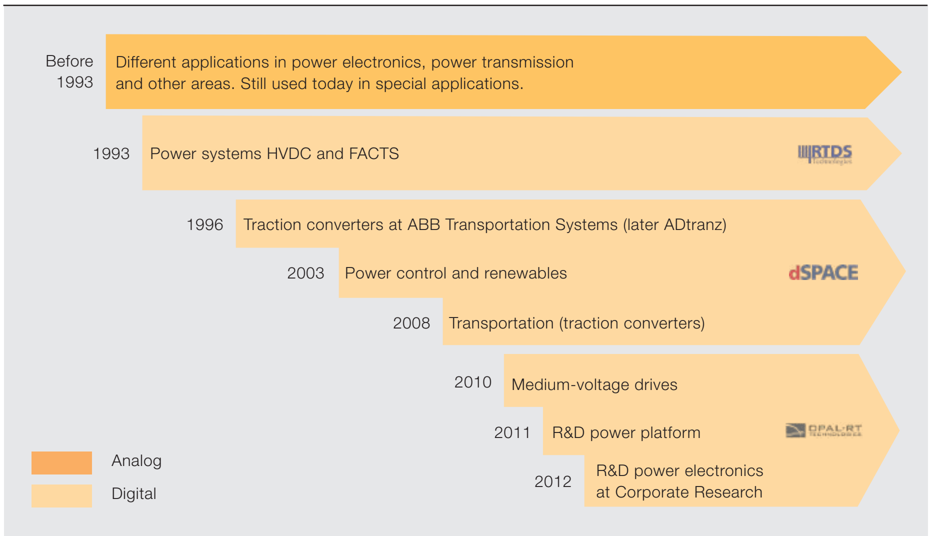
Need for speed

Real-time simulation for power electronics in railway applications and beyond

ROXANA IONUTIU, SILVIA MASTELLONE, XINHUA KE, ERICH SCHEIBEN, NIKOLAOS OIKONOMOU, DIDIER COTTET, DANIEL STUMP – Digital real-time simulation (RTS) has revolutionized the power electronics control system technology chain by bridging the gap between development of advanced control technology concepts and deployment of successful products. RTS meets possibly its most challenging application in power electronics, where the requirement for simulation performance of complex switched systems pushes the boundaries of the present technology. For many years, ABB has pioneered ever more sophisticated RTS tools to guarantee product reliability and low-cost, efficient testing for the next generation of high-performance power electronics systems.

1 History of RTS at ABB



Simulation tools have supported the development of engineering systems since the early 1950s, when analog and digital computers started to appear. The powerful computing power available today now allows fast simulation of complex systems. This is especially valuable in control systems simulation where, in order to test the controller running at its nominal operation speed, the computer model must run at the same rate as the actual physical system, ie, in real time.

In today's power electronics industry, RTS is a critical player across several stages of the technology chain that enables the transfer of new control concepts into successful power electronics products.

From the first custom analog versions to today's high-end, commercially available digital platforms, ABB has long relied on RTS to support the advancement of its power electronics control technologies → 1. RTS is essential not only for developing better control concepts, but also for improving software and product quality through early-stage, time-efficient testing. The key feature of real-time simulators is the hardware-in-the-loop (HIL) technology that allows the control software, running on the actual control hardware platform (ie, DSPs, FPGAs) to be connected to software models that emulate the power electronic converters and their environment. The HIL enables the controller to operate as if it were controlling the real system with its full features.

Modern power electronics systems, with their exceptionally fast dynamics, are a nontrivial challenge for simulation in real time. New ways to handle the design of models with variable structure, using constrained simulation time steps and ensuring minimal computational effort, are required.

Today, ABB uses RTS widely and is committed to advancing RTS technology to meet growing computational demands, cope with increasing system complexity and support the advancement of control algorithms.

The technology chain

The technology chain is the process that regulates how technology concepts are improved from one generation to the next. RTS plays a critical role in the technology chain for ABB converter systems.

This process begins with the knowledge of the existing technology (generation k-1) and guides the formation of new ideas, leading to an improved product. These have to be implemented, tested and verified before the control concept can become part of a product as generation k → 2.

RTS supports the concept formulation phase by providing an environment in which to investigate and gain a fundamental understanding of system behavior before defining a control concept.

Once a control concept is developed and implemented in the converter, it has to be rigorously tested according to defined standards before the product can actually be deployed. This phase encompasses several testing steps in different environments, from offline simulation to real-time simulation and finally on the real system itself. Typically, offline simulations are insufficient to reproduce the closed-loop system behavior with the actual integrated control software and hardware, and are computationally too expensive for the

Two highly interdependent criteria – satisfying critical timing constraints and ensuring fast and accurate physical models – lie at the heart of real-time simulation.

Title picture
Real-time simulation is an essential tool for developing the very sophisticated power electronics systems used in so many common applications, like railway vehicles.

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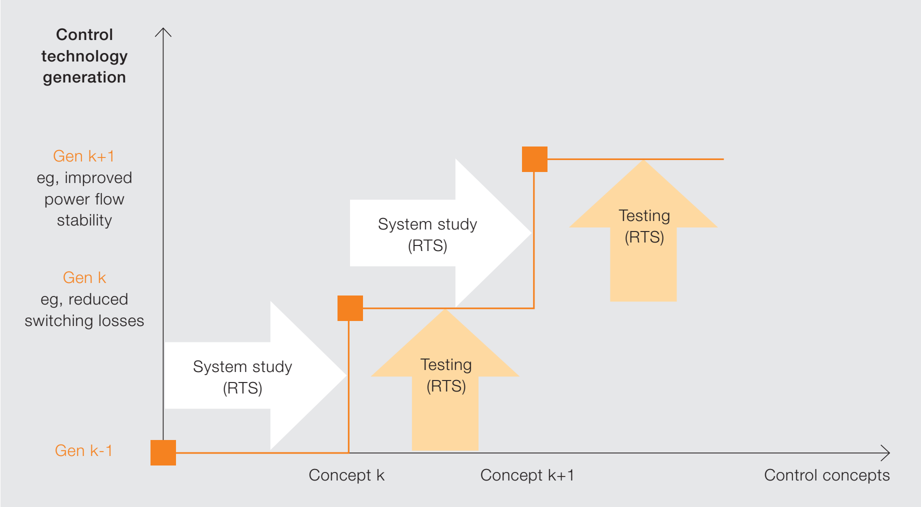
2 The technology chain



required accuracy. Furthermore, testing converter software on the real system can be expensive (daily testing can cost up to $60,000), time-demanding and even prohibitive for extreme parameters such as short circuits, excessive voltages or currents, large loads, high speeds, etc.

Real-time simulation is the key for handling the complexity of todays' systems. It compensates for the shortcomings of offline and onsite testing by adopting the powerful concept of online emulation. RTS reproduces the complexity of the real system in real time while preserving the benefits of a simulation: flexibility, fast implementation, easy debugging and wide test coverage. This enables control software to be thoroughly tested and improved during the early development stages, thereby guaranteeing software and product quality and shortening the final commissioning process on the real system.

Specialized teams of engineers are constantly working to meet the technological challenges posed by the high requirements on the RTS systems.

Challenges in real-time simulation

In order to guarantee reliable control system development and testing, the RTS must represent, with a high degree of accuracy, the real environment in which the controller operates. In the case of traction applications, for instance, the controller operates on the power electronics of the traction converter inside the train. The RTS emulates this environment using special hardware and software configurations, where complex mathematical models, collectively called the "physical model," replace the converter and the train, while the controller remains connected in a closed-loop fashion with this physical model → 3. Based on the inputs received from the controller (eg, switching pulses for operating the semiconductor devices inside of the converter), the physical model computes the necessary outputs (such as voltages, currents and speed) and sends them back to the controller for the next simulation cycle. Relevant states of the physical model can be visualized, monitored and manipulated through a user interface → 4.The traction RTS has, in addition, a virtual vehicle control unit on which the desired tractive effort or speed reference are set in the same way as on the real vehicle by the driver → 3.

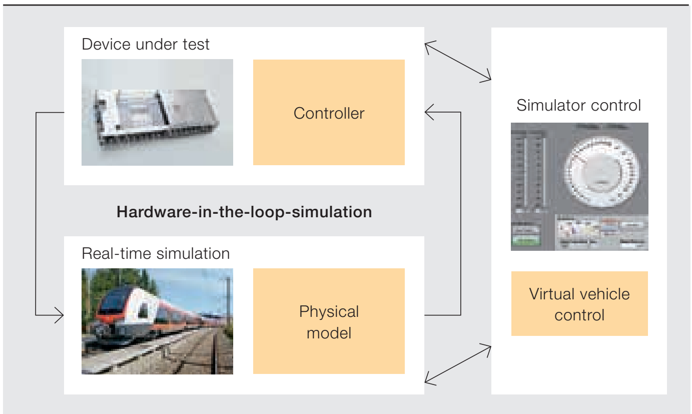
Within the ABB group, several real-time simulators have been developed in cooperation with various RTS system vendors, each one specific to a particular business sector → 1.

The simulators can differ in scale, in the hardware used or in the specifics of plant modeling, but they are all, nevertheless, challenged by the same fundamental issues. In particular, two highly interdependent criteria – satisfying critical timing constraints and ensuring fast and accurate physical models – lie at the heart of real-time simulation.

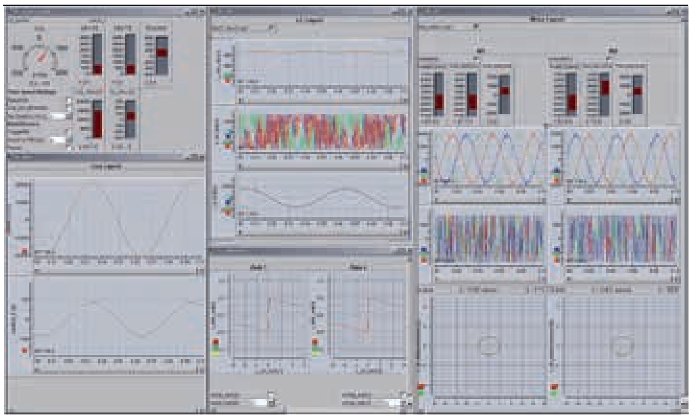
Critical timing constraints

A critical requirement for an RTS system is to achieve synchronization between

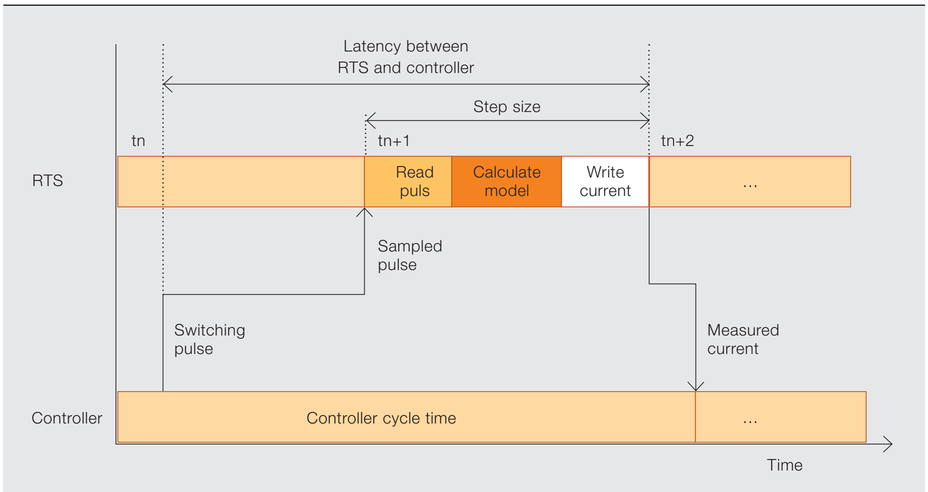
3 RTS setup for HIL simulation, with virtual vehicle control unit



4 RTS user interface for visualizing the state of the plant in real time and for directly interacting with the physical model



5 A maximum delay of twice the RTS step size occurs between the controller sending switching pulses to the RTS and the corresponding response.



real time and simulated time. In other words, the simulated inputs, outputs and states reached on the RTS after a certain simulation time should be the same as those on the real system when the same amount of time has passed. The rate at which the real-time clock achieves this synchronization is determined by the step size of the RTS, the length of which must be carefully chosen. On the one hand, the RTS step size must be as small as possible in order to minimize the latency of the simulated system, but, on the other hand, be long enough to allow the RTS to complete the operations required in one simulation step without causing overruns ➔ 5.

Fast and accurate physical models

Power electronics' high-frequency switching (kHz) imposes controller cycle times in the order of 100 to 300 µs. These, in turn, impose yet shorter cycle times on the RTS (less than 60 µs). Ensuring fast and accurate simulations with step sizes in the microseconds range is especially challenging for power electronics systems compared with applications with slower dynamics – for instance automotive or robotics, where RTS step sizes can reach milliseconds.

ABB's RTS systems win this challenging race against time thanks to the dedicated hardware and software solutions offered by vendors, coupled with ABB expertise in power electronic circuit modeling and simulation. As fast hardware alone is insufficient, the physical models and the numerical routines to solve them must also be optimized for maximum efficiency, an effort into which ABB invests significant know-how.

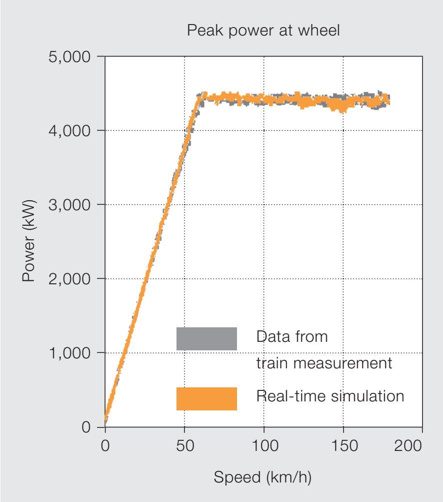
One of the most difficult challenges is the processing of the switching pulses received from the controller and sent to the converter switching devices – eg, IGBTs. To accurately simulate these, a granularity even finer than the RTS cycle time is required and this is achieved using FPGA technology [1]. To simulate the converter in rectifier mode, internal switching events caused by self-commutating diodes are also modeled. The frequent changes in switch positions and the nonlinear nature of some of the model components add complexity to the modeling and simulation task, as different switch configurations must be recognized and solved immediately during runtime. While such problems can be solved in offline simulations using sophisticated numerical time integration algorithms, these methods are computationally too expensive for real-time use, hence the need for special modeling and simulation solutions. Within ABB today, highly complex systems from different power electronics domains can be simulated on appropriate real-time platforms ➔ 1. An ABB dSPACE-based simulation platform has, for example, been used for traction RTS.

Vehicle in the lab

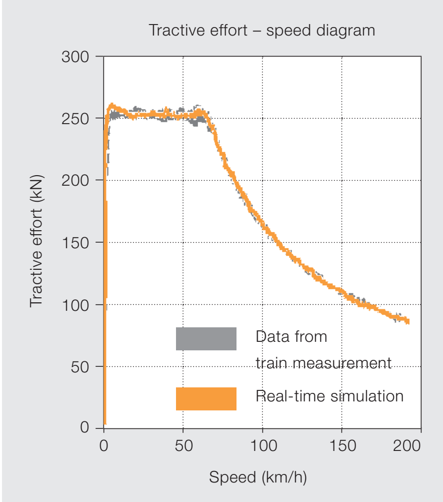
The RTS in the transportation product group provides flexible hardware and software setups for railway applications

6 ABB traction converter with PEC 800 controller

7 Acceleration test for NSB FLIRT



7a Real-time simulation



7b Results from measurements on the train match the simulations closely.

The future calls for smart simulation solutions that reduce the modeling effort for switched systems of increasing complexity, while satisfying the required speed and accuracy.

spanning power ranges from 100 kW to over 6 MW, for single- or three-phase AC, for DC and for multisystem or diesel electric systems.

The RTS modeling domains cover the locomotive power supply (overhead line, pantograph and main circuit breaker), transformer, traction converter (line converter, DC link with tuned filter, motor converter), motor, gear and axle, auxiliary converter, diesel engine generator, energy storage and wheel-rail contact. The RTS physical models are easily configurable and can meet diverse customer requirements by supporting various types of transformer setups, converter topologies (two- or three-level) or driven axle arrangements (single-axle or bogie-control), etc.

One of the projects running on the RTS involves the FLIRT electric low-floor multiple unit made by the Stadler Rail AG company. ABB supplies the traction converters, traction transformers and low-voltage components for this product → 6. The transformer and the converter are responsible for transforming the single-phase static frequency AC power from the supply line into the three-phase variable-frequency power needed to drive the motors and turn the wheels. For this, the complete conversion chain, from power supply down to the wheel-to-rail contact, is modeled on the RTS, so that the control software and hardware can be tested in a closed loop and as if it were in the actual train.

An important train performance parameter is the evolution of tractive effort as a function of speed. This characterizes the power of the train. For the FLIRT, a 4,500 kW peak power at wheel is attained with a maximum tractive effort of 250 kN and maximum speed of 200 km/h. The tractive effort versus speed characteristic can be simulated on the RTS → 7. Until the 4,500 kW peak power at the wheel is reached, a 250 kN maximum (constant) tractive effort is applied, after which the tractive effort decreases while the train accelerates to its maximum speed of 200 km/h, maintaining constant power. The curves obtained on the RTS closely match those obtained from measurements performed on the train itself, demonstrating the reliability of the RTS simulation.

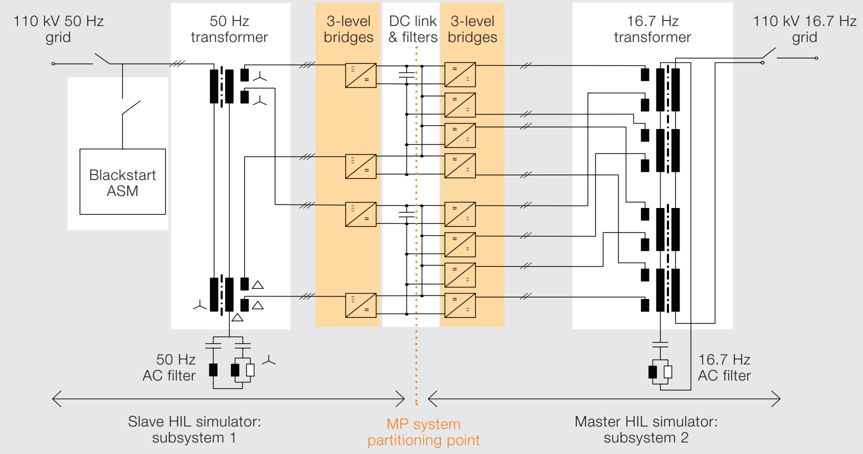
80 MW in the lab

Another challenging project involved the simulation of a static frequency converter responsible for the energy exchange between the three-phase 50 Hz national grid and the single-phase 16.7 Hz railway grid. A parallel processor implementation for the RTS was the solution for a problem of such large scale → 8.

RTS in the future

Today, the impact of RTS on control innovation in the power electronics industry is unquestionable. Unsurprisingly, there is a demand for even more efficient testing and for even more complex test scenarios – and it is here that automated software testing (AST) will play a major role. AST provides an environment for running and

8 Multiprocessor RTS configuration for a railway frequency converter: 3-phase 110 kV / 50 Hz to single phase 110 kV / 16.7 Hz.



- Components to be simulated:
  50 Hz grid with various fault situations
  50 Hz grid blackstart asynchronous machine (ASM)
  50 Hz transformer (linear)
  50 Hz AC filter (in Y)
  50 Hz AC/DC converters with 12 phases
  (each phase can be on or off)
  DC link with voltage limiting unit and various filters
  16.7 Hz DC/AC inverters with 16 phases
  (each phase can be on or off)
  16.7 Hz transformer with saturation
  16.7 Hz grid with load and various fault situations
- Number of I/Os to be handled:
  200 fast I/Os and around 750 slow I/Os
- Maximum step size: 60 µs

Problem: It is impossible to adequately simulate such a system with a single simulator due to the system's large size and complexity.

Solution: a multiprocessor system setup with two complete HIL simulators
In a multiprocessor system setup, two or more simulators must exchange measured/calculated quantities before and after their calculation since one subsystem requires the output of the other.

This arrangement can produce signal inconsistency, which leads to incorrect simulation results or even instability, if system partitioning is not properly done. Thus, the system partitioning becomes the key factor for the desired performance. In this application the system is partitioned into two subsystems from the DC link, where the system quantities are "relatively static."

All the 50 Hz-side components together with the DC link and its various filters are simulated on one simulator (slave) and the rest on the other (master) in parallel.

recording operator-free routine control tests automatically, thereby significantly shortening the control testing and commissioning phase.

Regarding RTS modeling, the future calls for smart solutions that reduce the modeling effort for switched systems of increasing complexity. Current techniques demand significant understanding of the entire system behavior and deep mathematical insight to obtain models and simulations that meet the required speed and accuracy demands. As power electronics systems become increasingly complex, highly optimized simulation solutions that exploit model hierarchy and parallelism gain importance. Looking in this direction, the novel quantized state system (QSS) approach [2] could revolutionize the nature of discrete simulation. In QSS methods, time is no longer discretized, rather, the state variables are quantized, allowing systems with frequent topology changes, such as power electronics systems, to be simulated more efficiently using a discrete event formalism.

Whether involved in power generation or transmission, renewables, industrial drives or electric trains, RTS for power electronics systems within ABB, in close collaboration with simulation platform vendors, will continue to push its boundaries. RTS will exploit improving computer performance, smarter models and faster solver algorithms to enable control technology to quickly innovate from one generation to the next across the technology chain.

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References

[1] P. Terwiesch *et al., "Rail vehicle control system integration testing using digital hardware-in-the-loop simulation,"* IEEE Transactions on Control Systems Technology, vol. 7, no. 3, pp. 352, 362, May, 1999.
[2] F. Bergero *et al., "A Novel Parallelization Technique for DEVS Simulation of Continuous and Hybrid Systems,"* Simulation, in press, 2013.