# JRA3.2 TC1a: Integration of HIL to Co-simulation

## Tasks of the JRA 3.2 - European Research Infrastructure supporting Smart Grid Systems Technology Development, Validation and Roll Out (ERIGrid)

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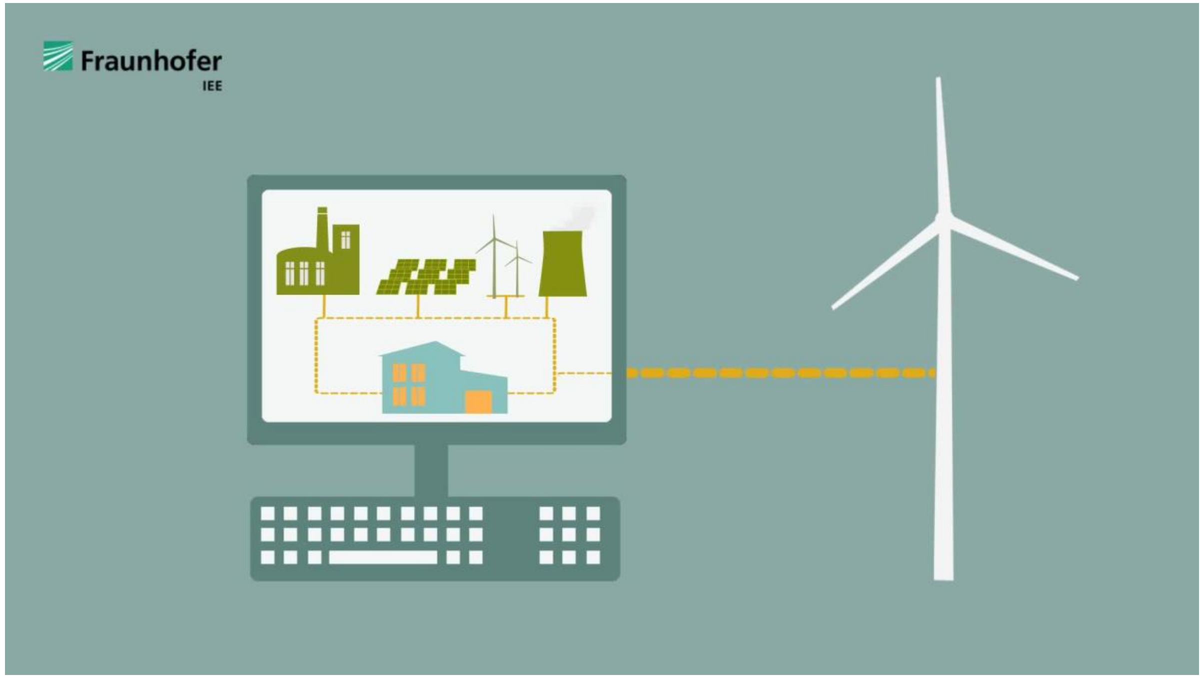
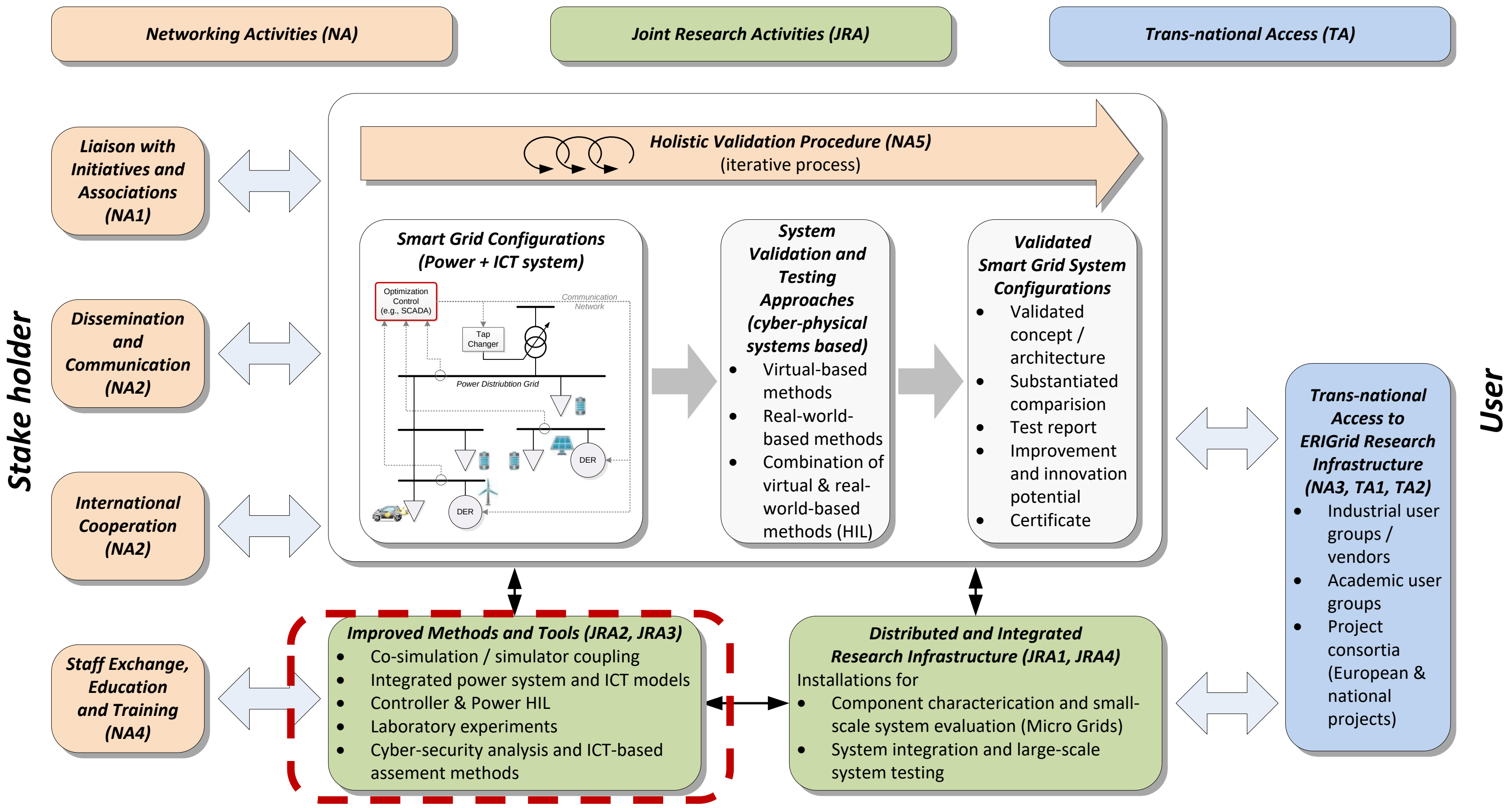
# Contents

# Background and Motivation
# What is Hardware-in-the-Loop?

1. A simulation model of a system executed on a Digital Real-Time Simulation (DRTS) in real-time mode
2. One or more salient components of that system existing outside of that DRTS
3. The DRTS simulation interacts with the salient component(s) outside the DRTS and vice versa



# Lab-based Assessment Methods (JRA 3.2)
# Activities and tasks schema



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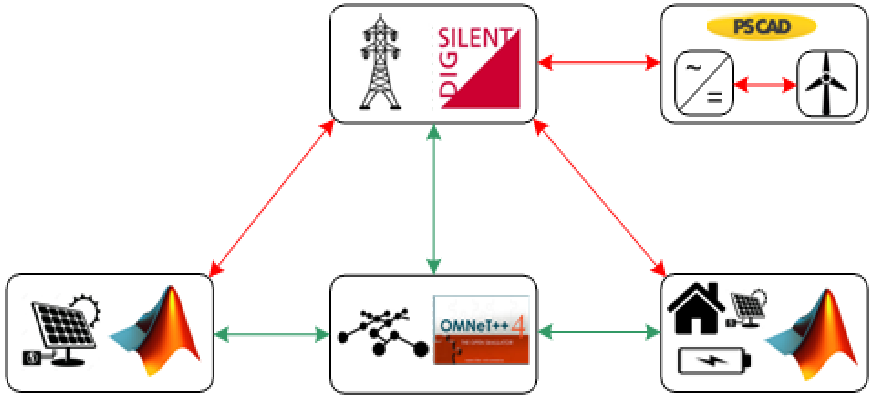
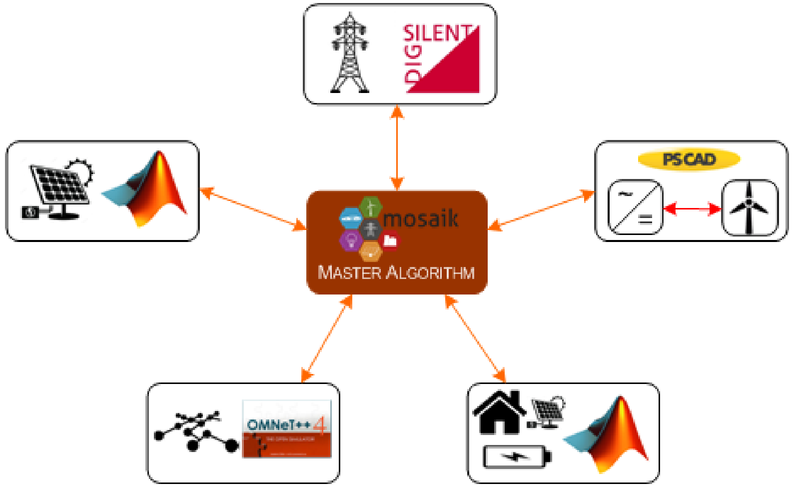
# Lab-based Assessment Methods (JRA 3.2)
## Status Quo of HIL: Co-simulation of Power and ICT systems

- Joint simulation of various simulators in an holistic test-case
  - Detailed and validated models with tailored solvers
  - Shared computational load
  - Model privacy
- Can be done ad-hoc or with Orchestrator





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# Lab-based Assessment Methods (JRA 3.2)
## Challenging the Status Quo: HIL and Co-Simulation Integration

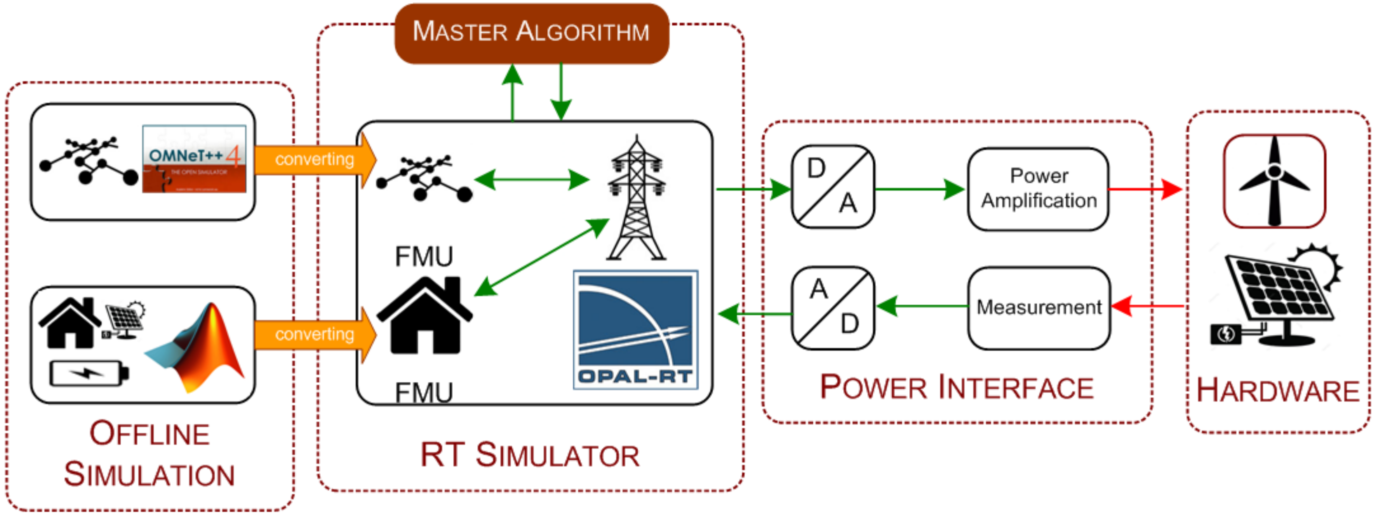
- Advantages:
  - Integrated multi-domains using Co-Simulation
  - Realistic behaviors of hardware
  - Collaboration multi-research-infrastructure in a holistic experiment
- Status-quo: Integration of HIL to Co-Simulation
  - Integration PHIL to Co-Simulation presents many challenges
  - Synchronization may not be possible

# Lab-based Assessment Methods (JRA 3.2)
# ERIGrid Approach to Address Challenges: Extending HIL Capacity

## ❖ 3 approaches for integration of HIL to co-simulation framework

### 1. « Offline » Co-Simulation Approach

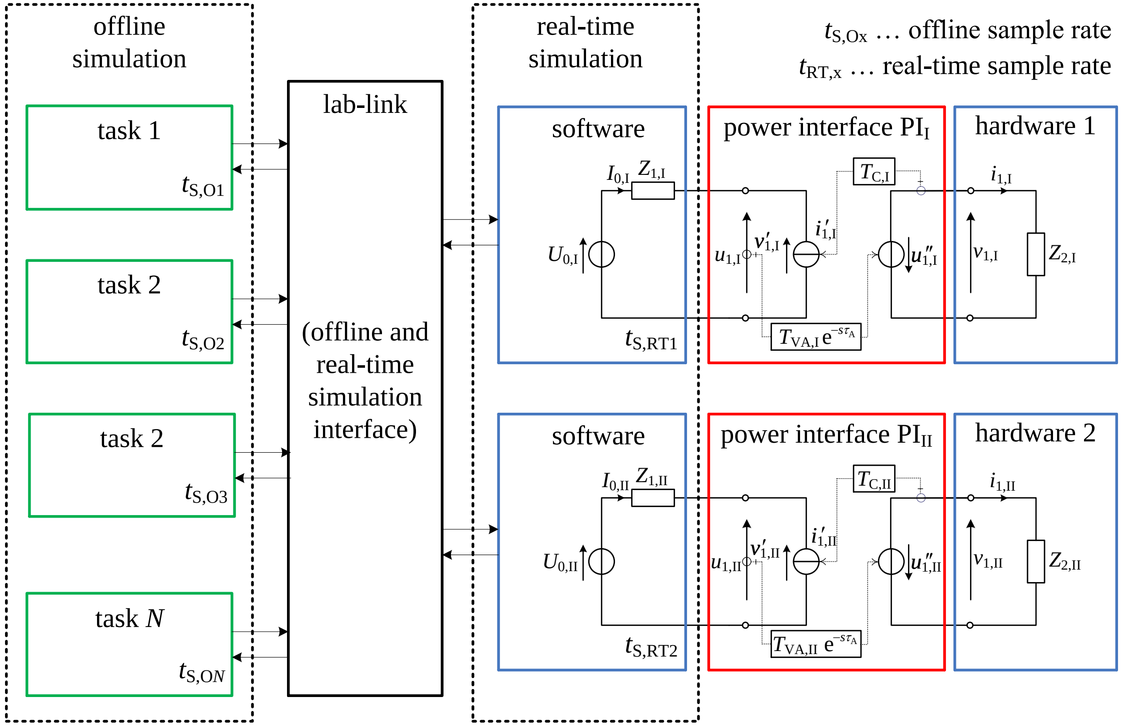
- Offline simulation is converted to FMU and integrated directly to the RT simulator's model -> forced to run at RT simulators time steps.
- Need of compilation verification (some DRTS require to compile the FMU)



# Lab-based Assessment Methods (JRA 3.2)
# ERIGrid Approach to Address Challenges: Extending HIL Capacity

## 2. « Online » Co-Simulation Approach – Without Synchronization

- Lab-link Architecture.




Sample rates of subsystems linked via lab-link:

a) offline tasks: $t_{S,O(N\text{-}1)}$ > 100 ms; operating sample rates [100 ms; 2 s]

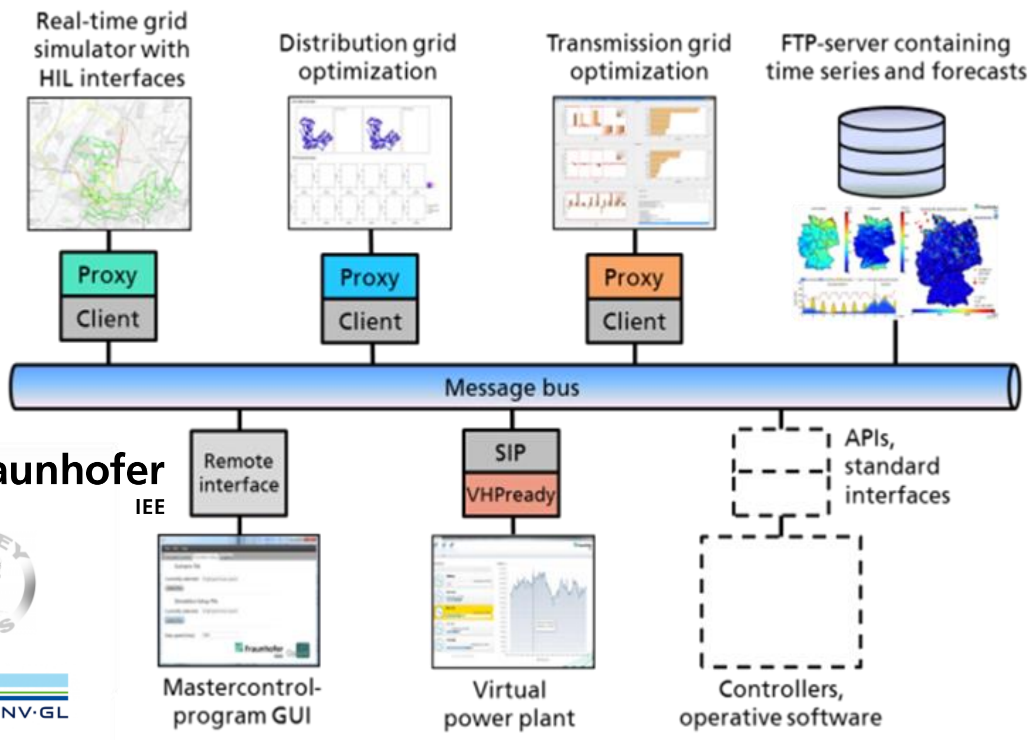
b) lab link: $t_{S,LL}$ > 1 ms; operating sample rates [100 ms; 2 s]

c) real-time simulation: $t_{S,RT}$ < 1ms (up to 100ns); operating sample rates [100 ns; 1 ms]

# Lab-based Assessment Methods (JRA 3.2)
# ERIGrid Approach to Address Challenges: Extending HIL Capacity

## 3. « Online » Co-Simulation Approach – With Synchronization

- OPSim Solution



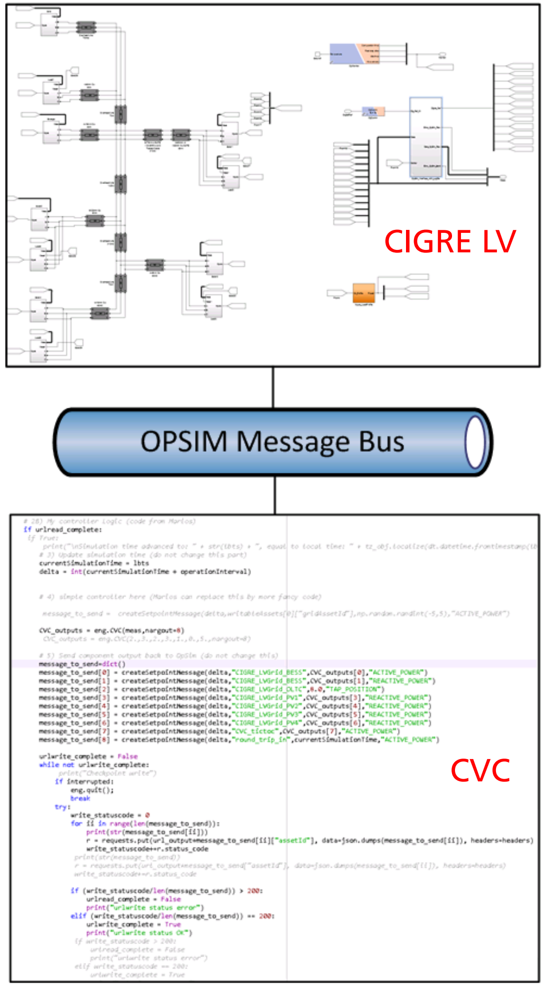

- Flexible Co-Simulation environment for modelling multi-actor power systems (e.g. DSO-TSO-grid interactions)
- Real-time mode for controller-in-the-loop (CIL) tests and offline-mode for seasonal simulation time spans
- Opal-RT can be connected to OpSim, which allows us to combine HIL tests with Co-Simulations (asynchronous interface)
- Accessible via various interfaces like IEC 61850, CIM, propriety data models and also via Webservice

# Integration of HIL to Co-simulation
## Objectives

- Assess delay limitations for the co-simulation and set boundaries in the environment OPSim.
- Determine a holistic performance of the Coordinated Voltage Control (CVC) algorithm through the co-simulation environment.
- Combination of computation power in different RIs.
- Use of confidential and private models.

# Integration of HIL to Co-simulation
# Test Case TC1a Description

- Purpose of Investigation (PoI)
  - Assessment of the delay impact on co-simulation with OpSim through the cloud.
  - Performance of the communication in real-time simulation.
  - Holistic CVC performance.
- Object under Investigation (OuI)
  - CVC algorithm.
  - Cigre Low Voltage Grid Benchmark in OPAL-RT (Cigre LV).
  - Co-simulation environment (OpSim).

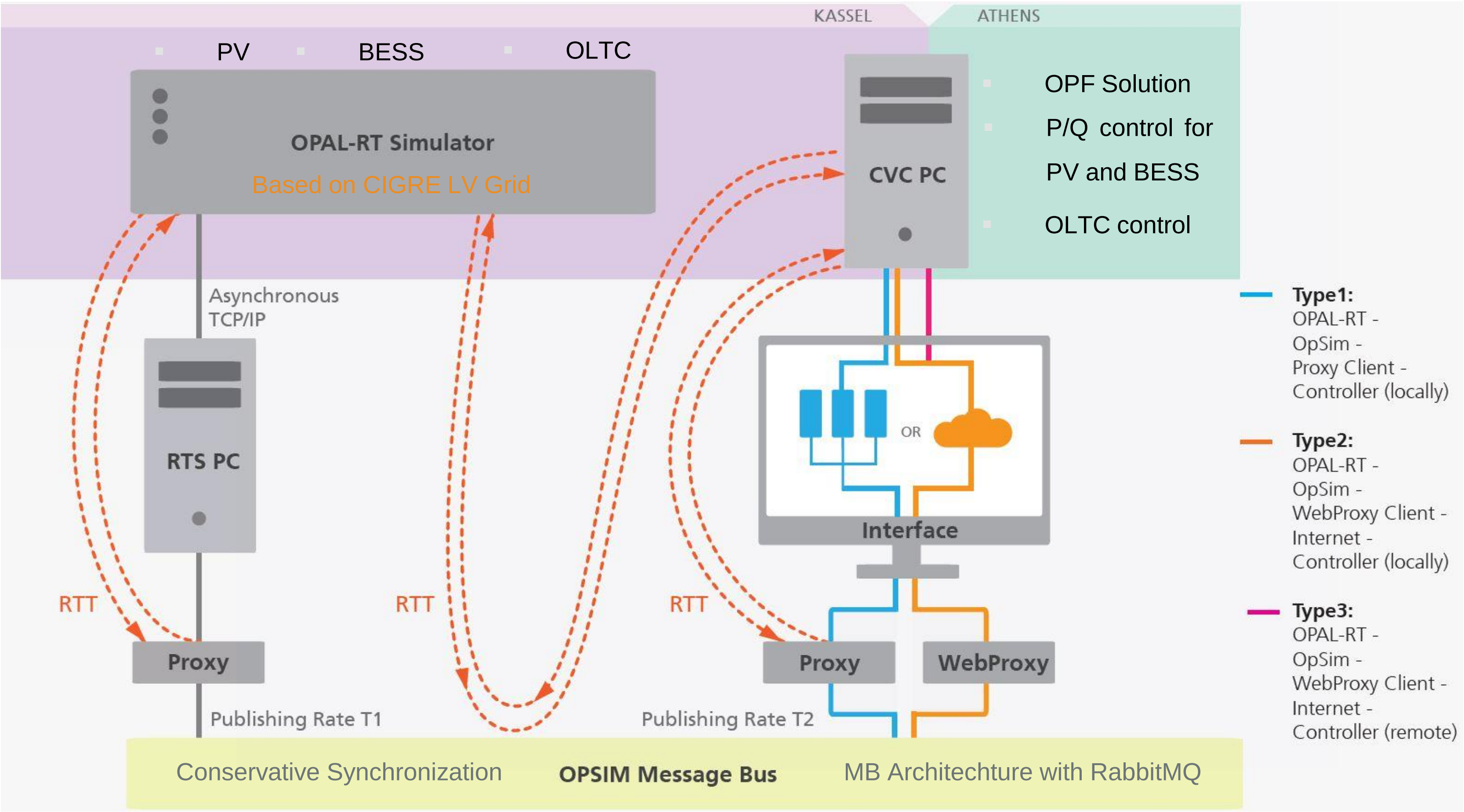


# Integration of HIL to Co-simulation
# Test Case TC1a Description

- Target Metrics
  - Communication latency.
  - CVC OPF convergence.
  - Voltage, P, Q response.

- Variability Attributes
  - Round-trip time, script execution convergence, steady state on simulated grid, system response in steady state after a controller reference change.

# Integration of HIL to Co-simulation
# Test Case TC1a Diagram

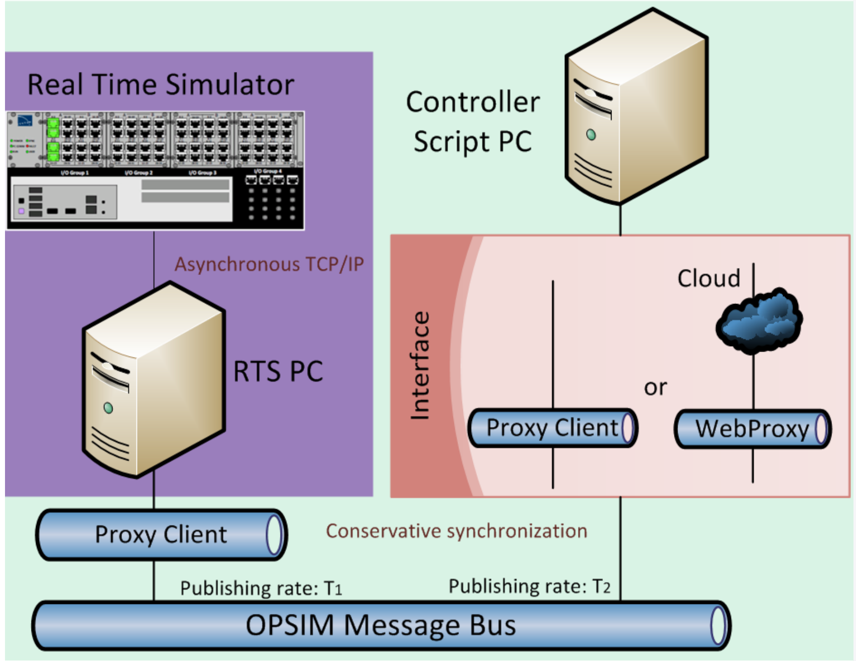


# Integration of HIL to Co-simulation
# Test TC1a Specifications

- TC1a.1
  - <u>Delay measurement with dummy controller</u>
    - In order to set the boundaries of the OpSim platform regarding time frames and to assess delays, two experiments will be made:
      - *Delay measurement with dummy controller locally implemented*
      - *Delay measurement with dummy controller remotely implemented*
- TC1a.2
  - <u>Remote HIL CIGRE LV grid response to CVC set-points.</u>
    - One experiment will be held to verify the CVC performance:
      - *Remote HIL CIGRE LV grid response to CVC set-points*

# Integration of HIL to Co-simulation
# TC1a.1: Delay measurement with dummy controller

- The main purpose is to determine the boundaries for the OpSim environment and assess the the ground reference of delay present in the communication between the two simulators. (local and remote)

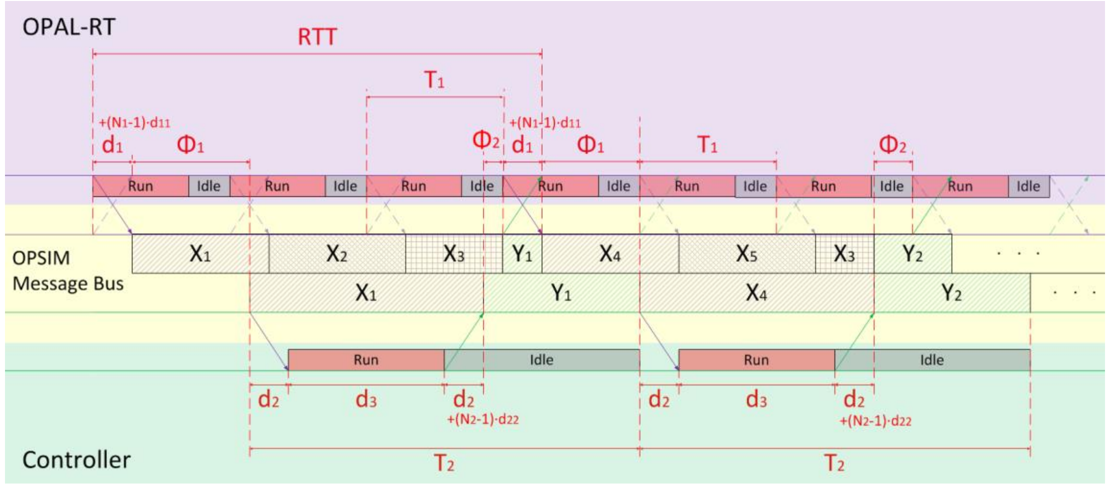



**Type1:**
OPAL-RT -
OpSim -
Proxy Client -
Controller (locally)

**Type2:**
OPAL-RT -
OpSim -
WebProxy Client -
Internet -
Controller (locally)

**Type3:**
OPAL-RT -
OpSim -
WebProxy Client -
Internet -
Controller (remote)

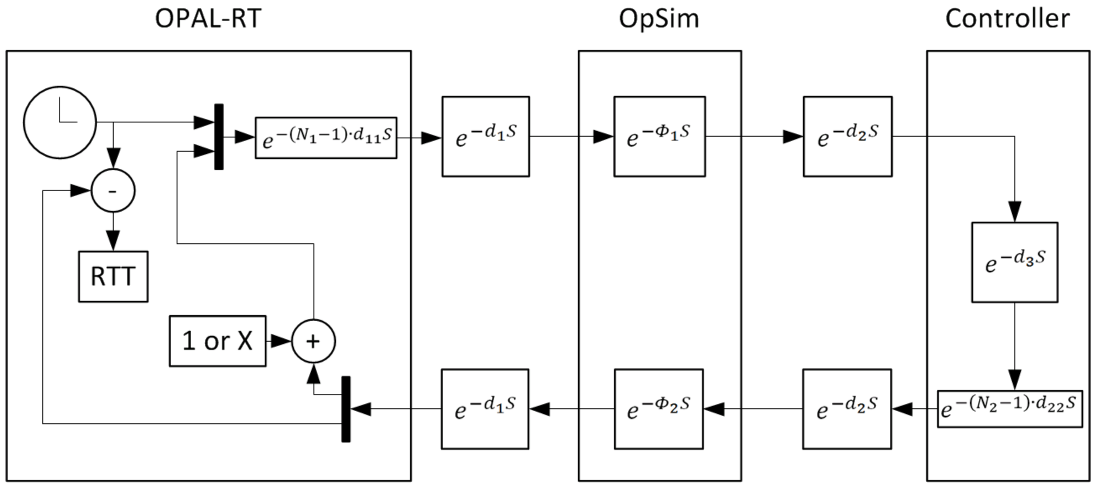
# Integration of HIL to Co-simulation
# TC1a.1: Delay measurement with dummy controller




- $d_1$: Channel delay between OPAL-RT and OpSim MB.
- $d_{11}$: Additional delay due to multiple variables writing from the OPAL-RT.
- $d_2$: Channel delay between OpSim MB and Controller algorithm.
- $d_{22}$: Additional delay due to multiple variables writing from the controller.

- $d_3$: Time convergence of the controller algorithm.
- $N_1$: Number of variables written by the OPAL-RT.
- $N_2$ : Number of variables written by the controller.
- $T_1$: Publish rate between OPAL-RT and OpSim MB.
- $T_2$: Publish rate between OpSim MB and Controller algorithm.
- $\Phi_1$: Asynchronous time gap between writing of the OPAL-RT and reading of the controller.
- $\Phi_2$: Asynchronous time gap between writing of the controller and reading of the OPAL-RT.

# Integration of HIL to Co-simulation
# TC1a.1: Delay measurement with dummy controller

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- $d_2$: Channel delay between OpSim MB and Controller algorithm.
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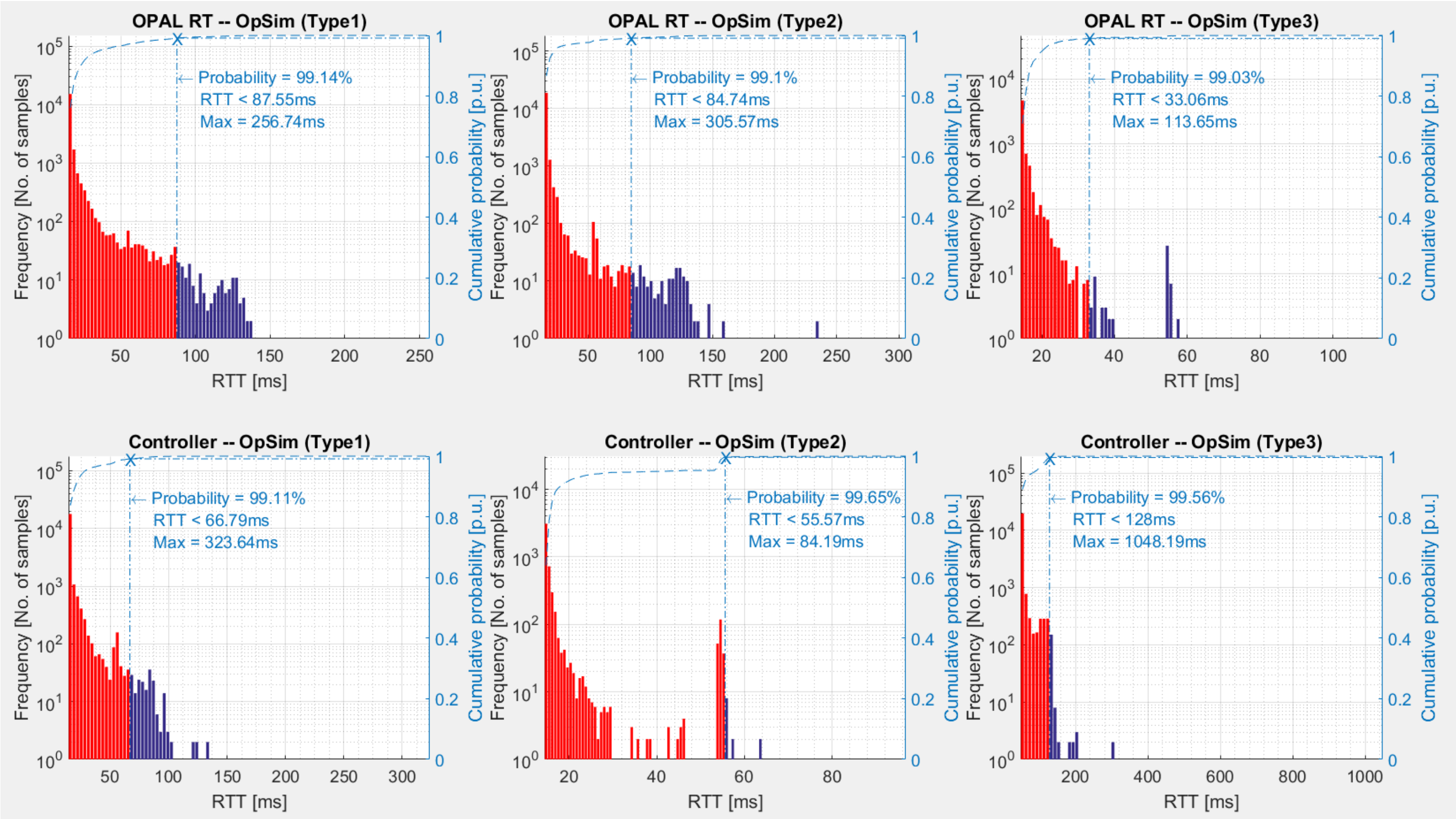
# Integration of HIL to Co-simulation
# TC1a.1: Delay measurement with dummy controller




| OPAL RT --- OpSim | Type1 | Type2 | Type3 |
|---|---|---|---|
| No. of Samples | 19979 | 21689 | 6563 |
| Max RTT [ms] | 256.74 | 305.57 | 113.65 |
| Min RTT [ms] | 15 | 15 | 14.2 |
| Average RTT [ms] | 19.6 | 18.2 | 15.9 |

| Controller --- OpSim | Type1 | Type2 | Type3 |
|---|---|---|---|
| No. of Samples | 21271 | 4849 | 22215 |
| Max RTT [ms] | 66.79 | 84.19 | 1048.19 |
| Min RTT [ms] | 14.2 | 14.4 | 48 |
| Average RTT [ms] | 17.7 | 17.5 | 54.5 |

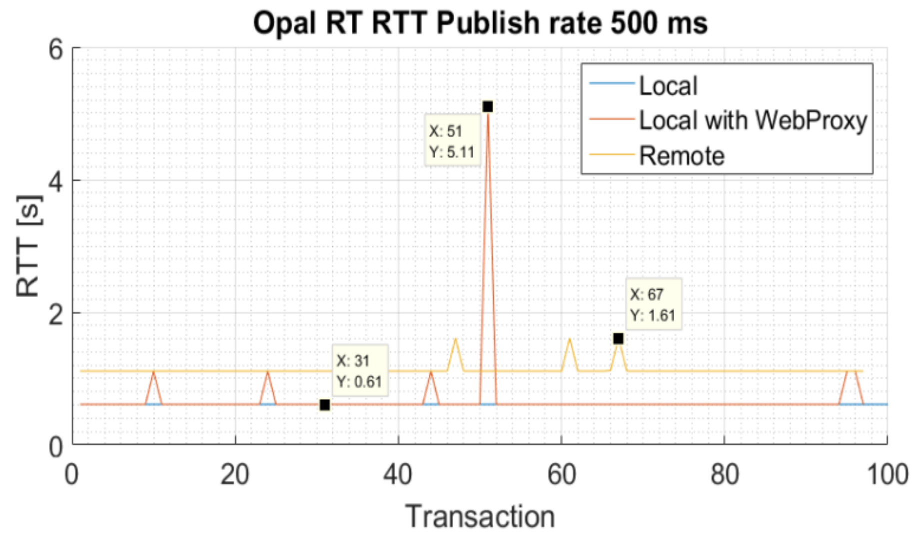
# Integration of HIL to Co-simulation
# TC1a.1: Delay measurement with dummy controller

| *Var.* | *Type* | *Value* | *Certainty* | *Boundaries/ Conditions* |
|---|---|---|---|---|
| $d_1$ | Measured value (Type 1) | 43.78 ms | 99.14 % | Client conn. through Eth |
| | Measured value (Type 2) | 42.37 ms | 99.09 % | Client conn. through Eth |
| | Measured value (Type 3) | 16.53 ms | 99.03 % | Client conn. through Eth |
| d11 | Measured value | 0.32 ms | 99.12 % | N/A |
| d2 | Measured value (Type 1) | 33.4 ms | 99.11 % | Client conn. through Eth |
| | Measured value (Type 2) | 27.79 ms | 99.65 % | Clients conn. through Eth |
| | Measured value (Type 3) | 64 ms | 99.55 % | Clients conn. through Eth |
| $d_{22}$ | Measured value | 16.53 ms | 99.05 % | N/A |
| $d_3$ | Measured + Performance-based value | >190.1 ms | 95.7 % | Controller response time must be added |
| $N_1$ | User-defined value | 17[a] | N/A | According to experiment |
| $N_2$ | User-defined value | 9[a] | N/A | According to experiment |
| $T_1$ | User-defined value | 500ms, 1s, 2s,3s,4s[a] | N/A | $T_1 > d_1 + (N_1-1) \cdot d_{11}$ |
| $T_2$ | User-defined value | 5s[a] | N/A | $T_2 > T_1$<br>$T_2 > 2 \cdot d_2 + d_3 + (N_2-1) \cdot d_{22}$ |
| *RTT* | Estimated value | N/A | N/A | $RTT = 2 \cdot d_1 + 2 \cdot d_2 + d_3 + \Phi + (N_2-1) \cdot d_{22} + (N_1-1) \cdot d_{11}$ |
| $\Phi_1$ | Random value | N/A | N/A | $0 < \Phi_1 < T_1$ |
| $\Phi_2$ | Complementary value | N/A | N/A | $0 < \Phi_2 < T_1$ |
| $\Phi$ | Estimated value | $\Phi_1 + \Phi_2$ | N/A | $0 < \Phi < 2 \cdot T_1$ |

[a]) Values for CVC experiments

# Integration of HIL to Co-simulation
# TC1a.1: Delay measurement with dummy controller

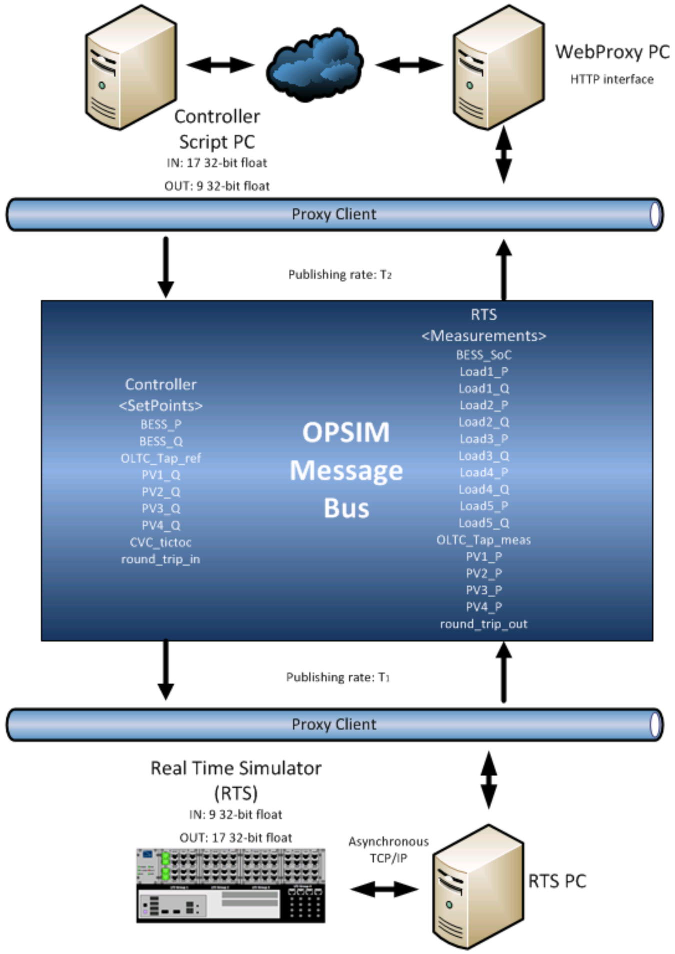
- Type1, RTT of 610 ms = 500ms + 110 ms.
- Type2, congruently with the Type1, except of some outliers and a spike (transaction 51).
- Type 3, 1200 ms, and spikes of 1610 ms.
- In real-time mode OpSim can only guarantee the delivery of packages and their correct order, but it cannot solve underlying hardware or network problems.




M. Vogt, F. Marten, J. Montoya, C. Többermann, M. Braun, “A REST based co-simulation interface for distributed simulations“, POWERTECH 2019

# Integration of HIL to Co-simulation
# TC1a.2: Remote HIL CIGRE LV grid response to CVC set-points.

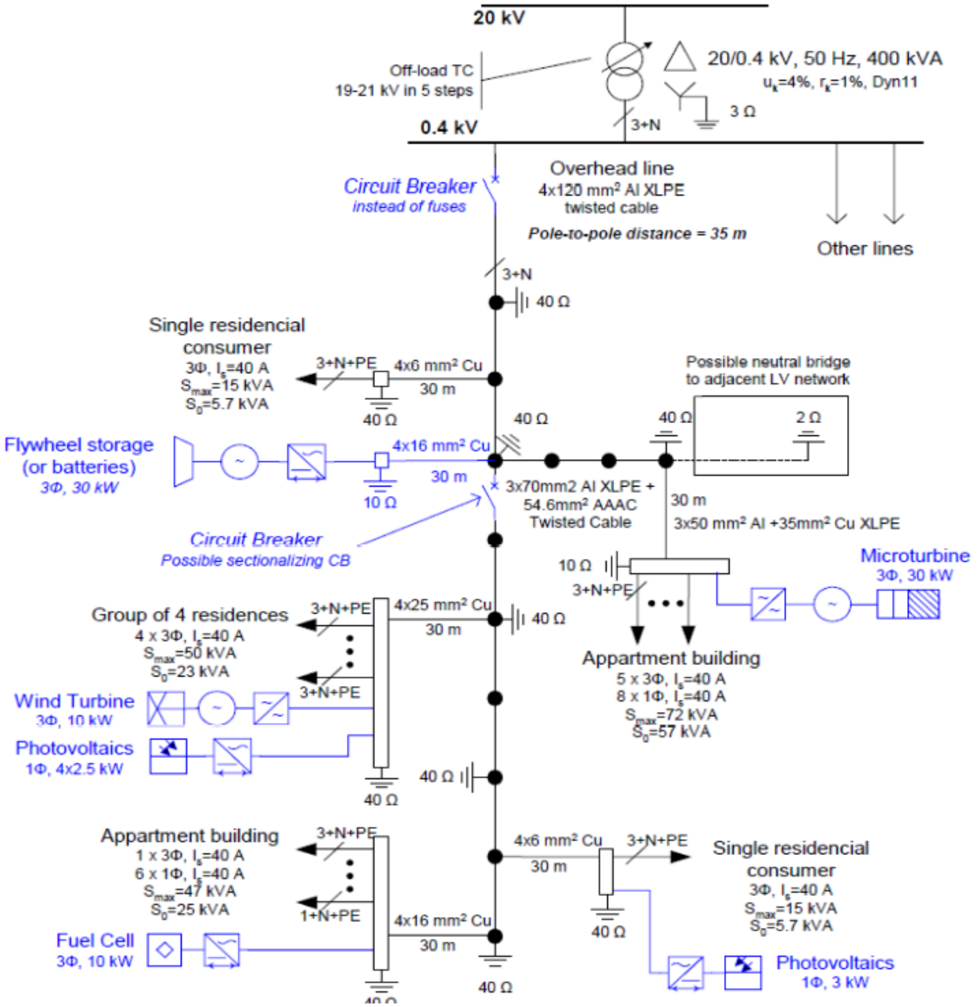
- The main purpose is to determine the response of the Real Time Simulator models to the reference set-points provided by the CVC controller.
- The convergence of the OPF in the CVC algorithm is analyzed to determine the limit of the refresh rate to publish data in the OpSim Message Bus and avoid data losses.



# Integration of HIL to Co-simulation
# TC1a.2: Remote HIL CIGRE LV grid response to CVC set-points.

The feeder is based on a benchmark low voltage microgrid. It was implemented in the OPAL-RT simulator with the following modifications:

- MV/LV transformer equipped with OLTC,
- length of all lines doubled,
- DER units replaced by PVs,
- flywheel storage replaced by BESS,
- symmetrical 3ph network @ Ts=200 µs.




S. Papathanassiou, N. Hatziargyriou, K. Strunz.: “A benchmark low voltage microgrid”



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# Integration of HIL to Co-simulation
# TC1a.2: Remote HIL CIGRE LV grid response to CVC set-points.

The CVC algorithm's main function is the solution of an OPF problem.

- Inputs (17 inputs):
  - Active and reactive powers of loads.
  - Active power of PVs.
  - State-of-charge (SoC) of BESS.
  - Tap position of the OLTC.
- Outputs (9 outputs):
  - Active and reactive powers of the BESS.
  - Reactive power of the PV inverters.
  - Tap position of the OLTC.

$$P_{\text{bat, charge - dischrage}} = P_{\text{bat, nom}} * \frac{\text{SoC} - \text{SoC}_{\text{ref}}}{\Delta \text{SoC}_{\max}}$$

$$\min_{x} f(x) = w_1 \sum_{i=1}^{n} \sum_{j=1}^{n} P_{\text{losses}, ij} + w_2 \sum_{k=7}^{12} (V_k - 1)^2 + w_3 \left| \text{tap}_{\text{new}} - \text{tap}_{\text{current}} \right|$$

$$x = [V_1 \quad \dots \quad V_{12} \quad \delta_1 \quad \dots \quad \delta_{12} \quad P_{\text{bat}} \quad Q_{\text{bat}} \quad Q_{\text{pv},1} \quad Q_{\text{pv},2} \quad Q_{\text{pv},3} \quad Q_{\text{pv},4} \quad \text{Tap\_changes}]$$

$$P_{\text{losses}, ij} = -G_{ij} * [V_i^2 + V_j^2 - 2V_i V_j \cos \delta_{ij}]$$

Voltage constraints

$$V_1 = 1$$
$$\delta_1 = 0$$
$$0.9 \le V_i \le 1.1$$
$$0^\circ \le \delta_i < 360^\circ$$

PV inverter constraints

$$\left| Q_{\text{pv},i} \right| \le P_{\text{pv},i} * \tan(\cos^{-1}(0.8))$$
$$P_{\text{pv},i}^2 + Q_{\text{pv},i}^2 \le S_{\text{pv, nom},i}^2$$

Line current constraints

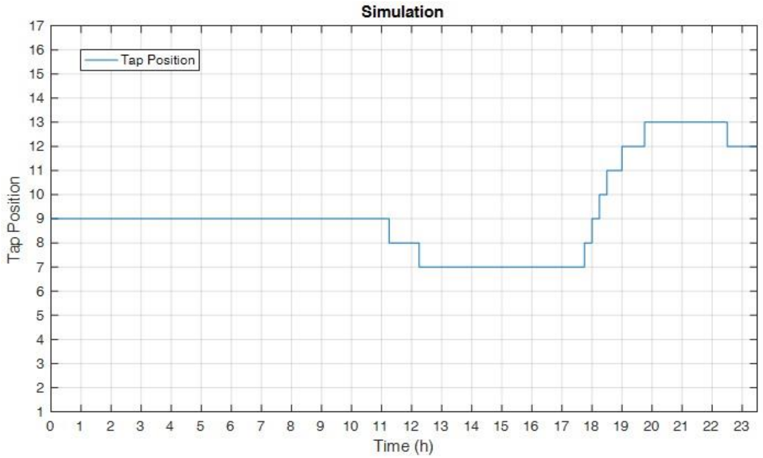
$$\left| Y_{ij} * \left( \widetilde{V}_i - \widetilde{V}_j \right) \right| \le I_{ij,\text{limit}}$$

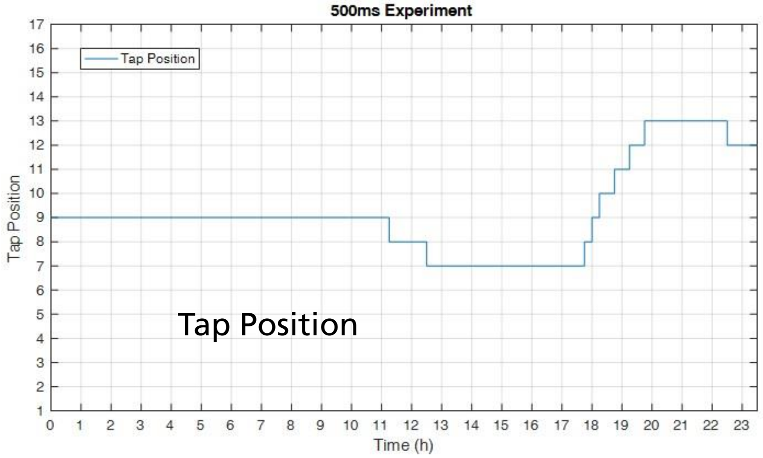
OLTC constraints

$$-8 \le \text{Tap\_changes} \le 8$$

M. Maniatopoulos, D. Lagos, P. Kotsampopoulos, N. Hatziargyriou,
"Combined control and power hardware in-the-loop simulation for testing smart grid control algorithms"

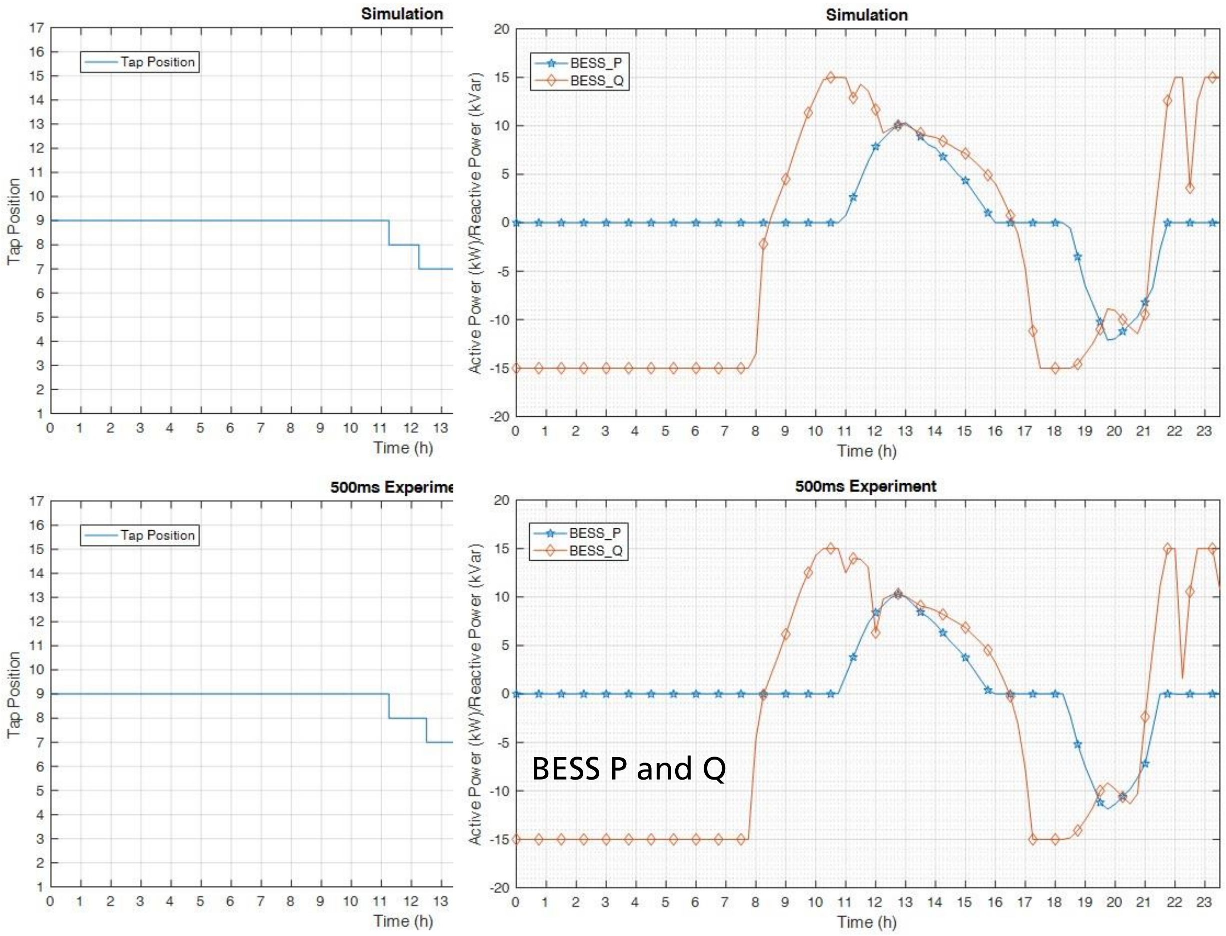
# Integration of HIL to Co-simulation
# TC1a.2: Remote HIL CIGRE LV grid response to CVC set-points.




Tap Position

# Integration of HIL to Co-simulation
# TC1a.2: Remote HIL CIGRE LV grid response to CVC set-points.



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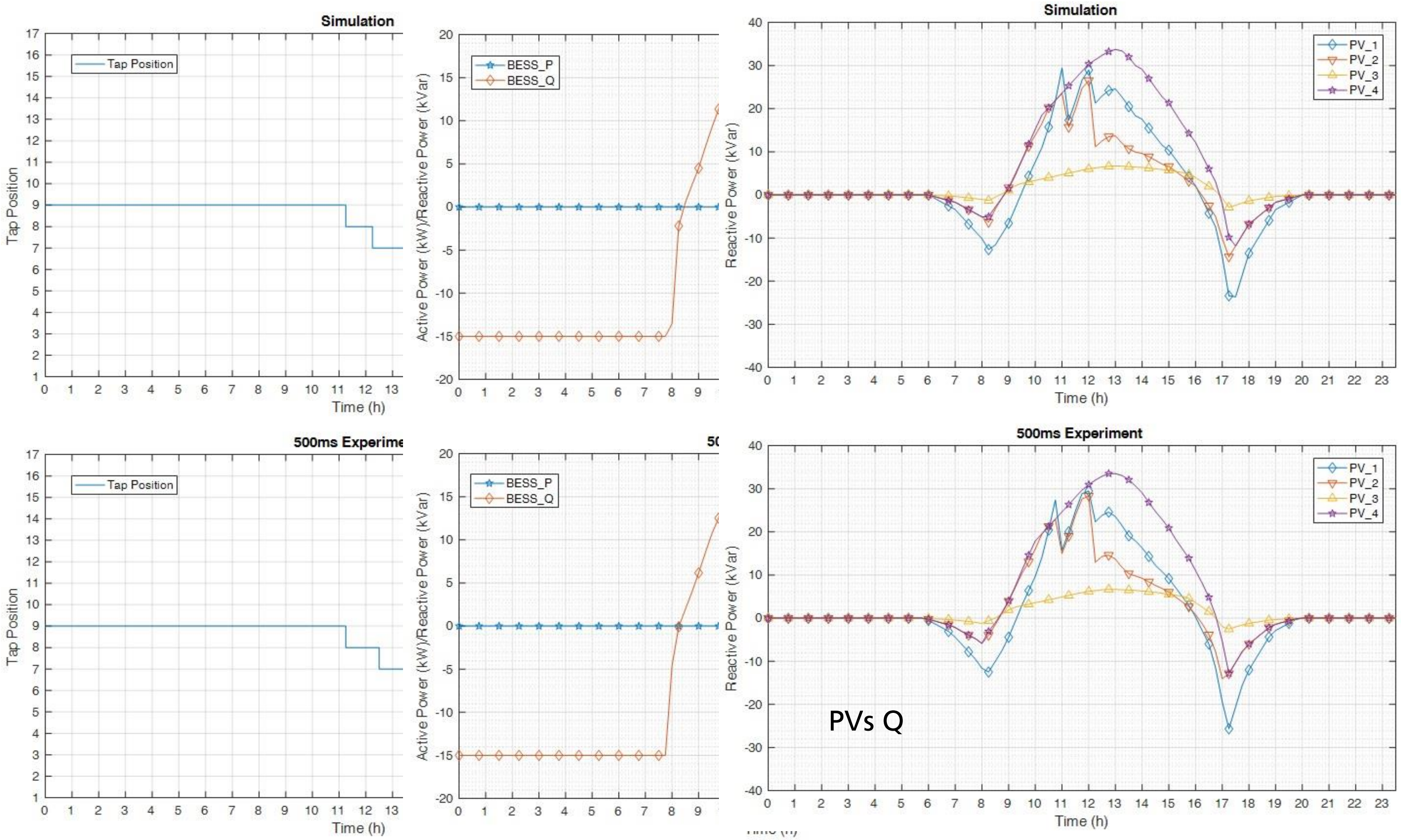




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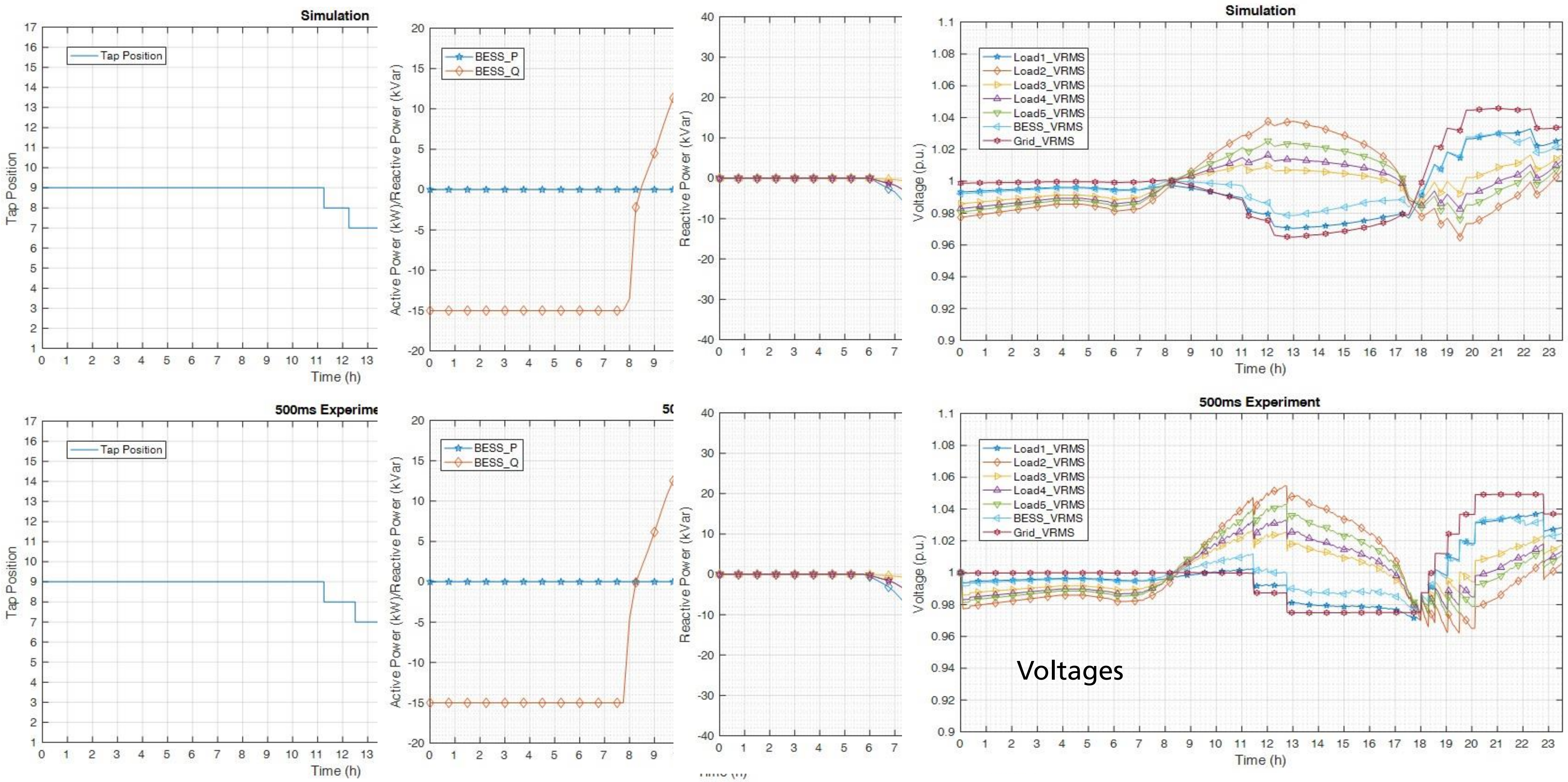

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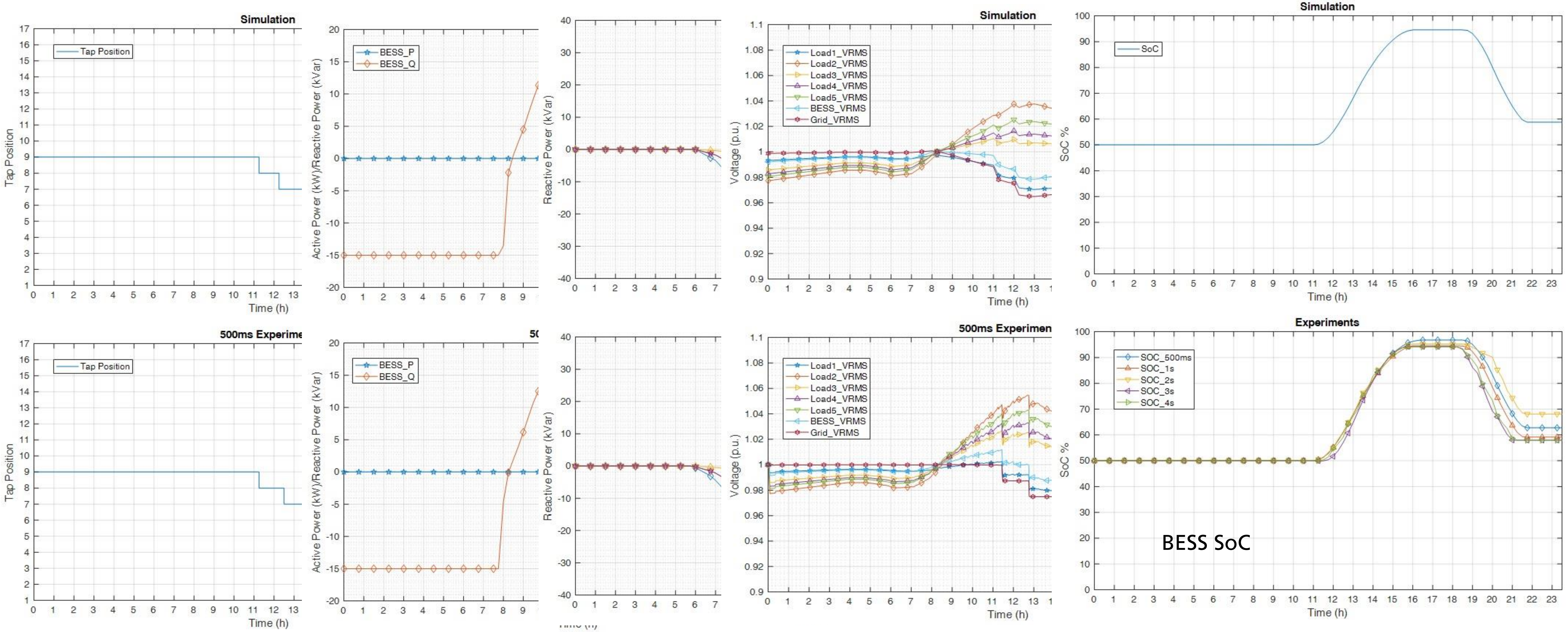


J. Montoya, R. Brandl, M. Vogt, F. Marten, M. Maniatopoulos and A. Fabian, "Asynchronous Integration of a Real-Time Simulator to a Geographically Distributed Controller Through a Co-Simulation Environment"



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# Integration of HIL to Co-simulation
# Conclusion

- OpSim is able to interconnect simulators in different research and exchange of information suitable for applications of low-bandwidth grid voltage control on real time.
- The presented estimations and boundaries provide a way to analyze beforehand if a real-time co-simulation experiment can be performed and which are the user-defined values, as number of variables and publishing rates, that can be defined for particular studies.
- The results presented show an accurate response compared to a reference software simulation test, confirming the real-time capabilities of OpSim for geographically distributed co-simulation.

# Thank you for your attention!

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