RTDS Technologies
AMETEK

WHITE PAPER

An Introduction to De-risking the Energy Transition with Real-time Simulation and Hardware-in-the-loop Testing

The power system as we know it is evolving, and a corresponding evolution is taking place in the way we must model and test power system behaviour and equipment in order to enable a reliable, resilient, and sustainable grid. Real-time power system simulation – and the hardware-in-the-loop (HIL) testing process that it enables – is becoming increasingly involved in the success of electric utilities, protection and control equipment manufacturers, research institutions, universities, and consultants throughout the energy transition.

This white paper from RTDS Technologies, the makers of the RTDS® Simulator, aims to educate power system professionals on the fundamentals of a rapidly growing technology: real-time simulation and HIL testing for de-risking innovative technologies and schemes for the power grid.

What is electromagnetic transient (EMT) simulation?

The energy transition and grid modernization – including the introduction and mass integration of renewable energy resources, energy storage, electric vehicles, microgrids, digital substations, smart grid schemes, and more – has created new challenges for the power community. These complex new schemes, particularly those involving power electronics, create the potential for undesired effects and adverse interactions with other assets on the grid. These transient phenomena, which can have major consequences for stakeholders – such as cascading outages – often occur at frequencies significantly outside the fundamental power system frequency of 50 or 60 Hz. **Traditional modelling tools used for power system operation and planning, such as phasor-domain simulation, lack the granularity to capture these issues that are all too common in the modern power system.**

EMT simulation provides an instantaneous time-varying output. Power system quantities, such as voltage or current, appear as waveforms in the same way they would if they were measured from the real network. This allows for a much greater depth of analysis than tools limited to fundamental frequency can provide. **EMT simulation represents the dynamic behaviour of the network over a wide frequency range, making it the best modelling tool for predicting and mitigating issues in the inverter-dominated power system of today and the future.**

Why *real-time* simulation?

EMT simulation has a much higher calculation density than its less detailed counterparts, and therefore higher utilization of computer processing resources. The typical simulation timestep – the time interval between consecutive outputs – of an EMT simulation for power system studies is in the range of 1 to 50 microseconds (µs). Many tens to hundreds of thousands of discrete outputs must be generated to capture a single second of power system operation. Because of this, EMT simulation programs that run on a regular PC are not capable of generating these outputs in real time.

Ten minutes of power system data – say, a portion of the start-up sequence for an HVDC link – may take many hours for the computer to generate, depending on the size and complexity of the simulated network.

Running the EMT simulation in real time means that one minute of power system data takes exactly one minute to generate. The real-world time necessary to calculate the network response for a given timestep is equal to the timestep value – all calculations are performed within the timestep itself. Real-time operation requires more advanced, dedicated processing technology than a regular PC, and it has major advantages:

- **Real-time simulation is much more efficient.** This is especially valuable when studying larger or more complex networks, when analyzing events occurring over a longer time horizon such as system start-up and shut-down procedures, and when evaluating many different scenarios and contingency conditions while adjusting parameters. Not only do simulation cases run much faster; users can also react and troubleshoot with much more ease and flexibility, increasing productivity.
- **Real-time simulation enables HIL testing.** Because the simulation operates continuously in real time, power system devices can be connected to the simulated environment in a closed loop and rigorously tested in a safe laboratory environment prior to deployment in a real substation or otherwise integrated onto the grid. This unique type of testing has distinct advantages.

What are the benefits of HIL testing?

HIL testing allows power system professionals to de-risk control and protection systems prior to deployment on the grid by connecting real devices to a simulated electrical network, running on a real-time simulator, in the safety of a laboratory environment. This unique type of testing is only made possible by real-time EMT simulation.

HIL testing is unique in that it considers not only the response of the device under test (DUT) to the inputs from the simulated power system, but also the dynamic response of the network to the operation of the device. This closed-loop interface enables a more comprehensive testing approach than is possible through other testing methods. HIL testing has many advantages:

- **De-risk, stress test, optimize, and demonstrate schemes in a controlled, convenient environment.** Using a lab-based HIL testbed means that many system conditions can be conveniently represented, including those that would be difficult or impossible to impose in the field. HIL testing allows for device and/or scheme performance to be demonstrated to stakeholders prior to project energization, increasing confidence in solutions.

- **Verify functional and dynamic performance in a true-to-life setting.** The EMT model running on the real-time simulator in the HIL testbed is a very accurate and granular representation of the grid. It allows for functional and performance testing under a wide range of operating conditions and is able to identify issues caused by faults, harmonics, resonances, and switching transients. This can support factory and site acceptance testing, integration testing, and more.
- **Test entire schemes working together.** HIL testbeds allow for multiple devices to be tested simultaneously, providing insight into system-level operation. This is key for identifying potential issues that may not be apparent when testing individual components separately.
- **Investigate multi-vendor interoperability.** In the modern power system, control and protection devices from different vendors may be expected to operate together seamlessly. Testing real hardware in an HIL testbed allows for validation of device interoperability while protecting the OEMs' intellectual property.
- **Eliminate unwelcome surprises by validating device models.** Models of devices, provided to utilities and system operators by vendors, may not accurately capture the behaviour of the actual device over a wide range of conditions. Testing the real hardware via HIL allows for comprehensive model validation prior to system integration.
- **Save on cost and project schedule.** As a key technology for reducing risk, HIL testing helps to prevent outages, poor performance, equipment damage, and other costly power system issues. It is often applied to support the commissioning process, allowing engineers to replicate issues they see in the field, reducing overall project schedules.

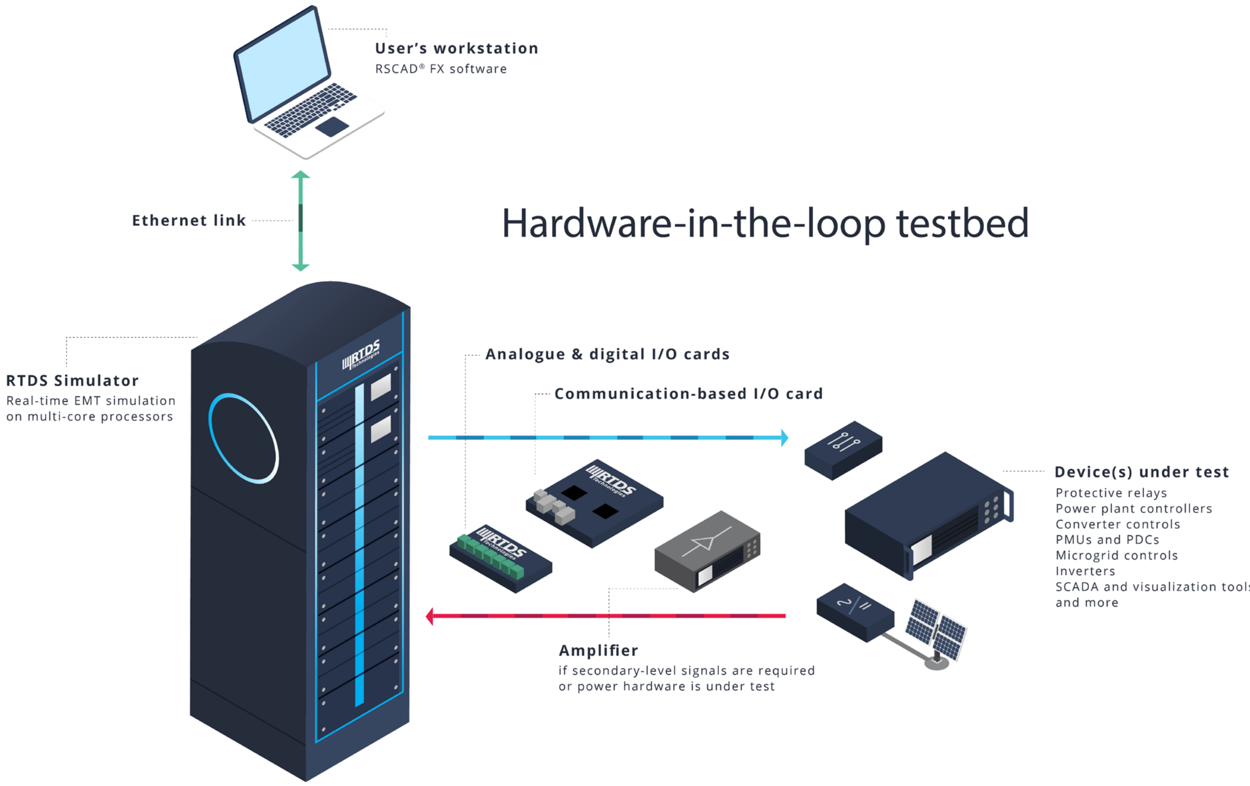
What are the components of a HIL testbed?

The RTDS® Simulator from RTDS Technologies is the industry standard for real-time power system simulation and HIL testing, and is a key component of HIL testbeds worldwide. Let's take a look at the hardware and software required to achieve HIL testing.

Real-time simulator – processing hardware

The RTDS Simulator requires **specialized, dedicated parallel processing hardware** to achieve continuous real-time power system simulation. The RTDS Simulator uses a multi-core processor which has been custom-integrated for this purpose. The result is much more efficient simulation than is possible using off-the-shelf processing technology.

A multi-core processor means highly scalable simulation via core licensing. An entry-level real-time simulator may have a single licensed core and be capable of simulating smaller networks, substations, and microgrids. The system is easily expanded by licensing additional cores, and multiple processing units can also be interconnected for larger-scale simulations. Large real-time simulators are capable of simulating regional transmission systems and beyond.



Components of a HIL testbed

Real-time simulator – input and output options

Input and output (I/O) devices are required to create the interface between the network model running on the real-time simulator's processing hardware and the external DUTs.

Analogue and digital I/O cards allow for the exchange of quantities such as bus voltage and breaker status between the simulated network and external DUTs as electrical signals. Analogue and digital I/O is available via cards that are highly modular – more cards means more available channels.

Communication-based I/O cards are also available. Ethernet-based standard protocols such as IEC 61850, MODBUS, DNP3, IEC 60870-5-104, IEEE C37.118.1, and generic TCP/UDP sockets can be used to interface the RTDS Simulator and DUTs. This I/O is also card-based and highly modular.

Aurora protocol links allow the RTDS Simulator to communicate with compatible external devices via high-speed serial communication over fibre cable.

Real-time simulator – simulation software and modelling library

The RTDS Simulator's software, RSCAD® FX, runs on the user's PC and is the main point of interaction between the user and the simulation. RSCAD FX is the graphical user interface that allows the user to define and parametrize the network being modelled, interact with the simulation dynamically, and collect and analyze data.

RSCAD FX's diverse modelling library equips users to create a realistic digital representation of their power system of interest. The library includes detailed models of renewable energy plants, power electronic converters, transmission lines, transformers, machines, dynamic loads, a wide range of control system components, and much more. **Documented sample cases and training videos** provide a foundation for users new to the software.

Amplifiers (application-dependent)

Certain applications require power amplifiers from a third party to complete the interface between the real-time simulator and the DUTs. Protective relays may require that low-level output signals from the simulator are amplified to secondary-level voltages and currents. Power-hardware-in-the-loop testing – in which power equipment, such as an inverter, is connected to the simulation – requires the use of a four-quadrant amplifier, which can source and sink real and reactive power.

Device under test

The RTDS Simulator is agnostic to the device(s) it is connected to in the HIL testbed. As long as a device is capable of being interfaced with the simulation via the I/O options described above, it can be tested via HIL.

What are the applications of HIL?

Real-time simulation and HIL testing have a wide and ever-expanding range of applications. Here are some of the most common areas of study and testing:

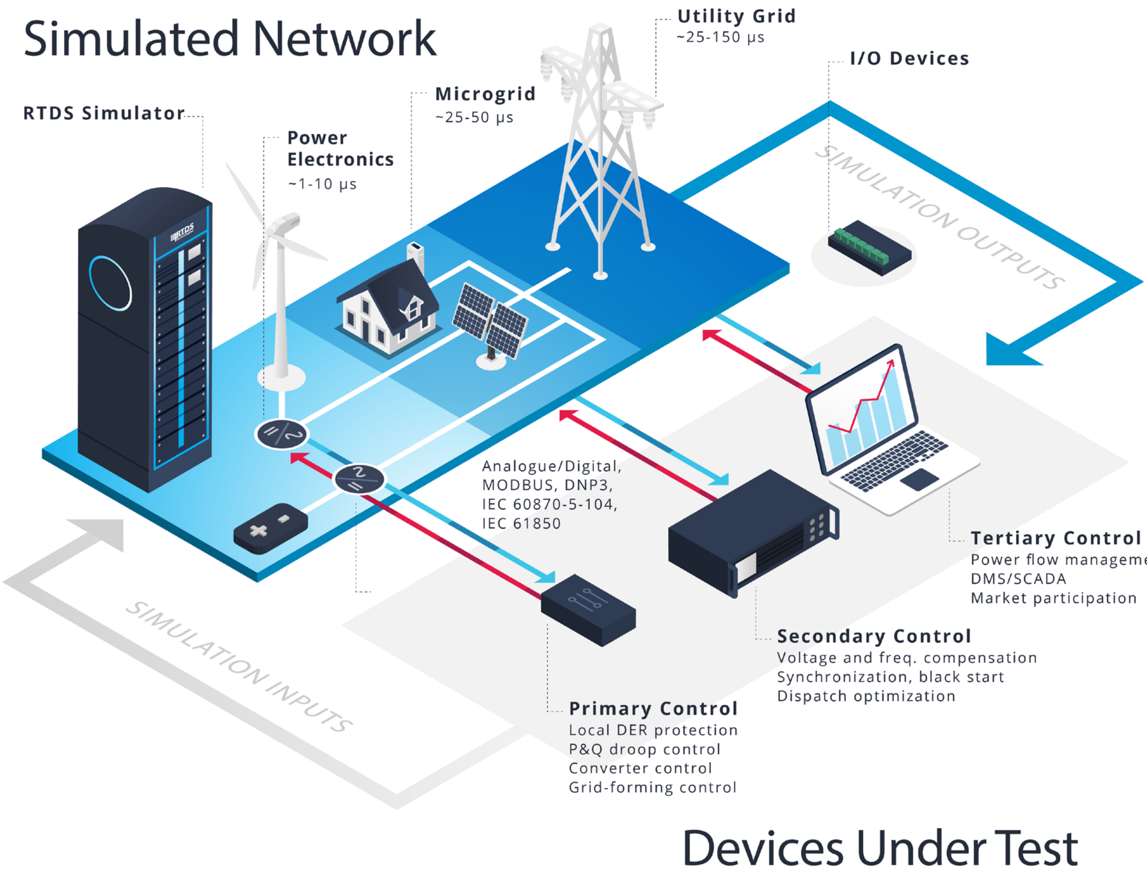
Hot topic: software-in-the-loop / black box control testing for inverter-based resources

Vendor-specific controls can be integrated into the real-time simulation, even if the vendor's hardware is not available. The RTDS Simulator can run a compiled version of an OEM's control code; this protects intellectual property while giving the user access to the vendor-specific model. **Accurately capturing the behaviour of proprietary fast-acting converter controls – which may significantly affect the power system – is a key part of de-risking the energy transition.**

- **Renewable energy:** Simulate inverter-based resources, including power electronics, and de-risk their integration. Test various aspects of control, protection, and management, including power plant controllers and grid-forming control. Test fault ride-through and other functional and performance requirements of distributed energy resources. Validate offline models prior to grid interconnection.
- **HVDC & FACTS:** Connect replica controls to the RTDS Simulator to support commissioning, demonstrate grid code compliance, and validate ongoing control and network changes. De-

risk and coordinate multi-vendor, multi-terminal projects using a solution widely accepted by OEMs, system operators, regulatory bodies, and other stakeholders.

- Protection: Test protection schemes for lines, generators, transformers, busbars, feeders, and more. Validate the performance of IEC 61850-based digital substations, wide area protection, and special protection schemes / remedial action schemes prior to deployment to ensure power system stability.
- Microgrids: Test multi-tier microgrid control and protection. Simulate power electronics and test their low-level controls, and/or focus on secondary-level control and coordination. Demonstrate successful islanding and optimize environmental/economic performance.



Multiple levels of control and protection might be tested for microgrid applications

- Cybersecurity: Connect the real-time simulation to a communications modelling layer to study the effects of cyber-physical attacks on the power system, including the response of real automation devices.
- Electrified transportation: Simulate electric vehicles, railway/traction, and aircraft systems. Test their low- and higher-level controls to ensure seamless operation and grid integration.

- **Education and training:** Expose operators to new technologies and operational protocol in the simulated environment. Improve situational awareness. Demonstrate phenomena and prove novel solutions in the research environment.

What are some examples of successful HIL projects?

Innovative projects across the power industry – and the globe – have real-time simulation and HIL testing behind them. The primary users of the technology are manufacturers of control and protection equipment, utilities and transmission/distribution system operators, consultants, and research and educational institutions in the field of power systems, power electronics, and electrified transportation. A few examples of projects supported by real-time simulation and HIL:

- The commissioning of the first multi-terminal VSC-HVSC link in Europe – the Caithness-Moray project in Scotland – was supported by HIL testing. Replica HVDC control hardware for all three terminals were connected to the RTDS Simulator for testing to address technical challenges including a weak AC network connection. The project was delivered successfully in 2024 after HIL testing at Great Britain's National HVDC Centre. (https://knowledge.rtds.com/hc/en-us/articles/360043133373 | https://www.hvdccentre.com/hosting/caithness-moray/)
- The largest neighborhood microgrid in Illinois was energized in 2024 after the successful HIL testing of its control and protection. At ComEd's Grid Integration and Technology Laboratory, several control and protection devices, including the microgrid's master controller, were connected to the RTDS Simulator for system-level microgrid testing. (https://knowledge.rtds.com/hc/en-us/articles/1500001668401 | https://www.renewableenergyworld.com/power-grid/grid-modernization/how-comeds-grit-lab-fosters-innovation-resiliency-and-reliability/)
- The first ever application of travelling wave-based relays to protect a high voltage line via tripping was tested with the RTDS Simulator in 2018. A real-time simulator was connected to travelling wave-based relays in order to prove their superior and secure operation in place of mis-operating phasor-based elements. Today, the relays are operating in the field after HIL testing gave stakeholders the confidence to be early adopters. (https://knowledge.rtds.com/hc/en-us/articles/360026332154 | https://selinc.com/company/news/124184/)

Where can I learn more?

To learn more about how real-time simulation and hardware-in-the-loop testing are changing the grid, visit our website at www.rtds.com.

You can get in touch with us directly at www.rtds.com/contact-us.
Stay in the loop by following RTDS Technologies on LinkedIn and subscribing to our newsletter.