NovaCor™

A revolution in real time.

the new world standard for

REAL TIME DIGITAL SIMULATION

RTDS Technologies

Agenda

Introduction

Background and Theory

RTDS Hardware

RTDS Software

RTDS Applications

Questions and Answers

History of RTDS Technologies

1986
RTDS development project begins

1989
World's 1st real-time digital HVDC simulation

1993
1st commercial installation

1994
RTDS Technologies Inc. created

- Technical Advisory Board (sponsors)
- Major funding from Manitoba Hydro
- Continued development and refinement to produce a commercial product

The Company Today

- Technology licensed from Manitoba Hydro under royalty bearing agreement
- Worldwide exclusive rights to technology
- Current number of employees ~70
- Expanded office space to accommodate company growth

Customers in 43 Countries

- 380+ customers
- 1500+ units
- Over 60% repeat customers

Our clients are leading…

- Electrical power utilities
- Electrical equipment manufacturers
- Research and learning institutions

Selected by Leaders in Manufacturing

A few companies who trust the RTDS Simulator:

SIEMENS

ABB

TOSHIBA

GE

Schneider Electric

MITSUBISHI

SEL

Selected by Leaders in Research & Education

A few research and educational institutions who trust the RTDS Simulator:

DTU Technical University of Denmark

UNSW THE UNIVERSITY OF NEW SOUTH WALES

MANCHESTER 1824 The University of Manchester

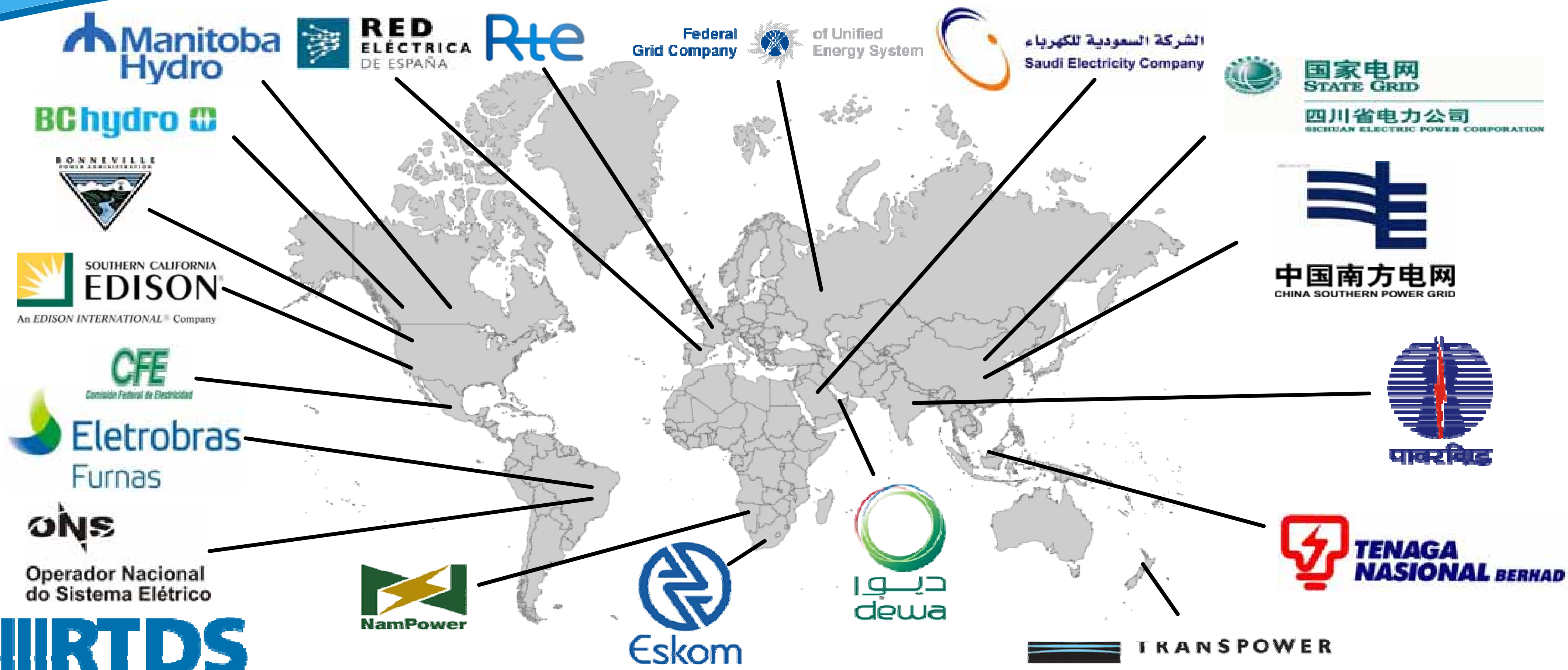
RWTH AACHEN UNIVERSITY

DUT DURBAN UNIVERSITY OF TECHNOLOGY

FLORIDA STATE UNIVERSITY 1851

CENTER FOR ADVANCED POWER SYSTEMS FSU

Trusted by Utilities Worldwide



Global Reputation for Excellence

SIEMENS (Germany)

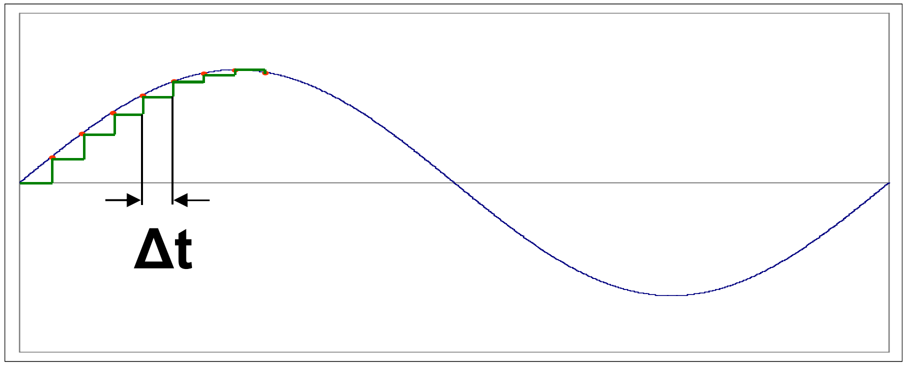
"Impressed and encouraged by the positive results, the **wide range of applications** and the **excellent support**… our main tool for pre-testing of new control and protection concepts and for off-site Functional and Dynamic Performance Tests… an **essential** part of SIEMENS study and testing schedule for HVDC and FACTS applications"

(USA)

"…RTDS Technologies has supported our efforts with **prompt repair** or replacement for the few component failures that we have experienced, with extensive software support for existing models, and with the **development of new models or requested features**."

Types of Digital Simulation

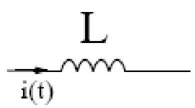
Type of Simulation	Load Flow	Transient Stability Analysis (TSA)	Electromagnetic Transient (EMT)
Typical timestep	Single solution	~ 8 ms	~ 2 - 50 µs
Output	Magnitude and angle	Magnitude and angle	Instantaneous values
Frequency range	Nominal frequency	Nominal and off-nominal frequency	0 – 3 kHz (>15 kHz)

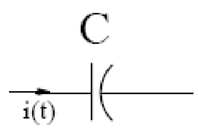


EMT Simulation Algorithm

Dommel Algorithm

Convert DEs to algebraic equations using **trapezoidal rule** of integration





$$v(t) = L * \frac{d\,i(t)}{dt} \qquad i(t) = C * \frac{d\,v(t)}{dt}$$

$$i(t) = \frac{1}{L}\int v(t)\,dt \qquad v(t) = \frac{1}{C}\int i(t)\,dt$$

applying trapezoidal rule of integration

$$i(t) = \frac{\Delta t}{2L}\,v(t) + I_h(t-\Delta t) \qquad i(t) = \frac{2C}{\Delta t}\,v(t) - I_h(t-\Delta t)$$

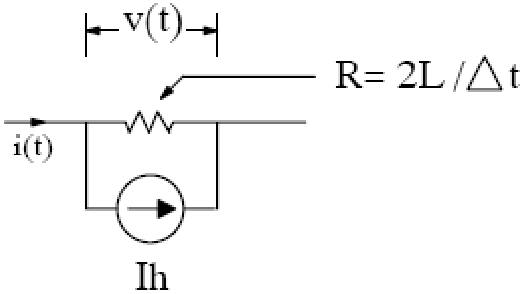
EMT Simulation Algorithm

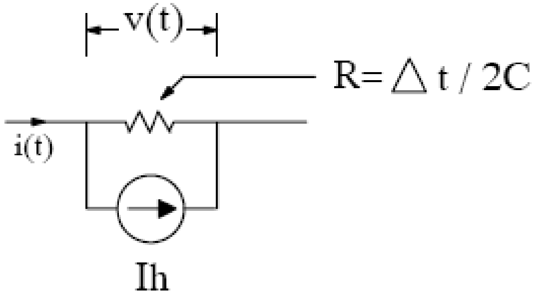
Dommel Algorithm

I_h: history term current – based only on quantities from previous timestep – v(t-Δt) and i(t-Δt)

$$i(t) = \frac{\Delta t}{2L} v(t) + I_h(t - \Delta t)$$

$$i(t) = \frac{2C}{\Delta t} v(t) - I_h(t - \Delta t)$$



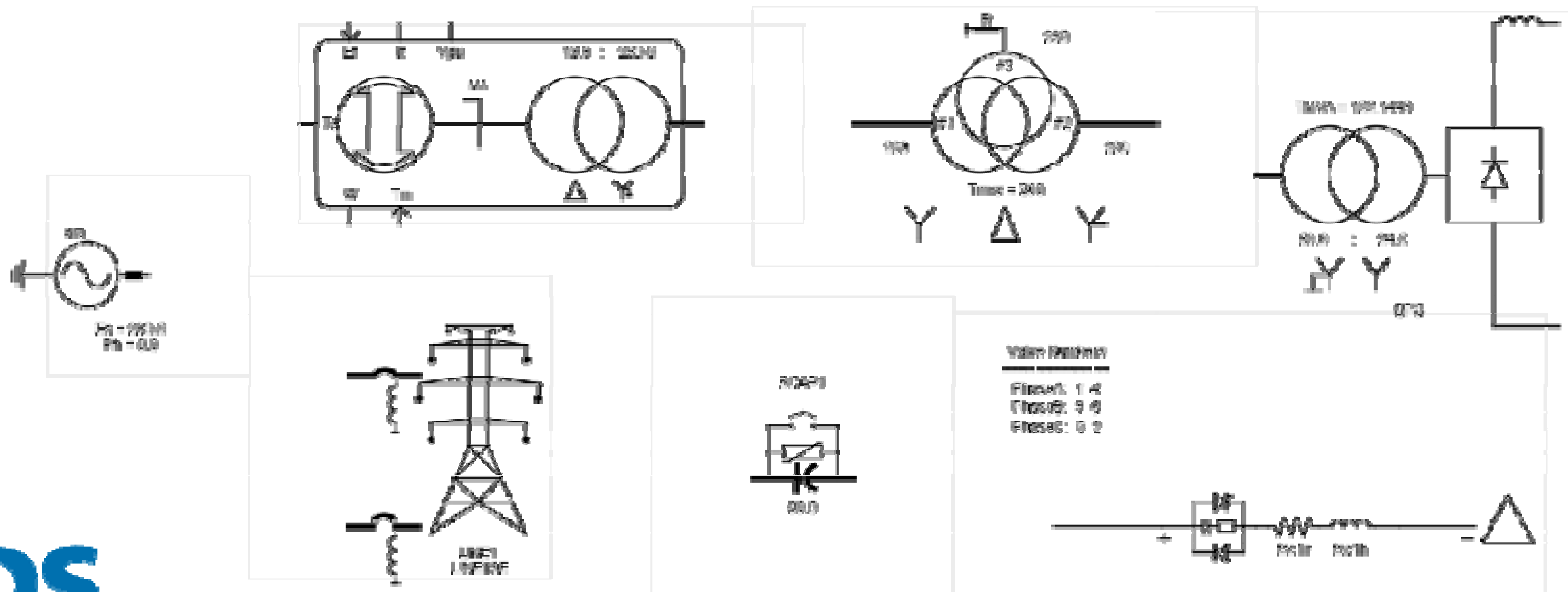


EMT Simulation Algorithm

Dommel Algorithm

All power system components are represented as **equivalent current source and resistor**

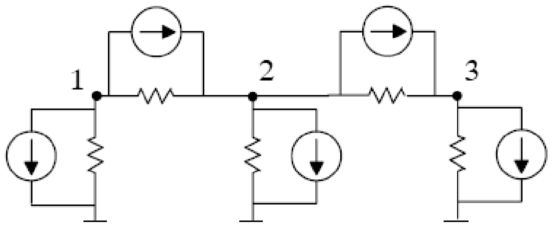
History term currents for complex components may require substantial computation



Power System Solution Process

1 Convert user-defined power system to equivalent network of only current sources and resistors

2 Formulate conductance matrix for equivalent network



$$\begin{bmatrix} V1 \\ V2 \\ V3 \end{bmatrix} = \begin{bmatrix} G11 & G12 & G13 \\ G21 & G22 & G23 \\ G31 & G32 & G33 \end{bmatrix}^{-1} \begin{bmatrix} I1 \\ I2 \\ I3 \end{bmatrix}$$

3 Using data from previous timestep (or initial conditions for first timestep), compute new [I] values

4 Solve for [V] using new values of [I]

5 Calculate branch currents with [V] and [I]

And repeat…

What is Real Time?

- Parallel processing required for practical systems
- Measured by counting clock cycles
- Calculations completed in real world time less than timestep
- Every timestep has same duration and is completed in real time
- The I/O is updated at a constant period equal to timestep

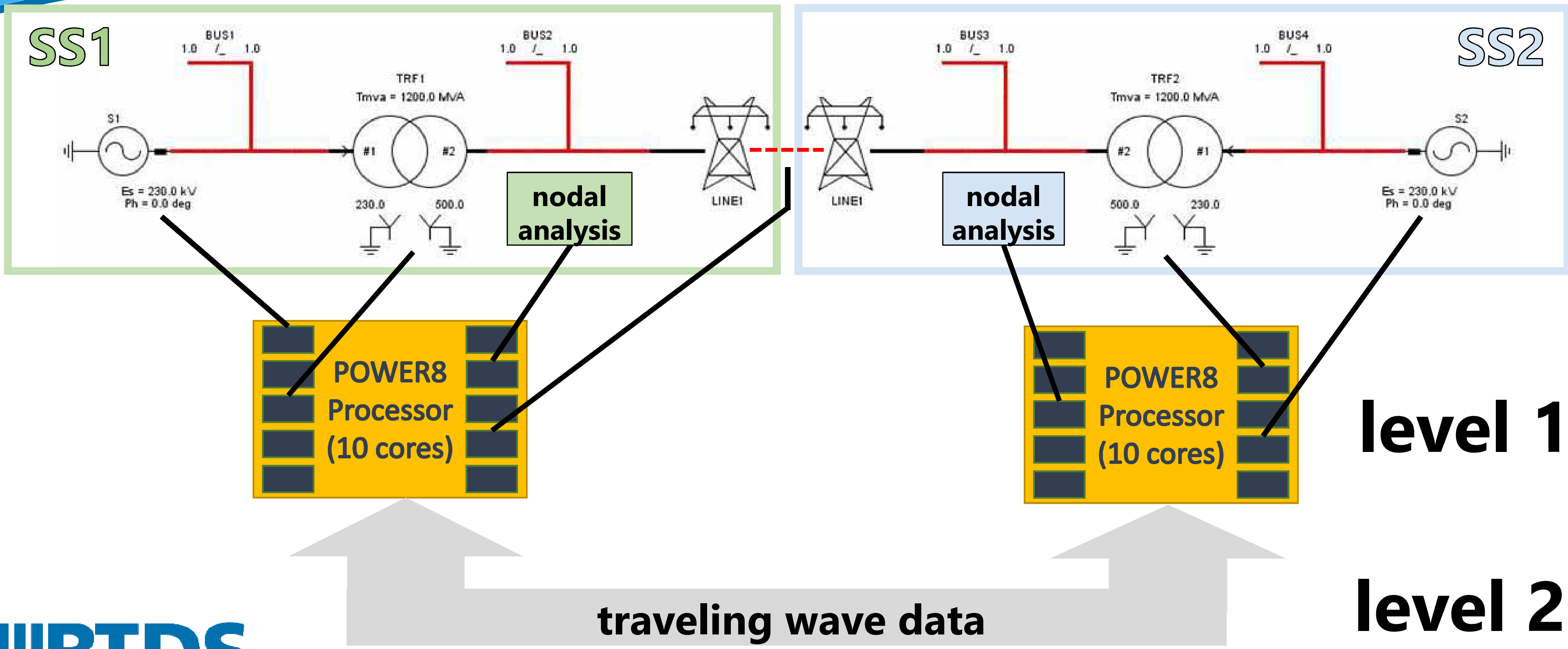
<1 s

<10 ms

RTDS

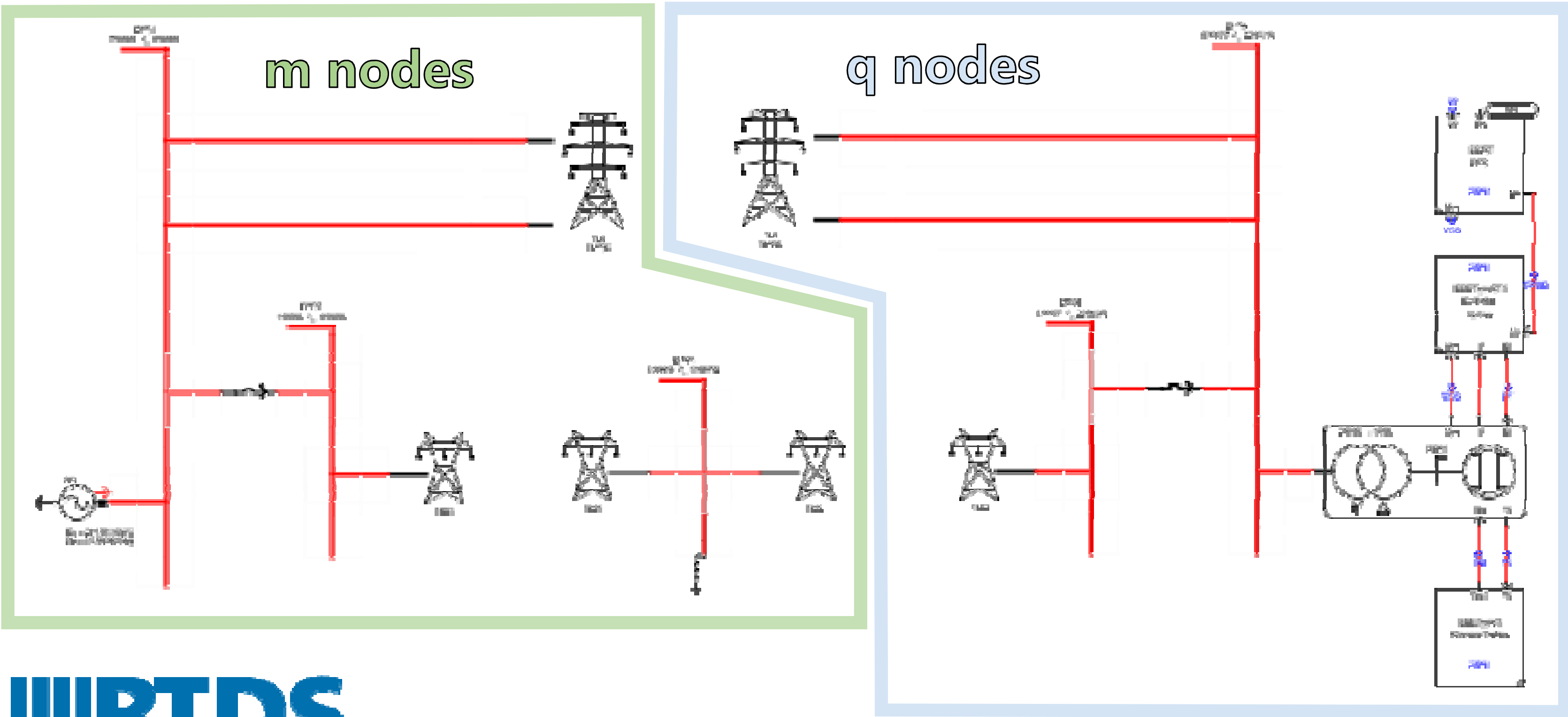
2 µs ~ 50 µs

Parallel Processing on Two Levels



Accommodating Large Networks

When the network gets too large for the available processing power, it must be split into subsystems using traveling wave models (lines or cables).



n x n matrix

$$\begin{pmatrix} \{m \times m\} & 0 \\ 0 & \{q \times q\} \end{pmatrix}$$

The Advantage of Custom Hardware

- Custom parallel processing computer
- Modular design

- Main interface is through user-friendly software
- Ample I/O to connect physical devices

mid-size cubicle

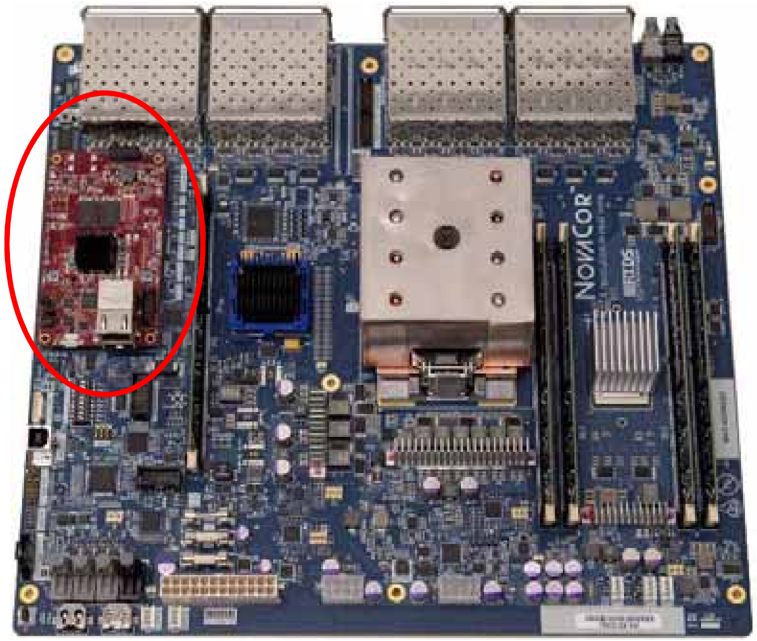
chassis

Flexible Hardware Configuration

Custom Hardware Components

WIF (Workstation Interface) Functionality

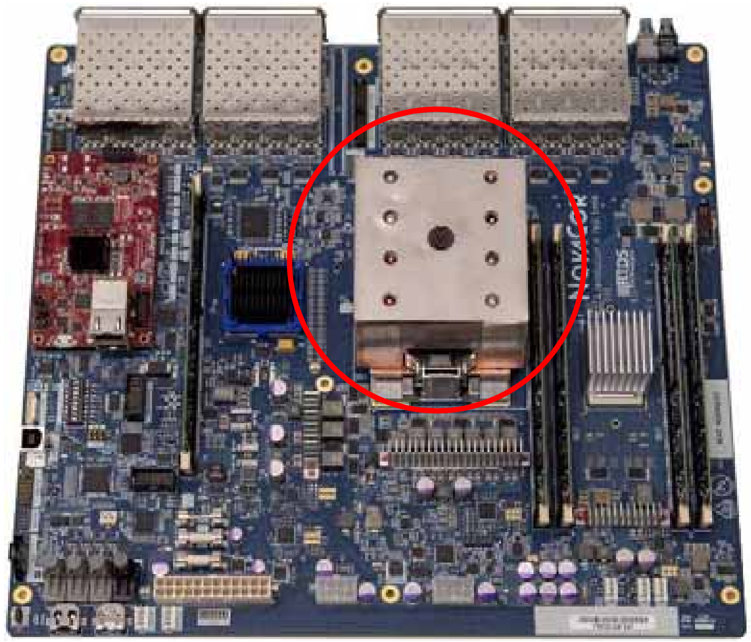
- Connects parallel processing hardware to computer workstation via Ethernet LAN
- Provides communication to load, start, stop the simulation case
- Enables user interaction with simulation
- Provides data exchange coordination and data record capability
- Direct fiber-optic connection to up to six other chassis



Custom Hardware Components

IBM's POWER8 RISC PROCESSOR

- Latest processing technology; April 2017
- 1-10 licensed cores, each running at 3.5 GHz
- Increased network solution and component modeling capacity
- Core function defined by software



Custom Hardware Components

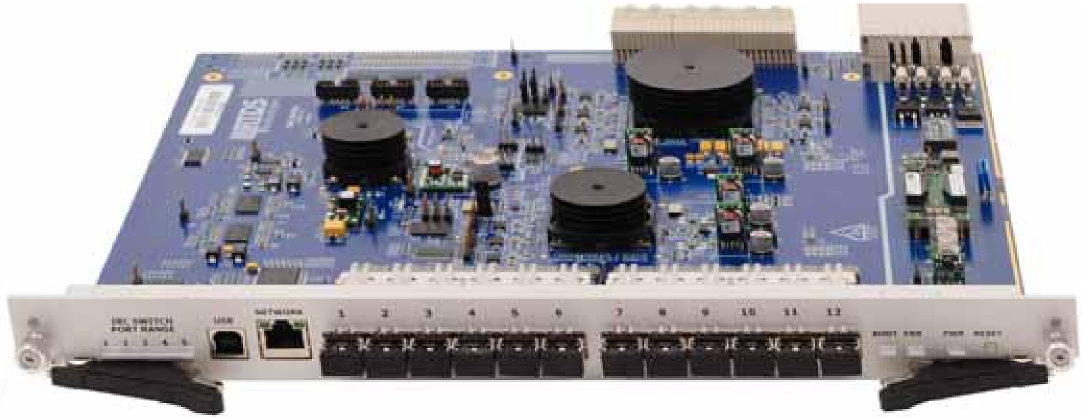
GBH: Global Bus Hub

- Allows distribution of common timestep for all chassis
- Master GTWIF defines the timestep clock
- Maximum of 60 chassis can be driven from one common timestep clock

Custom Hardware Components

IRC Switch: Inter-Rack/Chassis Communication Switch

- Provides direct data communication between as many as 60 chassis



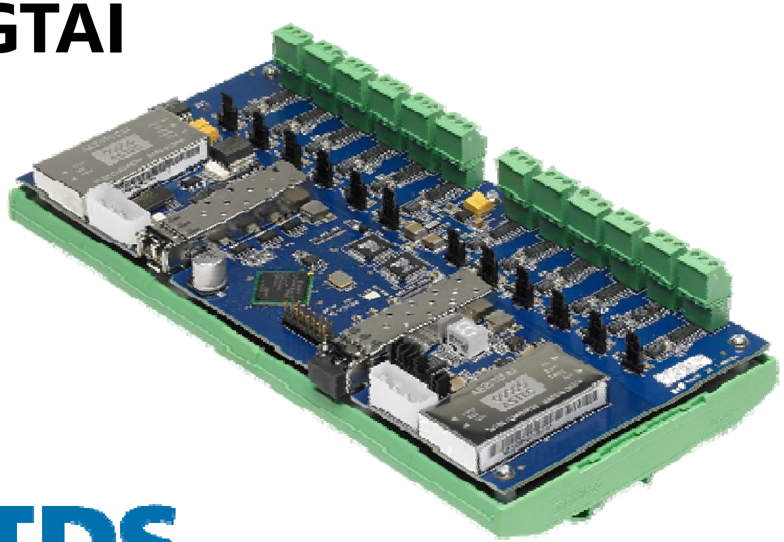
Custom Hardware Components

Flexible and Expandable Analogue I/O for the NovaCor

12 channel, isolated 16-bit analogue input/output cards

Easily daisy-chain connected to a single NovaCor fiber port

GTAI



GTAO

RTDS Technologies

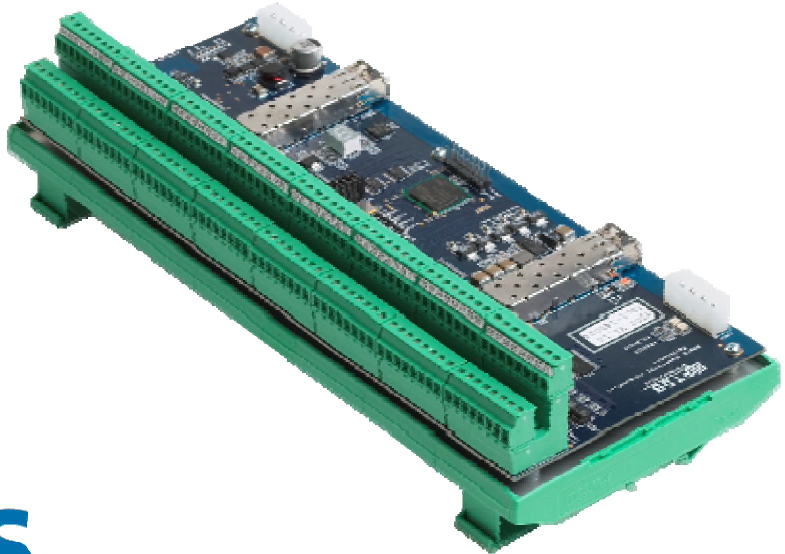
Custom Hardware Components

Flexible and Expandable Digital I/O for the NovaCor

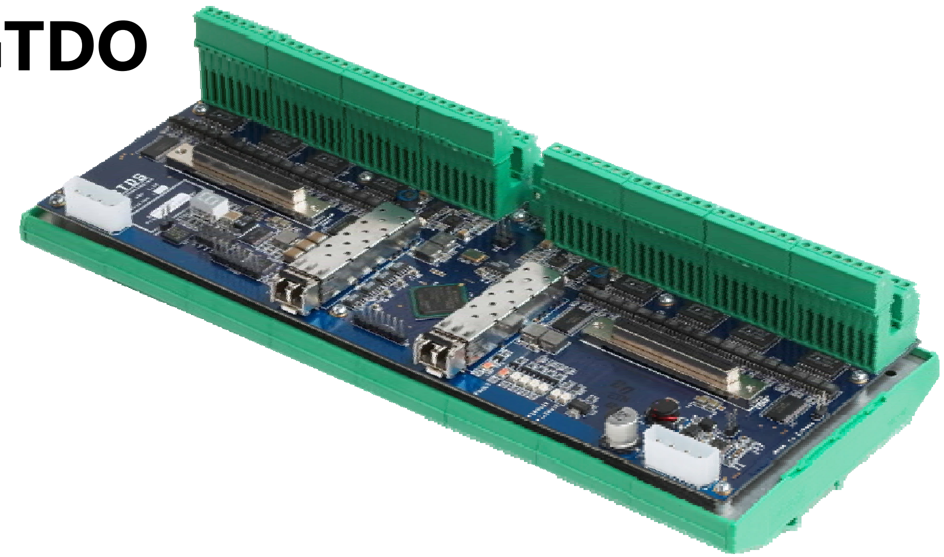
64 channel, isolated digital input/output cards

Easily daisy-chain connected to a single NovaCor fiber port

GTDI



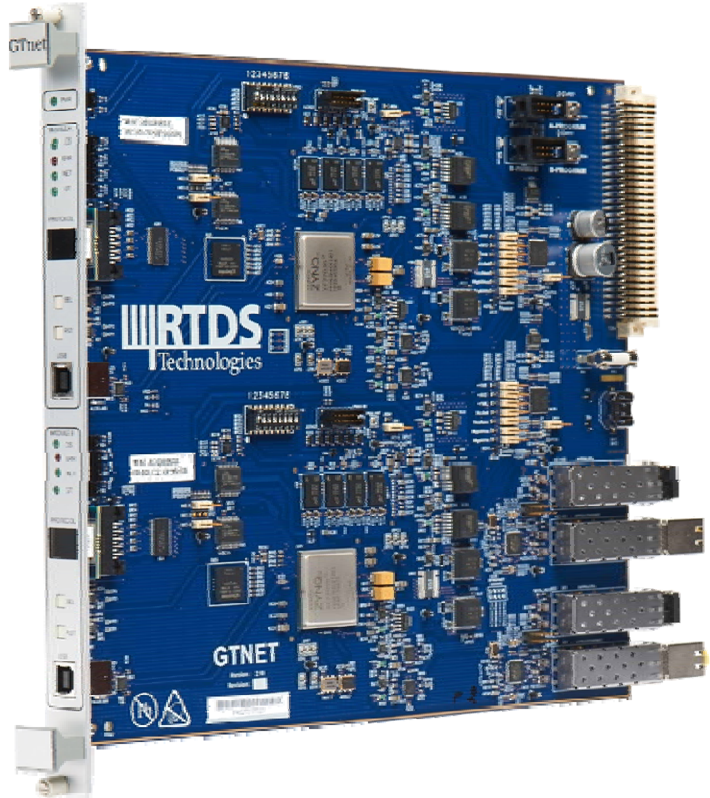
GTDO



Custom Hardware Components

GTNETx2: Network Communication

- Second generation of chassis-mountable GTNET card
- Allows communication with external devices over Ethernet
- Developed for IEC 61850 protocol
- Additional protocols implemented in response to customer requests
- Card has two "modules" and can have two network protocols operating simultaneously



RTDS Technologies

GTNETx2 Communication Protocols

IEC 61850

GSE: binary messaging

SV: sampled values

PLAYBACK

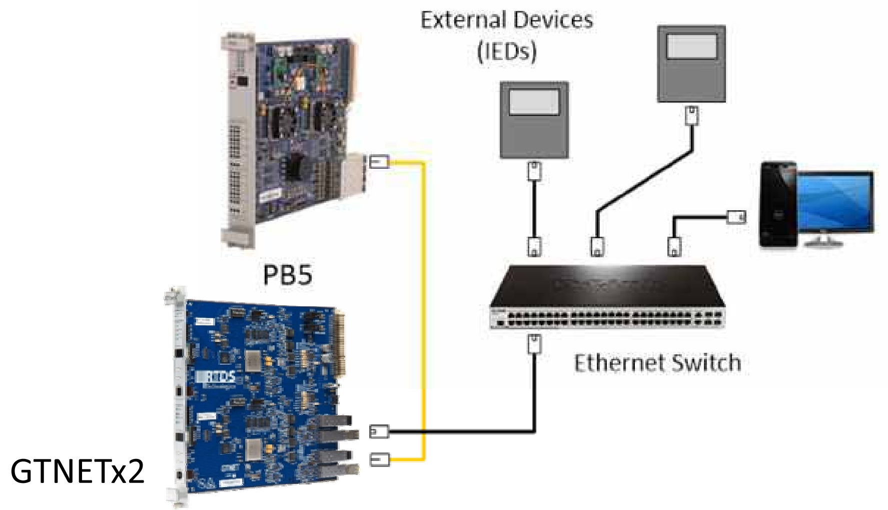
PB: very large data playback

SCADA

DNP3 and IEC 60870-5-104

PMU

PMU: IEEE C37.118



SKT

TCP/UDP (bidirectional, asynchronous)

MODBUS

TCP, RTU over TCP, ASCII over TCP

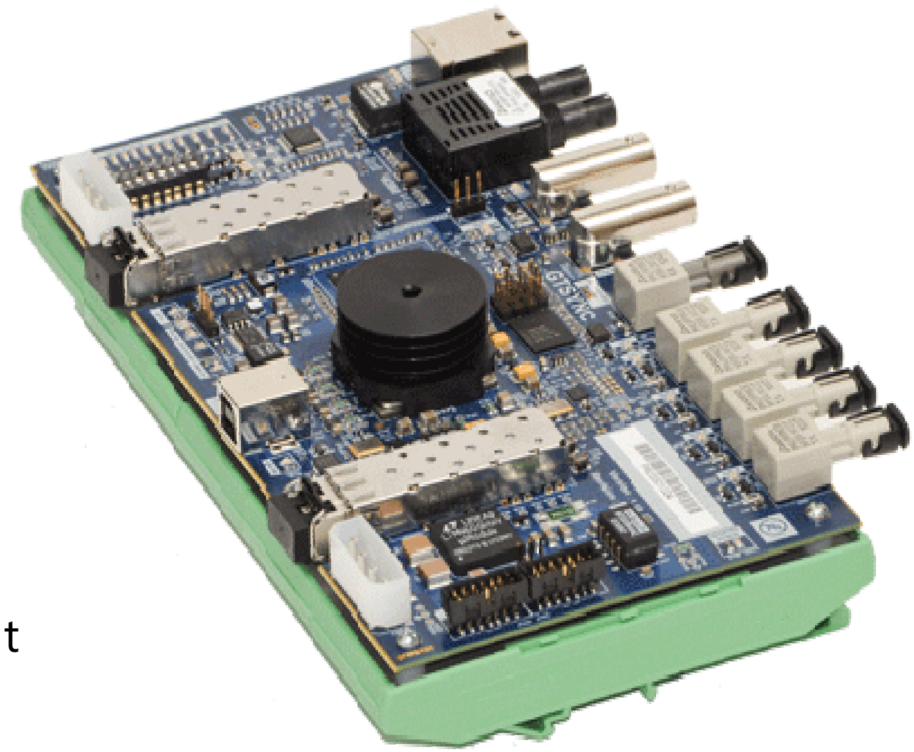
Aurora

- High speed serial interface directly to external devices via optical fibre
- Supported in large and small dt
- Direct digital link can eliminate need for conventional I/O in PHIL applications – some manufacturers have Aurora interface built into amps

Custom Hardware Components

GTSYNC: External time synchronization

- Synchronizes RTDS timestep to external time reference (e.g. GPS clock) and synchronizes devices under test
- 1 Pulse Per Second over BNC coax or ST fiber connectors
- IEEE 1588 over RJ45 or ST fiber connectors
- IRIG-B over BNC coax connection
- Necessary for PMU testing and advantageous for SV output

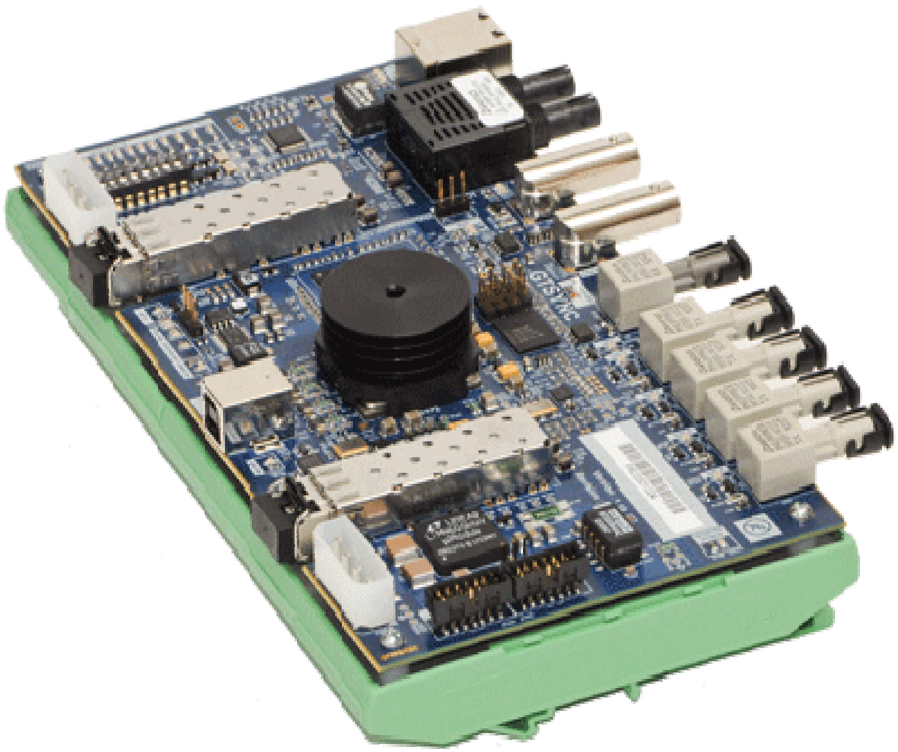


Custom Hardware Components

GTSYNC: External time synchronization

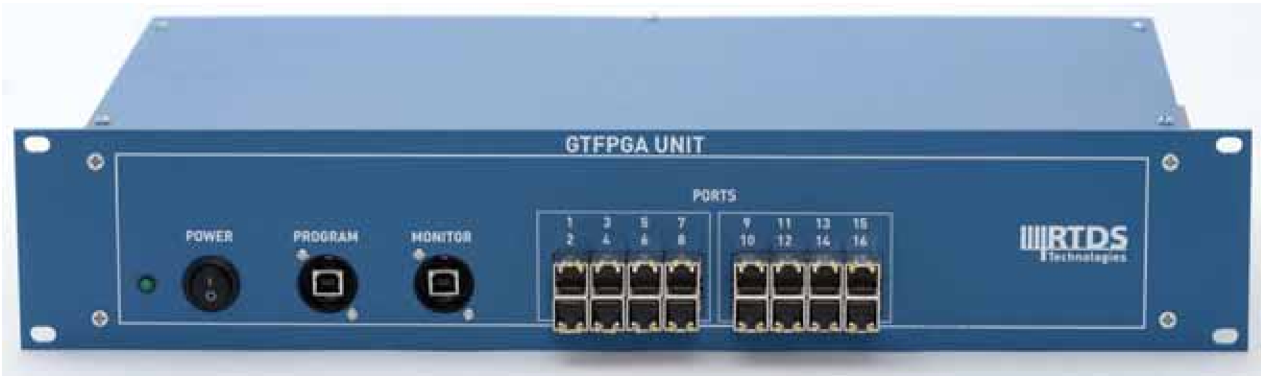
- Can also act as its own internal synchronization source in the absence of external sources

- Regardless of whether source is external or internal, and regardless of the external signal type, GTSYNC can provide 1PPS or IRIG-B type output



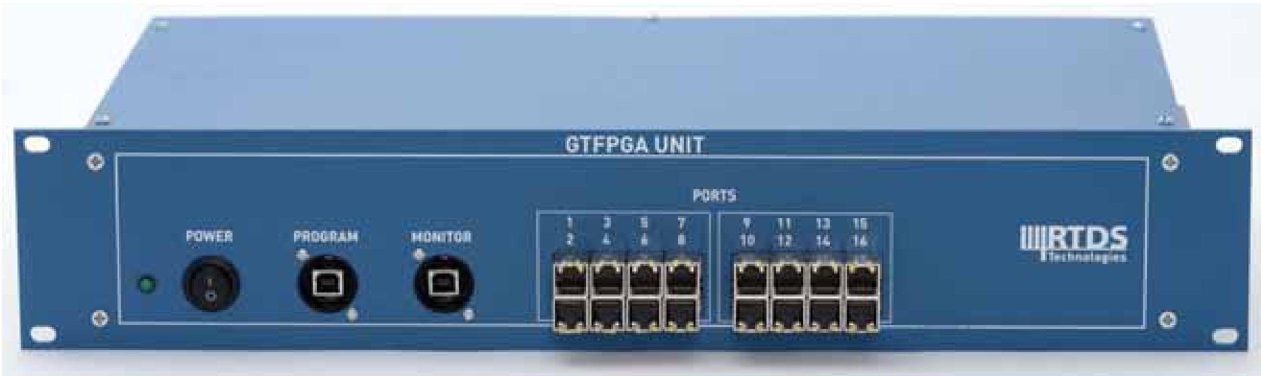
GTFPGA Unit

- Multiple firmwares available
  - MMC Valve
  - MMC Control
  - Sampled Values (-9-2LE + IEC 61869-9)
  - Small timestep frequency dependent tline (12 conductors)



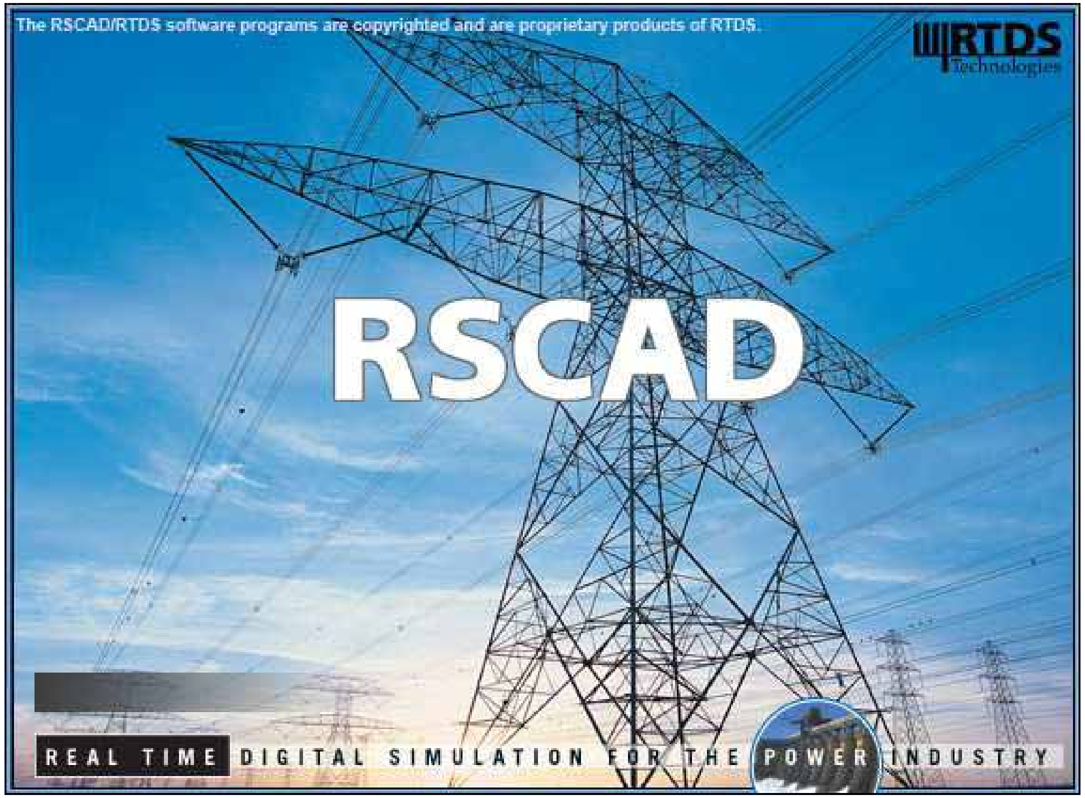
GPES

- Power electronic converter modelling on the GTFPGA Unit
- Freely configurable – custom topologies
- Timesteps in the nanosecond range
- Connect to small timestep subnetwork running on the rack/chassis
- Aurora interfacing block – receive firing pulses directly from external controls



Simulation Software: RSCAD

- Includes everything required for simulation studies
- No additional add-on modules required for any aspects of simulation
- No third party modules
- Site license and one maintenance agreement



RSCAD Modules

FileManager
The "home page" of RSCAD; organize simulation files and launch other modules.

Draft
Graphical assembly and data input for simulation circuit.

RunTime
Run, control and acquire results from simulations.

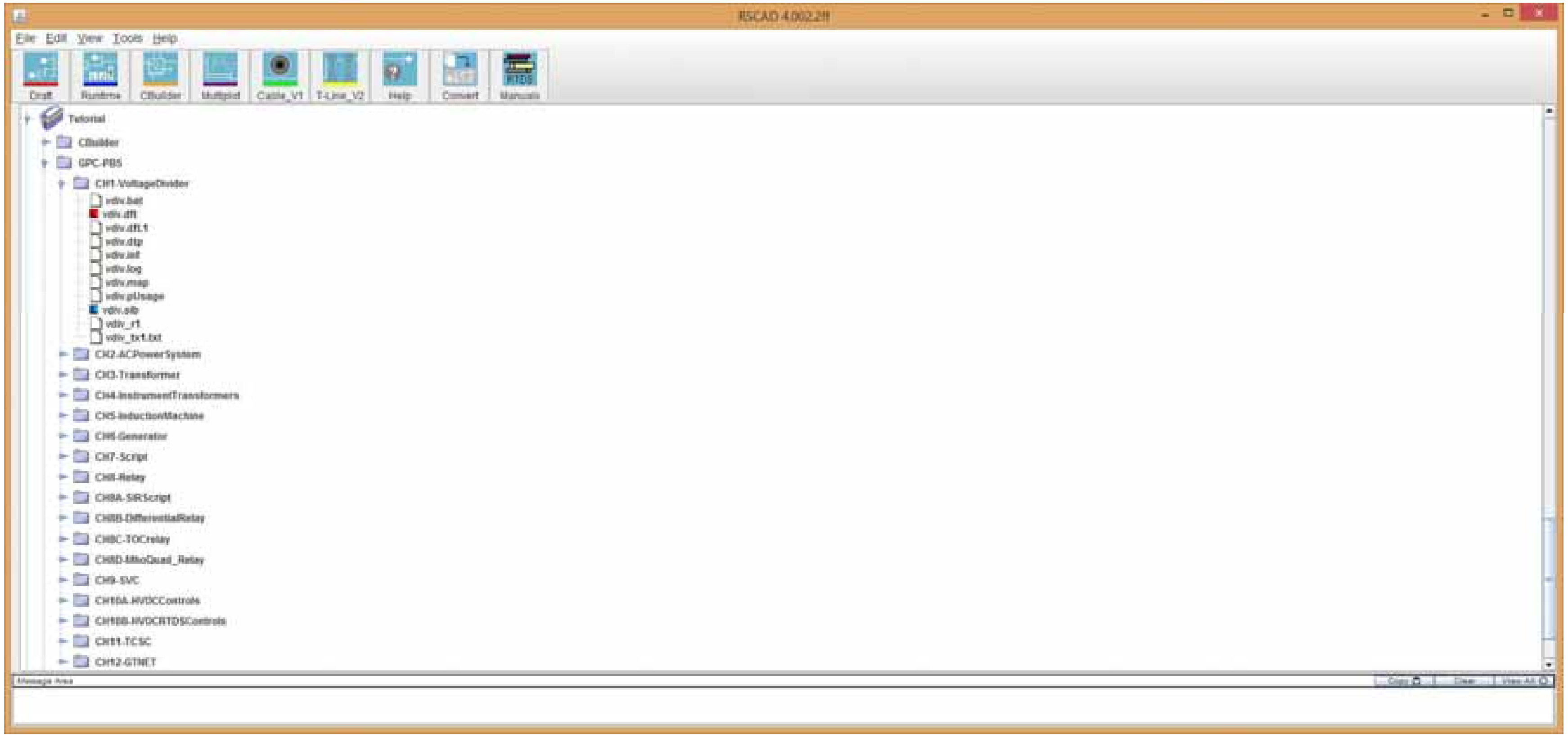
CBuilder
Create user-defined components including graphical representation, data menus and real-time code.

MultiPlot
Post analysis and annotation of results.

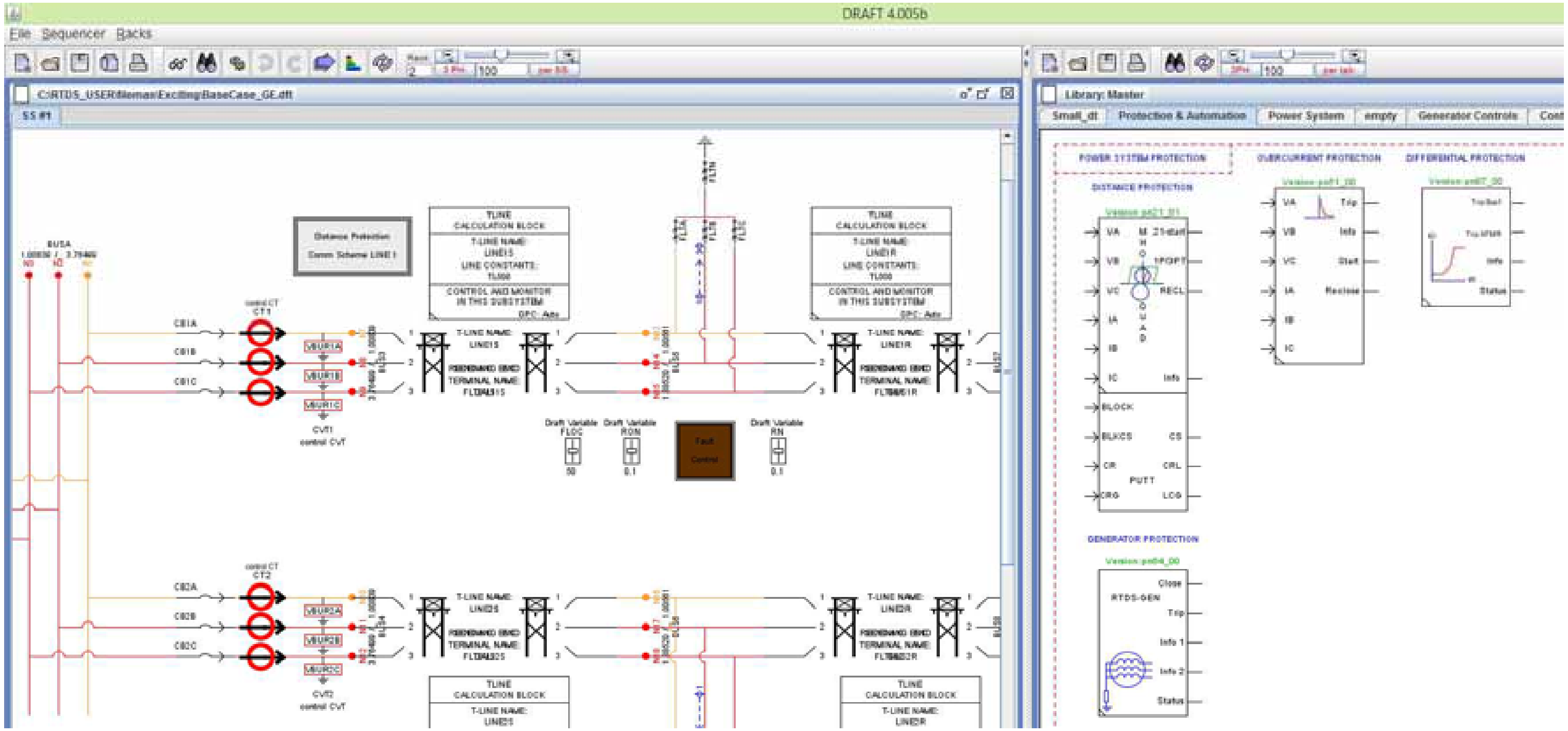
Cable
Calculation of cable characteristics based on physical data or sequence impedances.

TLine
Calculation of transmission line characteristics based on physical data or positive and zero sequence impedances.

RSCAD Modules: FILEMAN

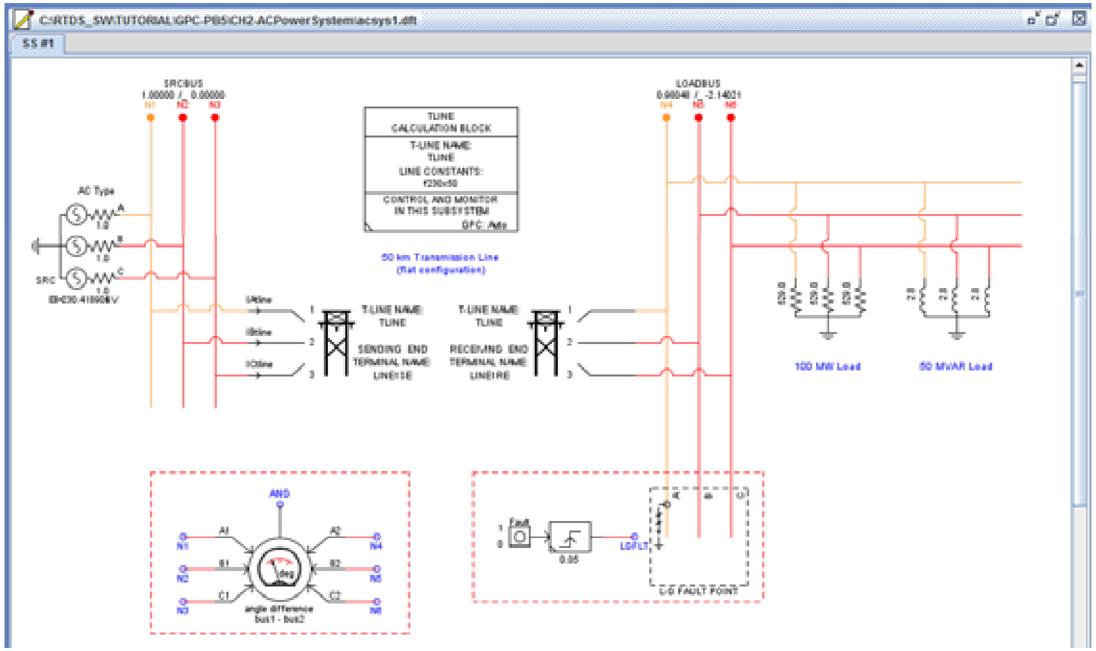


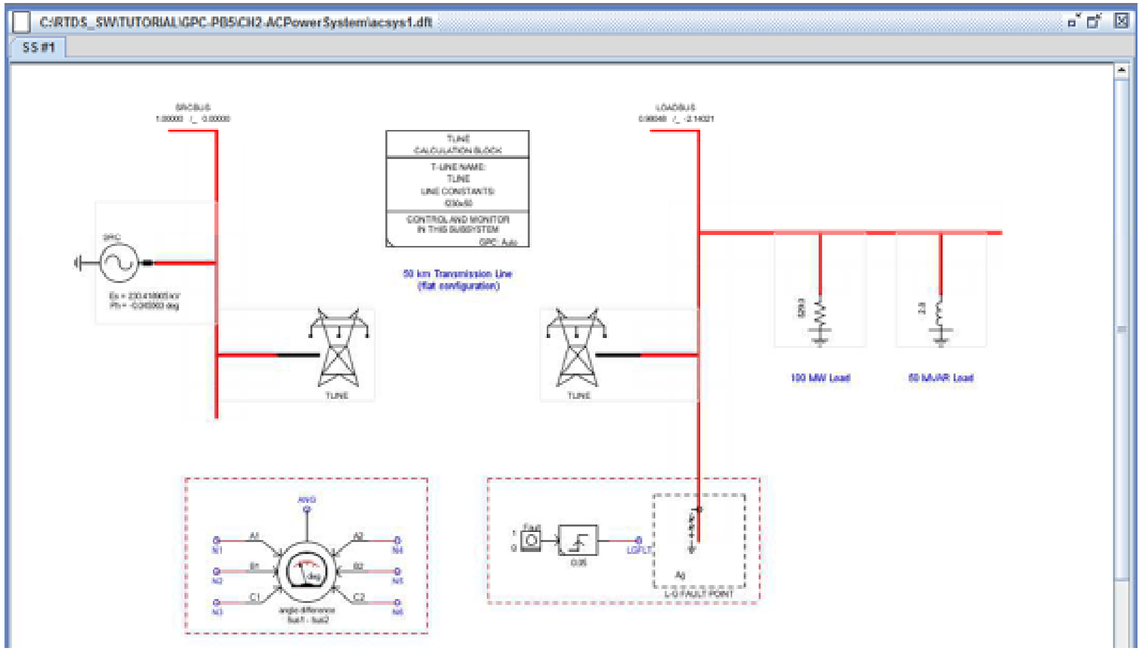
RSCAD Modules: DRAFT



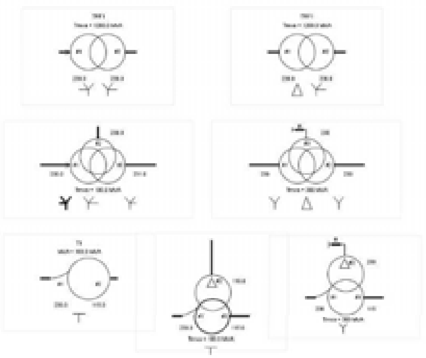
Circuit Construction in DRAFT

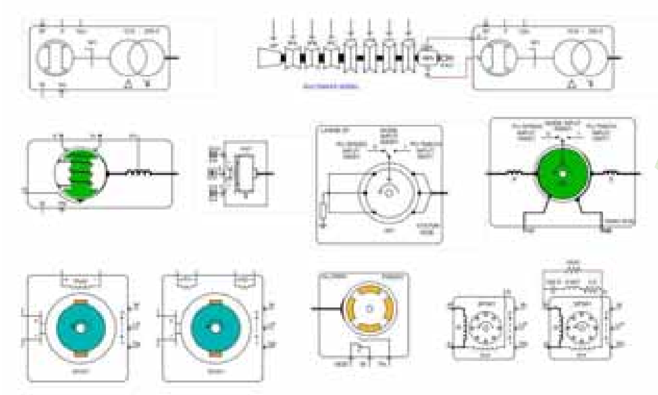
Three Phase or Single Line Drawing Mode

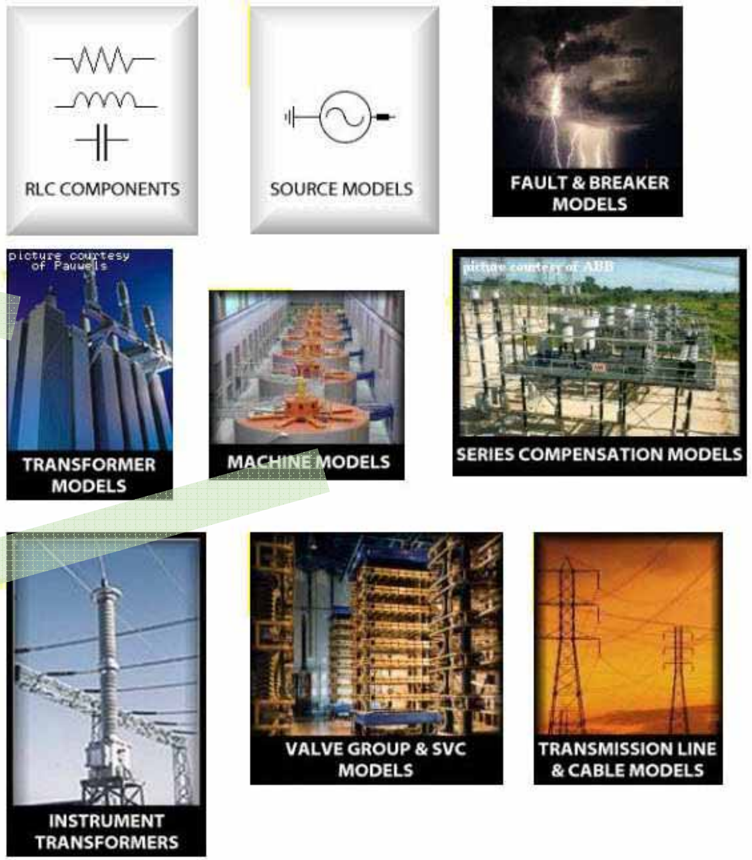




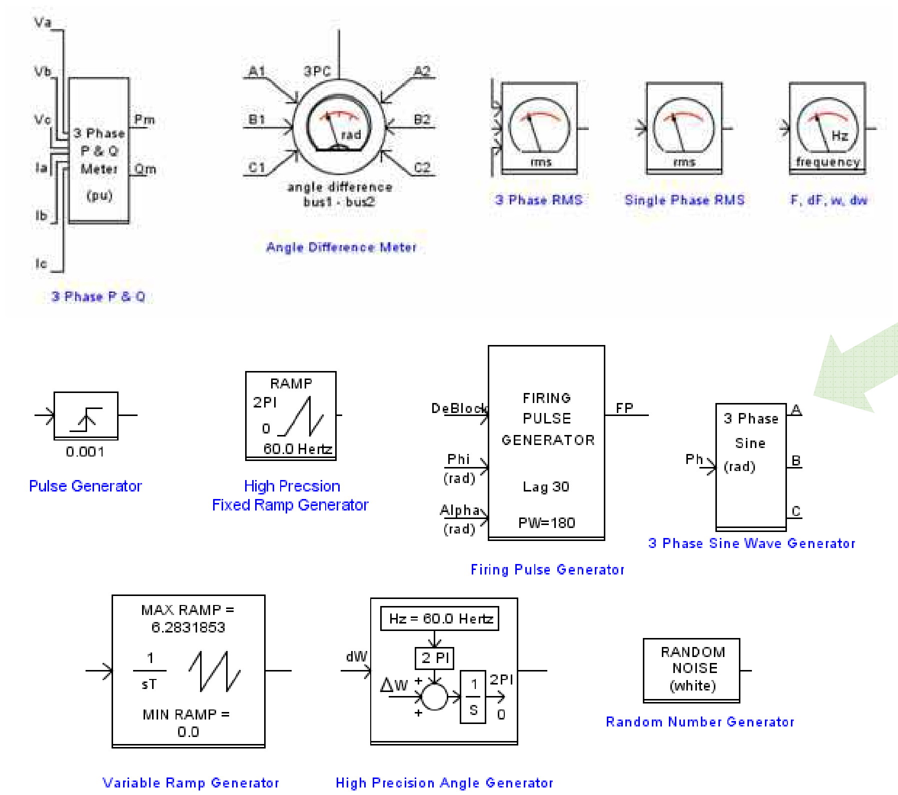
Power System Component Library

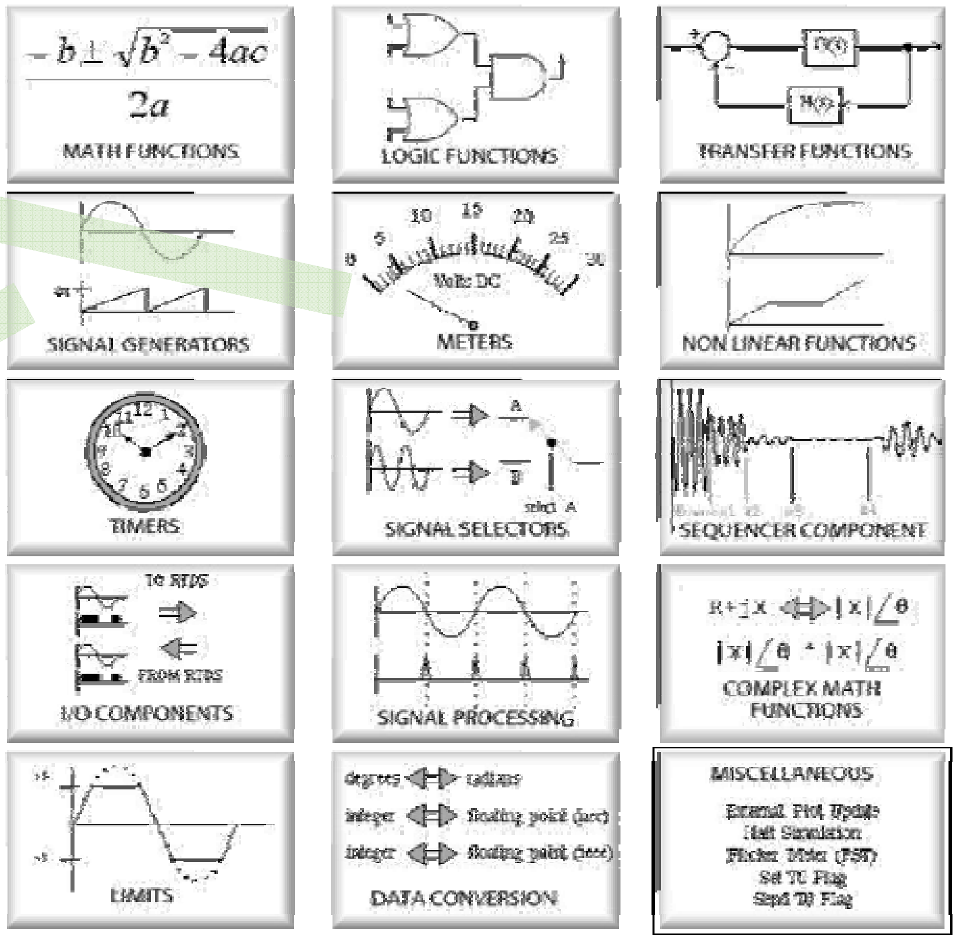




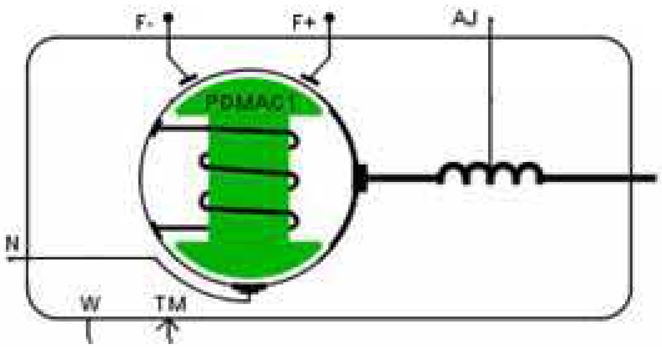


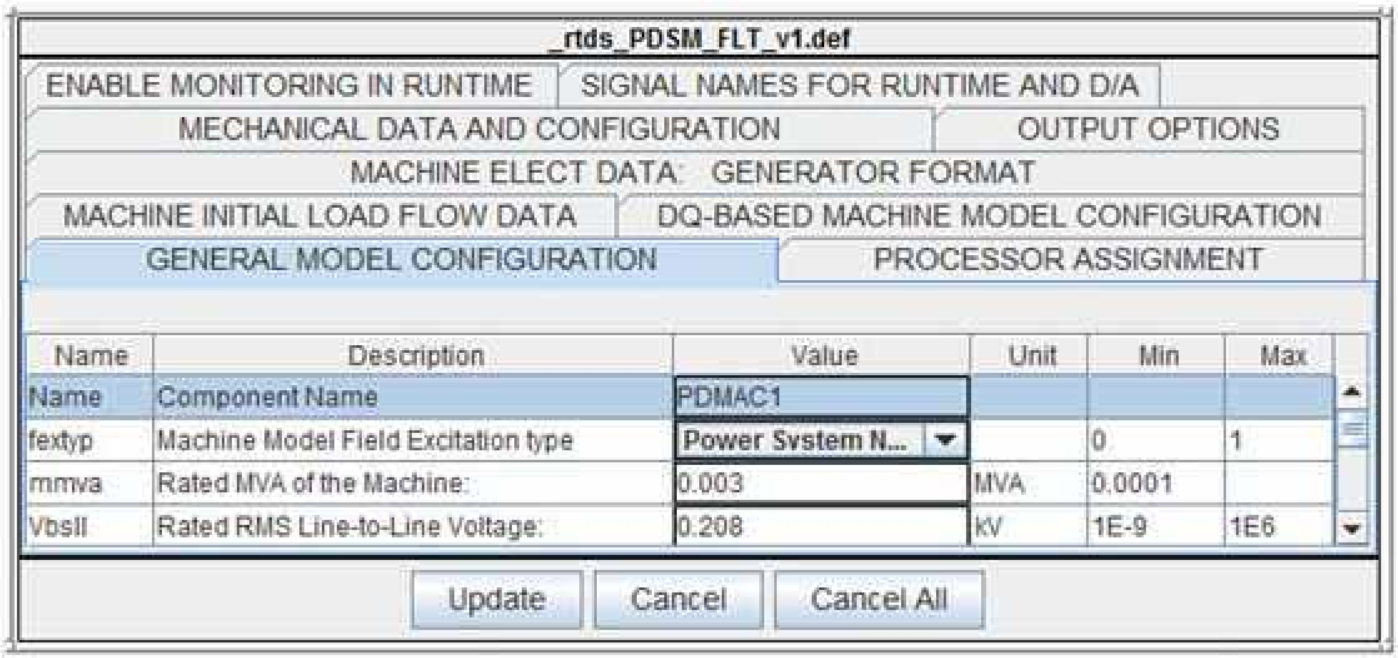
Control System Component Library



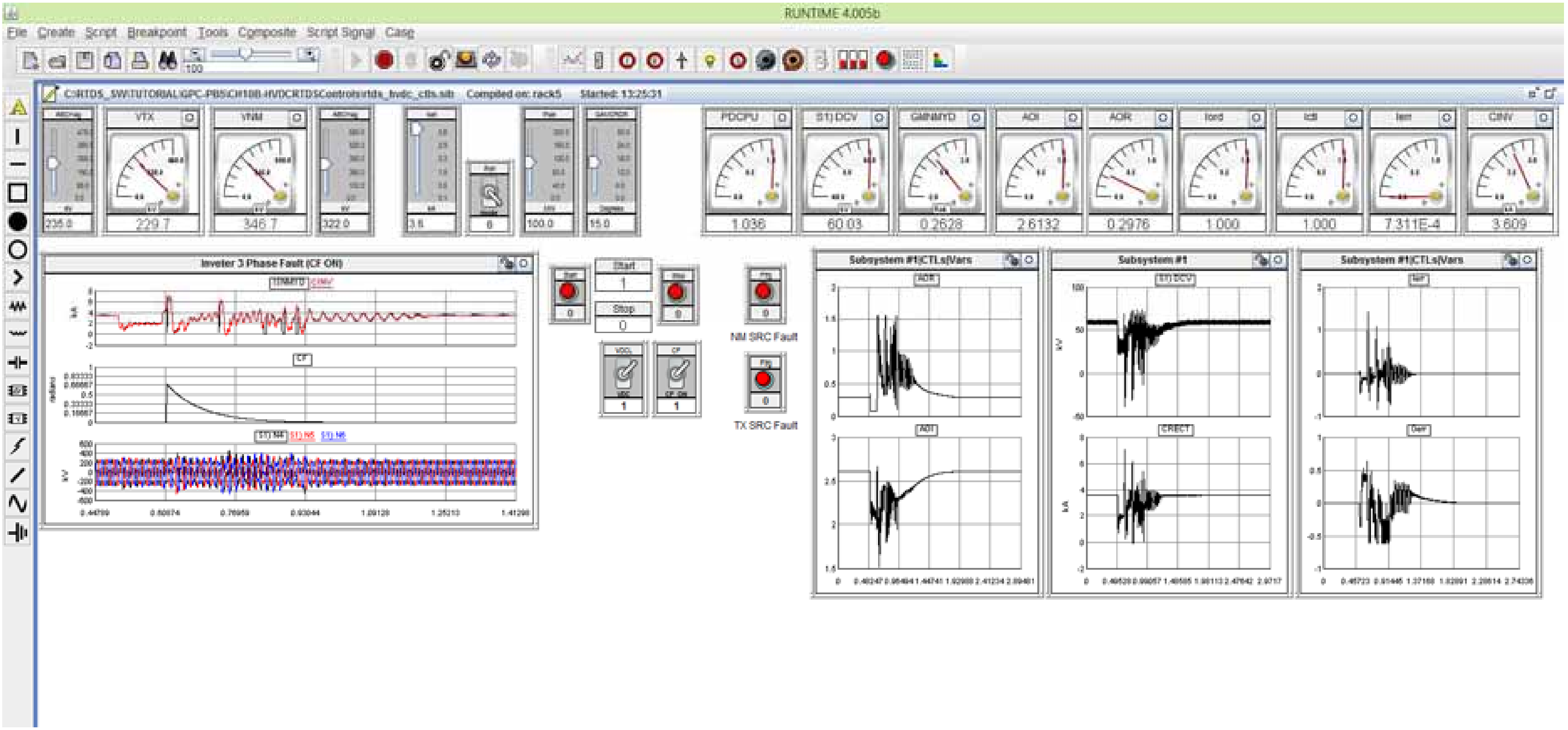


Model Data Entry



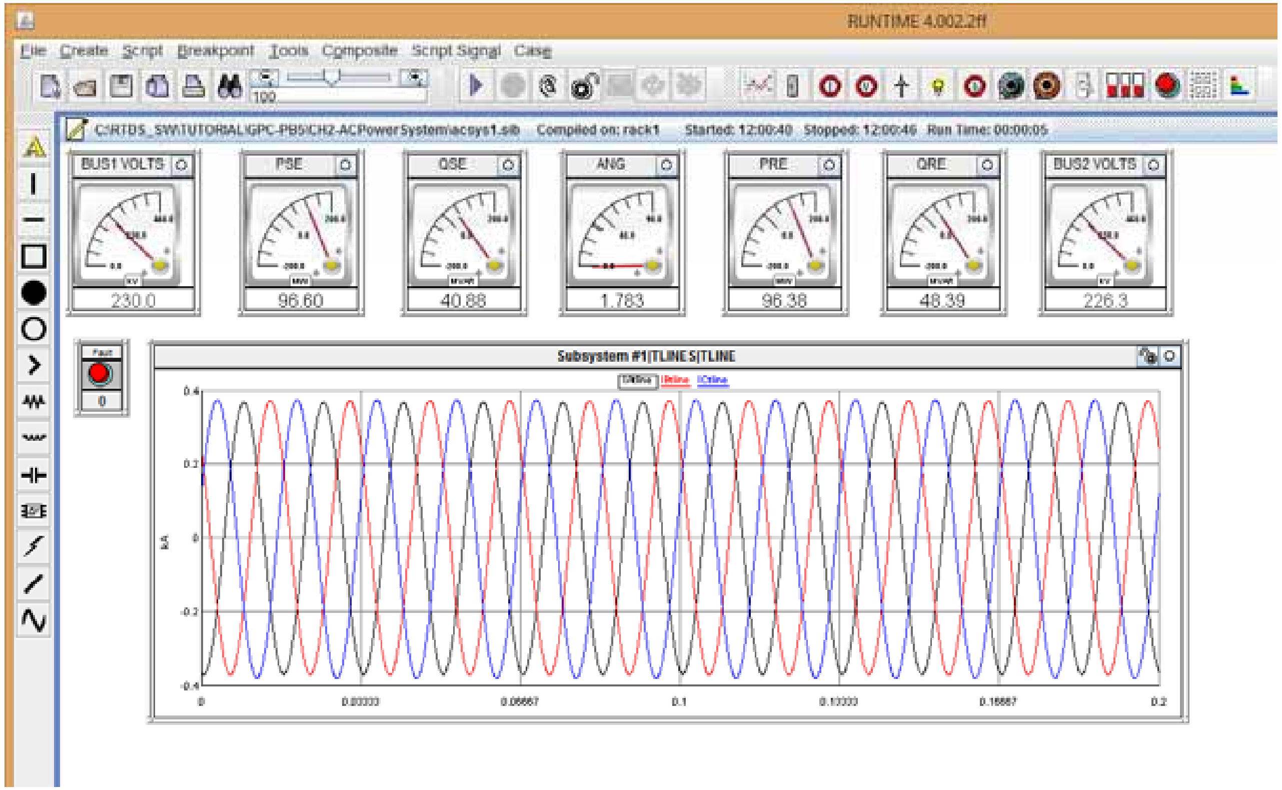


RSCAD Modules: RUNTIME



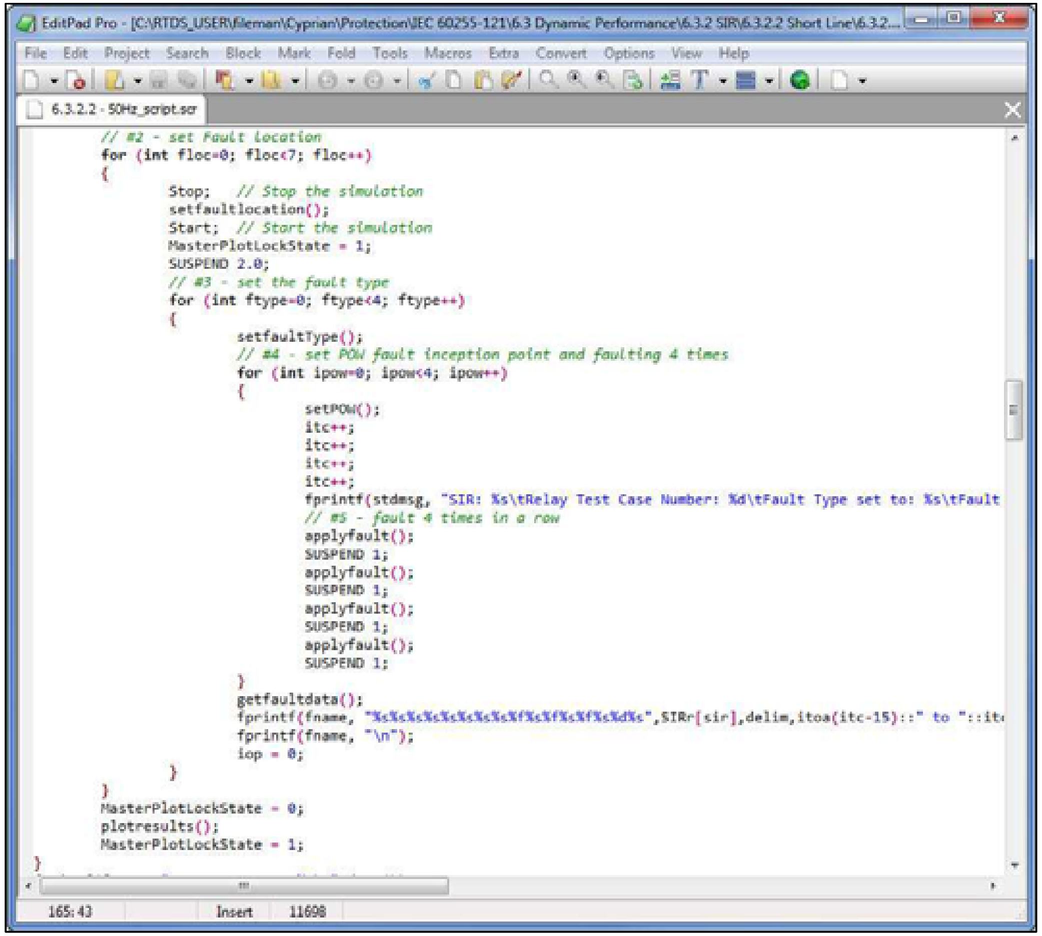
Running the Simulation in RUNTIME

- Real-time performance provides ability to operate the simulated power system interactively
- Simulator control
- Monitoring
- Data acquisition
- Manual and automatic modes

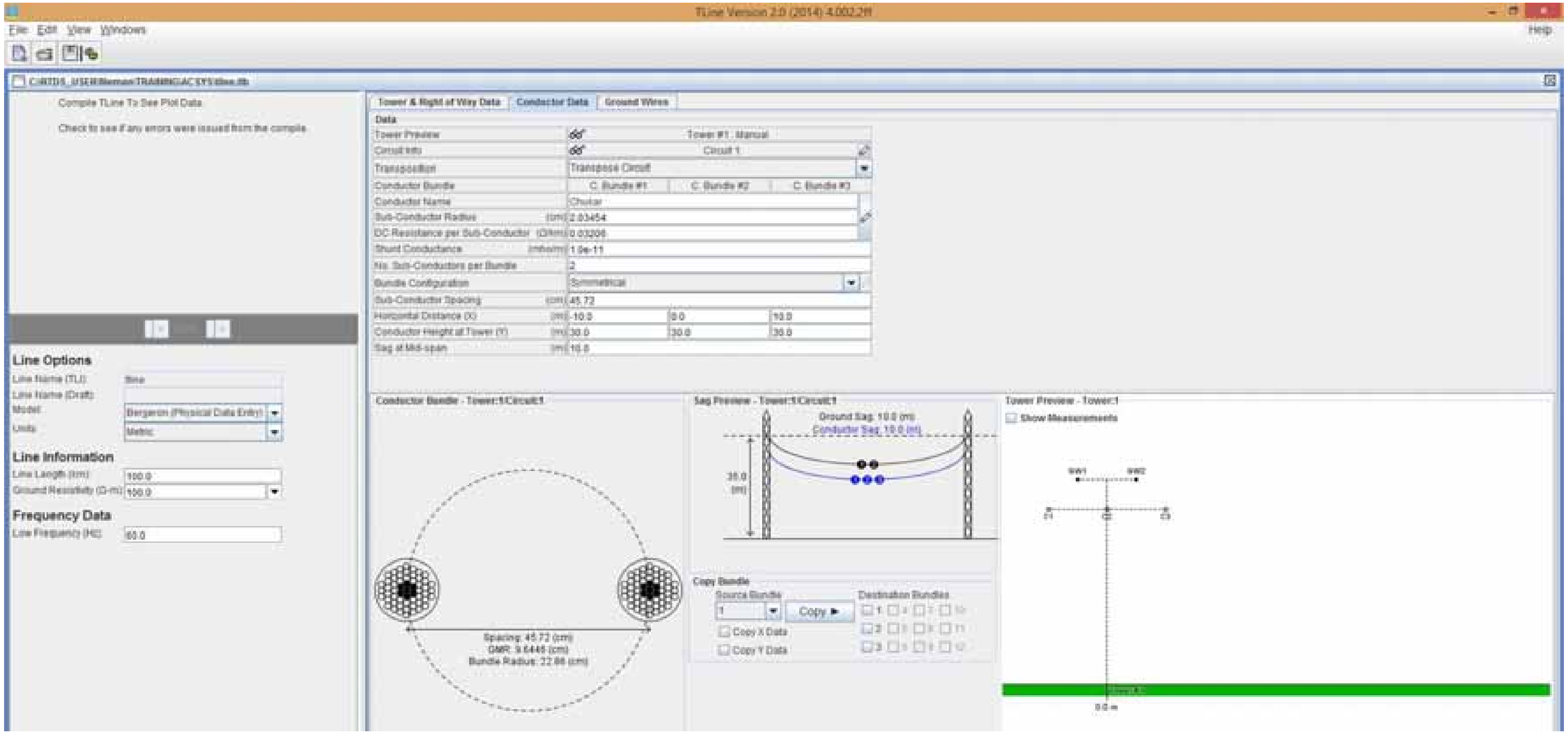


Automated Batch Mode Testing

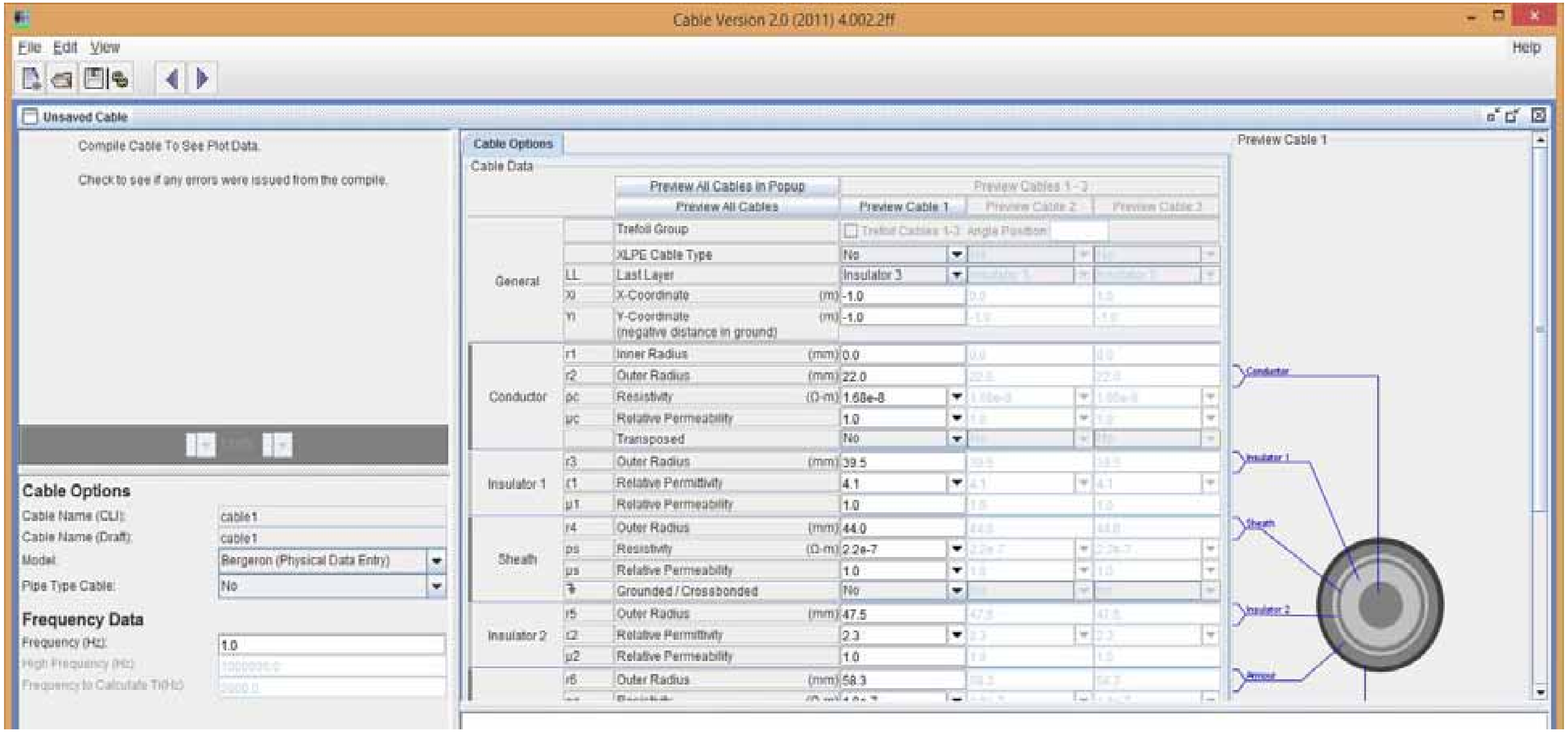
- Efficient means of running many cases
- Script file
  - C-like programming language
  - Adaptive via **if**, **for**, **while** statements
  - User-defined subroutines
  - Customized results reporting
  - Automated plot printing



RSCAD Modules: TLINE

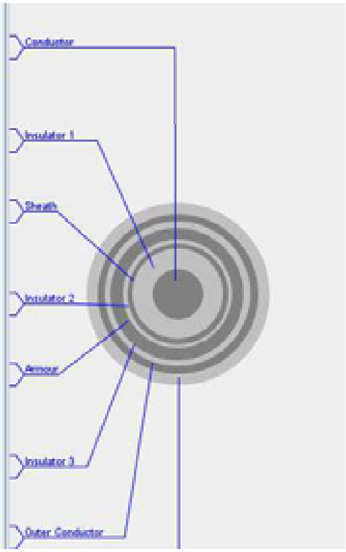


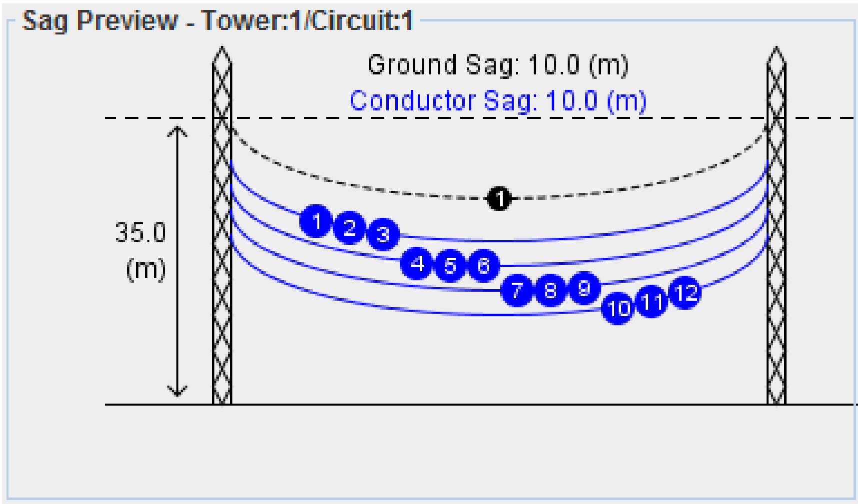
RSCAD Modules: CABLE

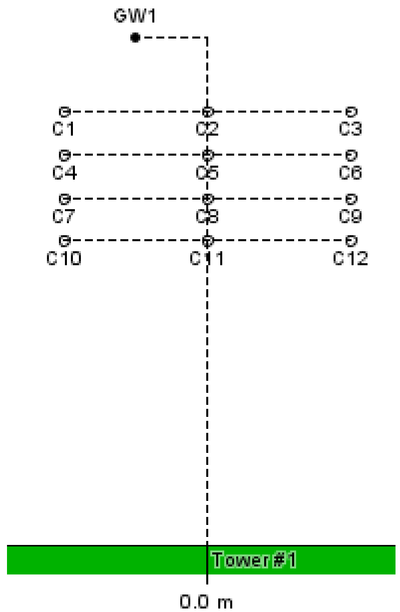


Tline and Cable Enhancements

- Frequency Dependent Phase Domain:
  - Up to 12 coupled conductors for tline
  - 3 coupled cables with 4 conductive layers per cable

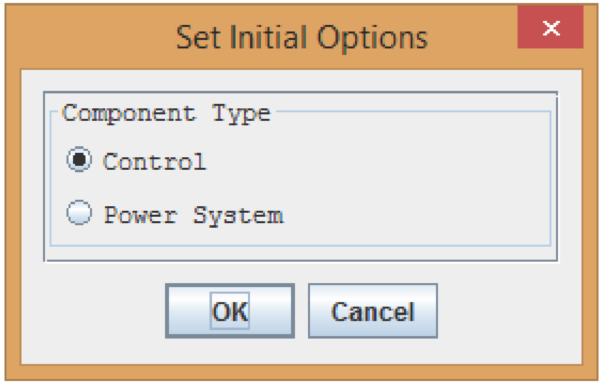


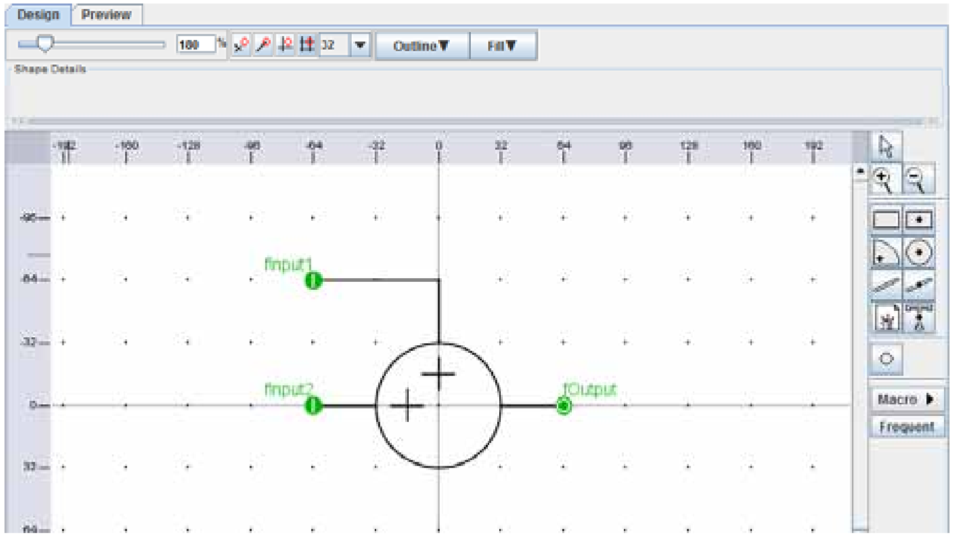




Component Builder (CBUILDER)

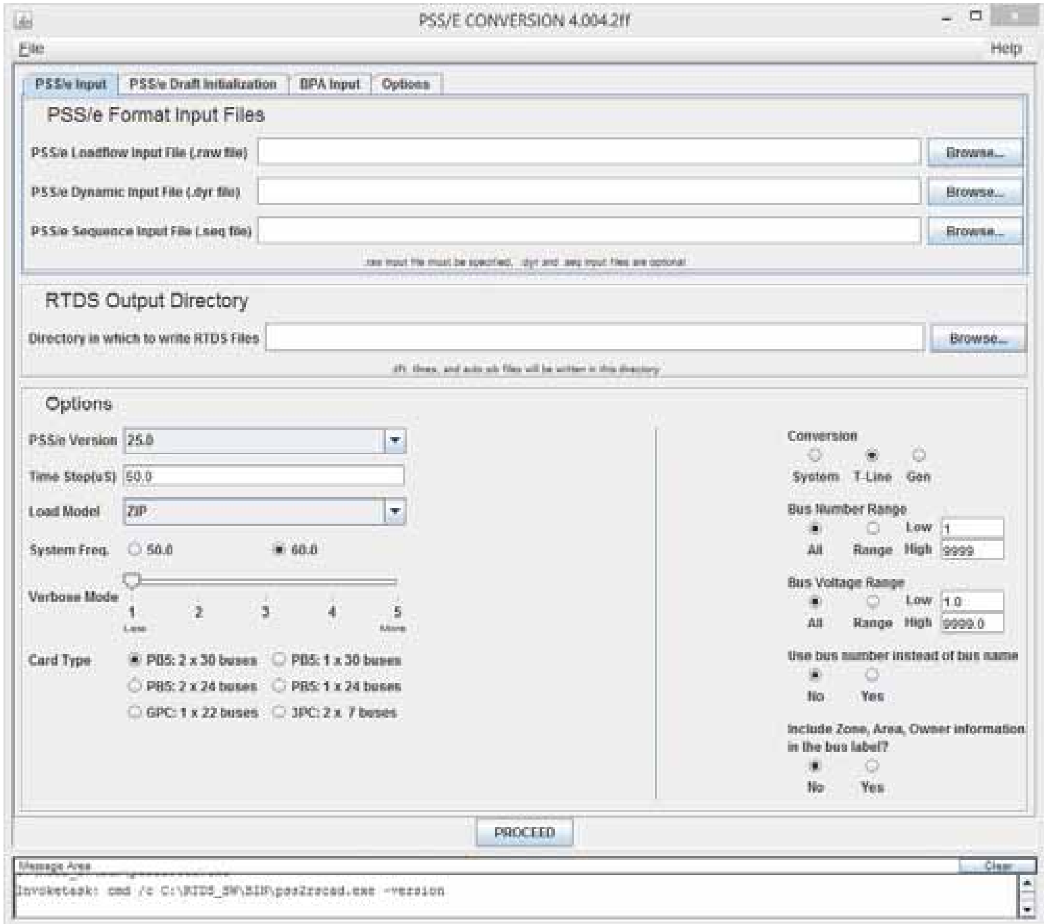
- Allows users to develop their own component models
- User-developed models run in real time with other models existing in library
- CBUILDER models can only run on NovaCor and PB5/GPC cards





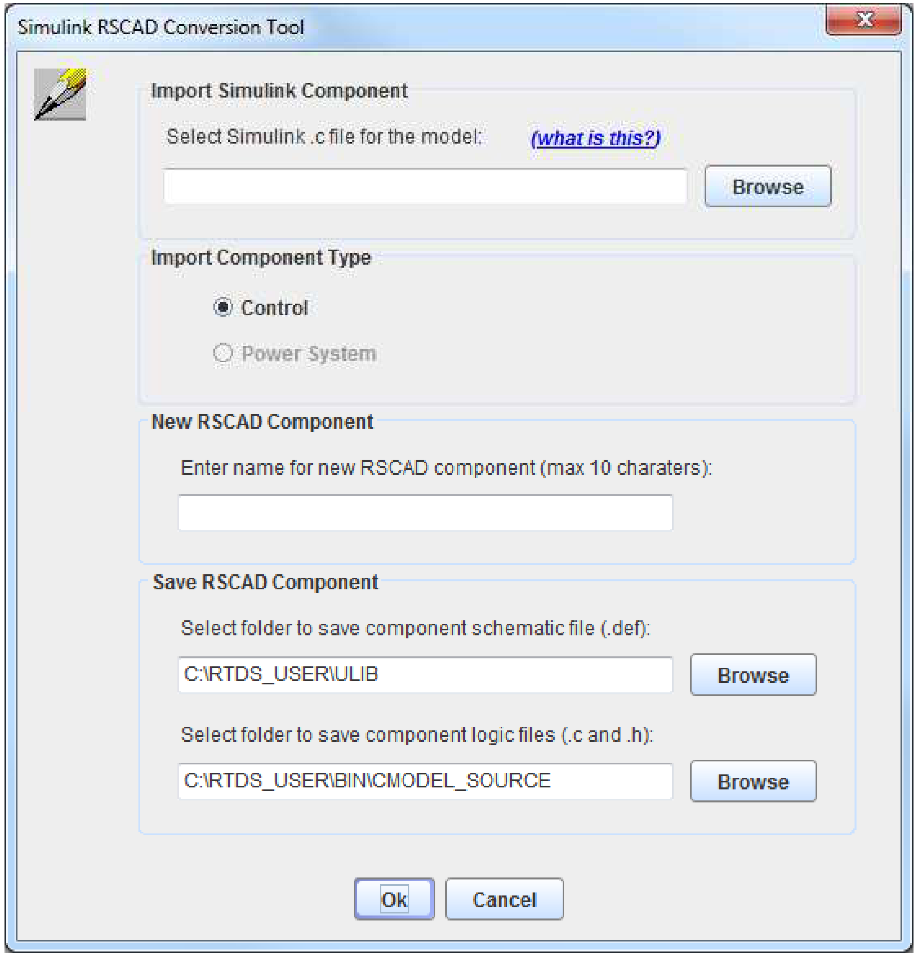
PSS/e to RSCAD Conversion

- Convert *.raw, *.dyr and *.seq data to RSCAD Draft picture format
- Facility enhanced over many years
- Partial conversion supported



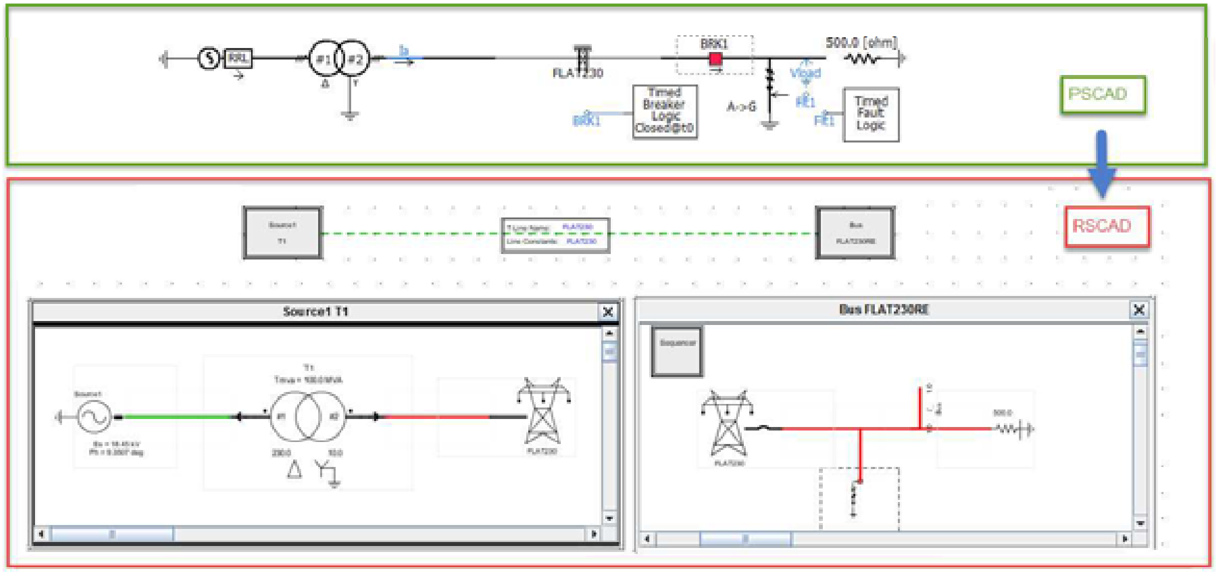
MATLAB/Simulink to RSCAD Conversion

- For control models only
- C code generated by MATLAB/Simulink Embedded Coder
- Imported using CBUILDER

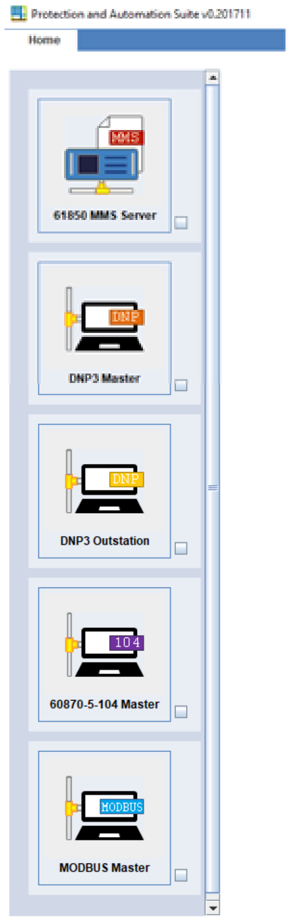


PSCAD to RSCAD Conversion

- Hierarchy boxes used to organize components
- In addition to built-in conversion scripts, user can specify (or override) how components are translated

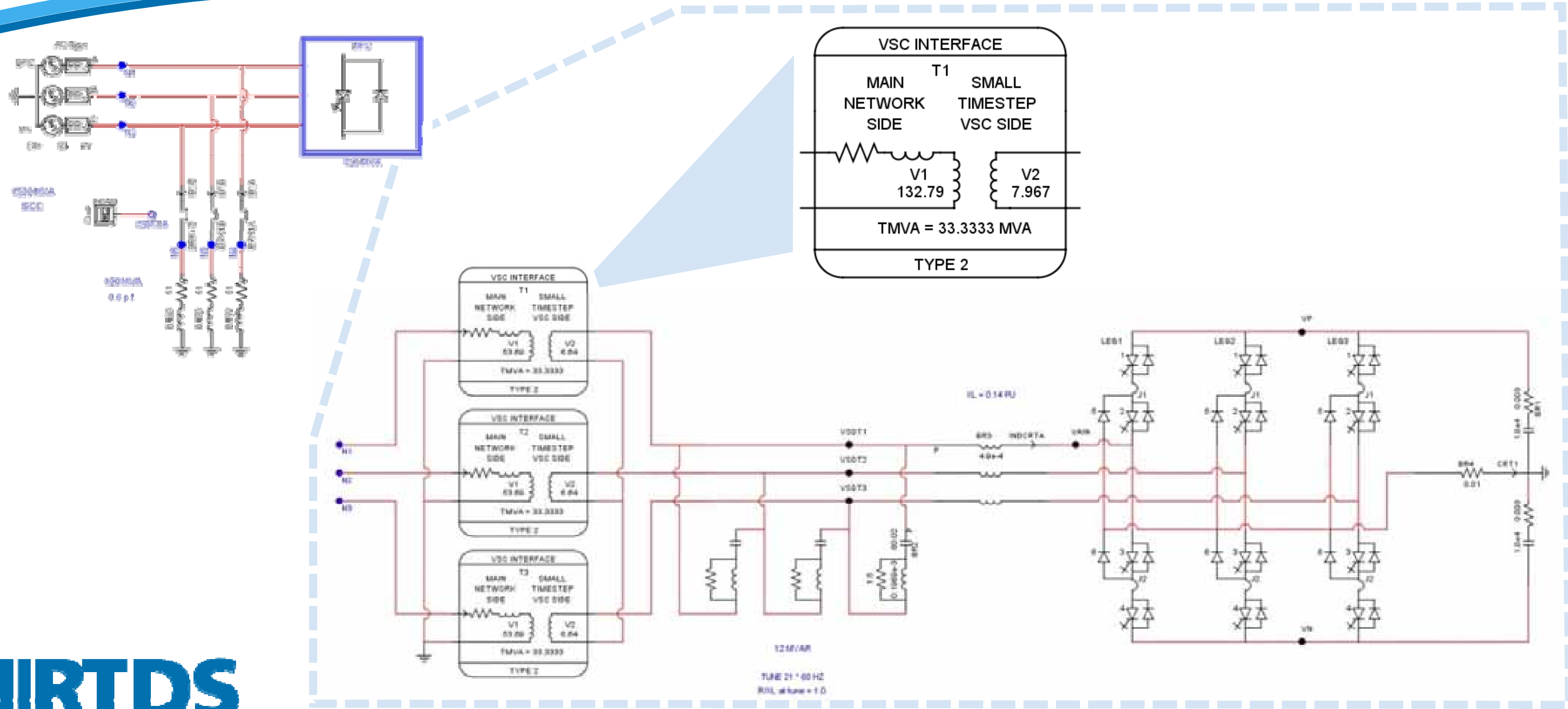


Protection and Automation Suite



- Standalone facility within RSCAD
- Test and validate substation automation protocols
- Use the RTDS Simulator to emulate the following and communicate with external compatible devices:
  - 61850 MMS Server
  - DNP3 Master and Outstation
  - IEC 60870-5-104 Master
  - MODBUS Master

Small Timestep Subnetwork Interface

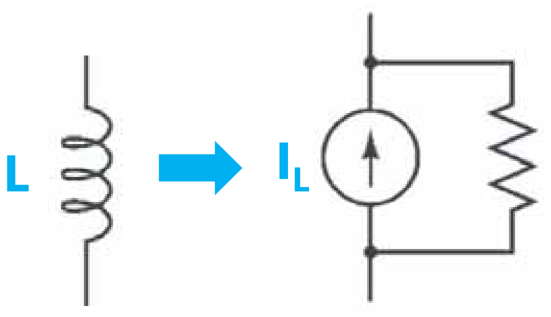


RTDS Technologies

Small Timestep Subnetwork Interface

- No need to recalculate admittance matrix for nodal solution
- Switches represented as small inductances in on-state, small capacitances in off-state
- Small dt required to maintain high on- to off-state ratio
- Technique allows freely configurable circuit topology

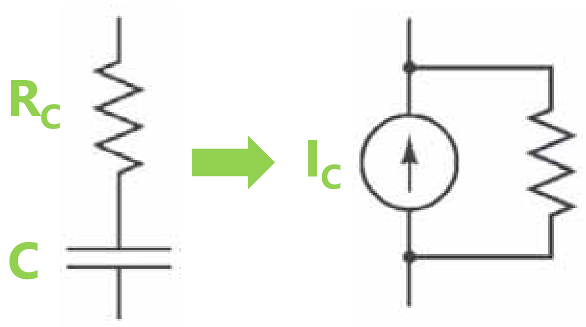
On-State



$$R_L = \frac{2L}{\Delta t}$$

FORCE $R_L = R_{RC}$

Off-State

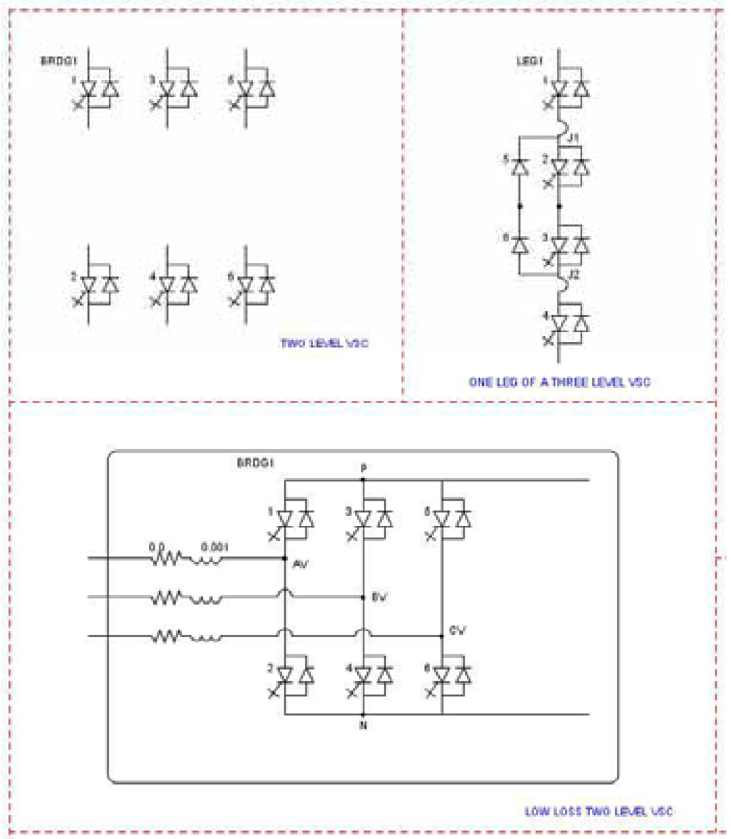


$$R_{RC} = \frac{\Delta t}{2C} + R_C$$

Small Timestep Subnetworks

Models

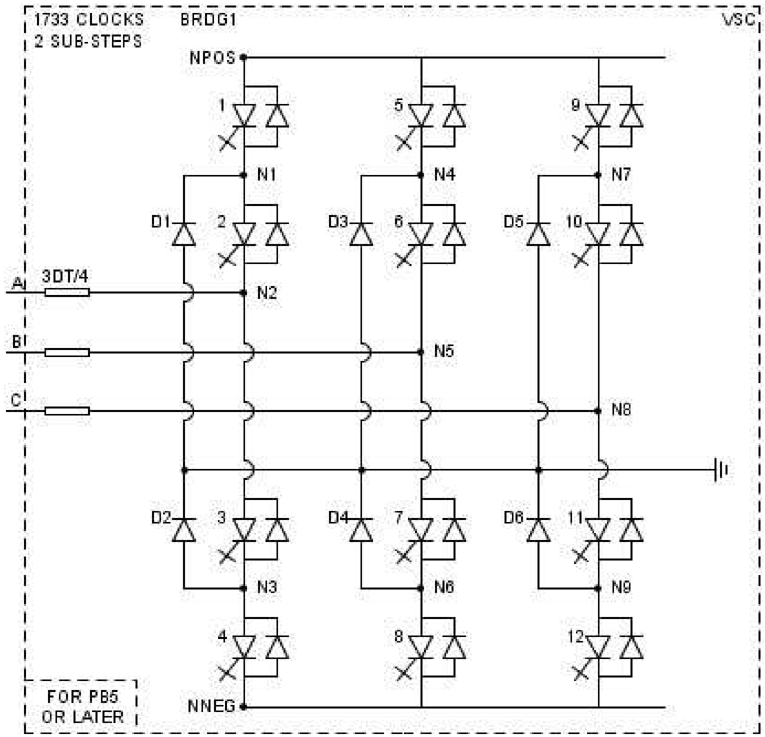
- 2, 3, and multilevel converters
- Freely configurable – no FPGA or VHDL experience necessary
- Individual components available for custom converters
- Each small dt subnetwork requires 1 or 2 processors
- Full set of I/O capabilities



Small Timestep Subnetworks

Sub-Small Timestep

- 2 or 3 sub timesteps in 1 small timestep
- Fixed topology
- 3 level bridge implemented
- Higher switching frequencies

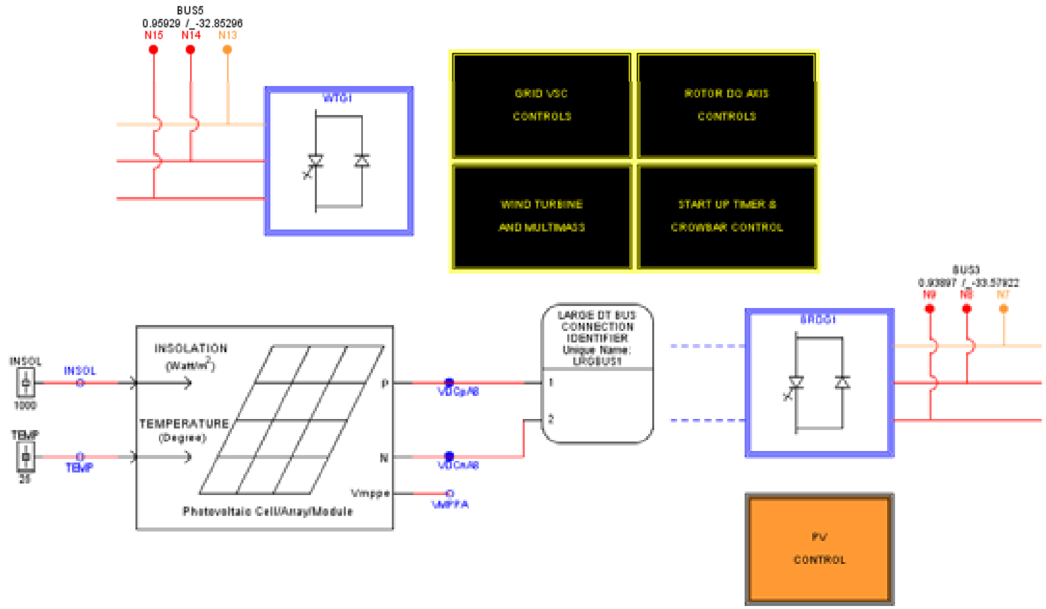


1 to 3 LEGS OF A THREE LEVEL VSC
LOW LOSS SUB STEP MODEL

Small Timestep Subnetworks

Capability Improvements

- 2 small timestep bridge boxes on one core
- Increased number of nodes per bridge box



Cutting-Edge Applications

Active Industry Participation

cigré

IEEE PES
Power & Energy Society®

UCA
International
Users Group

NASPI North American
SynchroPhasor Initiative

Protective Relay Test Methods

Synthetic testing

- No true power system signals used
- "Synthetic" waveforms often unrealistic and in some cases misrepresent how a relay will function in service

Playback testing

- Uses recorded or simulated power system signals
- Waveforms only valid until the relay trips
- Only one relay can be tested

Closed-loop testing

- Requires a real time simulator to provide realistic power system signals
- Closed loop response allows complete interaction between the relay and the simulated power system
- Multiple devices (relays and/or controllers) can be tested as if connected to an actual power system

The Advantage of Closed-Loop Testing

Open-loop protective relay testing

Testing tool → Device under test

Signals from power system

Closed-loop protective relay testing

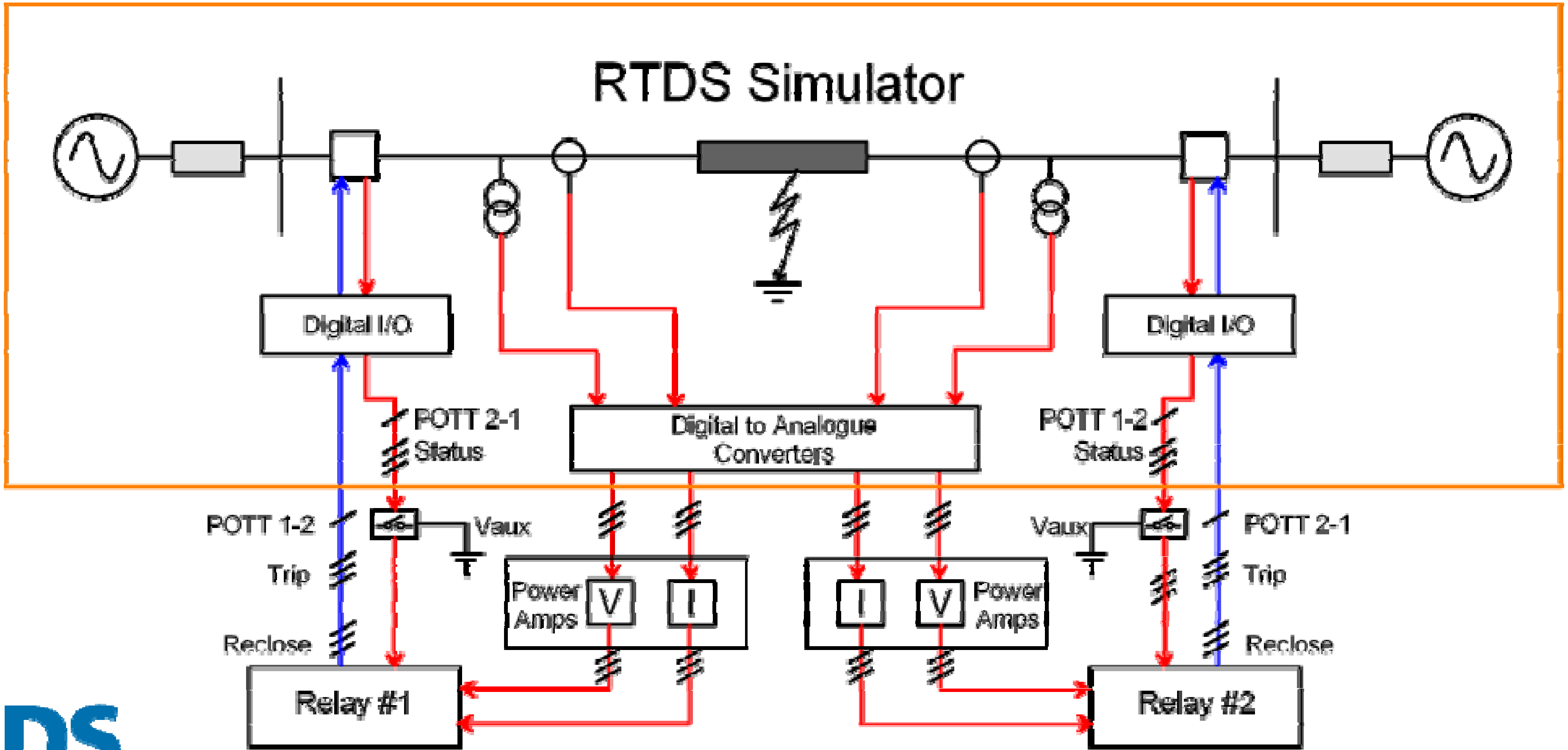
Testing tool → Device under test

Signals from power system

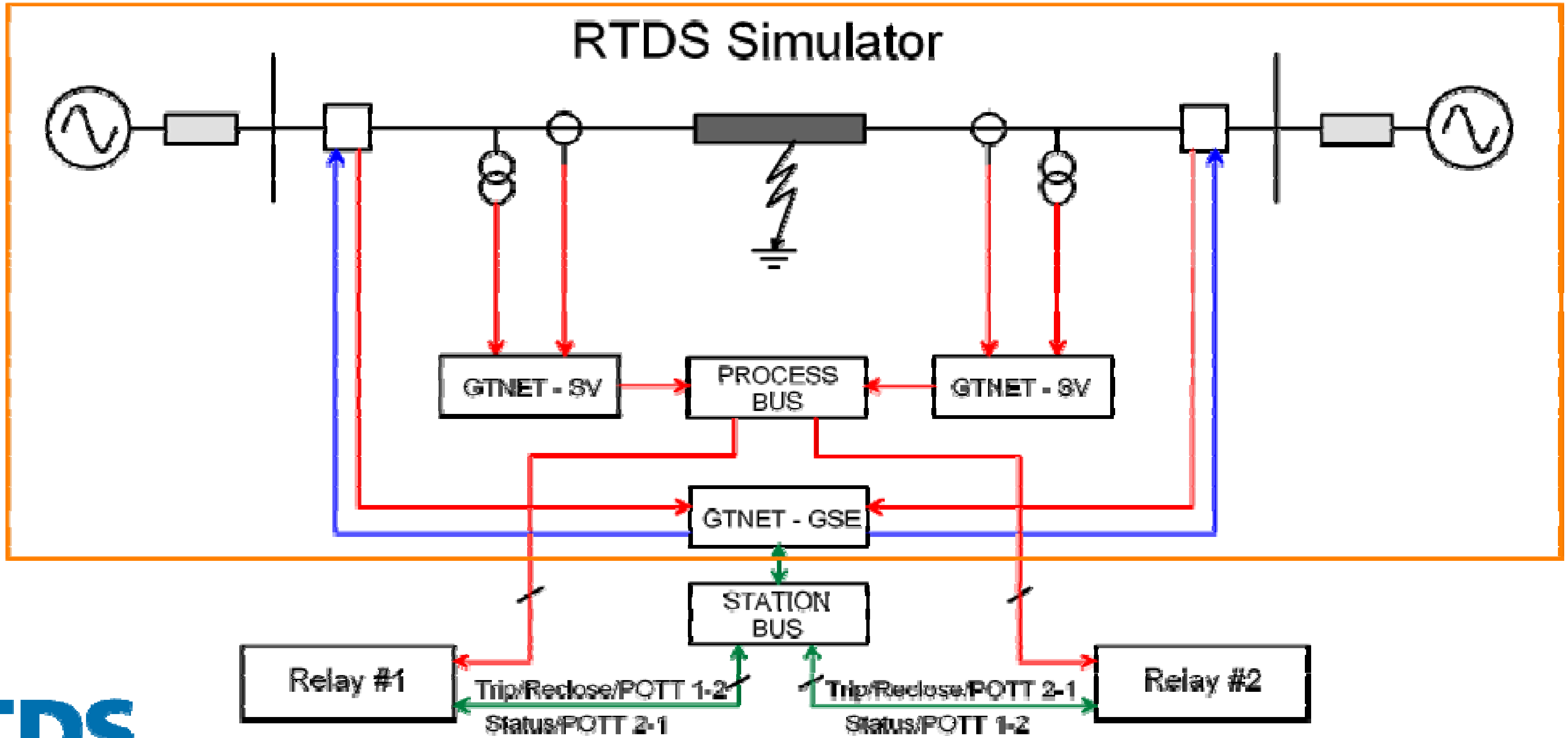
Device under test → Testing tool

Signals from relay (i.e. trip or reclose)

Electrical Interface

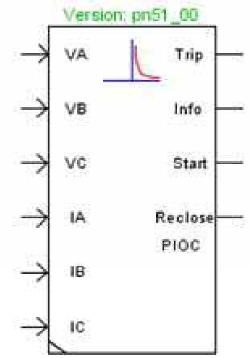


IEC 61850 Interface

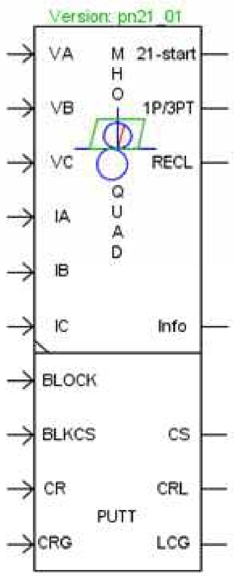


Protection and Automation Library

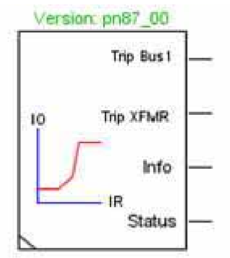
Overcurrent Protection



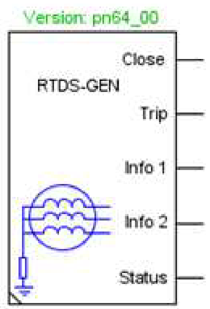
Distance Protection



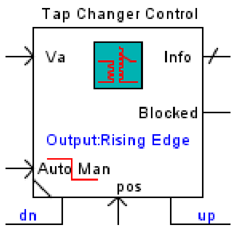
Differential Protection



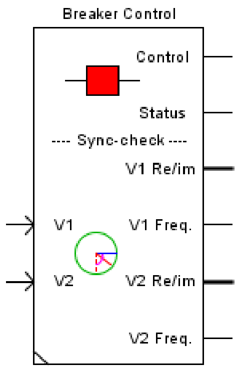
Generator Protection



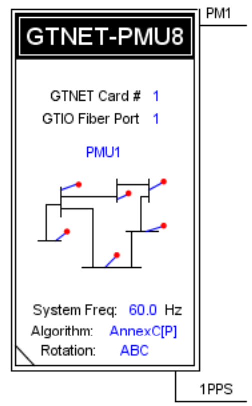
OLTC Control



Breaker Control/Sync Check



PMU

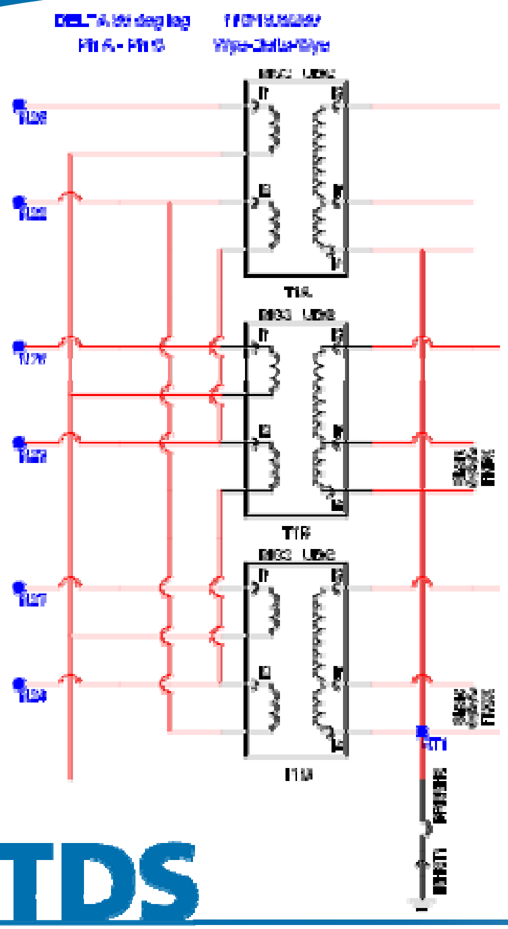


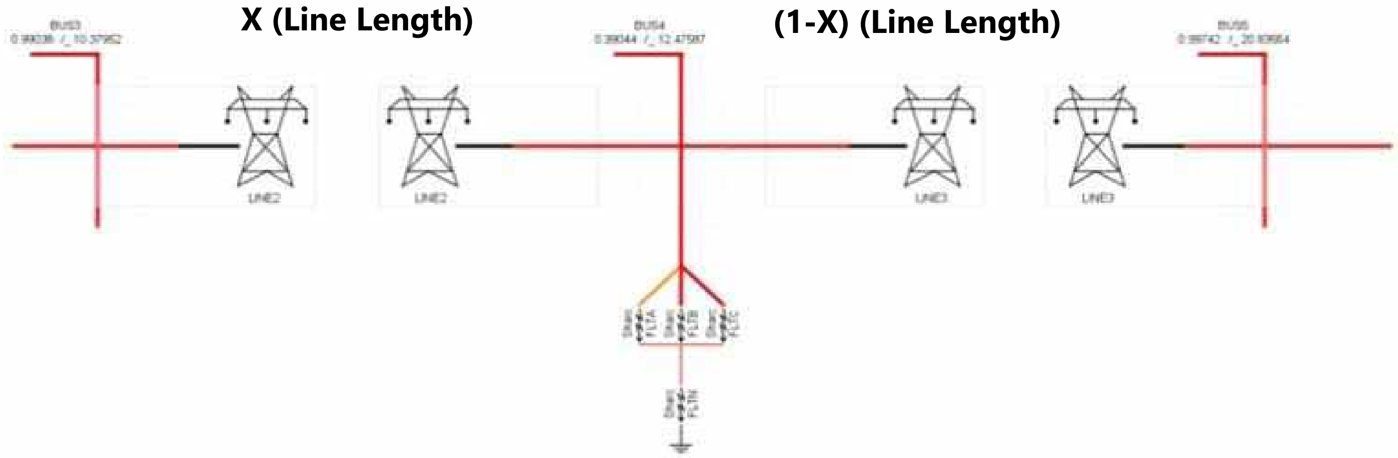
8 PMU models per component
Designed according to IEEE C37.118

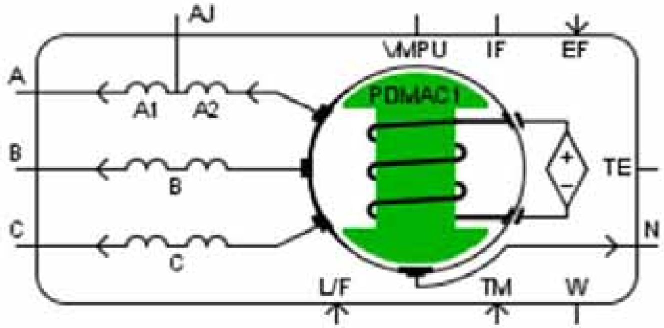
Our R&D team is continually updating our libraries in response to the needs of our customers.

RTDS Technologies

Special Models for Protection Testing



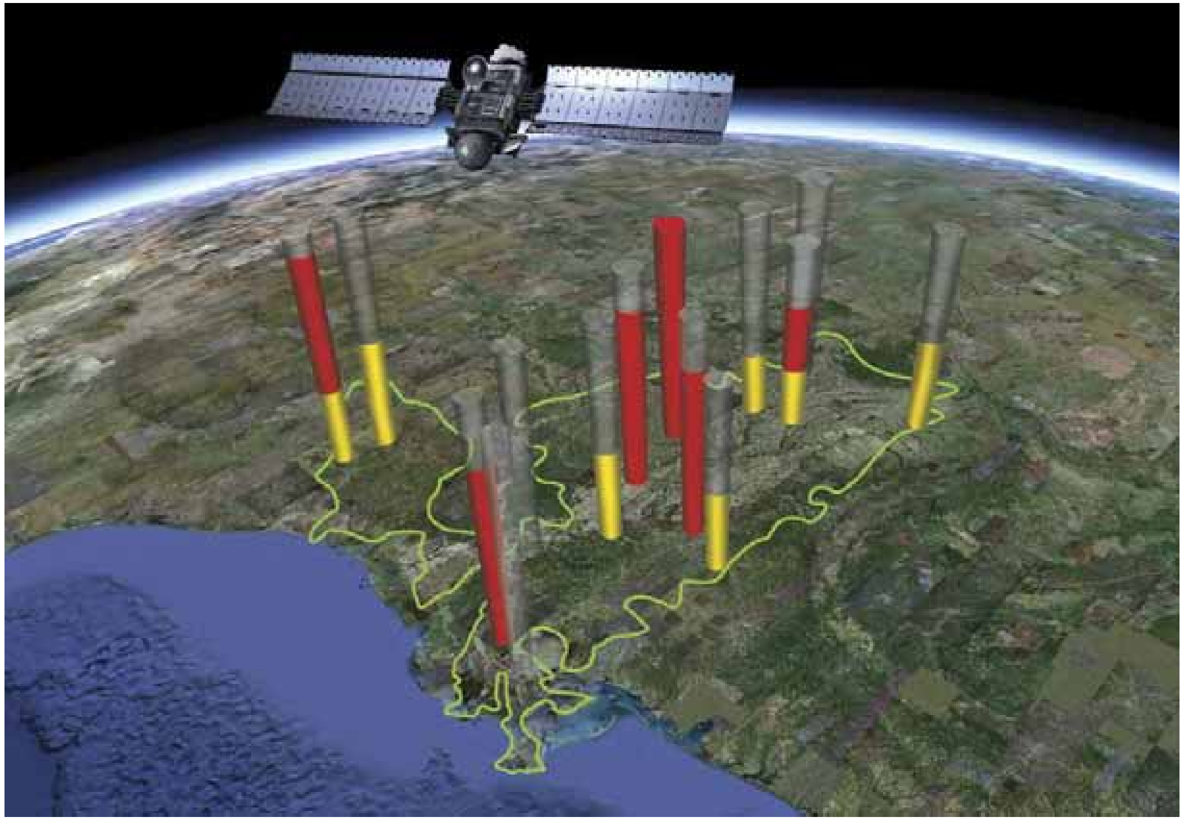




RTDS Technologies

Wide Area Protection and Control

- Thought to have many advantages
- Recent emphasis on interconnection of isolated systems
- The wide area measurement system based on PMU can provide information to a global or master control scheme



Wide Area Protection and Control

GPS time synchronization

- Time reference for result comparison
- Benchmark testing for steady state and dynamic response

GTSYNC

- Input card for 1PPS, IRIG-B, and IEEE 1588

IEEE C37.118 Communication

- PMU protocol for GTNET

Wide Area Protection and Control

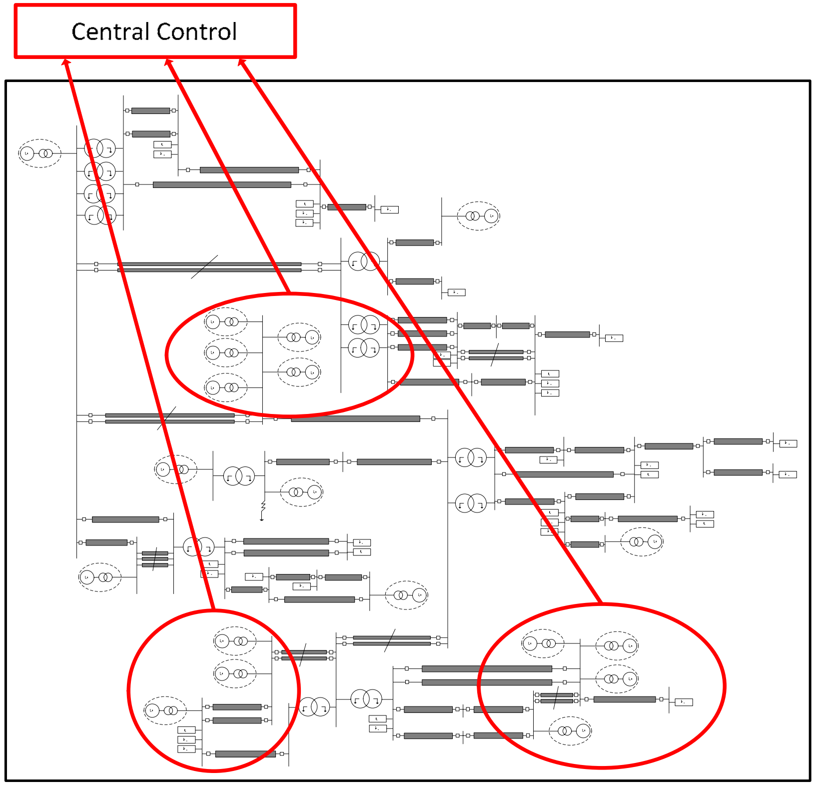
Projects around the world involving the RTDS Simulator

- **DTU** - SOSPO project
- **SCE** - C-RAS project
- **PG&E** - SynchroPhasor Proof of Concept facility

Wide Area Protection and Control

Application - SCE

- C-RAS Project
- PMU Studies
- 58 GTNET cards



Wide Area Protection and Control

Application - DTU

- SOSPO Project
- Nordic 32 System
- >170 PMU Streams
- Real-Time assessment of system security and stability

Control System Testing

- True hard real-time response while allowing interaction with external equipment
- Possibility for large-scale system representation
- Massive I/O requirements
- High-accuracy firing resolution
- Long-term simulation stability
- Must allow for user interaction and data retrieval during simulation

Control System Applications

HVDC (High Voltage Direct Current)

- Thyristor based schemes using improved firing algorithm
- 2- and 3-level VSC plus MMC based schemes using small timestep subnetworks

STATCOM

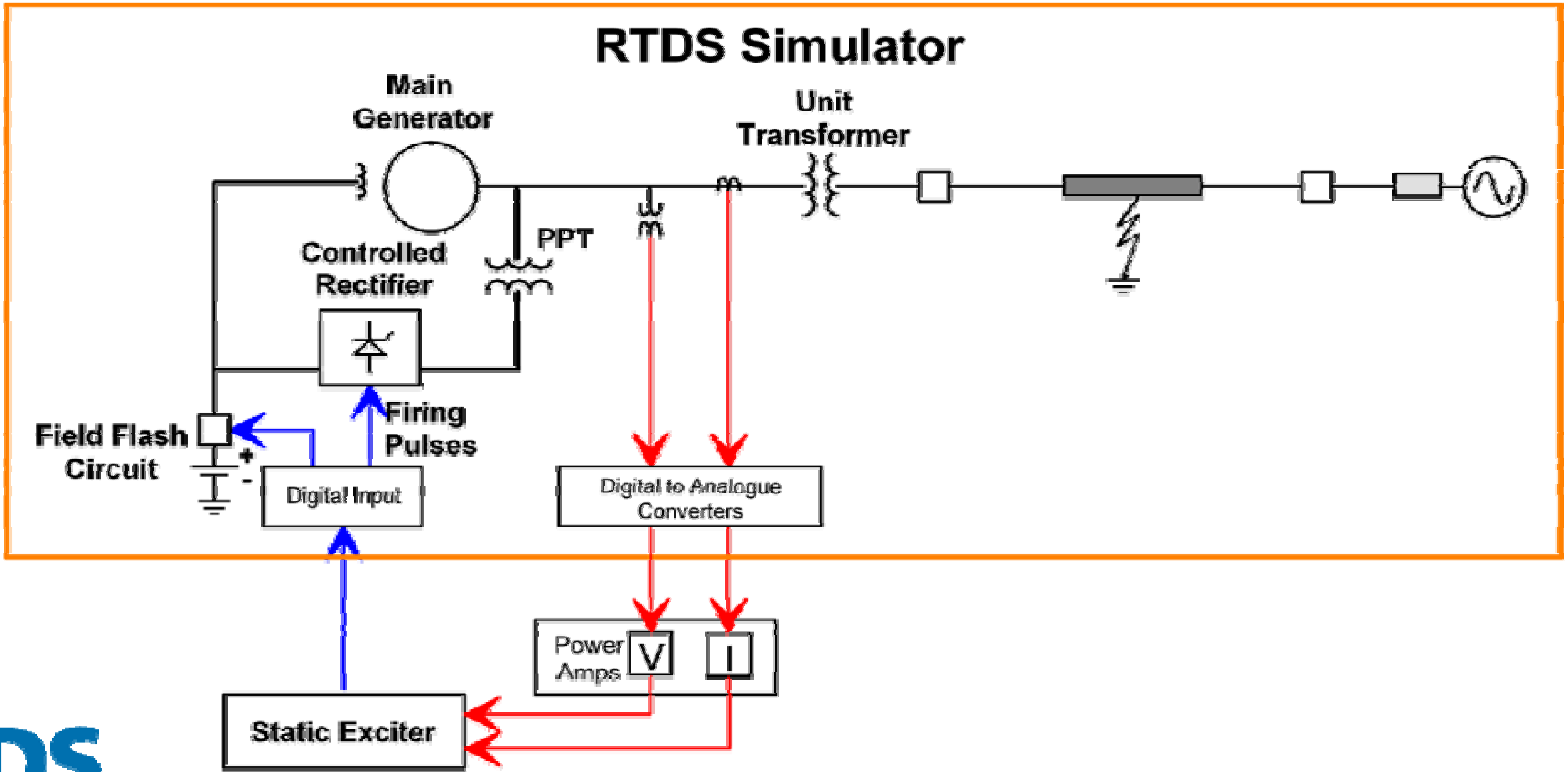
- 2- and 3-level VSC plus MMC based schemes using small timestep subnetworks

TCSC (Thyristor Controlled Series Compensation)

Generator (Exciter, Governor, PSS)

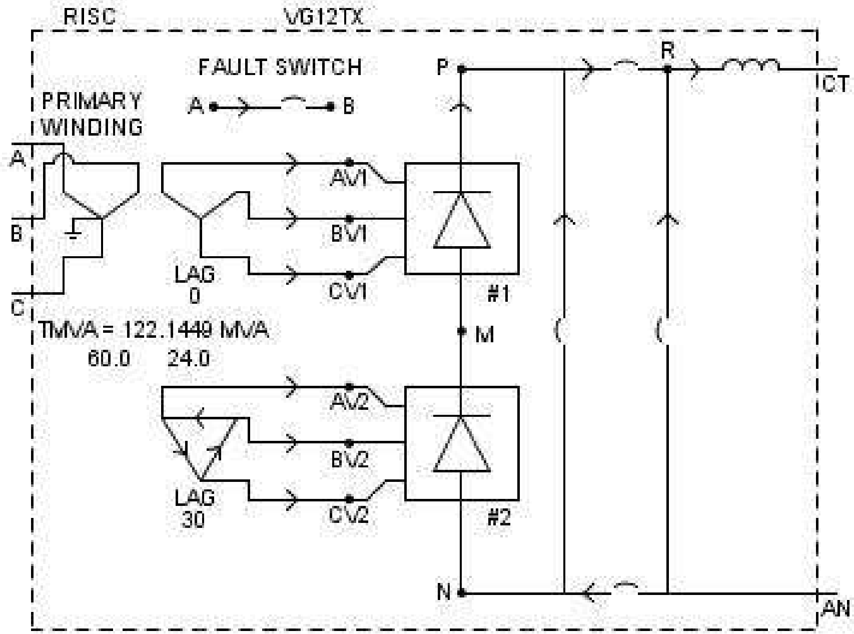
SVC (Static Var Compensator)

Testing of Excitation Controllers



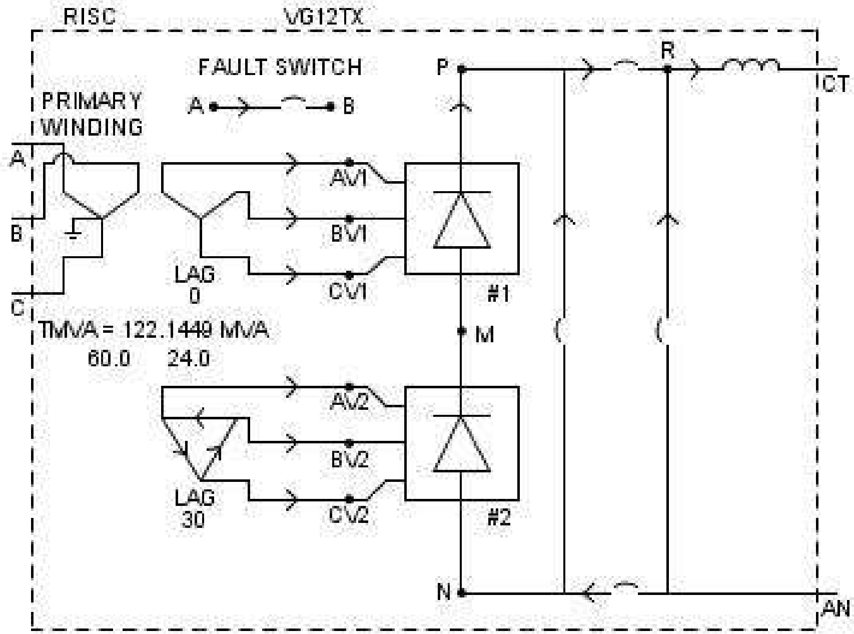
HVDC Converter Models

- Standard approach uses 2-state resistance (**off** is large resistance; **on** is small)
- Each time a switch changes state, admittance matrix must be reformulated
- 6- and 12-pulse valve group models include converter transformer, converter, internal faults



HVDC Converter Models

- Valve group models embed secondary buses and several DC nodes to reduce the burden on the network solution
- Valve group connects to network solution as variable conductance elements – no interface
- Improved firing algorithm used to provide continuously variable firing pulse response



HVDC

- The RTDS Simulator was originally developed to model HVDC schemes
- Used by all manufacturers of HVDC for Factory Acceptance Testing (FAT) of LCC and VSC/MMC based schemes
- Many utilities have purchased replica controls and RTDS Simulators as part of their projects

Replica Simulators

- Assist during commissioning
- Investigate proposed network changes
- Investigate proposed control modifications
- Test scheme upgrades and refurbishment
- Train personnel on scheme theory and operation
- Important to include in project specification

Replica Simulators

- Furnas (Brazil)
- TNB (Malaysia)
- CSG (China)
- SEPC (China)
- ESKOM (South Africa)
- SEC (Saudi Arabia)
- Power Grid (India)
- Powerlink (Australia)
- REE (Spain)

- DEWA (UAE)
- ONS (Brazil)
- NamPower (Namibia)
- RTE (France)
- BPA (USA)
- Manitoba Hydro (Canada)
- Transpower (New Zealand)
- SSE (UK)
- Zhejiang EPRI (China)

Smart Grid and Distributed Generation

Renewable Energy Resources

Micro Grid Integration Studies

Smart Grid and Distributed Generation

- Requires high-level communication

  IEC 61850

  DNP3

  IEC 60870-5-104

  IEEE C37.118

- Alternative energy sources

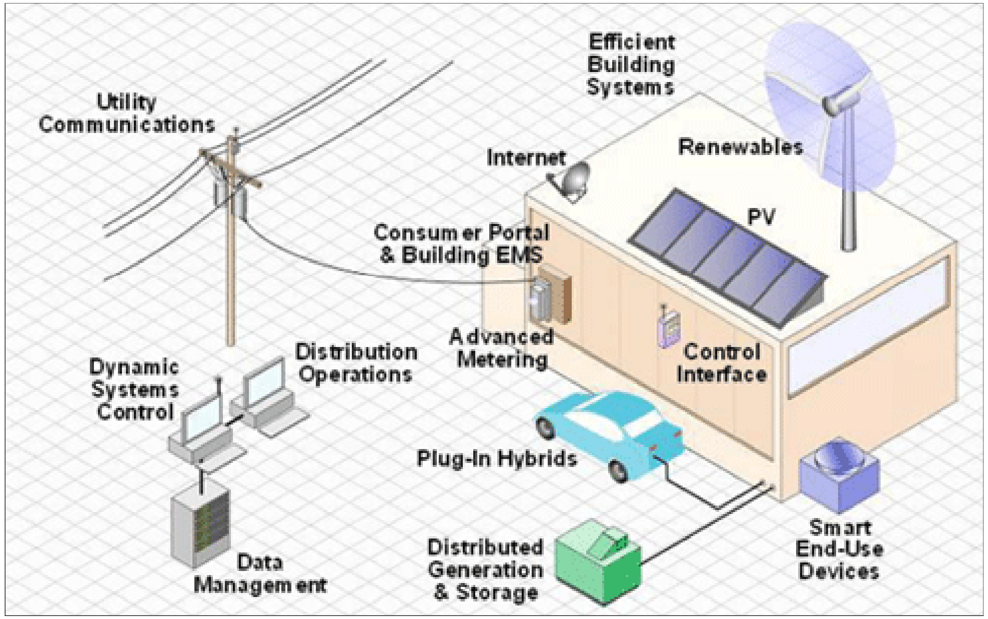
  Wind

  Solar

  Fuel cells

  Battery bank

  Power electronic converters



SCADA Systems

- GTNET – DNP & -104

Binary simulation status/output (i.e. breaker position)	1024 (scan rate 1000 Hz)
Binary simulation status/input (i.e. breaker commands)	512 (scan rate 1000 Hz)
Analogue output	500 (scan rate 4 Hz)
Analogue input	100 (scan rate 4 Hz)

The GTNET – DNP and -104 supports 1 master with a maximum polling rate of less than 5 Hz.

Electric Vehicle and Energy Storage

EV/V2G Simulation

Designing a storage system and interface DC/DC converter for Electric Vehicle (EV).

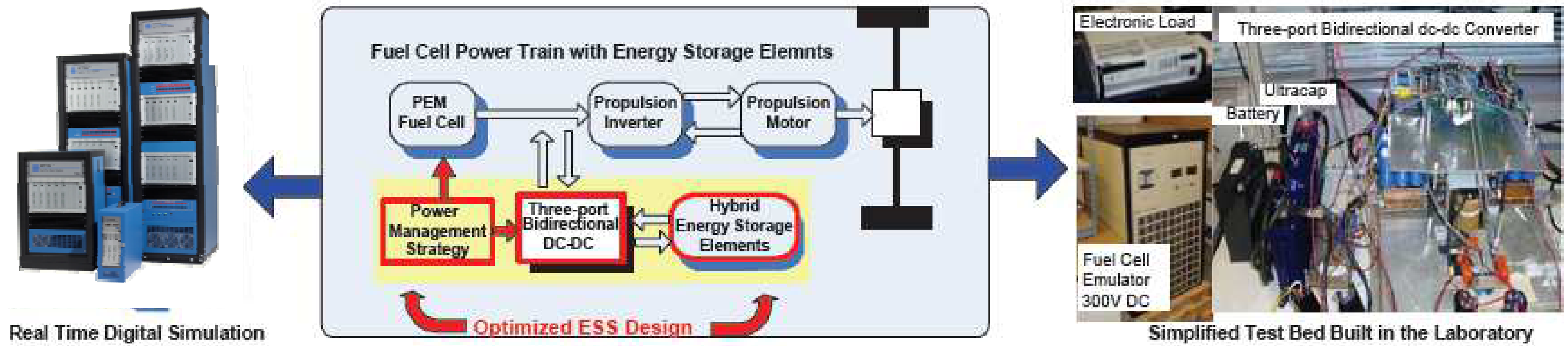


Fig. 1. Proposed optimized energy storage system (ESS) design for fuel cell vehicle application

Large Scale Simulation

Efficiency of Real Time

- More scenarios in less time yield more information and better understanding

Frequency Response from 0-3 kHz with one tool

- Full spectrum of operation observable
- All protection and control aspects can and should be included

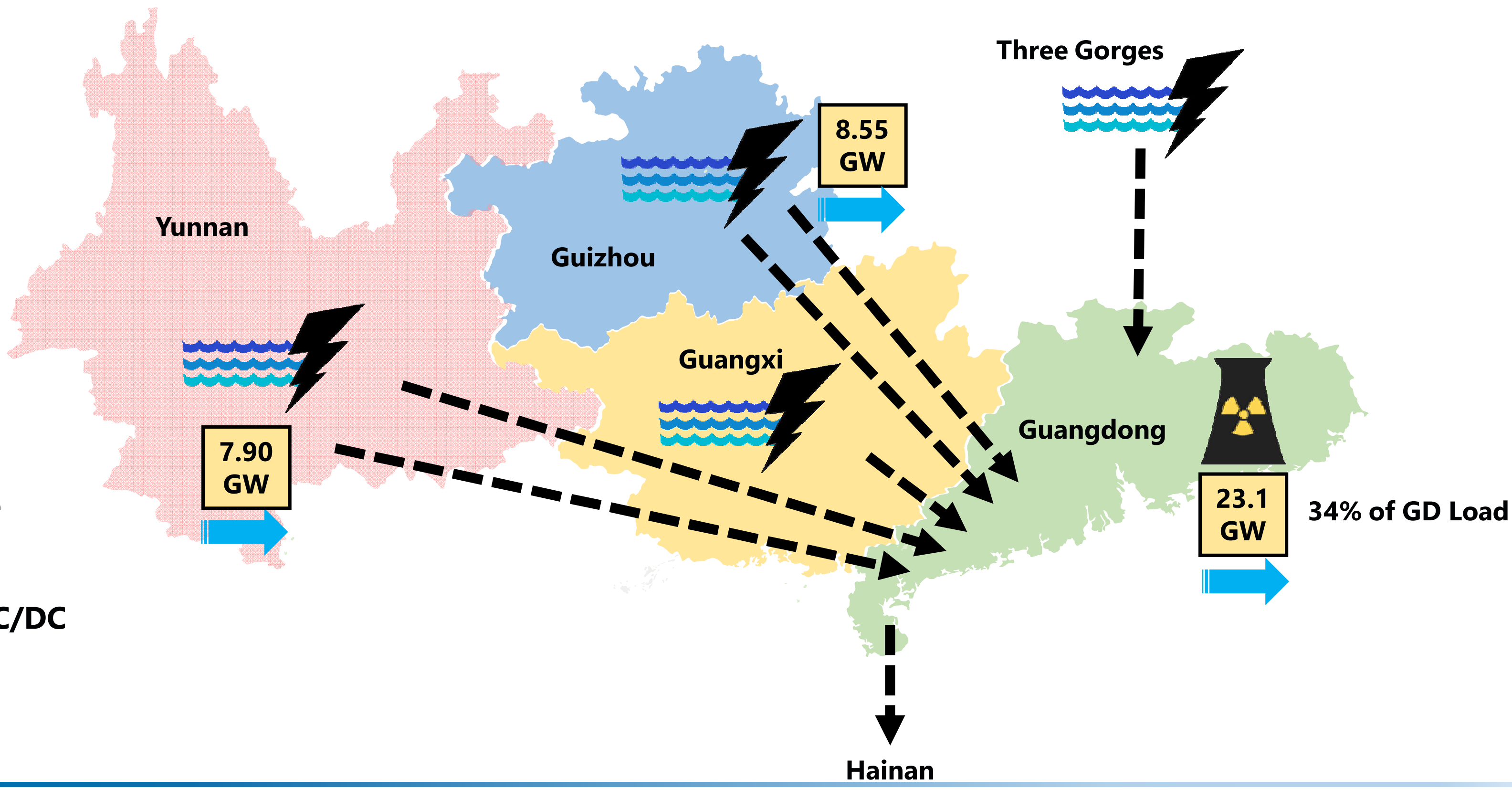
Detailed Control – Power System Interaction

- Fully simulated or with external equipment connected

Large Scale Simulation

Power System of Southern China

8 AC + 5 DC from west to east



Long Distance

Ultra High Voltage

Bulk Capacity

Hybrid Operation of AC/DC

System Restoration Studies

China Southern Grid Simulator

World's largest real time simulator

Current capacity +1400 three-phase buses

Unexpected benefits – Ice Storm 2008

- Extensive damage to 110 kV network
- More than 7000 lines damaged
- Millions of customers without power
- CSG engineers worked around the clock to model system
- RTDS Simulator used to help guide restoration

Cigré Meeting, Paris 2010 - Panel Session on Network Security

- RTDS Simulator identified as one of four key strategies to ensure security and reliability

Black Start Investigation

Procedure and Equipment Testing

Full system representation

- Grids with 3000 buses
- Detailed protection and control modes included
- Realistic behavior over entire operating range

Real time operation

- Allow testing of physical controllers
- Provide realistic feedback to operators
- Physical SCADA interface through DNP3 or IEC 60870-5-104

Validation

In-house

Independent validation by customers

Commercial studies

Industry benchmark

- ✓ Electromagnetic transient
- ✓ Electromechanical transient / transient stability
- ✓ Load flow / steady state

Validation

Non real time electromagnetic simulations

- ✓ PSCAD, EMTP, ATP, etc.

Transient stability

- ✓ PSS/E, Y-method, Netomac, BPA

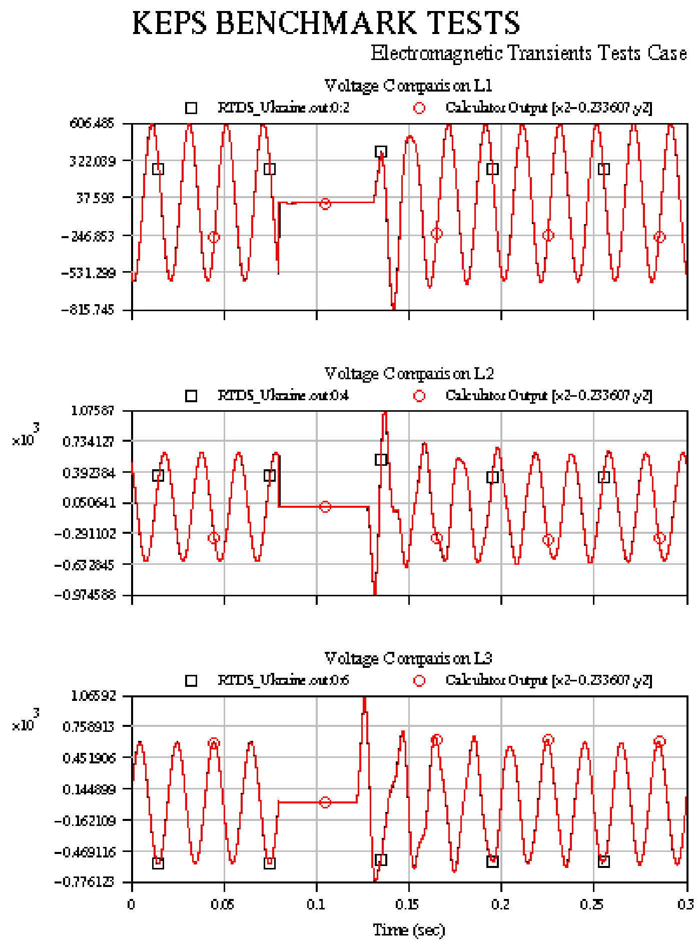
Load flow

- ✓ PSS/E, Netomac, BPA

Benchmark cases

- ✓ CIGRE, IEEE

Actual power system measurements



The Advantages of the World Leader

RTDS Technologies is the world leader in real time power system simulation.

- Customers in 43 countries – **trusted** by leading manufacturers, utilities, research institutions globally
- Proven reputation for a **quality** product and excellent customer **support**
- Continued product **development** in response to customer needs
- Flexible, **modular** solution composed of **custom** hardware and software designed in-house
- Global market leadership means **experience** with a range of applications
- Encourage **collaboration** through sponsorship program

Questions