

April 2014

Using the RTDS Simulator for the Analysis of Automatic Excitation Controllers

RTDS Celebrates 20 Years at the Top  
Component Highlight: The MMC Support Unit

## RTDS Technologies Celebrates 20 Years at the Top!

Since our inception in 1994, RTDS Technologies has become the industry standard for real time digital power system simulators. We can now proudly add that we have been the **world leader** in Real Time Power System Simulators for **20 years**, having celebrated our 20<sup>th</sup> anniversary on March 4, 2014.



The lead up to our 20<sup>th</sup> anniversary has been a particularly exciting time for RTDS Technologies. We have seen some phenomenal growth, achieving the sale of over 1000 racks of hardware and reaching 300 worldwide customers.

Celebrating 20 years in operation causes us to reflect on the qualities that have allowed us to remain the world leader in our field for such an extended period of time. We are committed to our customers and work to build strong relationships with them. We develop innovative hardware and software to address their simulation needs. We provide first rate technical support allowing our customers to make efficient use of the RTDS Simulator. We care about our customers and give them honest, sound advice. Our dedication to quality is second to none and it sets the standard for all of our products and services; a concept that is embraced by all of our employees. With these values at the core of RTDS Technologies, we will strive to remain the world leader for many years to come.



## Using the RTDS® Simulator for the Analysis of Automatic Excitation Controllers: Development of Test Circuits

**Guest Article from the Moscow Power Engineering Institute**

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*The RTDS Simulation Lab at MPEI*

The use of advanced digital modeling tools for technical systems and processes in power systems engineering significantly extends the capabilities of various studies. These tests ensure the stability of the operating parameters during repeated experiments, which is particularly important for the certification testing of Relay Protection and Automation (RPA). This article discusses the use of the combined hardware and software of a Real-Time Digital Simulator (RTDS) to test the operation of automatic excitation controllers for compliance with the JSC "SO UPS" standard [1].

The RSCAD software is used to create specific digital models to run on the RTDS Simulator hardware. The power systems circuit is drawn, and parameters of its elements are defined in the graphical user interface, Draft. The same editor also contains models to generate control signals as well as the circuits necessary to implement data processing algorithms. For the Automatic Excitation Controller (AEC) analysis, 6 circuit diagrams with 16 operating modes were developed as part of the Standard [1].

Control, monitoring and recording can be accomplished in RunTime to carry out all of the tests specified for certification according to the Standard [1]. Test reproduction and calculated emergency disturbances are made at the software level. Testing of synchronous generators AEC's is carried out by the simulated implementation of the following disturbances:

- 1) Disturbances with the following parameters:
  - A step change of the tested AEC by +5% of the rated value;
  - Single-phase short circuit (duration of 0.03s) at Bus 1;
  - A stepwise voltage change by connecting capacitance C3 to Bus 1;
- 2) Disturbances in accordance with the Guidelines on the stability of power systems [2] with the following parameters:
  - Duration of the short circuit is 0.12s;
  - Single-phase reclosing time is 1s;
  - Three-phase reclosing time is 2s;
  - Switch-off time of one phase caused by mis-operation of the breaker failure protection is 0.35s;



## RTDS Training Courses

We are currently accepting registrations for the following course:

### INTRODUCTORY RTDS SIMULATOR TRAINING

May 26—30 in Winnipeg, CANADA

Email [steph@rtds.com](mailto:steph@rtds.com) for more details.

\*\*If you have suggestions for future training course topics, please don't hesitate to get in touch.\*\*

## Upcoming Events

### IEEE PES T&D

Chicago, USA  
April 14-17, 2014  
Booth 4621

### PACWorld

Zagreb, CROATIA  
June 23-26, 2014

### RTDS India Users Group Meeting

Kanpur, INDIA  
July 11-13, 2014

### RTDS European Users Group Meeting

Lyngby, DENMARK  
October 8-9, 2014

In order to connect the tested AEC to the RTDS Simulator, an interface controller was designed. This controller contains a model of thyristor converter, controlled by a standard 6 pulse output from the AEC. It also includes a circuit which converts the signal from the output of the thyristor converter into a digital signal to be connected to the RTDS Simulator.

All of the tests required by the JSC "SO UPS" Standard [1] were performed successfully using the RTDS Simulator. Being able to record and display all of the necessary parameters allows effective presentation of the results. In addition, it is possible to obtain the necessary numerical characteristics of the transient (transient time, damping constant, overshoot) by processing the results.

The RTDS Simulator provides the opportunity to model operating conditions of the generating equipment in power systems of varying complexity in order to verify the operation of the AEC. It also allows existing algorithm or programming faults in the AEC to be rectified. Using real time digital simulation, the AEC can be adjusted for a particular power generating facility.

### BIBLIOGRAPHY

1. Standard of JSC "SO UPS" CTO 59012820.29.160.20.001-2012, approval date 03.04.2012. "Requirements to excitation systems and AUTOMATIC PD REGULATORS OF SYNCHRONOUS GENERATORS"
2. "Guidelines on the stability of power systems" (approved by the order of the Ministry of Energy of Russia 30.06.2003 № 277).

*To read the full article, please visit our website at [www.rtds.com](http://www.rtds.com)*

## Component Highlight: The MMC Support Unit

RTDS Technologies' FPGA-based MMC Support Unit is now being used by 17 clients in 8 different countries worldwide. With over 130 units currently in operation, manufacturers have once again put their trust in RTDS Technologies to provide solutions for the most complex power systems applications.

Detailed testing of physical MMC converter control equipment has been successfully completed by numerous manufacturers including ABB, ALSTOM, HICO, LSIS, NR, RXPE, SIEMENS, and XJ. In addition to testing the performance of the physical controllers of a particular converter, a number of simulation studies have been performed to evaluate overall network response and control interaction with other LCC and/or MMC based systems electrically *near* the scheme in question. This is an important and challenging aspect to consider when adding new HVDC converters to existing networks that are in close proximity to other HVDC links.

The MMC Support Unit uses a well-proven representation of the converter valve which has been available in RSCAD for several years. The processor version of the MMC valve model has been used by a large number of RTDS clients since its introduction in 2009. The more recently released FPGA version was introduced to overcome the difficulties of interconnecting the physical firing pulse controls as the number of MMC sub-modules in the converter increases. With the FPGA version, the user is able to accommodate interconnection of controllers for converters with more than 500 sub-modules (levels) per converter arm or over 3000 sub-modules per HVDC terminal.

The successful application of the RTDS Simulator for modern MMC-based systems serves to reinforce that, as the undeniable world leader in real time digital simulation, RTDS Technologies is also leading the way in real time modelling of MMC-based technology.

### Did you know?

RTDS Technologies recently welcome three new representatives to their team. With new representation in Chile, France and Germany, RTDS Technologies now has 24 worldwide representatives. Welcome to the team!

Please visit the Worldwide Representatives portion of the RTDS Technologies website for more details.

### You can find us on:



Facebook



RTDS Technologies Inc.



@RTDS\_Simulator

# RTDS<sup>®</sup> Simulator Hardware

The RTDS Simulator takes advantage of a custom parallel processing hardware architecture assembled in modular units called racks. Each simulator contains slot and rail-mounted cards. The specific composition of an RTDS Simulator depends on the processing and I/O requirements of the intended application. A common communication backplane links all slot-mounted cards within a rack to facilitate the exchange of information. In a multi-rack simulator, the backplanes function independently, and in parallel, thereby reducing communication bottlenecks. The communication among racks is then realized through Inter-Rack Communication channels.

The following table shows the major components of a typical RTDS Simulator categorized based on whether they are accessible from the front or the back of the simulator.

Accessible from the Front		Accessible from the Back *	
PB5	PB5 Processor Card	GTAO	Giga-Transceiver Analogue Output
GTWIF	Giga-Transceiver Workstation InterFace Card	GTAI	Giga-Transceiver Analogue Input
GTNET	Giga-Transceiver Network Interface Card	GTDO	Giga-Transceiver Digital Output
Low Voltage Digital I/O Interface Panel		GTDI	Giga-Transceiver Digital Input
250 Vdc Voltage Digital Output Interface Panel		GTTFPI	Giga-Transceiver Front Panel Interface
* For a brief description of these cards please refer to the <a href="#">GT-I/O cards feature sheet</a>		GBH	Global Bus Hub

## PB5

- The PB5 has 2 identical RISC processors (Freescale MC7448)
- Each PB5 includes 24 analogue output channels with 12-bit d/a converters.
- Each PB5 is equipped with eight GT optical transceivers for the connection of peripheral I/O devices and direct high speed card-to-card communication.
- Communication to I/O and other PB5 cards is serviced by a powerful on board FPGA
- Up to 2 processors in each rack can be assigned the task of the network solution. The other processors solve the equations of the power system and control components. The software determines the role of each processor in a simulation.



## GTNET

- The GTNET card is used to interface Ethernet based communication protocols with the RTDS Simulator.
- GTNET can support various protocols simply by switching between up to four firmware versions installed on the card.
- Unlike other I/O cards that are rail-mounted, the GTNET is installed in a slot and powered from the backplane. It communicates with a PB5 card through a GT optical port.
- The protocols supported by the GTNET card are detailed in the GT-I/O feature sheet and included, IEC 61850 (binary and sampled values), DNP and Playback.



**GTWIF**



• The GTWIF provides the communication interface between the Local Area Network (LAN) and the RTDS Simulator. Each GTWIF is assigned a unique IP address so that it may communicate with any computer or device accessible on the LAN.

• Communication takes place to load, start, and stop simulation cases; to retrieve results from the simulation while it is running; and to permit the user to interact with the simulation case while it is running.

- Once the GTWIF has started a simulation, it will run continuously in real time until a STOP command is issued.
- The GTWIF provides the timestep clock to all processors, synchronizing their calculations, and coordinates the communication between cards. In multi-rack simulations, one GTWIF is designed to provide the master

timestep clock which is passed to other racks via the GBH.

- To ensure true hard real time operation is always maintained, all processors are monitored by the GTWIF to guarantee they complete their calculations and service I/O every timestep.
- The GTWIF performs diagnostics on itself and on all of the other cards in-stalled in its rack
- Each GTWIF has six high-speed Inter-Rack Communication (IRC) channels.
- Each IRC channel is bi-directional and capable of transferring one gigabit of data per second.
- Fibre optic cables with industry standard LC connectors are used to connect IRC channels in different racks.
- Software will automatically determine the data that must be exchanged between racks. Only essential data is exchanged in order to reduce the amount of time required for communication. As well, data exchange between various racks is done in parallel.

**Interface Panels**

**Global Bus Hub**

- The GBH is required for simulators with 3 or more racks and allows the timestep clock to be passed from the master GTWIF to all other rack

**Low Voltage Digital I/O Interface Panel**

- 16 digital input and 16 digital output (max 5V) signals are made available via 4 mm banana plugs mounted in the front of the cubicle for quick connection of digital signals to external equipment.
- The Low Voltage Digital I/O Panel is wired in the back of the simulator to a GTFPI card which in turn is connected to a PB5 via a fibre optic cable.

**250 Vdc Voltage Digital Output Interface Panel**

- The 250 Vdc Digital Output Interface Panel has 16 solid state contacts rated for a maximum of 250 Vdc. The contacts can be controlled from the GTFPI digital output ports. The interface is configured as a panel that mounts in the front of mid- and full-size cubicles.
- The 250 Vdc Digital Output Interface Panel is connected inside the simulator cubicle to a GTFPI card which in turn is connected to a PB5 via a fibre optic cable.

**Cubicles**

**Full Size Cubicle**

- Maximum 3 racks
- Seismic Kit optional
- 209 x 61 x 74 cm (h x w x d)
- Approximately 365kg fully populated

**Mid-Size Cubicle**

- Maximum 2 racks
- On wheels
- 172 x 61 x 74 cm (h x w x d)
- Approximately 288kg fully populated

**Mini Cubicle**

- Maximum 1 rack
- On wheels
- Limited space for I/O cards
- 94 x 61 x 43.5 cm (h x w x d)
- Approximately 135kg fully populated

**Portable Cubicle**

- Maximum 1 rack (7 card slots)
- Limited space for I/O
- 54.5 x 21 x 59cm (h x w x d)
- Approximately 18 kg fully populated

**Portable I/O Cubicle**

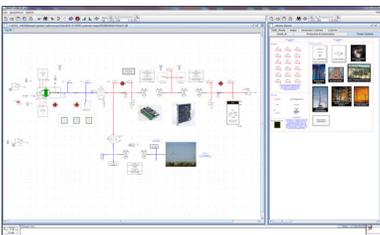
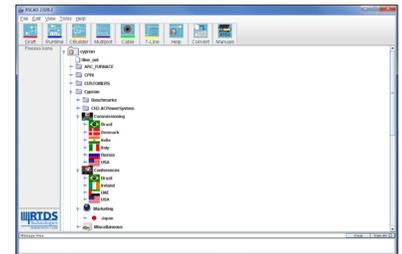
- 155cm DIN rail space to mount I/O cards
- Link to processor cards via optical fibre
- 103 x 30 x 30cm (h x w x d)
- Approximately 26 kg



# RTDS<sup>®</sup> Simulator Software—RSCAD

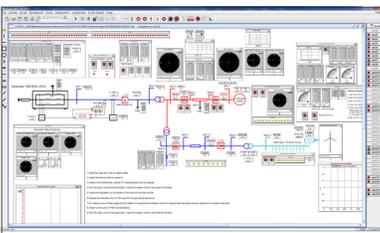
The RTDS Simulator has an advanced and easy to use graphical user interface - *RSCAD*. RSCAD is comprised of several modules designed to allow the user to perform all of the necessary steps to prepare and run simulations and to analyze simulation output. All modules provide a graphical interface to the simulator in an environment familiar to the power system engineer. The modules of RSCAD include: FileManager, Draft, RunTime, TLine, Cable, MultiPlot, and CBuilder.

**FileManager** Organization and sharing of simulation projects and cases is done from the RSCAD/FileManager module. Users can access their simulation files from anywhere on the LAN plus multiple users can share access to projects and cases, depending on permission settings. All other RSCAD modules are launched from FileManager and a link is provided to a complete documentation set (i.e. hardware, software and tutorial manuals).

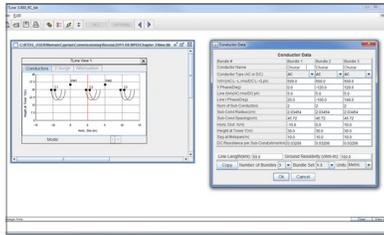


**Draft** Users graphically assemble a schematic diagram of the system to be simulated using the RSCAD/Draft module. The right side of the Draft screen contains comprehensive libraries of power system, control, protection and automation component models. To create a schematic, icons are simply copied from the library and pasted onto the Draft canvas on the left side of the screen. Model parameters are entered through a menu window to customize their behavior. Features such as, copy, paste, group/ungroup commands are provided

for easy on-screen arrangement and speed of operation. Once the circuit drawing is completed it can be compiled for the RTDS Simulator. The compile process creates the execution code for the simulator hardware and provides preliminary error checking of component and simulation parameters. Several advanced Draft features such as hierarchy components, single-line diagram mode, and load flow initialization are detailed below.

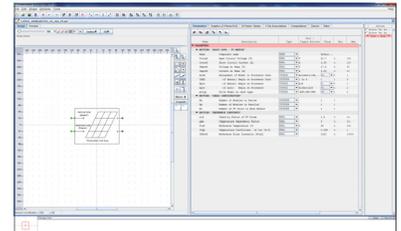


**RunTime** Loading, running, and controlling simulations is done entirely from the host computer via the RSCAD/RunTime module. This module is also known as the Operator's Console because it allows the user to interact with the real time simulation. The canvas is customized for each simulation by creating meters, plots, sliders, buttons, dials, switches, etc. The user is able to control and interact with the simulation through this graphical environment. Components can be grouped and minimized for efficient use of the space available on the canvas. RunTime automatically triggers plot updates when the user interacts with the simulation. Calculation functions are available to condition plots. As well, text, annotation and time stamps can be added to document simulation results. Plot data can be saved for post processing in MultiPlot or report-ready plots can be printed directly from RunTime. Plots can be saved in MultiPlot, COMTRADE, PDF, JPEG and EMF format.

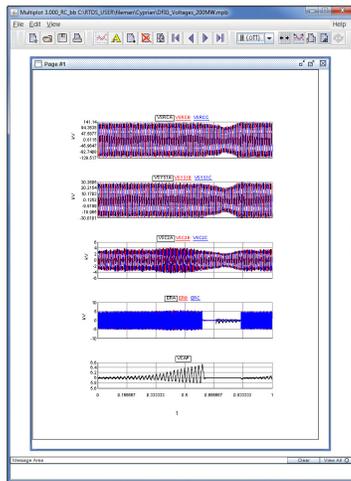


**TLine** Physical AC and DC transmission line data is entered into the RSCAD/TLine module that converts it into a form usable in the circuit assembly module (RSCAD/Draft). Parameter for both Bergeron and frequency dependent traveling wave models can be calculated. Alternatively the line sequence impedance data can be used to generate Bergeron line data.

**Cable** Similar to the RSCAD/TLine module, the RSCAD/Cable module provides the conversion of physical cable data into a form usable in the RSCAD/Draft module. Both Bergeron and Frequency data can be generated.



**CBuilder** Occasionally advanced users want to implement customized components and run them in real time on the RTDS Simulator. The RSCAD/CBuilder module facilitates this by providing an environment in which the user draws the icon for the new component, defines the parameters, the input/output nodes and writes the code. The code for CBuilder components is based on ANSI C.



**MultiPlot** Advanced data analysis, conditioning, and plotting functions are available in RSCAD/MultiPlot for post-processing, analysis and printing of results captured from the RTDS Simulator. Data can also be exported for post processing in other application software (Matlab, Mathcad, Excel, etc.)

### Additional Features

Automated batch operation makes it possible to run a series of simulations completely without user interaction. A script file can be created by record/replay, or through an editor, to describe a sequence of events (starting/stopping cases, initiating events, changing setpoints, saving results, printing, etc.). Even circuit parameters can be changed through the use of Draft Variables. Therefore thousands of cases can be run and a summary report created without the need for user interaction.

**Single line diagram (SLD) format in Draft** provides the flexibility to toggle between single line or three-phase format for viewing and printing. The SLD viewing mode provides an easy to understand circuit overview while the three-phase mode allows details such as unsymmetrical loading to be implemented.

**Load-flow initialization** provides the ability to calculate the load-flow for the Draft circuit prior to starting the simulation. By first initializing the simulation, the start up transient is minimized.

**Hierarchy** allows portions of a Draft circuit to be collapsed into a hierarchy box.

**Multiple RSCAD Software Installations** can be placed on any number of computers at a customer site. This allows different groups to work on real time simulation, circuit construction, post-processing, etc. all at the same time.

**SCD Editor** embedded in the RSCAD software suite can be used to edit/create the SCL files necessary to configure the IEC 61850 communication

# RTDS Simulator Software

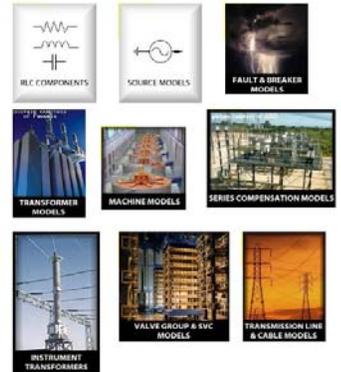
## Power and Control System Component Libraries

The RSCAD/Draft module allows the user to assemble power system and/or control system component icons to create the desired simulation circuit. Compilers automatically generate the low-level code necessary to perform the simulation using the RTDS hardware. The low-level code in turn determines the function of the processors for each simulation.

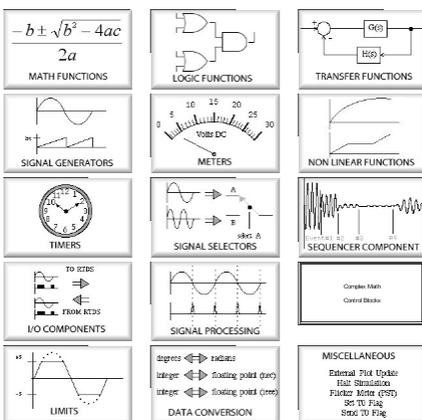
### Power System Component Library

The Power System Component Library contains models of the devices that are found in today's power systems. Examples of available models include the following groups of components:

- Real Time Network Solution – solution of the nodal equations including passive components (R, L and C), breakers and faults for a maximum of 66 single phase nodes per subnetwork
- Sources - voltage and current with variable network equivalent series impedance
- Transmission Lines – PI Section (max. 12 cond.), Bergeron traveling wave (max. 12 cond.) and modal or phase domain frequency dependent traveling wave (max. 6 cond.)
- Machines - synchronous (standard and permanent magnet) and induction (wound rotor and double fed) machines with optional multi-mass model (max. 11 masses)
- HVDC – valve groups with improved firing and internal faults for transmission and back-to-back schemes
- FACTS – STATCOM, SSSC, UPFC, etc
- SVC - TCR (with improved firing), TSC and filters
- Series Compensation – TCSC with improved firing and fixed series capacitor with MOV and bypass breaker
- Transformers - 2 and 3 winding transformers with on-load tap changers, saturation and hysteresis and internal faults, phase shifters
- Instrument Transformers - current transducer (CT), capacitive voltage transducer (CVT), potential transformers (PT)



### Control System Component Library



The Control System Library allows customized control systems to be created to interact with the model power system and/or the outside world. In addition to individual control blocks, some complex controllers have been assembled as composite controls and are provided (e.g. generator controls). The Control System Software also provides complete flexibility for the development of sequence of events control input. Examples of available models include the following groups of components:

- User-Input - Slider, switch, button, dial, etc.
- Constants – integer, floating point, PI
- Data conversion- deg-rad, rad-deg, int-float, float-int
- Math functions – gain, exp, log, ln,  $e^x$ ,  $x^y$ , sqrt, inverse, abs, sum, multiply, divide, max, min, etc.
- Complex math functions – multiply, divide, add, subtract, etc.
- Trigonometric functions – sin, arcsin, cos, arcos, tan, arctan, arctan2
- Standard control blocks - deadband, pulse generator, edge detector, time, counter, ramp, ramp limits, limiters, phase-locked loop (PLL), flip-flops, fourier transform, integrator, lead-lag, wash-out, lookup table, non-linear gains, etc.
- Logic functions – and, or, nor, bit shift functions, bit -> word, if-then-else, etc.
- Meters – real and reactive power, RMS (single- and three-phase), angle difference, frequency
- Signal processing – sample & hold, down sampler, moving average, FIR, DFT, ABC-DQ0, DQ0-ABC, ABC- $\alpha\beta$ ,  $\alpha\beta$ -ABC, vector rotator, etc.
- Generator controls – exciters (IEEE Type 1 to 5, AC1 to 4, ST1 to 3, X1, X2, 2A, SCR, DC2, IVO, etc.), governors (IEEE Type 1-3, IVO, European BGOV1, Gas turbine, steam turbine, hydro turbine, etc.), power system stabilizers (PSS2A, IEEEEST, IEE2ST)
- Relay models – line (mho & quad), transformer, differential, generator, overcurrent, etc.



# GTWIF

The primary function of the GTWIF is to handle communication between the RTDS Simulator and the host computer (i.e. Windows or Linux based PC). The communication medium used between the GTWIF and the host computer is a standard Ethernet (10/100baseT) TCP/IP based local area network. An additional function of the GTWIF is to synchronize the calculations taking place on the processor cards within a rack. When an RTDS Simulator consists of three or more racks, a special purpose hub, referred to as a Global Bus Hub (GBH) is required to exchange synchronization signals between GTWIF cards.

As mentioned below, the GTWIF also provides Inter-Rack Communication (IRC) between simulator modules to allow the system to be expanded.

## The GTWIF provides 2 new features:

- I. More than double the backplane transfer rate when using the PB5 or GPC (1.32 and newer). With the increased backplane transfer rate, the GPC network solution has been increased from 54 to 66 nodes per rack. However, the GTWIF can still support the 3PC (including all peripherals) and the IRC version 3 at the previous backplane transfer rate.
- II. Now facilitates inter-rack communication which was formerly handled by a separate Inter-Rack Communication (IRC) card. The GTWIF includes six Gigabit Transceiver (GT) optical ports through which inter-rack data is exchanged. The links run at 2GBd over 62.5/125 um multi-mode fiber using a proprietary protocol.



## GTWIF provides the following functions:

- Loading, starting and stopping cases
- Timestep generation
- Inter-rack synchronization together with the Global Bus Hub (GBH)
- Coordination of all backplane transfers during simulation
- Rack hardware diagnostics
- All communication with RSCAD (diagnostic and simulation data)

## GTWIF Specifications

- 8 mega point plot updates
- 10/100 Base Tx Ethernet communications
- VxWorks OS running on a PPC405
- Global bus for Multi-rack simulation
- Proprietary bus controller for VME backplane
- 6 2GBd optical ports for Inter-Rack communication
- 2 2GBd optical ports for future expansion
- USB accessible from the front panel for system diagnostics and configuration
- LED displays on the face plate for simulation and configuration information

# PB5 Processor Card

The PB5 processor card is the latest generation of processor cards developed for the RTDS Simulator. New simulators are being based exclusively on PB5 processor cards. The PB5 is also fully compatible with the GPC processor card and can be used to upgrade and enhance the capabilities of existing GTWIF – GPC based simulators. Each PB5 has two PowerPC RISC processors operating at a clock frequency of 1.7 GHz. The increased clock frequency provides increased computing capacity compared to the GPC card. One of the other significant new features provided by the PB5 is that it has eight (8) GT fibre ports. Two (2) GT ports are reserved for connecting to I/O and the other six (6) ports can be used to communicate directly to other PB5 or GPC cards.



## Comparison of PB5 versus GPC Processor Cards:

The table below provides a comparison overview for the new PB5 processor card versus the GPC processor card. The PB5 is the latest processor card to be developed by RTDS Technologies and it offers a number of benefits and features compared to the GPC card. The most significant advancements are the following:

- The PB5 provides 12 load units per processor compared to 10 for the GPC card. The additional load units allow more components to be included on one PB5 processor.
- The maximum number of nodes in a single network solution has been increased on the PB5 to 72 single-phase nodes (24 three-phase buses) from 66 single-phase nodes on the GPC card.
- With the PB5 card two network solutions can be included in one rack. Therefore two subsystems with 72 nodes each can be included on one rack. With the GPC card only one network solution was allowed per rack.
- The PB5 card has 6 communication ports to allow direct communication to other PB5 cards. The GPC had only 2 communication ports for direct communication to other processor cards. The additional communication ports on the PB5 card make it easier to model large scale systems using Small Timestep Subnetworks which can be a big advantage for modeling distribution level systems.

Card Type	<i>PB5</i>	GPC
Year of Production	<i>2011</i>	2005
Processor type	<i>Freescale - MC7448 RISC</i>	IBM - 750GX RISC
Clock speed	<i>1.7 GHz</i>	1.0 GHz
No. of processors per card	<i>2</i>	2
Load units per processor	<i>12</i>	10
Network solution (max nodes)	<i>72 x 2 = 144 *</i>	66
No. of I/O fibre ports	<i>2</i>	2
No. of comm. Ports	<i>6</i>	2
No. of 12 bit d/a's	<i>24</i>	24

### Advanced Features

One of the main motivators for developing the PB5 processor card was to increase the direct card-to-card communication capabilities. The additional communication ports allow many small timestep subnetworks to be interconnected using traveling wave models and therefore significantly increase the size of the network implemented in the small timestep domain.

### Exchange program

Customers covered under the extended warranty and maintenance program will benefit from the option to exchange old processor cards to receive a 50% reduction in the purchase price of PB5 cards.

# GTNET

RTDS Technologies has developed the GTNET to provide real time communication to and from the Simulator via Ethernet. Different firmware versions are used with the GTNET depending on the application. The different firmware versions, described below in detail, accommodate IEC 61850 GSE binary messaging, IEC 61850-9-2 sampled values, playback of large data files stored on a PC hard disk, and DNP communication.

## GTNET - Giga Transceiver Network communication card

The GTNET card occupies a single slot of an RTDS Simulator rack and draws power from the backplane. The card transmits and receives signals from a PB5 processor through one of the GT ports on the rear of the PB5 card.

The Ethernet connection to the GTNET is provided by a 100Base-TX RJ45 port or optical fibre port located on the rear of the unit.

The GTNET is equipped with a BNC and ST optical connector that can accept or provide a 1PPS timing signal. Alternatively an external time reference can be provided to the simulator via the GTSYNC card using 1PPS or IEEE 1588 and subsequently passed to the GTNET.

## GTNET - PMU

The PMU firmware option for the GTNET provides synchrophasor output data streams according to the C37.118 standard. A single GTNET-PMU can represent and provide output for up to eight (8) PMU's with symmetrical component information related to 3-phase sets of voltage and current using UDP or TCP connections. The frame rate of each PMU can be set individually between 1 and 60 frames per second. Frame rates as high as 240 frames per second are supported, but require the maximum number of PMU's represented by one GTNET to be reduced from eight. The GTNET-PMU requires the use of a GTSYNC card.

## GTNET - GSE



The GSE firmware option for the GTNET allows a maximum of 64 binary input (subscribe) and 64 binary output (publish) signals to be exchanged between the RTDS Simulator and up to five IEC 61850 compliant IED's. Both GSSE (UCA GOOSE) and GOOSE formatted messaging are supported, but cannot be provided simultaneously from one GTNET.

An SCD editor is embedded in the RSCAD software suite and can be used to edit/create the SCL files necessary to configure the IEC 61850 communication.

In addition to the binary messages, the GTNET-GSE IEC GOOSE can provide 8 analogue input and 8 analogue output control signals. IEC GOOSE fields such as the Test Mode, Needs Commissioning and individual Quality bitmaps can be dynamically changed and monitored during a simulation to allow many scenarios to be thoroughly tested and verified.

## GTNET - SV

The SV firmware option provides IEC 61850-9-2 sampled value messaging for power system voltages and currents. The



GTNET-SV can either publish or subscribe to sampled value data streams. In order to timestamp the sampled values, a one pulse per second (1PPS) signal can be input to the GTNET via a BNC or ST optical connection.

When used with a GTSYNC card, one GTNET card can simultaneously publish two sampled value output data streams each with a maximum of eight signals (e.g. 4 x V and 4 x I) and at a rate of 80 samples per cycle. It is also possible to publish one data stream at a rate of 256 samples per cycle.

When used for sampled value input, the GTNET-SV can subscribe to one IEC 61850-9-2 LE data stream (e.g. 4 x V and 4 x I) at 80 samples per cycle.

## GTNET - Playback

The Playback firmware option is used to read large data files stored on a PC hard drive and allow them to be played back in an RTDS simulation. Sampling frequencies as high as 20 kHz can be maintained in a true real time simulation.



Two components can be used with the GTNET Playback firmware option, namely `rtds_risc_ctl_GTNETCOMTRADE` and `rtds_risc_ctl_GTNETPLAYBACK`.

### ***rtds\_risc\_ctl\_GTNETCOMTRADE***

The `rtds_risc_ctl_GTNETCOMTRADE` component allows COMTRADE files with up to 8 channels to be played back on the RTDS Simulator. Because the COMTRADE data file is stored remotely on a PC, file sizes of several hundred MB can be handled easily. The component also allows for independent pre and post fault looping.

### ***rtds\_risc\_ctl\_GTNETPLAYBACK***

The primary application of the `rtds_risc_ctl_GTNETPLAYBACK` component has been to inject currents recorded at an actual installation (e.g. arc furnace or rolling mill) in an RTDS simulation. It is very difficult to accurately simulate the behavior of such installations so the recorded waveforms are often the best representation of the on site dynamics. By injecting the recorded current into the plant simulation, the performance of compensation equipment (e.g. SVC or STATCOM) can be accurately evaluated for the expected operating conditions. Simulation/playback times in excess of 30 minutes allow even the flicker (PST) reduction factor to be observed.



## GTNET – DNP

The DNP firmware option allows the GTNET to act as a DNP slave using the DNP 3.0 protocol. DNP is a SCADA protocol commonly used in substations.

Using the DNP protocol, the GTNET can communicate with one DNP master and accommodate the following maximum communication capacity:

- Binary simulation status (i.e. breaker position)  
1024 (scan rate 1000 Hz)
- Binary simulation control (i.e. breaker commands)  
512 (scan rate 1000 Hz)
- Analogue status (i.e. output from simulator)  
500 (scan rate 4 Hz)
- Analogue control (i.e. input to simulator)  
100 (scan rate 4 Hz)

# GTIO CARDS

The Giga-Transceiver Input/Output (GTIO) cards have been developed for use with the PB5 Processor Card (PB5) card and are driven from the Giga-Transceiver (GT) optical ports provided on the PB5. To allow greater freedom of connection and flexibility, the cards have been designed to allow a daisy-chain connection between them. Depending on the configuration, as many as 8 GTIO cards can be connected to each GT port.

The physical link between the PB5 and the GTIO cards is provided by a fibre optic cable with industry standard LC connectors. The GTIO cards are normally mounted on DIN rails in the rear of the RTDS Simulator cubicle. However, the 2 Gbit/s bandwidth of the link allows the GT-I/O cards to be located up to 35 m from the RTDS Simulator cubicles.

## GTDI – Giga-Transceiver Digital Input Card

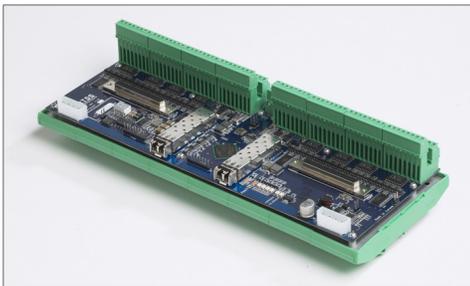


The GTDI provides optically isolated digital input to the real time simulation from external equipment. The card has a total of 64 inputs for use in regular or small timestep (1-2  $\mu$ s) simulations running on the PB5 card.

The GTDI input is current driven ( $\sim 10$  mA), allowing a wide range of input voltages to be connected to the card by providing the appropriate value of current limiting resistor.

If being used in a small timestep simulation, the GTDI card should be first in the daisy chain.

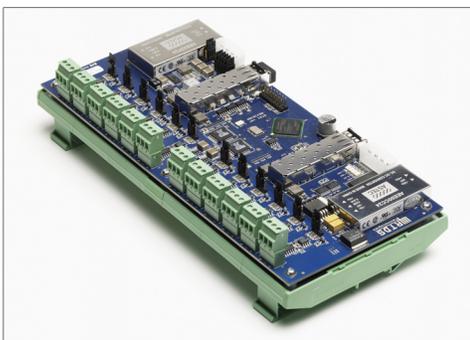
## GTDO - Giga-Transceiver Digital Output Card



The GTDO provides optically isolated digital output from the simulation to external equipment. The card has a total of 64 outputs which can be sent from either a regular or small timestep simulation running on the PB5 card.

The GTDO has a source driven output that can provide up to 100 mA with a voltage supply range from +7 to +24 V.

## GTAI - Giga-Transceiver Analogue Input Card

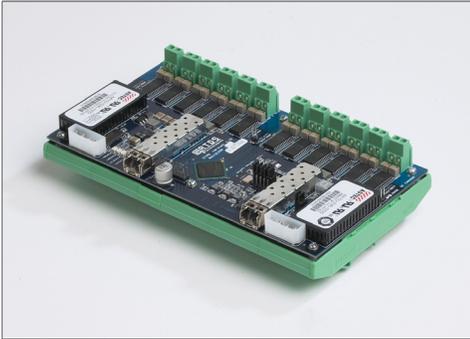


The GTAI provides optically isolated analogue input from external equipment to the simulation. The card has a total of 12 true differential inputs which can be read by simulation components running on the PB5.

The GTAI can provide updates to the PB5 card at a minimum of 6  $\mu$ s intervals.

The GTAI input can range between a maximum of  $\pm 10$  V<sub>peak</sub>.

## GTAO - Giga-Transceiver Analogue Output Card



The GTAO provides optically isolated analogue output from the simulation to external equipment. The card has a total of 12 outputs which can be sent from either regular or small timestep simulations running on the PB5.

Special care has been taken in the design of the GTAO to provide the communication bandwidth required for small timestep applications.

The GTAO output can range between a maximum of  $\pm 10$  V<sub>peak</sub>. When operating with a regular timestep simulation, the GTAO card can provide oversampling of the output at 1.0  $\mu$ s intervals.

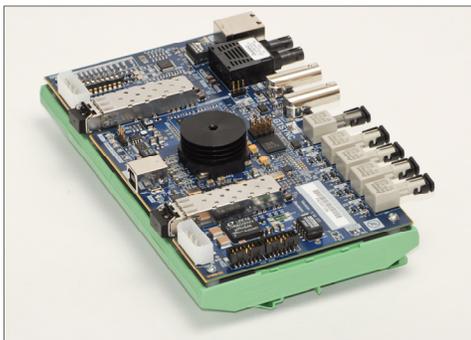
## GTFPI – Giga-Transceiver Front Panel Interface Card



The GTFPI card is used to read and write signals between the front panel and the RTDS Simulator. The GTFPI can be used with both the TTL level digital I/O panel and the dry contact (high voltage) panel.

Data exchange between the front panels and the GTFPI is via a ribbon cable, while the data exchange between the GTFPI and PB5 is via a GT port.

## GTSYNC – Giga-Transceiver Synchronization Card



The GTSYNC card is used to synchronize the RTDS simulation timestep to an external time reference (eg. GPS clock) and to synchronize devices under test. The GSYNC connects to the GT port on the GTWIF and cannot be daisy chained to other I/O cards.

The GTSYNC supports 1 Pulse Per Second (1PPS) over BNC coax or ST type fibre connectors, IEEE 1588 over RJ45 or ST fibre connectors as well as IRIG-B over a BNC coax connection. Synchronization of the simulation timestep to an external time reference is necessary for PMU benchmark testing and it is advantageous for IEC 61850-9-2 sampled value output.

## MMC (Multi-Module Converters) Modeling



MMC (Multi-Module Converters) offer many advantages compared to conventional thyristor based schemes and are becoming widely used in HVDC and FACTS applications. They also present significant challenges for modeling with Electro-Magnetic Transient (EMT) simulation techniques. However RTDS Technologies has developed a number of models during the past several years to overcome these challenges. Three

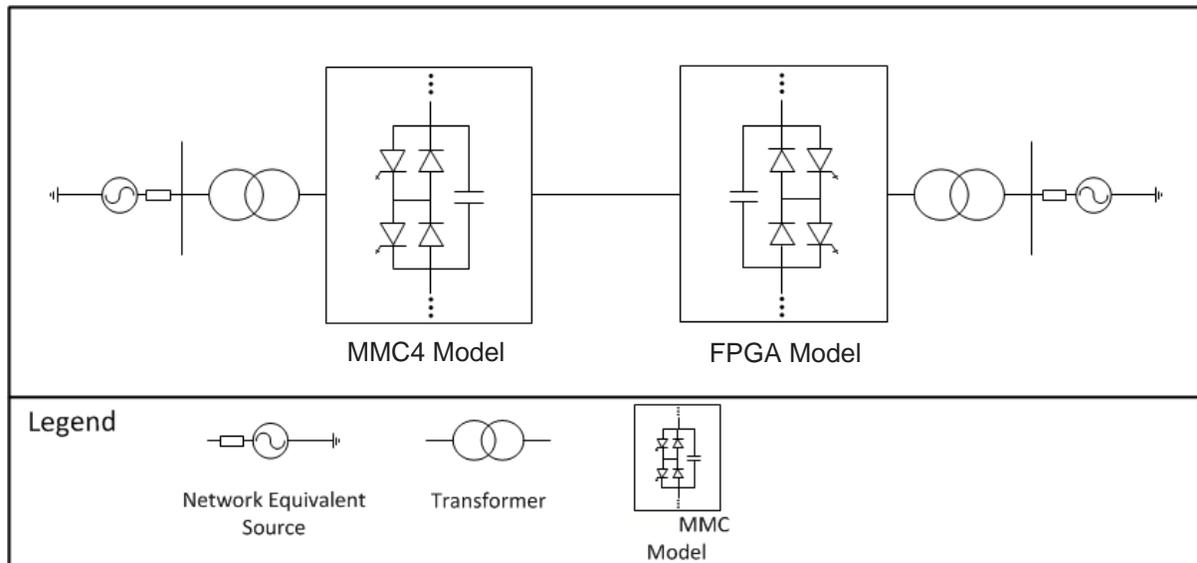
models are presented below. All three models are small timestep sub-network components which allows great flexibility of configuration as well as very low loop delay between the real time simulation and external controls.

**FPGA-Based MMC:** The latest MMC development from RTDS Technologies is an FPGA based component that is fully integrated into the small timestep sub-network providing valuable modeling flexibility with detailed representation of up to 512 submodules per valve or more than 3000 submodules per HVDC station! The model is used for detailed control development and detailed factory acceptance testing where a physical connection to external firing pulse controls is required. The FPGA-based model supports various internal faults for in-depth control testing.

**CHAINV5:** The CHAINV5 model uses the same algorithm as the FPGA-based model described above, but it is a processor based model (i.e. it is simulated using a PB5 or GPC processor). CHAINV5 can support 40 / 50 levels in the full / half bridge configuration and it is designed to test the actual firing pulse controls.

**MMC5:** The MMC5 model is designed to study and test high level control and uses a simplified control interface (i.e. it does not take in firing pulses as input). The input to the model is number of deblocked submodules and the number of positively or negatively inserted submodules. MMC5 can represent more than 600 levels per valve (1200 per phase - 3600 per HVDC station).

# MMC Modeling



## Demonstration Case

### MMC-Based HVDC Using MMC5 and FPGA-Based Model

The MMC-based demonstration includes a 2-terminal HVDC scheme. The MMC valves each contain 512 submodules. The valves at one end of the scheme are modeled using the MMC5 component while the valves at the other end are modeled in full detail using the FPGA-based component. Two MMC Support Units represent the FPGA-based valve models while three other MMC Support Units provide the capacitor voltage balancing and firing pulse control for the terminal. The high level control for the HVDC scheme is represented using PB5 processors.

As mentioned above, not only are six MMC valves represented using FPGA's, but also their respective capacitor balancing and firing pulse controls. The MMC Support Units representing the valves are connected to the MMC Support Units containing the firing pulse controls via optical fibre. The valve models calculate the valve current and the capacitor voltage for each level and send it to the controller. The control in turn provides the firing pulses for each level. The signal exchange uses a standard serial protocol known as Aurora which can be adopted and used for the connection of any external controller.

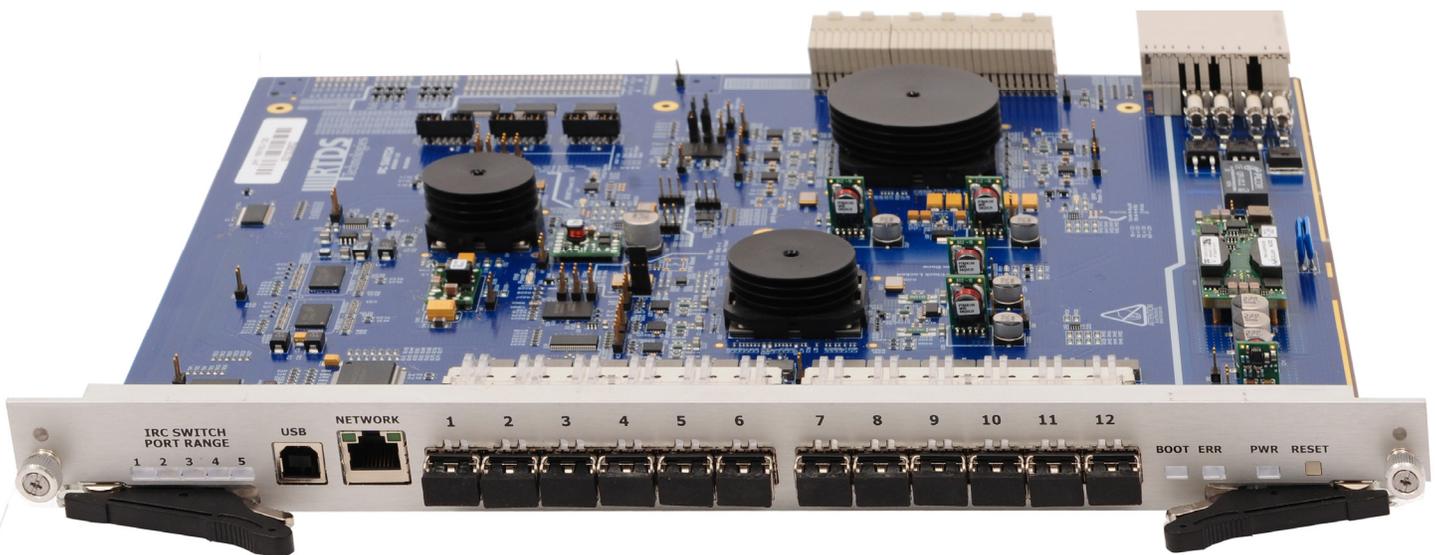
# IRC SWITCH

Large scale real time power system simulation is becoming more and more common. Utilities, manufacturers and research groups are looking to large scale simulators to develop, investigate and demonstrate new technologies as well as network behaviour. Wide area protection and control, integration of renewables, Smart Grid initiatives and many other factors are pushing the use of large scale real time simulation.

RTDS Technologies is committed to providing the best possible technology for real time power system simulation and has invested significant effort directed to large scale simulators. Part of that effort included the development of the IRC Switch to provide direct Inter-Rack Communication (IRC) between as many as 60 racks. The primary function of the IRC Switch is to act as a high speed switch used to augment IRC connections for inter-rack communication. The IRC Switch is used in systems with many racks. For large Simulators (over 7 racks) the IRC Switch becomes advantageous. Direct interconnection between up to 60 racks in a system is possible. In fact, the more racks the simulator has, the more benefit the IRC Switch will bring.

The IRC Switch is for use with GTWIF based simulators which are otherwise limited to six IRC connections per rack. If the IRC Switch is not used for a simulator with more than seven racks, not all racks will have direct communication with one another.

Very large scale networks have been successfully built and operated on simulators with more than twenty racks, but the restriction on the IRC connections had to be taken into consideration. With simplified connections and full communication between all racks, the IRC Switch allows the implementation of large scale simulations without restrictions.



The IRC Switch provides several benefits over GTWIF and previous generation IRC connected systems

- Greater connectivity: Without the IRC Switch, each rack can directly communicate with up to 6 other racks. The IRC Switch provides full interconnection between all racks on systems up to 60 racks.
- Greater flexibility: Without the IRC Switch, on systems greater than 7 racks care must be taken to ensure proper rack connections. The user has to know which racks are connected together while building their case. With the IRC Switch, each rack can communicate directly with all the other racks in the system, simplifying case building.
- Simplified wiring: Instead of up to 6 connections per rack to other racks, the IRC Switch requires only one fiber connection per rack to it, allowing for easy setup of larger systems. For example, in a 30 rack system,  $30 \times 6 = 180$  connections were required to 30 different locations. With the IRC Switch, only 30 connections are required and they are all routed to one location.



## IRC Switch Specifications

- 12 to 60 communication ports (1 to 5 cards)
- Each port communicates at 2GBd using 62.5/125  $\mu\text{m}$  multi-mode fiber
- Fully bi-directional interconnect between all racks in a simulation
- Broadcast capability allows a rack to transmit a packet to all potential receiving racks
- Housed in a mid-size cubicle together with the Global Bus Hub

## TESTING WITH IEC 61850

The RTDS® Simulator is a real time power system simulator widely used for closed-loop testing of physical protection and control equipment. For over 15 years now conventional protection equipment has been tested by driving power amplifiers (voltage and/or current) from the simulator's analogue output channels and by reading back the status of contacts for trip, reclose and other miscellaneous elements. Since the simulator operates in true real time, the protection equipment and the response of the simulated network are just as they would be in the real system. For example if a fault simulated in the network results in a trip being issued by the protection, a breaker in the simulated network will be opened and the subsequent voltages and currents affected correspondingly. The closed-loop response of the real time simulator also allows multiple relays to be connected simultaneously so their interaction can be evaluated.

To address the testing of IEC 61850 compliant protection equipment, RTDS Technologies has developed the GTNET card. Depending on the active protocol, the GTNET card can provide IEC 61850 GOOSE messaging or IEC 61850-9-2 sampled values for voltage and current.

### GTNET - Giga Transceiver Network communication card



The GTNET card occupies a single slot of an RTDS Simulator rack and draws power from the backplane. The card transmits and receives signals from a PB5 processor through one of the GT ports on the rear of the processor card. Other GT-I/O cards can be connected in daisy chain to the GTNET and serviced through the same PB5 GT port.

The Ethernet connection to the GTNET is provided by a 100Base-TX RJ45 port, or optionally by a 100Base-FX port with ST connectors located on the rear of the unit.

The GTNET is equipped a BNC coax that can accept or provide a 1PPS timing signal for IEC 61850-9-2 synchronization. It also has two ST optical connectors, one for receiving and one for transmitting a 1PPS signal optically.

## GTNET – GSE for IEC 61850 GOOSE Messaging



The GTNET-GSE firmware option for the GTNET card can be used to model 1-4 individual IEDs (Intelligent Electronic Devices). Each model is capable of sending and receiving up to 64 points (or 32 points with associated quality bitmap). For each GTNET card, GOOSE messages can be received from a total of 16 unique external IEDs. The GTNET GOOSE configuration is done via an SCD file. RSCAD contains a built in SCD editor which helps the user to easily and conveniently configure the publication and subscription of GOOSE messages.

IEC GOOSE fields such as the Test mode, Needs Commissioning and individual Quality bitmaps can be dynamically changed and monitored for both transmit and receive messages during a simulation to allow many scenarios to be thoroughly tested and verified. The GOOSE messaging provided by the GTNET card is KEMA certified.

## GTNET – SV for IEC 61850-9-2 Sampled Value Messaging

The SV firmware option provides IEC 61850-9-2 sampled value messaging for power system voltages and currents. The GTSYNC card is used to synchronize the SV timestamps with an external 1PPS (one pulse-per-second), IEEE 1588, or IRIG-B signal from a synchronized time source (ie. GPS clock). A 1PPS signal can also be generated directly from the GTSYNC card.

Two data streams with up to 4 current and 4 voltage channels each can be transmitted at a rate of 80 samples/cycle. Alternatively, one data stream can be transmitted at 256 samples/cycle.

It is also possible to receive SV data from one Merging Unit (4 currents and 4 voltages) at either 80 or 256 samples/cycle.



## Interoperability

The GTNET-GSE and GTNET-SV options have been successfully tested with products from a number of different vendors. RTDS Technologies has also demonstrated closed-loop testing that included IEC 61850 GOOSE messaging and sampled values with multiple vendor products interoperating. RTDS Technologies has also participated in IEC 61850 Inter-Operation events along with major protective relay manufacturers where the RTDS Simulator and GTNET card were an integral part of the testing.

# PORTABLE RTDS<sup>®</sup> SIMULATOR

The Portable RTDS Simulator uses the same proven hardware and software as the full-size RTDS Simulator, packaged in a compact cubicle that is easily picked up and moved from place to place. Like all RTDS Simulators, the Portable provides continuous real time electromagnetic transient simulation and can be used for conducting closed-loop testing of protection and control.

## Simulation Capabilities

The Portable is capable of simulating a variety of power systems. Some examples include the Cigre HVDC-SSR benchmark case with a 12-pulse monopolar system and controls, double-ended line protection test systems with twin circuit lines, systems for testing generator controls, distributed generation systems, etc. Seventy-two single-phase nodes can be included in the power systems. Diagrams of these or other sample systems can be provided upon request.

## Simulation Hardware

The Portable has 7 card slots and that are typically populated with one Giga-Transceiver Workstation InterFace (GTWIF) card and three PB5 Processor Cards (PB5).

Optionally, one PB5 can be removed and replaced by one or two GTNET cards to provide full IEC 61850 testing capability through the GTNET-GSE firmware option.

Since the GTWIF card includes IRC channels, the Portable can be connected to other racks for larger network simulations.

A GTFPI card is installed in the top drawer of all Portable cubicles and provides external access to low level digital inputs and outputs.

An access hole is provided in the side of the Portable cubicle to allow fibre optic connections to GTIO cards from PB5 cards and IRC connections from the GTWIF to other simulator racks.

## Dimensions

Weight ~ 40 lbs (18 kg)

Dimensions 23" x 8 1/8" x 20"  
(58 cm x 21 cm x 51 cm)



## Portable I/O Cubicle



Due to the limited capability to mount GTIO cards within the Portable cubicle (there is room for one GTFPI card), a separate I/O cubicle can be provided to house additional GTIO cards. The portable I/O cubicle has a 24 V power supply to run the GTIO cards and casters so that it can easily be moved from place to place. A flight case is also available for the portable I/O cubicle as an optional item.

The portable I/O cubicle contains two DIN rails on which GTIO cards can be installed. The following GTIO cards can be installed in the portable I/O cubicle:

**GTAO** - (analogue output) optically isolated digital to analogue (d/a) converter card which provides 12 output channels with 16-bit resolution.

**GTAI** - (analogue input) optically isolated analogue to digital (a/d) converter card that provides 12 input channels with 16-bit resolution.

**GTDO** - (digital output) optically isolated card that provides 64 digital output channels.

**GTDI** - (digital input) optically isolated card that provides 64 digital input channels.

**GTSYNC** - (synchronization card) time synchronization for 1PPS, IEEE 1588, or IRIG-B

**250 Vdc Digital Output Interface Panel** - 16 dry contact outputs typically used to send status signals (e.g. breaker status) to protection equipment at station level voltages.

## Dimensions

Weight ~ 53 lbs (24 kg) without High Voltage panel

~ 60 lbs (27kg) with High voltage panel

Dimensions 12" x 12" x 39" (31 cm x 31 cm x 99 cm)

Total DIN Rail Space 59" (150 cm)



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Queensland University of Technology

## Brazil

ABB Brazil  
CEMIG  
CTEEP  
FPTI  
FURNAS  
ONS  
Siemens Brazil  
UFABC  
UFCG  
UFJF  
UNICAMP  
UNIFEI  
Universidade de Sao Paolo

## Canada

ERLPhase Power Technologies  
GE Multilin  
Kinetrics Inc.  
Manitoba Hydro  
University of Manitoba  
University of Saskatchewan  
University of Toronto  
University of Western Ontario

## Denmark

Aalborg University  
TU Denmark

## Finland

Alstom Grid Oy Ltd.  
Tampere University of Technology

## France

RTE  
Schneider Electric

## Germany

Alstom Konstanz  
RWTH Aachen  
Siemens AG  
Siemens EA  
Siemens Mobility  
Technical University of Ilmenau

## Greece

NTU Athens

## India

ABB HVDC India  
Bharat Heavy Electricals Ltd.  
CPRI  
IIT Bhubaneswar  
IIT Kanpur  
Power Grid  
University of Calcutta

## Indonesia

PLN

## Italy

Ansaldo Energia  
ENEL  
ENEL-Bari  
Terna  
University of Cassino  
University of Catania

## Japan

Aichi Electric  
CHUBU EPCO  
Chugoku EPCO  
FUJI Electric Co., Ltd.  
Hiroshima I.T.

Hitachi  
J-Power Co. Ltd  
Kansai EPCO  
Kansai Training Center  
Kinkei Systems  
Kyusyu University  
Meidensha Corporation  
Mitsubishi Electric  
Takaoka Electric  
Tohoku EPCO  
Toshiba Corporation

## Malaysia

Pestech Sdb Bhd  
SESCO  
Tenaga Nasional Berhad  
University of Malaya

## Mexico

CIMAT  
CFE - LAPEM  
University of San Luis Potosi

## Netherlands

TU Delft

## New Zealand

University of Canterbury  
TransPower (Siemens)

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BDCC  
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China Central Power Group  
China EPRI  
China EPRI FACTS  
Chongqing EPRI  
Chongqing University  
CSG EHV  
CSG TRC  
CYG Shen-Rui  
Dong Fang Electronics  
East China EPRI  
Fujian EPRI  
GNA  
Guangdong EPRI  
Guangdong PDC  
Guangxi EPTRI  
Guangxi University  
Guizhou University  
Inner Mongolia Research Inst.  
Inner Mongolia University  
Jibe EPRI  
Jiangsu EPRI  
Jiangxi EPRI  
Jilin EPDC  
NARI  
NARI Relays  
Ningbo Ligong  
NCEPU  
North East China EPRI  
North East China Power Group  
Rongxin Electric Power Corp  
SGCC-OP  
SGCTC  
Shaanxi Electric Power Corp  
Shandong EPC  
Shandong EPRI  
Shandong University  
Shanghai EP  
Shanghai Jiaotong University  
Shanghai Power T&D  
Sichuan Electric Power Corp.

Sifang EPRI  
Southwest Jiaotong University  
South China University of Technology  
Suzhou Heshun  
Taiyuan University of Technology  
Tianjin EPRI  
Tianjin University  
Tsinghua University  
Wuhan University  
XIHARI-HVDC  
XIHARI-Smart Grid  
Xi'an Jiaotong University  
Xian University of Technology  
XJ Group Corporation  
Yunnan EPRI  
Zhejiang EPRI  
Zhejiang University

## Philippines

NGCP  
University of the Philippines

## Poland

University of Lodz

## Portugal

University of Porto

## Qatar

Qatar University

## Russia

EKRA  
NTC FSC EES  
MEI University  
NTC EES  
Tomsk University  
VNIIR

## Saudi Arabia

KACST  
KFUPM  
Saudi Electric Company

## Singapore

Nanyang TU  
NUS  
Vestas

## Slovenia

University of Ljubljana

## South Africa

CPUT  
DUT  
ESKOM  
University of Kwazulu-Natal

## South Korea

Chang Won University  
Chonnam National University  
DGIST  
HHI  
HICO  
EESRI  
Inha University  
KEPRI – ITSPR  
KEPRI – KEPS  
KEPRI - HVDC  
KEPRI - SSA  
KERI  
KEPCO  
KESRI  
KIER  
Korea University  
LSIS  
Myongji University / NPTC

National Fusion Research Institute  
SNUT  
Uiduk University  
Xelpower  
Yonsei University  
Youho Electric

## Spain

GE Multilin  
Ingeteam  
REE  
University of Zaragoza  
ZIV P+C, S.L.

## Sweden

ABB AB

## Taiwan

NTUST  
TPRI

## Thailand

PEA

## United Arab Emirates

Petroleum Institute

## United Kingdom

Alstom Grid UK  
Cardiff University  
Durham University  
Siemens UK  
University of Bath  
University of Manchester  
University of Strathclyde

## USA

ABB USA  
Alstom Grid USA  
American Electric Power  
American Superconductor  
Basler Electric  
Baylor University  
Clemson University  
Clemson University - WIND  
Dominion Technical Solutions  
Florida State University - CAPS  
General Electric - CRD  
Idaho National Laboratory  
Iowa State University  
Michigan State University  
Mississippi State University  
Missouri University of S&T  
National Renewable Energy Lab  
North Carolina State University  
Oak Ridge National Laboratory  
Pacific Gas & Electric  
Pennsylvania Power & Light  
Quanta Technology  
Savannah River Nuclear Solutions  
Schweitzer Engineering Labs  
Southern California Edison  
Tennessee Tech  
Texas A&M University  
Texas Tech University  
University of California - Riverside  
University of Connecticut  
University of Idaho  
University of Illinois  
University of North Carolina  
University of Tennessee - Knoxville  
University of Wyoming  
Washington State University

## Venezuela

Corpoelec