Co-simulation for model coupling

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TU Delft

Outline

- A few examples of problems
- Co-simulation as methodology
- Examples of IEPG projects
- Open challenges

Example #1: Technical grid studies of interconnected power systems

- COBRAcable - HVDC connection: 325 km, 320 kV, 700 MW
- Stability and reliability studies must be completed before deployment
- Tennet uses PowerFactory
- Energinet.dk uses PSS/E

Options:

- Model migration
- Co-simulation

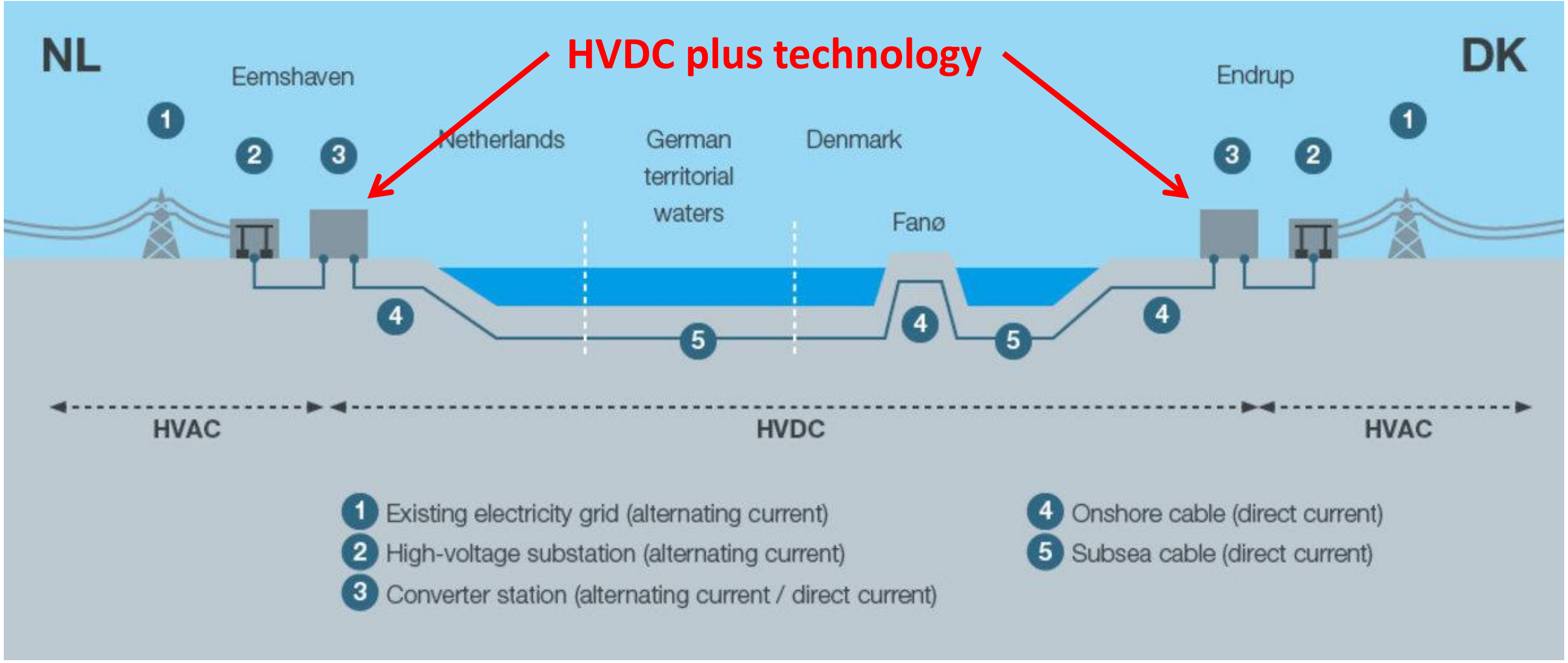
http://www.cobracable.eu/

PSS®E

DIgSILENT

Figure: www.prysmiangroup.com

Example #2: Proprietary technologies



The technology providers are not always open to disclose details of the implementation

Options:

- Controller 're-implementation'
- Encryption
- Share Dynamic Link Library (DLL)
- Co-simulation

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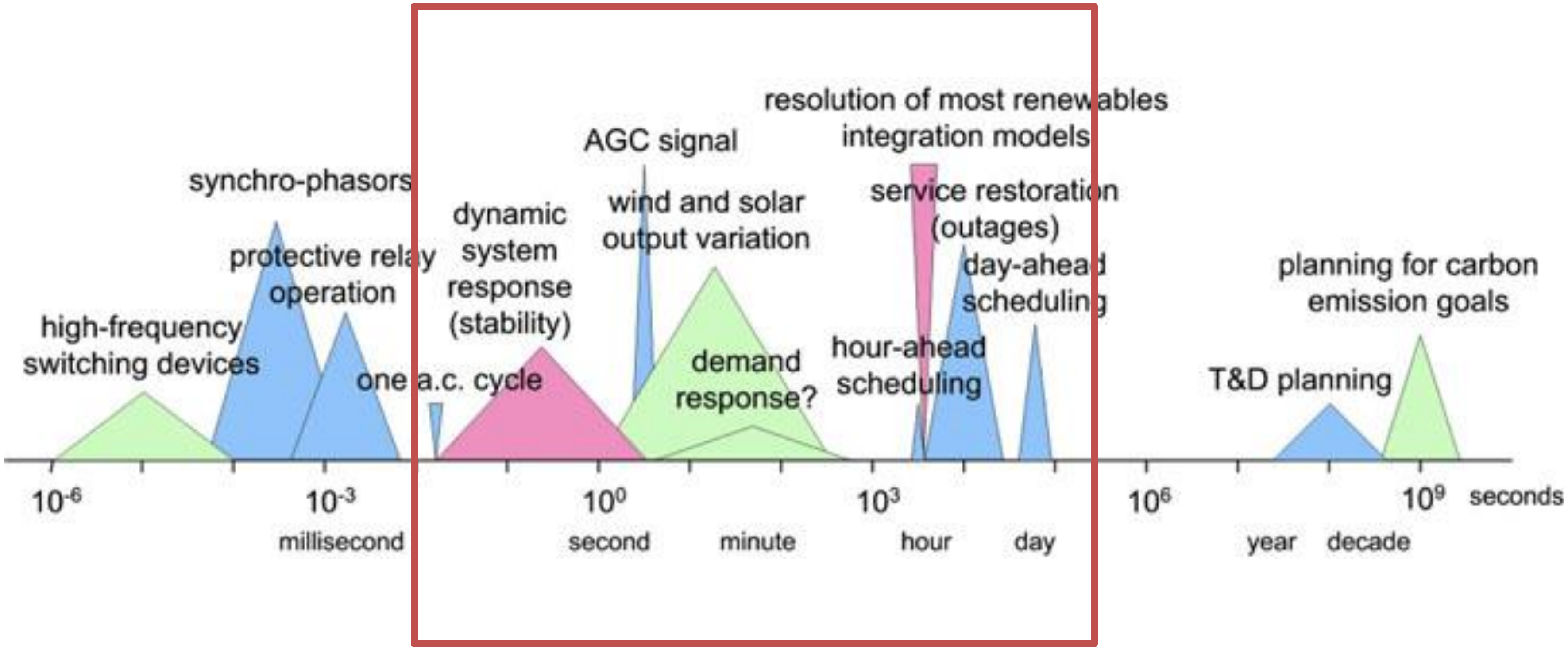
When do we @IEPG use co-simulation?

- Technical studies of interconnected systems
- Inclusion of proprietary (controller) models
- Verification of controllers with ICT
- Modeling of multi-energy systems
- Validation of impact of cyber-attacks
- Digital twin in the control room
- Interconnection of laboratories

- Improving performance of co-simulation solutions

Time scales



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Examples of co-simulations for power systems

Grid and ICT:

- EPOCHS, OpenDSS & OMNet+, Adevs & NS-2, GECO, PowerNet, VPNET, INSPIRE, OpenDSS & NS-2, TASSCS, etc.
- Summary in P. Palensky et. al, "Co-simulation of intelligent power systems", IEEE Industrial Electronics Magazine, 2016.

EMT + RMS:

- V. Jalili-Marandi et al. "Interfacing Techniques for Transient Stability and Electromagnetic Transient Programs", IEEE Tran on Power Delivery, 24 (4), Oct 2009.
- M. O. Faruque et al. "Interfacing Issues in Multi-Domain Simulation Tools", IEEE Tran on Power Delivery, 27 (1), Jan 2012.

Hardware in the Loop:

- W. Ren et. al, "Improve the Stability and the Accuracy of Power Hardware-in-the-Loop Simulation by Selecting Appropriate Interface Algorithms," 2007 IEEE/IAS Industrial & Commercial Power Systems Technical Conference, 2007.

Other big initiatives:

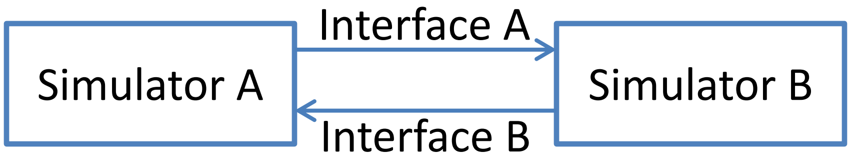
- EriGrid consortium, Real-time super lab, etc.
- DOE's Grid Modernization initiative (HELICS, GridSpice, FNCS, OpenHybridSim, etc.)

When is co-simulation useful in general?

- For interconnecting models encapsulated within domain-specific tools
- For overcoming privacy concerns
- For interconnection of more domains (heat, electricity, governance, etc.)
- For interconnection across spatial scales and time-scales
- For interconnection of continuous and discrete models (grid and ICT)
- For validation of algorithms
- For scalability, transparency, flexibility of the simulation environment

Co-simulation development in action

- Co-simulation – a methodology for coupling of two or more software packages or models whose execution depends on each other
- The models, their solvers and software packages are typically assumed as given



- The methodology focuses on:
  – **Development (deployment) of master algorithm for coupling**
  – **Interface development**
  – **Performance improvement**

- Skills needed: programming, computer science,
  signal processing, numerical mathematics
- EE4655 Co-simulation of energy systems (course at EWI)

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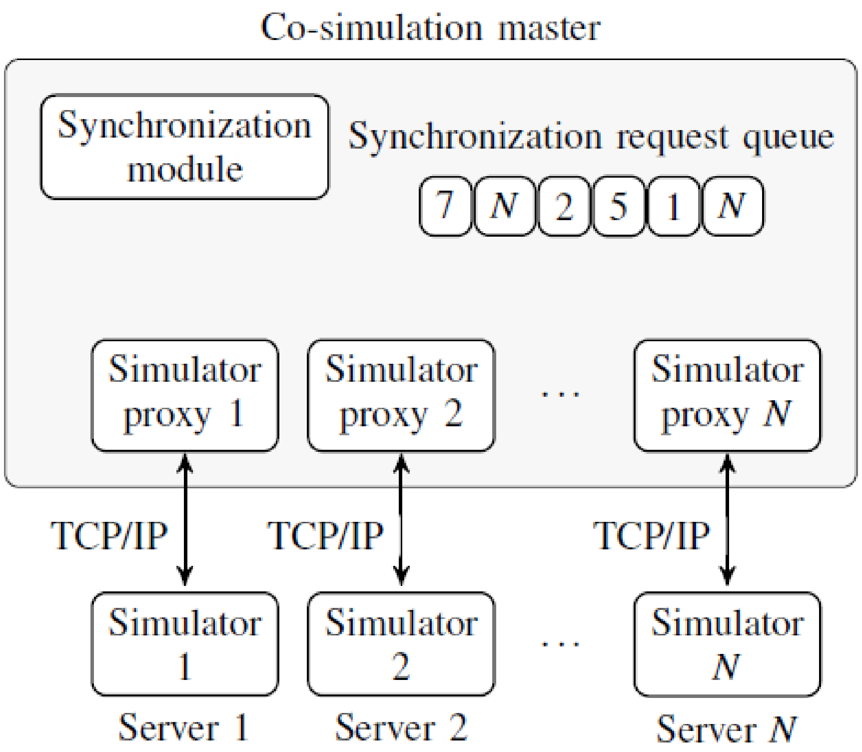
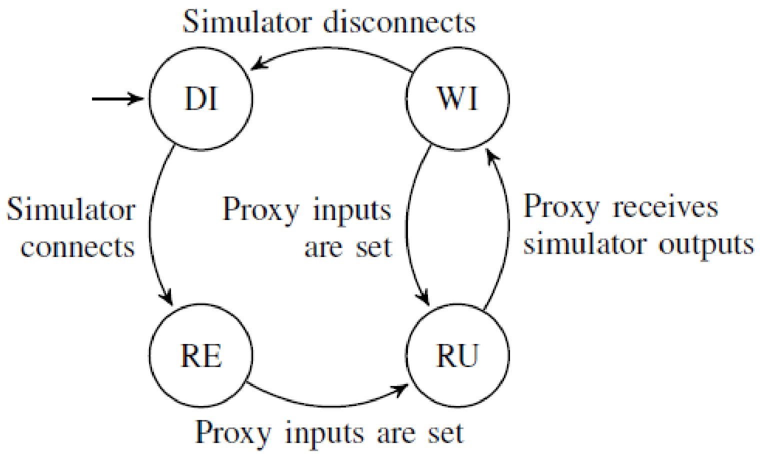
Master algorithm

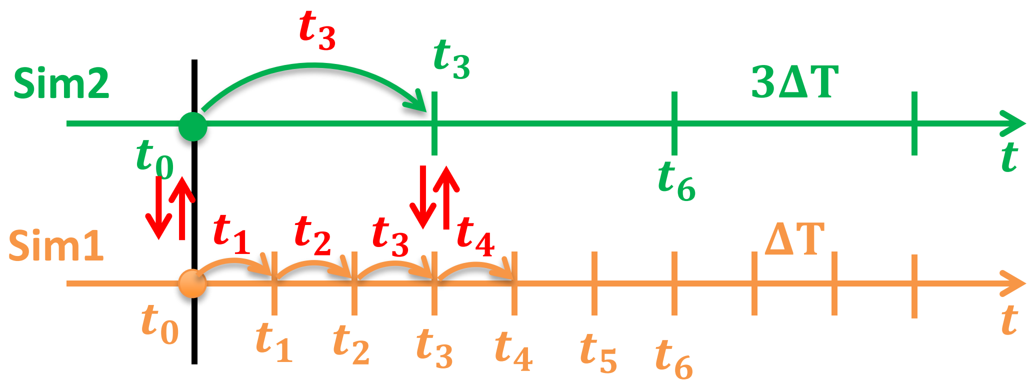
- A software code which manages synchronization and message exchange





C. D. Lopez, A. V. D. Meer, M. Cvetkovic, P. Palensky, "A Variable Rate Co-simulation Environment for the Dynamic Analysis of Multi-area Power Systems", IEEE Power & Energy Society PowerTech, Manchester, UK, June 2017.

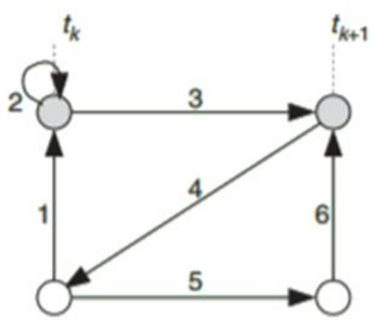
Co-simulation synchronization



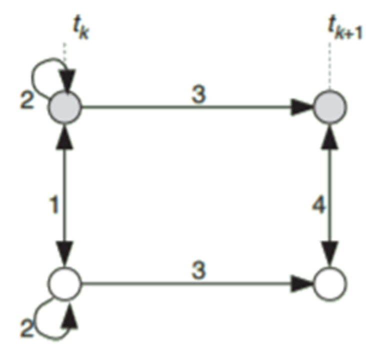
t – global time

t – local time for Sim1

t – local time for Sim2



Serial (Gauss-Seidel)



Parallel (Jacobi)

Handling asynchronous events?

Choice of the co-simulation master

1. One simulator as a master
   - All simulators synchronize to internal clock of one simulator
   - Examples: OMNET++, RTDS
   - Synchronization points and sequence are implicitly defined in this tool

2. Top-down approach (strongly coupled simulators)
   - One tool orchestrates the whole co-simulation
   - Example: Mosaik
   - Synchronization points and sequence are explicitly defined in the master code

3. Bottom-up approach (loosely coupled simulators)
   - Each simulator decides on its synchronization method
   - Example: HLA
   - Synchronization points and sequence
     are explicitly defined by communication points
     and synchronization requests of each simulator

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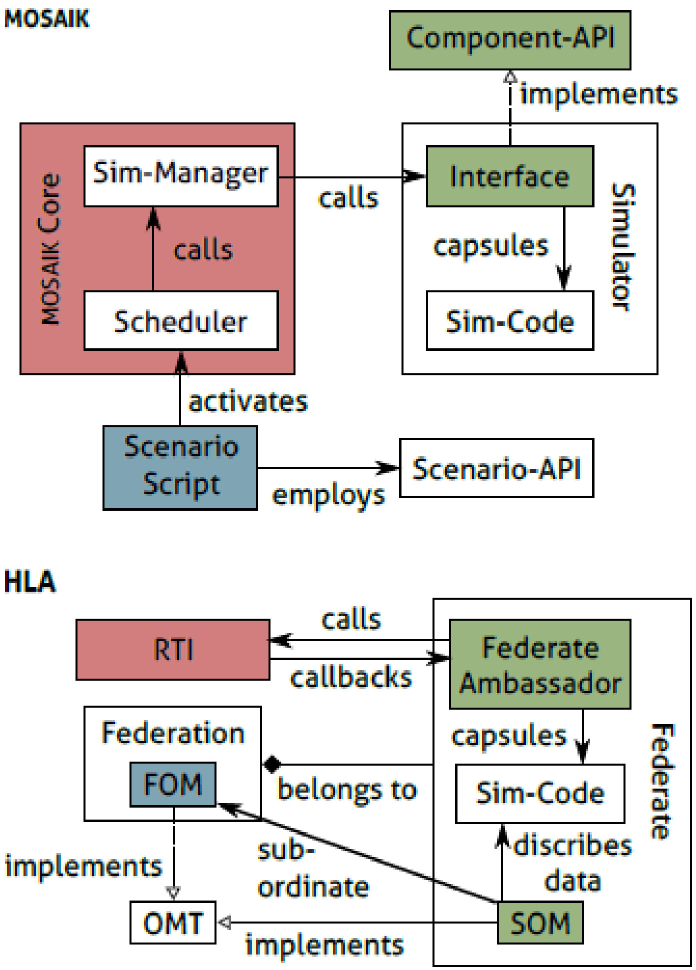
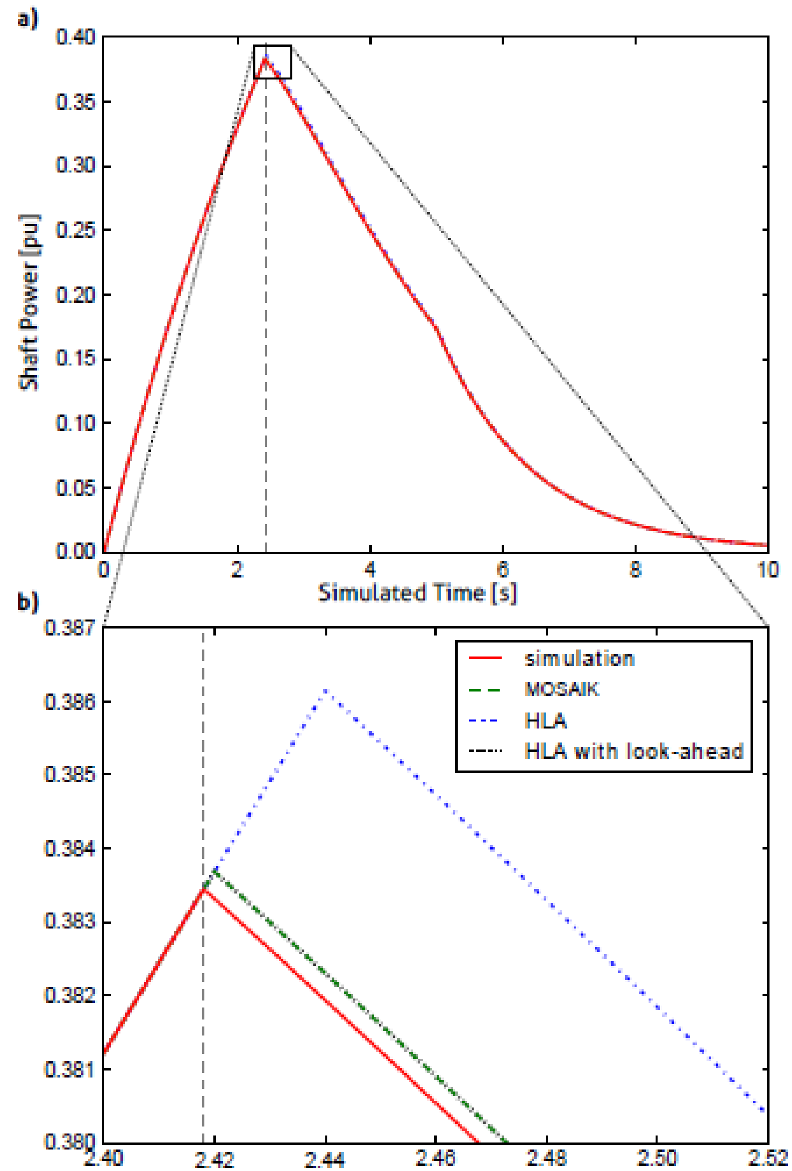
Mosaik vs. HLA

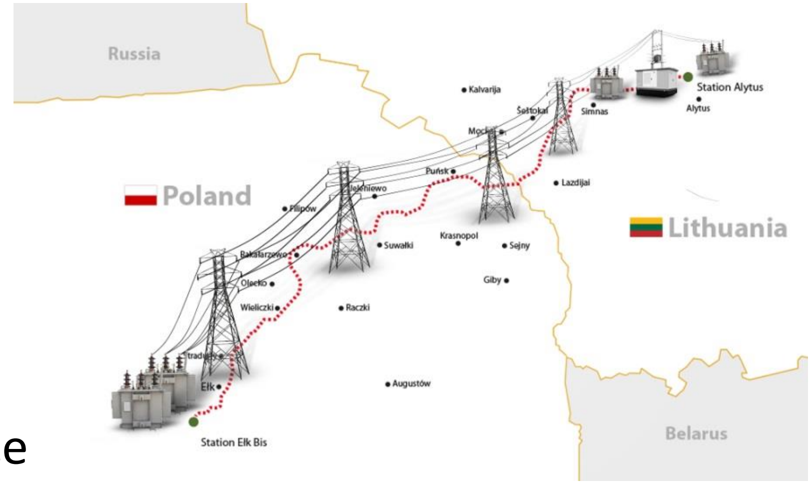




Interface model

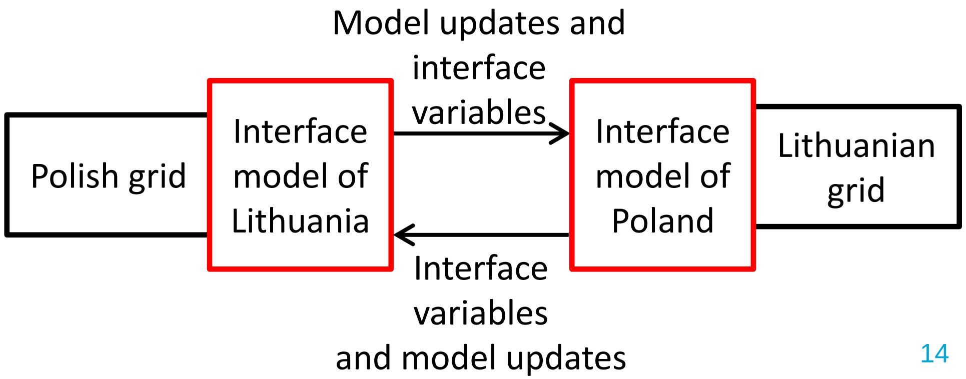
- Interface model is a representation of the second simulator/model as seen from the interface of the first simulator/model

- Interface model could be taught of as a surrogate model whose purpose is to improve stability and/or speed of the co-simulation



Some interface options for circuit models:

- Ideal transformer (voltage/current) source
- Thevenin/Norton equivalent
- Partial Circuit Duplication
- Damping Impedance Method



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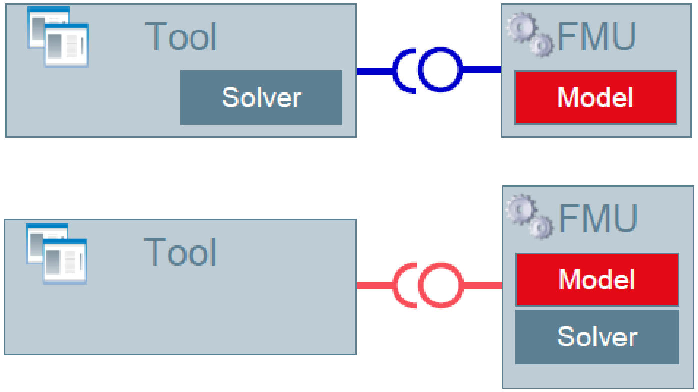
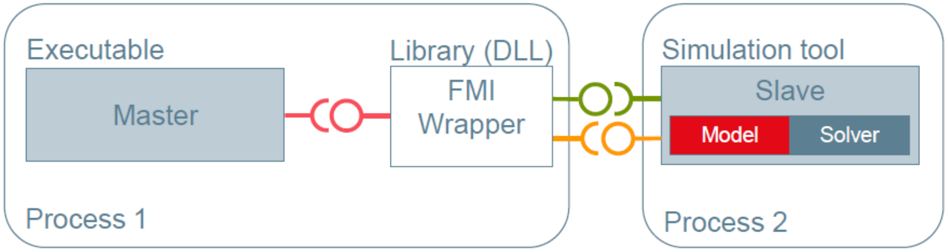
Functional Mockup Interface (FMI) standard

- Open standard for co-simulation of differential equation-based models
- The models are packaged inside Functional Mockup Units (FMUs)

- Provides the possibility to evaluate the model and its Jacobian
- Provides options for initializing, starting, stepping and stopping the model, etc.





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Performance considerations

- Co-simulation has a high overhead if the message exchange is of relatively high frequency while the internal model computations are relatively fast

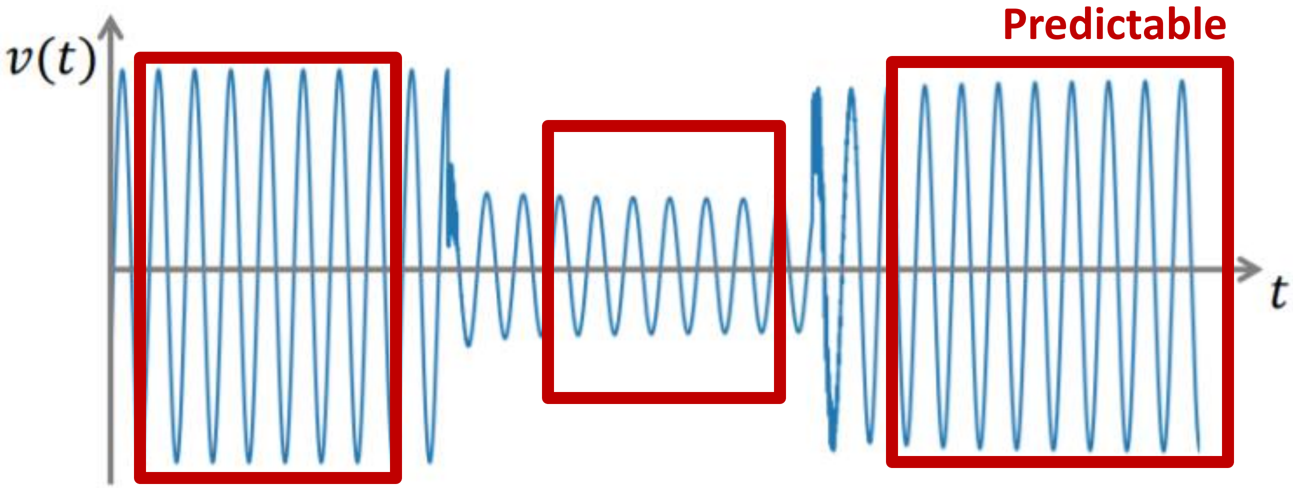
- Grid simulations often fall in this category

- Improving speed, accuracy and/or scalability by smart choice of interface

Improving grid co-simulation performance

Claudio Lopez

- Q: Can we speed up co-simulations by selectively decoupling predictable states without significant loss of accuracy?



- Methodology: Find a trajectory function that predicts simulator inputs. Decouple and recouple simulators based on the evaluation of this function.
- Implemented using Python and ZeroMQ. PowerFactory to come.

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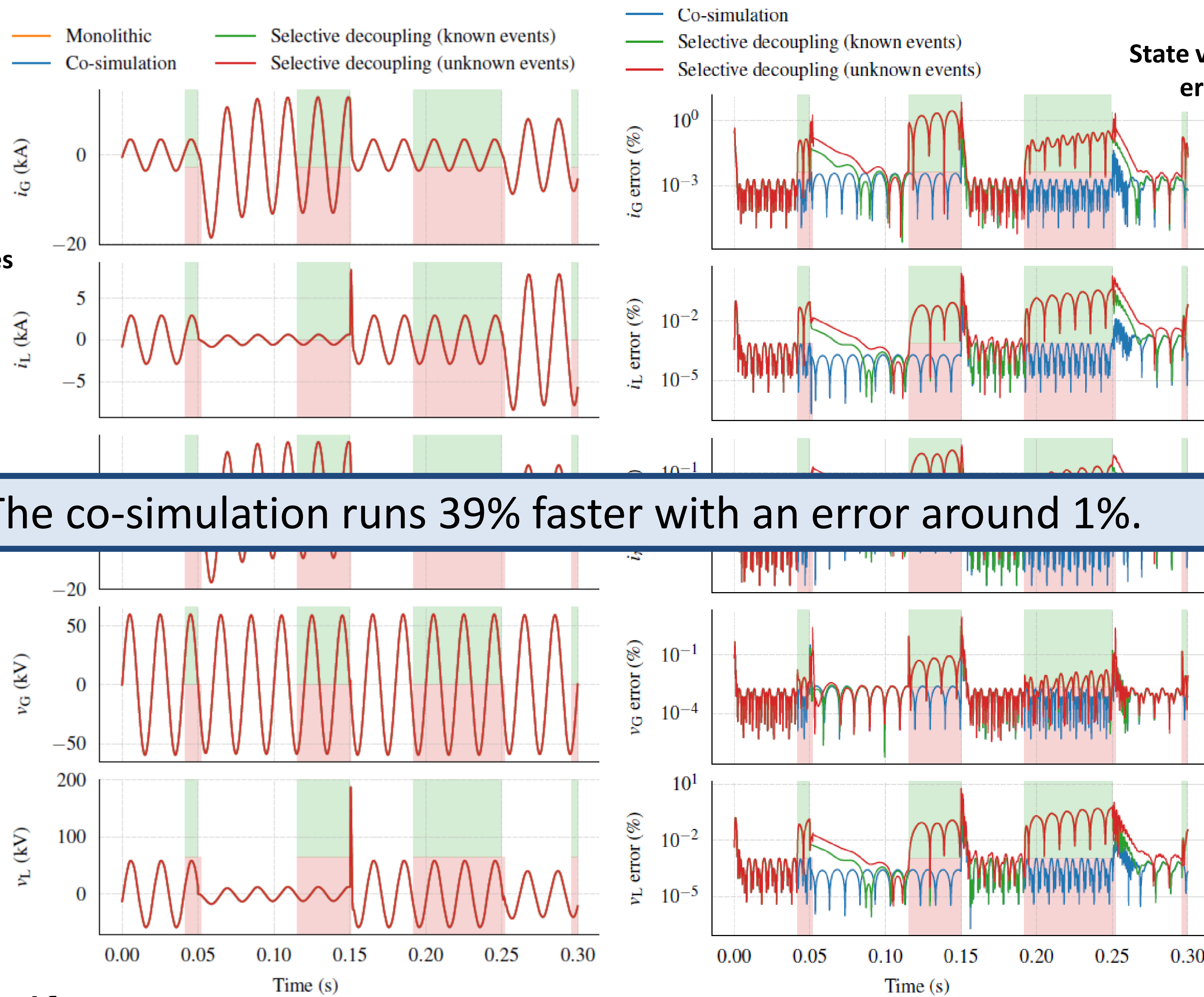
[*] C.D. López, M. Cvetković , P. Palensky, “Speeding Up AC Circuit Co-Simulations through Selective Simulator Decoupling of Predictable States,” IEEE Access, vol. 8, April 2019.

State variables

State variable error



The co-simulation runs 39% faster with an error around 1%.

[*] C.D. López, M. Cvetković , P. Palensky, “Speeding Up AC Circuit Co-Simulations through Selective Simulator Decoupling of Predictable States,” IEEE Access, vol. 8, April 2019.

Co-simulation projects at IEPG

- Modeling of multi-energy systems
- Validation of impact of cyber-attacks
- Digital twin in the control room
- Interconnection of laboratories

Modeling of multi-energy systems

Digvijay Gusain

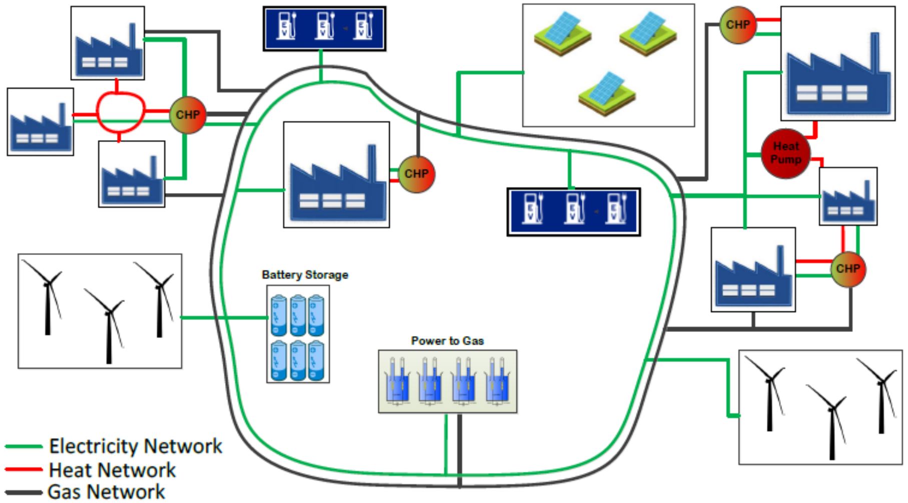
HaPSISH Heat and Power Systems at Industrial Sites and Harbours

- Q: Can we develop a multi-energy system simulation tool based on existing open source models?

- Methodology: Use Modelica as a base due to a large number of existing libraries and models. Package models as FMUs. Co-simulate FMUs in Python.

Modelica:

- Non-proprietary modeling language
- Multi-domain physics modeling
- Equation-based and object-oriented
- FMI/FMU compatible



D. Gusain, M. Cvetkovic, P. Palensky, “Energy Flexibility Analysis using FMUWorld”, Powertech 2019.

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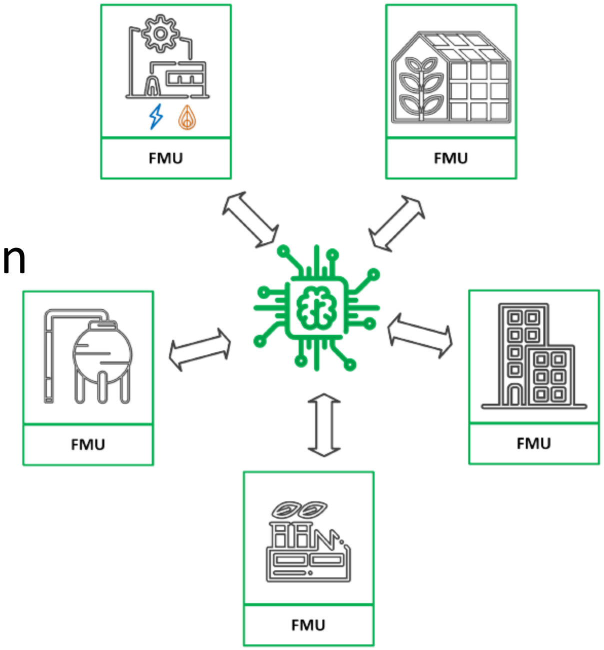
FMUworld

HaPSISH
Heat and Power Systems at Industrial Sites and Harbours

- Python based tool that connects multi-domain models packaged as FMUs
- Supported Modelica libraries:
  - OpenIPSL – benchmark power system models (iTesla project, KTH, RTE)
  - ThermoSysPro – thermal systems library (EDF France)
  - AixLib – thermal system library (IDEAS project, RWTH Aachen)
- In progress: PyPSA



Applications:

- Testing aggregator actions and microgrid operation
- Testing control and coordination strategies
- Sensitivity analysis
- Quick reconfiguration

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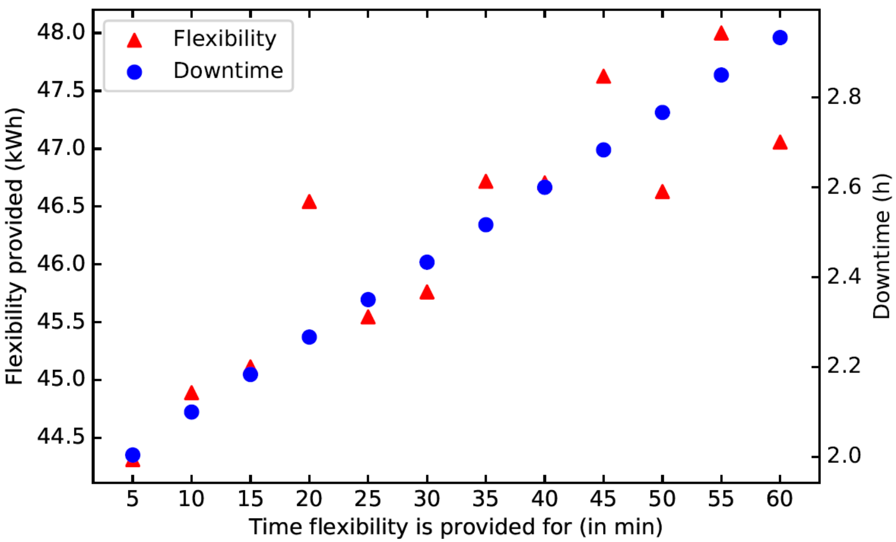
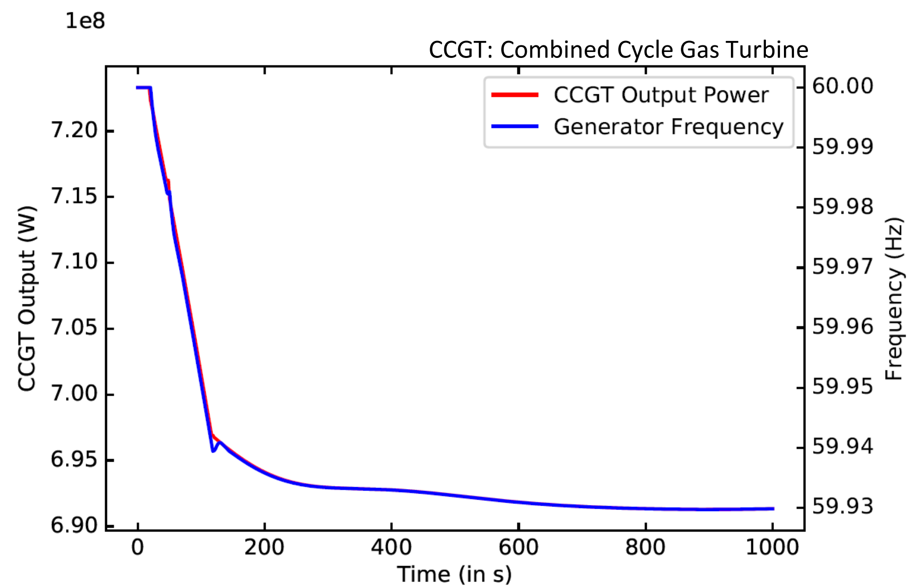
D. Gusain, M. Cvetkovic, P. Palensky, "Energy Flexibility Analysis using FMUWorld", Powertech 2019.

Flexibility analysis with FMUworld



Sensitivity analysis: analysing the impact of flexibility activation duration on downtime and total flexibility provided



Multi-energy simulation of a thermo-mechanical CCGT in a dynamic model of an IEEE test network

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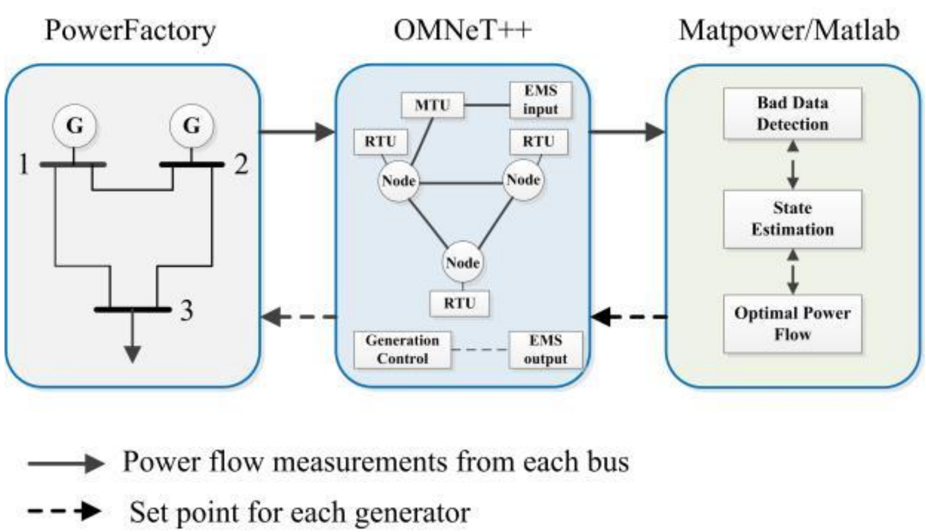
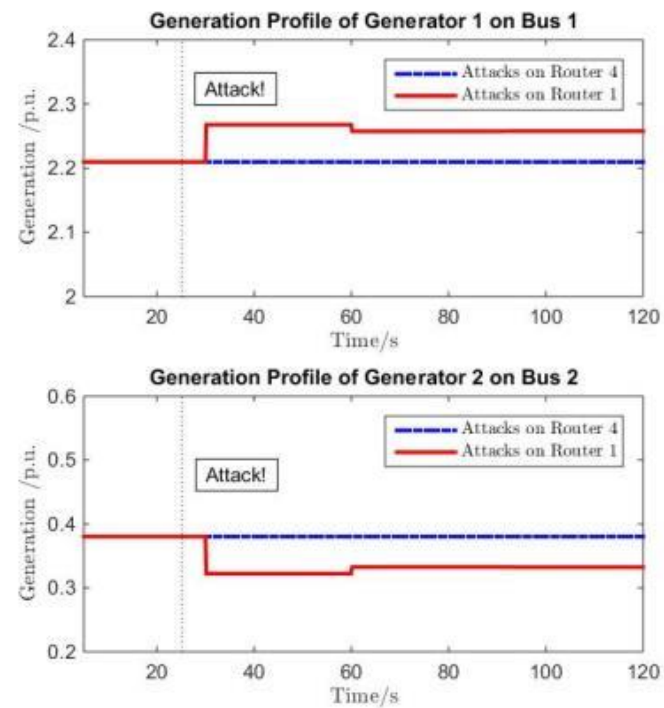
D. Gusain, M. Cvetkovic, P. Palensky, "Energy Flexibility Analysis using FMUWorld", Powertech 2019.

Validation of impact of cyber-attacks

Kaikai Pan

- Q: Validate the impact assessment of cyber-attacks using accurate numerical simulation tools.
- Methodology: co-simulation of PowerFactory (grid), OMNeT++ (attack model) and Matlab (state estimation)
- Challenge: customized scheduler in OMNeT++





K. Pan, A. Teixeira, M. Cvetkovic and P. Palensky, "Cyber Risk Analysis of Combined Data Attacks Against Power System State Estimation," in *IEEE Transactions on Smart Grid*. doi: 10.1109/TSG.2018.2817387

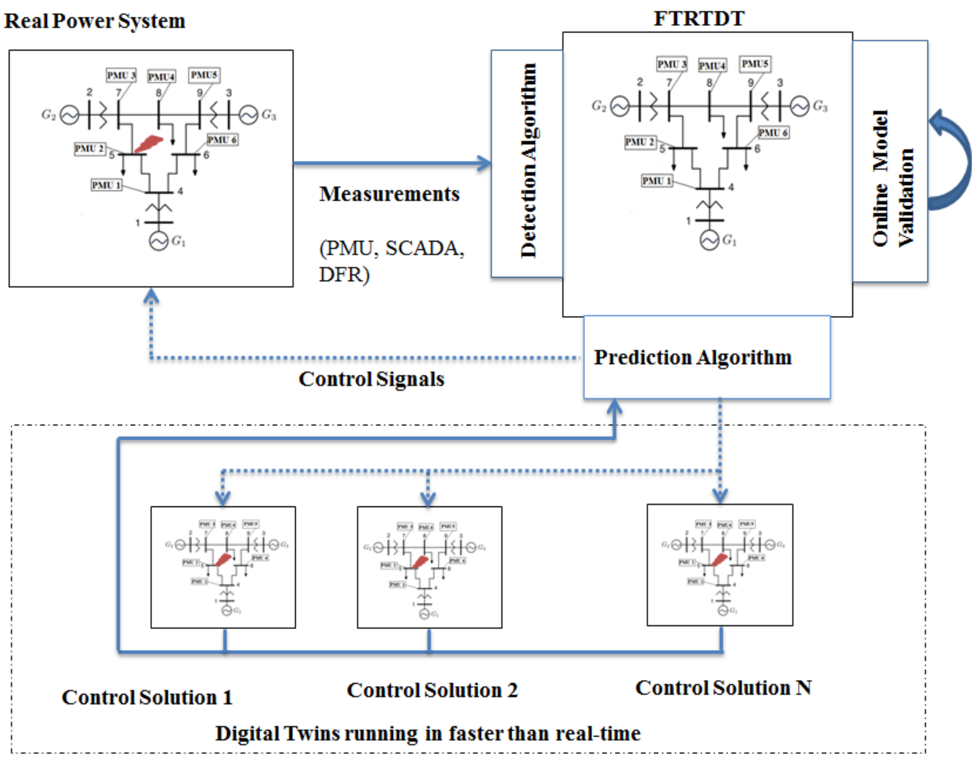
Digital twin in the control room

Arun Joseph

- Q: Can we implement a digital twin of power system for predictive control?
- Methodology: evaluate performance of simulation tools. Develop detection, model validation and prediction algorithms.

Digital twin:

- RTDS for power system emulation
- PowerFactory as the digital twin
- Master in Python, spawning replicas for evaluation of control solutions



A. Joseph, M. Cvetković, and P. Palensky, “Predictive Mitigation of Short Term Voltage Instability Using a Faster Than Real-Time Digital Replica,” in *IEEE PES ISGT-Europe*, 2018, pp. 1–6.

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EriGrid project

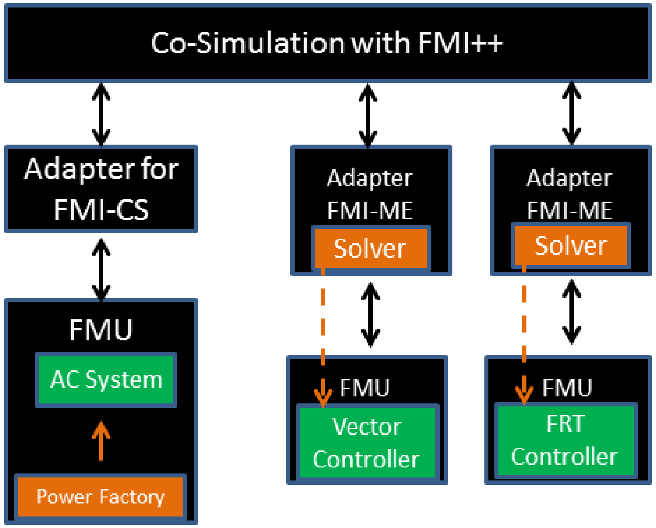
Rishabh Bhandia, Arjen van der Meer, Vetrivel Rajkumar

- Focus: develop co-simulation methodologies further. Deploy co-simulation for experimentation and testing.

- Targets: adaptation of FMI to power tools, improvement of co-simulation master algorithms, etc.

Latest test case:

- PowerFactory: IEEE 9 bus with a wind farm
- Matlab: FRT and converter controller
- FMI++ for interfacing
- Python script as a master

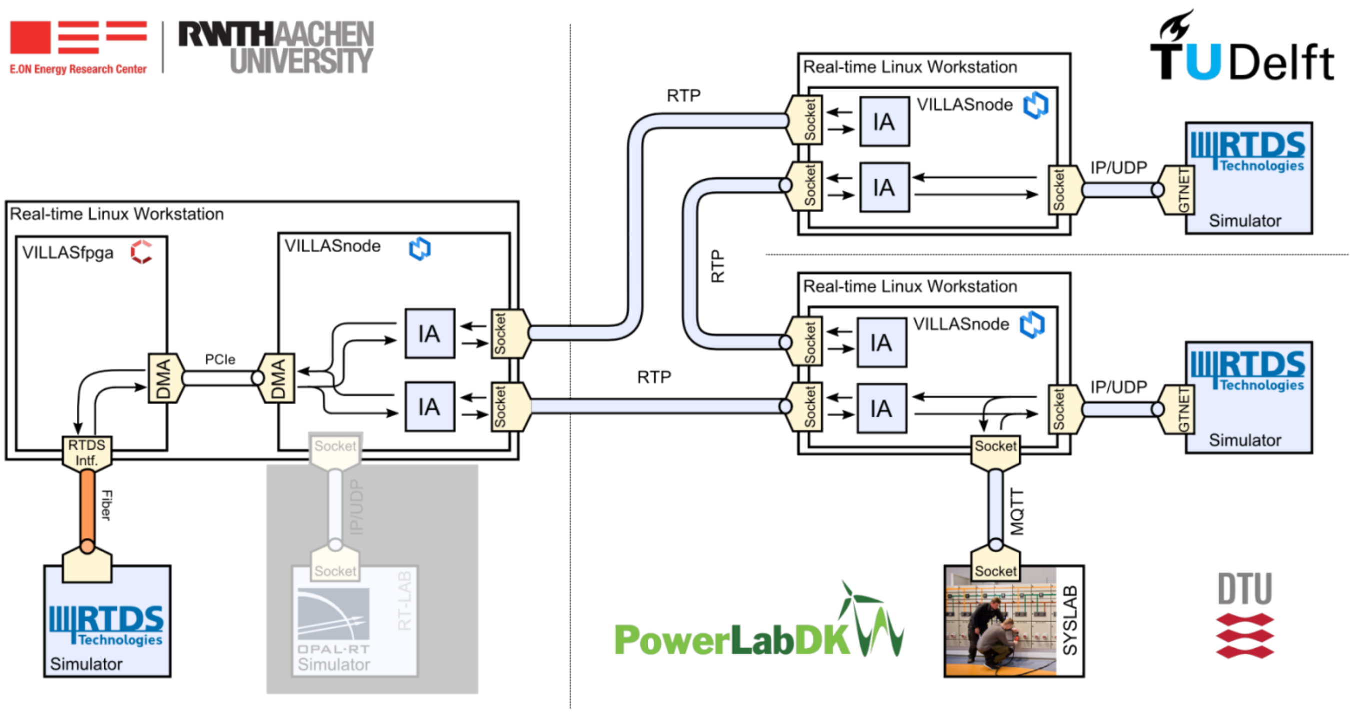


https://erigrid.eu/
Interfaces and test systems available at: https://github.com/ERIGrid/JRA2-TC1

Multisite co-simulation

Rishabh Bhandia, Vetrivel Rajkumar, Arjen van der Meer

- Q: Can we perform a geographically distributed real time co-simulation in order to perform join experimentation?
- Challenges: design of the Interface Algorithm (IA) to ensure simulation fidelity (accuracy, degree of similarity to the monolithic)
- Tools: RTDS, Villas framework (RTWH and PoliTo)



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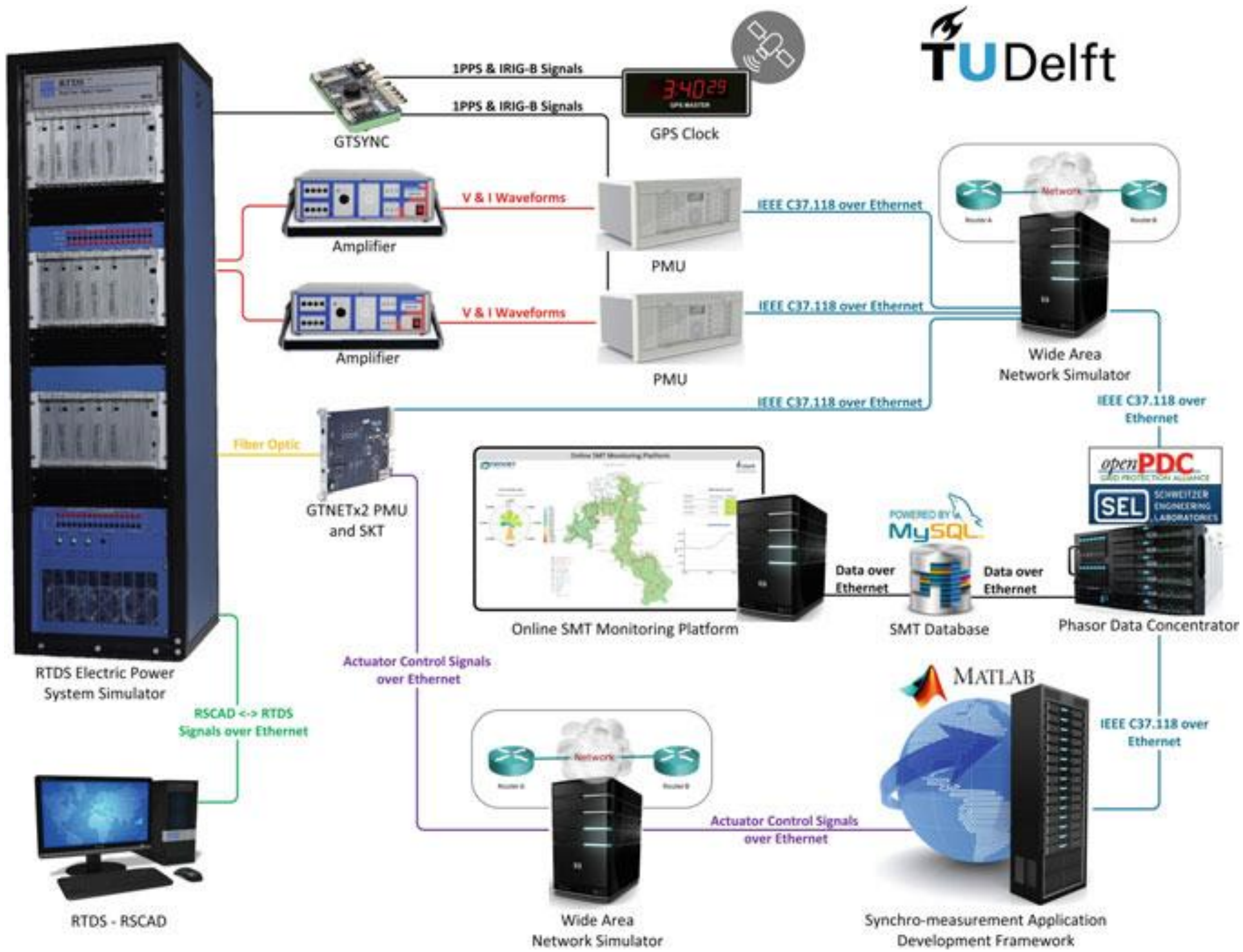
RTDS-lab of TU Delft - virtual control room



Additionally:
- Protection
- HIL

In future:
- control HIL

Projects:
- Migrate
- Promotion
- EriGrid
- Easy-Res
- TSO2020

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Open challenges

- Consolidation of time scales – short step operational models and long term decision making models
- The tradeoff between model fidelity vs. model/parameter/data uncertainty
- Accuracy vs. speed in relation to interface/surrogate models
- Guarantees on the performance (accuracy and speed) based on external limitations of the tools/models

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