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REAL-TIME DIGITAL SIMULATION: ENABLING RAPID DEVELOPMENT OF POWER ELECTRONICS

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Abstract: *In this paper, we present the Typhoon Real Time Digital Simulation (T-RTDS) platform for high-power electronic systems, the fastest simulation platform of its kind. T-RTDS is based on novel simulation algorithms and proprietary high-throughput low-latency processor architecture. This approach enables simulation with a 1µs time-step, including input/output (I/O) latency. As a case study, we present modeling, simulation and experimental results for a system comprising a rectifier, an inverter, an output filter and a load. In addition, we demonstrate the T-RTDS capabilities for testing and verification of control hardware and software for various operating conditions.*

Key words: ***power electronics / real-time / simulation / testing /hardware in the loop / controls***

1 INTRODUCTION

Power electronics is one of the key enabling infrastructural technologies that promises to deliver up to 30% electric energy savings [1]. It is a technology that allows energy savings across all aspects of conversion of primary energy into electricity and electricity into useful work. Furthermore, power electronics is one of the instrumental technologies in the effort to reach 20% renewable energy generation by the year 2020.

In order for power electronics to reach its full potential, cost, reliability, and performance must be significantly improved. Improvements need to address long design cycles, lack of standardization, and reliability problems due to labor-intensive manufacturing, testing, and verification. In addition, performance and flexibility need to be significantly enhanced by means of standardization and automation of control software and hardware tools (e.g., automatic code generation, automatic code verification).

Typhoon RTDS has developed a novel digital platform for design and testing of high-power electronics. This technology, based on what we believe is the world's fastest real-time digital simulator platform for power electronics, is enabled by a new approach to system description/algorithms and a proprietary high-throughput low-latency digital processor architecture tailored to those algorithms.

2 A BIT OF A HISTORY

Almost eighty five years ago MIT engineers lead by Prof Vannevar Bush started a revolution in scientific computing and simulation tools with the invention of what came to be known as the *Differential Analyzer* [2]. The search for advanced analysis tools — motivated by the need to understand the dynamics of power transmission networks — resulted in development of the first analog computer ("Differential Analyzer") capable of solving differential equations in real time: arguably the world's most important computer until the end of the Second World War. Since those days, many technologies had been developed to enable real-time simulation of dynamic systems. However, the power electronics industry today still largely relies on analog simulators (low-voltage/low-power versions of real converters) and in some cases on digital simulation technologies that were designed for continuous dynamic systems with relatively slow time constants.

With the advent of T-RTDS technology, real-time simulation in power electronics will radically change, because it is a tool designed to help power electronic engineers reinvent the design and testing of power electronics and for the first time, allow flexible real-time measurement and control — with extremely high fidelity — of prototype systems that can be redesigned, refined or tuned for increased reliability and efficiency.

3 HARDWARE FINALLY GETS INTO THE “POWER ELECTRONICS LOOP”

Real-time digital simulation makes it possible to replace a physical system with a computer model for the design and testing purposes. This concept is illustrated in Figure 1 where a detailed model of a power electronics controlled wind turbine is simulated on the *T-RTDS* platform. The *T-RTDS* simulation interacts with a real physical controller via a fast input/output in *real-time*. From the controller perspective there is no difference between the physical system and its real-time simulation. Indeed, the controller (and here we mean also the high speed part of the controller which includes the modulator and the protection functions) “feels” that it is controlling a real physical system.

Real-time digital simulation as a means of testing control systems is not a new idea [3]. For example, the aerospace industry has been using it since software became a safety-critical component of flight control systems. The automotive industry is another example where real-time digital simulations have become an invaluable design and testing tool.

There are four compelling reasons for using real time hardware in the loop simulation that can be summarized as:

- reduction of development cycle,
- demand to extensively test control hardware and software in order to meet safety and quality requirements,
- the need to prevent costly failures, and
- increased availability of hardware in the loop components.

Indeed, real-time digital simulation has been a central tool for aerospace and automotive control and systems design engineers. However, real time hardware in the loop digital simulators are still rare in power electronics industry, and one may wonder why is that the case?

Power electronics systems control the flow of electric power by means of *fast* switching actions. In other words they belong to a class of hybrid systems called switched dynamic systems which can be represented with a set of discrete states and their associated continuous dynamics. Depending on external controls and internal state variables, they switch between different continuous descriptions. Combination of high-frequency switching actions and fast continuous dynamics makes such systems hard to simulate in real time using current technology.

To illustrate this point consider a variable speed wind turbine generator example from Figure 1 where power flow and turbine speed are controlled with a four-quadrant rectifier-inverter operating at a switching frequency of several kHz [4]. In order to simulate this system in real-time with good fidelity a simulation time step on the order of 1 µs which accounts for both latency and computation time is needed. This is almost two orders of magnitude improvement when compared to today's 50 µs time step of commercially available digital hardware in the loop systems.

3.1 Benefits of a high-speed low-latency T-RTDS platform

T-RTDS platform simulates all the time critical parts of the wind-turbine system (and other power electronics systems) with the simulation time step and latency of 1 µs. This performance requires formidable parallel processing power, specially formulated power electronics models and algorithms suitable for parallel execution, a very fast digital input/output interface with low-latency and a sophisticated high throughput software for data analysis and processing.

T-RTDS technology is geared for power electronics developers in the following areas:

- control hardware design, testing and tuning,
- control software testing and verification,
- fault response and recovery testing,
- testing against regulatory standards,
- education, and
- service and maintenance.

Industries that we expect to be early adopters and that are to profit the most from this approach are:

- renewable energy: wind and solar,
- transportation (automotive, traction, and aerospace),
- power generation, and
- industry automation.

4 THE T-RTDS PLATFORM DESCRIPTION

T-RTDS platform supports 1 µs simulation time step thus enabling high-fidelity real time simulations. Simulation algorithms are based on fixed time step

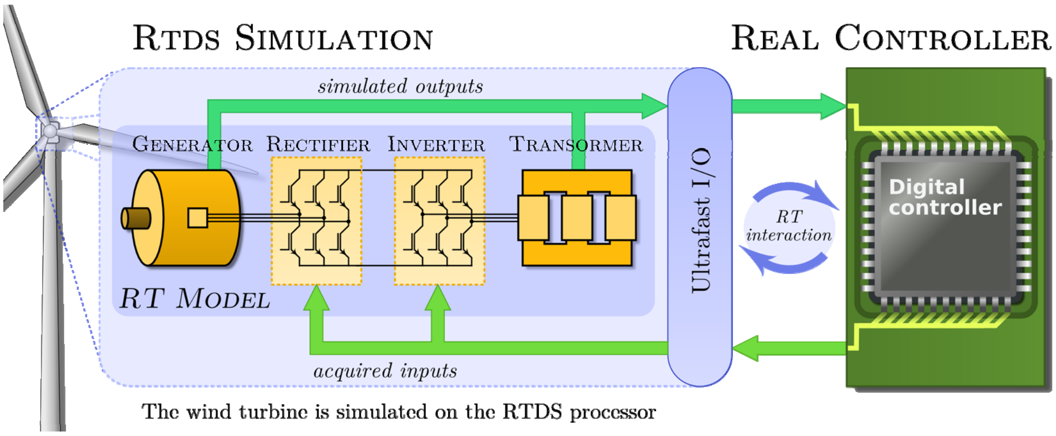


Figure 1. *Block diagram of a wind turbine real-time simulation. RTDS Simulation interacts in Real Time with real controller*

integration algorithms. The T-RTDS platform is based on our innovation in three key areas from Fig. 2:

- minimal circuit description
- proprietary compiler and
- processor architecture tailored for low latency implementation of the minimal circuit description

4.1 T-RTDS Modeling Approach

To achieve “hard” real time digital simulation of switched dynamic systems we have developed algorithms that use ideal models of the switches and generate a minimal representation of power electronics systems. Indeed, combination of ideal switches and minimal dynamic system representation enables completely *deterministic* simulation time step, which is the key to real-time simulation. None of the circuit/system simulation algorithms available, to the best of our knowledge, provide completely deterministic time execution for switched dynamic systems such as power electronics systems.

4.2 Available RTDS Architectures

Commercially available real-time simulation hardware platforms are based on standard of the shelf processors for computing and field programable gate arrays (FPGA) for input/output interfaces [5]. This traditional approach offers cost effective and flexible solutions down to 50µs simulation steps.

One of the biggest problems when using standard processors for real time digital simulation is their inherent latency. Latency can be defined as the time delay between an event at the input of the RTDS and the corresponding reaction of the RTDS at the output. Most of the standard processors ineed have large throughput but also large latency simply because they tend to achieve the throughput with the use of architectures with long pipelines.

Table 1 shows peak floating-point performances of current state of the art processing platforms. At first glance all the platforms considered easily satisfy the requirements for real time simulation of power electronics circuits. However, most general purpose processors sustained computing performance for I/O intensive algorithms can drop way below the peak performance.

Table 1. Processing platform performance comparison

	General purpose processors		GPU	FPGA
Processing platform	Cell PowerXCell 8i	Intel Core2 QX9775	Nvidia GTX 295	Virtex5 VSX240T
GFLOPS (single)	≈ 200	≈ 50	≈ 2000	≈ 192
GFLOPS (double)	≈ 100	≈ 25	≈ 200	≈ 68
Fastest interface	FlexIO	FSB	PCIe	Custom

On the other hand, latest commercialy available FPGA platforms [6] offer lower latency high bandwidth interface to the x86 CPUs using either FSB (Intel) or Hypertransport (AMD) interface. It is also shown that an IBM Cell processor can establish a high-bandwidth interface to an FPGA using FlexIO interface developed by Rambus [7]. With these newly developed interfacing capabilities, communication latency between the processing element and the external world is significantly reduced. The problem is that the mentioned platforms are expensive, are not commercially available and lack software support. In addition, loop-back latencies are still in the order of 10 µs.

Another approach is to perform all the computation on an FPGA device [8]. Today’s FPGA devices offer the comparable peak computing power to the state of the art general purpose processors even though they operate at order of magnitude slower clock speed. When it comes to computation efficiency with I/O intensive algorithms the FPGA technology is a clear winner. The programmable structure of an FPGA allows application optimized solutions resulting in a sustained performance close to the peak performance [8]. Figure 3 illustrates the performance space of standard off the shelf processors compared to our custom processor in terms of latency v.s. processing power given in giga floating point

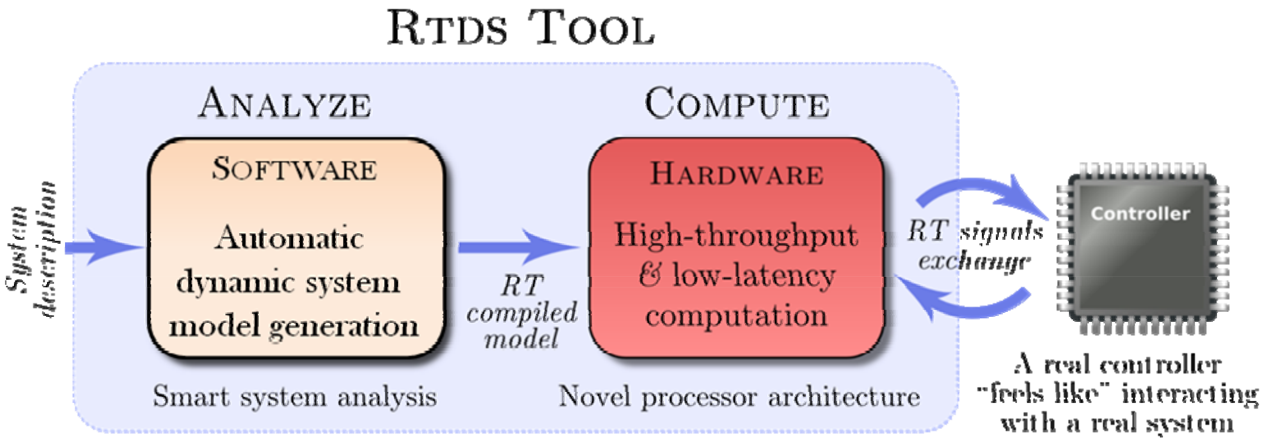


Figure 2. *The RTDS platform architecture depicts the relationship between software and hardware components. Their symbiotic design is the foundation enabling real-time operation where software compiles a model that is specifically tailored for execution on our custom processor.*

operations per second (GFLOPS). While in terms of processing speed T-RTDS algorithms require relatively modest GFLOPS number, the latency requirement our processor satisfies is almost two orders of magnitude better than what can be achieved with standard processors and holds the key to real time digital simulation of power electronics systems.

4.3 T-RTDS Architecture

Earlier work on FPGA based RTDS implementation was mostly based on implementing custom hardware models [5]. That way the hardware architecture of the system is customized for each instance of the problem and results in highly optimized digital simulator at the cost of flexibility and model development time.

This work on the other hand proposes an architecture that is general enough to cover a wide variety of power electronic models and is at the same time as high performing as the dedicated solutions. In addition, it is platform independent in the sense that it does not count on the flexibility of the FPGA technology and can later be migrated to ASIC for an additional ten fold reduction in simulation time step and latency.

4.4 High-speed Input/Output interface

Because there are no standard interfaces available for power electronics controllers their interface to RTDS almost always has to be custom made. Combining the glue logic and a processing engine in a programmable structure of an FPGA device allows the loop-back latency in the order of 1µs which is the key advantage of this technology for RTDS application.

5 A CASE STUDY: VARIABLE SPEED DRIVE SYSTEM

To demonstrate our RTDS modeling and simulation process we have simulated a rectifier-inverter-filter system from Figure 4. A SimPowerSystem (SPS) toolbox is used as a graphic user interface to specify a model that is simulated in real time on our processor platform. The model consists of single phase diode rectifier (four ideal diodes), three phase voltage source inverter, eight energy storage elements (inductors and capacitors) and five resistors.

After the schematic is specified in SimPowerSystems a netlist file is created. In the subsequent steps netlist is used as an input to T-RTDS compiler which generates a set of state space equations which are part of the minimal dynamic system representation. Once the minimal system representation is complete compiler generates a final binary file that is ready to be loaded into T-RTDS processor. Compiler generated processor code guarantees "hard" real-time with 1µs execution time.

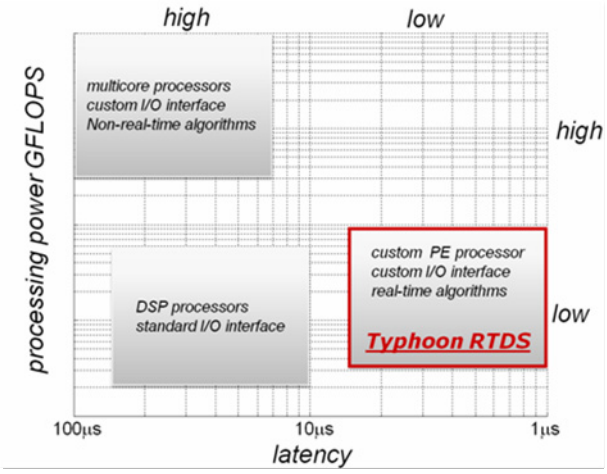
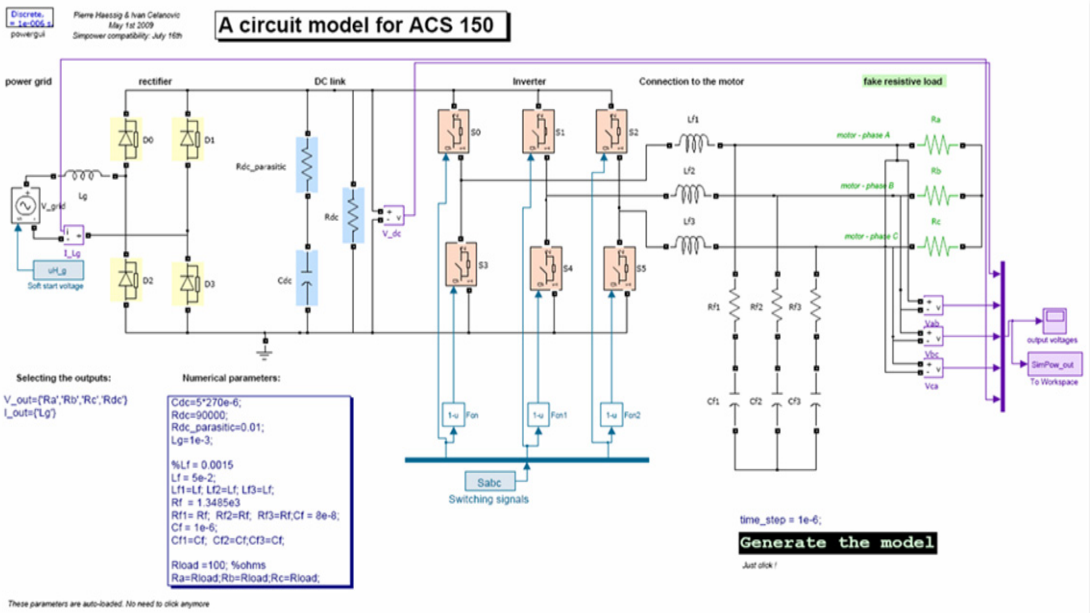


Figure 3. *Processing power vs. latency graph for standard processors and our RTDS processor.*

To benchmark the accuracy of our simulation approach based on ideal switches and minimal dynamic system representation we compared the results of our T-RTDS simulation (instead of running it on hardware, for ease of comparison, we were emulating our platform in software) with SimPowerSystem, a commercially available simulation toolbox for Matlab. Results of simulation (DC link voltage, line to line load voltage, and DC link current) are shown in Figure 5. The difference in simulation results between the two approaches is shown with red traces magnified by one thousand. Although T-RTDS (green) and SimPowerSystem (blue) curves overlap almost ideally slight differences can be observed at switching transitions because T-RTDS approach uses ideal switches while SimPowerSystem approach relies on numerical snubers. As a result, unlike other simulation tools, T-RTDS algorithms with ideal switches exhibits clean, oscillation free transitions between switching states under all operating conditions.

6 SUMMARY AND CONCLUSIONS

We presented a new real time digital simulation platform for high-power power electronics systems. It simulates power electronics systems with 1µs sampling time and latency and is based on innovation in: minimal circuit representation, compiler and proprietary processor architecture tailored for low latency implementation of the minimal circuit description.



Selecting the outputs:

```
V_out={'Ra','Rb','Rc','Rdc'}
I_out={'Lg'}
```

Numerical parameters:

```
Cdc=5*270e-6;
Rdc=90000;
Rdc_parasitic=0.01;
Lg=1e-3;

%Lf = 0.0015
Lf = 5e-2;
Lf1=Lf; Lf2=Lf; Lf3=Lf;
Rf  = 1.3485e3
Rf1= Rf;  Rf2=Rf;  Rf3=Rf;Cf = 8e-8;
Cf = 1e-6;
Cf1=Cf;  Cf2=Cf;Cf3=Cf;

Rload =100; %ohms
Ra=Rload;Rb=Rload;Rc=Rload;
```

These parameters are auto-loaded. No need to click anymore

```
time_step = 1e-6;
```

Figure 4. *Parametrized SimPowerSystem model of grid connected single-phase rectifier feeding three-phase voltage source inverter with output filter and resistive load.*

These three components enable T-RTDS to guarantee 1μs latency for a broad selection of power electronics topologies and systems.

As for the technology adoption rate we believe that power electronics industry will follow the footsteps of both automotive and aerospace industries and that tools like T-RTDS will play a decisive role in this transformation. The ease of design, testing and verification of both control hardware and software that T-RTDS platform brings hold promise for enormous time savings during the development and testing of power electronics systems, increased reliability, and improved performance. In addition, educational and training benefits of RTDS should not be neglected. Our platform brings a true emulator performance, until recently available only in the high power laboratories, to the desktop thus enabling safe and fully realistic training of engineers, technicians, maintenance staff, users and power electronics students on intricate aspects of developing, using, commissioning and debugging high-power power electronics systems.

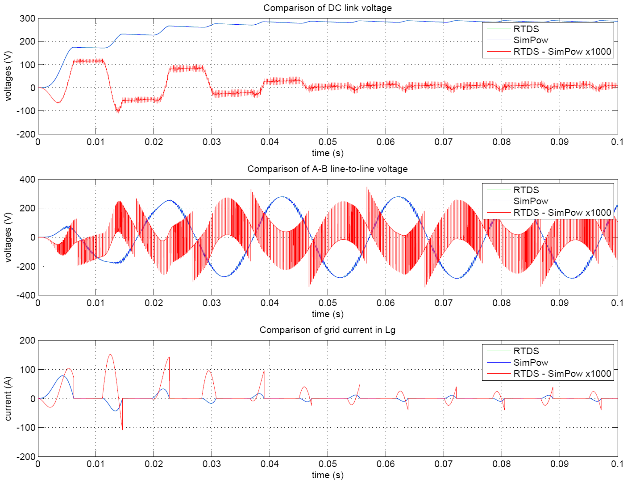


Figure 5 *Comparison of simulation results using T-RTDS modelling (green traces) and SimPowerSystems (blue traces) approach. Graph 1: dc-link voltage; graph 2: A-B line-to-line voltage; graph 3: grid side phase current.*

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