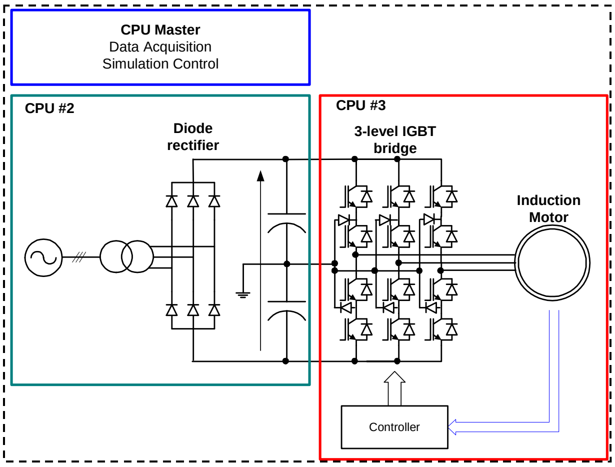


Fig. 7 AC-DC-AC drive circuit with three-level inverter

As shown on table 3, the circuit is easily simulated in real-time with a sampling time of 50 µs, with a margin that exceeds 20 µs, the system overhead being of few microseconds only.

Table 3. Simulation times of the ac motor drive (P3, 1 GHz)

	Master	**AC-DC**	**DC-AC**
CPU	CPU1	CPU2	CPU3
Calculation Time (µs)	20	18	10
Sampling Time (µs)	100	50	50

For PWM with higher switching frequencies, a time step of 50 µs is insufficient to achieve an acceptable precision or even to achieve convergence and stability. The study of a permanent magnet synchronous motor drive with a switching frequency of 10 kHz (100 µs) has demonstrated that the simulation sampling time necessary to achieve a good precision is about 10 µs. Currently, the complete PMSM drive with speed and current controllers and a complete firing pulse generation unit is simulated in real-time at 22 µs. For hardware-in-the-loop application where the drive circuit (converter and motor) is connected to a real control via I/O boards (analog outputs and time-stamped digital inputs and outputs), the authors project to achieve this very low sampling time (10 µs) in the following weeks with the new development of very fast, FPGA-based, I/O boards.

VI. CONCLUSIONS

This paper demonstrates that high-precision, fully digital, real-time transient simulation of power electronic systems and drives can be achieved on commercial Pentium-class processors, with time steps as low as 30 µs and with switching event interpolation technique.

The practical implementation has been demonstrated with Simulink / PSB and the RT-LAB Electrical Engineering Simulator.

Other recent tests not reported in this paper show that, with the recent Pentium P4 processor and with fast FPGA-based IO boards, the simulation time step of a multi-CPU simulator can be as low as 10 µs.

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