A Modular Real-Time Simulation Platform Based on the Virtual Test Bed

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Abstract—This paper describes a novel real-time simulation platform, namely VTB-RT, especially suited for power electronics systems. Using a combination of open-source packages, FPGA-based modules, and the Virtual Test Bed software, VTB-RT constitutes a simulation platform characterized by its low-cost, modularity, and versatility. In this paper, we briefly describe each VTB-RT component, and then we concentrate on a new interrupt module developed for real-time geographically distributed simulations. A distributed simulation of a DC motor drive is presented as an application example.

Keywords—real-time simulation, real-time distributed simulation, hardware-in-the-loop (HIL), power-hardware-in-the-loop (PHIL), field programmable gate array (FPGA)-based hardware modules, real-time geographically distributed simulation

I. INTRODUCTION

In real-time simulation, events must meet the timing constraints imposed by the real-time behavior of the external world. This relevant feature of real-time simulation allows engineers to easily introduce real signals and systems into the simulation loop (e.g., man-in-the-loop, hardware-in-the-loop, and power-hardware-in-the-loop). In the field of power electronics, hardware-in-the-loop (HIL) and power-hardware-in-the-loop (PHIL) simulations have become key tools in the development of new systems. HIL and PHIL facilitate virtual prototyping, testing, and validation of power systems in real-time; they make it possible to substitute critical components in a real power system with virtual objects that model the behavior of such components. This alleviates the challenges associated with testing real hardware components, especially when these components are unsafe, expensive, or simply unavailable.

The main distinction between HIL and PHIL, in the context of this paper, is given by the type of coupling between the virtual (simulated) system and the hardware under test. HIL refers to the hardware testing case in which only low-power signals are interchanged between software and hardware (e.g., digital control signals and encoder signals). PHIL, on the other hand, refers to the case in which natural coupling between software and hardware is enabled, hence power is exchanged between the virtual system and the hardware under test.

While extensive research is being carried out in both academia and industry to develop a suitable real-time simulation platform [1][2], many of the available commercial platforms for real-time simulation are either costly or inflexible. In order to be practical, a real-time simulation platform must meet the requirements of both affordability and versatility while observing high standards of performance. In this paper, we present a novel real-time simulation platform based on the Virtual Test Bed (VTB) [3][4], named VTB-RT. VTB-RT is a low-cost, modular and customizable platform for real-time simulation [5]. As shown in Figure 1, the VTB-RT platform architecture is basically composed of two complementary software environments and three hardware modules. VTB-RT developers have striven to maintain low implementation costs by using open-source software packages and field programmable gate array (FPGA)-based hardware modules. Similarly, modularity and customizability have been intensely searched for in the process of developing both the software and hardware user interfaces.

The latest addition to the VTB-RT platform has been the interrupt and global positioning system (GPS) synchronization hardware module. Previous works related to the use of VTB-RT have presented the bi-directional signal interface for HIL testing [6][7] and the power interface for PHIL testing [8]. The new interrupt module greatly increases the range of applicability of the VTB-RT platform since it allows real-time geographically distributed simulations. This type of simulation not only permits parallelism and computational resource sharing, but also team work and reduction of system complexity.

Depending on the power system to be simulated and the type of testing to be performed, the basic architecture of the VTB-RT platform can be adapted to accommodate HIL, power-hardware-in-the-loop (PHIL) and distributed simulations. These and a combination of these simulation options (e.g. geographically distributed HIL simulation), will be easily achieved by conveniently arranging the different hardware modules in the VTB-RT platform. In short, this novel real-time simulation platform will allow engineers in any field to safely design and test complex power electronic systems, reducing the risk, the cost, and the time consumption of the final hardware testing process in a wide variety of simulation scenarios.

Figure 1. VTB-RT Platform Architecture: modular, low-cost, versatile
The paper is organized as follows. First, the software and hardware structure of the proposed platform are briefly described in Sections II and III. Section IV explains in detail the new interrupt module for real-time distributed simulation. Section V discusses an application example of a DC motor drive, which demonstrates the use of the VTB-RT platform for real-time geographically distributed simulation. Finally, Section VI presents conclusions about this work.

II. VTB-RT

VTB-RT is based on the Linux version of the Virtual Test Bed, which is a new environment for design, analysis, and virtual prototyping of multidisciplinary systems. Since its inception in 2002, VTB-RT has been developed as a low-cost and versatile platform for HIL simulations.

The functionality of the VTB-RT simulation platform relies on three main elements: VTB intrinsic features, VTB-RT real-time framework, and VTB-RT FPGA-based modules. Each element is described in the following subsections.

A. VTB intrinsic features

The computational core of VTB-RT is its signal resistive companion solver (detailed information about the VTB solver can be found in [4]), which supports both structural and behavioral modeling. This solver is shared by both the Windows and the Linux version of VTB.

In addition to exploiting the capabilities of the flexible VTB solver, VTB-RT takes advantage of the graphics capabilities of the Windows version of VTB, such as the VTB’s schematic editor (SE) and advanced visualization engine (VXE).

VTB-RT users employ VTB SE to design their systems and then port the schematics to a VTB-ready Linux machine, where the real-time simulation is performed [9]. In turn, real-time simulation results can be easily analyzed in VTB VXE.

B. Real-time framework

Two open-source software packages provide the real-time framework for VTB-RT: Adeos [10] and Xenomai [11] (or alternatively RTAI [12]). They add to the standard Linux distribution the features of an industrial real-time operating system without losing the useful non-real-time characteristics of Linux, such as access to TCP/IP, graphical display and windowing systems, file and data base systems, etc. Moreover, VTB-RT uses freely-distributed Comedi [13] software drivers for the connectivity of the simulation to the real world through commercial data acquisition boards.

C. VTB-RT modules

VTB-RT has been developed following a modular concept, so that it can be easily configured for different user requirements. The VTB-RT modules are mainly implemented in an FPGA device, exploiting its modularity and parallelism. The FPGA-based modules are developed in the MATLAB® Simulink environment using the Xilinx System Generator for DSP (XSG) software [14]. This approach enables users to include modular components in their designs using Simulink subsystems, thereby making the modules easy to use and configure. The following section describes briefly the available VTB-RT hardware modules.

III. VTB-RT FPGA-BASED MODULES

VTB-RT modularity provides the user with accuracy, flexibility, and ease in the design process. Currently, the VTB-RT simulation platform features three modules that are detailed below.

A. Bi-directional Signal Interface

The bi-directional signal interface enables the VTB-RT simulation platform to accurately send and receive fast-switching signals, i.e. pulse width modulated (PWM) and encoder signals. These signals require high time resolution in the simulation and are typical in power electronics applications. This module increases greatly the bandwidth of the VTB-RT platform [6]. The main application of the bi-directional signal interface is HIL testing of electric drives; however, the module has been used in diverse applications [15].

This module implements the gating signal averaging (GSA) method [6] for accurately acquiring the duty value of PWM signals sent by a digital controller; therefore, this module improves the accuracy of the real-time simulation of switched circuits [7]. In addition, this module implements the generation of realistic encoder signals, making it possible to test a digital controller for electric drives under realistic conditions. The structure of the bi-directional signal interface is presented in Figure 2.

B. Natural Coupling SW/HW Interface

PHIL not only involves the correct transfer of signal between the simulation and the hardware, but also the conservation of energy between these two entities. The key element in PHIL simulation is the natural coupling software/hardware (NC SW/HW) interface, which enables the natural coupling between the actual power hardware and the simulation software [8]. As shown in Figure 3 the NC SW/HW interface comprises a virtual object and hardware components. The virtual object runs in VTB-RT to approximate the behavior of the simulated system and communicate this characteristic to the hardware components. The hardware part of the interface consists of a silicon H-Bridge controller with an FPGA device and a fast analog-digital converter. The FPGA device performs executes a rapid control algorithm and data acquisition procedures to meet the bandwidth requirements the platform need for this application.

![Figure 2. Structure of the bi-directional signal interface](image)
C. Interrupt/Synchronization Module

The interrupt and GPS synchronization module is implemented to coordinate the advancing of all simulation clocks synchronously in a distributed simulation. A low-cost Global Positioning System (GPS) receiver as shown in Figure 3 provides a reference real-time clock to pace the advance of time steps in the simulation. An FPGA-based interrupt module generates, in turn, a clock suitable for VTB-RT.

IV. INTERRUPT/SYNCHRONIZATION MODULE FOR REAL-TIME DISTRIBUTED SIMULATION

Real-time distributed simulation is desirable when the complexity of the system models is greater than the complexity that a single simulation platform can handle, or when systems components are being developed at different locations and gathering these virtual or real components in one facility is unpractical, expensive or can infringe intellectual property restrictions.

To ensure synchronization of two simulation processes in a real-time distributed simulation setup the interrupt/synchronization module described above has been developed. The VTB-RT approach is based on paced time-stepped synchronization [16] to make both simulation processes to follow a reference real-time clock. This approach takes advantage of affordable GPS tools for PC synchronization. The GPS hardware used by VTB-RT is the XL-750 GPS Time Source from Symmetricom [17], which is ideally suited to providing synchronization for different devices by means of a fixed one pulse-per-second (pps) signal. An FPGA is used to generate a configurable real-time clock, since one second time resolution in a simulation is not flexible enough for most experiments. Depending on the simulation requirements, the FPGA receives the one-pps signal and generates a clock with a smaller period which is synchronized with the one pps signal as depicted in Figure 4.

As with the other VTB-RT modules, the interrupt/synchronization module is implemented using the XSG as shown in Figure 5.

VTB-RT has already performed distributed simulation decoupling the system at a signal connection [18]. However, more important and challenging is to decouple the system at a natural coupling level. VTB supports two coupling schemes to ensure the conservation of energy at the decoupled boundary; these schemes are implemented in Server/Client virtual objects that keep correct current and voltage values in both ends of the distributed simulation of the decoupled parts.
V. APPLICATION EXAMPLE

The DC motor drive shown in Figure 4 is built using the VTB schematic editor in Windows. The purpose of this simple application is to show the performance of the dc-bus and the power converters parts once they are separated in different subsystems as shown in Figure 5. The Server and Client VTB objects shown in this figure allow network communication between the computers running the two separate subsystems.

The experimental results are shown in Figure 1. The simulation time frame was 10 seconds and the plot shows that the motor speed transient in the distributed simulation (blue line) closely matches that of the original simulation (red line). In this example, the motor is controlled in open-loop, reaching 20% of its rated speed (557 RPM or 58.4 rad/s), that is 11.68 rad/s, in approximately 2.5 sec.

The dc-bus voltage transient can be observed in Figure 2. In the distributed simulation (blue line), the dc-bus presents essentially the same behavior as that of the original simulation; however, small numerical errors are introduced in the distributed simulation as can be observed in the zoomed window in Figure 2. These numerical glitches are negligible and do not affect distributed the simulation results dramatically since the dc-bus values is maintained at the same level in both the original and the distributed simulation results.

VI. CONCLUSIONS

VTB-RT, a modular real-time simulation platform based on the Virtual Test Bed, has been presented in this paper. This novel platform is especially suited for power electronics systems and allows HIL, PHIL and geographically distributed simulation. VTB-RT has been shown to utilize a combination of open-source software...
packages and FPGA-based hardware modules, which make VTB-RT a low-cost, modular, and versatile solution for diverse application settings.

We have shown through an example that VTB-RT is suited for real-time geographically distributed simulation. A distributed simulation of a DC motor drive has been presented and the results have shown that natural coupling between the dc-bus and the power converter and motor subsystems is achieved successfully when using VTB-RT.

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Figure 2  DC motor application: DC bus voltage transient (V)

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