Real-time FPGA-based solutions for Power Electronics and Power Systems

FPGA-based HIL platform combining performance and flexibility
The story began ten years ago. OPAL-RT worked on the first hybrid and electric vehicle designed by Toyota. At that time, we succeeded in simulating the electrical motor at 10 µs (10 Khz), which was a technological breakthrough. This demanding challenge required to pushing Real-time simulation on CPU to its limits.

Indeed, the main limitation of HIL simulation on CPU is the time required to transfer data between the CPU and the I/Os that are connected to the Field-Programmable Gate Array (FPGA). Transfers pass through the PCIe bus, with data transfer times in the microseconds, therefore it wasn't possible to lower the timestep below a few microseconds.

By using the FPGA for the same process, we are now able to send data directly to the I/Os without needing to go through the PCIe bus, which enables a faster calculation step. This is why OPAL-RT pioneered Real-time simulation on FPGA, and why we are one of the few companies capable of addressing the challenges related to it and, consequently, making endless test possibilities.

Perfect for simulating power electronic systems such as photovoltaic grid-connected converters or electrical motor drives with FEA-based (Finite Element Analysis) motor models, our eFPGAsim suite can be used for feasibility studies, protection, control system development and testing using hardware-in-the-loop (HIL) and power-hardware-in-the-loop (PHIL). This suite encompasses an FPGA based general purpose electromagnetic transient (EMT) solver implemented on FPGA called eHS (electrical Hardware Solver), designed to accept and solve a variety of simulation problems on the FPGA using a simple circuit editor without complex VHDL programing. Time step below 500 ns (2 Mhz) can be achieved for complex multi-level converter simulation. In addition, RT-LAB XSG software provides the user with a state-of-the-art solution for advanced FPGA Real-time and HIL system simulation of user developed models and control systems. Users generate custom application and specific models that can easily be implemented onto an FPGA device.

eFPGAsim also includes a suite of multi-modular voltage source converter (MMC) models capable of simulating up to 1500 MMC cells in 500 ns (2 Mhz) in a single FPGA chip including optical-fiber interfaces and the low-level controller. This level of performance is still out of the reach of our competitors. FPGA models can also be interfaced with models subsystems running on multi-core Intel processors with time step larger than 10 µs, which is convenient for simulating complex micro-grid, distributed generation systems, and HVDC MMC grids.

Synonym of flexibility and simplicity, this suite is in line with the company's vision; to democratize Real-time simulation. Thanks to our unique eHS solver, no advanced VHDL and FPGA knowledge is required; meaning that FPGA-based simulation is now accessible to control and simulation system specialists without requiring any FPGA programming skills.
eFPGAsim highlights

eFPGAsim combines the performance of high fidelity digital simulators with very low communication latency to provide power electronic engineers with a state of the art HIL platform for the development and testing of control and protection systems that require sub-microsecond time step capacity.

Ease of use

- Decrease FPGA model preparation and validation by using the advanced electrical system solvers (eHS)
- No VHDL programming skill is required.

Test Performance for Optimal Accuracy

- Up to 10,000 times faster than what is achievable by offline simulation tools
- Increase simulation accuracy of fast power electronic subsystems

Effective and Scalable Solution

- Scalable and cost-effective solution designed to test very small and fast power electronic systems requiring a few I/O channels or, very large and complex power electronic controllers requiring thousands of distributed I/O.

A Flexible Solution for a Wide Range of Applications

- Perfect for simulating power electronic systems and electrical motors, eFPGAsim is used for feasibility studies, protection and control system development as well as testing HIL simulation:
  - Industrial and traction motor drives
  - Industrial power converters
  - Solar power conditioners
  - Multilevel converters and inverters

Key Features

- eHS solver
- RT-XSG software
- Electric drives

Compatible Hardware

- OP4500: 4 core Kintex-7 FPGA.
- OP5600 offers a compact and affordable solution with one VIRTEX6 FPGA.
- OP7000 multi-FPGA simulate very complex systems requiring several FPGAs interconnected with point-to-point low latency 5-Gbits/s links.

Business Focus

- Test faster, easier and more reliably
- Shorten time-to-market for a better return on investment
- Reduce maintenance and workload
The innovative eHS technology, a generic electrical FPGA Hardware Solver, is at the heart of the eFPGAsim suite. This world premiere provides the same ease of use as standard PC-based HIL simulators.

Thanks to a convenient circuit schematic graphical user interface, the FPGA code is automatically generated, making FPGA-based simulation accessible to the largest number of users.

eHS’s goal is to facilitate the use of FPGA for high-fidelity Hardware-In-the-Loop simulation with sub-microsecond time steps by avoiding the difficulties associated with the coding of FPGA devices. It is intended to facilitate the design cycle of complex circuit simulation on the FPGA by allowing a gradual simulation integration set-up from off-line simulation to FPGA on-chip simulation.

Automatic FPGA model generation from the circuit with eHS

Automatic generation of electric circuit model:

• No mathematical modeling
• No FPGA expertise
• No VHDL programming
• No need for Xilinx Blockset or other Xilinx FPGA tools
**Key Features**

- From modelling to FPGA in a few seconds
- The model can be recompiled without crashing the FPGA depending on the circuit size and speed.
- No advanced VHDL or high level programming knowledge required
- RT-LAB multi-core Real-time framework with time step below 10 μs to analyze the interaction between the power electronic and grid components.
- Provide very low latency from PMW inputs to Analog Outputs, important in the accurate testing of fast control systems.

**Benefits**

eHS increases the simulation accuracy of complex and fast electric circuits, as well as, drives, by achieving very small model time step updates. It also facilitates the use of FPGA chips to enable control and system engineers to take advantage of FPGA-based simulation.

- Easy-to-use
- Powerful and accurate
- Low-sample time
- Enhanced resolution

**Real-time Simulation Set Up**

The typical configuration between the CPU cores and the FPGA board simulator is performed internally by the RT-LAB simulation engine using PCI Express bus link, enabling multi-rate Real-time simulation.

Fast power electronic subsystems are simulated with sub-microsecond time steps using eHS with the VIRTEX 6 processor while other electrical circuits such as transformers, lines, cables, generators and loads are simulated with a time step of 10 μs or larger on standard INTEL multi-core processors.

**Partners’ compatible design tools with eHS**

OPAL-RT collaborates with expert partners such as MathWorks, Plexim and Powersim™ to deliver world-class solutions to our customers. The structure of the eHS tools enables the use of schematic capture graphical interface with popular simulation software. Such a feature facilitates the use of FPGA-based simulators the result validation.

Plecs™ is a toolbox for system-level simulations of electrical circuits developed by Plexim™ for high-speed simulations of power electronic systems.

SimPowerSystems™ is a Simulink™ product developed by MathWorks™, which provides analysis tools for modeling and simulating electrical power systems.

PSIM™ is a simulation environment for power electronics and electric drives developed by POWERSIM™.

* Available 2014Q2 watch OPAL-RT website for update
RT-LAB XSG

RT-XSG is a Simulink™ toolbox that enables engineers to generate custom, application specific models that can be implemented on an FPGA device. It allows the use of dedicated FPGA processors for sub-microsecond computation loops. RT-LAB Real-time platform also enables ultra-fast Real-time models and I/Os.

**Benefits**

RT-XSG provides a convenient, Simulink-based way to build models. It offers greater flexibility by allowing users to implement their own calculations and models on FPGA.

Using the RT-XSG toolbox saves time when conducting FPGA-based co-simulation, since it automatically manages configuration file generation on each supported platform. It also manages the configuration of the platform, along with the transfer of high-bandwidth data between RT-LAB simulation models and the user-defined custom model, built using RT-XSG, and executed on an FPGA device.

While conventional processor designs operate sequentially on a set of instructions, FPGA processors perform operations in parallel. This makes them ideally suited for very fast simulation of loosely-coupled models.

**Applications**

Some examples of applications already implemented using RT-XSG are:

- High-speed digital and/or analog waveform generators
- Signal processing, windowing and analysis
- Embedded simulation of stiff (high-speed dynamics) models, such as electrical motor models
- I/O synchronization (i.e. pulse-width modulated synchrophase with analog in)
- Critical timing application

**Key Features**

- Allows use of Xilinx Blockset
- Allows for FPGA target code to be included as part of a larger Real-time simulation model.
- Handles the model C code generation via Real-Time Workshop™ directly from Simulink models and the FPGA HDL code generation via XSG transparently.
- Automatically loads the generated firmware on the hardware during the loading of the Real-time model.
- Facilitates FPGA hardware design for those who are not familiar with FPGA.
- Enables transparent access to FPGA signals from RT-LAB and vice versa.
- Allows high-speed communication between various FPGAs, hardware or expansion units (Aurora, Gigabit Ethernet, serial protocols and more).
RT-LAB XSG™
Rapid Control Prototyping and Hardware-In-the-Loop
on INTEL™ Processor and XILINX™ Platforms

Library

RT-LAB XSG software provides the user with a state-of-the-art solution for advanced FPGA-accelerated Real-time and HIL system simulation of user developed models and control systems. Users generate custom, application specific models that can be easily implemented onto an FPGA device. A library of pre-made machine models and custom blocks such as inverters models as well as a library of ready-to-use and reconfigurable models are available.

OPAL-RT provides a comprehensive library with the following features:

- Frequency measurement
- Mean square and average
- PWMI (input)
- PWMO (output)
- Time-stamped I/Os
- Quad decoder and encoder
- Resolver in and out
- TOM, TSDI and TSDO
FPGA Electric Drives

Reaching a reliable HIL implementation for a new generation of electric drives controllers requires sound models, fast program execution with reaction times below a few microseconds, and fast I/O communication. OPAL-RT provides solvers, FPGA architecture and CPU capability that define us as a leader in a wide range of electric drives simulation and bring HIL-testing very close to reality.

**Challenges of Electric Motor Control Testing**

- Test the motor controller with non-ideal behavior
- Test the motor controller with different points of operation, such a saturated regime
- Test fault conditions (short, converter open circuit)
- Simulate the motor inductance at high currents

**Virtual Fault Injection on Converters, Bridges and Electrical Motors**

OPAL-RT’s unique FPGA solver allows the creation of faults on converters and motors such as:
- Open-fault and short-circuit for any IGBT
- No-gate signals at IGBT
- Inverter diode open fault and IGBT/diode short-circuit
- Motor open-phase and phase-phase faults are also possible

**Finite Element Analysis (FEA)**

Combining RT-LAB Real-time simulation technology with FEA tools enables the simulation of complete motor drives with much higher precision compared to conventional motor models.

**Key Benefits**

- Reduce testing time on real dynamometer
- Get motor parameters as soon as possible, even before manufacturing
- Detect errors at earlier stage of the design

**Electrical Motor Models**

- Models provided such as PMSM, IM, SRM, BLDC, DC and AC
- Ability to develop Real-time models of atypical motors
- Multiple-converter configurations available that can be changed on-the-fly

**Partners**

For the EV/HEV market, OPAL-RT’s HIL platform includes a suite of FPGA-based high-fidelity Real-time motor simulation solutions that integrate leading finite-element analysis (FEA) models from companies such as JMAG, Infolytica and ANSYS which include nonlinear effects such as field saturation and harmonic effects.
Graphical User Interface

For complete model visualisation, configuration and calibration

Our high-fidelity motor solution comes with a very flexible and intuitive user interface made with TestDrive HMI, allowing users to visualize all the signals as if using a real oscilloscope, parameterize all electrical motors components and calibrate I/Os. The electrical motor user interface comes with an easy-to-use Python scripting, helping you create comprehensive test sequences.

Inter-FPGA Communication

OPAL-RT pushes the limits of one FPGA’s computing resources by implementing Inter-FPGA communication for micro-grid, MMC, more electrical aircraft or other large power electronics applications.

Our recent simulators are equipped with SFP sockets that allow 5Gbits inter-FPGA communication through optical fiber.
MMC Model on FPGA

The Modular Multilevel Converter (MMC) system has many advantages over conventional voltage source converters and therefore can be used in direct current power transmission, micro grid, or renewable energy applications.

While MMC’s distinctive topology offers several new features, it also necessitates a sophisticated controller to deal with extra control requirements and smart ways of testing the controls such as HIL.

MMC FPGA models include up to 511 MMC submodules per valve and 6 valves, and run at 250ns. The MMC FPGA modules include features such as: cells short-circuit fault, AC fault and DC fault. The FPGA model can also be coupled with SFP optical fiber (Small Form-factor Pluggable).
\textbf{eFPGAsim Showcase}

\textbf{CONTEXT:} The Applied Electronics Research Team (APERT) is formed by teachers and researchers of the Electronic Technology Area of the Electronics Department and all of them carry out their activities at the Faculty of Engineering of Bilbao, Spain. Part of the research work of APERT is focused on power and control circuits for energy converters.

\textbf{CHALLENGE:} Simulation of a model containing power converter is tedious. Likewise, considering that the validation of certain features may require very long simulation time, the model should be simulated in real time.

\textbf{SOLUTION:} Using OPAL-RT eFPGAsim digital simulator and its parallel computing capability along with new averaging methods, Real-time simulation of complex models with power converters has been performed. All these models were built in MATLAB/Simulink\textsuperscript{TM} and separated into two subsystems in order to maximize parallel execution. Likewise, the control algorithms validated in simulation were implemented in the eMEGAsim simulator, giving rise to the Rapid Control Prototyping. To do this, the modulation techniques for the power converters were implemented in the OP5130 FPGA using eFPGAsim (RT-XSG).

\textbf{BENEFITS:} The simulation platform increases the speed of development and implementation of new control algorithms, therefore decreasing cost and duration at the test bench.

\textbf{CONTEXT:} The Renewable Energy Solutions unit at AEG Power Solutions develops utility-grade solar inverters and battery storage converters for on- and off-grid operation. They aim to maximize the efficiency and reliability of their systems that are used in smaller industrial micro-grids up to large multi-megawatt solar power plants.

\textbf{CHALLENGE:} Optimization and verification of the inverter’s hysteresis current control for use in dynamic large scale systems using traditional methods is a challenging task. Offline simulation on one hand is usually not able to model the exact characteristics of the control hardware in a reasonable amount of time. Laboratory tests on single units or small scale models on the other hand suffer from power limitations and can be very costly and inflexible. Additionally, fault testing can be dangerous.

\textbf{SOLUTION:} Using eFPGAsim and the eHS solver, a Simulink model for controller hardware-in-the-loop simulation achieving a sub 1 µs step time can be set up. The computation speed is enough to fulfill the requirements of the hysteresis control. Using a CPU/FPGA co-simulation, larger grid structures can be simulated on the slower CPU without losing the advantage of the FPGA simulation.

\textbf{BENEFITS:} The simulation platform increases the speed of development and implementation of new control algorithms, therefore decreasing cost and duration at the test bench.
From Imagination... to Real-time

About OPAL-RT TECHNOLOGIES

OPAL-RT is the world leader in the development of PC/FPGA Based Real-Time Digital Simulators, Hardware-In-the-Loop (HIL) testing equipment and Rapid Control Prototyping (RCP) systems.

Our systems are used to design, test and optimize control and protection systems used in for power grids, power electronics, motor drives, automotive industry, trains railway, aircrafts and various industries, as well as R&D centers and universities

www.opal-rt.com