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Digital Twin of a Dynamic Hardware Emulator: Challenges and Opportunities

ISGAN-SIRFN-Power System Testing - Cluster 4

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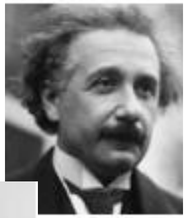
About ZHAW SoE IEFE

- The Zurich University of Applied Sciences (ZHAW) is one of the leading universities of applied sciences in Switzerland
- In short, in strategic research at the ZHAW we concentrate on energy and social integration
- With locations in 3 major cities in the canton of Zurich, the ZHAW is strongly integrated in the local region and collaborating with many international partners as well
- Today’s School of Engineering (SoE) was est. in 1874, has 3’000 students today
- Most famous lecturer: Albert Einstein (1901)



- Most famous former student: Charles Brown (1880-3), founder of ABB Ltd.

- Institute of Energy Systems & Fluid Engineering est. in 2001 (IEFE) – 55 employees
- About me:
  - Since 2012 with ZHAW
  - Deputy Head of IEFE institute & Head of electric power systems group
  - 15y industrial experience with ABB Ltd.
  - Author & co-author of more than 100 US & EU patents and more than 150 publications
  - Lecturing 6 courses in 2 study programs at ZHAW and 1 course at ETH Zurich
  - Co-director of the Swiss Competence Centre for Energy Research (2013-)

Research interests
10 assistants & 3 senior researchers

Electrical Power Systems Lab

Smart Distribution Automation

Power system dynamics & control

Development of laboratory demo set-ups



Big Data Analytics for stability assessment of power systems

Leading the corresponding IEEE Task force

Distribution grids

- Integration of renewable energy sources & electric vehicles
  - Optimal storage sizing, siting, voltage control
  - Converter-interfaced generation --> low-inertia grids
- Grid simulations & techno-economic analyses
- Co-operations with more than 10 distribution system operators

Transmission grid

- Wide-area monitoring, protection & control (WAMPAC) based Phasor measurement units (PMUs)
- Developing & testing algorithms for
  - Estimation of inertia
  - Monitoring of grid stability
  - Synthesis of controllers stabilizing the grid
- Co-operation with the Swiss Transmission System Operator Swissgrid AG

- Funds from all kinds of sources (incl. national + international competitive funds as well as direct industrial sponsorship)

- ***To test the results of our research we built unique laboratory equipment based on real hardware provided by existing manufacturers whereas others use only digital simulations…***

Laboratory hardware equipment (1)
Smart Grid Lab @ ZHAW, IEFE

Wide-area monitoring platform based on a real-time measurements

Phasor data concentrator (PDC) collecting data from PMUs located around the world in 50Hz & 60Hz systems

Example: Big data collection of real measurements (growing by about 100GB/month) enabling tests of developed on-line/off-line monitoring algorithms without violating any NDA rules

- Started as a EU project
  - PMUs installed in all involved university labs
- # of PMU measurements continuously growing
  - Besides the participating countries we are exchanging data with Latin America in real-time already (Brazil, Chile, Mexico), Russia …
  - China coming soon…

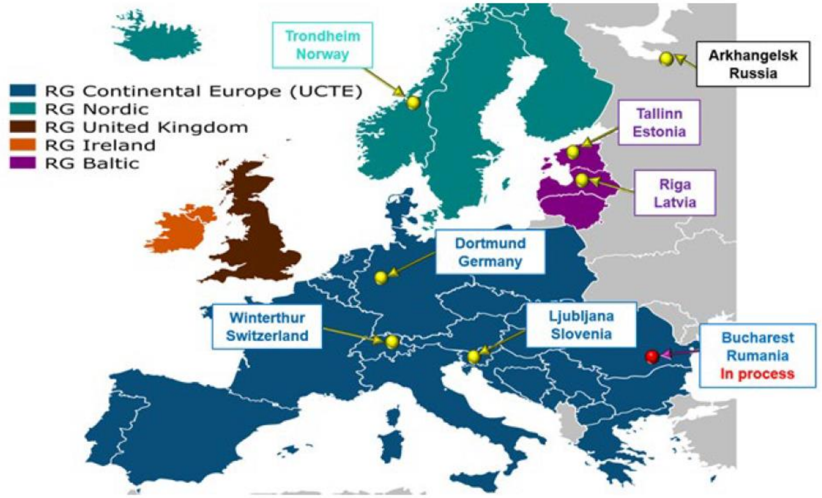


Figure 2 Interconnection of Labs in Europe

Figure 3 Snapshot of Frequency Measurements

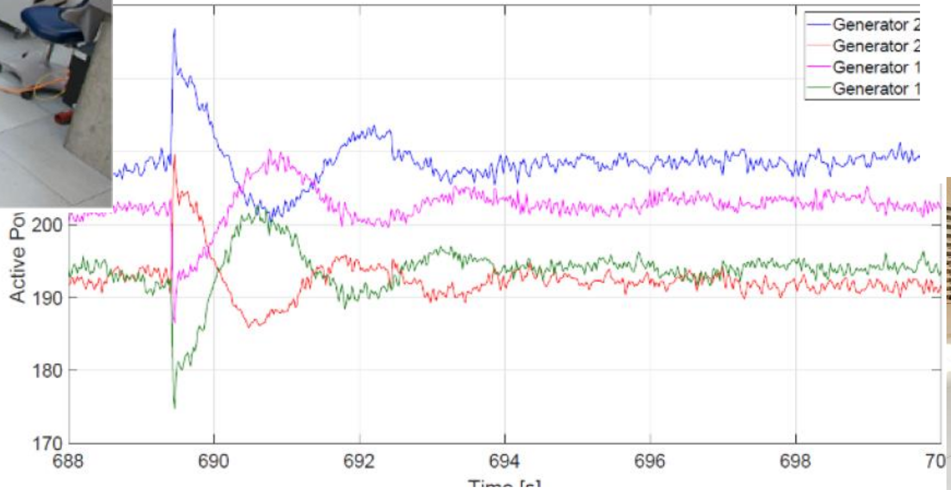
Laboratory hardware equipment (2)
Smart Grid Lab @ ZHAW, IEFE

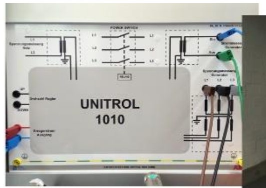
Dynamic hardware power system emulator

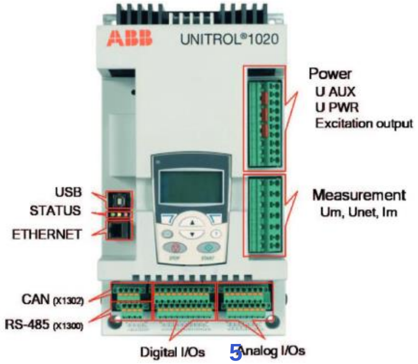
3phase dynamic emulator in hardware combining real/existing, new and laboratory components, incl. conventional and renewable generation, PMUs (ABB, NI, SEL), primary & secondary control, servo motors acting as programable inertia attached to synchro-gens, wide-area monitoring & control etc.

Example: wide-area control - PMU signals fed back to ABBs excitation systems used for our synchro-gens to control badly damped inter-area power oscillation

- Development & integration of new devices of collaborating manufactures (e.g. ABB Switzerland)
- Research on new solutions improving the monitoring & stability of electric power systems…







Laboratory hardware equipment (3)
Smart Grid Lab @ ZHAW, IEFE

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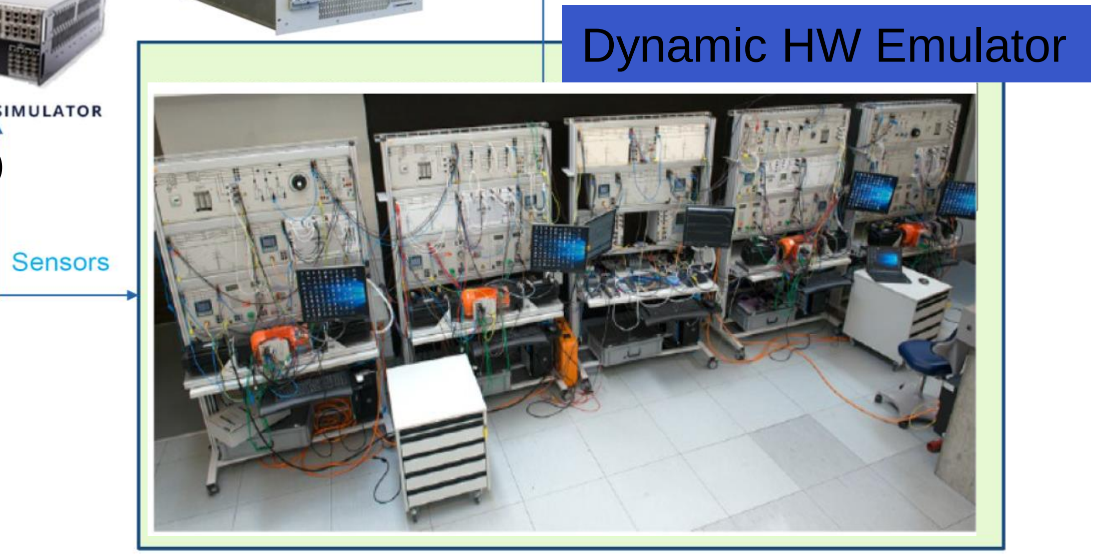
Real-time simulator based on OPAL-RT & 4Q-Amplifiers

Examples:

1. Real-time simulation of the large European power system model (continental ENTSO-e) with hardware-in-loop (PMUs – ABB & NI, Unitrol 1000 serie - Excitations systems for synchro-gens provided by ABB, protection relays (fast ROCOF problems) → Digital twin to evaluate the functionality of real devices

2. Connection to the ZHAW dynamic power system emulator (to increase size & complexity by adding more virtual/simulated components):

3. Cooperation with Canadian OPAL-RT (Montreal)
   - Using HW in the lab (incl. real-time simulator & intelligent amplifier)
   - World-wide largest dynamic system on this platform (ENTSO-e model)
   - Organization of a global event – Int. DynPower Workshop
     International Workshop DynPOWER | ZHAW Institut für Energiesysteme und Fluid-Engineering IEFE
     (460 registered participants, 46 countries, incl. industry & academia)



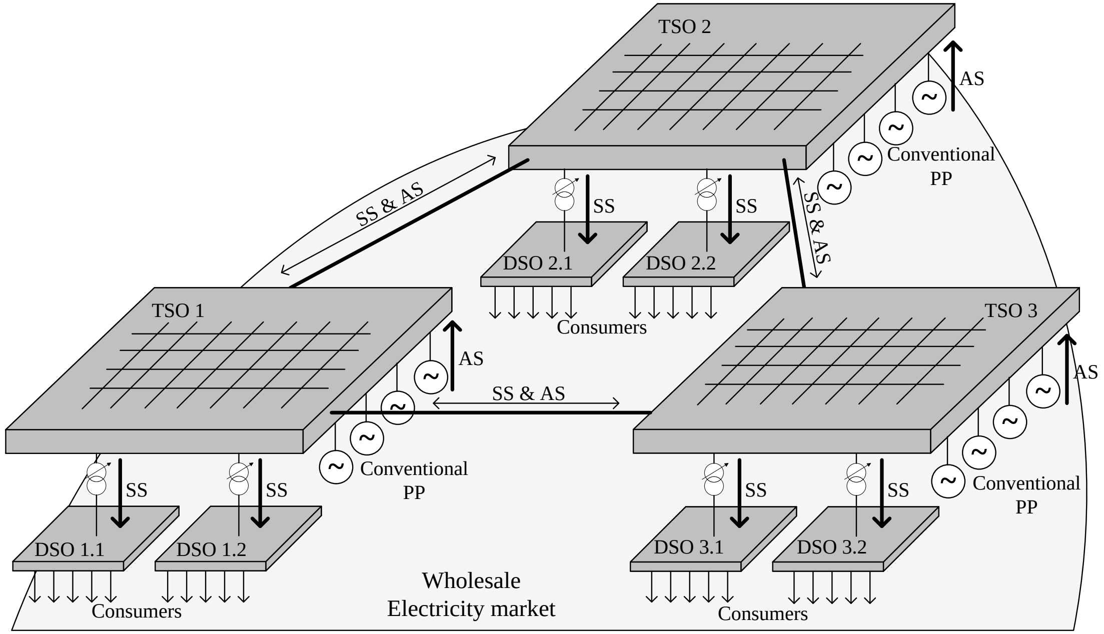
ISGAN WG_5: Smart Grid International Research Facility Network (SIRFN)

Focus Area 3: Power System Testing

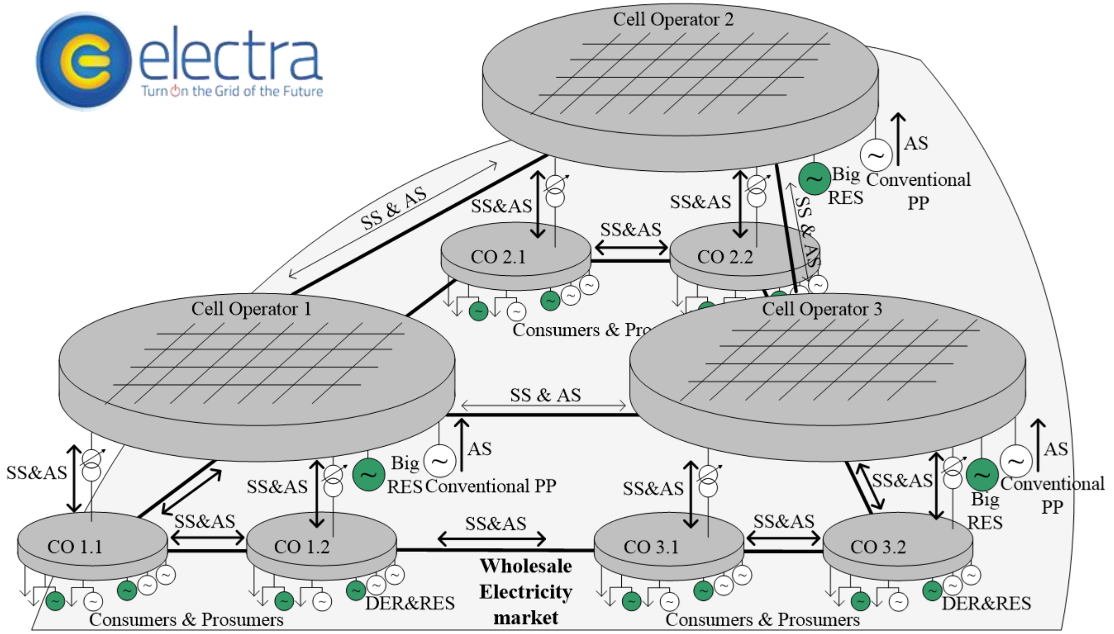
Cluster 4: Stability of Low-inertia transmission interconnections

Motivation

Traditional Power System Representation



2030+ Power System Representation

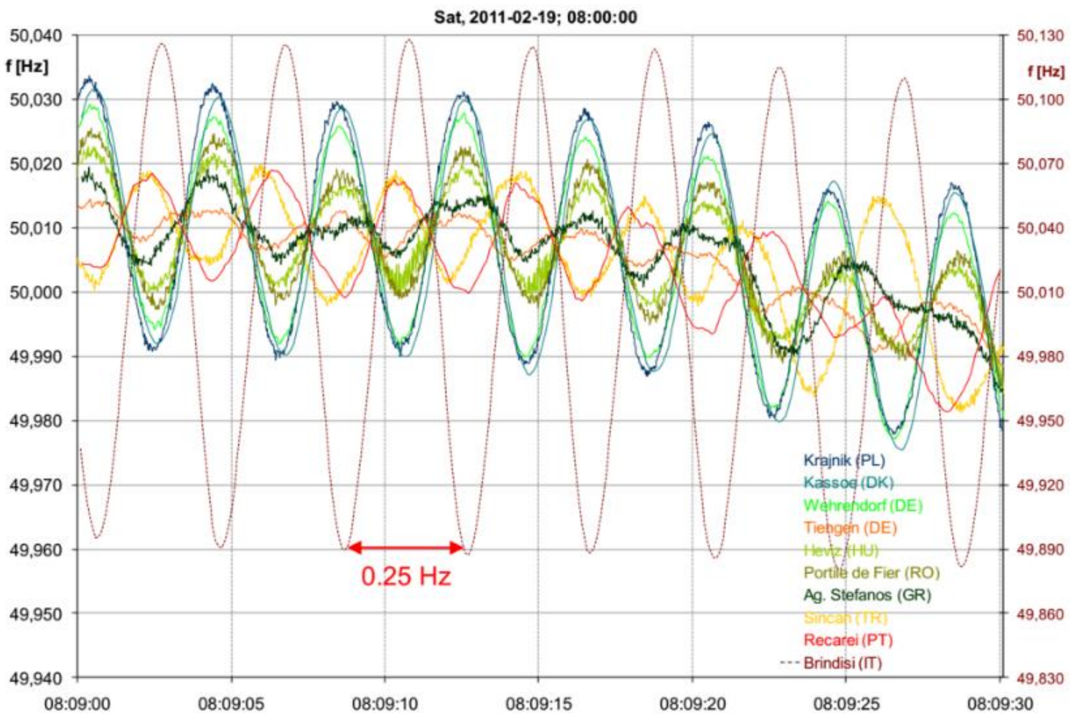


- Significant amounts of variable renewable capacity have been installed already and a lot more will be deployed beyond. In recent years the impact of the deployment of RES on electricity market, through marginal costs concept, has becoming even stronger. The increase in numbers causes significant changes in power system operation manner.
- Power system generation shift from **classical dispatchable units** to more **intermitted renewables**, and as consequence of this, generation and provided services shift from central transmission to decentralized distribution system

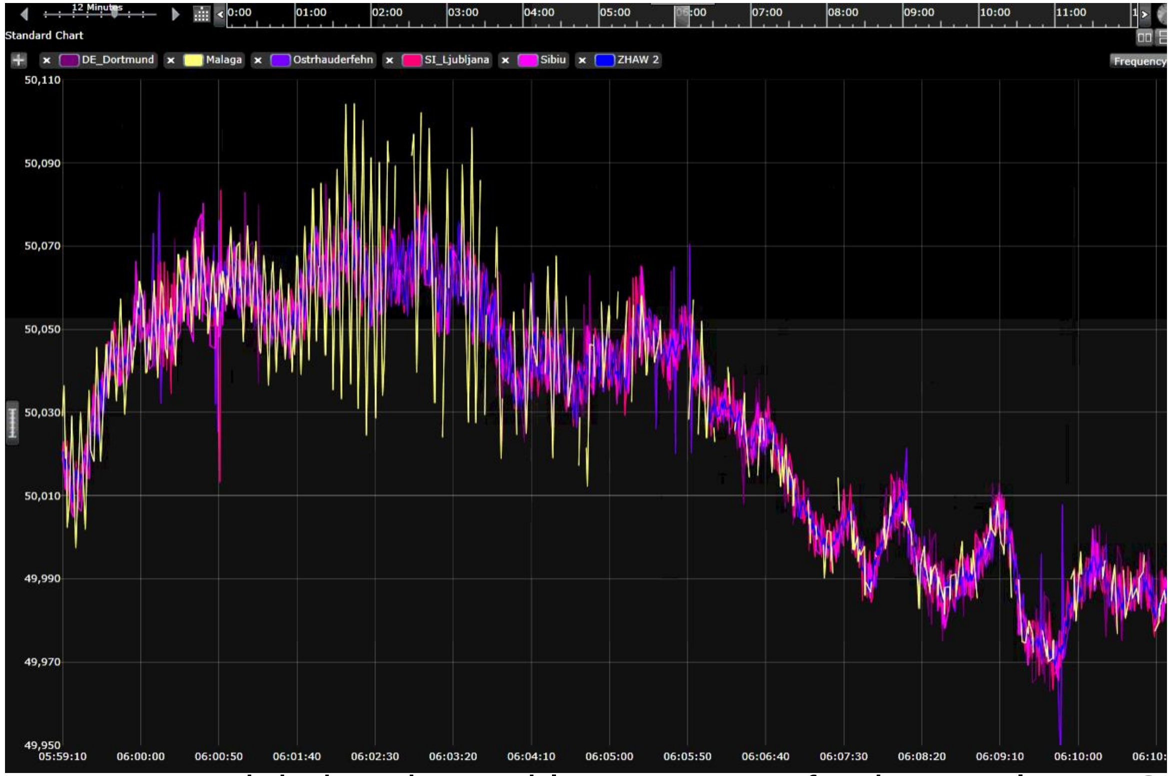
Objective

- With the growth of extensive power systems, and especially with the interconnection of these systems by ties of limited capacity, low-damped inter-area oscillations may appear. Due to insufficient damping, an unstable operation may occur, potentially leading to uncontrolled separation of the power system into islands and consequently blackouts.

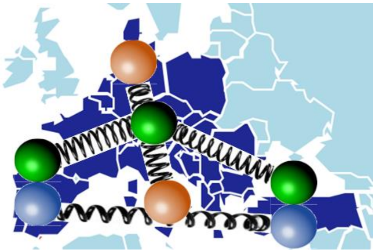
Source ENTSO-E



Source ZHAW WAMS - Event: September 1, 2020, Iberic Peninsula Oscillation



- Objective is to investigate small signal inter-area stability phenomena and derive observables necessary for the novel WAMS-based control methods and test WAMS on proposed Cyber-physical energy system



Main oscillation modes in Continental Europe system

North-south (0,3 Hz aprox)

East-Centre-West (0,22 Hz aprox)

East-West (0,16 Hz aprox)

- Bulk power systems stability
  - Multi-Machine interactions
  - Sub-synchronous oscillations

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Inter Area Oscillation 11 October 2021 - Iberian peninsula oscillates again central part of the system (Source ENTSO-E)

- HVDC Spain-France in the East-Pyrenees. Specific control: Angle difference control

Figure 2. Transmission network in the French-Spanish border

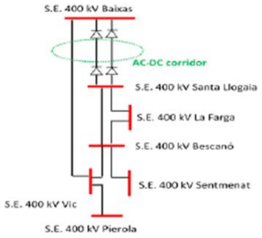


Figure 3. AC-DC corridor formed by the HVDC link and the Vic-Baixas line

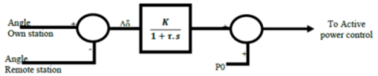
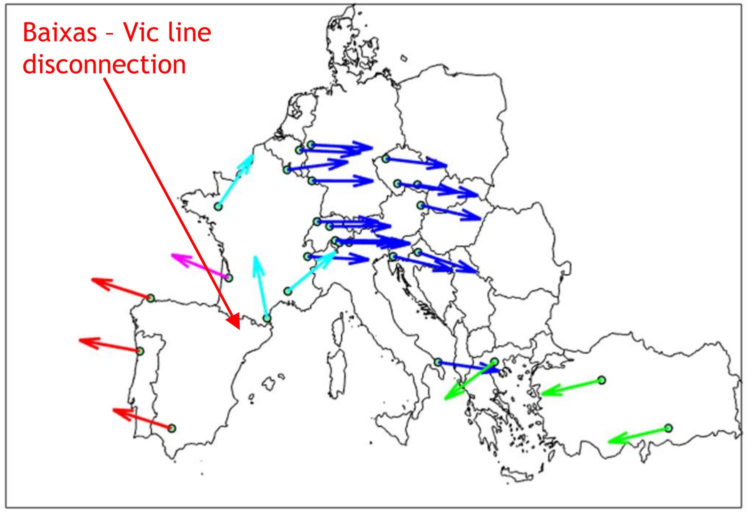


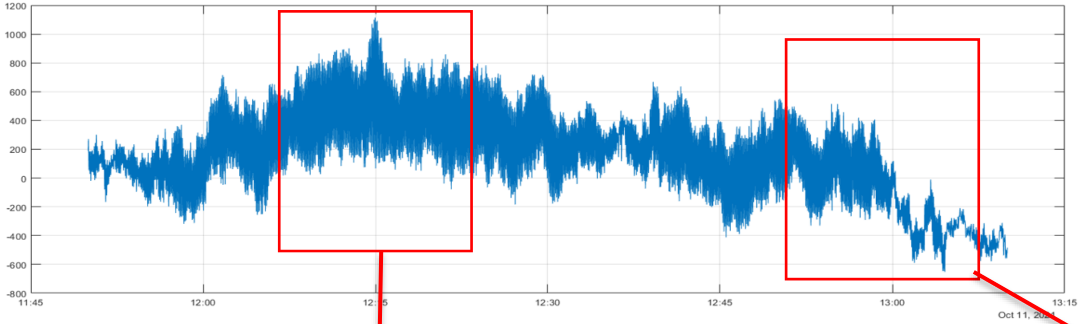
Figure 4. ADC model

- K=360 MW/°
- τ=750 ms
- P0=0 MW

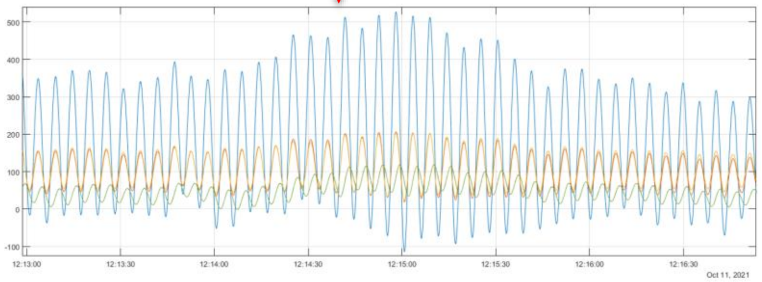
- Mode shapes

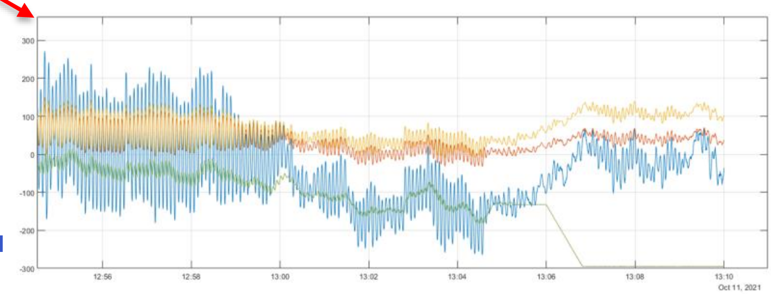


- Power flows border ES-FR



- Change of HVDC control mode



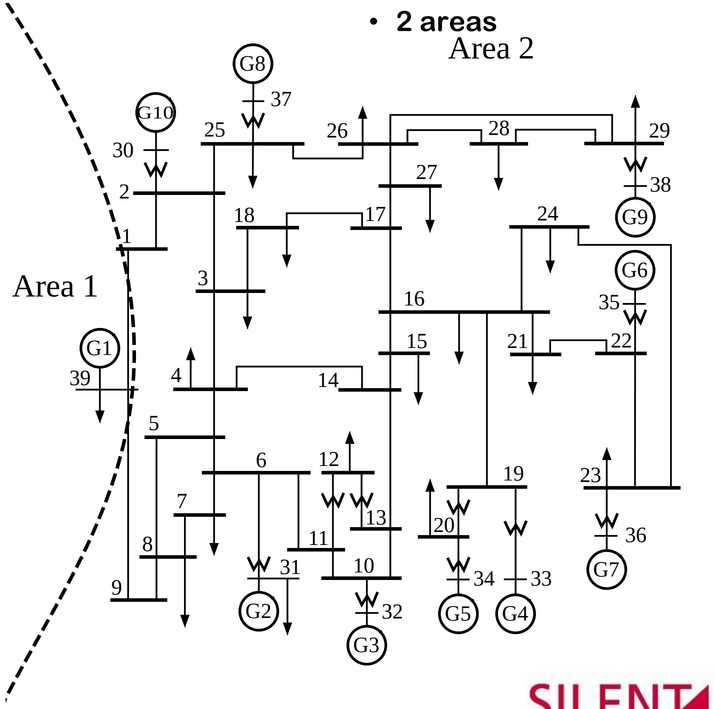


Solutions for transmission grid investigation

Power system-oriented software: Simulation only

New England model:

- 10 generators
- 39 buses
- 19 loads
- 2 areas



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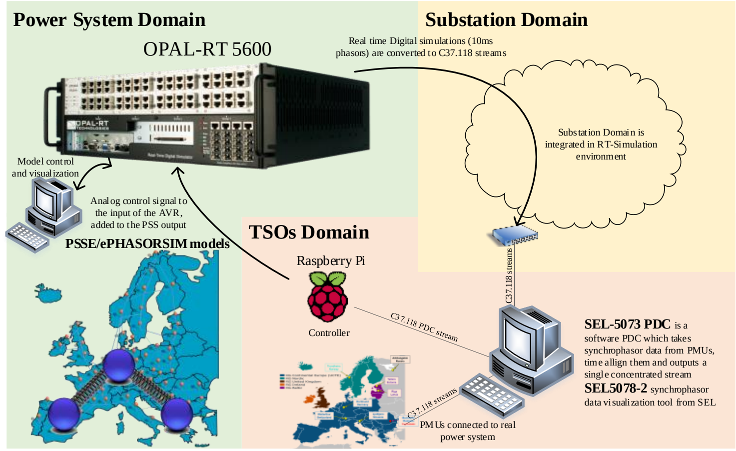
Initial dynamic model of ENTSO-E:

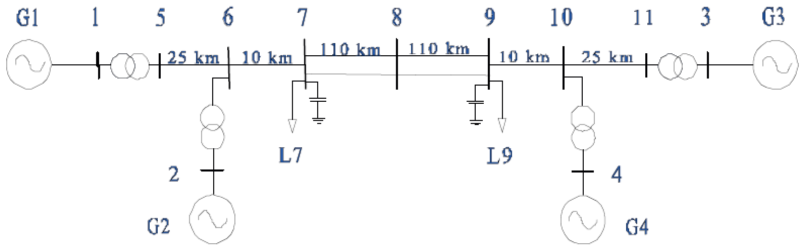
- 6147 generators
- 23253 buses
- 7377 loads
- 3-4 areas

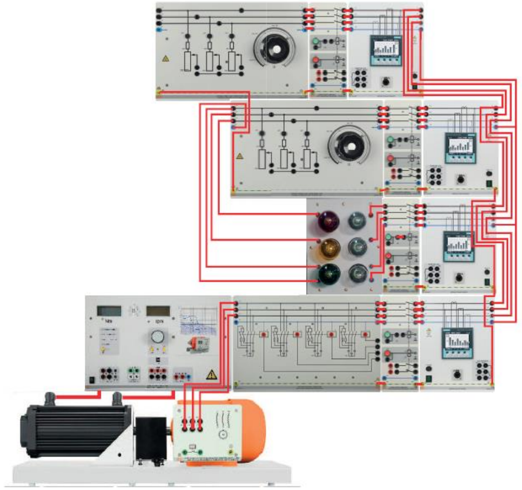


Kundur two-areas model:

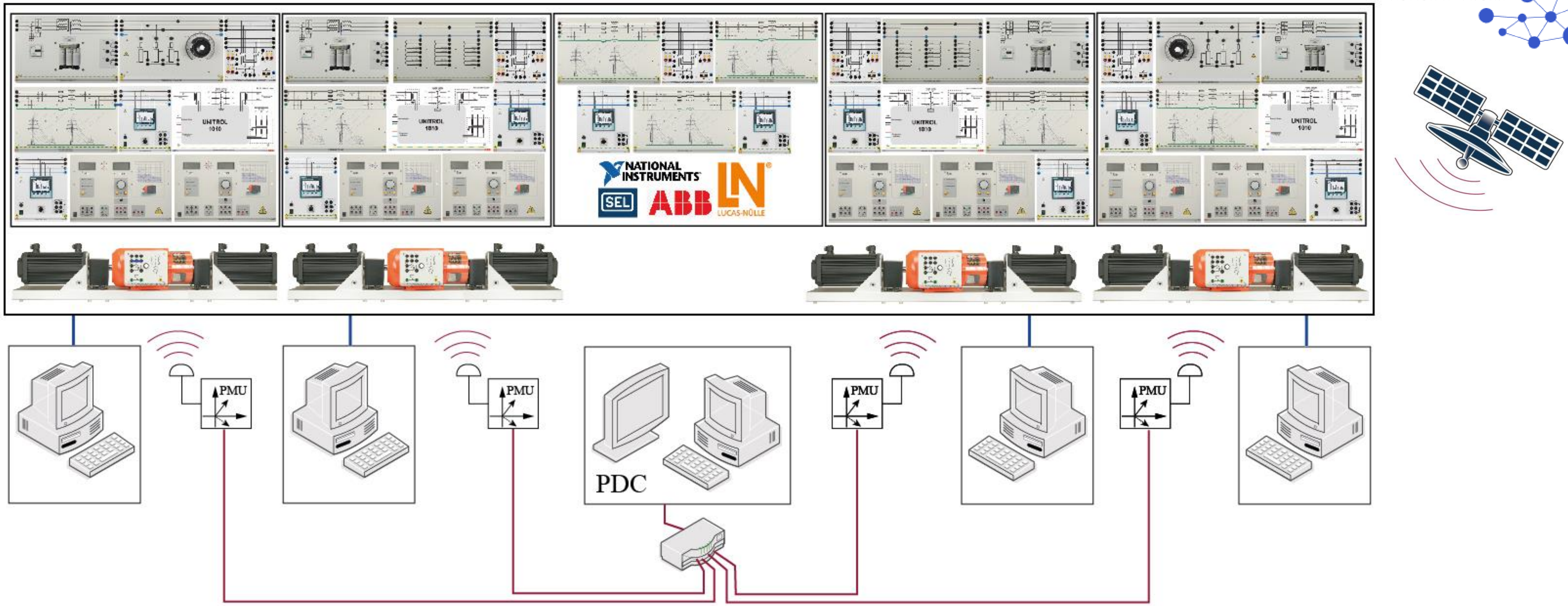
Dynamic emulator

- 4 generators
- 11 buses
- 2 loads
- 2 areas





Kundur model: Laboratory implementation

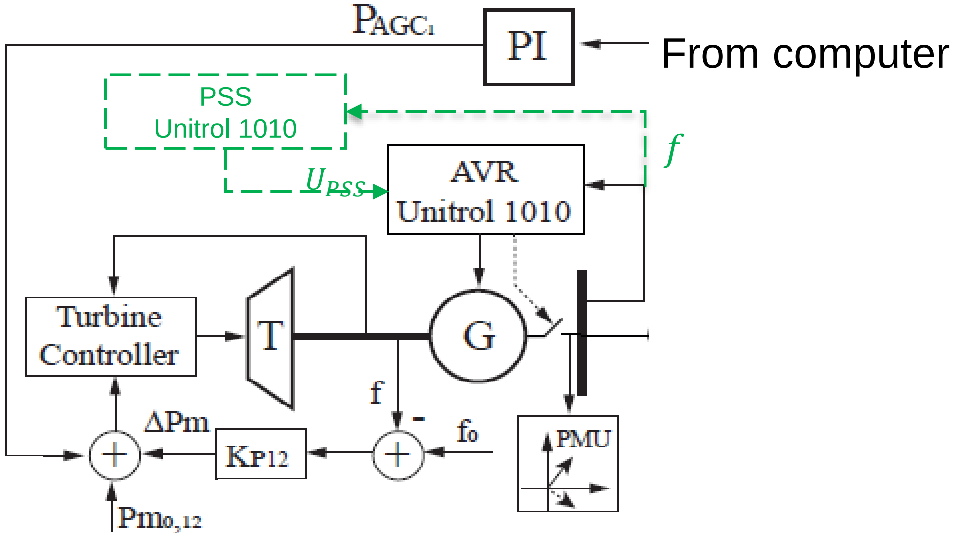


Generators 1kVA; Lines 10, 25, 150, 300 km; Servo machines (turbine & inertia); Adjustable ohmic loads; PMU's from National Instruments

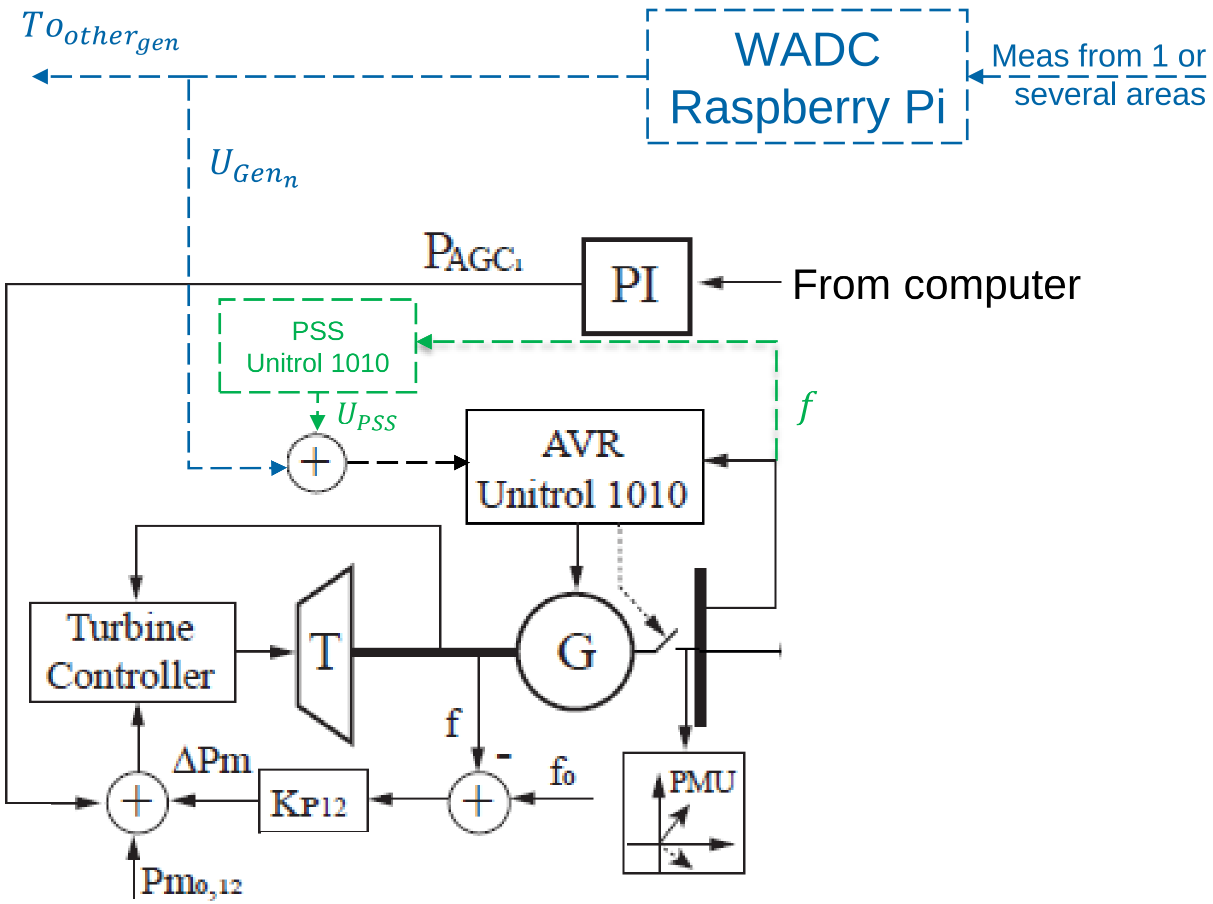
Baltensperger, D., Dobrowolski, J., Obushevs, A., Sevilla, F.R.S., and Korba, P. (2020). Scaling Version of Kundur's Two-Areas System for Electromechanical Oscillations Representation. In 2020 International Symposium on Power Electronics, Electrical Drives, Automation and Motion, SPEEDAM

Ongoing work:

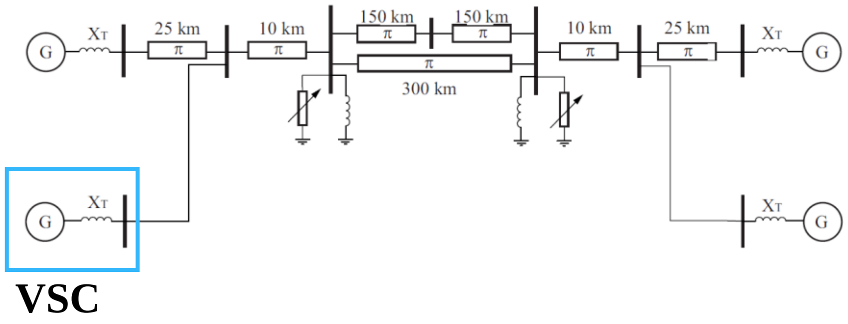
Step 1 : PSS implementation



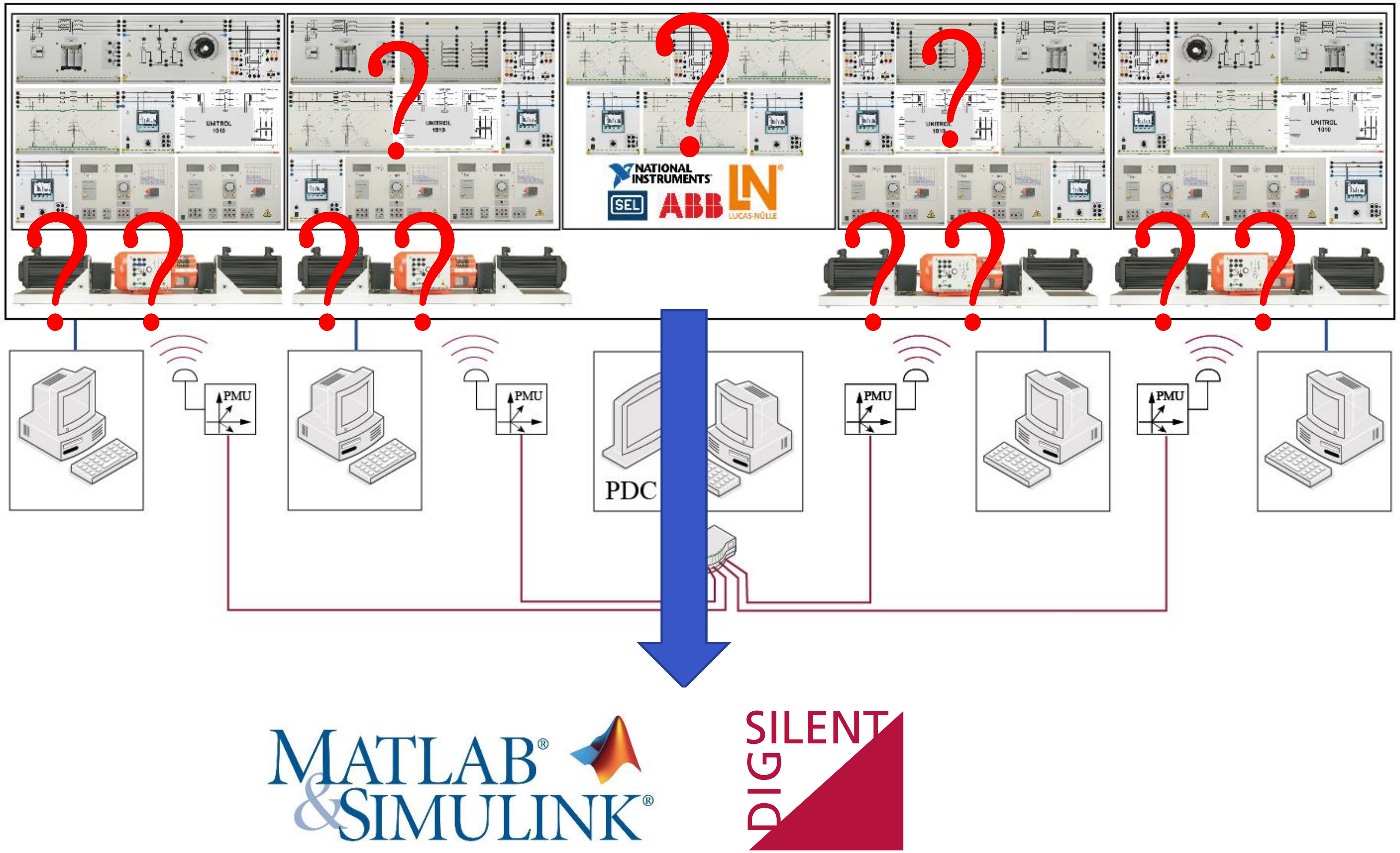
Step 2 : WADC implementation



Step 3 : Substitution of one generator with VSC



Development of a Digital Twin of the laboratory implementation of the Kundur System



Synchronous machines

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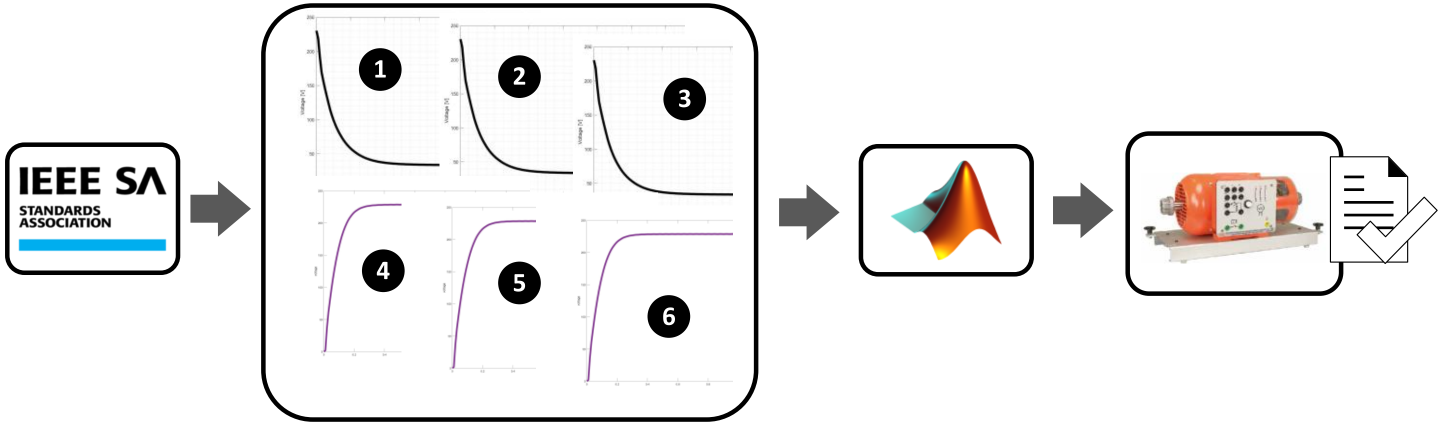
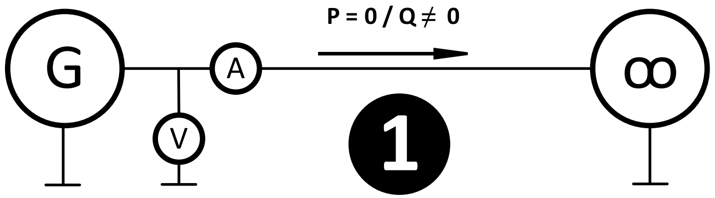
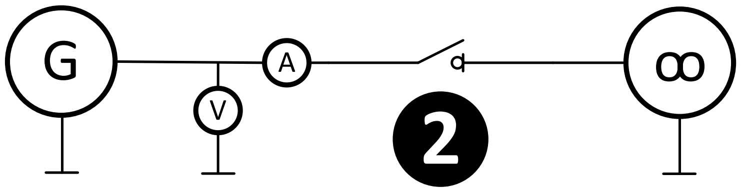
Perform different standard tests according to the IEEE guide and estimate the shared parameters



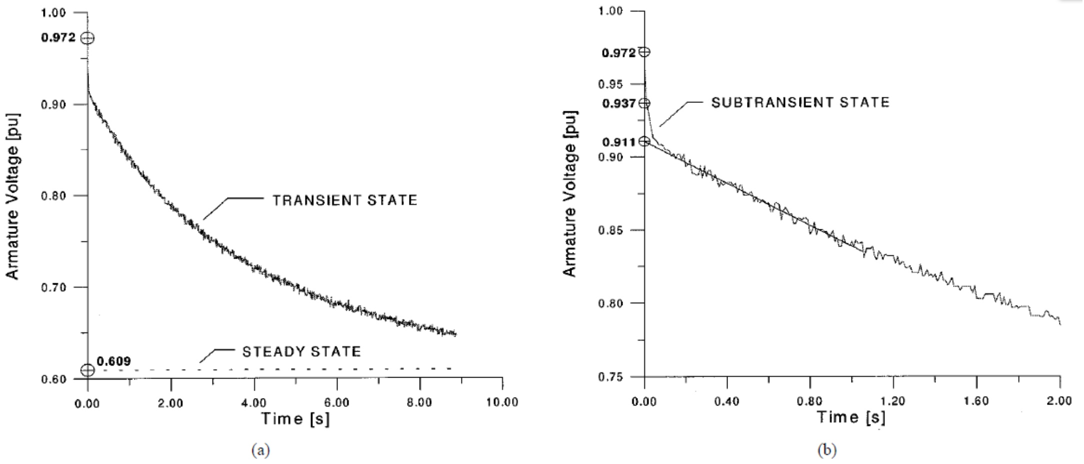
d-axis load rejection test:



1. Initial conditions: synchronized with the grid with P = 0 and Q ≠ 0



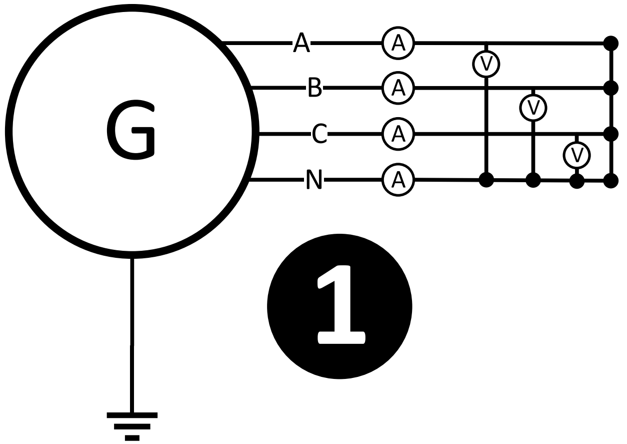
2. Open the circuit breaker and measure the transient voltage at the generator terminals

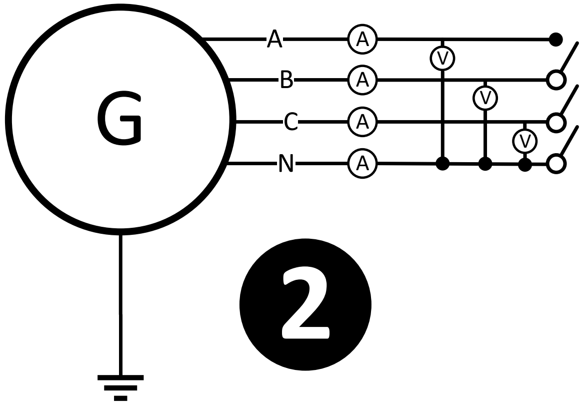


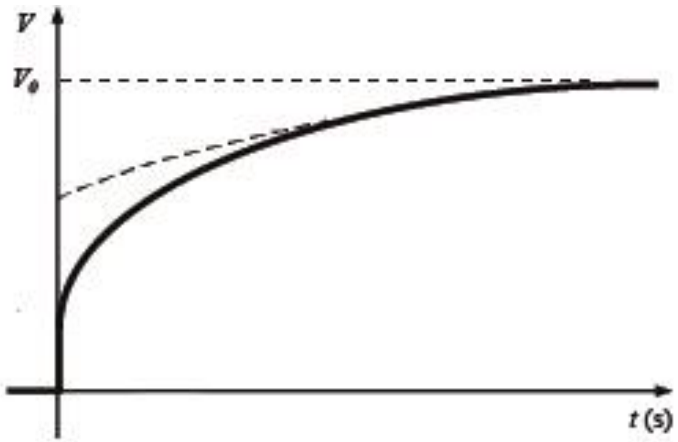
$$E(t) = E_0 - \left(X_d - (X_d - X_d')e^{\frac{-t}{T_{do}'}} - (X_d' - X_d'')e^{\frac{-t}{T_{do}''}}\right) I_0$$

Synchronous machines / d-axis

Voltage recovery test:







1. Initial conditions: short circuited phases, rated speed, excitation voltage $U_{ex} > 0$

2. open the circuit breaker between the phases and the neutral phase and record the transient voltage

$$E(t) = \left(X_d - (X_d - X_d')e^{\frac{-t}{T_{do}'}} - (X_d' - X_d'')e^{\frac{-t}{T_{do}''}}\right) I_0$$

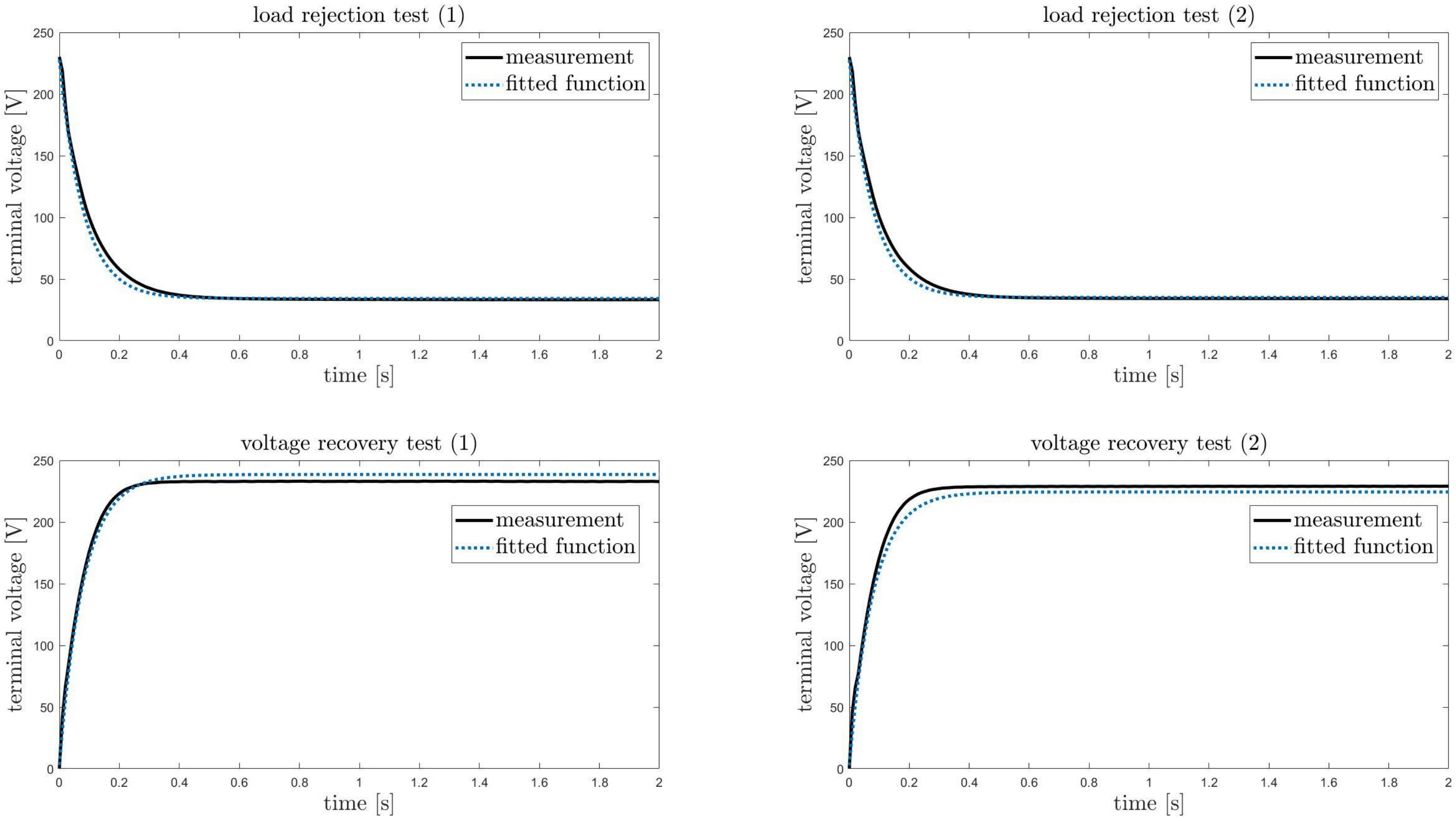
Simplifications and results

- Subtransient state of the load rejection and voltage recovery test are neglected
  - Load rejection test:

$$E(t) = E_0 - \left(X_d - (X_d - X'_d)e^{\frac{-t}{T'_{do}}}\right) I_0$$

  - Voltage recovery test:

$$E(t) = \left(X_d - (X_d - X'_d)e^{\frac{-t}{T'_{do}}}\right) I_0$$



Parameter values:

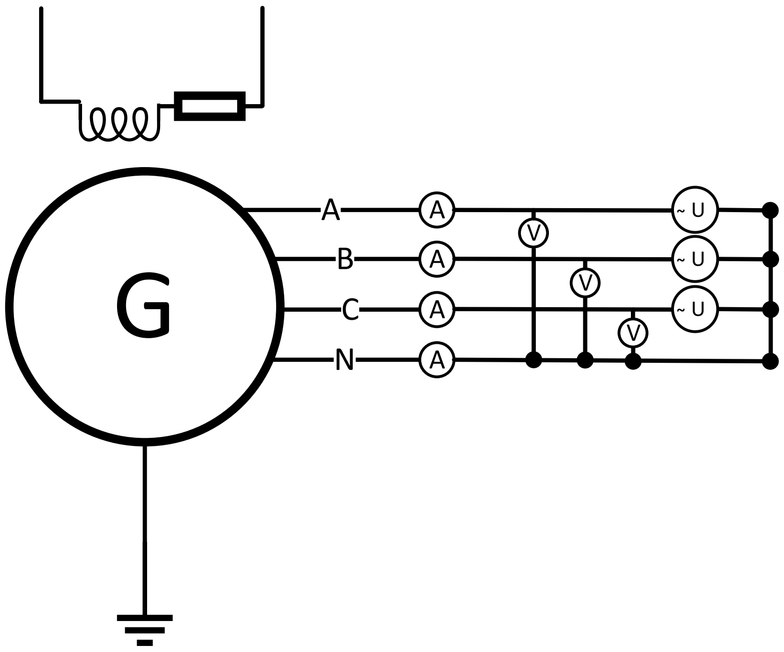
$X_d = 322.8\ Ohm$

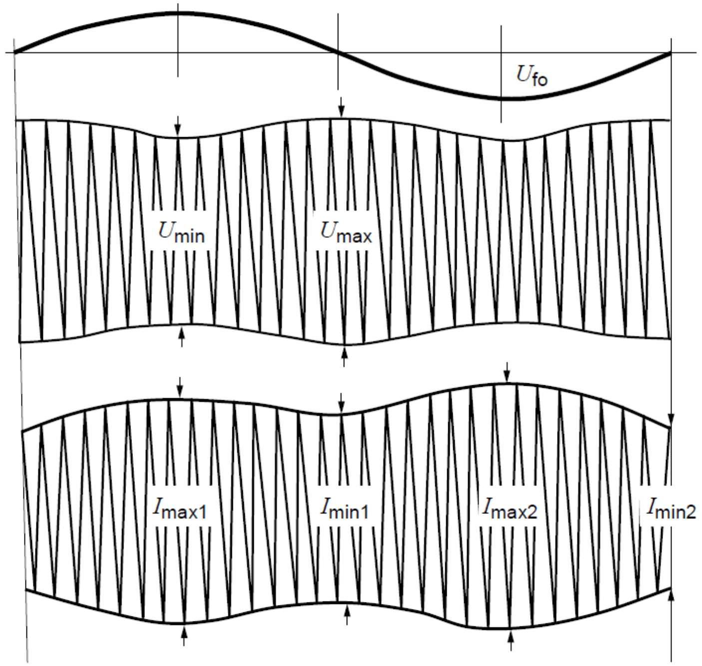
$X'_d = 3.9\ Ohm$

$T'_{do} = 0.0789\ s$

Synchronous machines / q-axis

Slip test:





$$x_q = \frac{U_{min}}{I_{max}}$$

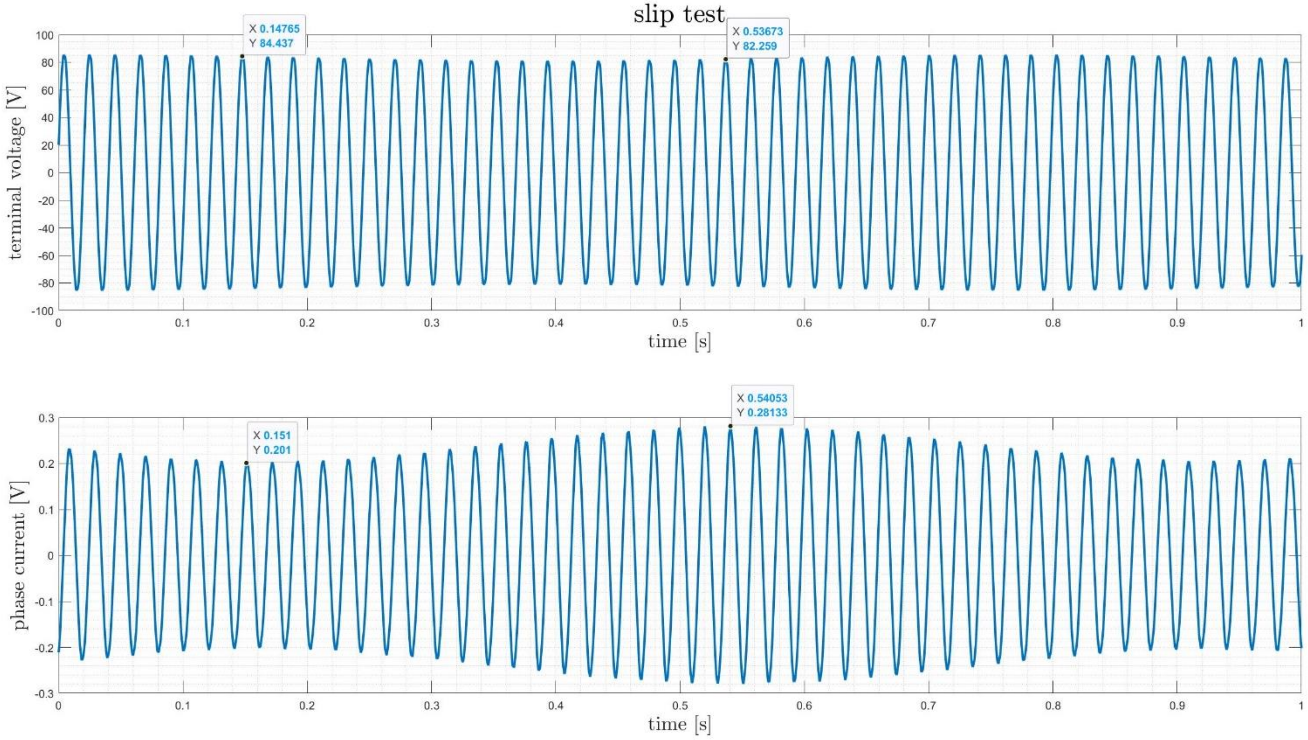
$$x_d = \frac{U_{max}}{I_{min}}$$

$$saliency\ ratio = \frac{x_q}{x_d}$$

Multiply the saliency ratio with X_d from the d-axis tests → X_q

- Field circuit is open $i_{ex} = 0$
- Generator runs at a speed sligthly different than synchronous speed
- Terminals of the generator are energized with a balanced three phase voltage at rated frequency

Results Slip Test



$$x_d = \frac{U_{max}}{I_{min}} = \frac{84.44}{0.20} = 422.2\ Ohm$$

$$x_q = \frac{U_{min}}{I_{max}} = \frac{82.26}{0.28} = 293.79\ Ohm$$

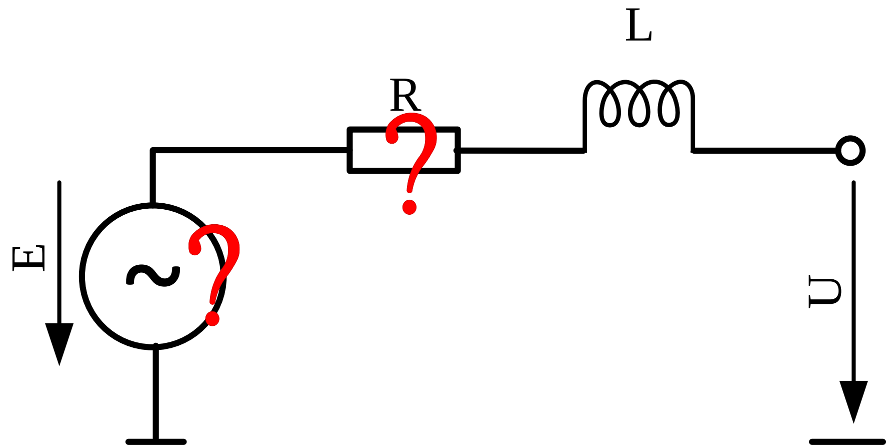
$$saliency\ ratio = \frac{x_q}{x_d} = 0.70 \rightarrow$$

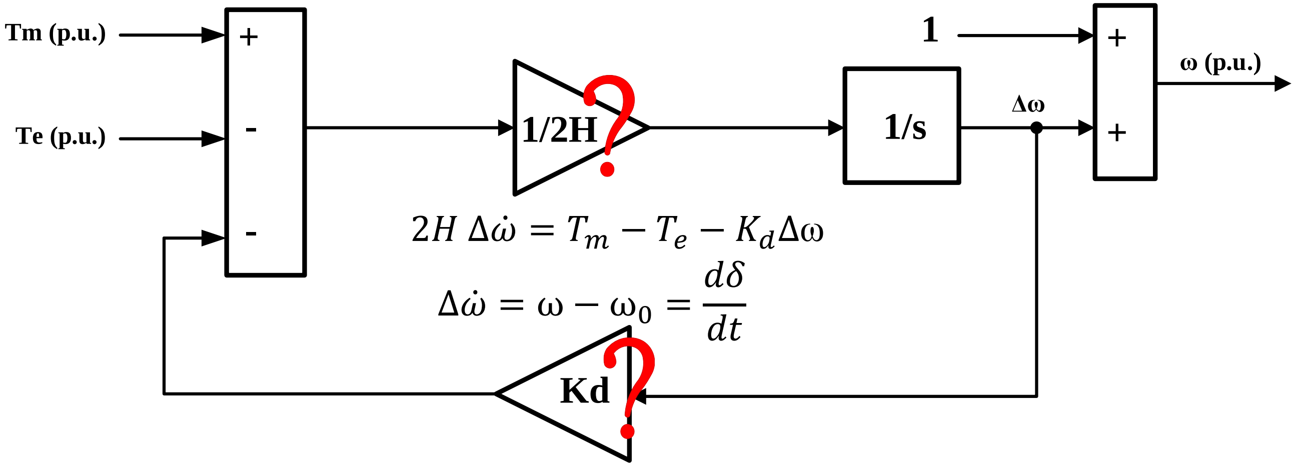
$$\boldsymbol{X_q = 0.70 * 322.8 = 225.96\ Ohm}$$

Comparison data sheet / measurement

parameter	measurement	data sheet LN	deviation
$\boldsymbol{X_d}$	322.8 Ohm	301 Ohm	6.8%
$\boldsymbol{X'_d}$	3.9 Ohm	4.56 Ohm	16.9%
$\boldsymbol{X''_d}$	-	2.3 Ohm	-
$\boldsymbol{T'_{do}}$	0.0789 s	-	-
$\boldsymbol{X_q}$	225.96 Ohm	-	-

Modelling of the synchronous machine – Classical Model



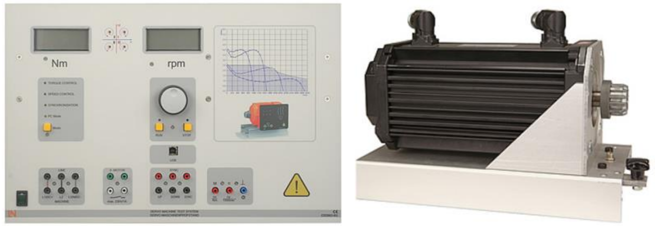


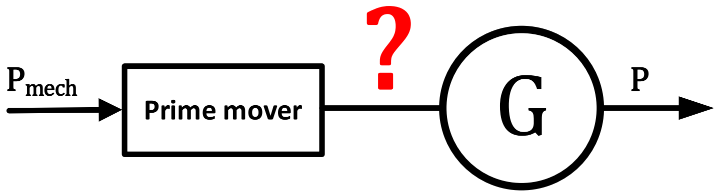
E = internal voltage or induced voltage
U = terminal voltage
L = synchronous inductance
R= omic resistance

Tm = mechanical torque
Te = electrical torque
H = inertia constant
Kd = damping coefficient
ω = rotational speed

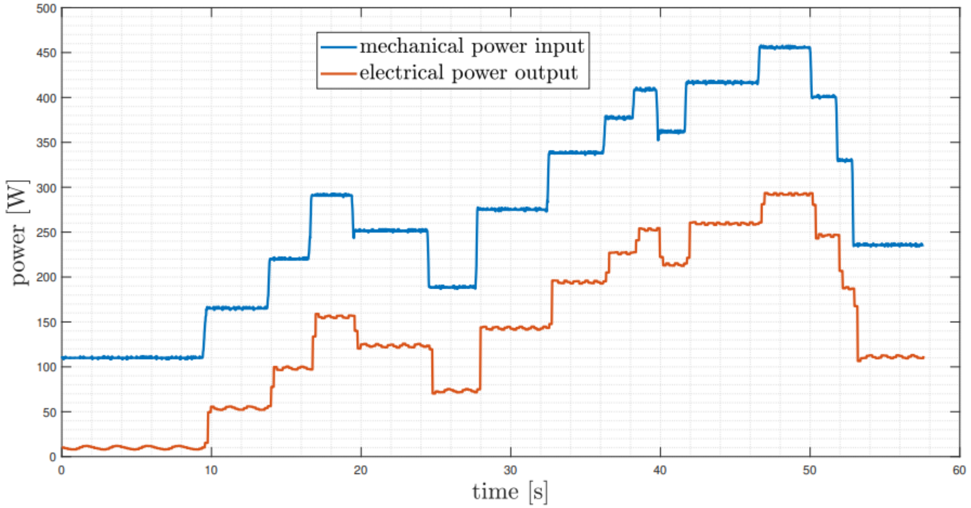
Prime mover

Frequency converter and servo machine

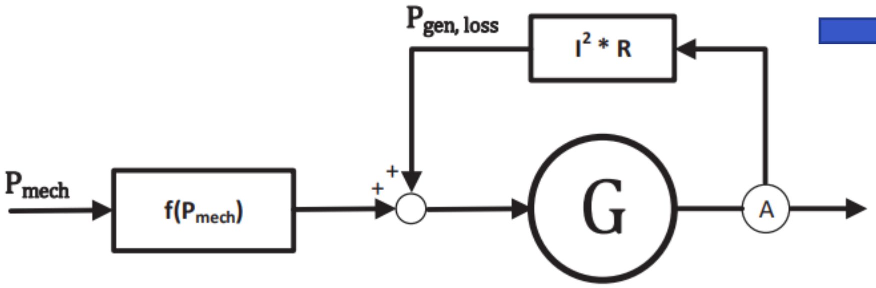




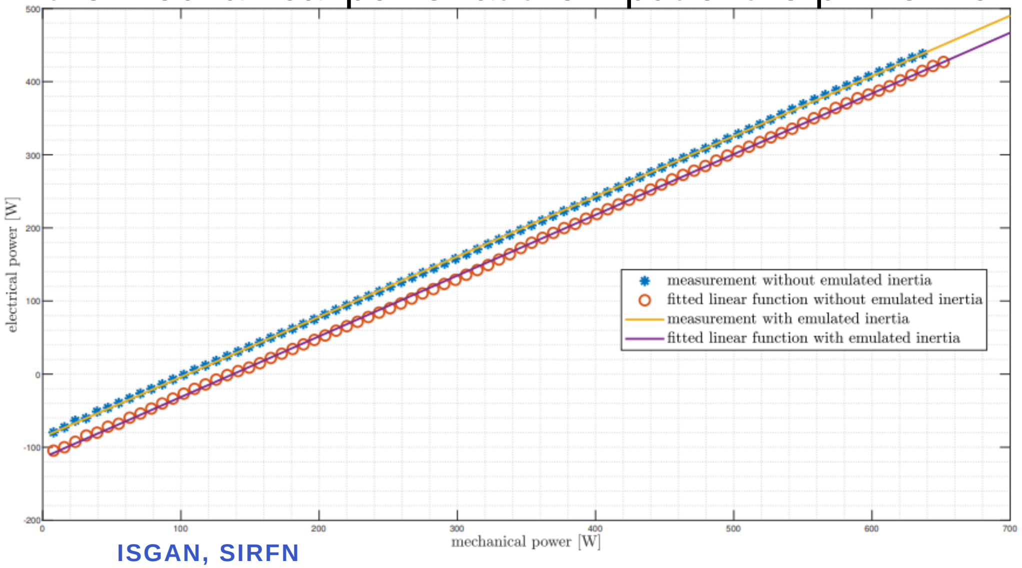
Comparison of mechanical power at the input of the prime mover and electrical power at the output of the SM



Schematic drawing of the implementation in Simulink

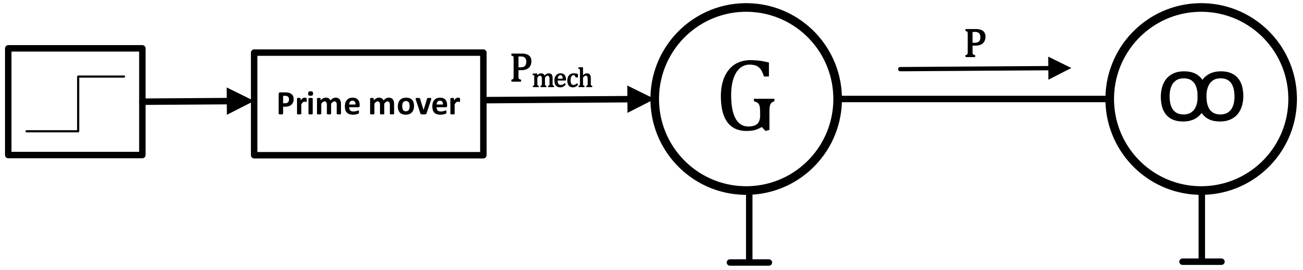


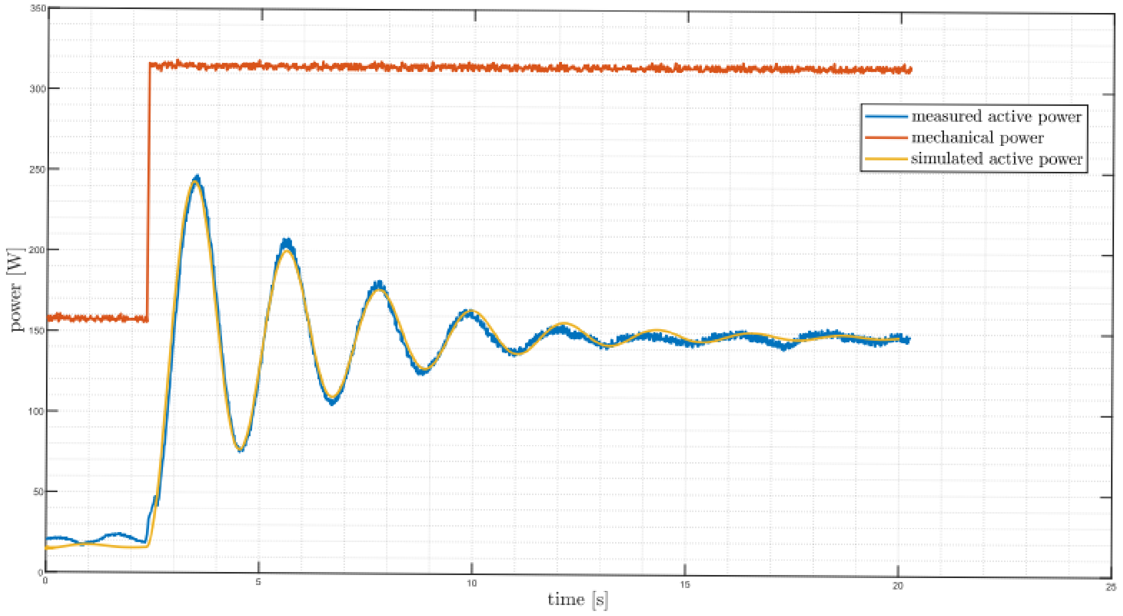
Electric power at the output of the SM as a function of the mechanical power at the input of the prime mover

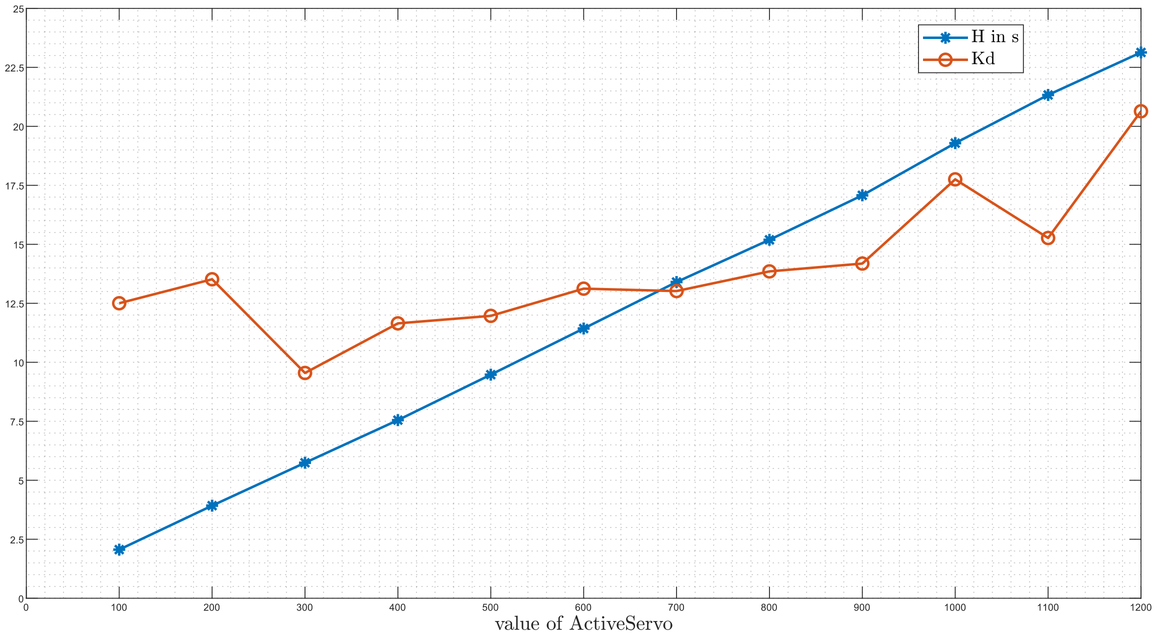


Inertia and damping factor of the synchronous machines

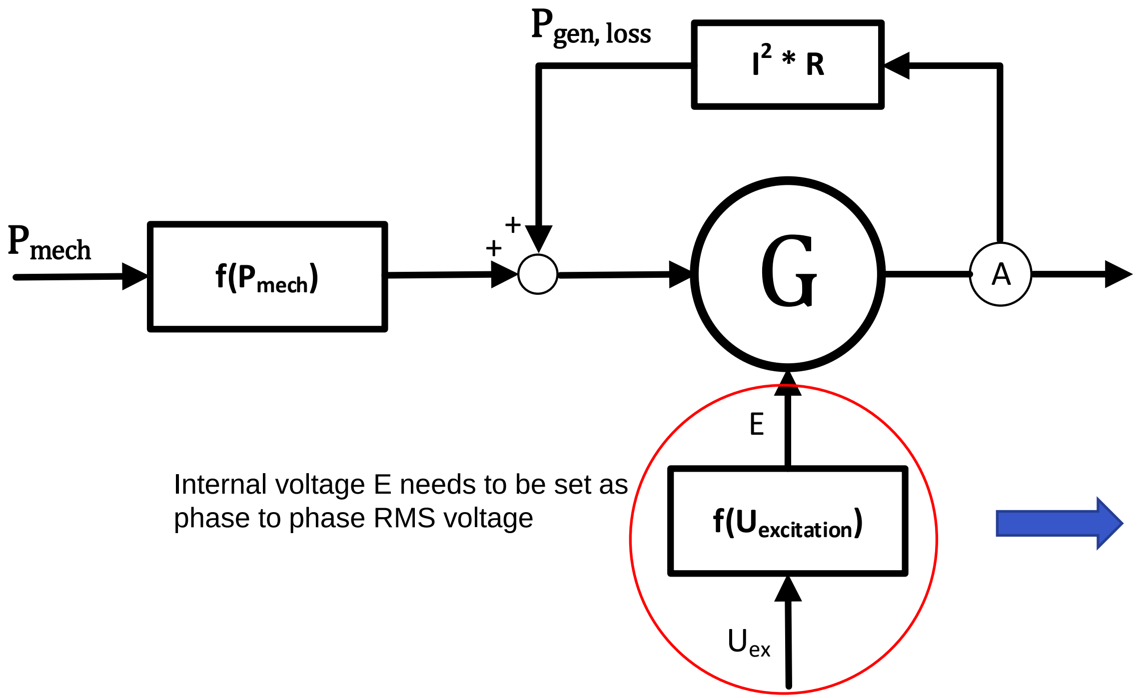
- To estimate the inertia H and the damping coefficient Kd, electromechanical oscillations are provoked
- Frequency and damping of the electromechanical oscillations are dependent of H and Kd



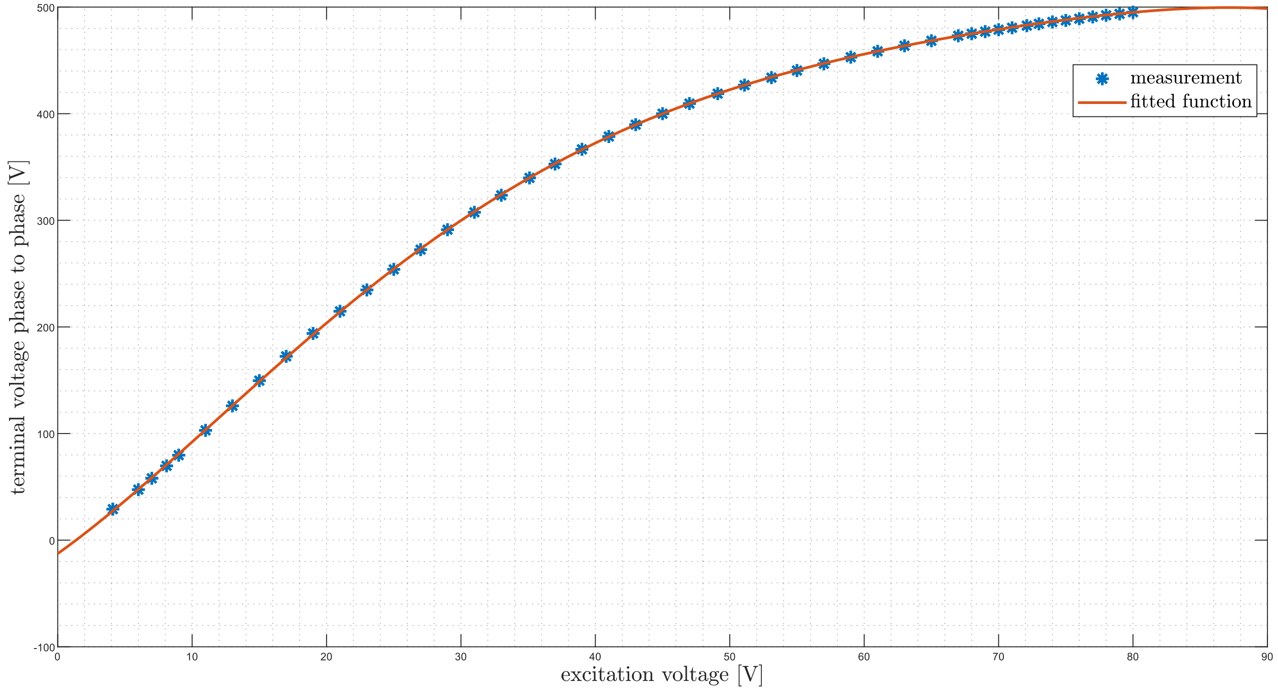




Conversion field voltage to internal voltage E



Internal voltage E needs to be set as phase to phase RMS voltage

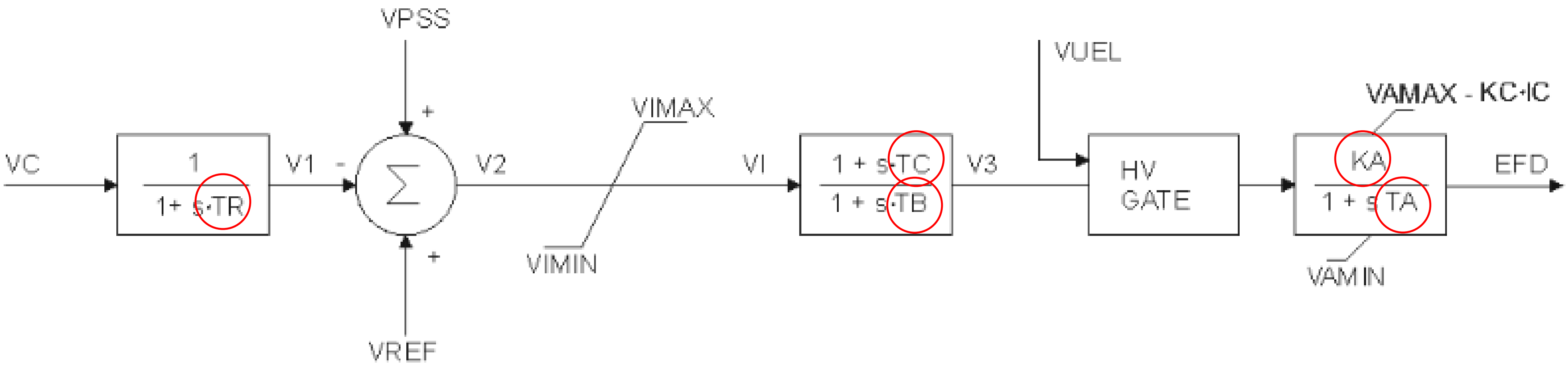


Excitation system and AVR

Laboratory

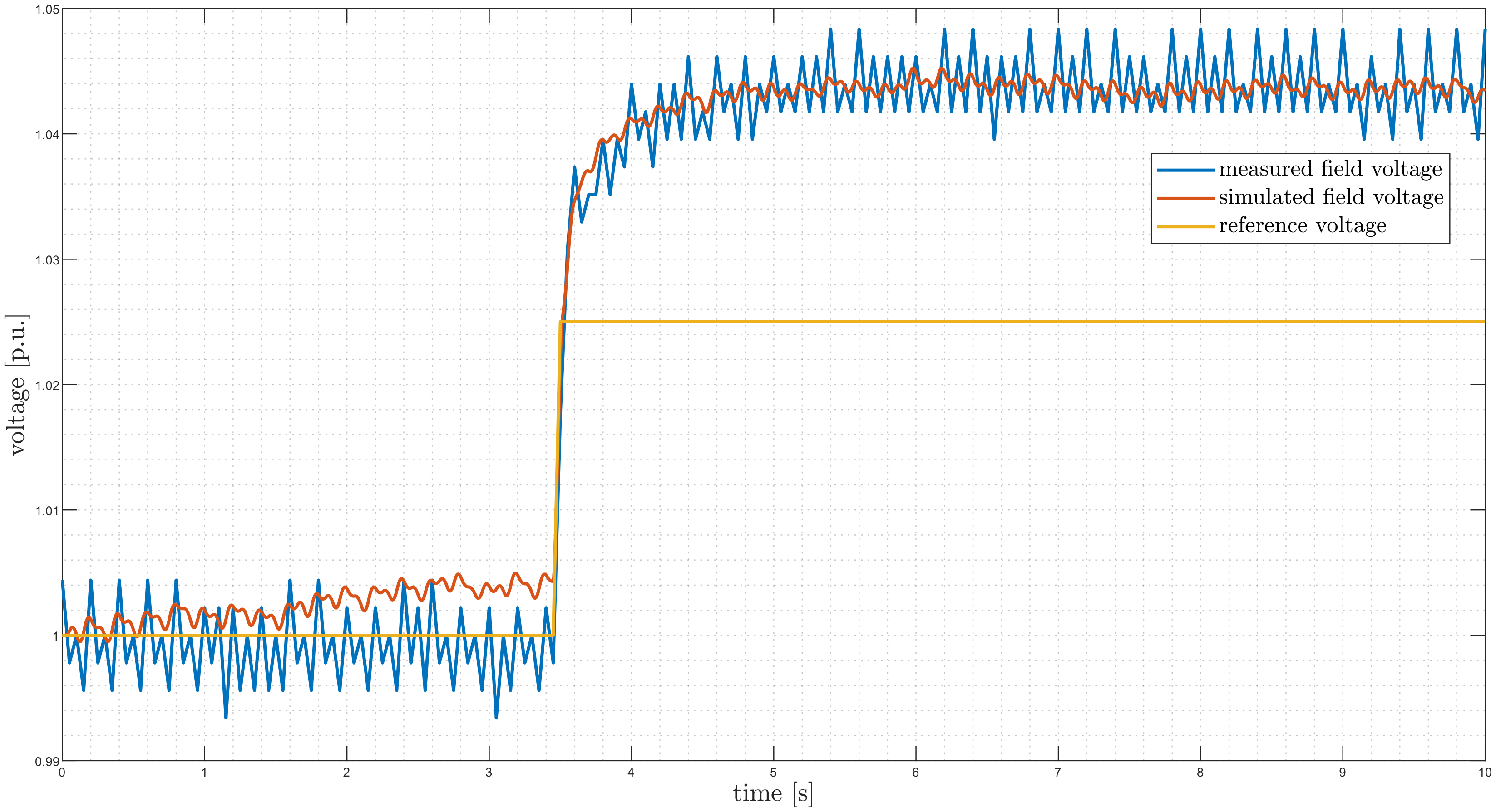
The excitation system and the AVR implemented in the lab are from the type Unitrol 1010 and Unitrol 1020 from the manufacturer ABB

AVR IEEE type AC4A was selected as for the Digital Twin:



Excitation system and AVR

- In order to estimate the missing parameters of the AVR of the Unitrol, a step in the reference voltage of 2.5% has been applied
- Field voltage and generator voltage have been measured
- The identification process has been done with the parameter estimation tool from Simulink
  - Generator voltage and reference voltage serve as inputs and the field voltage as output to be fitted by adjusting the parameters



Parameters:

$T_R = 0.01$

$T_B = 32.6876$

$T_C = 0.34078$

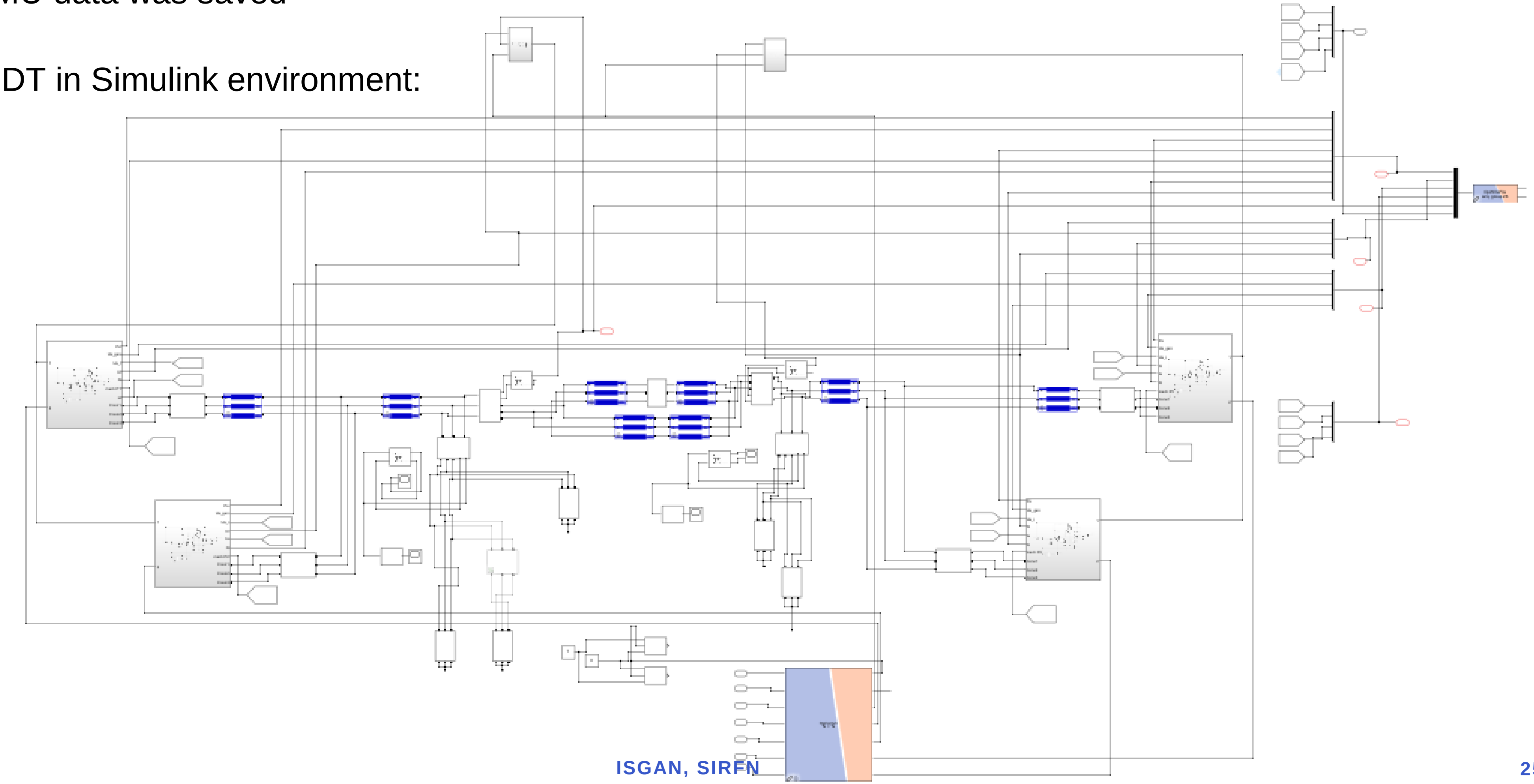
$K_A = 310$

$T_A = 0.03469$

Digital twin - 1st realization

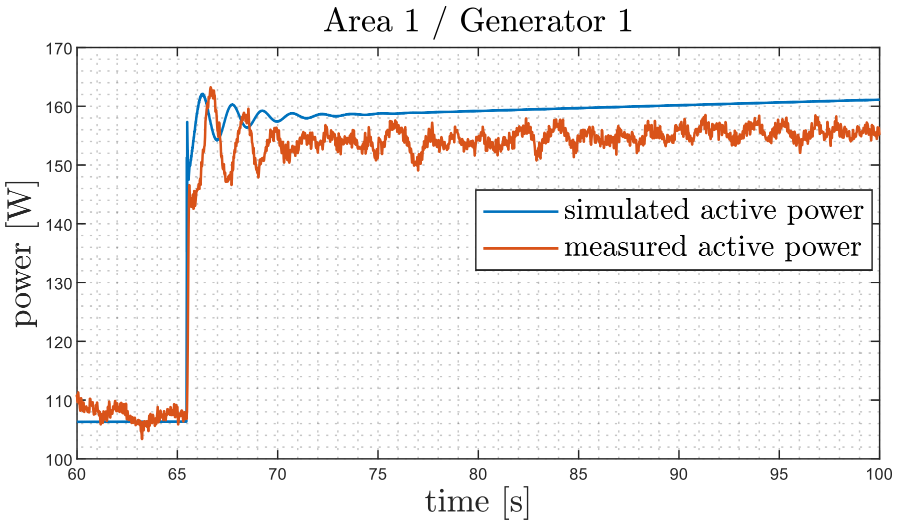
- A digital twin of the laboratory implementation of Kundur's Two Area system has been built from scratch in Simulink
- Primary and secondary control have also been implemented according to the physical system in the lab
- To compare the digital twin with the physical system a load change in area 1 has been performed and the corresponding PMU data was saved

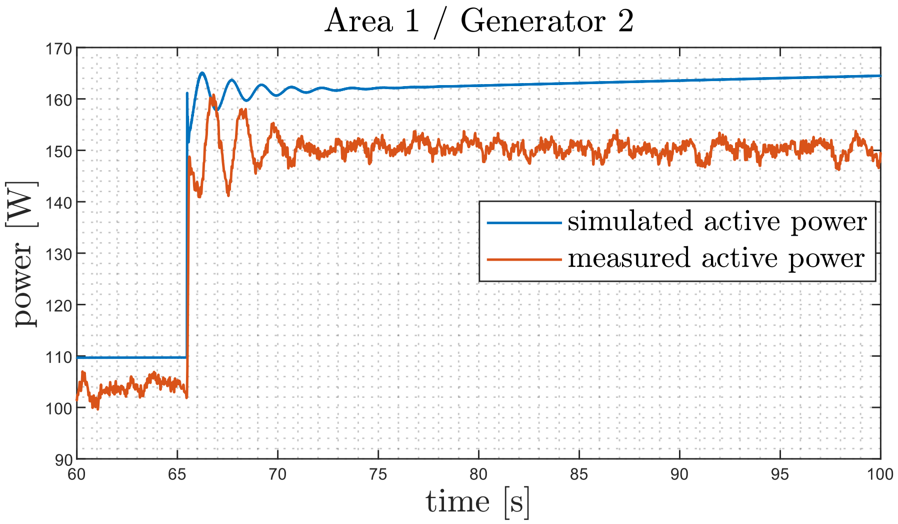
Representation of DT in Simulink environment:

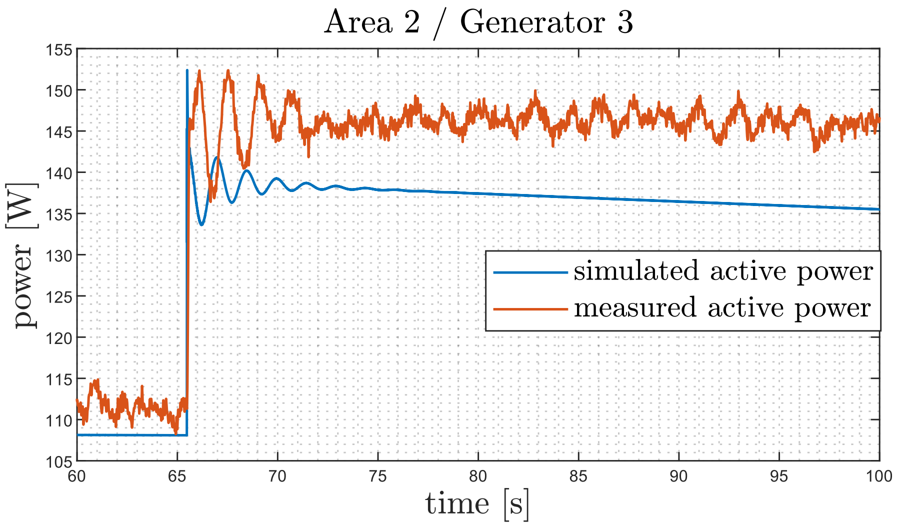


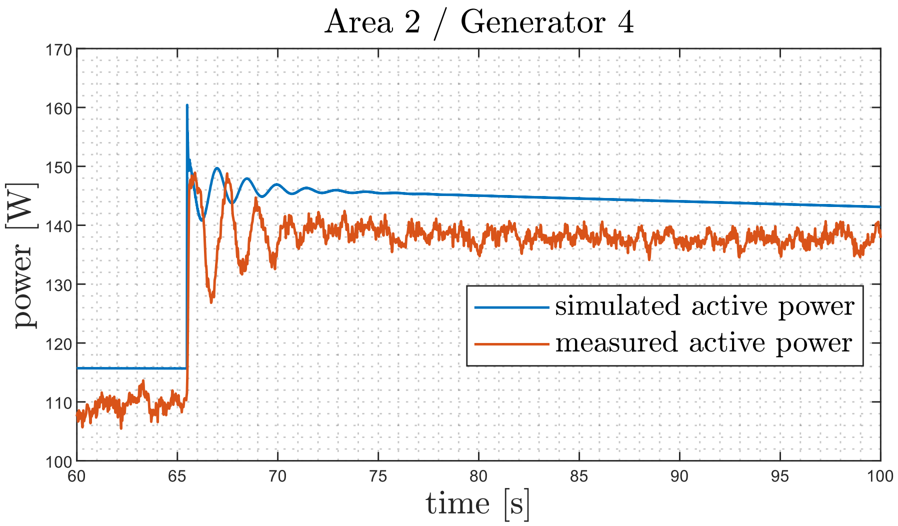
Digital twin - 1st realization

Active power:



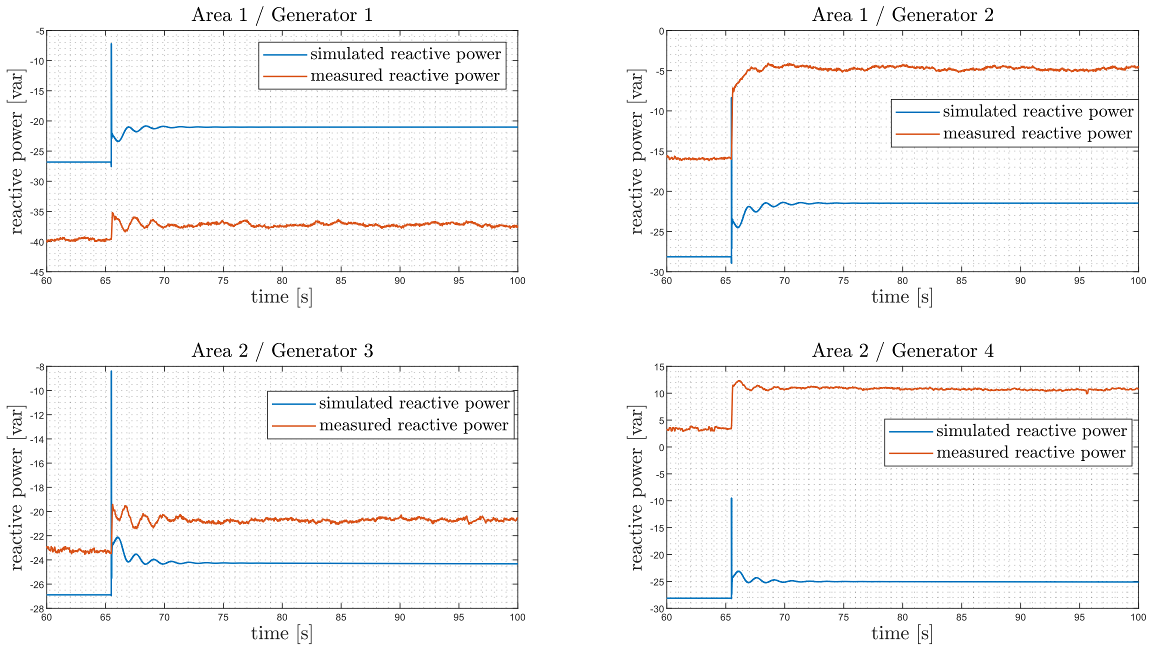




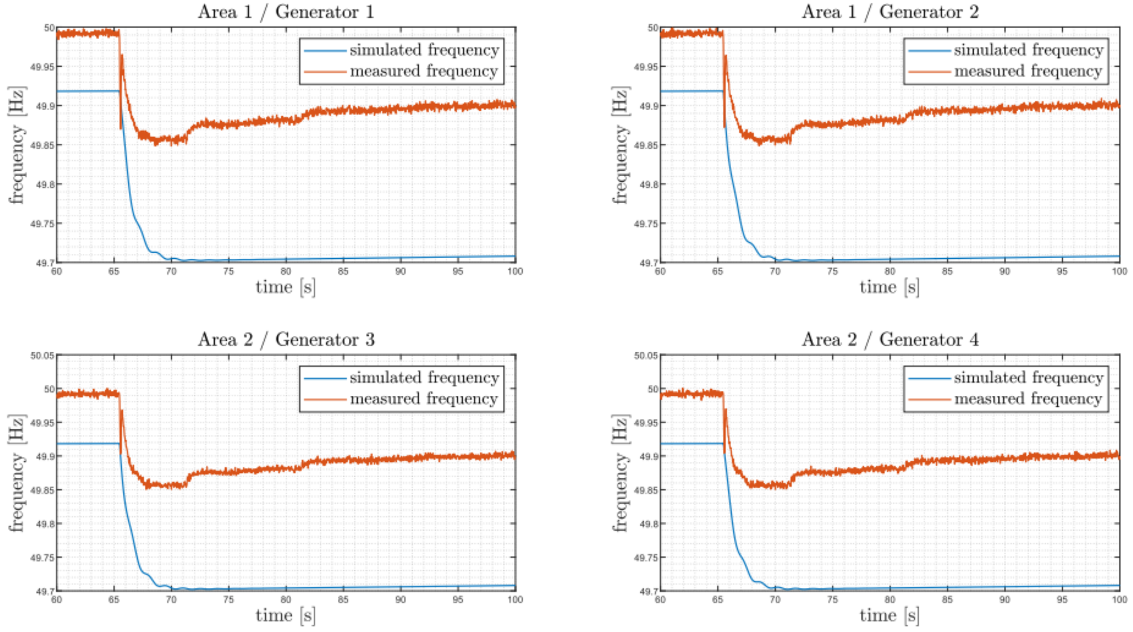


Digital twin – 1st realization

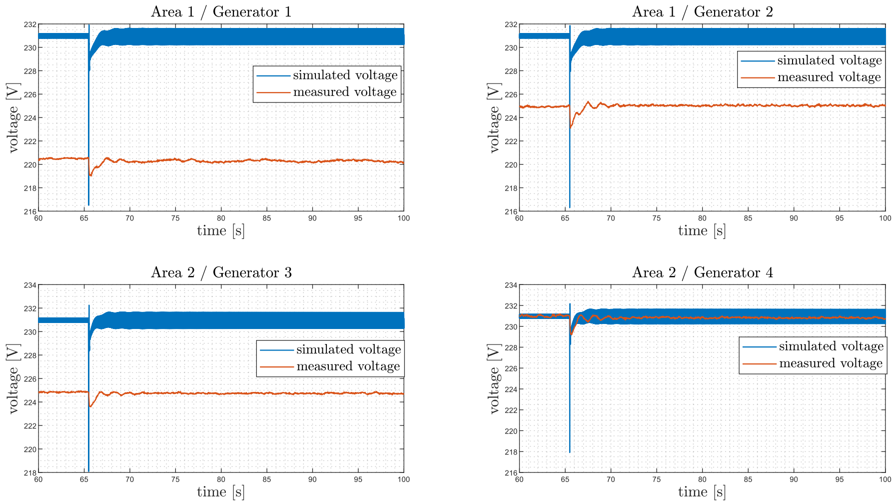
Reactive power:



Frequency:



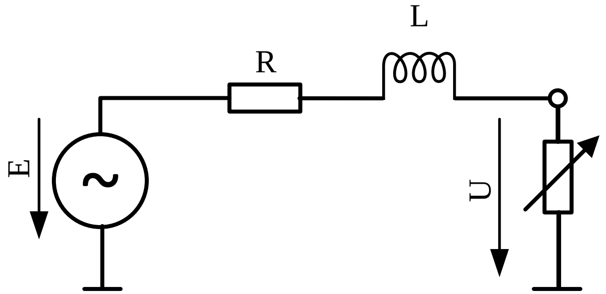
Voltage:

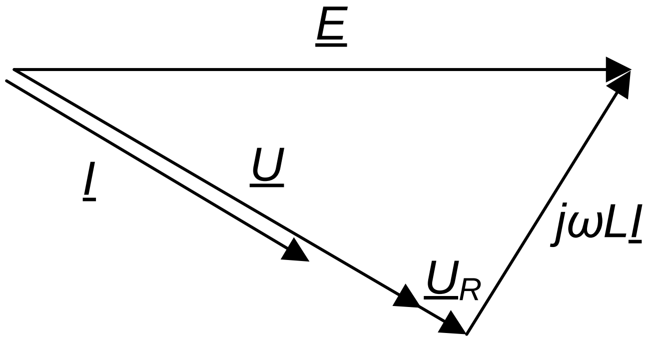


- There are many uncertainties in the model: every generator, transmission line etc. is different
- Since many parameters and components are estimated, the model shows significant differences compared with the physical model

Digital twin – Improvements of 1st realization

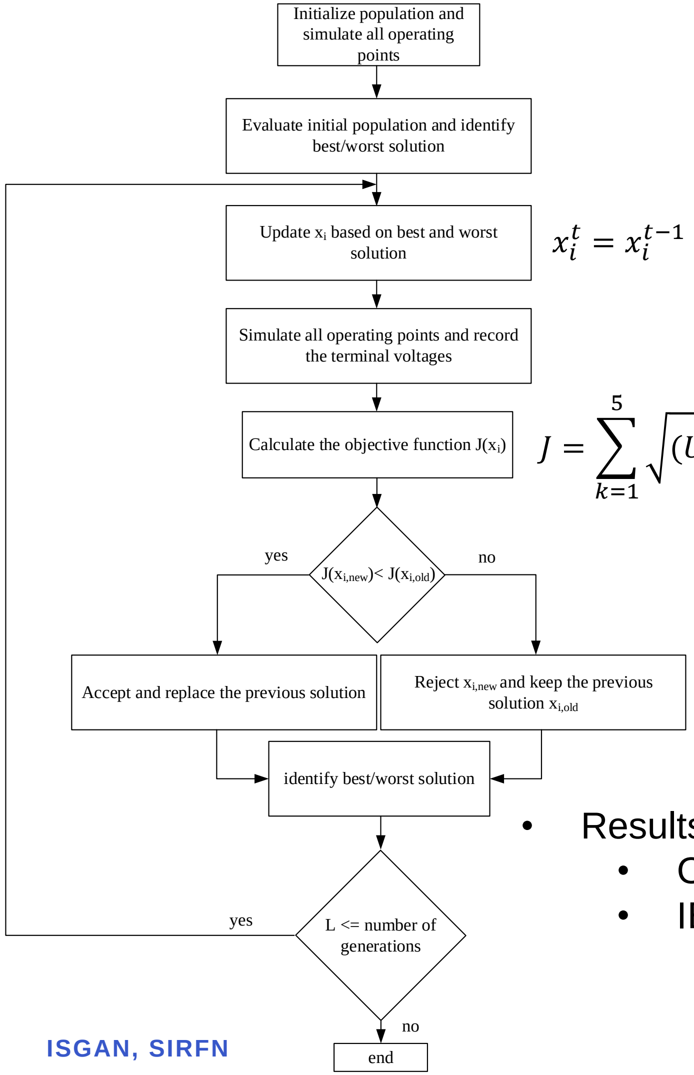
- Parameter to be optimized is the synchronous inductance jωL
- Generator is connected to a variable ohmic load without using an AVR and a proportional frequency control is used to keep the frequency stable





Several measurements have been done with different loadings

To compare and optimize the synchronous inductance (jωL), the Jaja Optimization Algorithm has been used (Jaya)



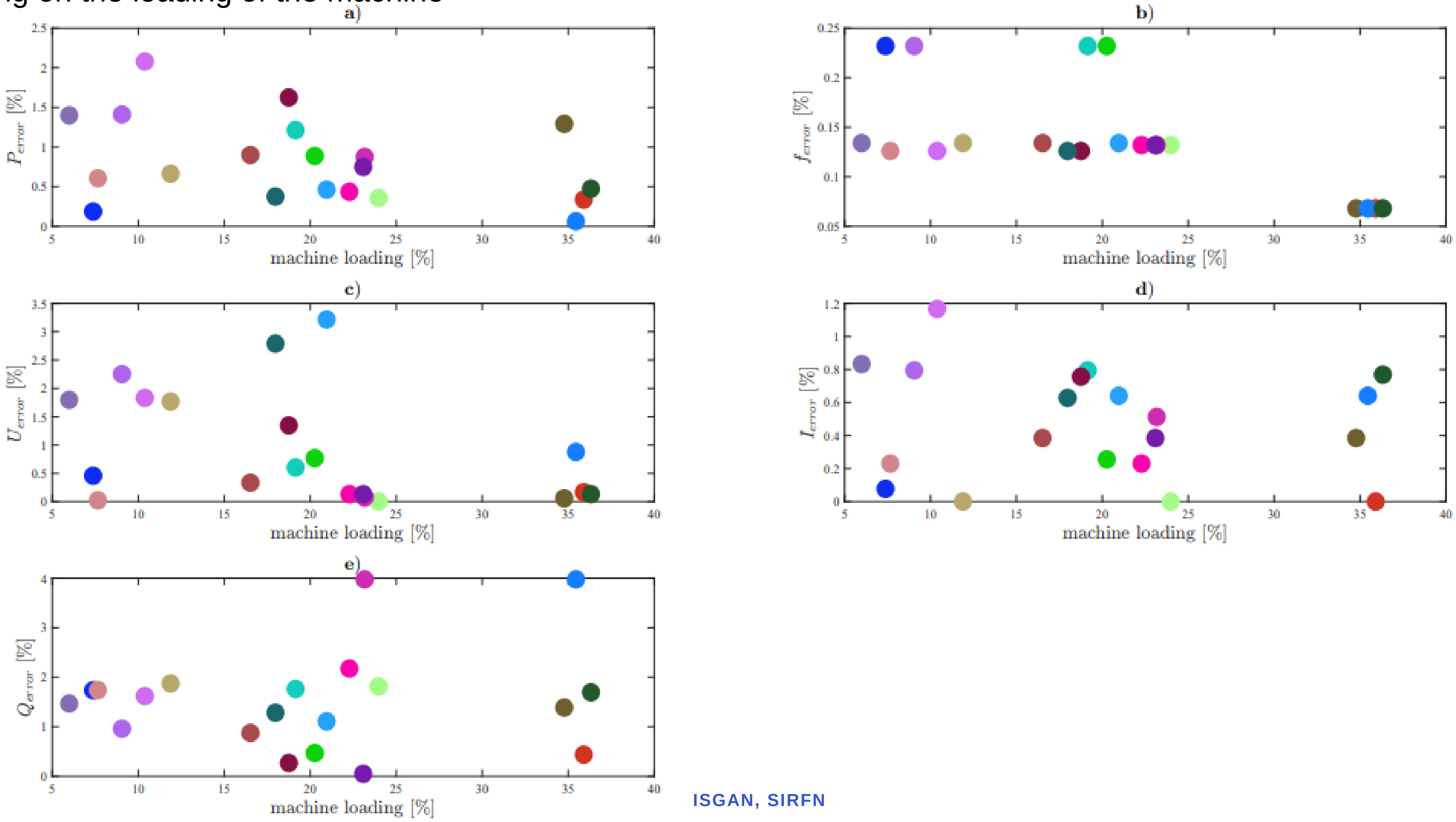
$$x_i^t = x_i^{t-1} + rand_1\left(x_{best} - x_i^{t-1}\right) - rand_2\left(x_{worst} - x_i^{t-1}\right)$$

$$J = \sum_{k=1}^{5} \sqrt{\left(U_{k,sim} - U_{k,lab}\right)^2}$$

- Results:
  - Optimal Solution JOA for Xd: **307.9 Ohm**
  - IEEE standard tests : **322.8 Ohm**

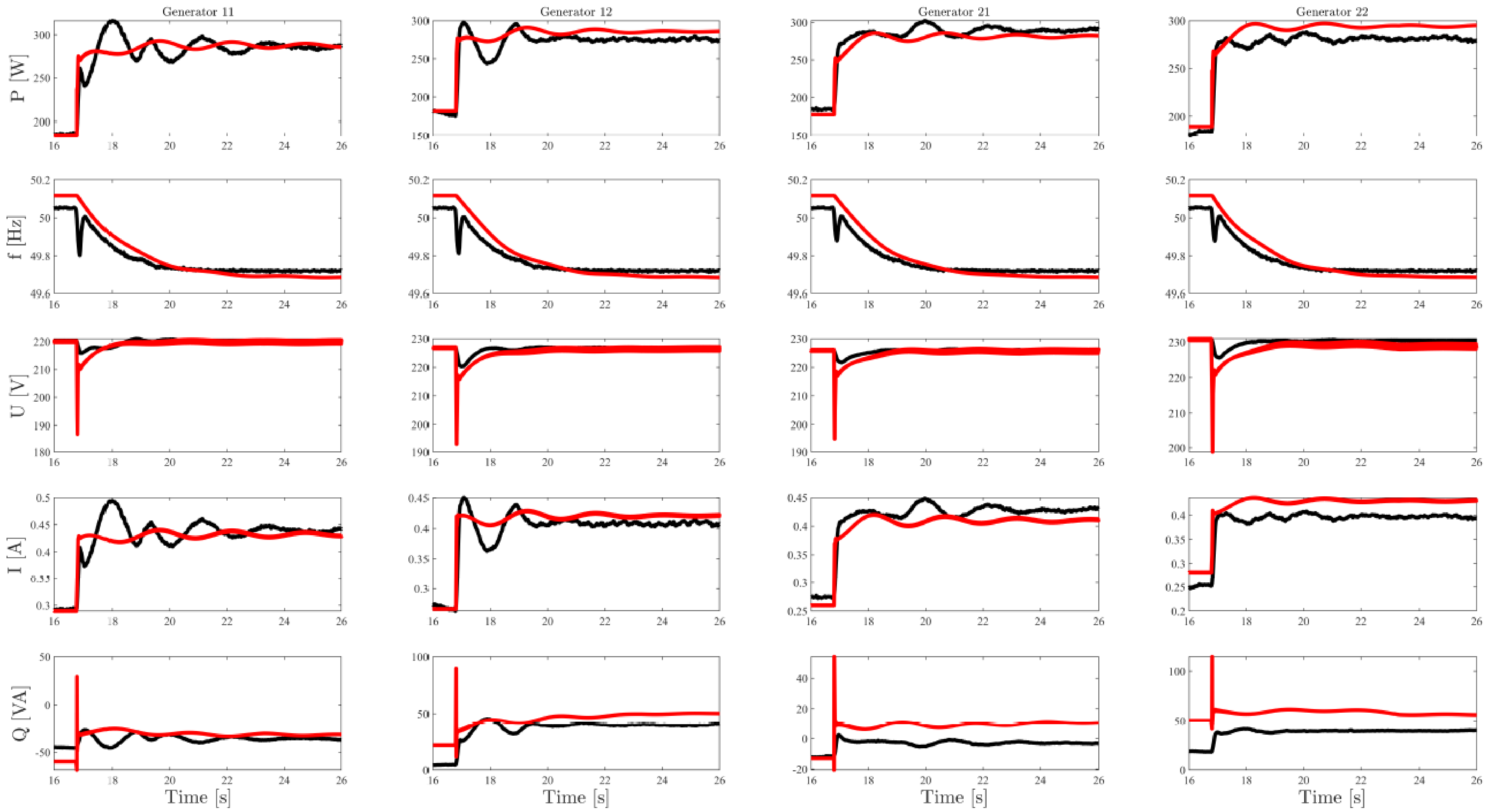
Digital twin – 2nd realization with adjusted parameters

Static operating conditions: errors of the measured signals compared to the simulation output in % depending on the loading of the machine



Digital twin – 2nd realization with adjusted parameters

Dynamic operating conditions: Measured (black) and simulated (red) signals (active Power P, frequency f, terminal voltage U, phase current I and the reactive power Q)



Digital twin – 2nd realization with adjusted parameters

RMSE in % of the dynamic operation conditions

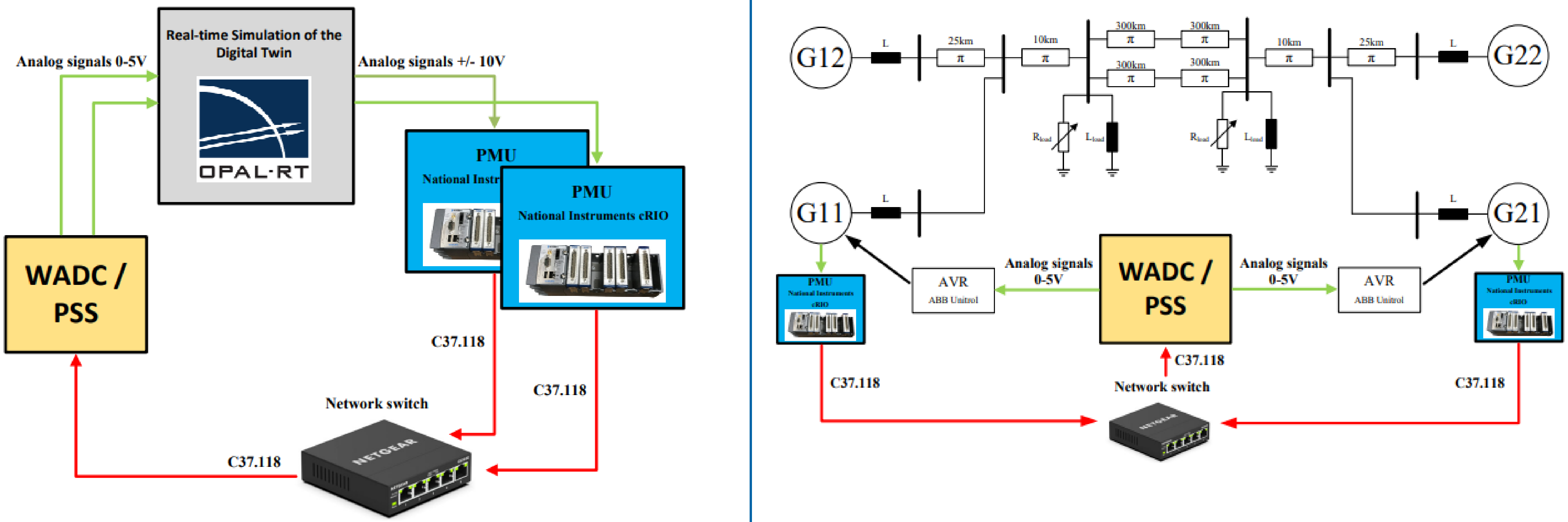
	Generator 11	Generator 12	Generator 21	Generator 22
RMSE P in %	0.96	0.56	1.00	1.28
RMSE f in %	0.05	0.05	0.05	0.05
RMSE U in %	0.23	0.24	0.44	0.02
RMSE I in %	0.35	0.31	1.21	0.65
RMSE Q in %	1.61	1.07	2.99	1.00

- Errors are in general acceptable for the static and the dynamic cases
- Biggest errors are associated with the reactive power Q
- Special attention should be given to the current errors due to the current limitation through the 10km lines

Digital twin – Test case: WADC Controller design, implementation and testing

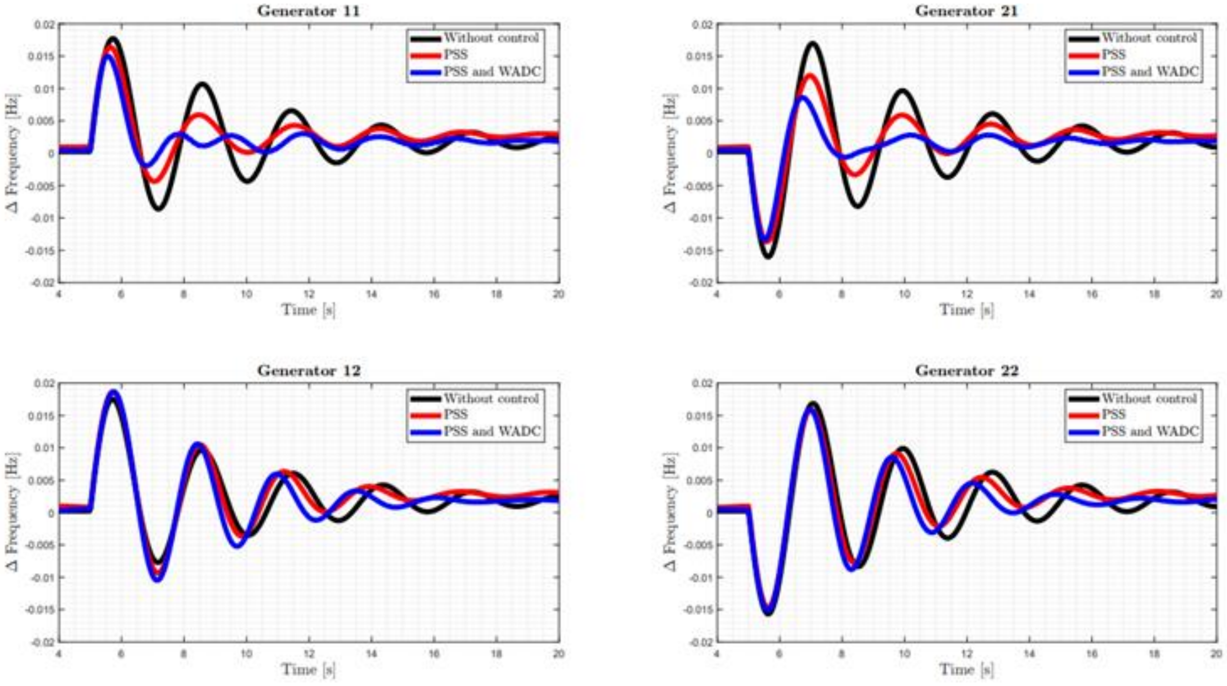
- Two stage approach has been implemented, where the controller was tested first in a CHIL setup and then transferred to the dynamic hardware emulator in the lab
- Conventional PSS has been used together with a proportional WADC

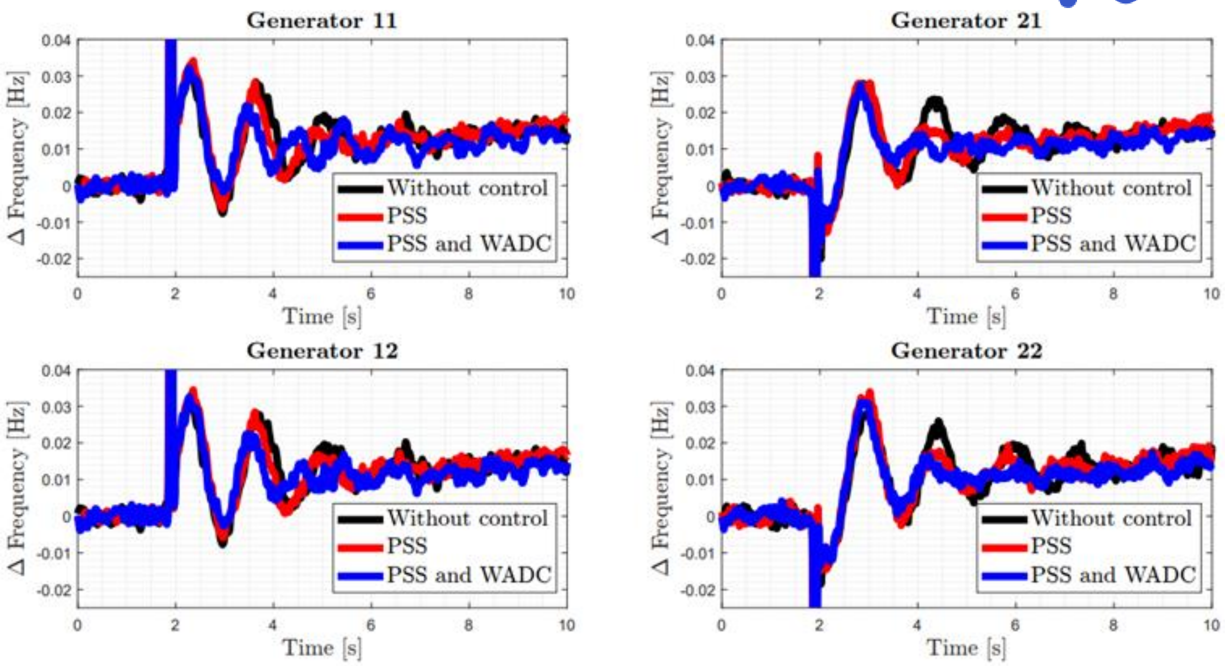
Schematic drawing of the CHIL (left) and dynamic hardware emulator (right) setups



Digital twin – Test case: WADC Controller design, implementation and testing

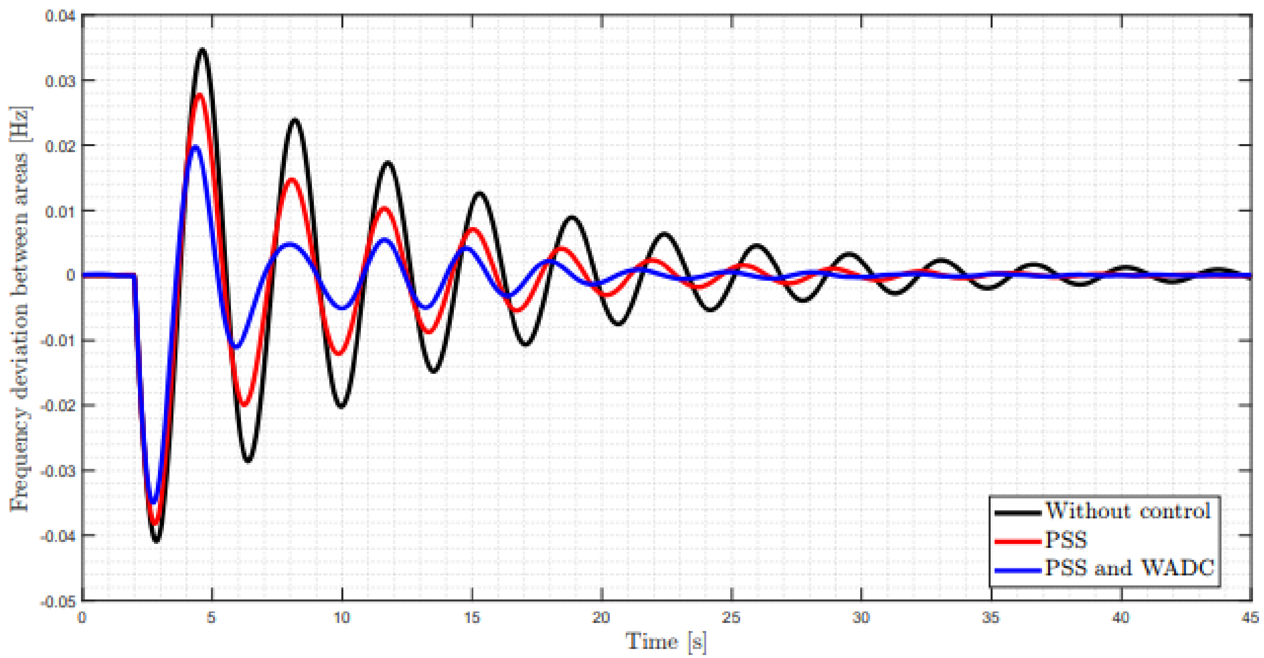
Local frequency deviations between the CHIL (left) and dynamic hardware emulator (right) behaviour



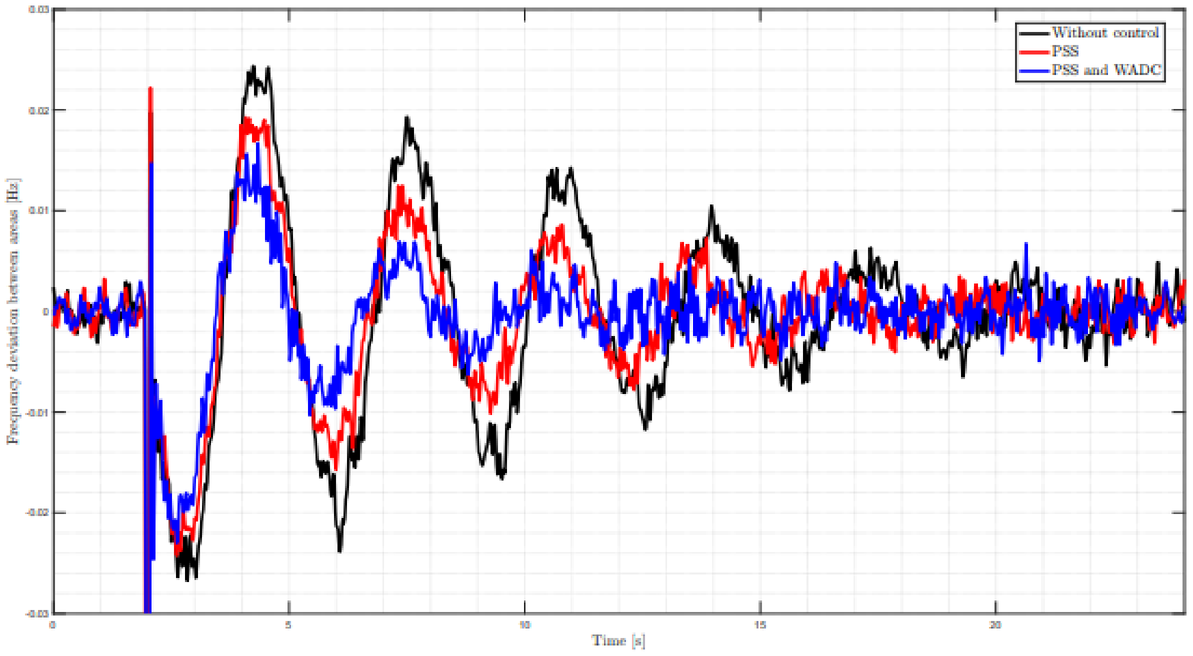


Digital twin – Test case: WADC Controller design, implementation and testing

Frequency deviation between area 1 and area 2 for the three scenarios after the tie line trip within the CHIL (left) and dynamic hardware emulator (right) setup



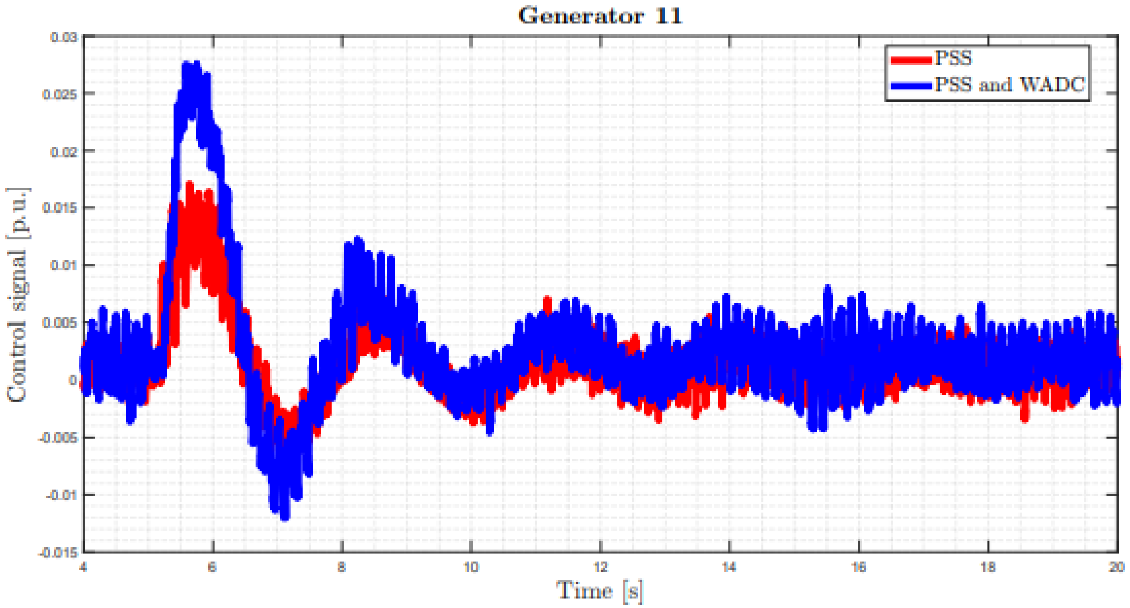
Performance index	Value
Without control	1
PSS	0.52
PSS and WADC	0.26



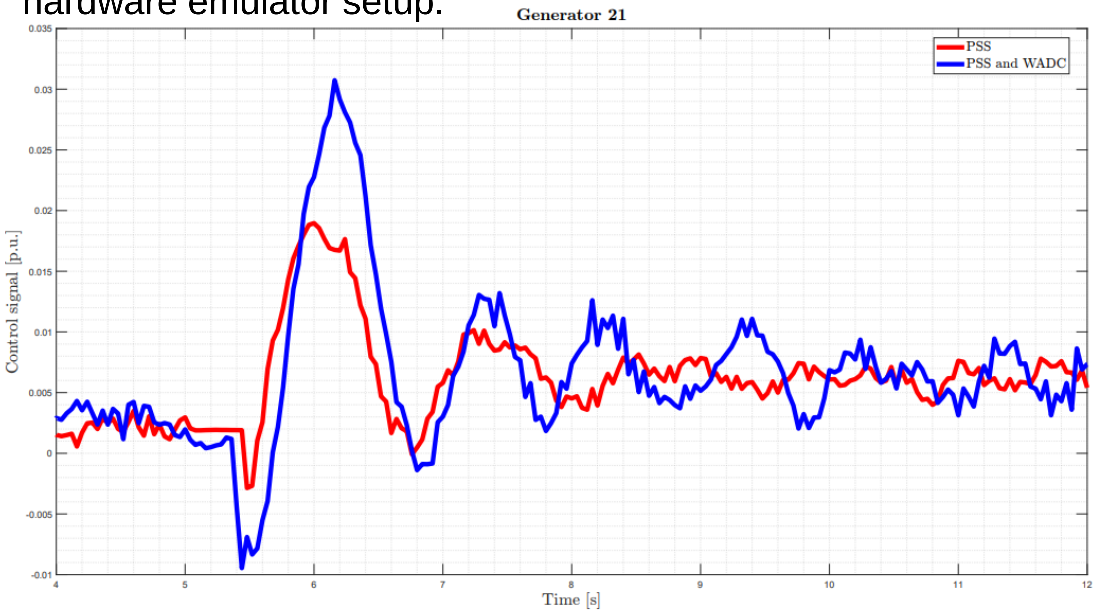
Performance index	Value
Without control	1
PSS	0.88
PSS and WADC	0.79

Digital twin – Control signals

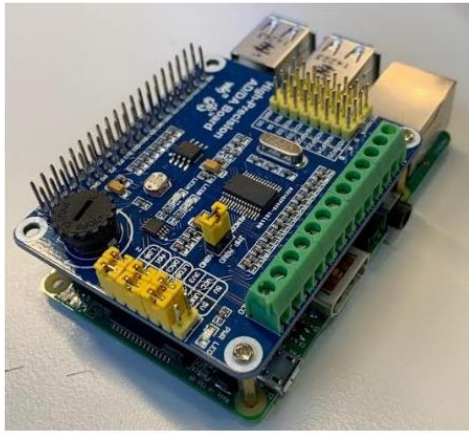
Control signal of the PSS (red) and PSS / WADC (blue) case in p.u. within the CHIL setup.



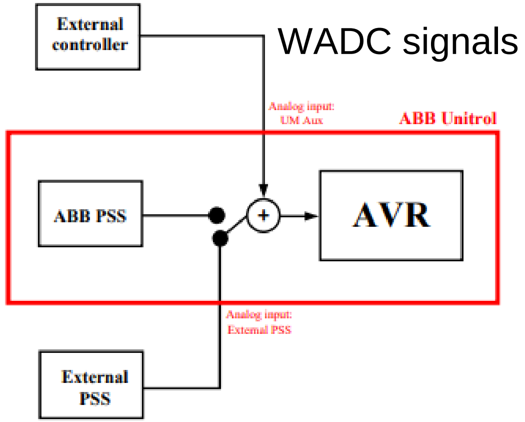
Control signal (Unitrol measurements) of the PSS (red) and PSS / WADC (blue) case in p.u. within the dynamic hardware emulator setup.



Raspberry Pi with High-Precision AD/DA expansion board

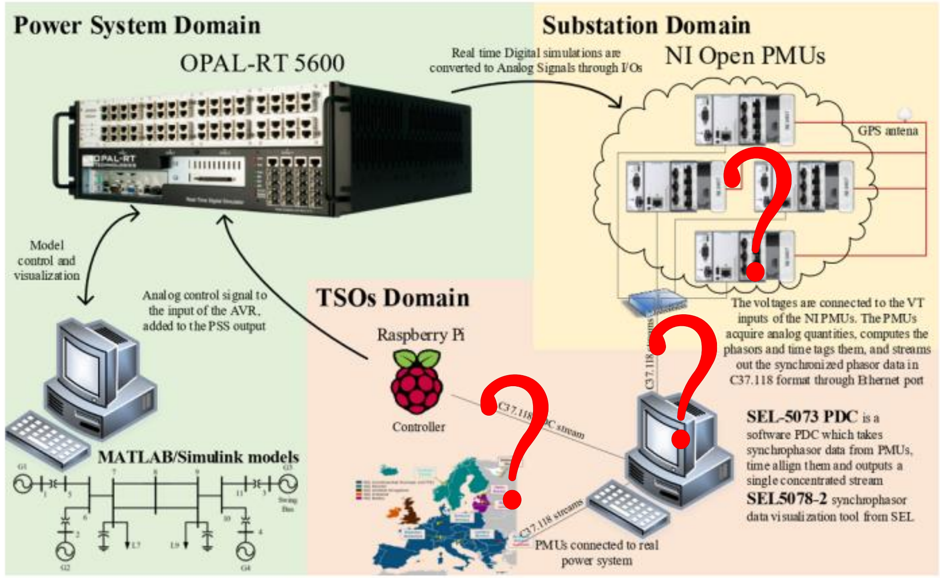


Different control possibilities of configuration in the Unitrol



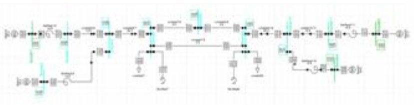
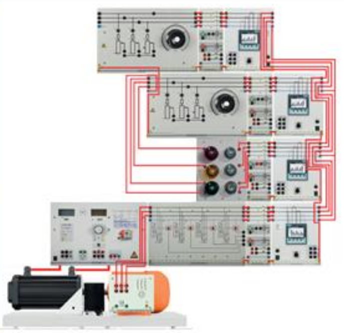
Future and Ongoing work:

Consideration of ICT issues: Communication congestions / Communication channel events (interactions, delays, package loss)



Migrate digital twin into a power system-oriented software such as DigSilent Power Factory for:

- further exploitation with a wide range of functions for analysis
- extensive evaluation of scenarios through highly automated tasks
- investigation of advanced analytic applications

PowerFactory model	Digital Twin	Dynamic emulator
		
high flexibility high scalability low fidelity	high flexibility medium scalability medium fidelity	low flexibility / medium flexibility (PHIL) low scalability high fidelity

Conclusions:

- Challenges
  - working with real devices, such as measurement devices, digital controllers and the dynamic hardware emulator, has generally been challenging as the signal noise involved is sometimes difficult to handle
  - asynchronous measurements prevent data from being used directly (oscilloscopes, synchrophasors, PQ analysers); pre-processing is needed
  - communication between devices can be lost without any obvious reason
  - parameter deviations from original values provided by the manufacturer
  - digital twin has been built, which is not perfect, but it shows a comparatively similar behaviour as the physical model in the laboratory
  - current limitations in some components restrict system loading to less than 50%. Alternatives should be analyzed and implemented to get rid of this constraint
  - inter-area oscillations in the dynamic hardware emulator are, in general well damped, and the amplitudes are small – *We are looking at how to stress the system*

- Opportunities
  - room for improvements of the digital twin → continuous accuracy and flexibility improvements
  - impact of low inertia sources (RES/BESS) on power system dynamics
  - equipment/protection behaviour in case of a high rate of change of Frequency (RoCoF)
  - testing and validation of advanced wide area measurement, protection and control (WAMPAC) systems
  - validation of data-driven solutions, including oscillation detection, classification and source allocation
  - de-risk grid control approaches and algorithms to achieve secure and resilient operation in normal and emergency grid conditions, including constraint violation avoidance
  - communication delays and packet loss in a ‘risk-free’ environment

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“A theory is something nobody believes, except the person who made it.
An experiment is something everybody believes, except the person who made it.”

- Albert Einstein

Thank you for your attention

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