Power System Real-Time Simulation using Modelica and the FMI

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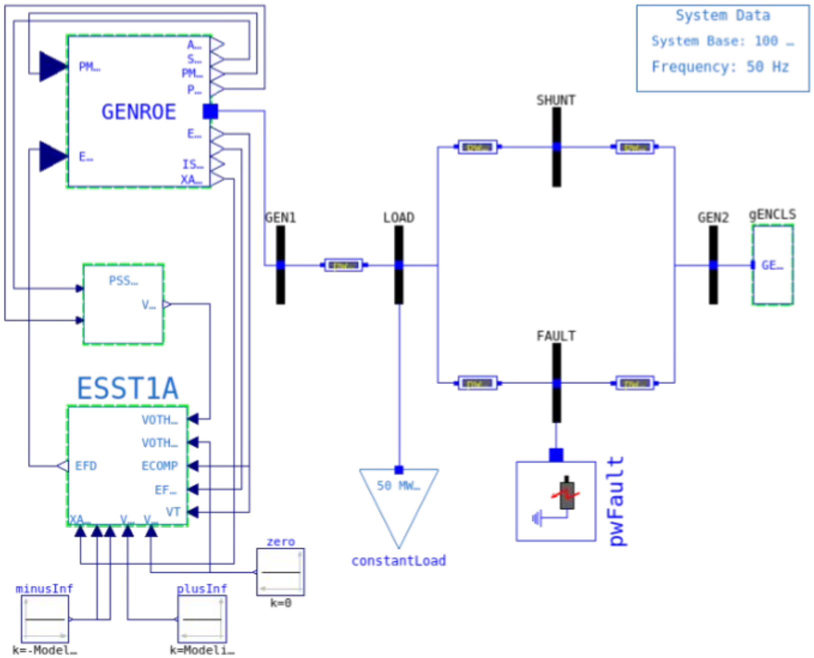


Historic Background

Power System Simulation

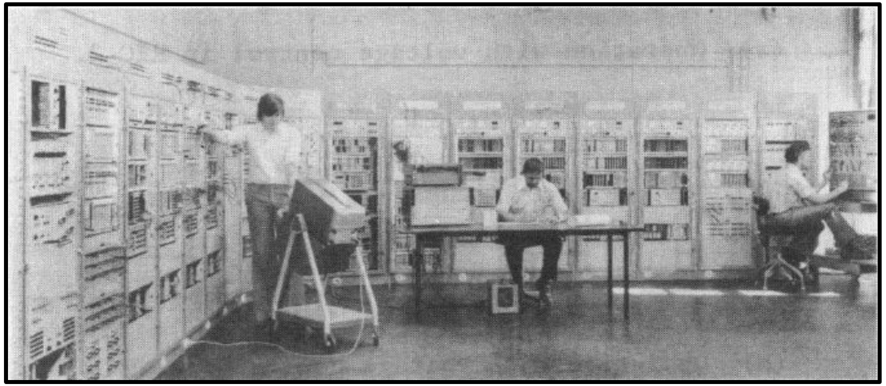
- The study of such complex systems rely heavily on the modeling and simulation.
- Several strategies have been developed in order to enable appropriate representation of power systems in its intrinsic complexity.

History Background: Analog World

- Models representing power systems, in the beginning needed to be tested using hand calculations and equivalent miniatures.
- Later on, with the development of analog electronic integrators, large analog computers were developed in order to reproduce the behavior of larger systems.

Digital World

- With the development of digital computers and appropriate algorithms, digital simulation became the most attractive strategy when representing power system models and its simulations.

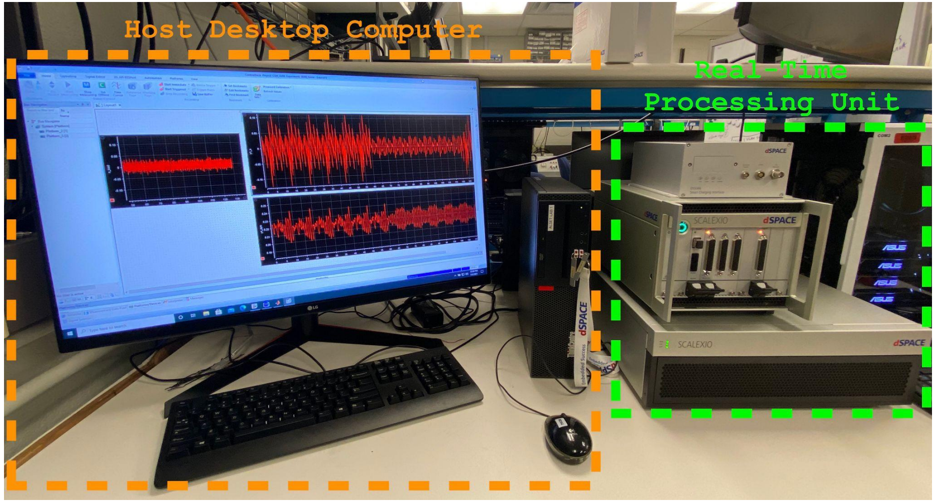


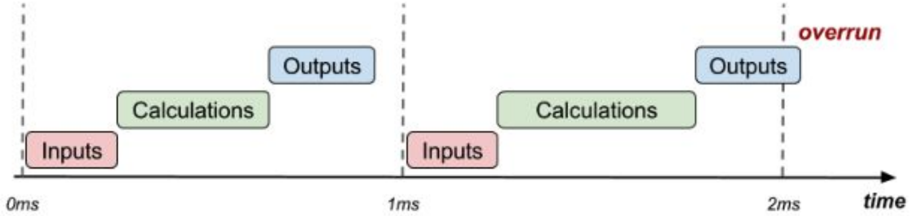
A group of highly trained engineers manipulating analog circuits in order to perform studies in this HV*dc* simulator owned by ASEA in the late 1970s.

Real-Time Simulation

Real-Time Digital Simulation

- First efforts dating from the end of last century with efficient algorithms being implemented in Digital Signal Processors (DSPs).
- Strategies are used in power systems to test solutions before they are experimented on the real power grid.
- Solution methods usually implement fixed-step solvers in order to guarantee that outputs (previous time-step) are available before the required time for an input to be obtained (next time-step).
    - If this time requirement is not achieved, an overrun occurs (it does not make simulation invalid!)





Motivation and Objectives

Current Approach in RT Simulation

- Different proprietary tools with closed source are used for:
  - Offline simulation
  - Control design
  - Real-Time testing.
- Lack of portability and tractability can be a bottleneck that should be addressed.

Modelica and FMI

- Real-time simulators have adopted model standards:
  - Functional Mock-up Interface
  - Modelica is compliant with the FMI
- Modelica can be used in offline simulations and control design of power systems.

Objective

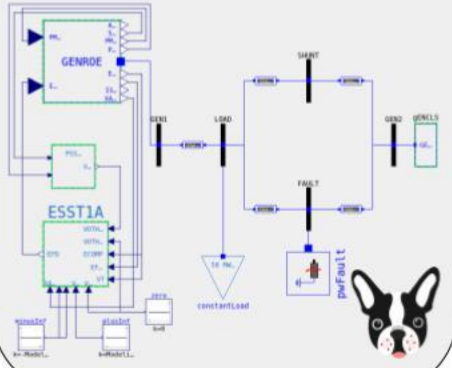
- Usage of standardized dynamical models, using Modelica language and the FMI standard, for deployment of power system models in real-time platforms.

Research Contributions

- Introduction and assessment of a framework using Modelica and the FMI as means to address the portability and tractability challenges that are common in power system studies involving real-time simulation.
- Assessment of OpenIPSL models, originally made for offline simulations, in a real-time environment with minimal modifications.

Real-time Framework Using the FMI: Step 1

1. Modelica Model Configuration



FMU Export

2. Application Configuration

Build & Load

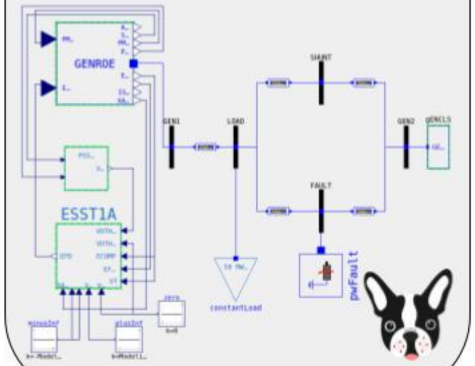
3. Real-Time Simulation

Step 1: Modelica Model Configuration

- Offline power system model is assembled in Modelica, and Dymola is used to add outputs to the original model.
- Export characteristics are also configured: co-simulation FMU, CVODE solver and simulation total time.
- Modifications are done using `equation` and `annotation` environments within Modelica model.

Real-time Framework Using the FMI: Step 2

1. Modelica Model Configuration



FMU Export

2. Application Configuration

Build & Load

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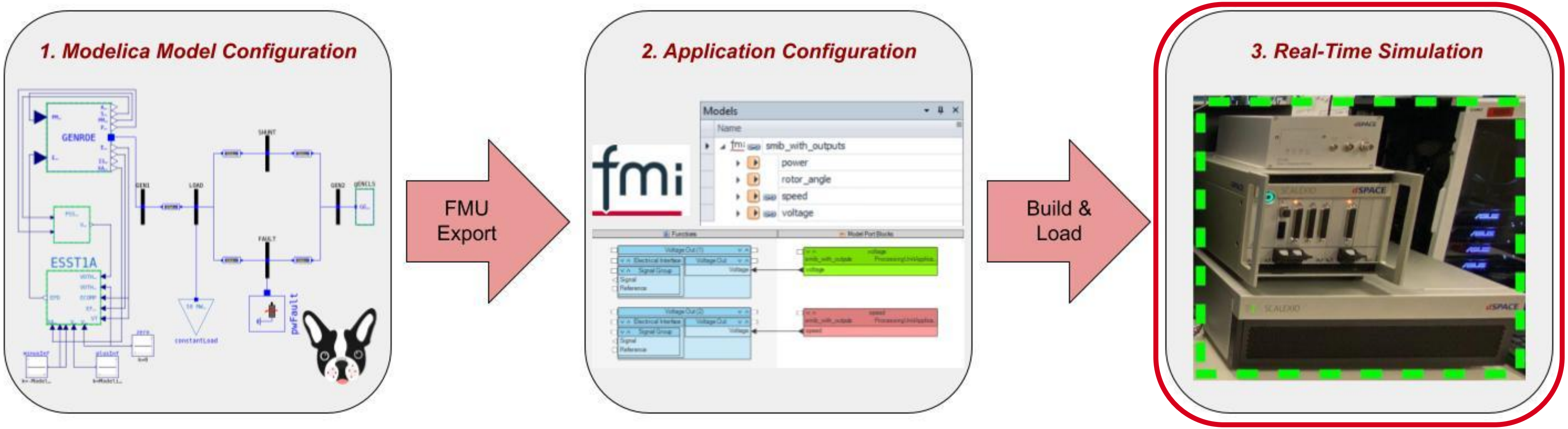
Application Configuration

- FMU is loaded into ConfigurationDesk:
    - Real outputs from Modelica model are assigned to output pins from I/O board & simulation time is assigned for real-time application
- Model is built for real-time simulation.

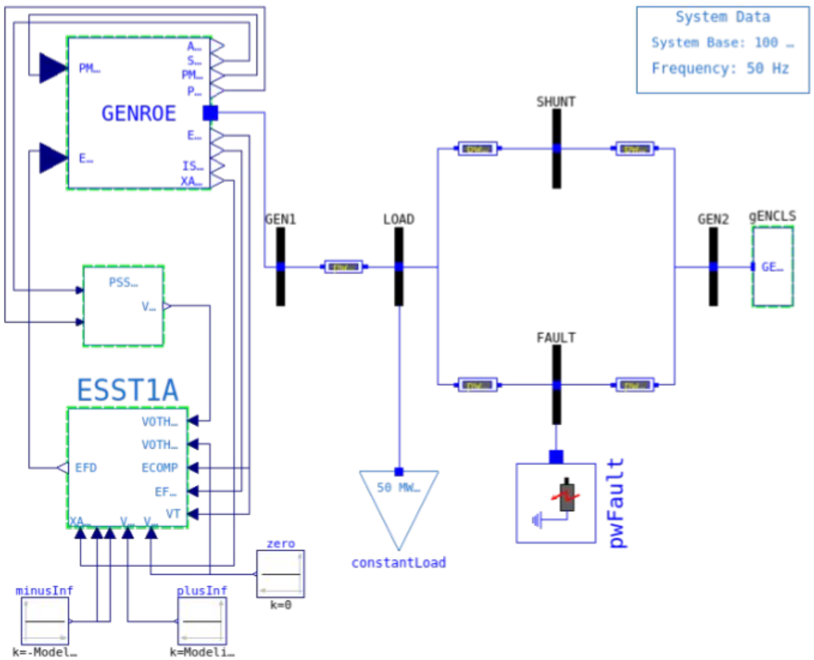
Real-time Framework Using the FMI: Step 3



Real-Time Simulation

- Output channels are connected to oscilloscopes and real-time application is loaded into processing unit.
- Simulation runs in dSPACE Scalexio.

Real-Time Model for SMIB

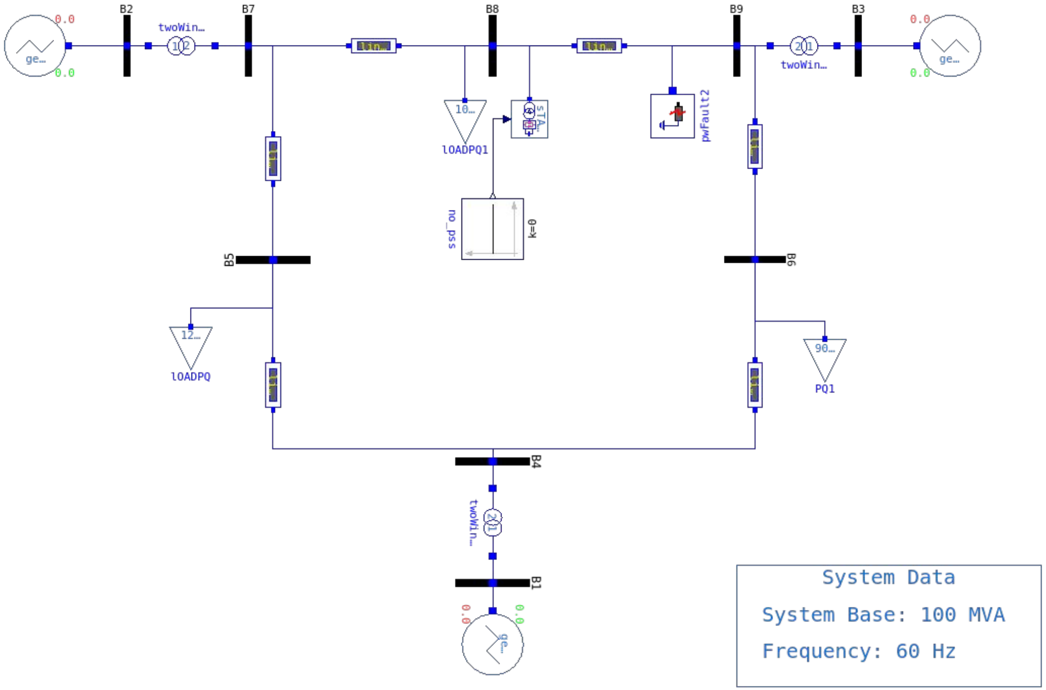


Single Machine Infinite Bus (SMIB) system tested for real-time simulation of a three-phase fault at 2.0 seconds.

Listing 1. Equations added to SMIB model for representing outputs of interest.

```
equation
  dfreq = 2 + gENROE.SPEED*SysData.fn
  "Frequency deviation with offset";
  rotor_angle = gENROE.ANGLE
  "Rotor angle measurement";
  voltage = gENROE.ETERM
  "Generator's terminal voltage magnitude";
  power = gENROE.PELEC
  "Generator's active power output";
```

Real-Time Model for IEEE 9-Bus 3-Machine



IEEE 9-bus 3-machine with STATCOM, tested for real-time simulation of a three-phase fault at 2.0 seconds.

Listing 2. Equations added to IEEE 9-bus model for representing outputs of interest.

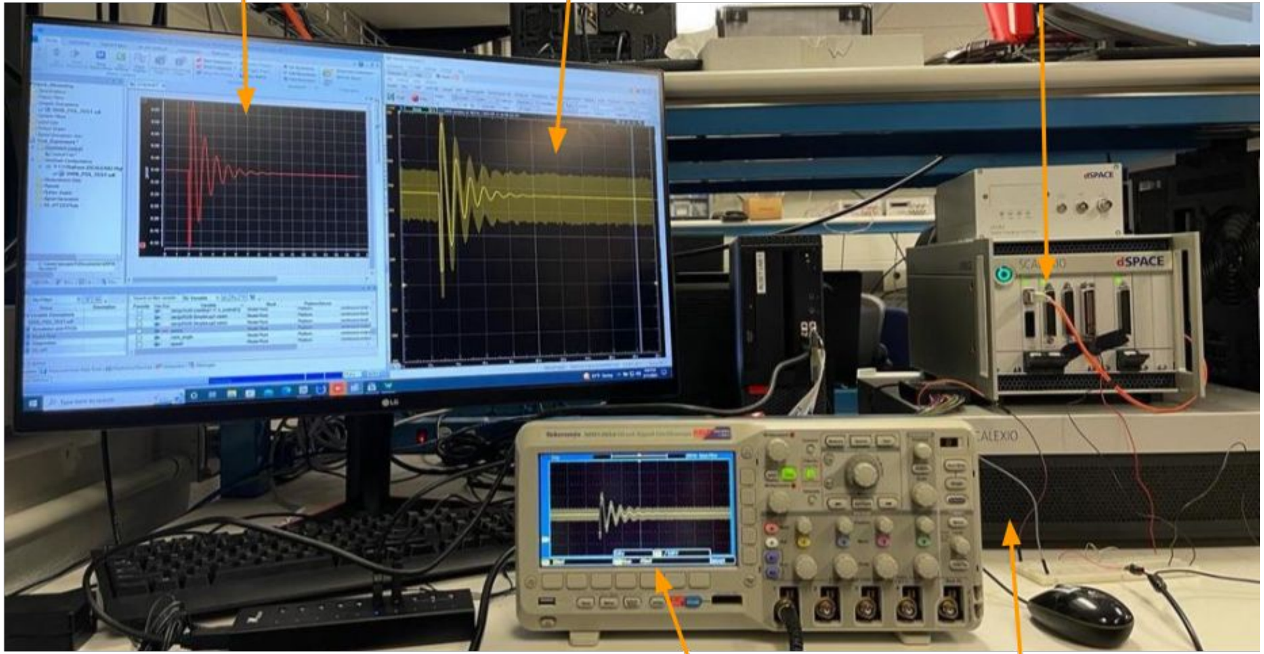
```
equation
  statcom_out = sTATCOM.Q + 0.5
  "STATCOM's reactive output with offset";
  gen_Q = gen1.gen.Q + 0.5
  "Gen 1 reactive output with offset";
  freq_gen1 = gen1.gen.w*SysData.fn-59
  "Gen 1 frequency deviation with offset";
  freq_gen3 = gen3.gen.w*SysData.fn-59
  "Gen 3 frequency deviation with offset";
```

Real-Time Simulation Setup

Real Time Simulation Result

USB Oscilloscope Measurement

Input/Output Boards



Oscilloscope Measurement

Real-Time Processing Unit

Setup description

- Host computer can control configuration aspects from model to be simulated;
- Host computer is connected to real-time processing unit using ethernet cable;
- I/O board is directly connected to processing unit;
- Reading devices use I/O board pins.

Real-Time Simulation Setup

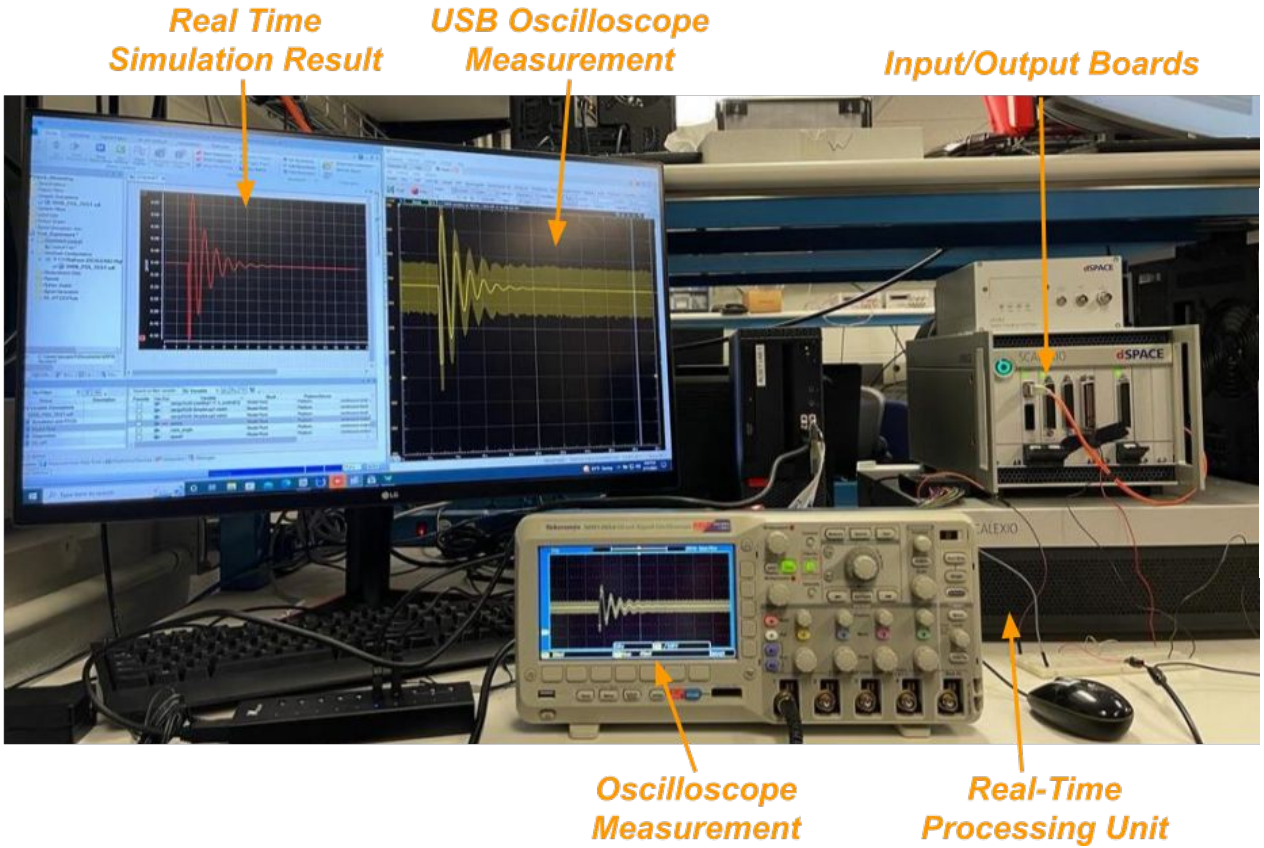
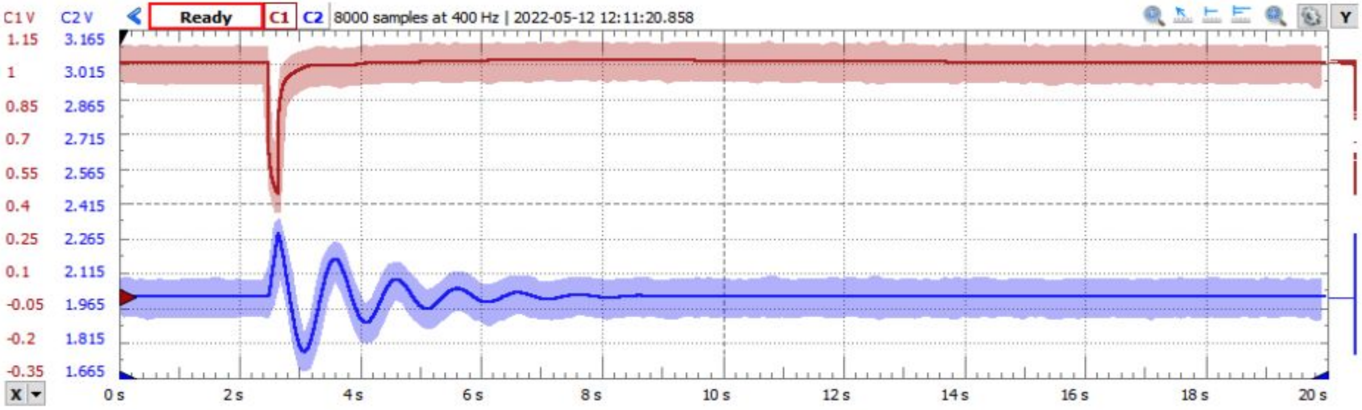


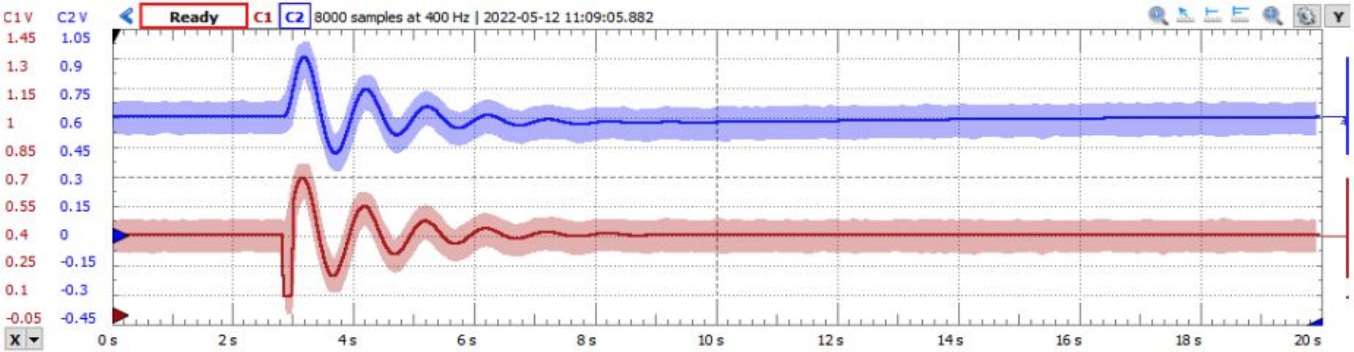
Table 1. Hardware and simulation specifications.

Parameter	Description
Processor	Intel® Xeon® E3-1275 v3
Number of cores (used)	4 (1)
Clock Frequency	2.8 GHz
RAM size	8 Gb
Flash size	512 Mb
Allocated task stack size	1024 Kb
Task time step	1 ms
Overrun Count Max.	150

Real-Time Results for SMIB

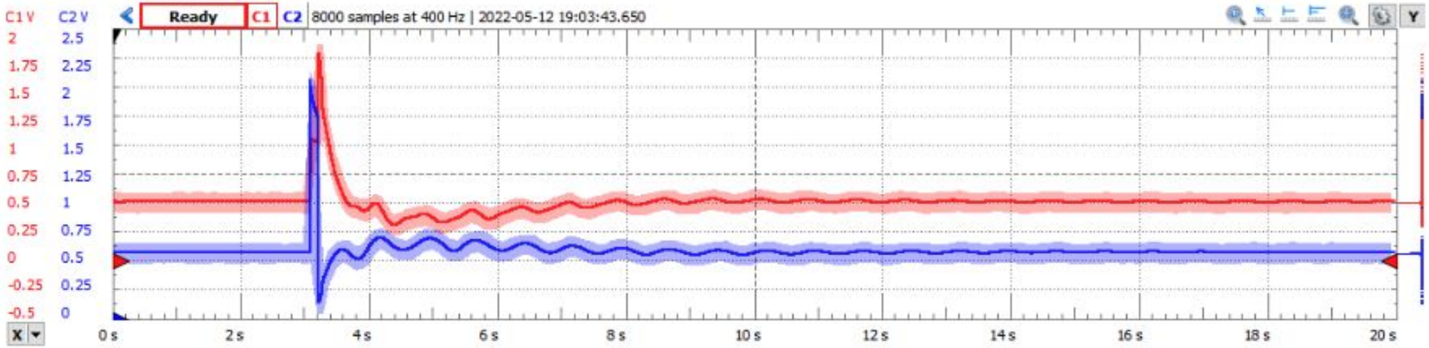


Red: generator's terminal voltage; Blue: deviation from nominal frequency, centered at 2 V.

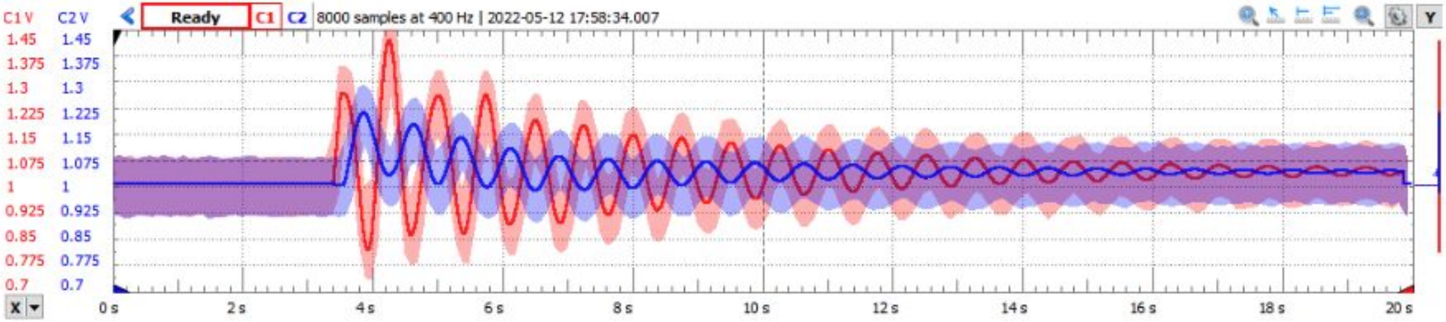


Red: generator's electrical power output; Blue: generator's rotor angle.

Real-Time Results for IEEE 9-Bus 3-Machine



Red: STATCOM reactive power, center at 0.5 V; Blue: Gen. 1 reactive power, centered at 0.5 V.



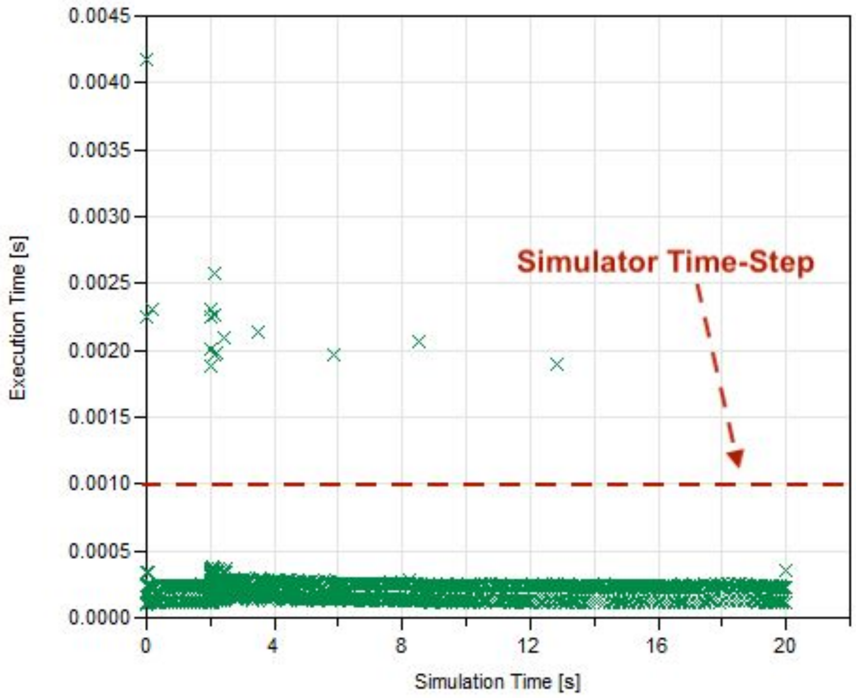
Red: Gen. 1 frequency deviation, center at 1 V; Blue: Gen. 3 frequency deviation, center at 1 V;

Real-Time Simulation Execution Time: SMIB

Discussion

- IEEE 9-bus is 29% larger, in terms of DAEs, but overruns are more than 3.22 times the value observed for the SMIB.
- Offline analysis allow engineers to understand selection of time-step and its limitations in real-time simulation.

Studied System	SMIB	IEEE 9-bus
DAEs	369	476
Initialization Overruns	2	3
Simulation Overruns	16	106
Task Turnaround Time (μs)	≈ 83	≈ 268



Execution time in Dymola and simulator time step for SMIB system, with 18 total overruns.

Real-Time Simulation Execution Time: IEEE 9-bus

Discussion

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- Offline analysis allow engineers to understand selection of time-step and its limitations in real-time simulation.

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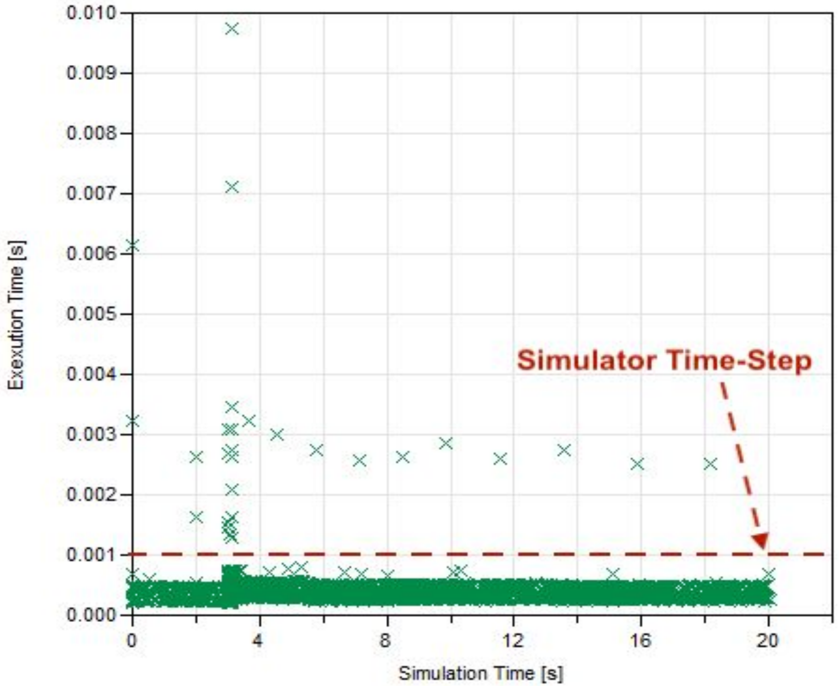

Execution time in Dymola and simulator time step for IEEE 9-bus 3-machine system, explaining 109 total overruns.

Conclusions and Future Works

Conclusions

- Presentation of a framework that allows power system simulation studies to be performed using power network models, built using Modelica and the OpenIPSL and exported using the FMI.
  - Models built using Modelica and the FMI are usually built for offline studies and control design
  - This study show their potential for real-time study
  - Overrun analysis
- Adopting the framework, the same system can be used for ***both*** offline and real-time simulations.
- Enhanced portability and model tractability.

Future Works

- Parallelization:
  - The authors want to assess how models can be separated in order for computation to be parallelized, enhancing simulation performance.
  - Connection of multiple FMUs should also be challenging.
- Control-hardware-in-the-loop:
  - This would close the existing gap, allowing the same model to be used from offline simulations, control design, and real-time testing of control architectures.
  - This would allow Modelica models to be tested under maximum portability and tractability.

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Thank you!

Questions?

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