NovaCor™
A revolution in real time.

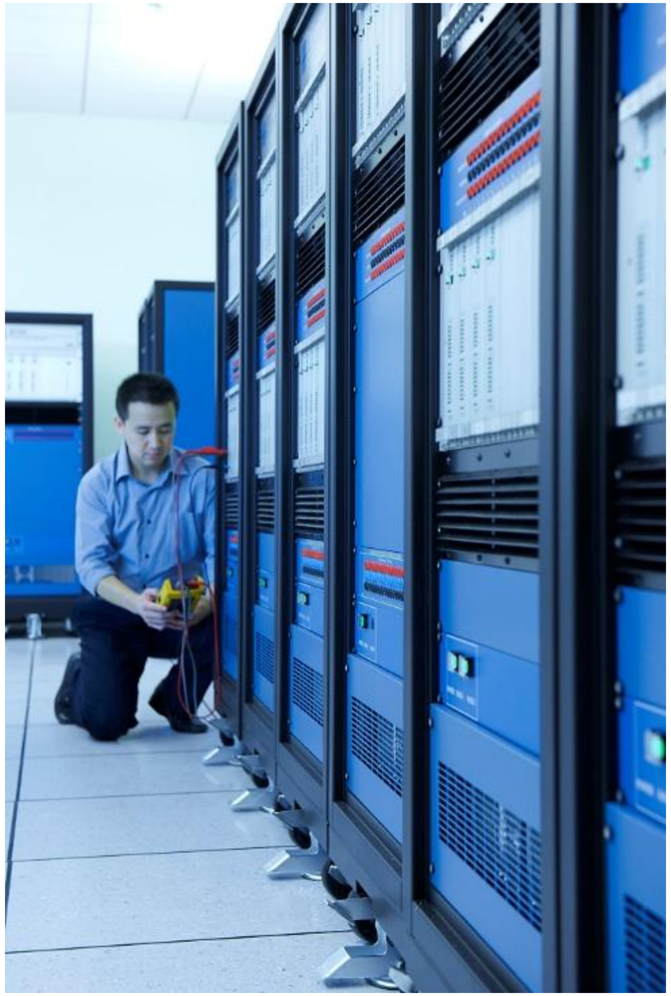
Modern real time power systems simulators

History and development plus applications now and in the future

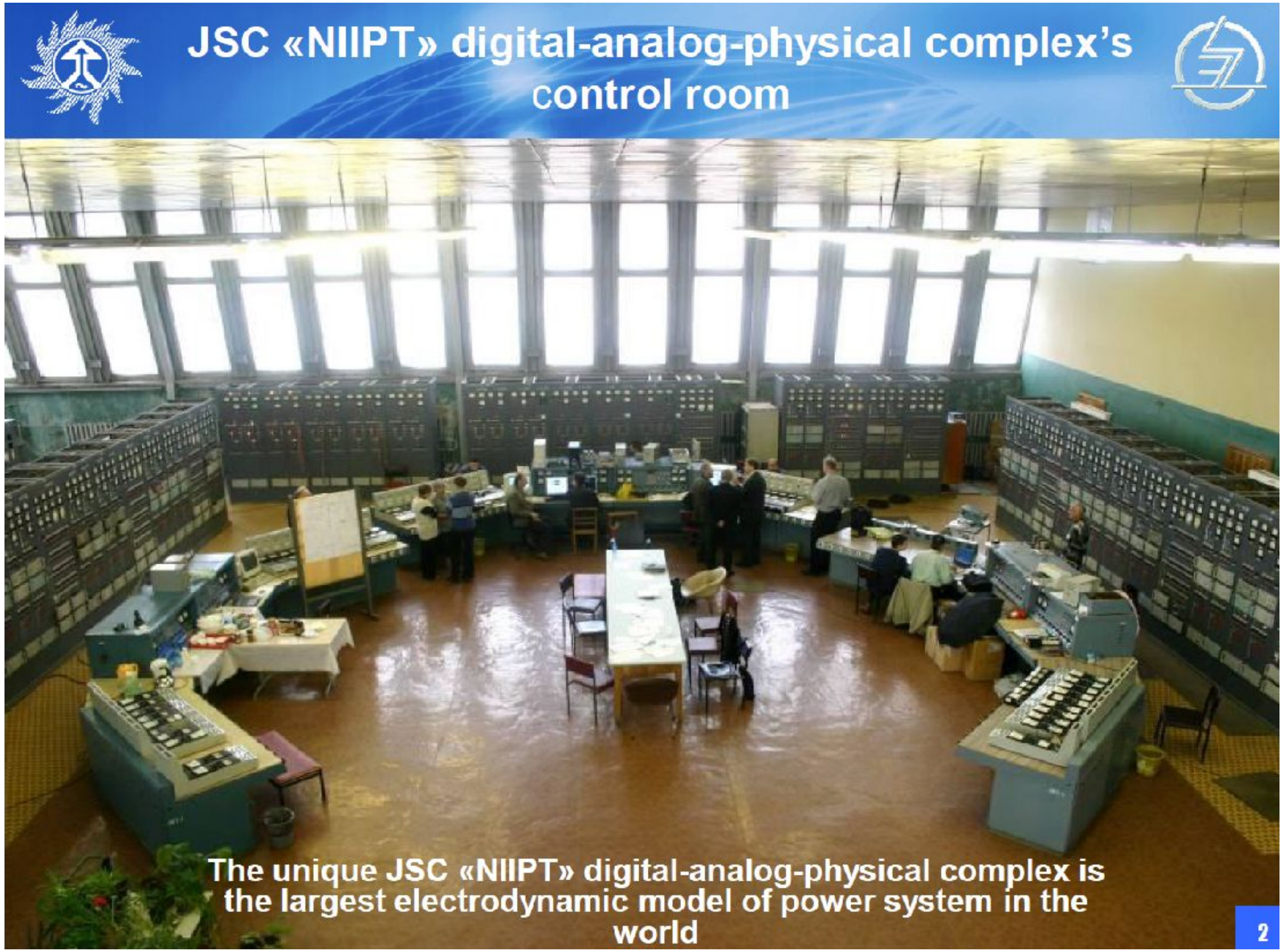
RTDS Technologies

Agenda

- History of real time simulation
- RTDS development path
- Digital simulation overview
- EMT simulation
- Real time EMT simulation techniques
- Current applications
- Future applications
- Questions



History



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History of Digital Simulation

1969
Dommel's IEEE paper published

1983
EMTDC used commercially

1986
RTDS development project begins

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

1993
1st RTDS commercial installation

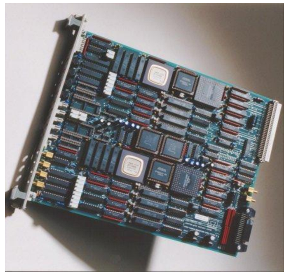
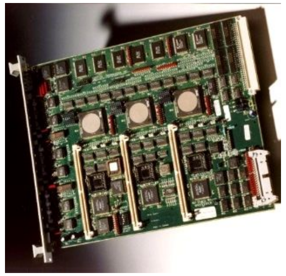
1994
RTDS Technologies created

History of Digital Simulation

- The release of the RTDS Simulator in 1994 has had a very important effect on power system development
- Developers were provided with a very well controlled and flexible environment to test and prove new protection and control equipment (repeatable, reliable, accurate)
- Real time simulators were more accessible (cheaper and smaller) and quickly became an everyday tool for all manufacturers of HVDC and FACTS schemes
- Protective relay manufacturers were able to easily perform exhaustive testing with complete flexibility to introduce faults and define circuit parameters
- Universities and R&D institutes were able to afford real time simulators to investigate and test new developments
- Today there are many 100s of real time simulators in operation around the world where there we less than 50 before fully digital real time simulators were available

RTDS Development Path

- Continuous advancements and an upgrade path has been provided to customers
  - TPC → 3PC → RPC → GPC → PB5
  - WIC → WIF → GTWIF
  - Backplane 175 ns → 125 ns → 60 ns → Fibre Enhanced Backplane (FEB)
  - I/O cards moved from copper to fibre optic connection with the simulator
  - Backplane communication could account for 30-50% of the timestep
- NovaCor released in early 2017
  - New architecture based on multi-core processor, eliminating backplane transfers
  - Sixth generation hardware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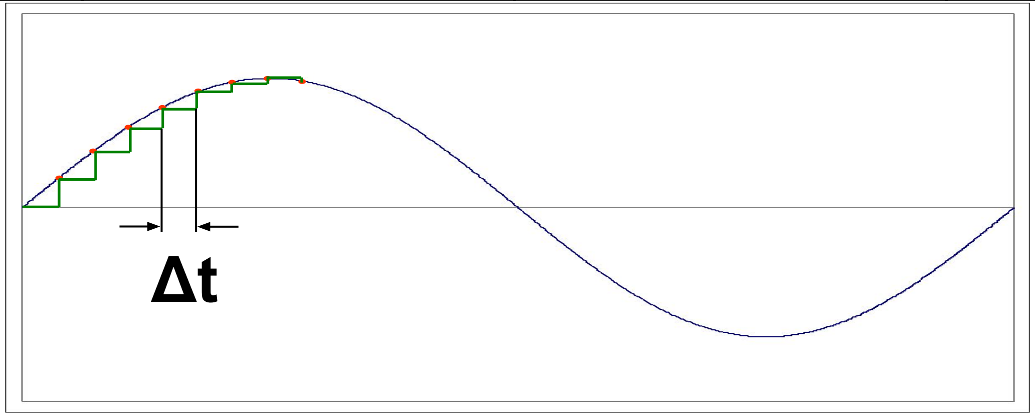
Types of Digital Simulation

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

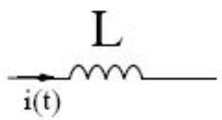
- Nodal Analysis – Dommel Algorithm
  - Very widely used algorithm for power system simulation (PSCAD, EMTP, etc.)
  - Implemented in many off-line simulation programs
  - Inherent parallel processing opportunities

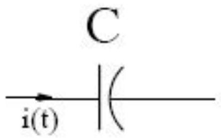
- State Variable Analysis
  - Very widely used for control system modeling, but also used for power system simulation
  - Matlab/Simulink uses state variable analysis
  - Often combined with nodal analysis (e.g. DQ0 machine models)

EMT Simulation Algorithm

Dommel Algorithm

Convert DEs to algebraic equations using trapezoidal rule of integration





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

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

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

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

applying trapezoidal rule of integration

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

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

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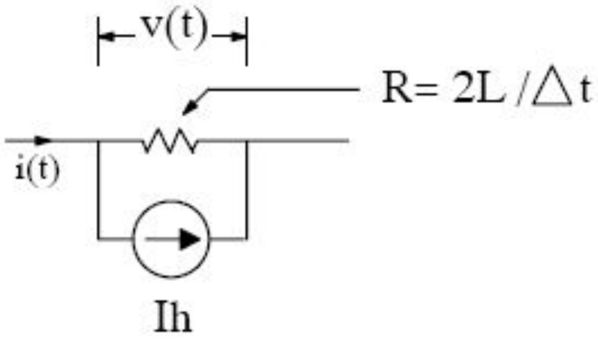
EMT Simulation Algorithm

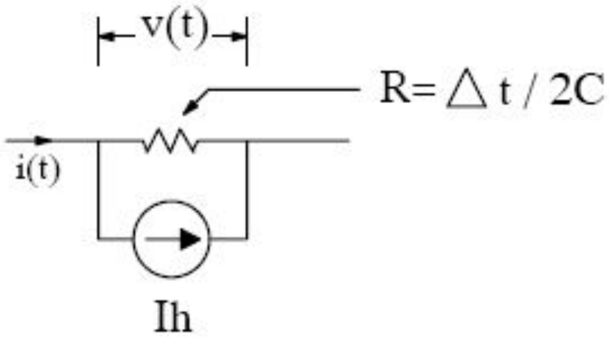
Dommel Algorithm

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

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

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



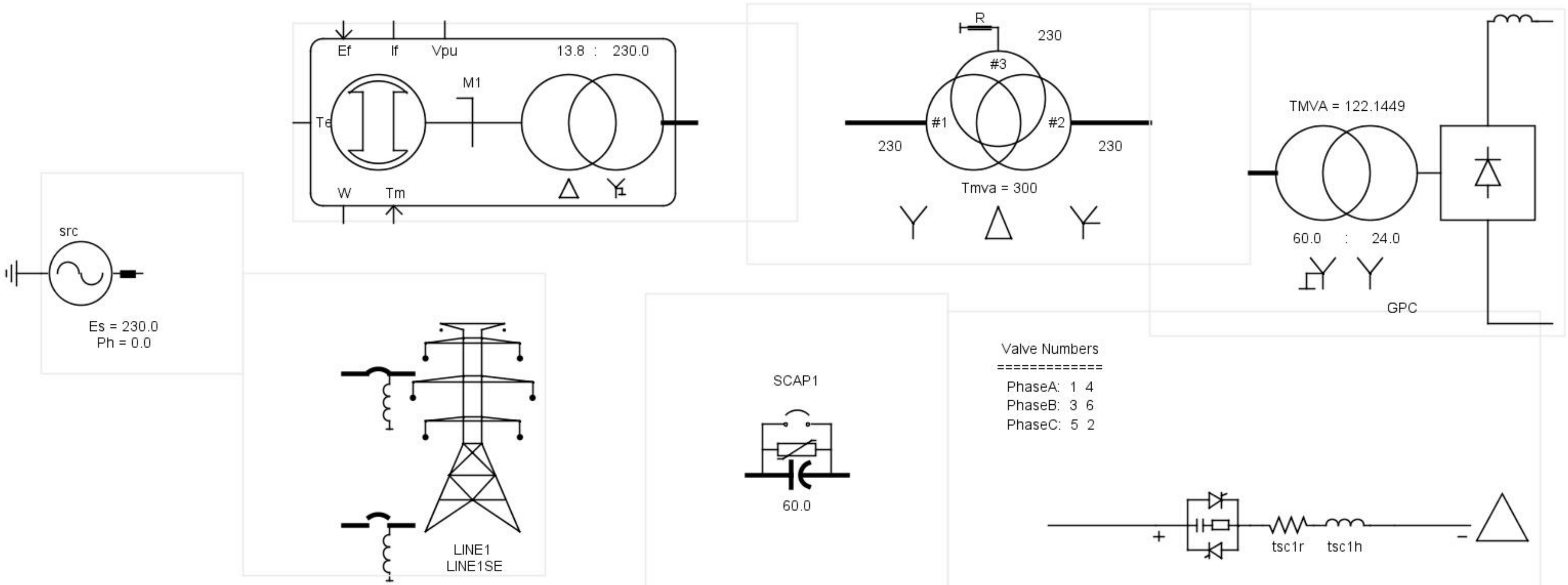


EMT Simulation Algorithm

Dommel Algorithm

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

History term currents for complex components may require substantial computation

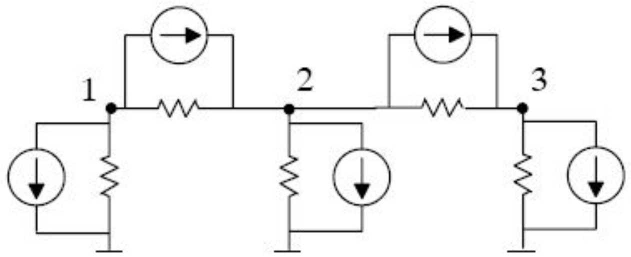


Technologies

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

RTDS Technologies

Real Time Simulation

Stored Matrices

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} = \begin{pmatrix} Ga_{11} & Ga_{12} & Ga_{13} \\ Ga_{21} & Ga_{22} & Ga_{23} \\ Ga_{31} & Ga_{32} & Ga_{33} \end{pmatrix}^{-1} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix}$$

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} = \begin{pmatrix} Gb_{11} & Gb_{12} & Gb_{13} \\ Gb_{21} & Gb_{22} & Gb_{23} \\ Gb_{31} & Gb_{32} & Gb_{33} \end{pmatrix}^{-1} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix}$$

⋮

- 2^n pre-calculated matrices
- n is number of switches

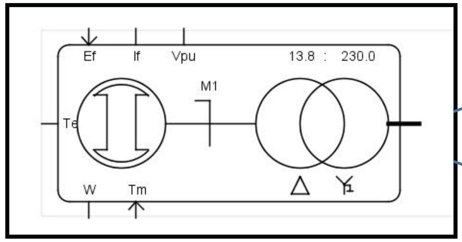
Real Time Decomposition

$$\begin{bmatrix} V_1 \\ V_2 \\ V_3 \end{bmatrix} = \begin{pmatrix} G_{11} & G_{12} & G_{13} \\ G_{21} & G_{22} & G_{23} \\ G_{31} & G_{32} & G_{33} \end{pmatrix}^{-1} \begin{bmatrix} I_1 \\ I_2 \\ I_3 \end{bmatrix}$$

- Minimal memory requirements
- Large number of switches can be represented
- All G values can change from timestep to timestep

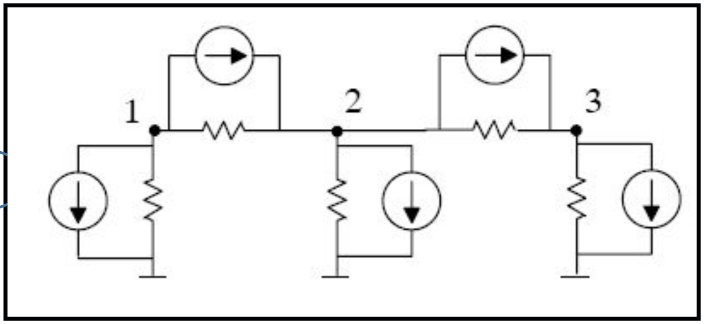
Real Time Simulation

DQ0 model



Read voltage
v(t)

Send back
current
i(t+Δt)



Note 1 timestep delay

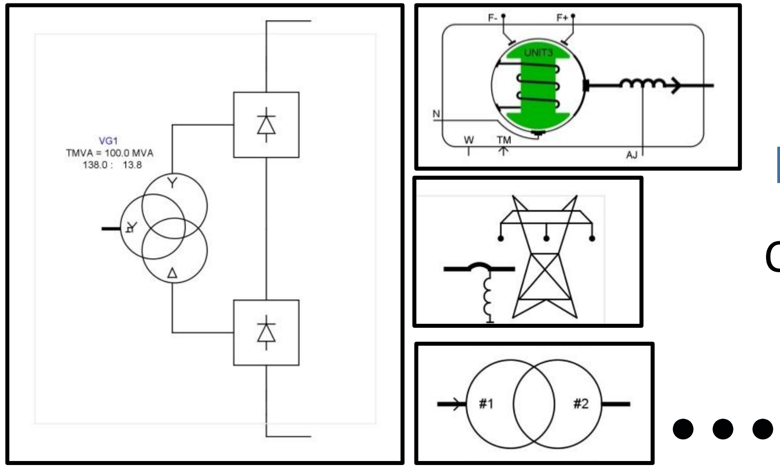
Admittance elements constant

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

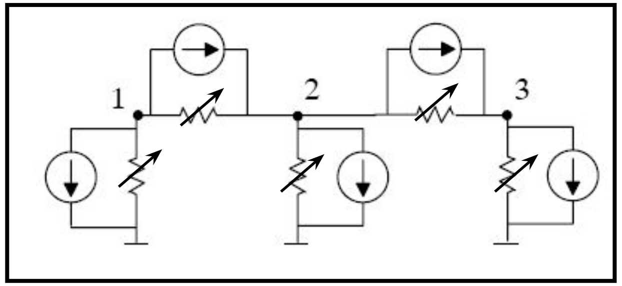
RTDS Technologies

Real Time Simulation

- Non-Interfaced components *eliminate timestep delay*:



Current injections and variable admittances



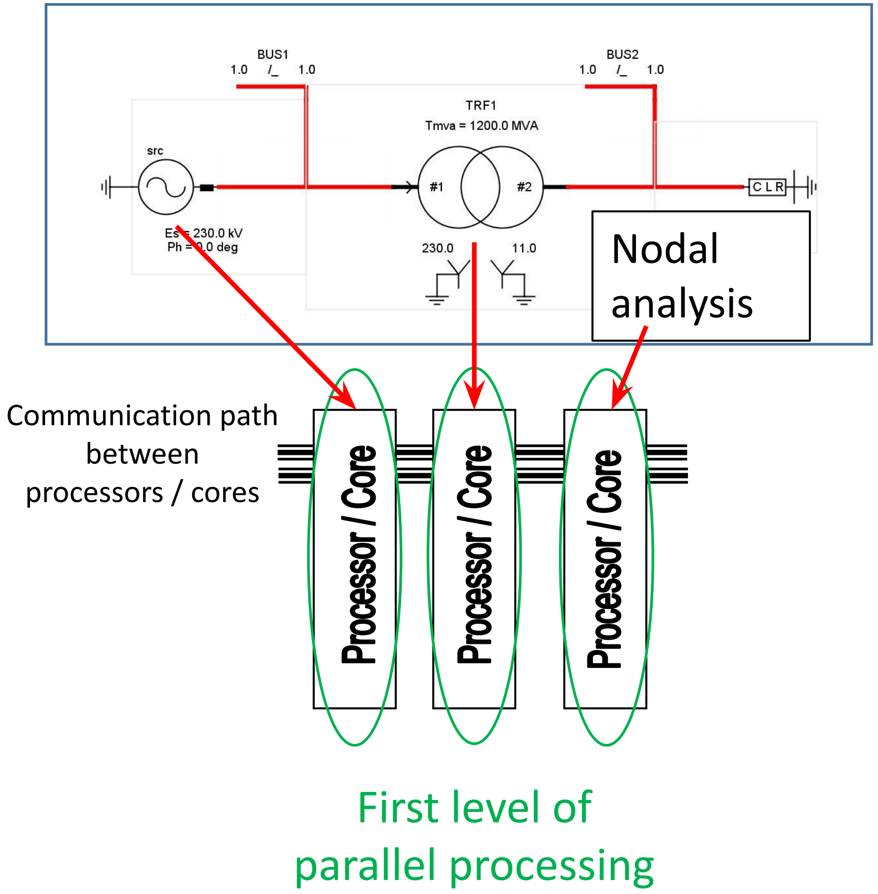
- Requires decomposition of admittance matrix every timestep

Variable admittance elements

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

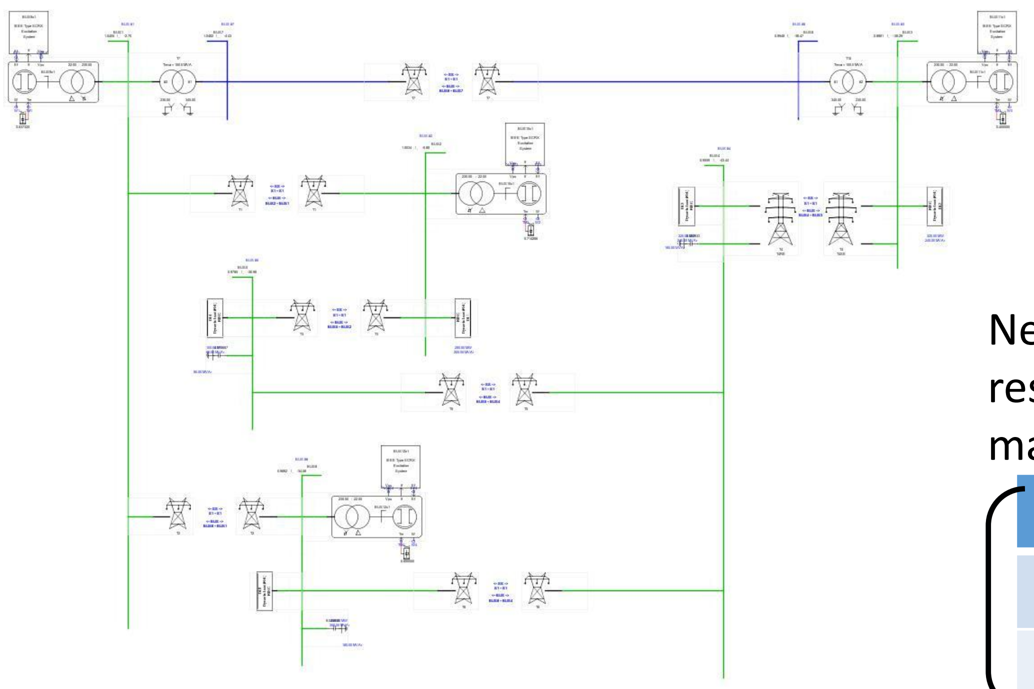
Real Time Simulation

- Parallel Processing within a Subsystem
  - Network components are assigned to available processors / cores
  - Combined power of processors / cores accelerate solution
  - Communication between processors / cores allows the overall solution of the system



Real Time Simulation

- Splitting the Network into Subsystems
  - As the network gets bigger the size of the conductance matrix also increases (one matrix element per system node)
  - Eventually it will not be possible to solve the conductance using one core

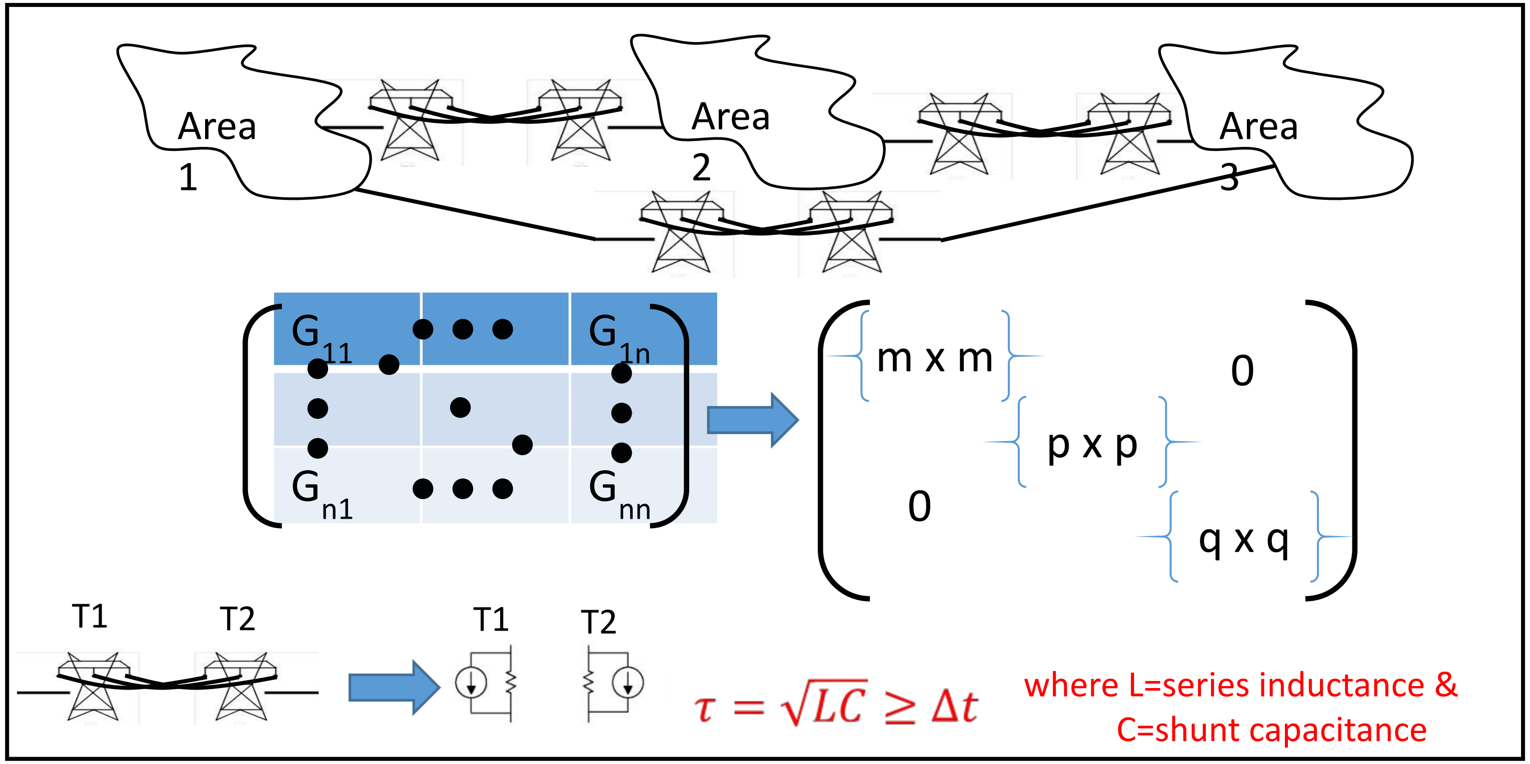


Network with n nodes results in admittance matrix n x n in size.

$$\begin{pmatrix} G_{11} & \cdots & G_{1n} \\ \vdots & \ddots & \vdots \\ G_{n1} & \cdots & G_{nn} \end{pmatrix}$$

Real Time Simulation

- Splitting the Network into Subsystems
  - Traveling wave models (transmission lines or cables) are used to split a network into subsystems
  - Conductance matrix broken up into block diagonals that can be treated separately

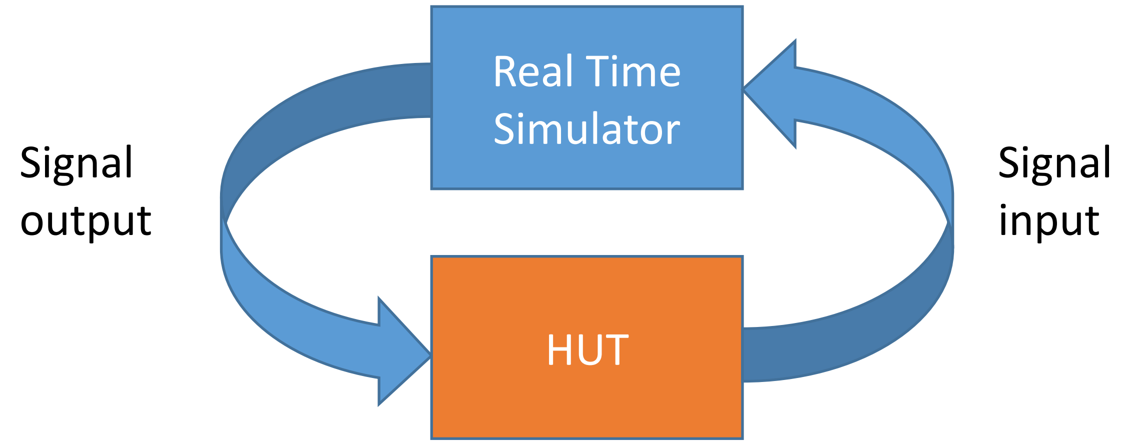


$$\tau = \sqrt{LC} \geq \Delta t$$

where L=series inductance &
C=shunt capacitance

Real Time Simulation

- Remember the purpose of real time simulation!
  - Closed-loop testing of protection and control
  - Power hardware in the loop simulations
- Input / Output capabilities are essential
- Conventional analogue and digital signal exchange
- High level industry standard protocols (Ethernet)
- Large amount of data exchange may be required

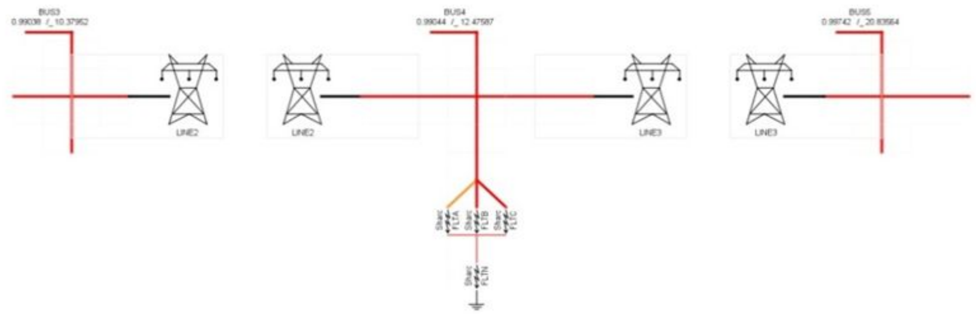


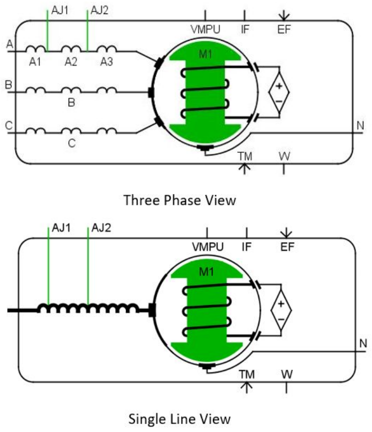
Real Time Simulation

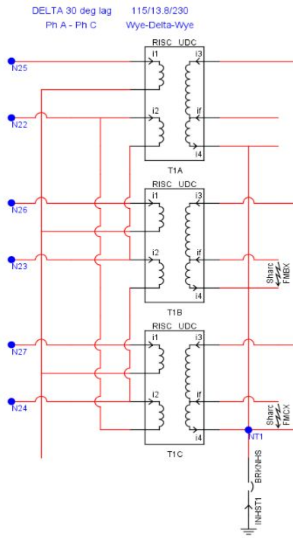
- Not all techniques available for off-line simulation are available for real time simulation
  - Chatter removal
  - Interpolation
  - Iterations
- Chatter removal and interpolation both require the simulation to go back in time – not possible for hard real time simulation
- Iterative solutions are not realistic when the timestep must always be completed in real time
- Iteration and interpolation of part of the network is not sufficient

Current Applications

- Protection system testing
  - Conventional protective relay testing and scheme testing
    - Analogue signals driving amplifiers to provide secondary voltage and current
    - Trip, reclose and status signals exchanged using dry contact
  - IEC 61850 Compliant relay testing
    - Voltage and current signals provided to relay via IEC 61850-9-2 sampled values
    - Trip, reclose and status signals exchanged using GOOSE messages
  - Special models available to model internal faults on transformers, generators, lines, etc.







RTDS Technologies

Current Applications

 Wide Area Measurement Protection and Control – WAMPAC

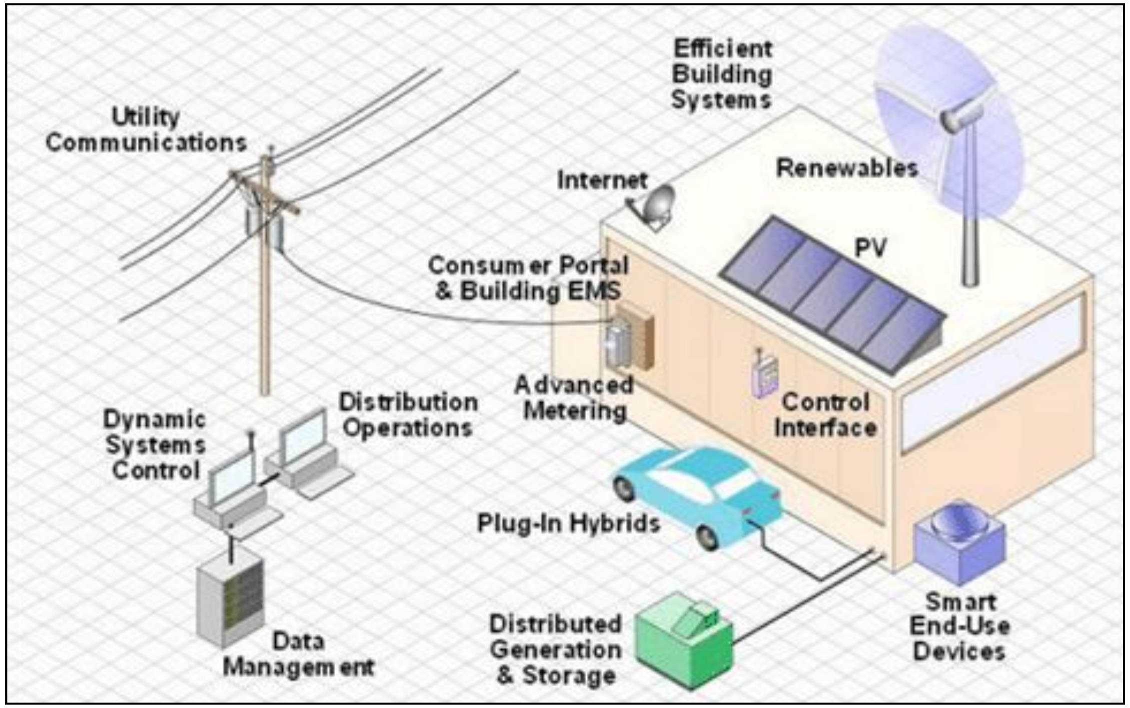
- Large scale modeling capability required
  - Conventional lines, generators, breakers, transformers, etc.
  - HVDC, FACTS, DER, microgrid, etc.
  - Protection and control models required
- PMU modeling
  - Model developed to adhere to C37.118.1-2011 structural and performance requirements values
  - P and M type devices
  - Reporting rates from 1 – 240 fps
  - Capability for 10's to 100's of PMU's
  - Template for customized PMU algorithms
  - C37.118 data stream publishing required
- Time synchronization with external source required
- Communication via industry standard protocols required (e.g. IEC 60870, DNP, C37.118, IEC 61850)

Current Applications

- Mirogrid, Smart Grid and DER
  - Requires high-level communication

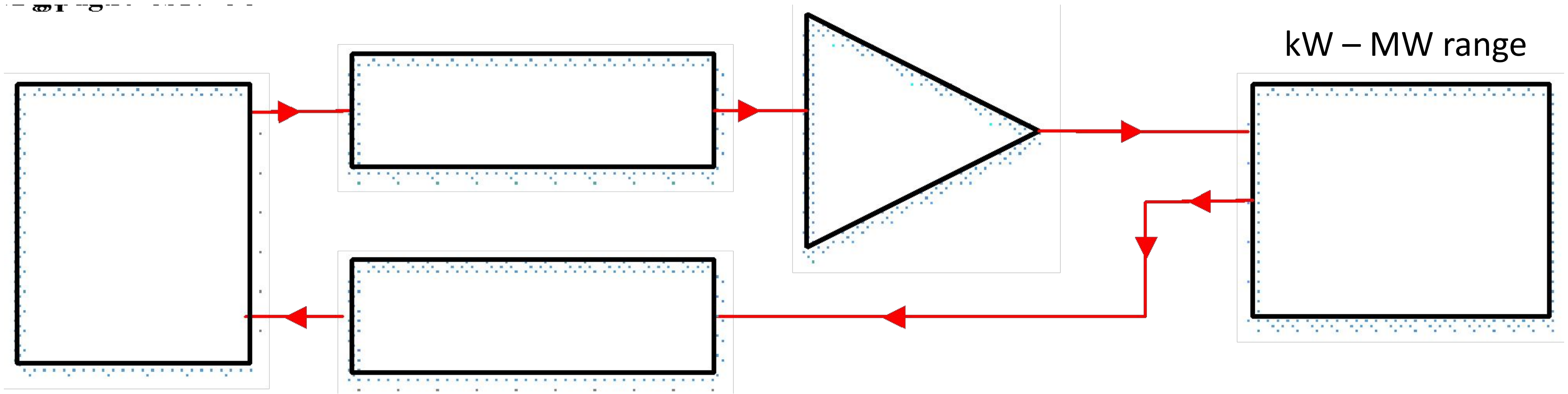
    IEC 61850
    DNP3
    IEC 60870-5-104
    IEEE C37.118
    Modbus
  - Alternative energy sources

    Wind
    Solar
    Fuel cells
    Battery bank
    Power electronic converters



Current Applications

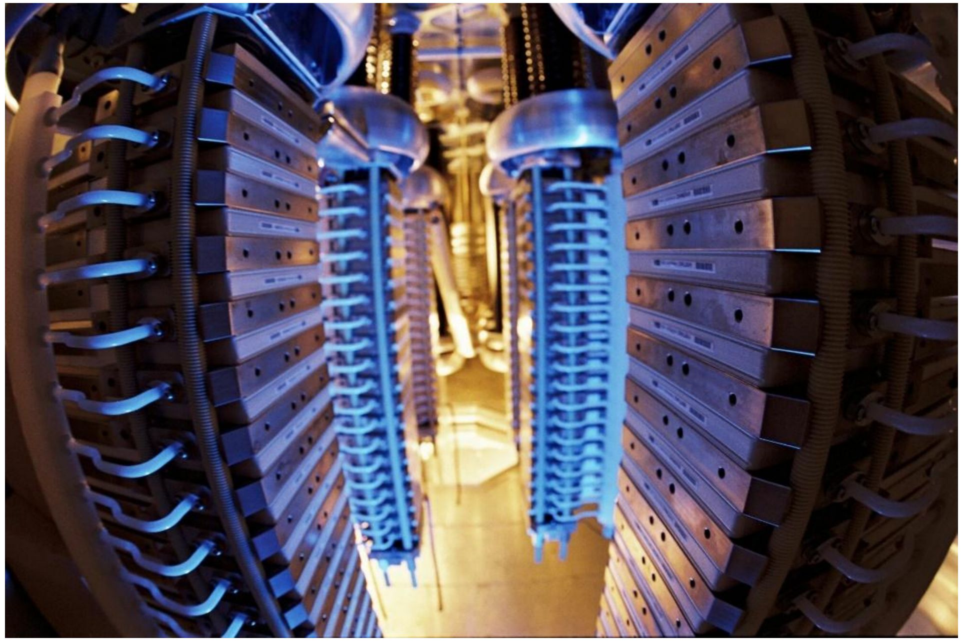
- Power Hardware In the Loop (PHIL) Simulation
  - Test physical power equipment
  - Devices from kW to MW level tested
  - Special 4-quadrant amplifiers required
  - Time delays critical to simulation stability



Current Applications

- HVDC and FACTS
  - Thyristor based schemes using improved firing algorithm
  - 2- and 3-level VSC based schemes using small timestep subnetworks
  - MMC based schemes using small timestep subnetworks and FGPG based solution techniques

- Generator (Exciter, Governor, PSS)



Current Applications

- Replica Simulators for HVDC and FACTS
  - 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

Current Applications

- Large Scale Simulation

Power System of Southern China

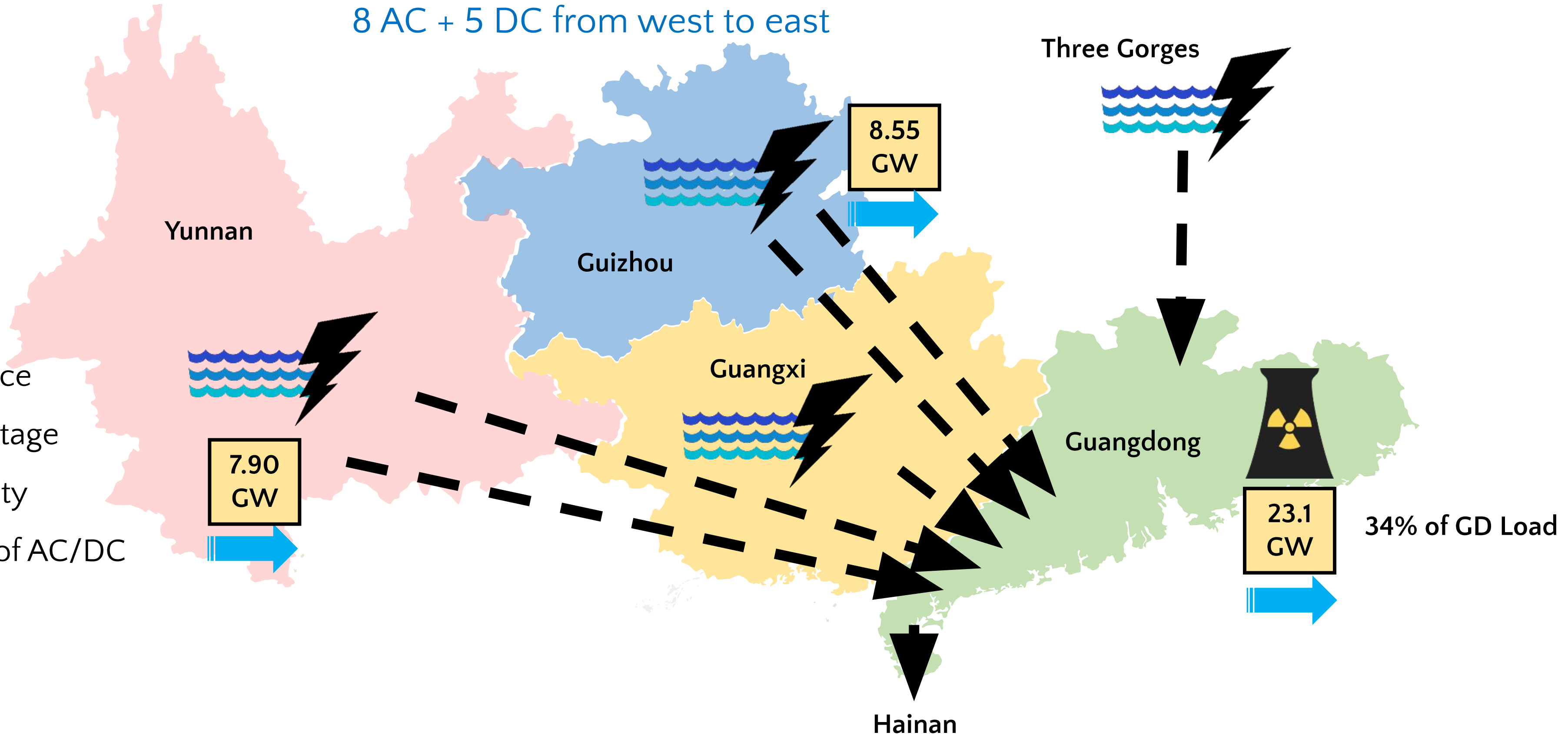
8 AC + 5 DC from west to east

Long Distance

Ultra High Voltage

Bulk Capacity

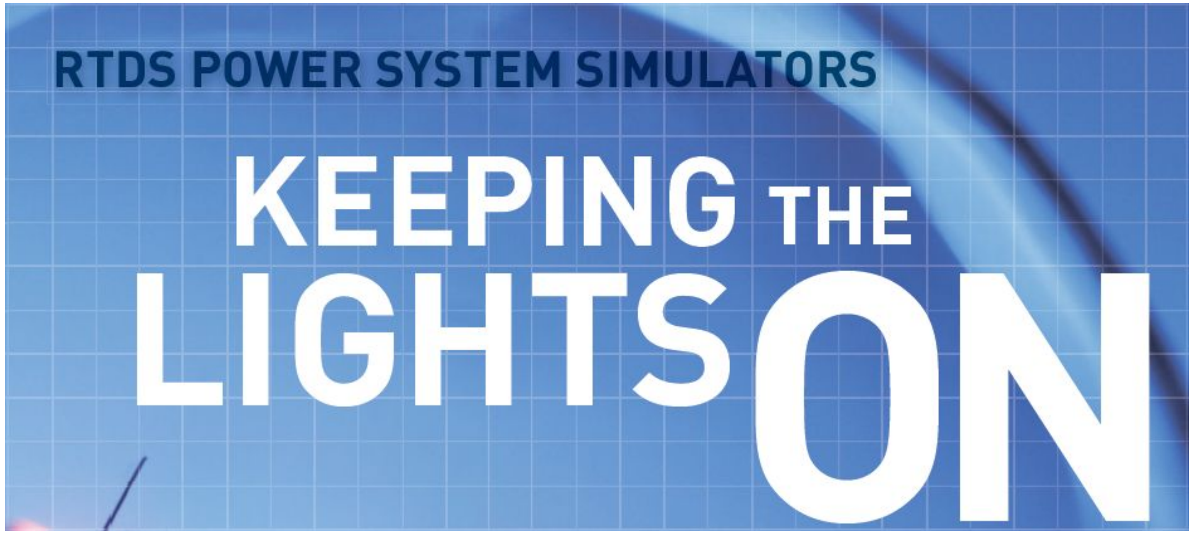
Hybrid Operation of AC/DC



Current Applications

 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



Future Applications

- Operations support
  - Simulation models covering 50,000 buses entirely based on EMT
  - Network models including detailed representation of protection and control functions
  - Live switching status read from EMS SCADA interface
  - Load flow read from EMS SCADA interface
  - Contingency analysis
  - Protection setting coordination and verification
  - Replace other types of simulation (e.g. short circuit analysis, transient stability analysis, etc.) for electric utilities

Questions