

Concepts, Methods, and Tools for Validating Cyber-Physical Energy Systems

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Motivation and Aims for the Tutorial

- Ongoing challenges and needs
 - Integration of renewables requires advanced Information and Communication Technology (ICT), automation, and control
 - The raising complexity of such Cyber-Physical Energy Systems (CPES)/ smart grid systems urge for integrated, multi-domain based validation methods and tools
 - Well-educated researchers and engineers in the domain of CPES



Motivation and Aims for the Tutorial

- Tutorial introduces and provides
 - Challenges in CPES development and validation
 - The integrated ERIGrid validation approach
 - A holistic validation procedure for CPES-based system-level testing
 - Enhanced simulation and lab-based testing methods
 - An overview of selected validation examples
 - Information about the free access to smart grid laboratories



About the Speaker

- 2001 MSc Industrial Engineering,
Vienna University of Technology (VUT), Vienna, AT
- 2003 PhD Mechanical Engineering, VUT, Vienna
Researcher at PROFACTOR Research, Steyr, AT
- 2007 Senior Researcher at PROFACTOR Research
- 2010 AIT Austrian Institute of Technology, Vienna, AT
Scientist Electric Energy Systems
- 2012 AIT Austrian Institute of Technology, Vienna, AT
Senior Scientist Electric Energy Systems
- Involvement in several national and international research projects
- Evaluator for various international research programs
- Teaching at VUT as a docent (Privatdoz.) and active in IEEE, CIGRE and IEC
- Core topic(s): power utility automation, design and validation of smart grid systems



Acknowledgements

- This work is supported by the European Communities Horizon 2020 Program (H2020/2014-2020) under project [ERIGrid](#) (Grant Agreement No. 654113)
- Special thanks to all [ERIGrid](#) partners for their contributions to this tutorial
- This tutorial is also sponsored and technically supported by the
 - [IEEE SMC TC on Intelligent Industrial Systems](#)
 - [IEEE SMC TC on Distributed Intelligent Systems](#)



Outline of the Tutorial

- Background and motivation
- Status quo in validation and future needs
- The ERIGrid vision and approach
- Holistic validation procedure
- Simulation and lab-based testing methods
- Selected validation examples
- Discussion, feedback, and conclusions

Background and Motivation

SMC 2018 Tutorial

Concepts, Methods, and Tools for
Validating Cyber-Physical Energy Systems



Societal Challenges

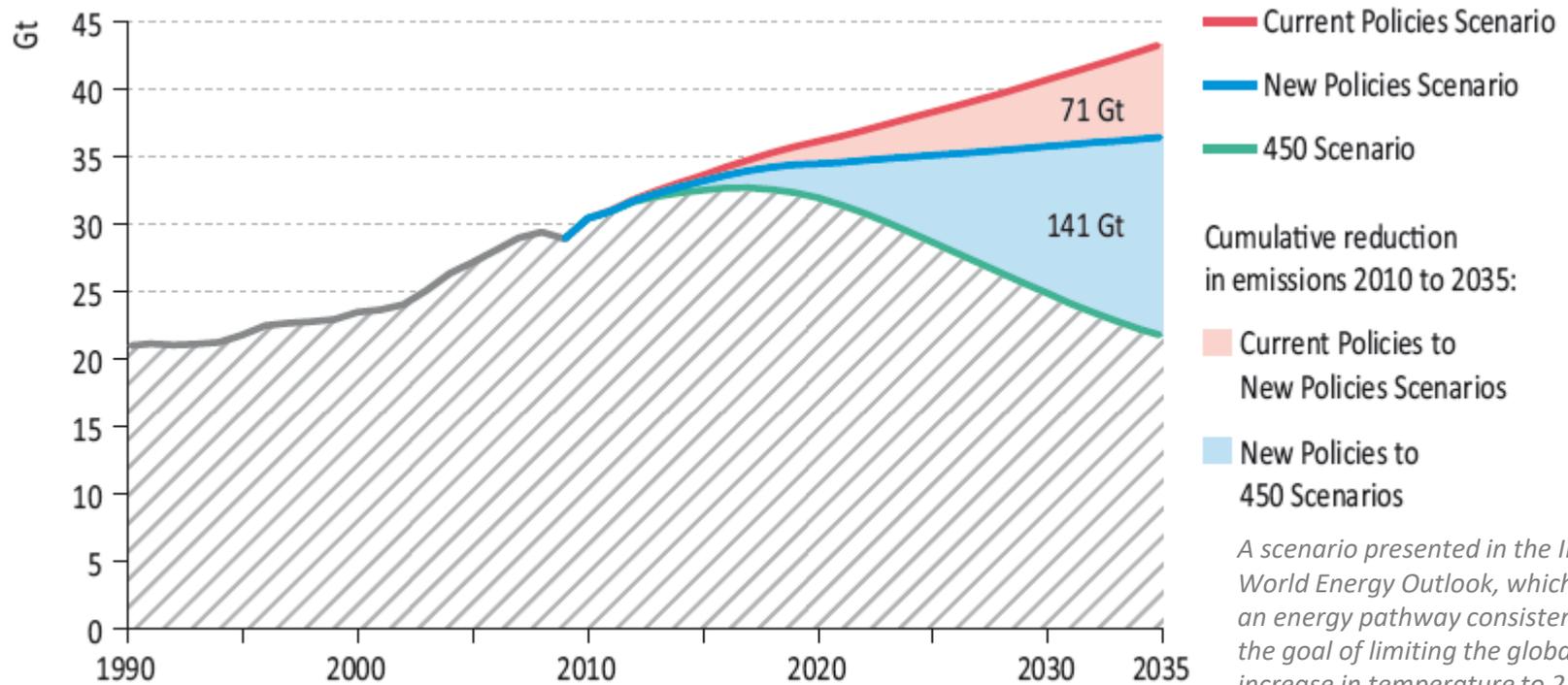
- Climate change
- Fossil fuels
 - Political instability of producing countries
 - Increase in demand and volatile prices
- Economic crisis
- Demographic and economic development in China, India & South East Asia
 - Increasing impact on quality of water, air, land resources
- European position in a fast changing world
 - Economic development – quo vadis?
 - Demographic development (ageing society etc.)
 - Welfare of the society

International Energy Agency (IEA)

- IEA Energy Technology Perspectives 2008
 - ... “... a global energy technology revolution is needed ...”
- IEA World Energy Outlook 2008
 - ... “... The world’s energy system is at a crossroads. Current global trends in energy supply and consumption are patently unsustainable environmentally, economically and socially ...”
 - What is needed is nothing short of an energy revolution ...”



World Energy-related CO₂ Emissions by Scenarios



Sources: OECD/IEA, World Energy Outlook, 2011, P. 73

Cumulative reduction
in emissions 2010 to 2035:

Current Policies to
New Policies Scenarios

New Policies to
450 Scenarios

A scenario presented in the IEA World Energy Outlook, which sets out an energy pathway consistent with the goal of limiting the global increase in temperature to 2°C by limiting concentration of greenhouse gases in the atmosphere to around 450 parts per million of CO₂.

European Policy

- Changing Europe's energy system according to climate policy needs
 - Energy efficiency
 - Renewable integration
- Safe, secure, and affordable energy supply
- Strengthening the role of cities (high living standards, sustainable environment for next generations)
- Europe's leadership in energy technology and innovation
- Horizon 2020
 - Excellence in R&D
 - Industrial leadership
 - Societal challenges

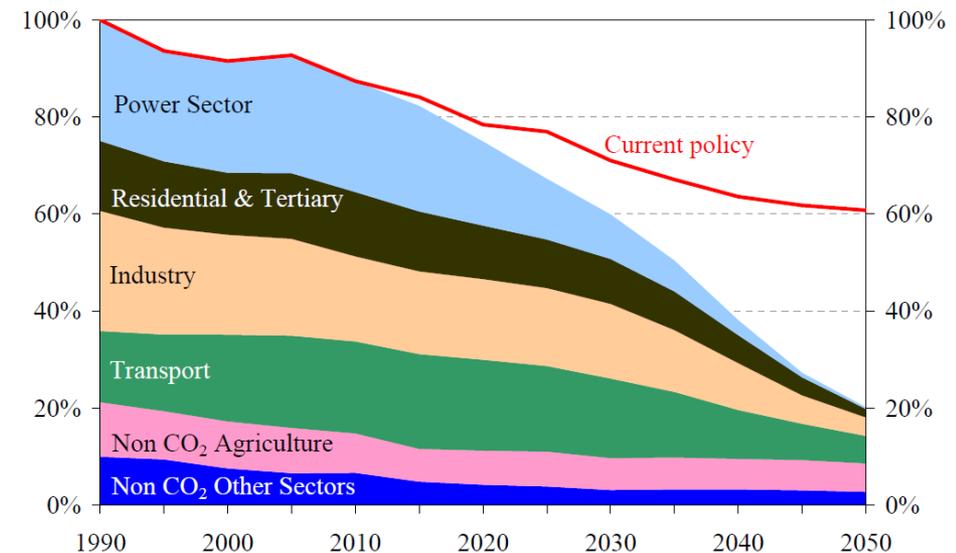
Source: G. Öttinger, 10.11.2010



Europe 2020 Strategy and 2050 Roadmap

- Climate change and energy: The “20-20-20 targets” (in 2020)

- Reduce Green-House-Gas (GHG) emissions by 20%
- Increase share of renewables in EU energy consumption to 20%
- Achieve an energy-efficiency target of 20%



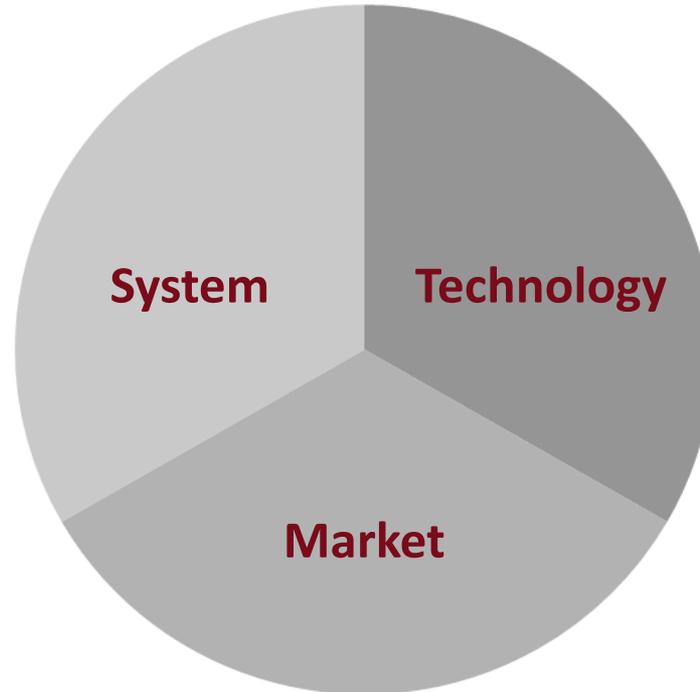
Source: EC, Low Carbon Economy Roadmap 2050

- Roadmap 2050: -80% GHG reduction

- -80% GHG Reduction needs Radical Innovations!!!

Driving Forces for Research in Electric Energy Infrastructure

- Urbanization
- Stochastic behavior of renewables
- Distributed generation
- Electrification of mobility
- Aging infrastructure

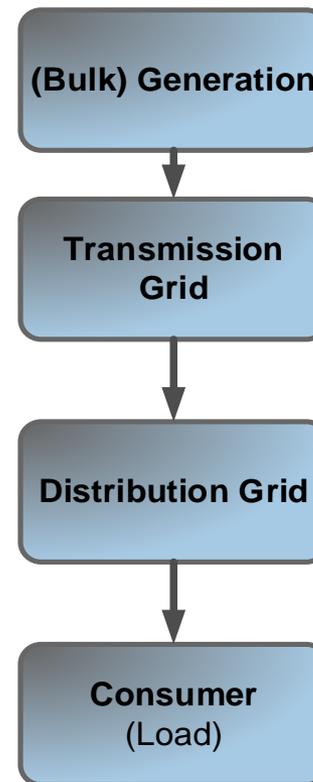


- Power electronics
- Communication and automation
- Electrical storages
- Generation (PV, wind power, etc.)
- Condition monitoring

- Liberalization and regulation of markets
- New business models for energy and mobility
- New industry players in energy business
- Market for primary energy, CO₂, nuclear waste, etc.

Power Distribution Grids in the Past

- Typical structure of the electricity system (~1900-2000)
 - Central generation infrastructure
 - Unidirectional power flow
 - Hierarchical structure

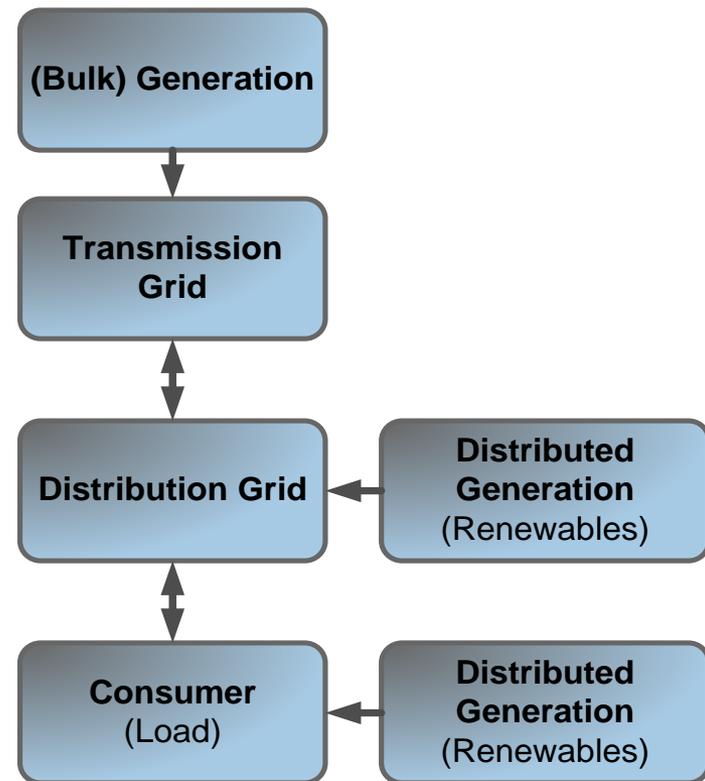


Transmission Grids (e.g., 380 kV, 220 kV, 110 kV)
 Medium Voltage Distribution Grids (e.g., 10 kV, 20 kV, 30 kV)
 Low Voltage Distribution Grids (e.g., 0,4 kV)

Source: H. Brunner (AIT)

Integration of Renewable Generation

- “New” structure of the electricity system (from ~2000)
 - Central and distributed generation infrastructure
 - Fluctuating distributed generation (e.g., solar, wind)
 - Bidirectional power flow
 - Hierarchical structure



Source: H. Brunner (AIT)

Integration of Renewable Generators

- Example: Denmark



16 central power plants

Source: www.ens.dk



16 central power plants

+ 1000 CHPs

+ 6000 Wind turbines

Intelligent Electricity Networks

“Smart Grids”

- Possible actions?
 - Best solution
 - Build a new power grid
 - Thicker lines, storages, etc.
 - However, that is beyond price
 - Smart solutions required
 - ICT, advanced automation and control
 - Monitoring and advanced measurement systems, etc.



Intelligent Electricity Networks “Smart Grids”

- Vision



Source: European Technology Platform Smart Grids

Intelligent Electricity Networks

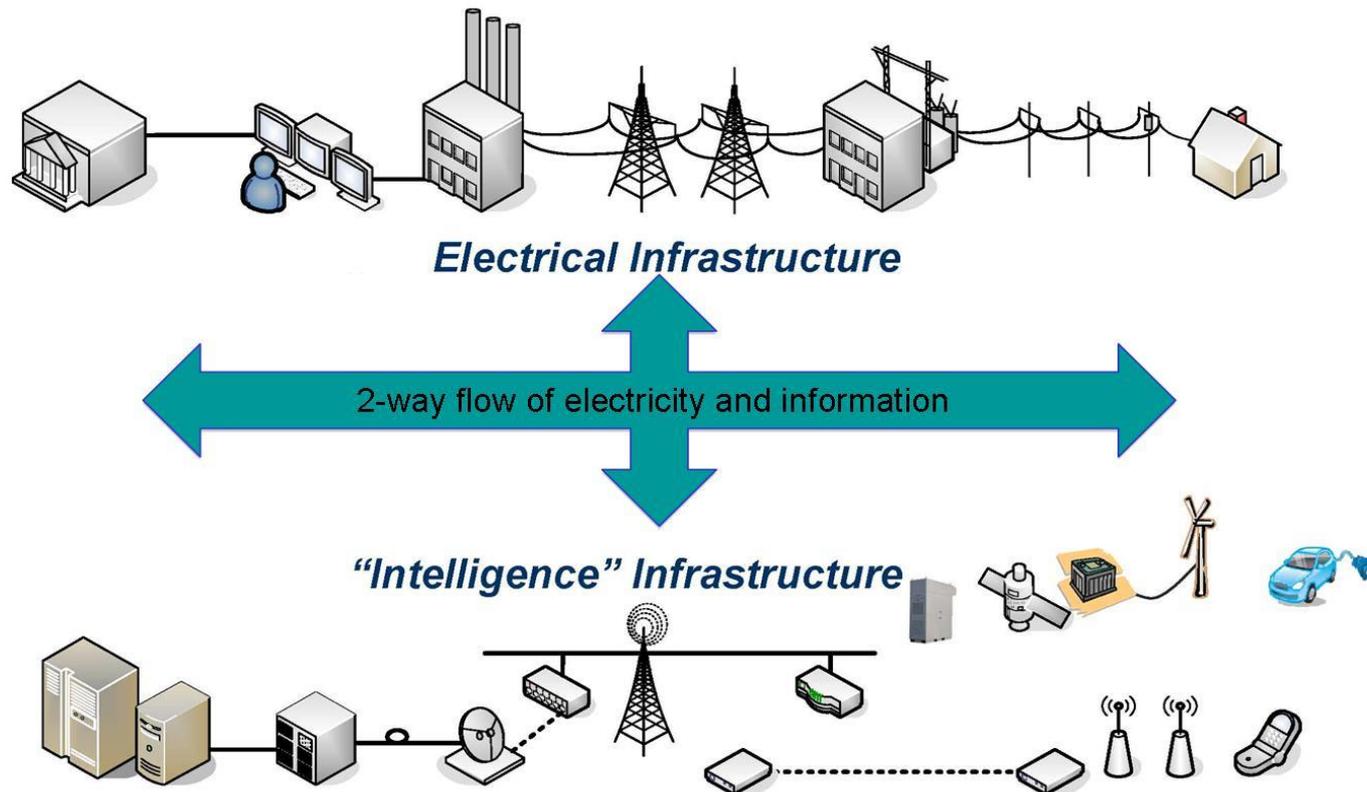
“Smart Grids”

- Smart grid activities/developments at different levels
 - Transmission system
(Trans-European demand/supply matching)
 - Super grids (offshore wind farms in northern Europe – hydro storages in the Alps – large scale solar/PV systems in southern Europe/Africa)
 - Medium Voltage (MV) / Low Voltage (LV) distribution system
 - Smart grids (active distribution grids, integration of distributed generators and storage systems)
 - Local energy community/system
(e.g., for buildings or small areas; low voltage systems)
 - Micro grids (islanded, grid-connected)

Intelligent Electricity Networks

“Smart Grids”

- Integration of (critical) infrastructure systems: electrical + ICT/automation

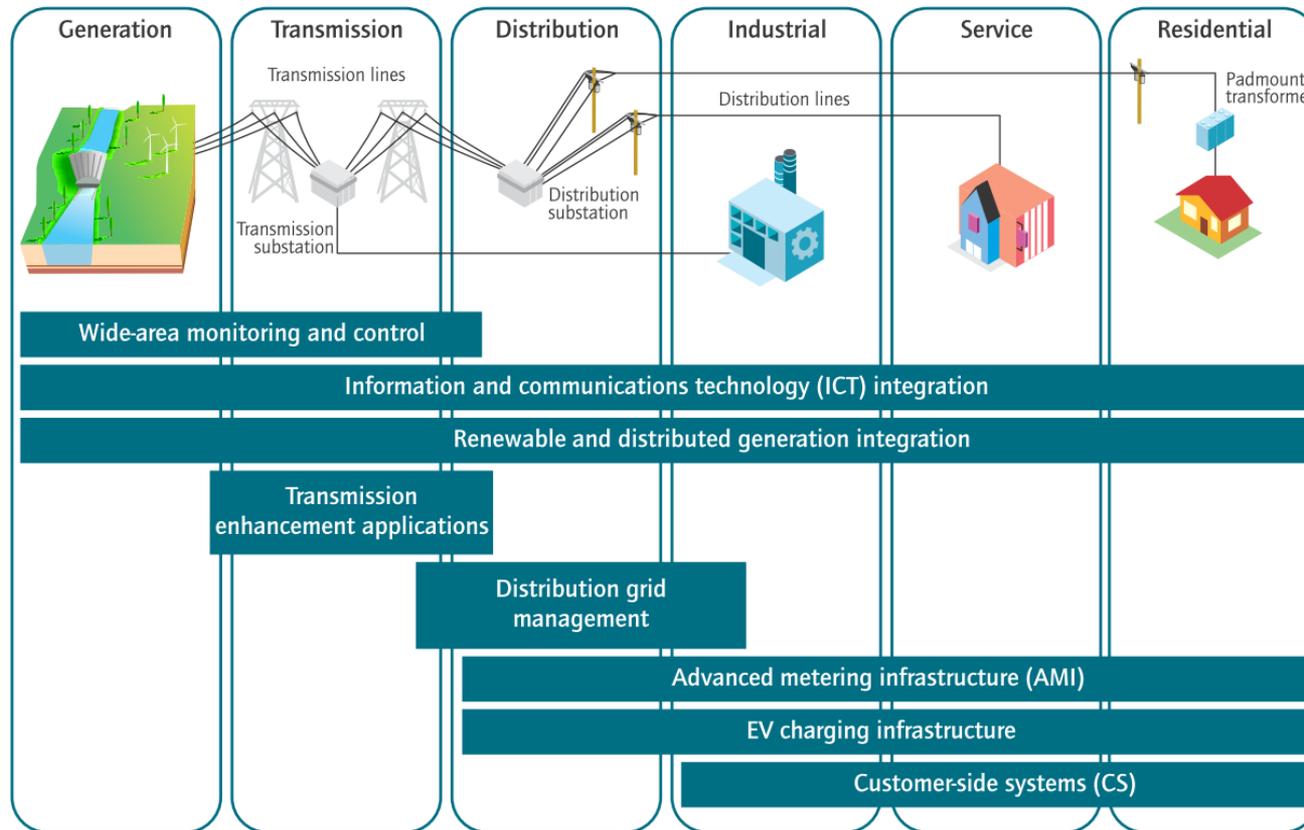


Source : NIST

Intelligent Electricity Networks

“Smart Grids”

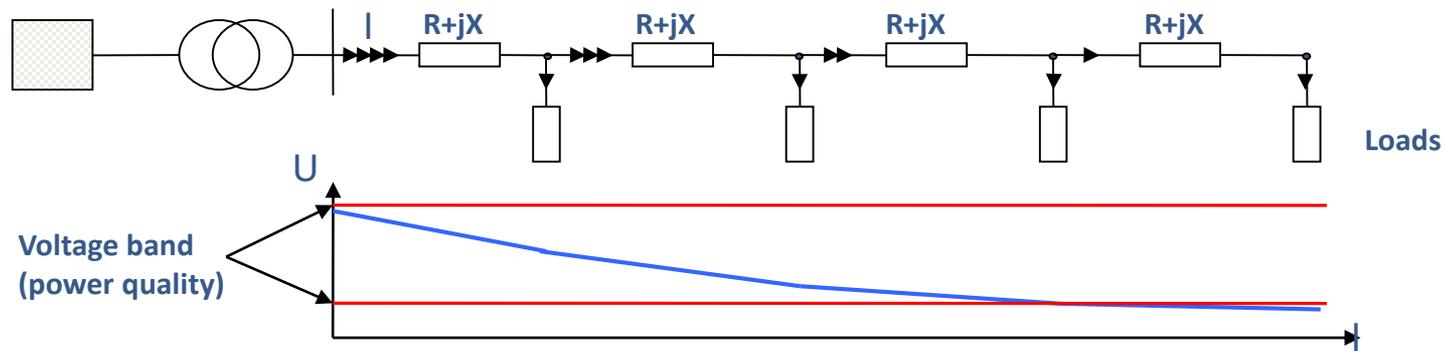
- Technology areas



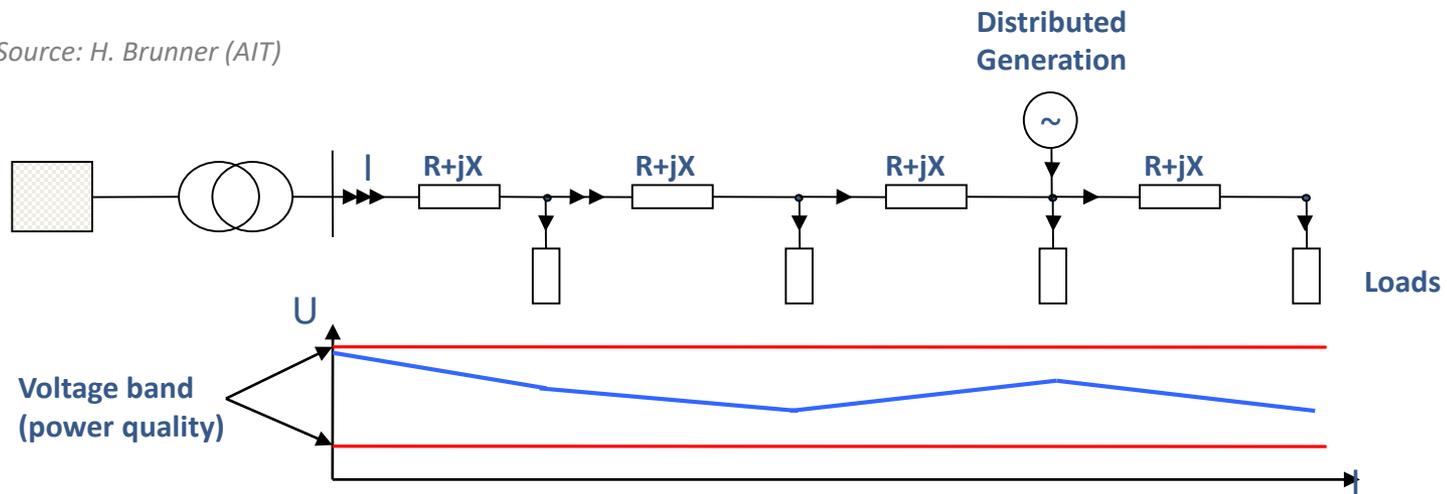
Source: IEA

Example Voltage Control

- Voltage drop along (distribution) lines and distributed generation

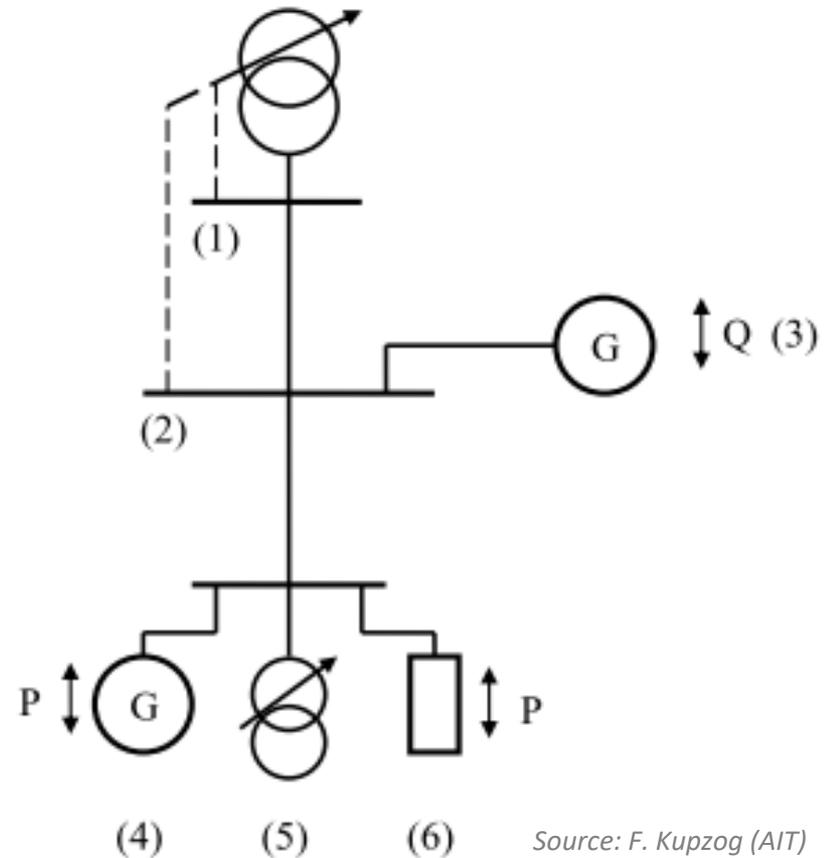


Source: H. Brunner (AIT)



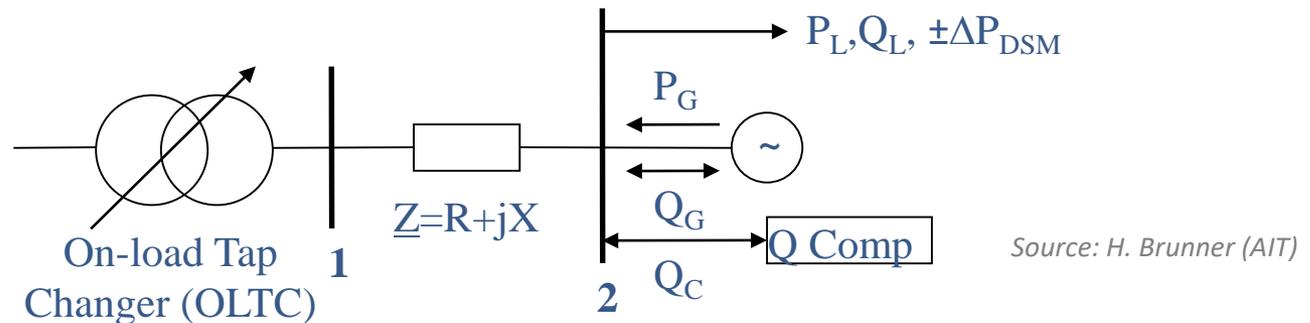
Example Voltage Control

- What can be influenced?
 - On-load Tap Changer (OLTC) (1,2)
 - Generators (3, 4)
 - Adjustable transformers (low voltage) (5)
 - Demand Side Management (DSM) (6)



Example Voltage Control

- Voltage band management through changes in generation and consumption

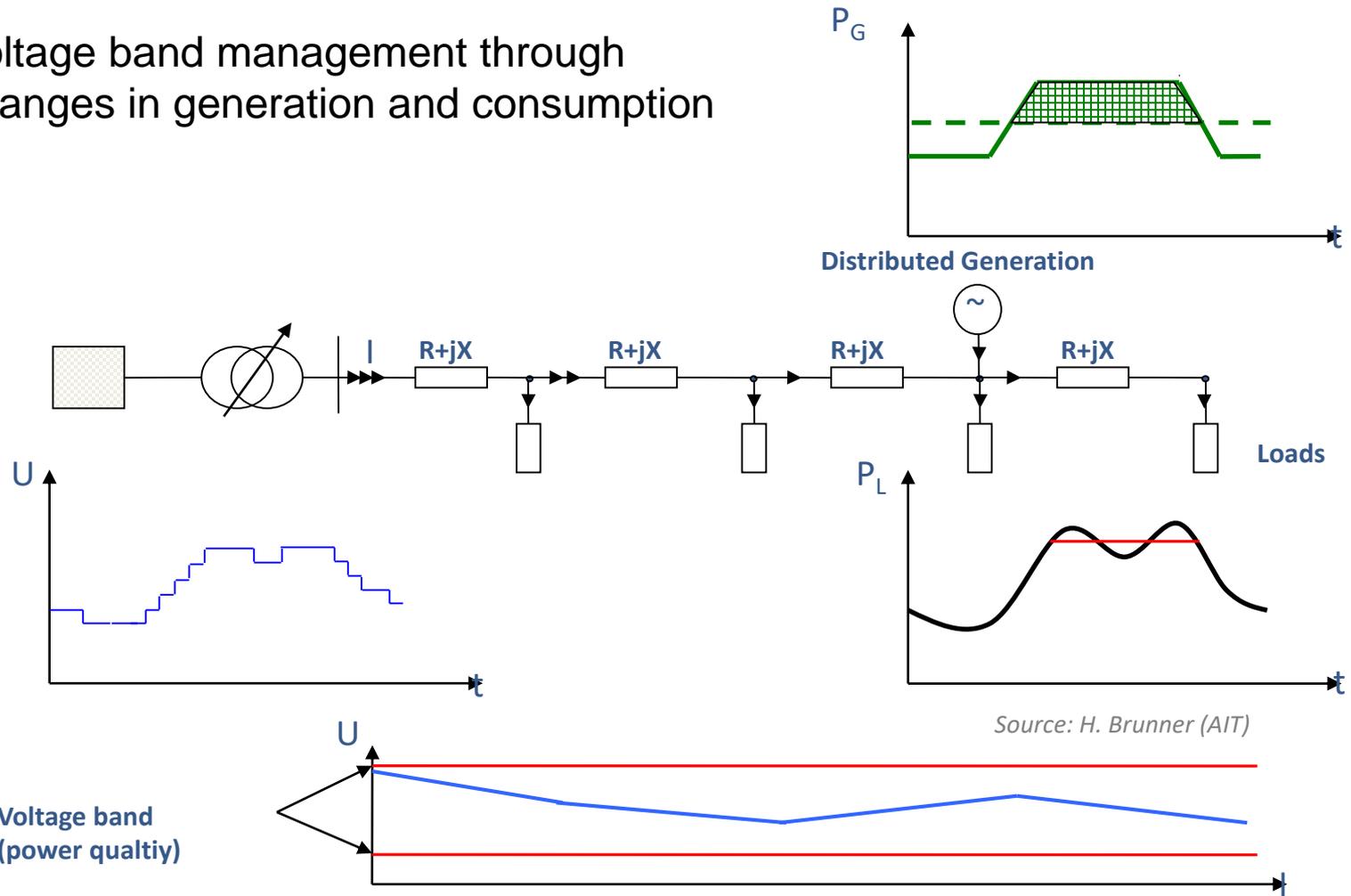


$$U_2 \approx U_1 + \underbrace{(R \cdot (P_G - P_L \pm \Delta P_{DSM}))}_{\text{Active Power}} + \underbrace{X \cdot (\pm Q_G - Q_L \pm Q_K)}_{\text{Reactive Power}} / U_2$$

Voltage level	R/X ratio	Voltage level influenced by
Transmission Grid (>110kV)	$R_{Line} \ll X_{Line}$	Reactive Power
MV Distribution Grid (5 - 60 kV)	$R_{Line} < X_{Line}$	Active and Reactive Power
LV Distribution Grid (0,4 kV)	$R_{Line} > X_{Line}$	Active Power

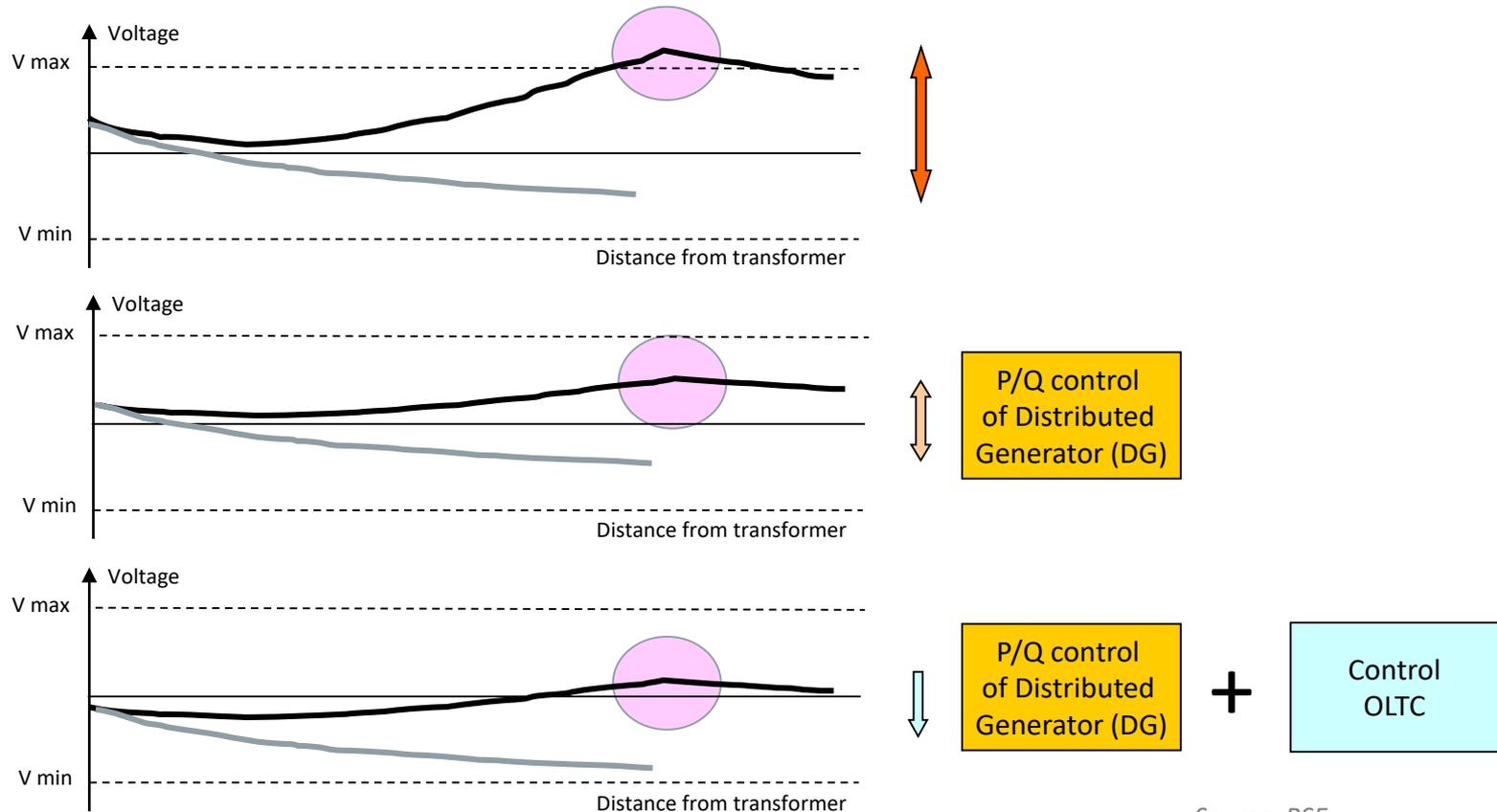
Example Voltage Control

- Voltage band management through changes in generation and consumption



Example Voltage Control

- Voltage band management through changes in generation and consumption



Source: RSE

Status Quo in Validation and Future Needs

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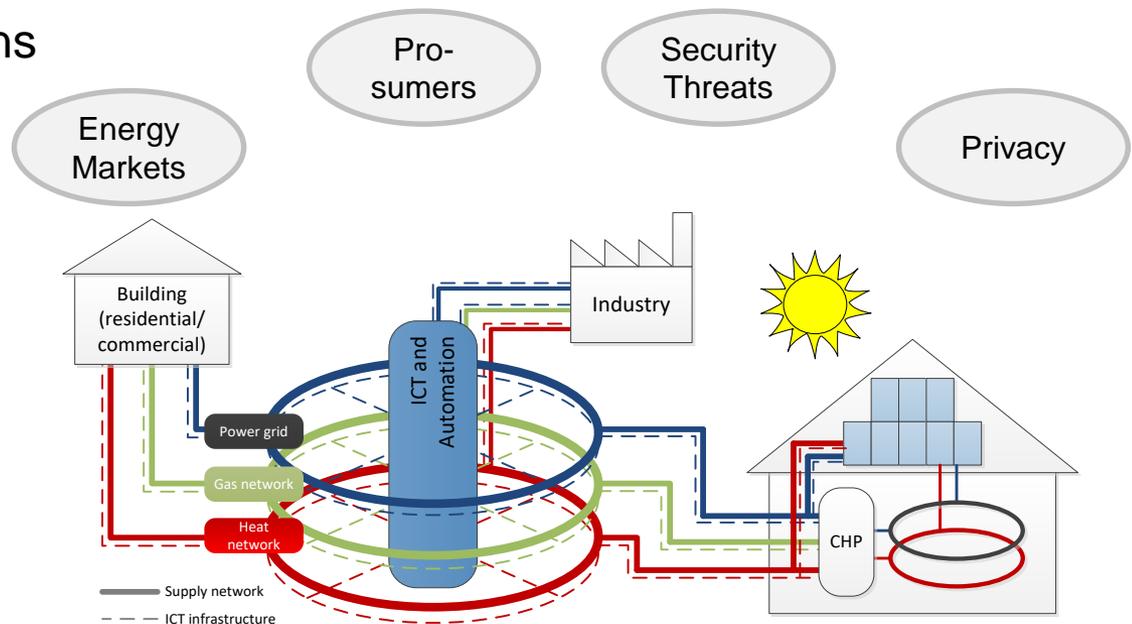


Cyber-Physical Energy System

- Planning and operation of the energy infrastructure becomes more complex
 - Large-scale integration of renewable sources (PV, wind, etc.)
 - Controllable loads (batteries, electric vehicles, heat pumps, etc.)

- Trends and future directions

- Digitalisation of power grids
- Deeper involvement of consumers and market interaction
- Linking electricity, gas, and heat grids for higher flexibility and resilience

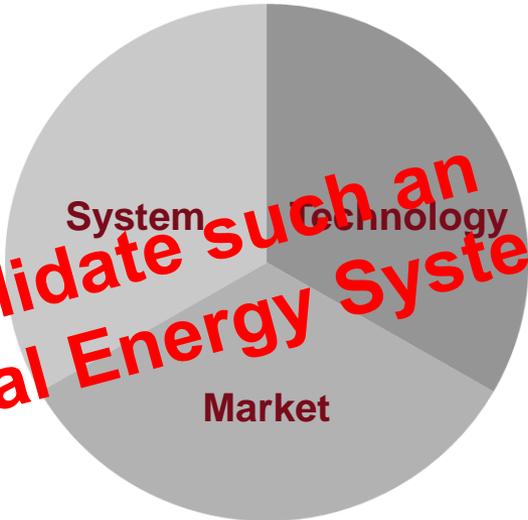


→ *Integrated Cyber-Physical Energy System (CPES) or smart grid*

Cyber-Physical Energy System

- Key elements of future integrated smart grids for mastering the increasing requirements and system complexity are
 - Power electronics
 - Advanced communication, automation[^], and control systems
 - Smart algorithms
 - Monitoring and data analytics

How to design and validate such an Integrated Cyber-Physical Energy System?



The diagram consists of a circle divided into three equal segments. The top-left segment is labeled 'System', the top-right segment is labeled 'Technology', and the bottom segment is labeled 'Market'. A large red text overlay is positioned diagonally across the circle, reading 'How to design and validate such an Integrated Cyber-Physical Energy System?'.

Status Quo in Design and Validation

- In the past individual domains of power and communication systems have been often designed and validated separately
- Available methods and approaches are

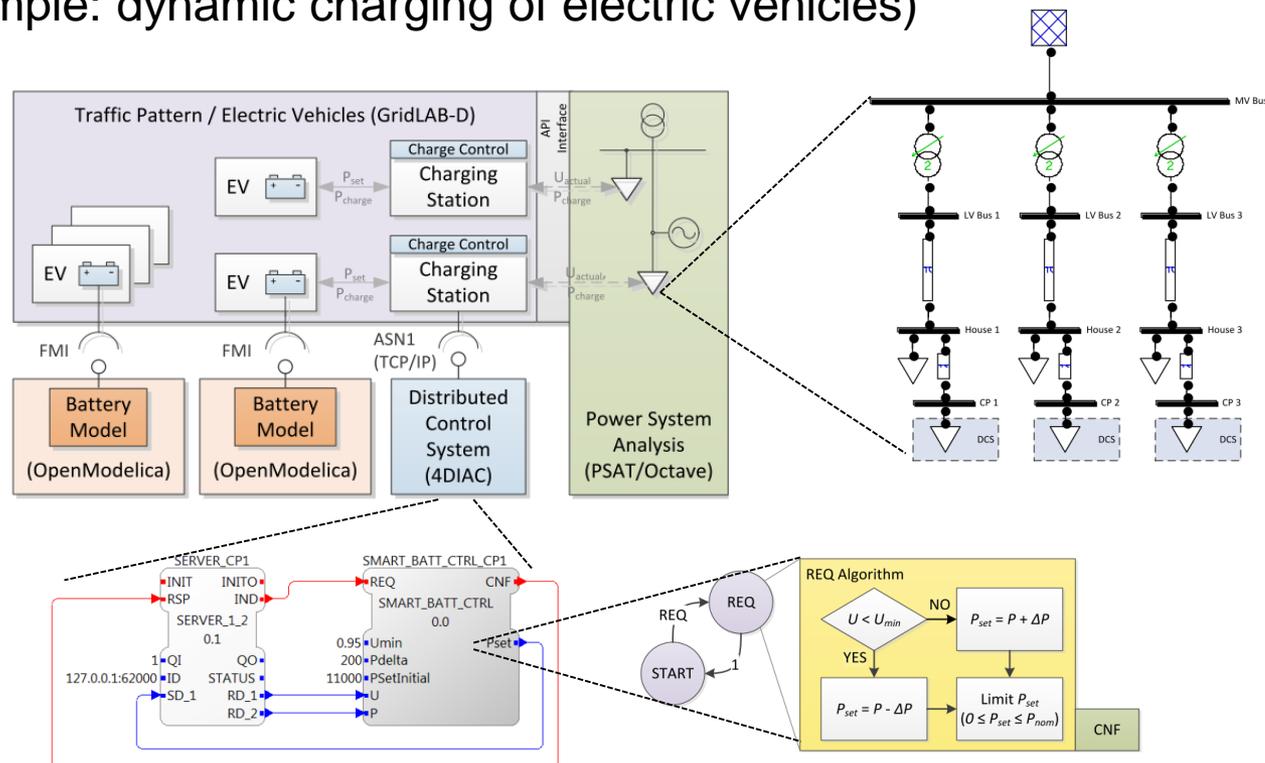
	<i>Req. & Basic Design Phase</i>	<i>Detailed Design Phase</i>	<i>Implementation & Prototyping</i>	<i>Deployment / Roll Out</i>
Software Simulation	+	++	o	-
Lab Experiments and Tests	-	-	++	+
Hardware-in-the-Loop (HIL)	-	-	++	++
Demonstrations / field tests / pilots	-	-	-	++

Legend:

- ... less suitable, o ... suitable with limitations, + ... suitable, ++ ... best choice

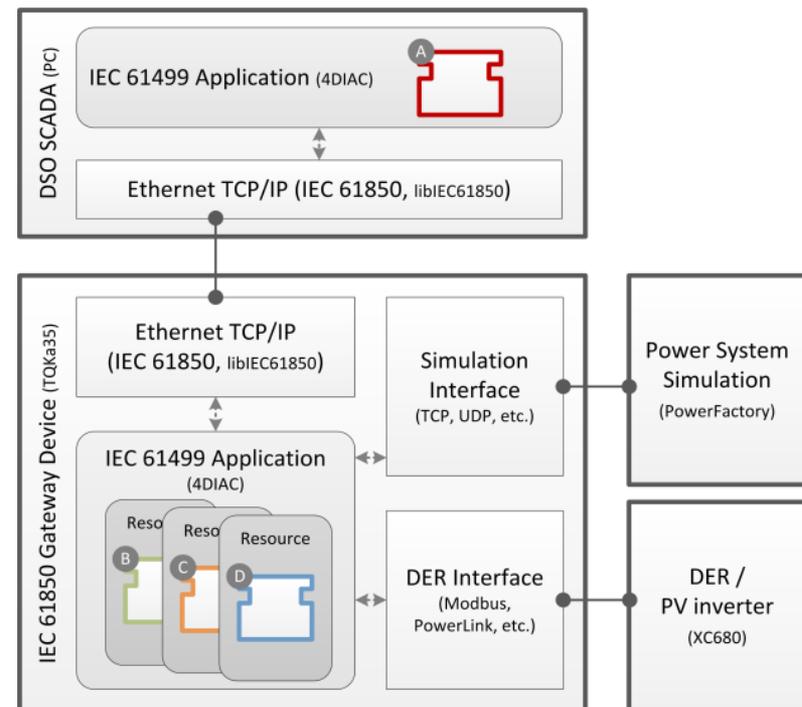
Status Quo in Design and Validation

- Promising validation approaches
 - Co-simulation: coupling of domain-specific simulators (example: dynamic charging of electric vehicles)



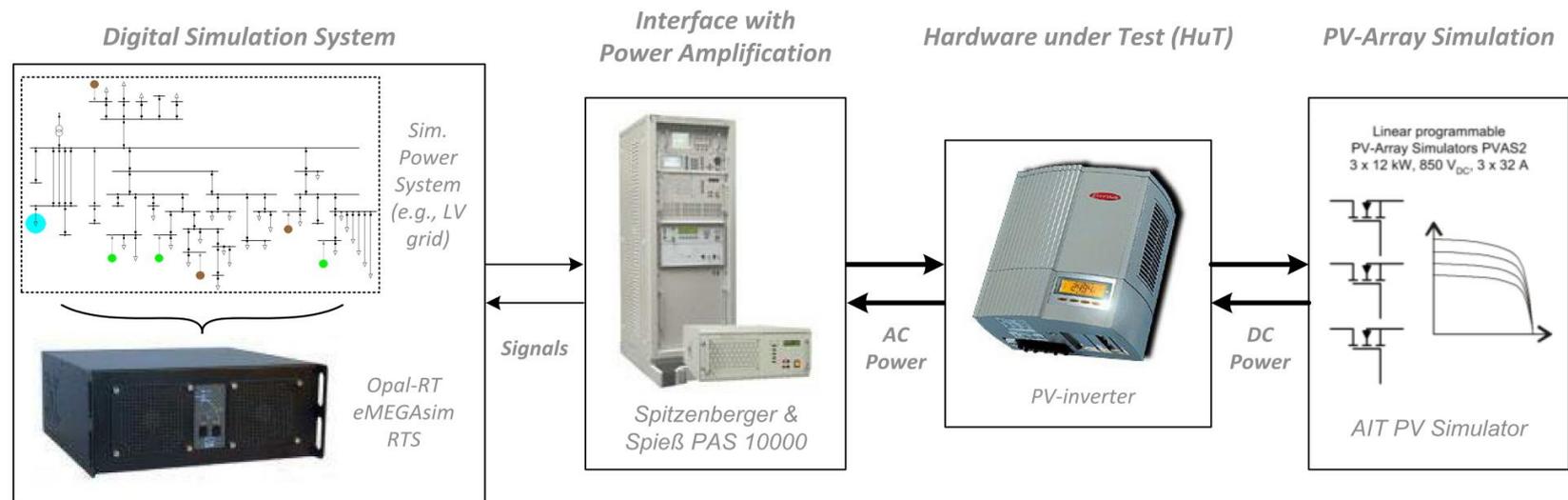
Status Quo in Design and Validation

- Promising validation approaches
 - Hardware-in-the-Loop (HIL) experiments
 - Controller-HIL (CHIL)
(example: remote control of inverter-based DER)



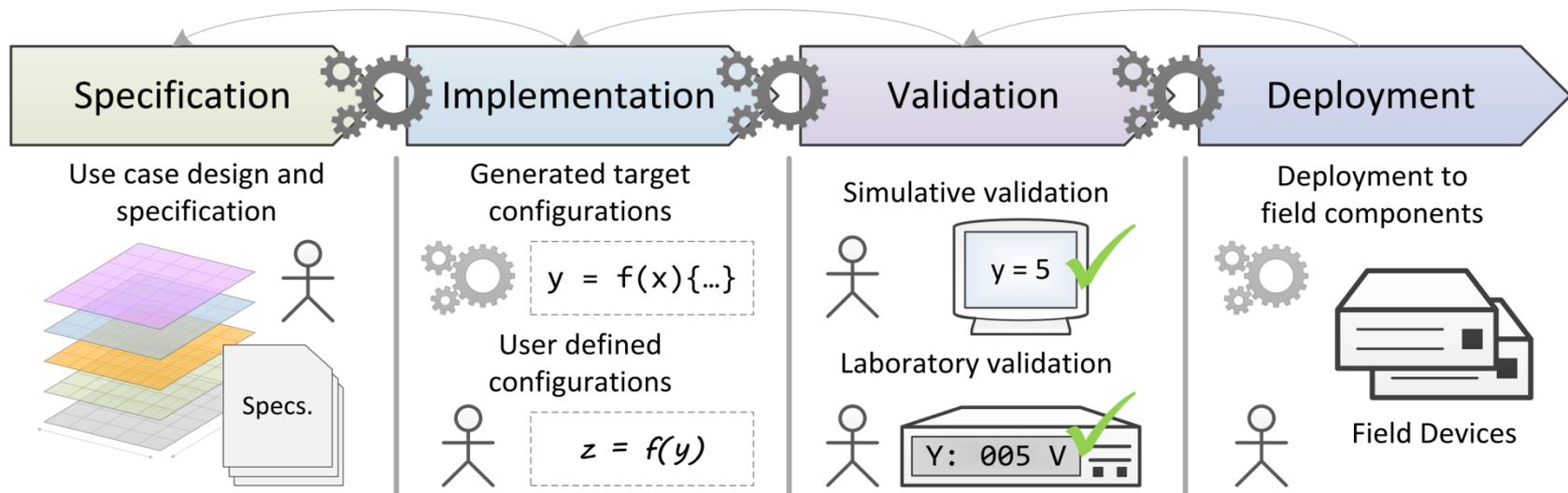
Status Quo in Design and Validation

- Promising validation approaches
 - Hardware-in-the-Loop (HIL) experiments
 - Power-HIL (PHIL)
(example: testing of a PV inverter)



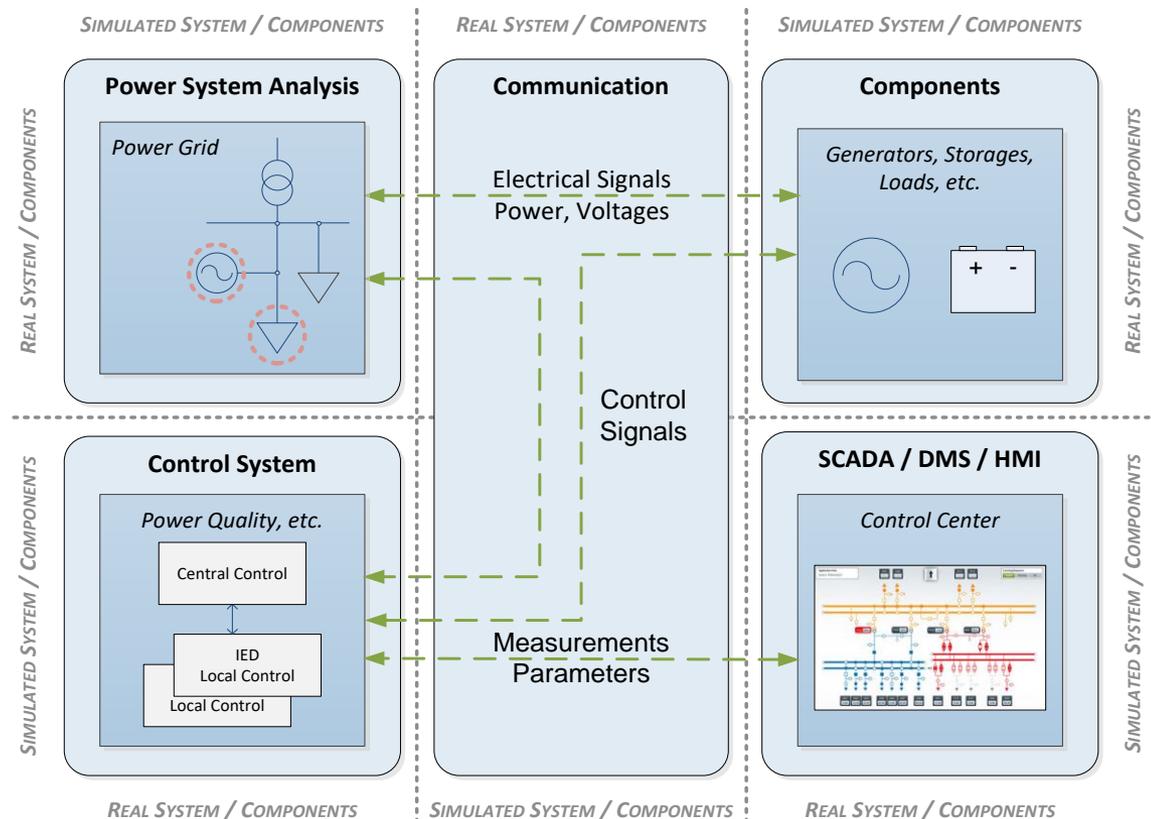
Future Needs and Developments

- Vision: *“Providing support from design to implementation & installation”*
 - Integrated system design
 - Validation and testing
 - Installation and roll out



Future Needs and Developments

- A cyber-physical (multi-domain) approach for analysing and validating smart grids on the system level is missing today
 - Existing methods focusing mainly on component level issues
 - System integration topics including analysis and evaluation are not addressed in a holistic manner



Future Needs and Developments

- A holistic validation and testing framework for advanced system-level testing needs to be developed with a multi-domain focus on
 - Proper methods and tools
 - Comprehensive research infrastructure
- Harmonized and standardized evaluation procedures need to be developed
- Well-educated professionals, engineers and researchers understanding integrated smart grid configurations in a cyber-physical manner need to be trained on a broad scale



The ERIGrid Vision and Approach

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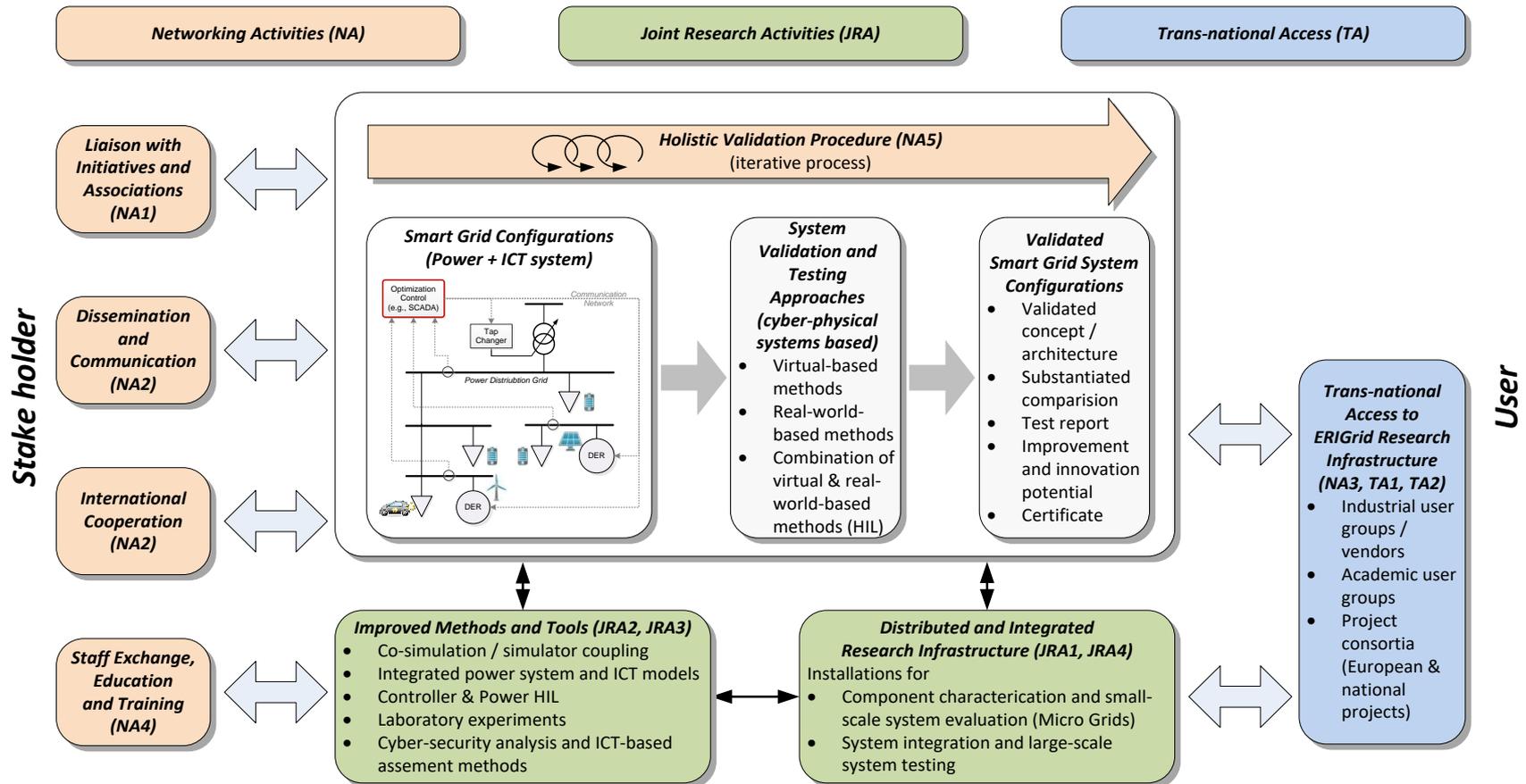


Main Goals

- Supporting the technology development as well as the roll out of smart grid approaches, solutions and concepts in Europe with a holistic, cyber-physical systems approach
- Integrating the major European research centres with a considerable, outstanding smart grid research infrastructure to jointly develop common methods, concepts, and procedures
- Integrating and enhancing the necessary research services for analysing, validating and testing smart grid configuration
- System level support and education for industrial and academic researchers in smart grid research and technology development is provided to foster future innovation
- Strengthening the technical leadership of the European Research Area in the energy domain

Overview ERIGrid Approach

- Leading Research Infrastructure (RI) in Europe for the domain of smart grids



The ERIGrid Trans-national Access opportunity

- Free of charge access to best European smart grid research infrastructures
 - **Scientists** from research, academia and industry are invited to apply for the Trans-national Access (TA)
 - Successful applicants will be provided with **free of charge** access to ERIGrid research facilities (incl. lab installations)



SmartEST Laboratory at AIT



Smart metering communication platform at TECNALIA

- The **expenses**, including travel and accommodation will be **reimbursed** under ERIGrid conditions
- Calls open **every 6 month**

Provided Smart Grids Research Infrastructures

- Various testing and research possibilities are provided such as
 - DER/power system components characterization and evaluation
 - Smart Grid ICT/automation validation
 - Co-simulation of power and ICT systems
 - Real-time simulation and Power/Controller Hardware-in-the-Loop (HIL)



How to Apply?

- User Groups have to fill out the application template from the website (<https://erigrd.eu/transnational-access/>) and send it to erigrd-ta@list.ait.ac.at
- Targeted topics includes smart grid concepts and configurations like
 - Fluctuating renewable energy, distributed energy resources
 - Active prosumers (incl. EVs)
 - Demand side management
 - Power system components
 - ICT, cyber-security, electricity markets, regulation, etc.

Support for filling out an application can be asked to the targeted RIs.

TA calls are launched every 6 months.

Evaluation criteria can be found on the project website.

Next call will opened on 15.08.2018 and closes on 15.11.2018

Holistic Validation Procedure

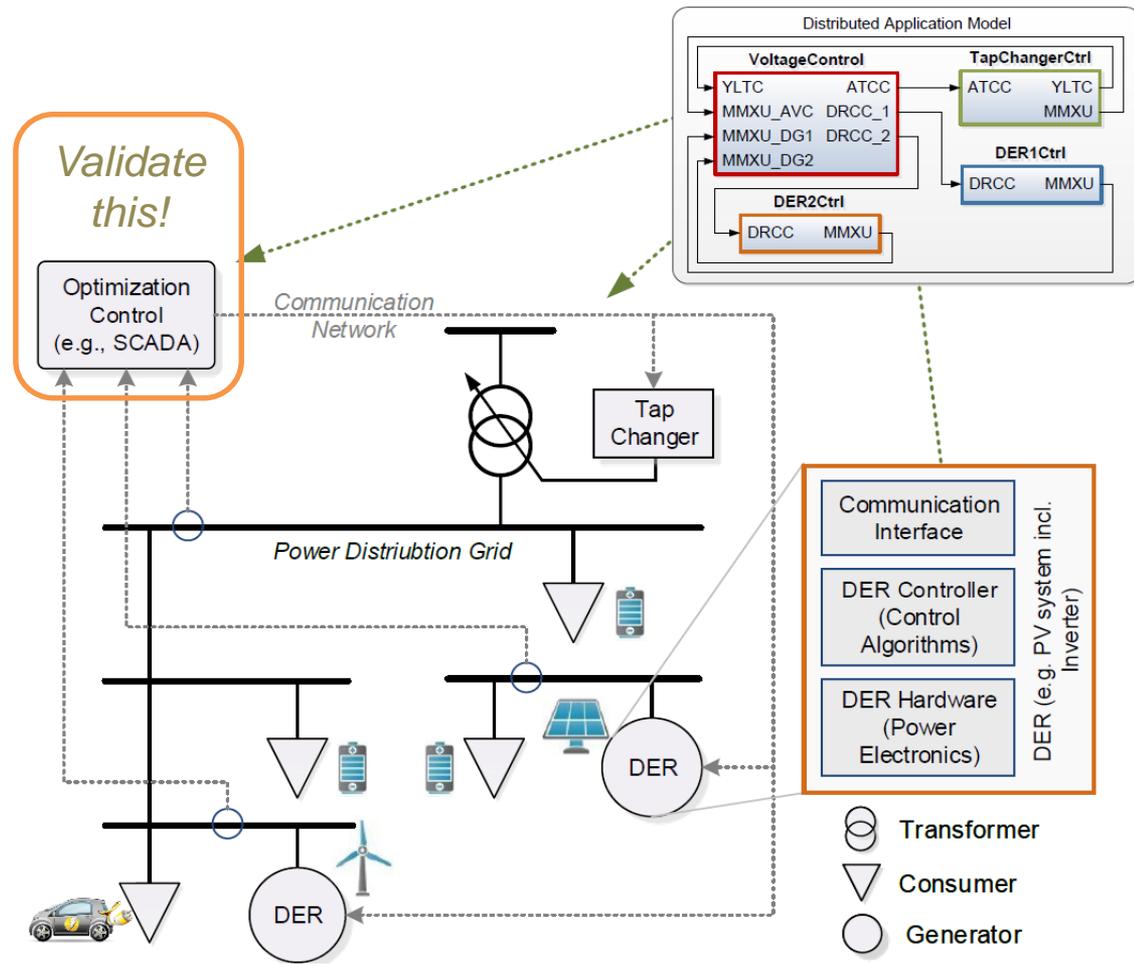
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Challenges

- Testing/validation of novel CPES components and concepts
- Many domain involved (holism)
- **Setups/workflows differ across Research Infrastructures (RI)**
 - Experiments are often **hardly reproducible**
 - Often limited by RI capabilities



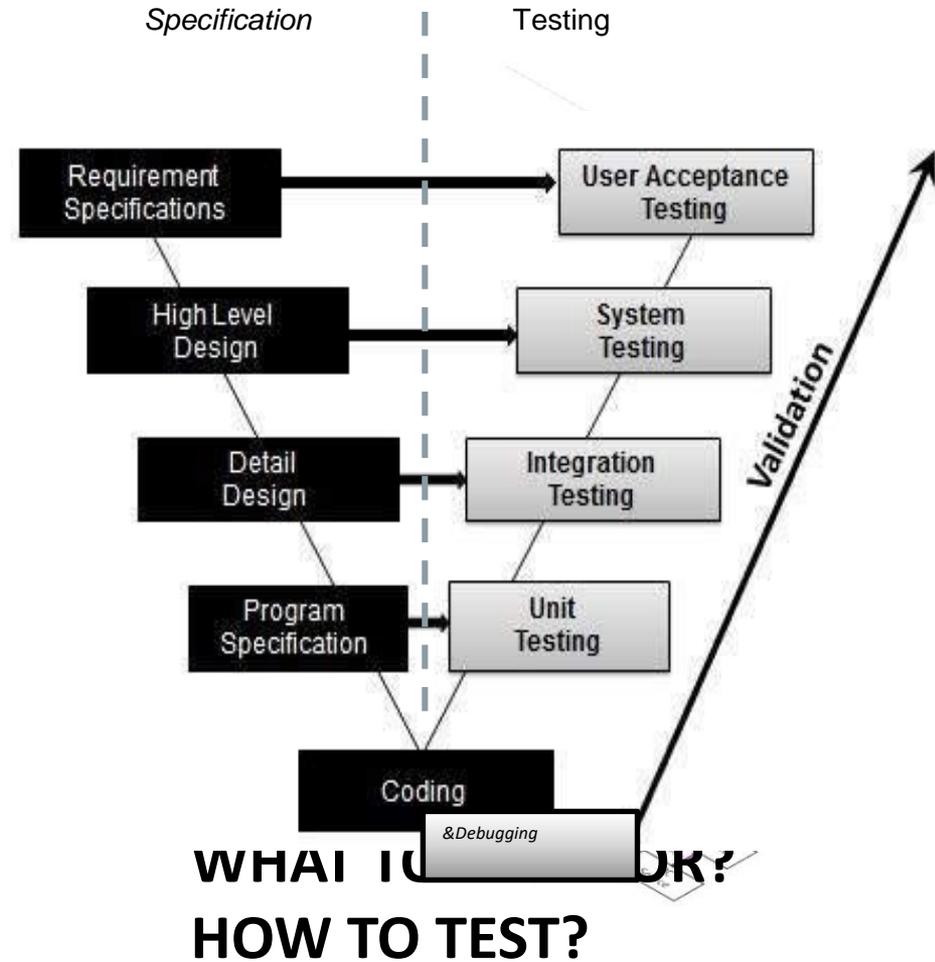
Aims and Objectives

Aims

- Formalize testing process
 - Testing → documented and reproducible
 - Basis for knowledge exchange

Objectives

- **Formal process covering all stages of test planning**
 - Overview of resources
 - Consider state-of-the-art
 - Operationalize, refine



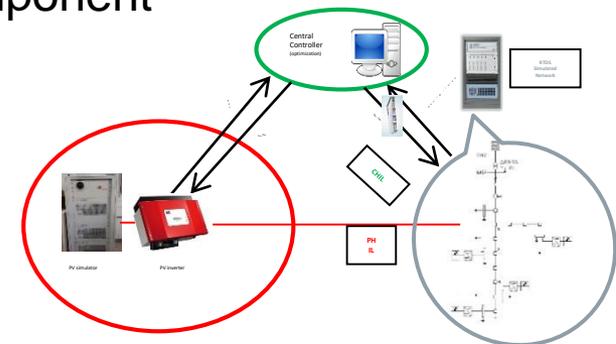
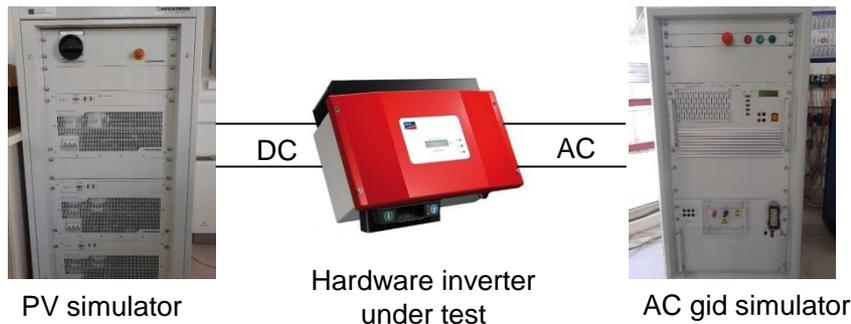
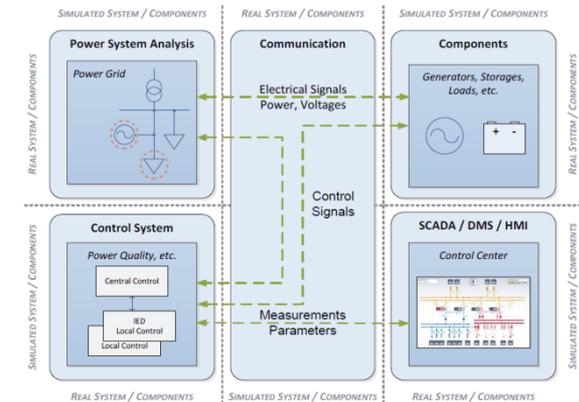
Component Test vs. Holistic Test

Component Test

- Example: inverter MPPT tests, anti-islanding and LVRT tests
- No interactions with the system
- Usually open loop test (predefined voltage, frequency; setpoints are applied to the hardware under test)

Holistic/System Test

- Combining several tests (testing process)
- Using simulations
- Testing a system rather than just component



“Holistic” System Validation

- I. **System validation**
alignment of Specifications & Testing
- II. **Integrated hardware & software testing**
Validate “systems” not components
- III. Tests that **combine multiple domains**
e.g., power, comm., and automation
- IV. **Systematically design tests & integrate results** from various experiments for a holistic assessment
i.e., combine simulation, co-simulation, HIL, PHIL, CHIL, different labs, etc.

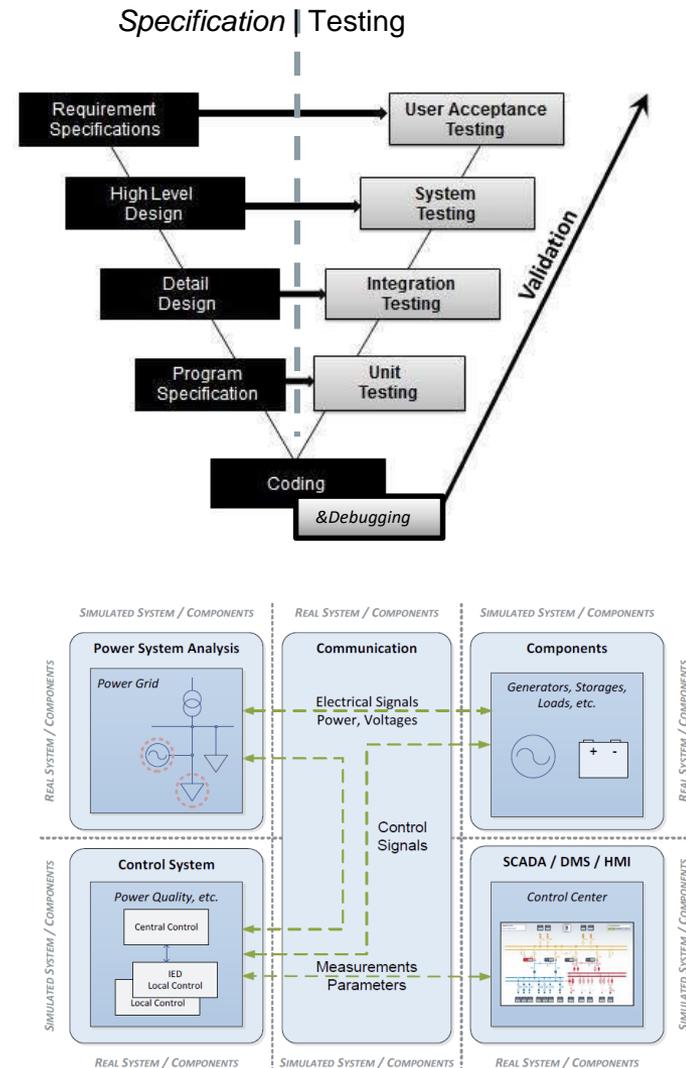
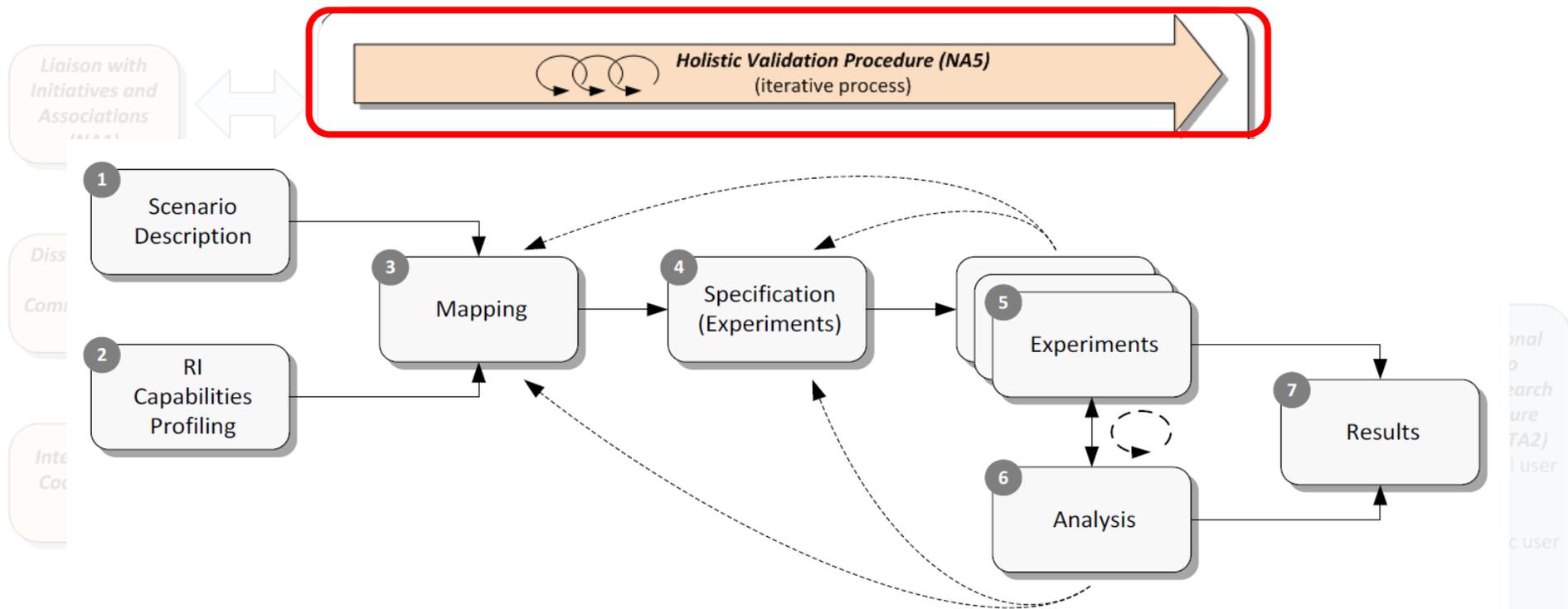


Figure 1.3: Improved methods and tools for Smart Grid validation and testing – possibility to combine virtual (simulated) and real components

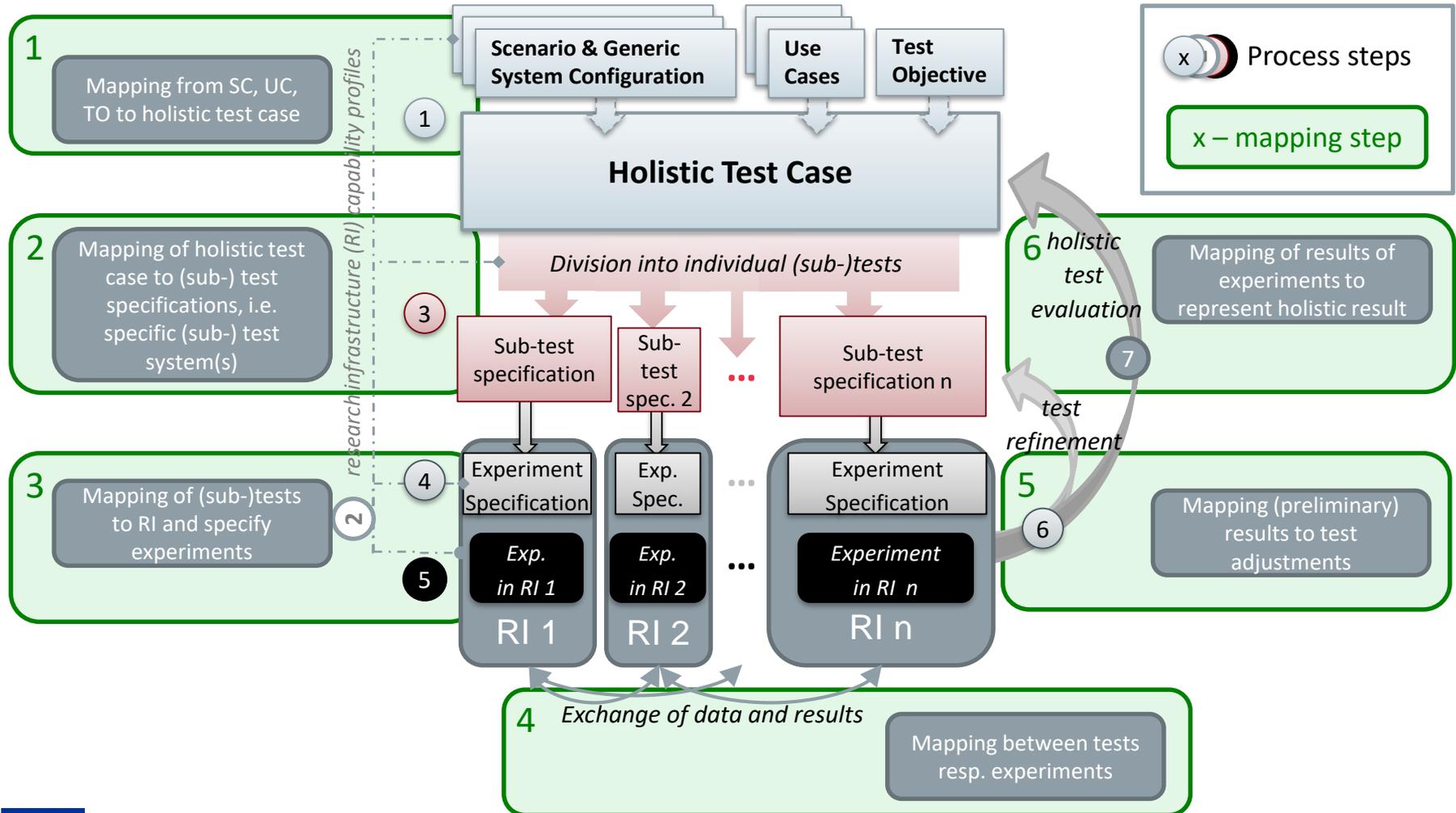
System Validation – A Holistic Procedure



"Holistic testing is the process and methodology for the evaluation of a concrete function, system or component (object under investigation) within its relevant operational context (system under test), corresponding to the purpose of investigation"

Holistic Testing Procedure

Different Mapping Steps



A Generic Experiment / Validation

- Defines components of a system
- Includes: **Object of investigation**

System Configuration

- Defines functions of a system
- Requirements define **Test Criteria**

Use Case

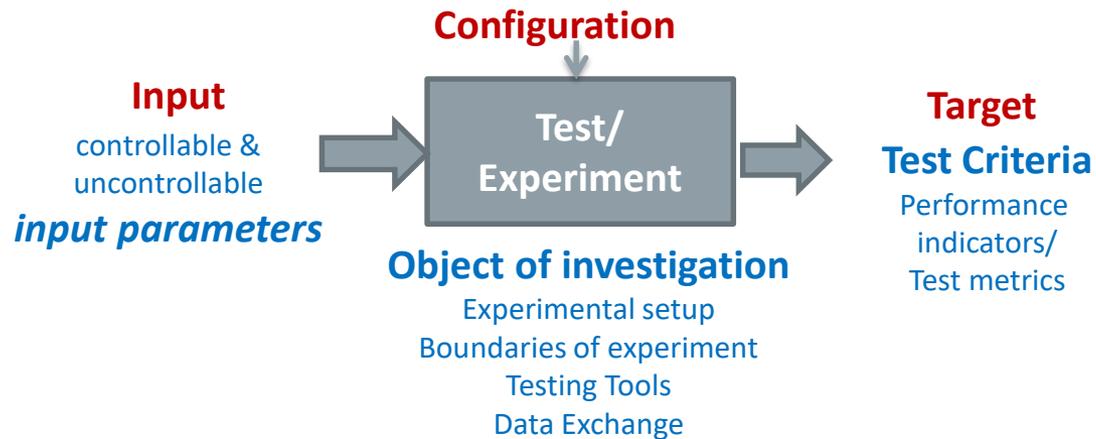
SGAM?
CIM?

IEC 62559

Purpose of Investigation

- Experimental design
- Test procedure

Test Case

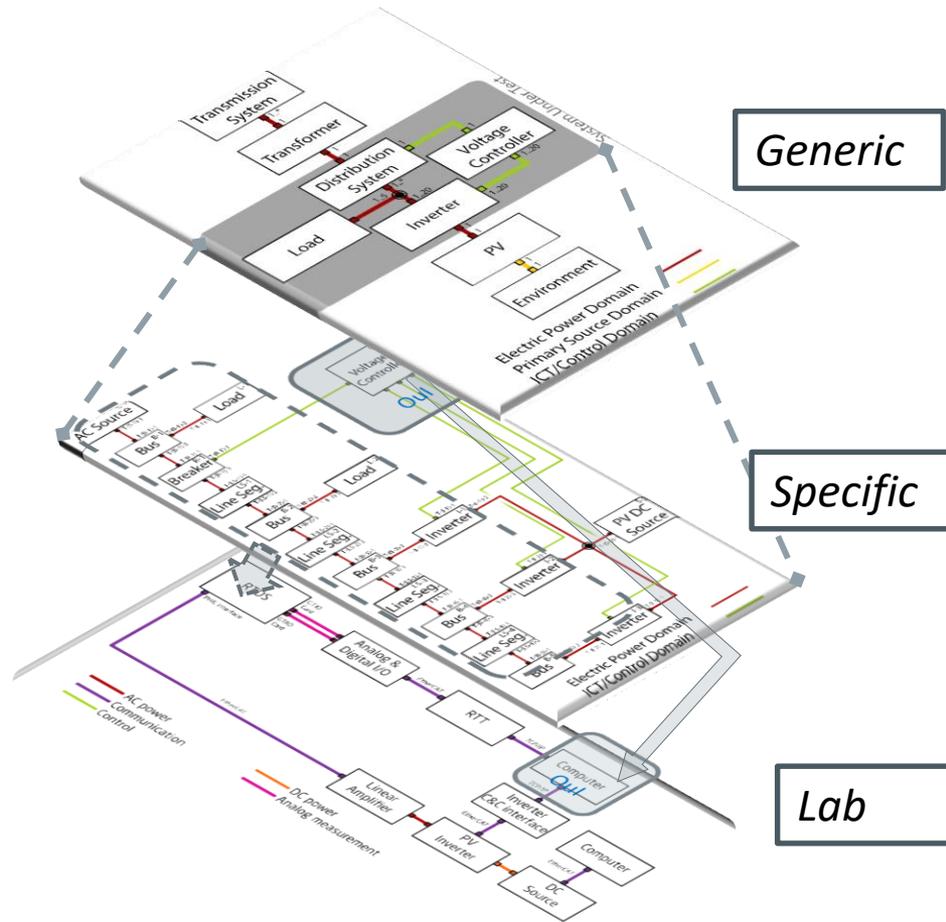
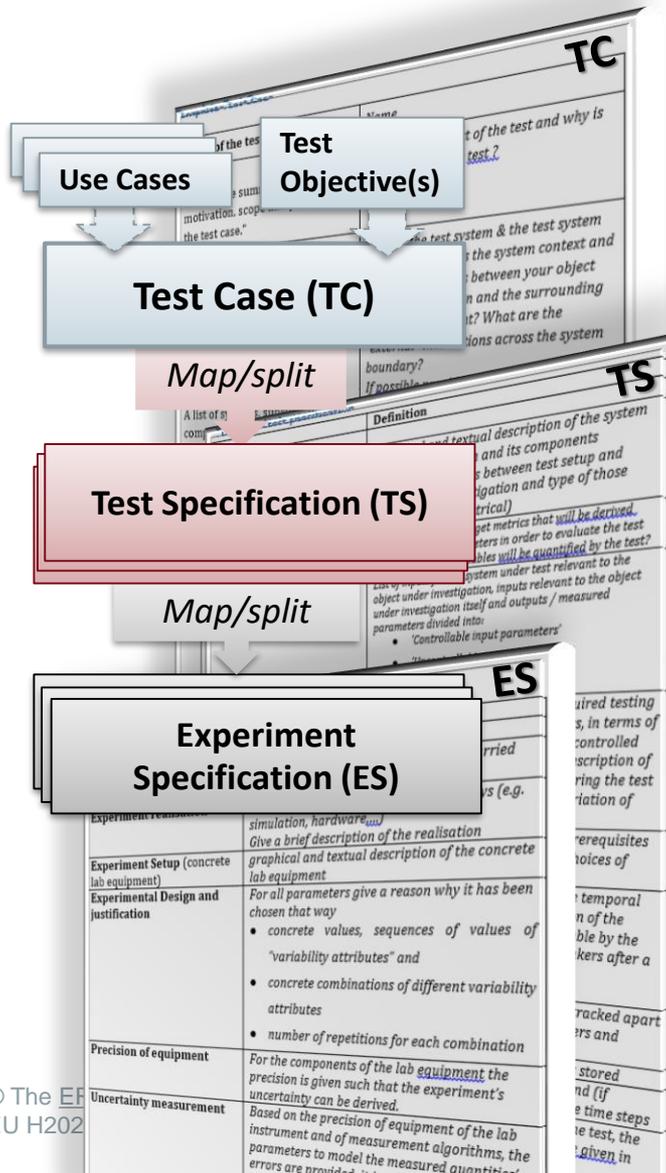


**experiment
assessment:**

**Quality of experiment: error type;
uncertainty; quantification of error**

Holistic Test Description (HTD)

THREE levels of specification



Holistic Test Description (HTD)

- Template-based process
 - Structured test development (documentation & test quality)
 - Common understanding of concepts (avoid misunderstandings)
 - Separating test planning from RI (replicability/reproducibility)
 - Splitting into sub-tests (allow for complex validation)

Holistic Testing

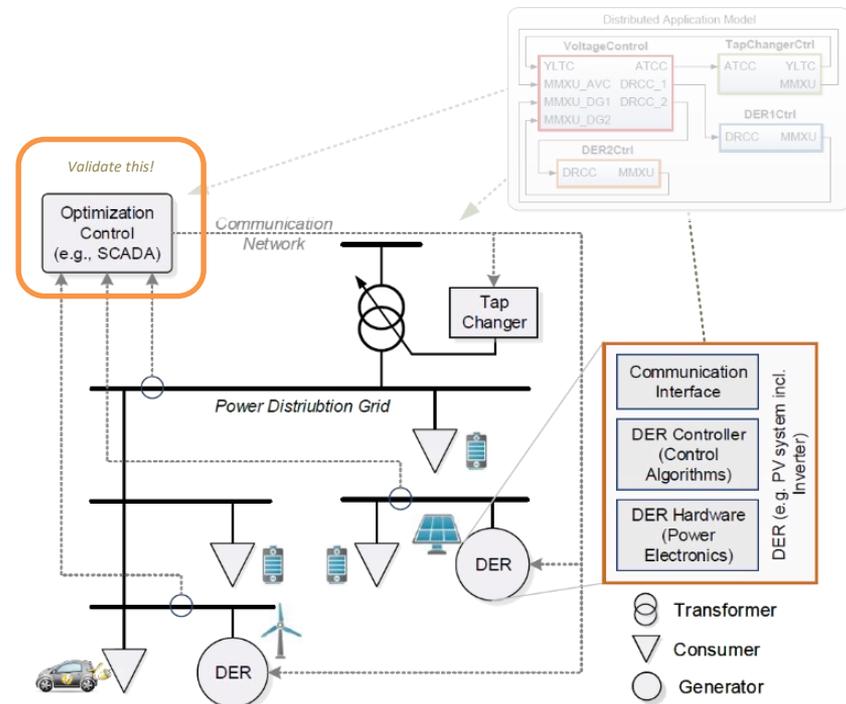
- Key questions to be answered for **test specification**

Why to test?

What to test?

What to Test *For*?

How to test?



Test System & Domain

System under Test (SuT):

Is a system configuration that includes all relevant properties, interactions and behaviours (closed loop I/O and electrical coupling), that are required for evaluating an Oul as specified by the test criteria

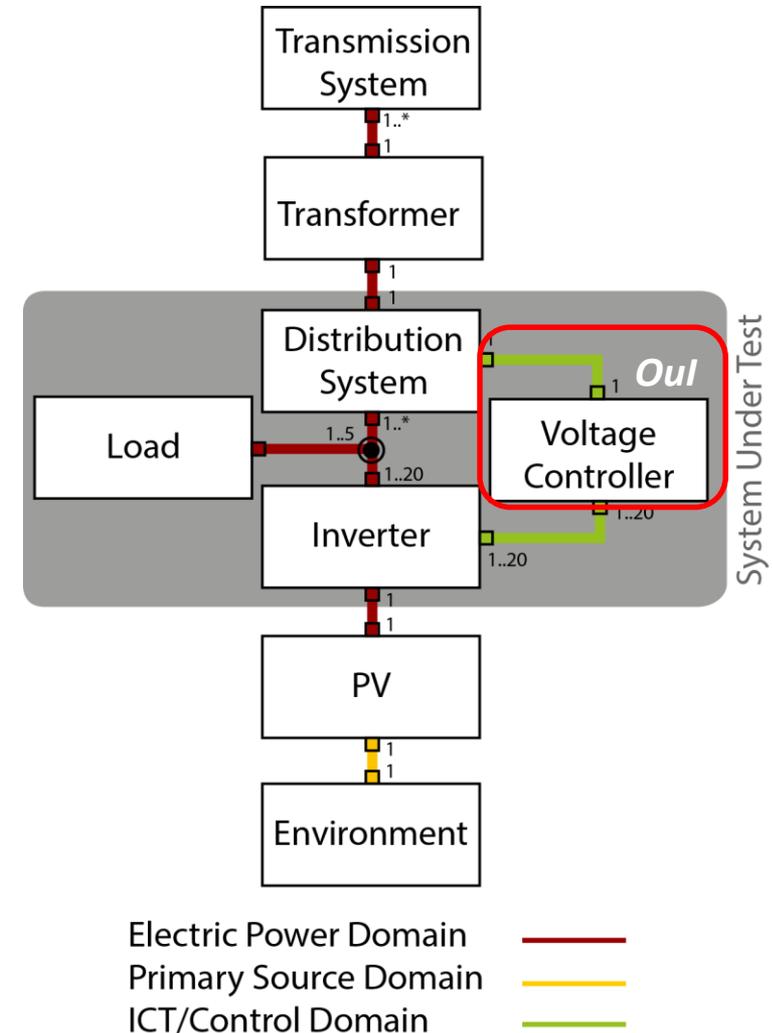
Object under Investigation (Oul):

The component(s) (1..n) that are subject to the test objective(s)

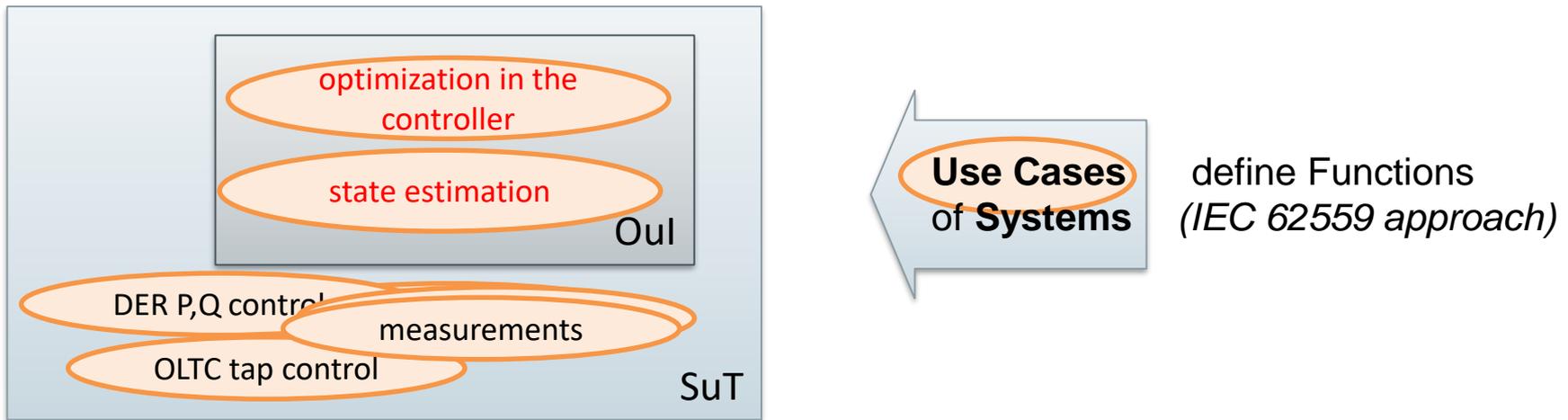
Remark: Oul is a subset of the SuT

Domain under Investigation (Dul):

Identifies the domains of test parameters and connectivity relevant to the test objectives



Test System Functions



Functions under Test (FuT):

The functions relevant to the operation of the system under test, as referenced by use cases

Function(s) under Investigation (Ful):

The referenced specification of a function realized (operationalized) by the object under investigation

Remark: the Ful are a subset of the FuT

Holistic Testing

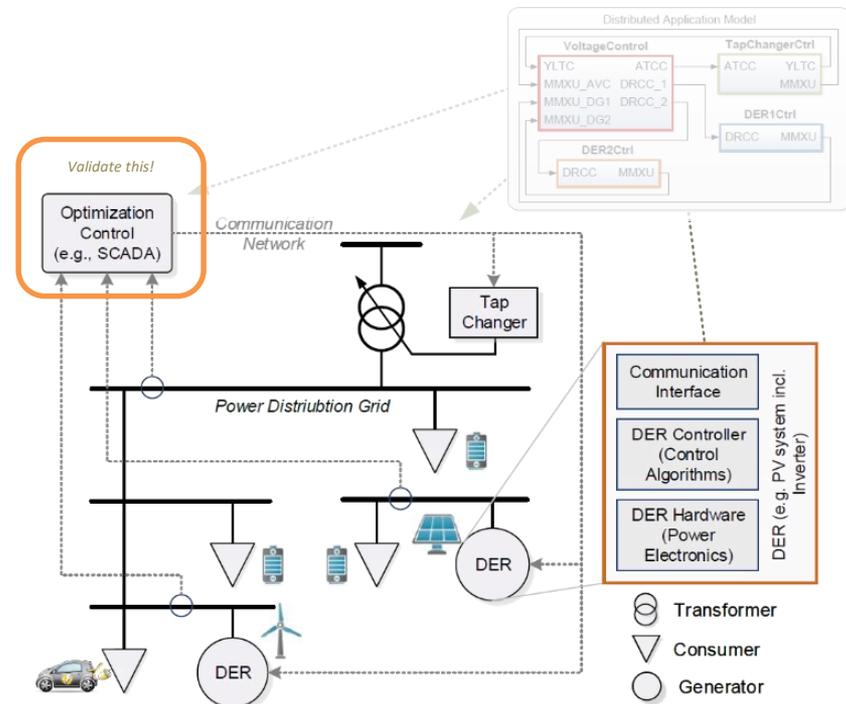
- Key questions to be answered for **test specification**

Why to test?

What to test?

What to Test *For*?

How to test?



Purpose of Investigation (PoI)

- **Verification**



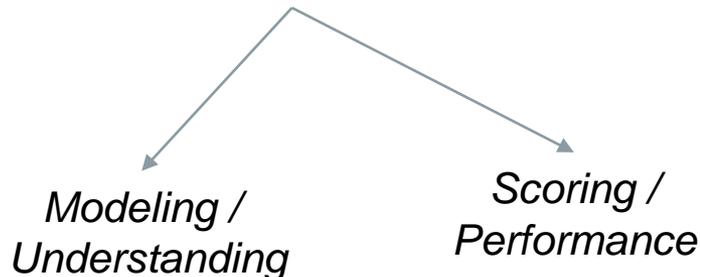
FAIL

- **Validation**



PASS

- **Characterization**



Test objectives/PoI:

Characterization and validation of the DMS controller

1. Convergence of the **optimization** (*validation*)
2. Performance of the **optimization** under realistic conditions (*characterization*)
3. Accuracy of the **state estimation** (*characterization*)

Designing Test Criteria

Detailing Sequence

- **Test objective → Pol → Test Crit.**
- **Test criteria:**
How to break down the Pols?
 - *Target Metrics* (TM, criteria):
List of metrics to quantify each Pol
 - *Variability attributes:*
Controllable or uncontrollable parameters to “disturb” SuT
 - *Quality attributes* (thresholds):
Test result level or quality of the TM required to pass or conclude the testing

Target metrics:

1. 1.1 convergence (when/how often?),
1.2 how fast?
1.3 solution quality
2. 2.1 voltage deviation
2.2 number of tap changes,
2.3 network losses
3. Voltage, P, Q estimation errors

Variability attributes: load patterns

(realistic, annual variation; applies to criteria 1-3); communication attributes (packet loss, delays)

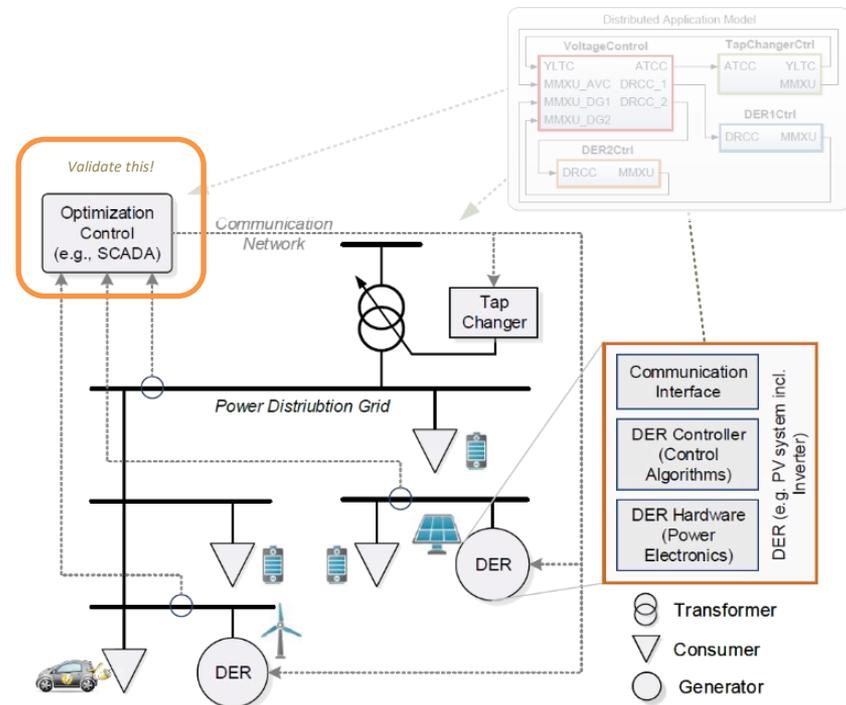
Quality attributes (thresholds):

“1.2: convergence within 2 sec” (*validation*)
“3.* estimation quality characterized with confidence 95%” ...

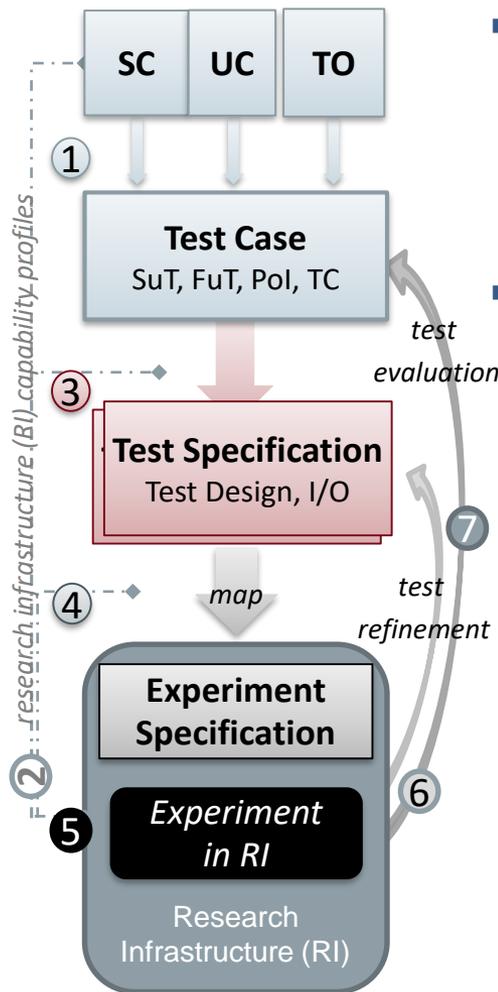
Holistic Testing

- Key questions to be answered for **test specification**

Why to test?
 What to test?
 What to Test *For*?
 How to test?



Test Specification and Design



- **Given**

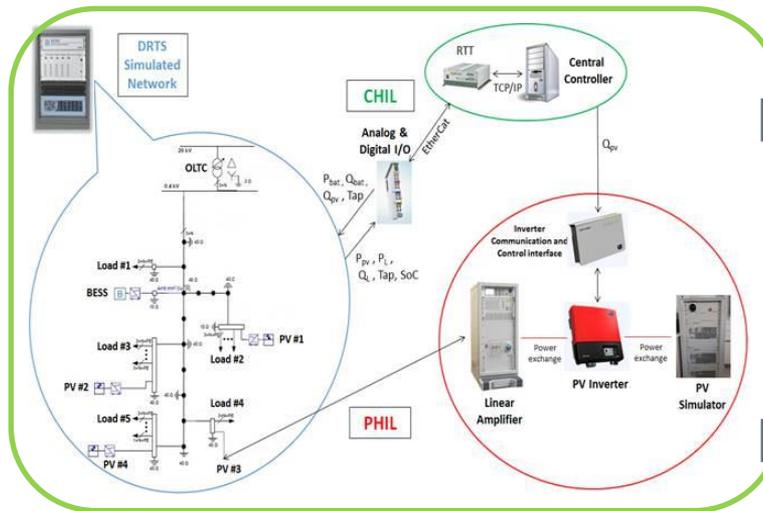
- ✓ Purpose of Investigation (Pol) and Test Criteria
- ✓ System and Domain categories and relations

- **To Specify**

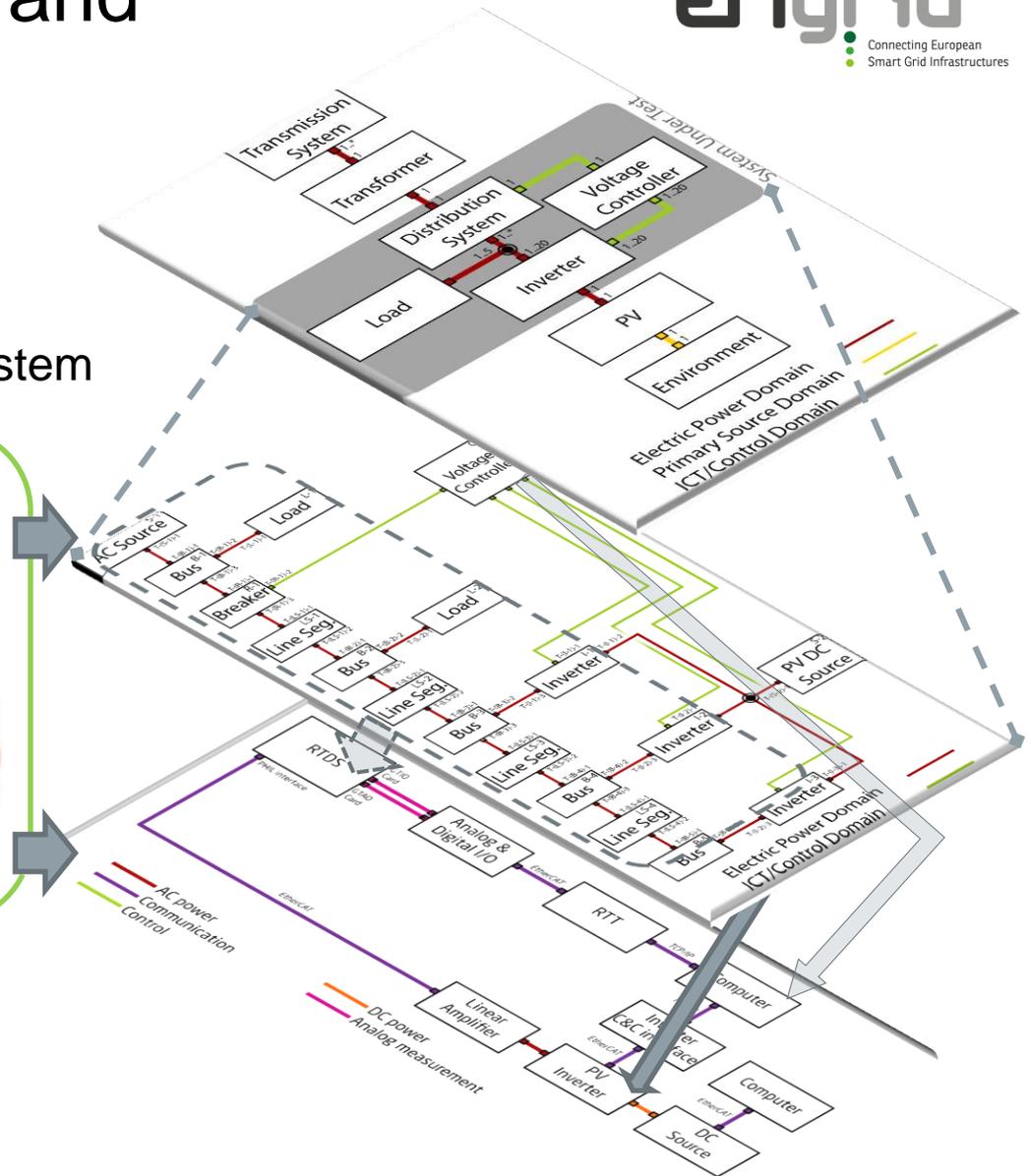
- ❑ Precise system (specific system configuration)
- ❑ Which variables to manipulate and which to measure?
- ❑ How to quantify the test metrics (based on test data)?
 - ❑ Sampling of the input spaces (design of experiments methodology)
 - ❑ Combination and interpretation of the outputs
- ❑ The test design / procedure
- ❑ Mapping to actual lab setup (experiment setup)

Detailing Test Setup and Mapping to the Lab

Scoping & specification of test system

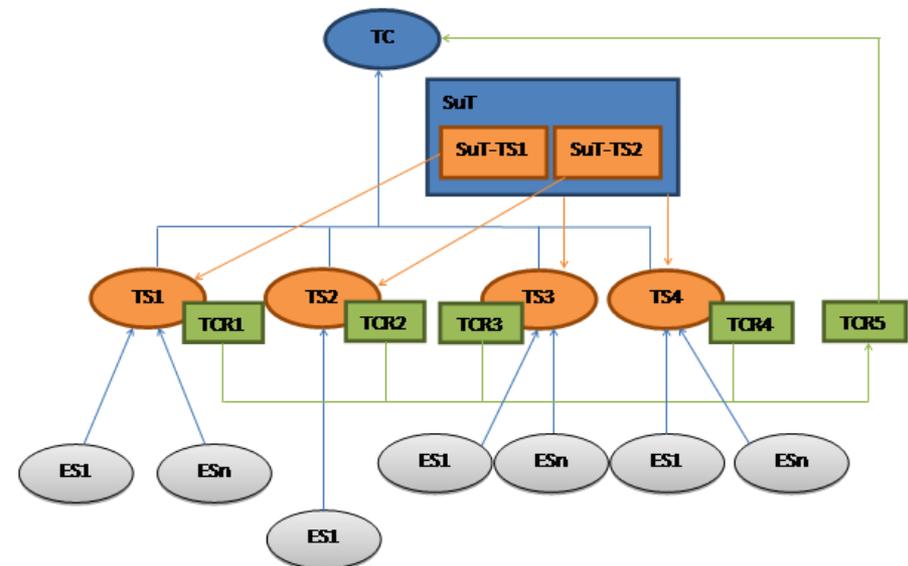


Separate specification of lab implementation



Additional Structure and Documentation

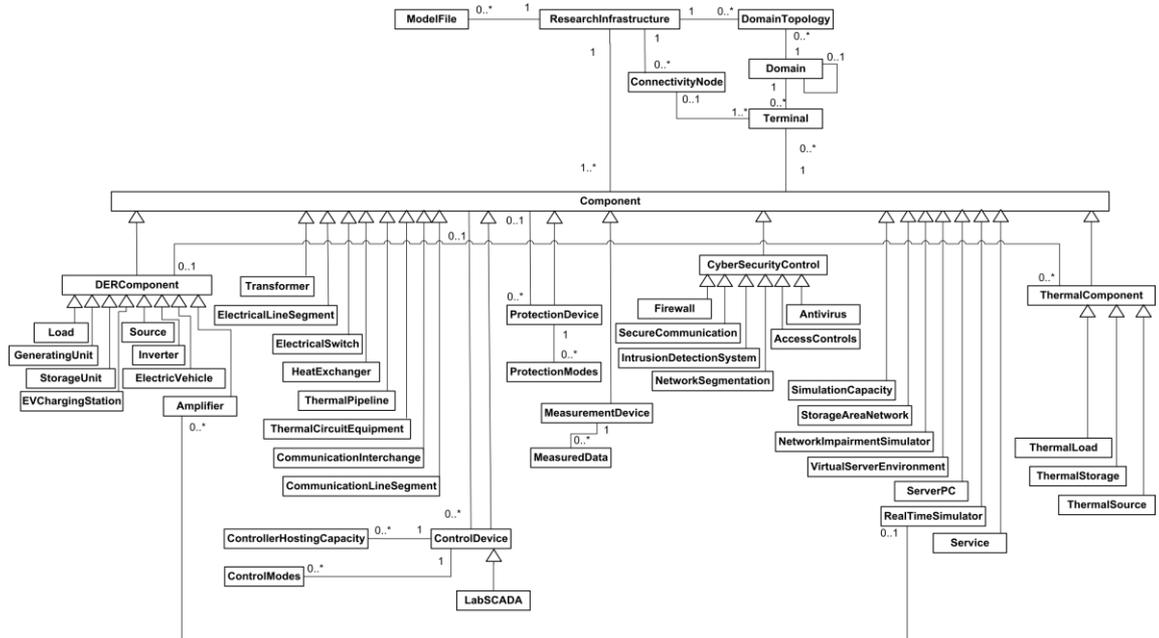
- Qualification strategy
 - How many tests/experiments are derived from the test case?
 - Which PoI & Test Criteria are associated with which test?
 - Are different SuT associated with different tests?
 - Which tests/experiments need input from each other? Or can be done in parallel?
 - Information gained from comparison between tests



Additional Structure and Documentation

- RI selection and mapping
 - Prerequisite: open RI database
 - Guidelines to...

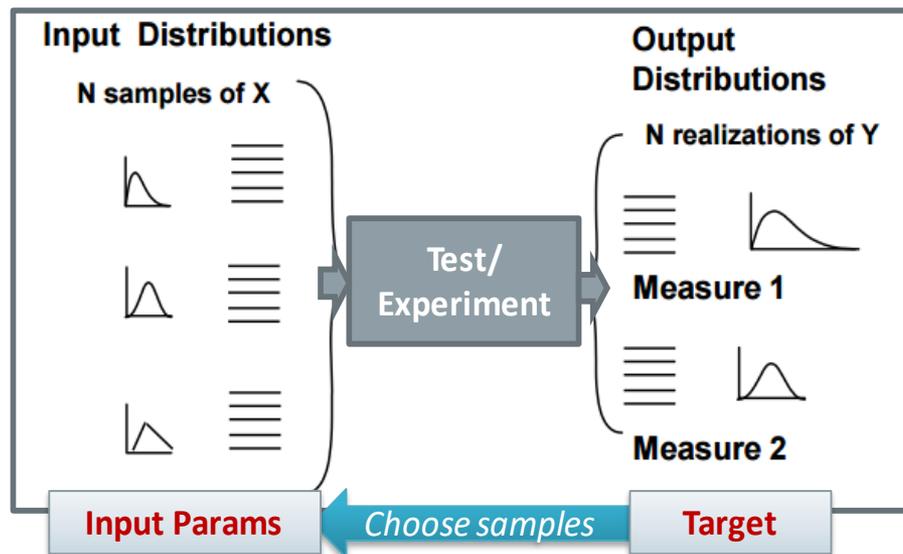
- Select the most suitable RI for the realization of a test
- Find the right components in an RI
- Check cross RI potential (if gaps exist)



RI-Database Data Model

Additional Structure/Documentation

- Design of Experiments (DOE)
 - Aligning the testing process with statistical experiment planning
 - Efficiency → maximal information from limited experiment number
 - Result significance (against system noise)



- Target measures/ metrics (e.g., “average control error”)
- Design sampling space on a ‘need-to-know’ basis (e.g., 3 levels of package loss rate, 20 levels of disturbance)

Holistic Test Case Example

TEST CASE:

- **Narrative:** For a DMS controller in development stage (simple implementation) the performance of the DMS algorithm and controller should be evaluated under realistic conditions. This test, could be seen as the last step before installing the DMS in the field.
- **SuT:** DMS, DER, OLTC, transformer, distribution lines, telecom network
 - Ouls: **DMS_controller**
 - Dul: **Electric power** and **ICT**
- **FuT:** DER P,Q control, measurements, OLTC tap control, comm. via ICT
 - Ful: **optimization in the controller, state estimation**
- **Test objectives/Pol:** *Characterization and validation* of the **DMS controller**
 1. Convergence of the **optimization** (*validation*)
 2. Performance of the **optimization** under realistic conditions (*characterization*)
 3. Accuracy of the **state estimation** (*characterization*)
- **Test criteria** – *how to formulate these objectives?*

Target criteria - Variability attributes: - Quality attributes

Potential Test setups:

- Pure simulation (e.g., co-simulation)
- Combination of virtual & physical interfaces and simulated components (PHIL and CHIL)
- Full hardware setup

Application Examples

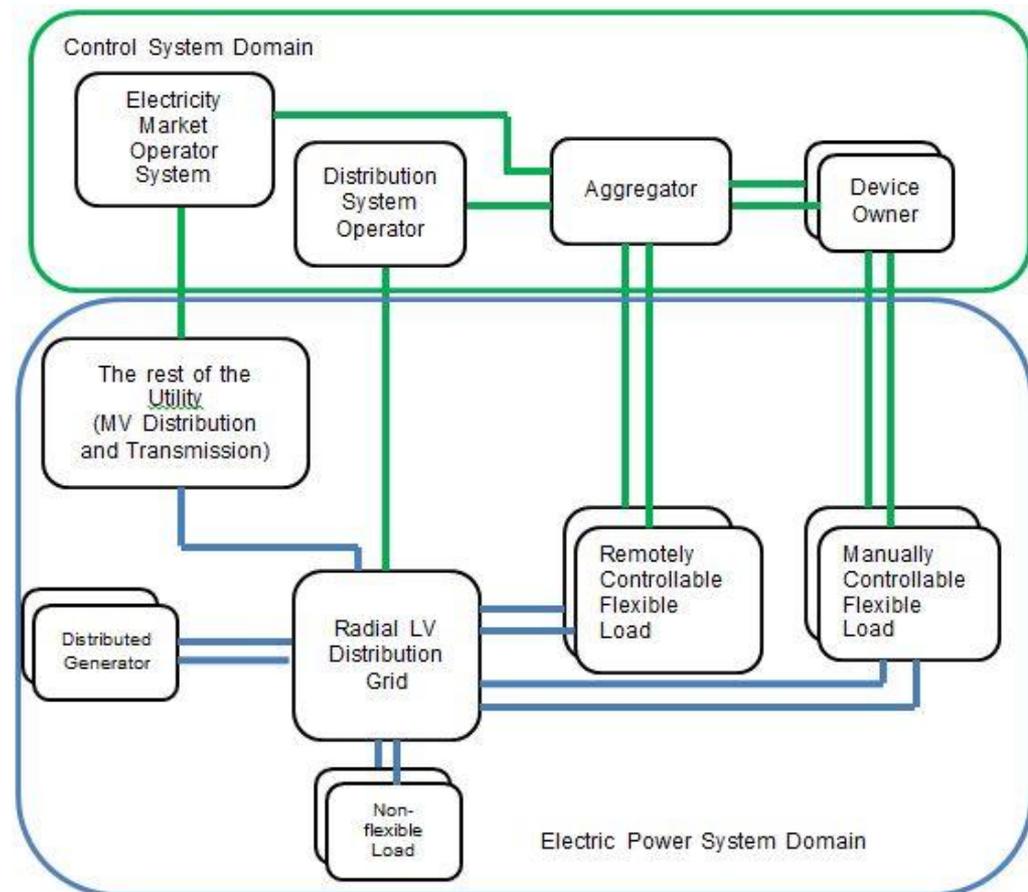
- Applied in the ERIGrid project
 - Project-internal demonstration cases
 - Transnational Access (TA) projects
 - Gathering feedback and continuous improvement/extension
- Other EU projects



- Official publications
 - First papers out
 - Comprehensive guideline paper and templates soon to be public

Application Examples

- TA project “DiNODR” at SYSLAB (DTU)
 - Mitigating local problems in distribution grid via aggregated flexible loads (Demand Response – DR)
 - Coordinate distribution-level DR with utility-driven DR



Application Examples

- Three test cases → list associated Pol
 - TC1: Validate usefulness distribution-level DR
 - Validate voltage improvement (Pol1), overload prevention (Pol2), phase balancing (Pol3), network reconfiguration support (Pol4)
 - TC2: Characterize harmful impact of utility-driven DR
 - Characterize impact on bus voltage (Pol5), and line loadings (Pol6)
 - TC3: Validate application of concurrent DR approach
 - Verify local DR effectiveness (Pol7), and utility-level DR effectiveness(Pol8)
- All Pol are associated with several Target Metrics
- Each TC split up into several Test Specifications

ERIGrid Transnational Access: Preparation & Documentation

“The preparation work helped us a lot. Except minor changes in the plan and configurations due to a number of device, communication and control unavailabilities, we are following our test and experiment specifications. The template is also useful for our user team to exchange ideas in an organized and effective way.”
- Alparslan Zehir (DiNODR)



Simulation and Lab-based Testing Methods

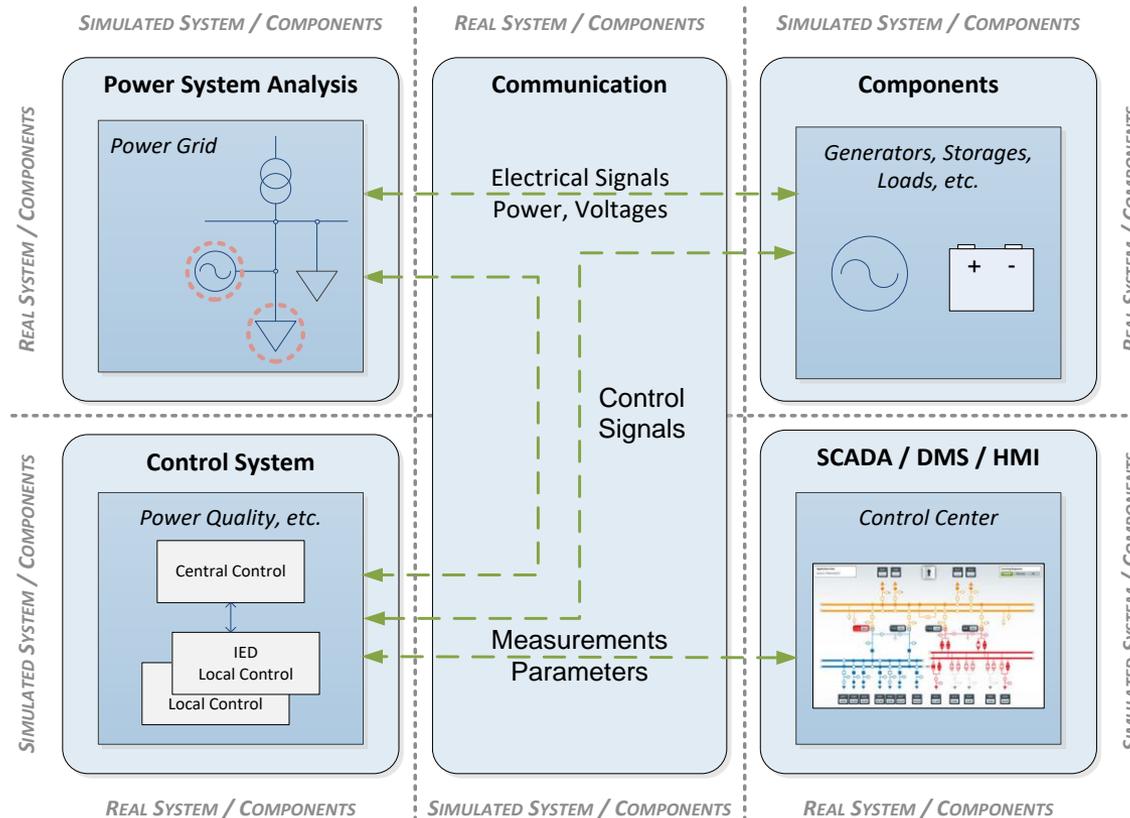
SMC 2018 Tutorial

Concepts, Methods, and Tools for
Validating Cyber-Physical Energy Systems

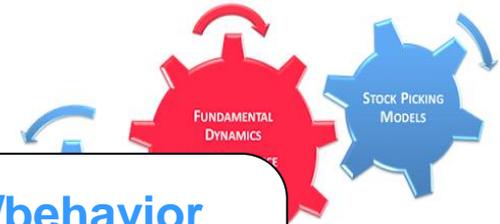
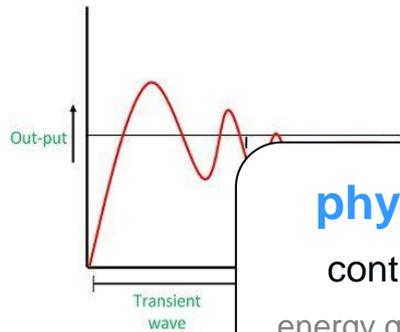


Improved Testing Methods and Tools

- Simulation-based approaches



Simulation Challenges



Cyber-Physical Energy System

physical world

continuous models
 energy generation, transport, distribution, consumption, etc.

roles/behavior

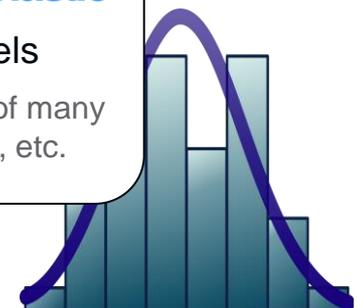
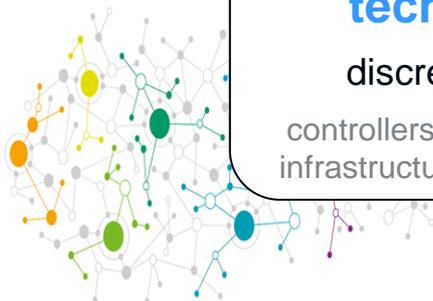
game theory models
 agents acting on behalf of a customer, market players, etc.

information technology

discrete models
 controllers, communication infrastructure, software, etc.

aggregate / stochastic

statistical models
 weather, macro-view of many individual elements, etc.



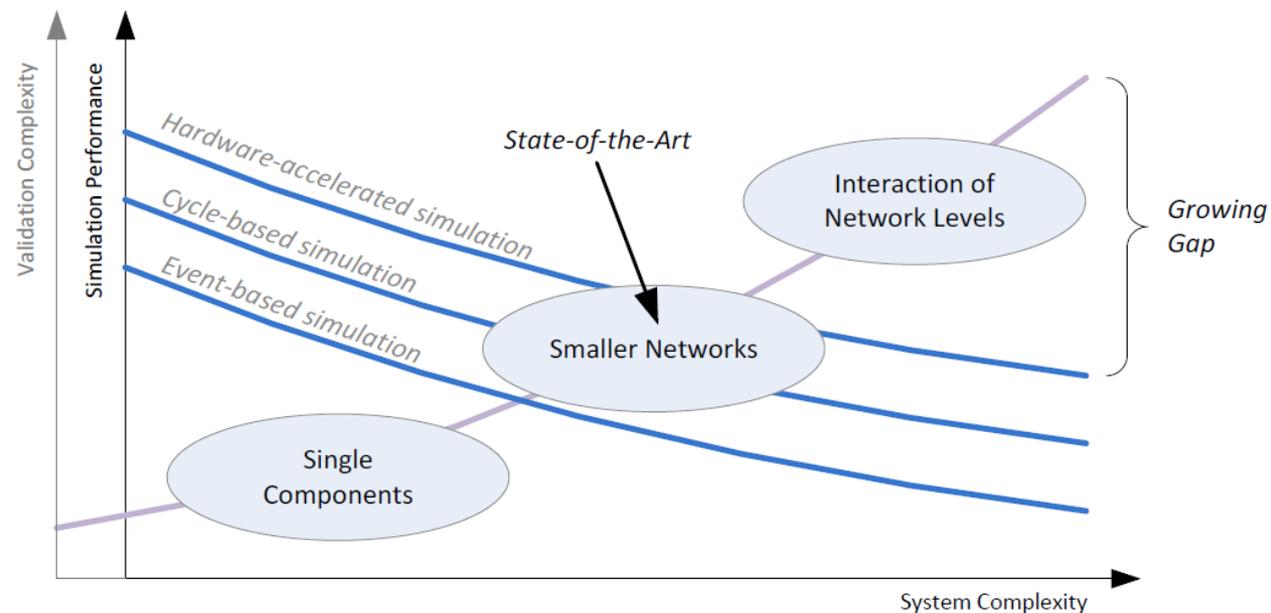
Aims and Objectives

- Develop advanced co-simulation based methods
- Simulation-based validation of smart grid scenarios
- Utilisation of standardised interfacing methods such as the Functional Mock-up Interface (FMI)
- Application and adaptation of existing scenario development and execution tools like mosaik
- Application of optimisation techniques, design of experiments, ICT assessment methods beyond state-of-the-art
- Develop tool-specific FMI wrappers
- Develop FMI-based smart grid model library
- Assess and large-scale system phenomena by an integrated simulation environment



Co-Simulation

- Smart grid system comprises of complex infrastructure, involving interaction among various domains
- This continuous interaction among the various components, devices and domains leads to huge amounts of data being exchanged
- Co-simulation helps in coupling among these domains to create a realistic representation of any smart grid infrastructure and its behaviour



The Tools

Functional Mock-up Interface (FMI)

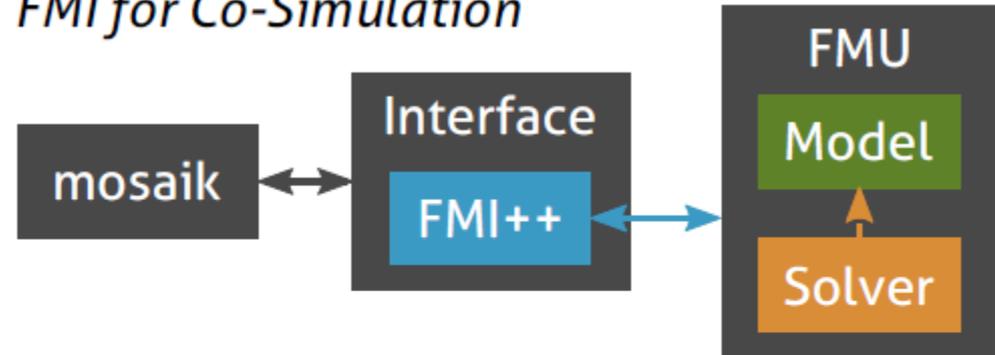
FMI is a tool independent standard to support

- Co-simulation of dynamic models
- Model exchange

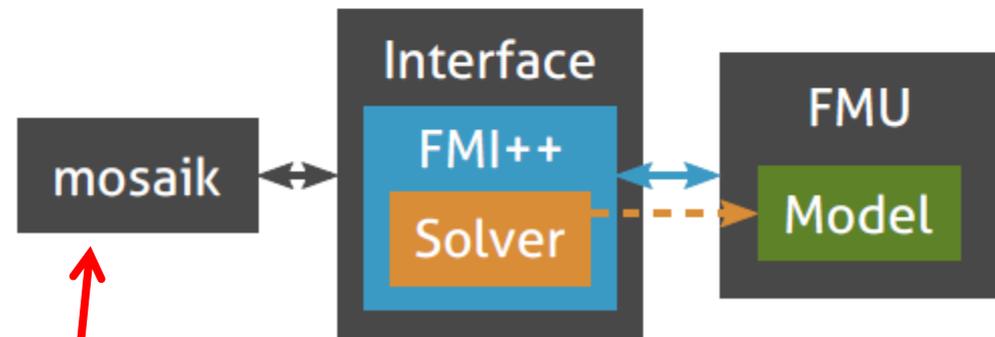
Specifies the functionality that a model or simulator should offer when connected externally

Stems from automotive industry, currently supports over 100 tools

FMI for Co-Simulation



FMI for Model Exchange



Master algorithm

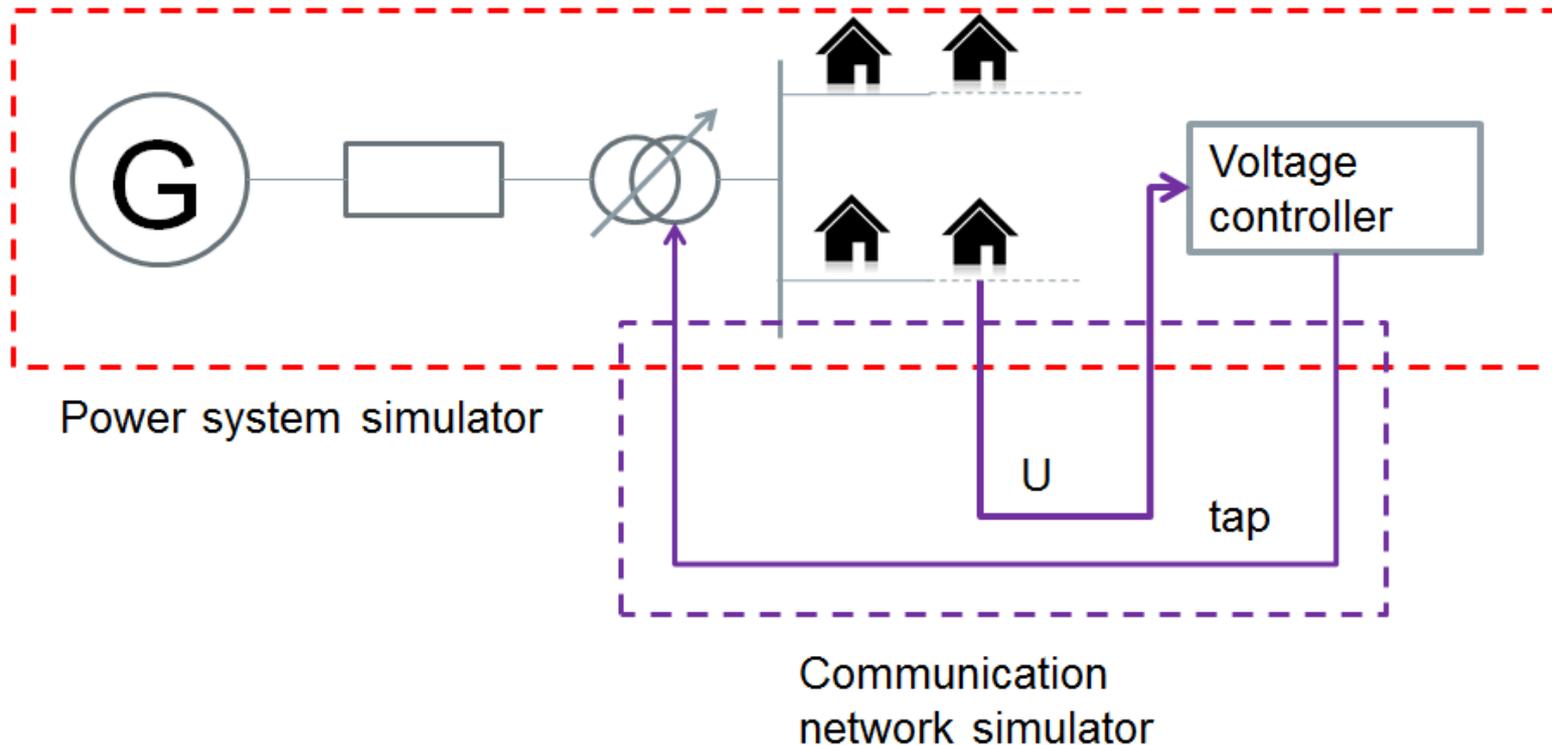
The Tools mosaik

- Orchestrates the overall simulation study
- Testbed for multi-agent systems
- Adapted for continuous and discrete simulations
- Flexible scenario description
- High modularity



Validation Example

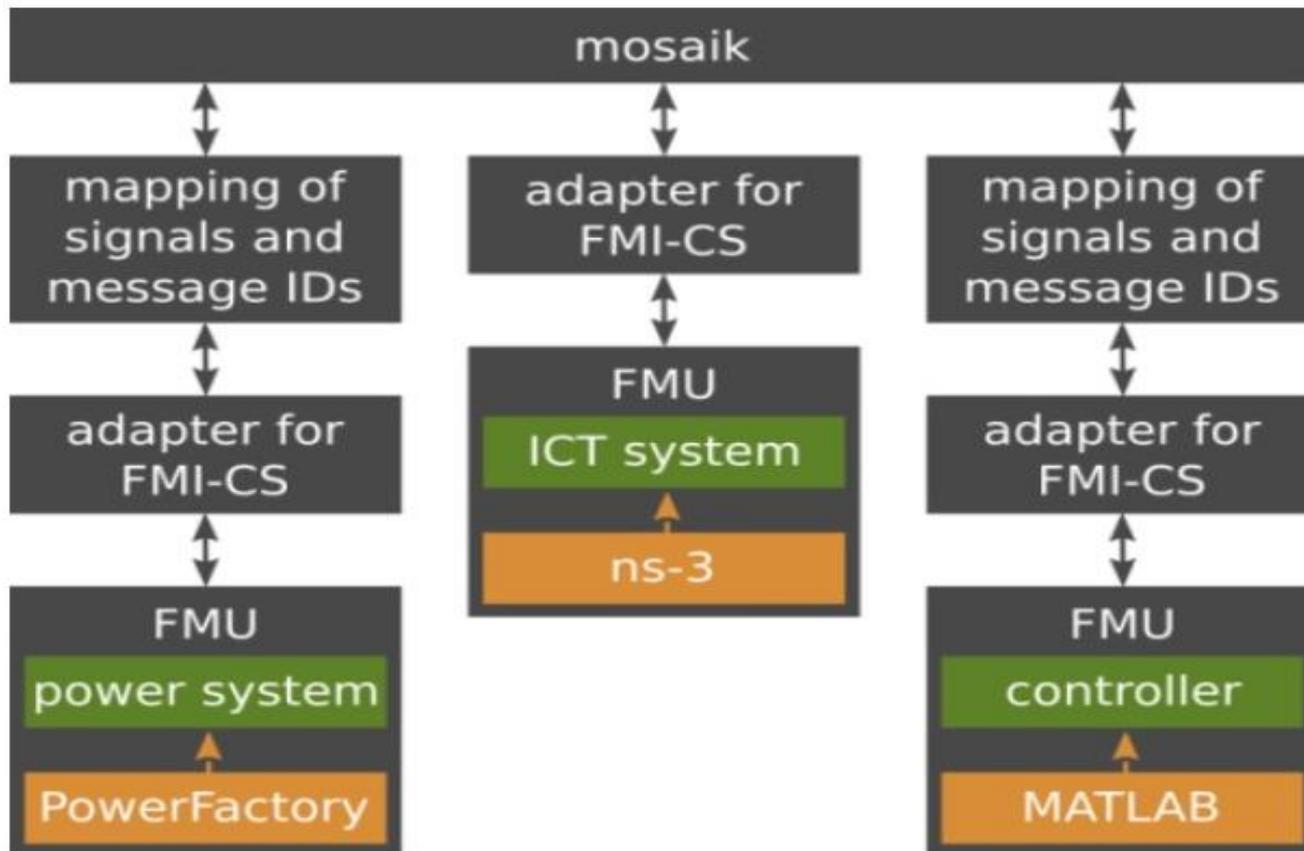
Coord. Voltage Controller (CVC)



General Setup of CVC system

Validation Example

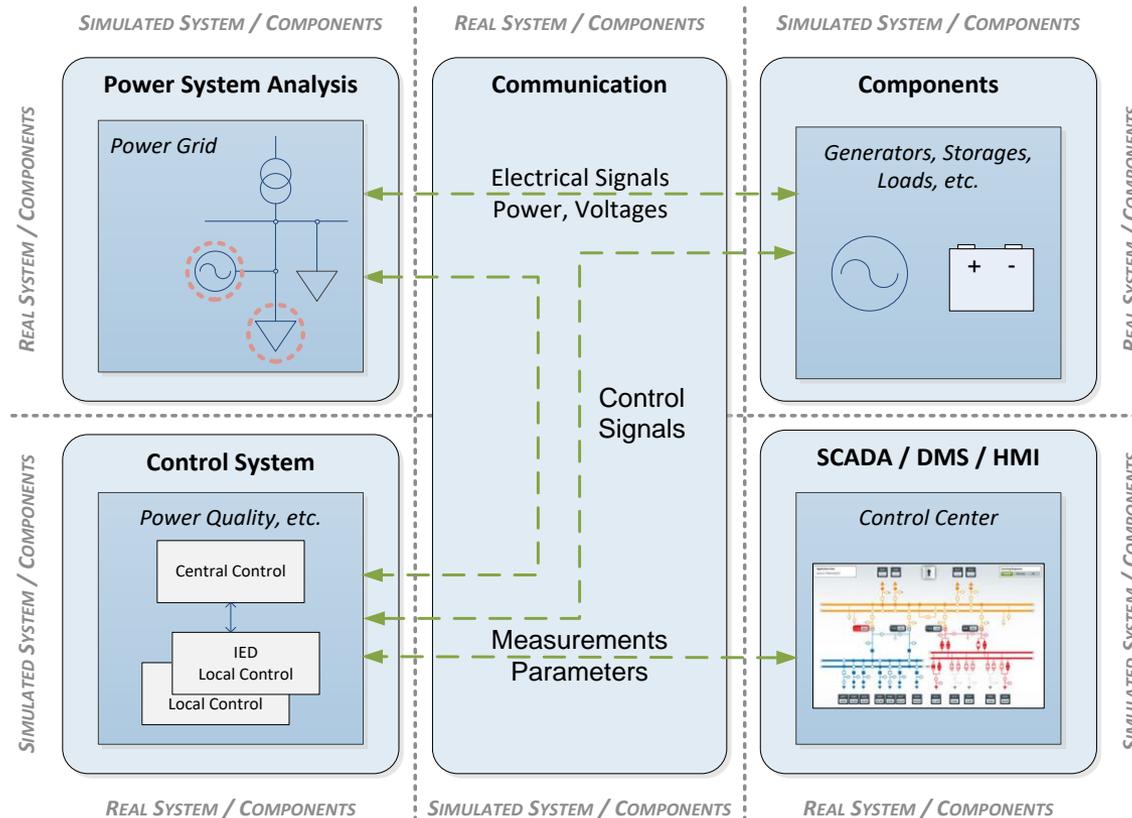
Coord. Voltage Controller (CVC)



Experimental setup of CVC system

Improved Testing Methods and Tools

- Lab-based approaches



Laboratory Integration Obstacles

- Power grids are mature infrastructures and have been extensively standardised
 - No standards for smart grid labs or what their primary purpose should be
 - Consequently, the use of ICT/automation systems (architectures, interfaces, etc.) is subject to large variations between facilities
- Smart grid labs are complex infrastructures with unique properties
 - Experimental nature of the installations
 - Changing user groups
 - Evolving configurations
- Finding a common ground when talking about lab integration can be a challenge



SmartEST Laboratory at AIT



Smart metering communication platform at TECNALIA

Issues Addressed in ERIGrid

- Generic reference model for control hierarchies, interfaces and data flow in smart grid laboratories
- Documentation of complex DER behaviour
- Documentation of controller deployment procedures
- Uniform naming of signals and objects

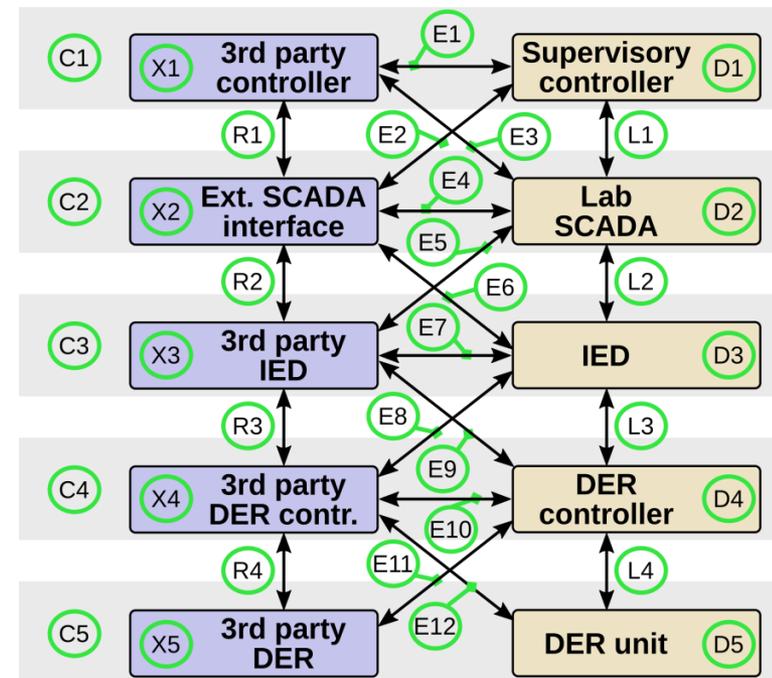


Need for a Generic Reference Model

- Status quo
 - Availability of communication interfaces between the different parts of a lab determines to which degree the lab presents itself to the user as a collection of hardware components or as an integrated system
 - The automation and control aspects are often missing from descriptions of lab capabilities which tend to focus on the performance of the power equ.
- A one-size-fits-all model is complicated because
 - A wide range of automation levels/concepts is found among partner labs
 - Ad-hoc automation for individual experiments is not uncommon
 - Automation may involve communication between lab components and/or between the lab and third party equipment (under test)
 - The automation may be considered as infrastructure, as part of the system under investigation, or a combination of both

Generic Reference Model Description

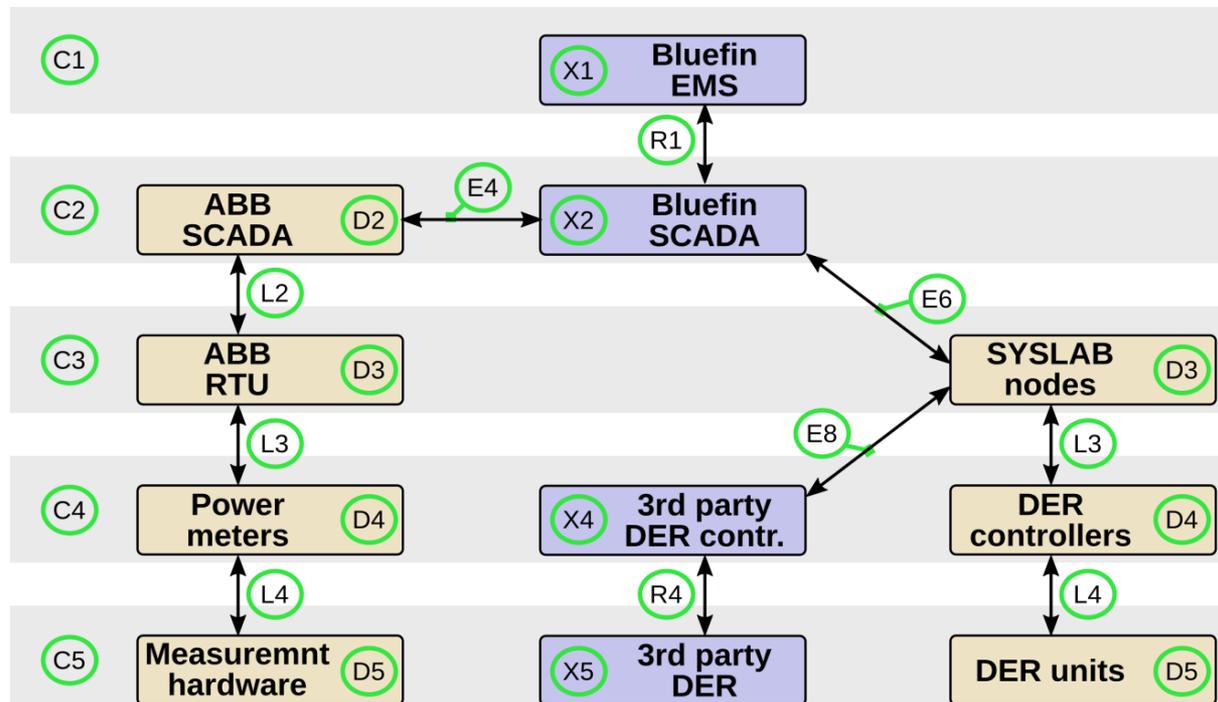
- The model abstracts away from individual devices, controllers, protocols etc. as well as time, in order to focus on classes of controllers and interfaces
- Definition of five hierarchy levels at which control functionality may be deployed (both internal to the lab & external)
- Definitions of 20 communication interface locations
- Use cases for 12 interfaces between lab installations and external systems
- Partner examples of concrete experiment configurations



Generic Reference Model

Example DTU SYSLAB & Electric lab

- Performance evaluation of a third-party smart grid automation system
- Augmentation of a low automation host lab (DTU Electric lab) with components and control infrastructure from a highly automated lab (DTU SYSLAB)



Complex DER Component Behaviour

- Lab equipment (esp. DER units) often exhibits complex and undocumented behaviour when operated during experiments
 - Documentation often focuses on the operation under standard conditions
 - Examples include deratings, internal limits, safety circuits, alternate operating modes, functions added as part of laboratory integration etc.
- The productive use of a particular component often relies on unofficial knowledge associated with experienced lab staff – sometimes a single person
- ERIGrid conducted a survey of examples across partner labs, the results can be seen as a first step towards a more systematic documentation



Controller Deployment Procedures

- Deploying controllers – software or hardware, from the unit level to the system level – is important for many types of smart grid testing
- It is very difficult for an outside user or research partner to gain an overview of the exact capabilities of a laboratory with respect to controller deployment. This complicates the selection of a suitable facility for an experiment.
 - Uniqueness of the individual laboratories
 - Many possible interaction patterns
 - Policies and safety/stability concerns (an interface exists, but it should not be used)
- Survey of controller hosting capabilities across partner labs
 - Physical capabilities
 - Interfaces
 - Procedures

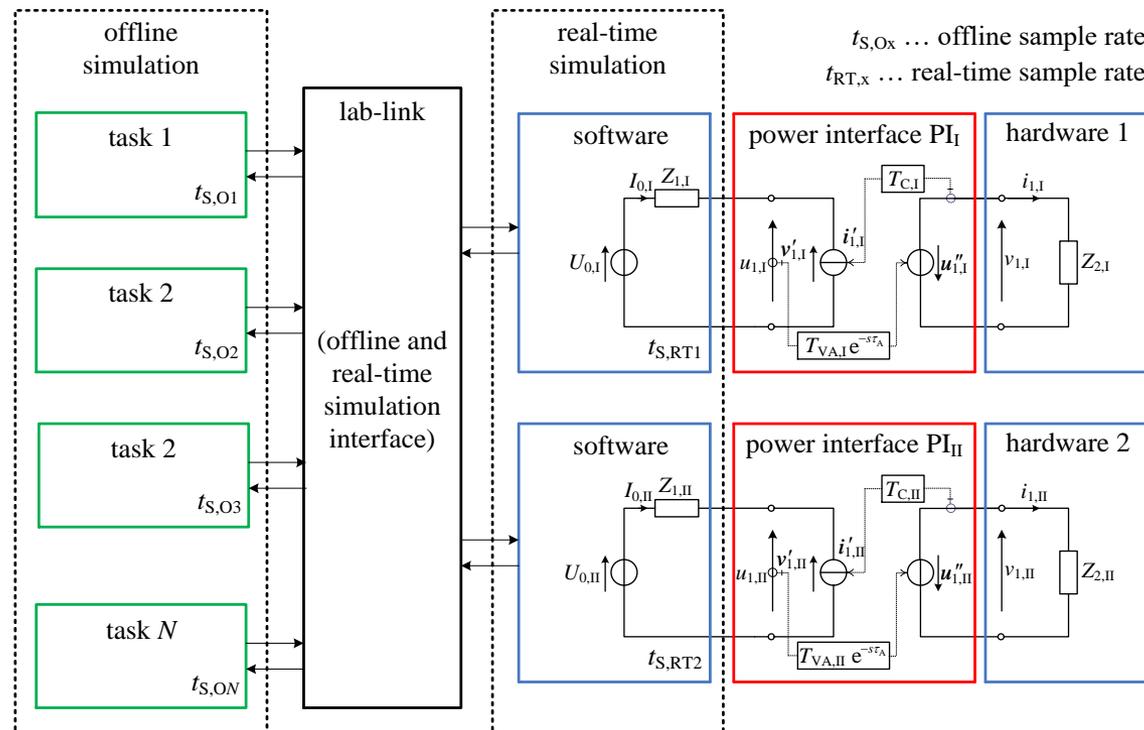
Signal and Object Naming

- The partner labs have been developed from very different architectural viewpoints, resulting in different ways of modelling information
- Establishing a harmonized object and signal naming convention is necessary for machine-to-machine communication between labs
- Existing standards lack flexibility
 - Lab-specific description of primary hierarchy (physical, electrical, automation based, information based, etc.)
 - Additional domains (control, communication, etc.)
 - Unambiguous description of components which belong to multiple hierarchies and/or multiple domains
- ERIGrid has developed naming conventions suitable for the detailed description of static (objects) and dynamic (signals) data in smart grid laboratories.



Coupling Co-Simulation and Real-Time Hardware-in-the-Loop (HIL)

- Cyber-physical (multi-domain) approach for analysing and validating smart grids on system level
- Improved validation and testing methods with focus on co-simulation & HIL



Connecting Smart Grid Labs

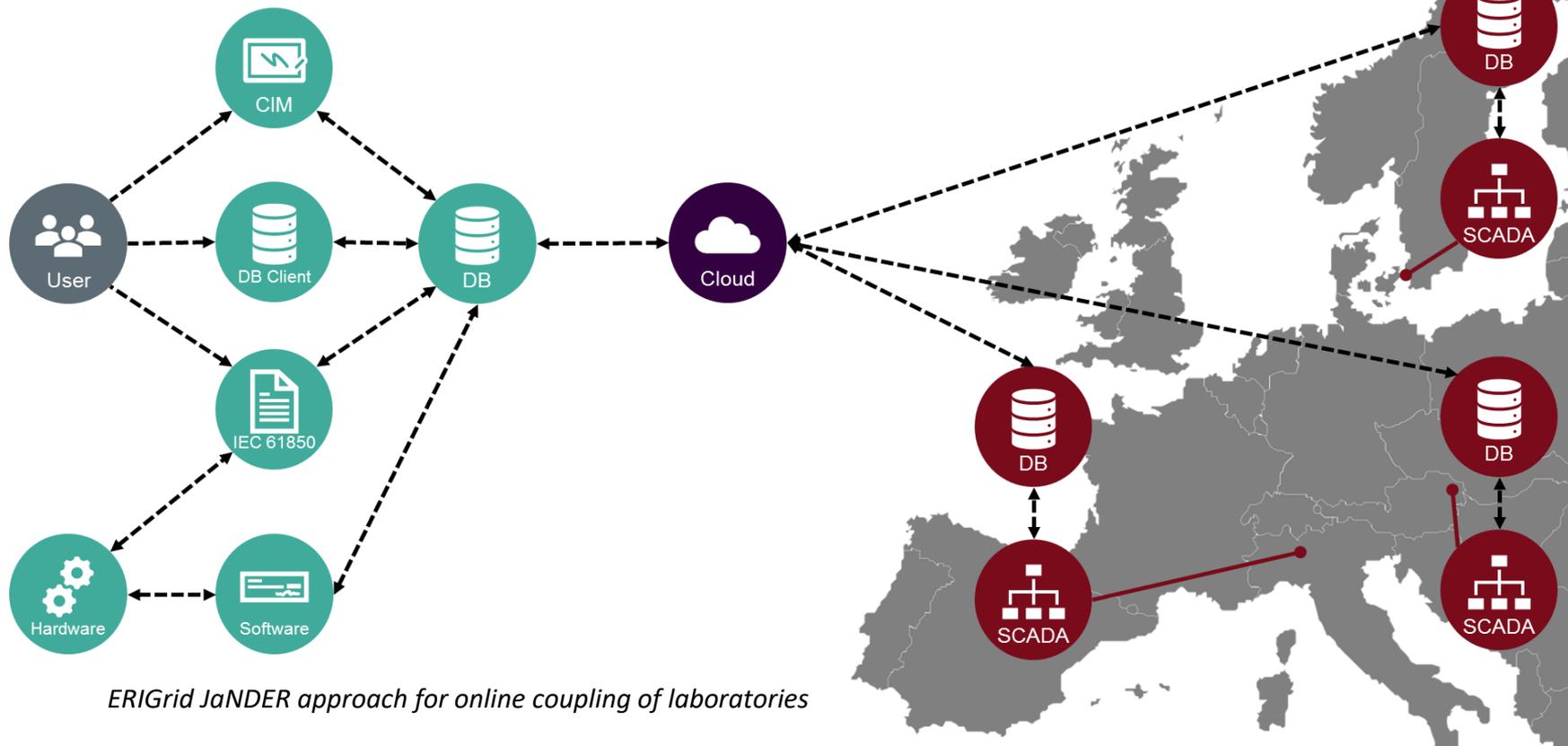
Real-Time Data Exchange via JaNDER

- Joint Test Facility for Smart Energy Networks with DER (JaNDER)
 - Result from FP7 DERri
 - Proof-of-concept of real-time data exchange between lab facilities
- Several shortcomings of DERri JaNDER version (addressed in ERIGrid)
 - Installation effort (e.g., requirement for firewall changes)
 - Lack of official multi-lab test cases in DERri
 - No context information beyond raw real-time data
- Virtual Research Infrastructure (VRI)
 - Integration of all ERIGrid participating labs
 - Virtually integrated pan-European smart grid research infrastructure



Connecting Smart Grid Labs JaNDER Architecture

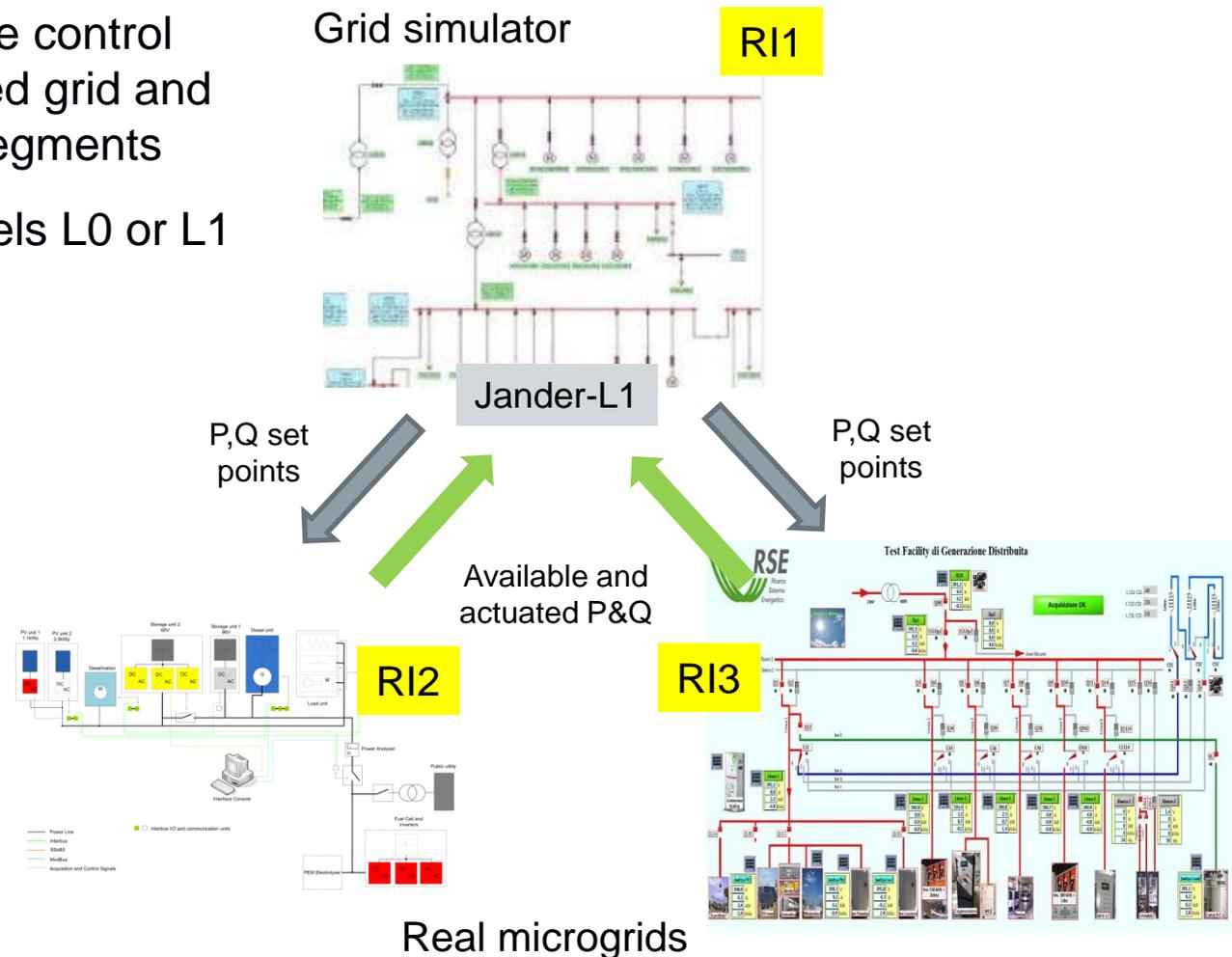
- Coupling of research infrastructures for integrated and joint testing (multi-lab)



Connecting Smart Grid Labs

JaNDER Example

- Coordinated voltage control between a simulated grid and two physical grid segments
- Using JaNDER levels L0 or L1



Selected Validation Examples

SMC 2018 Tutorial

Concepts, Methods, and Tools for
Validating Cyber-Physical Energy Systems



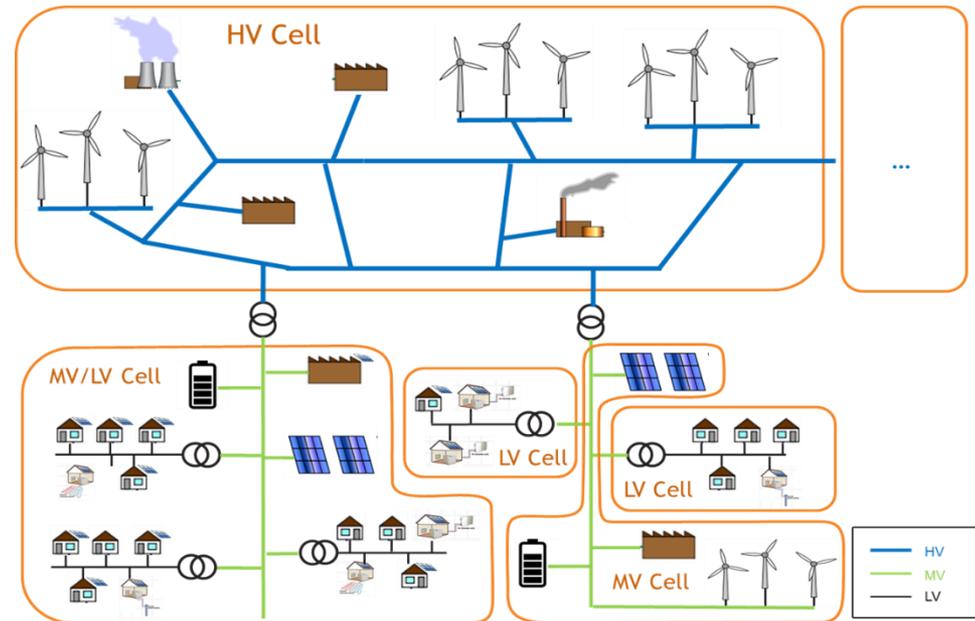
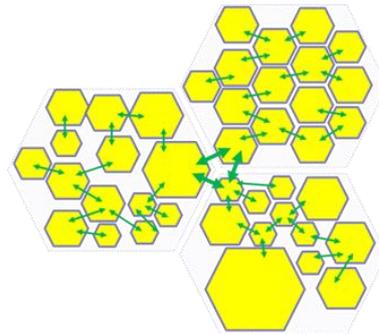
Selected Validation Examples

- Power system control testing
- Cyber-physical attacks investigation



Power System Control Testing

- Cell-based power systems control
 - ELECTRA IRP Web-of-Cells (WoC) approach
- Controller analysis and investigation
 - Focus on cell voltage control
- Validation goal
 - Testing of the WoC control implementation



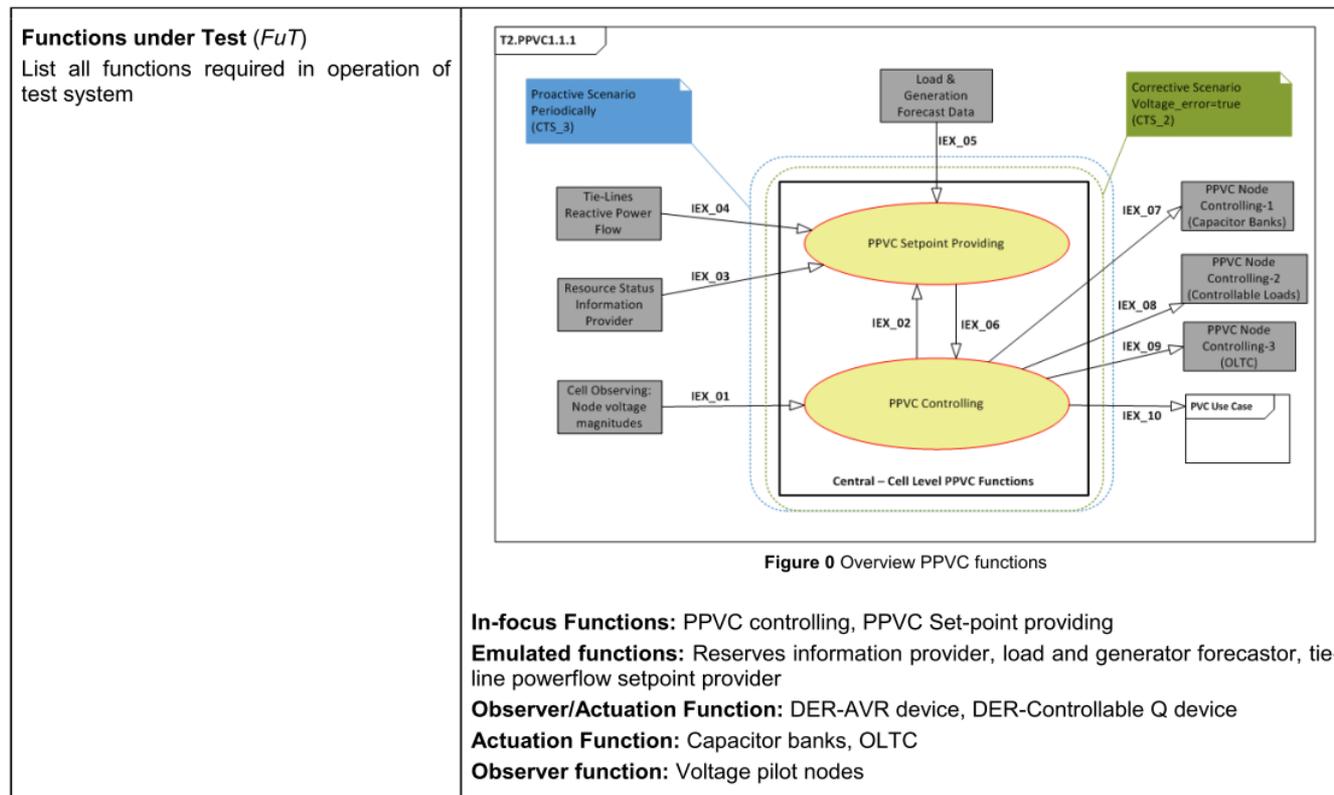
Power System Control Testing

- Holistic Test Description: Test Case

Name of the test case		Power quality and voltage control (PVC+PPVC)
<p><i>Narrative</i> "a storyline summarizing motivation, scope and purpose of the test case."</p>		Can PPVC replace the present secondary (local) and tertiary voltage control (global) schemes existing in power grids by a decentralized control located at a cell level? How would PPVC interact with PVC and balancing control? How would PPVC respond to different network conditions?
<p>System under Test (SuT): (power system & ICT boundaries): SRPS + CTL</p>		Power distribution network (several voltage levels), On-Load-Tap Changing Transformers (OLTC), inverter-based Distributed Energy Resources (DER) (PV, wind turbine, energy storage systems), synchronous and induction machines, (controllable) loads
	<p>Objects under Investigation (Oul) "the component(s) (1..n) that are to be characterized or validated"</p>	PVC+PPVC controlling
	<p>Domain under Investigation (DuI): "Identifies the relevant domains or sub-domains of test parameters and connectivity."</p>	<ul style="list-style-type: none"> Power system Control/ICT

Power System Control Testing

- Holistic Test Description: Test Case



Power System Control Testing

- Holistic Test Description: Test Case

	<p>Function(s) under Investigation (FuI) “the referenced specification of a function realized (operationalized) by the object under investigation”</p>	<ul style="list-style-type: none"> • PPVC Set-point providing • PPVC Controlling
	<p>Purpose of Investigation (PoI) “a formulation of the relevant interpretations of the test purpose (e.g. in terms of Characterization, Verification, or Validation)”</p>	<p>3.4 Simulation-based proof-of-concept analysis of the PVC+PPVC use case, incl. sensitivity analysis, clustering concept for the identification of potential ELECTRA cells, scalability analysis, comparison with a business as usual case.</p> <p>3.5 Hardware-in-the-Loop based proof-of-concept analysis of the PVC+PPVC use case incl. a selected number of DER units (PV system, Energy Storage Systems, etc.), sensitivity analysis.</p>
	<p>Test criteria: “the measures of satisfaction that a need to be evaluated for a given test to be considered successful.” A formalization of the purpose of investigation wrt. SuT and FuT attributes.</p>	<ul style="list-style-type: none"> • Optimal cell division for voltage control • TCR28: Minimum power losses in the cell • TCR30: Safe and robust voltage for all nodes
	<p>target metrics (criteria) A numbered list of measures to (quantify) each identified criterion</p> <p>variability attributes (test factors):</p> <p>quality attributes (thresholds):</p>	<ul style="list-style-type: none"> • Minimum power losses in the cell, Reactive power flows in the tie-lines within safety limits • Safe and robust voltage for all nodes • Topology change resulting in change in number of tie-lines • Loss of a line • Loss of a generator • Power quality standard EN50160 • All node voltages within the specified limit (+ or -10%)

Power System Control Testing

- Holistic Test Description: Test Specification

		Table 1 Modifications to the CIGRE MV test network															
		Node 3	Node 4	Node 5	Node6	Node 7	Node 8	Node 9	Node 10	Node 11							
Source Type		PV;	PV	PV; FC; BAT	PV	WT	PV	PV; FC; CHP	PV; FC BAT;	PV							
Source rating [kVA]		22;	22;	33; 1000 ; 1000	30;	1500	33;	30; 500 ; 500	40; 14 ; 210	10;							
Tfmr rating [kVA]		500	500	500; 800; 500	800	2500	500	500; 500; 500	500; 500	500							
		Table 2 Modifications to line length															
		Line 01	Line 02	Line 03	Line 04	Line 05	Line 07	Line 08	Line 09	Line 10	Line 11	Line 12	Line 13	Line 14	Line 15	Line 16	
Research Infrastructure		---															
Input parameters		<ul style="list-style-type: none"> • Generation profiles • Load profiles • Grid topology • Tie-line exchanges • DER controllers parameters 															
Output parameters		<ul style="list-style-type: none"> • Power losses • Node voltages 															
Target measures		<ul style="list-style-type: none"> • Optimal cell division for voltage control • TCR28: Minimum power losses in the cell • TCR30: Safe and robust voltage for all nodes 															
Test Design		Comparison of different cell-configurations and different OPF implementations															
Initial system state		<i>Description of conditions that are prerequisites to actually run the test and initial choices of parameters.</i>															
Evolution of system state and test signals		<i>Quantitative characterization of the temporal evolution of test events and evolution of the relevant test parameters, as adjustable by the input parameters (e.g. opening breakers after a certain amount of seconds); incl. variability attributes</i>															

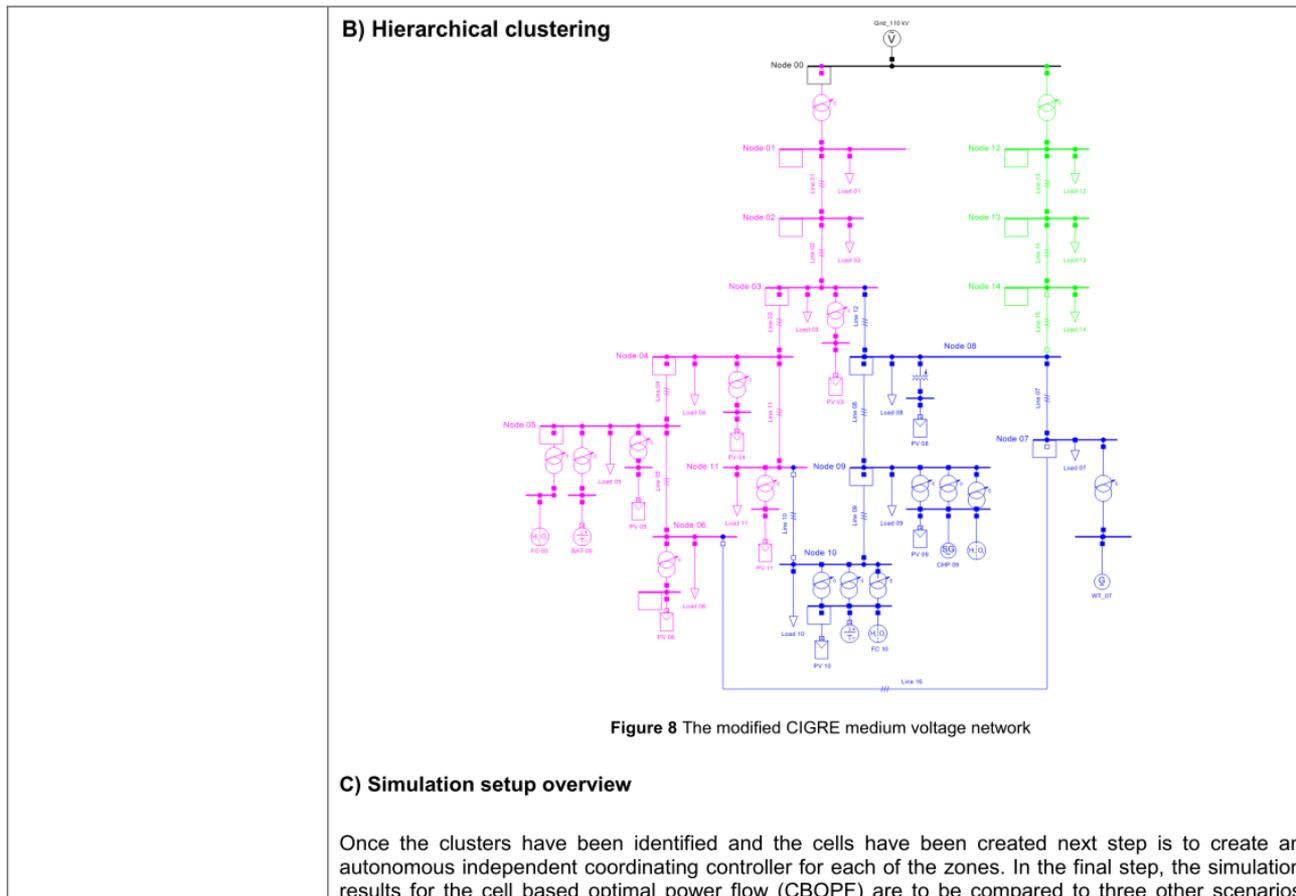
Power System Control Testing

- Holistic Test Description: Experiment Specification

Title	Simulation of PVC+PPVC with CIGRE MV test grid
Ref. Test Spec.	Test Case 3, Test Specification 3.4
Research Infrastructure	PowerFactory, Python API, Python Scripts
Experiment Realisation	Simulation
Experiment Setup (concrete lab equipment)	A) Sensitivity Analysis of the CIGRE MV test network 1. Calculation of normalized electrical distance a. Calculate the Jacobian matrix and use it to obtain the $\partial Q/\partial u$ matrix. $\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} \frac{\partial P}{\partial \delta} & \frac{\partial P}{\partial u} \\ \frac{\partial Q}{\partial \delta} & \frac{\partial Q}{\partial u} \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta u \end{bmatrix}, \quad J_4 = \frac{\partial Q}{\partial u}$ b. Calculate the sensitivity matrix B by calculating the inverse of J_4 . $B = J_4^{-1} = \frac{\partial u}{\partial Q} \text{ where } b_{ij} = \frac{\partial u_i}{\partial Q_j}$ c. Calculate the attenuation matrix α by dividing the non-diagonal elements by the diagonal elements using the following equation. $\alpha_{ij} = b_{ij} / b_{jj}$ d. Calculate the electrical and obtain the normalized distance matrix $D_{ij} = -\log(\alpha_{ij} \cdot \alpha_{ji})$ $D_{ij}^{\text{norm}} = D_{ij} / \max(D_i)$
Experimental Design and Justification	

Power System Control Testing

- Holistic Test Description: Experiment Specification



Power System Control Testing

- Holistic Test Description: Experiment Specification

namely QDS with no control, QDS with local var control and the centralized OPF. The sensitivity of voltage regulation capability and the objective function to the number of cells formed is important to understand.

Figure 9 given a graphical overview of the overall simulation process. An instance of PowerFactory has been created using the Python API provided by DlgSILENT. Within the network, multiple cell objects have been created (one for each cell). Each cell object can have multiple resource objects. These objects correspond to controllable VAR devices connected within the cell boundary. These resources can have both continuous (e.g. PV inverters) or discrete (e.g. Transformers) operation. Within the resource object, operational limits for each resource should also be defined. Finally, a coordination controller object within the cell object is responsible for calculating the new optimal set points for the resources connected with the network. The coordinating controller uses a differential evolution solver provided by SciPy. Each cell controller runs autonomously and independently.

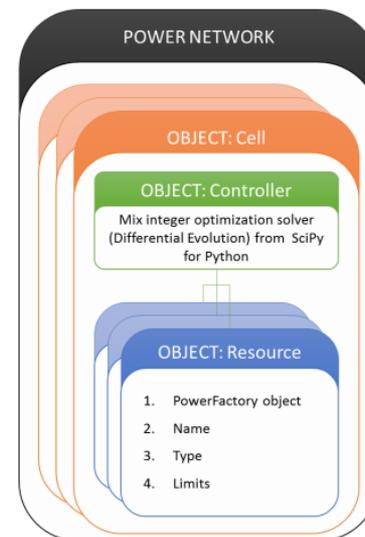
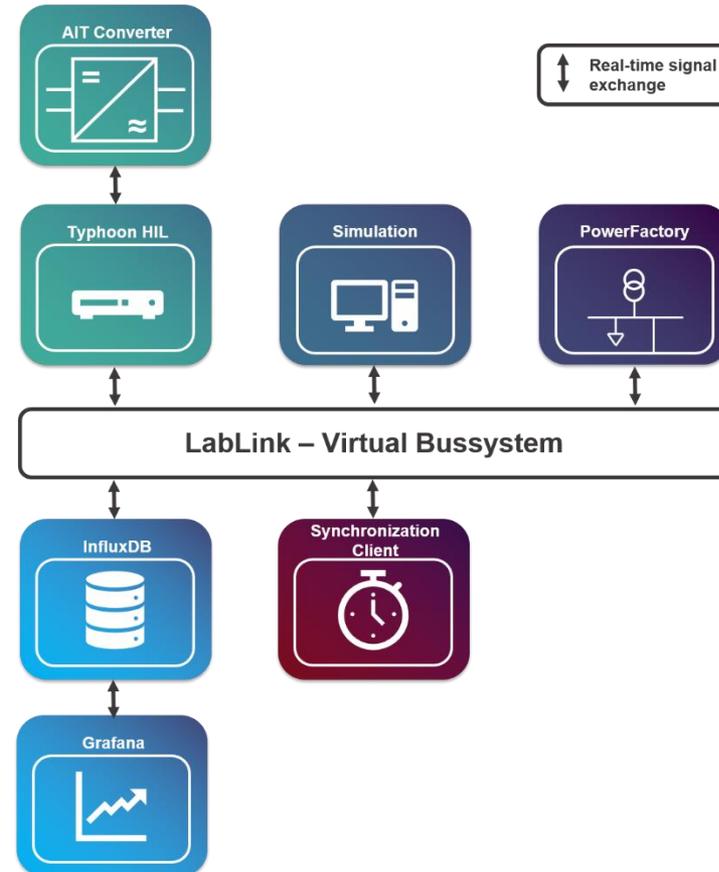


Figure 9 Python code overview

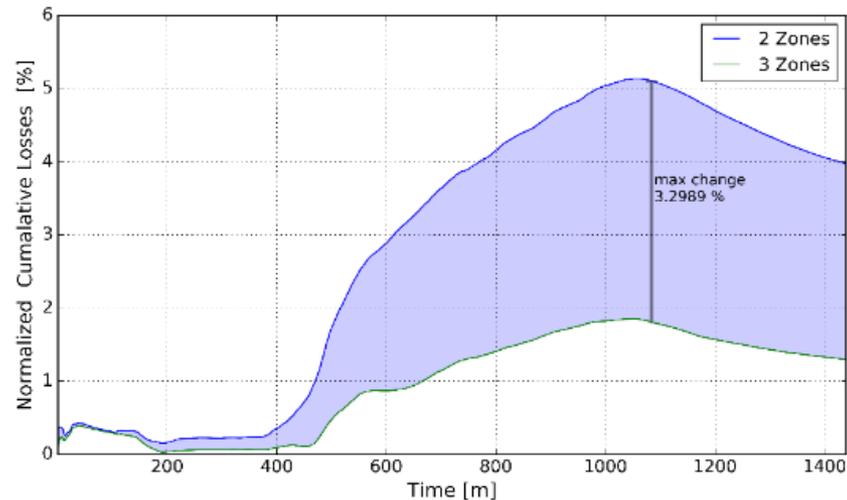
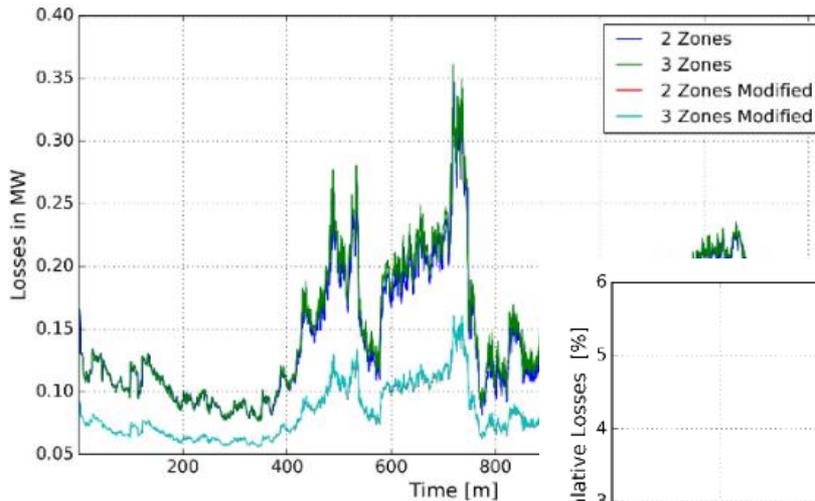
Power System Control Testing

- Realized test with
 - PowerFactory Client
 - Simulation Client
 - Typhoon HIL Client
 - InfluxDB Client
 - Synchronization Client



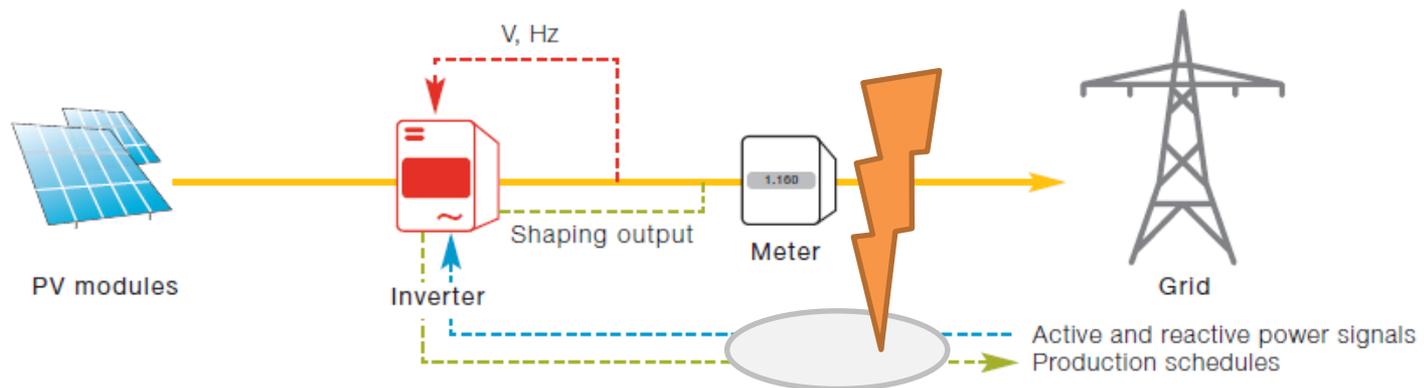
Power System Control Testing

- Achieved results



Cyber-Physical Attacks Investigation

- Energy application
 - IEC 61850 remote controlled inverter-based DER
- Cyber-physical attacks investigation
 - Man-in-the-Middle attack scenario
- Validation goal
 - Analysing the influence of the attack on the energy infrastructure



Cyber-Physical Attacks Investigation

- Formal test case description

Template Test Case

Name of the test case	<i>Name</i>
Narrative "a storyline summarizing motivation, scope and purpose of the test case."	<i>What is the subject of the test and why is the purpose of the test?</i>
System under Test (SuT): "a (specific) system configuration that includes all relevant properties, interactions and behaviours (closed loop I/O and ...)"	<i>What is the test system & the test system boundary? What is the system context and which interactions between your object under investigation and the surrounding system are relevant? What are the ...</i>
Scenario & Generic System Configuration	Use Cases
Test Objective	
Holistic Test Case	Test Criteria
Functions under Test (FuT) "the functions relevant to the operation of the system under test, as referenced by use cases"	<i>Which use cases apply to this test case or which system functions are required for an operational FuT to be investigated? List all functions required to be operational in the final test setup.</i>

Template test specification

Title	Definition
Ref. Holistic test case	
Test System Setup (also graphical)	<i>Graphical and textual description of the system under investigation and its components including interfaces between test setup and Object under investigation and type of those interfaces (e.g. electrical)</i>
Target measures	<i>Specification of the target metrics that will be derived, from measured parameters in order to evaluate the test objectives. Which variables will be quantified by the test?</i>
Input and output parameters	<i>List of inputs for the system under test relevant to the object under investigation, inputs relevant to the object under investigation itself and outputs / measured parameters divided into:</i> <ul style="list-style-type: none"> • 'Controllable input parameters' • 'Uncontrollable input parameters' • 'Measured parameters'
Test Design	<i>The choice of mapping between required testing target and available test parameters, in terms of</i>

Test Specification
Test Design, Test System Config., Input & Output

Evolution of system state and test signals	<i>to actually run the test and initial choices of parameters.</i> <i>Quantitative characterization of the temporal evolution of test events and evolution of the relevant test parameters, as adjustable by the input parameters (e.g. opening breakers after a certain amount of seconds)</i> <i>Evolution of variability attributes</i>
Other parameters	<i>Information of data that should be tracked apart from the input and output parameters and system state, test signals</i>
Storage of data	<i>In which format are the parameters stored</i>
Temporal resolution	<i>Discrete or continuous simulation and (if applicable) resolution of the discrete time steps</i>
Source of uncertainty	<i>In order to evaluate the quality of the test, the possible sources of uncertainties are given in how they can be quantified.</i>
Suspension criteria / Stopping criteria	<i>Under which conditions are the test results not valid or the test is interrupted</i>

Template experiment specification

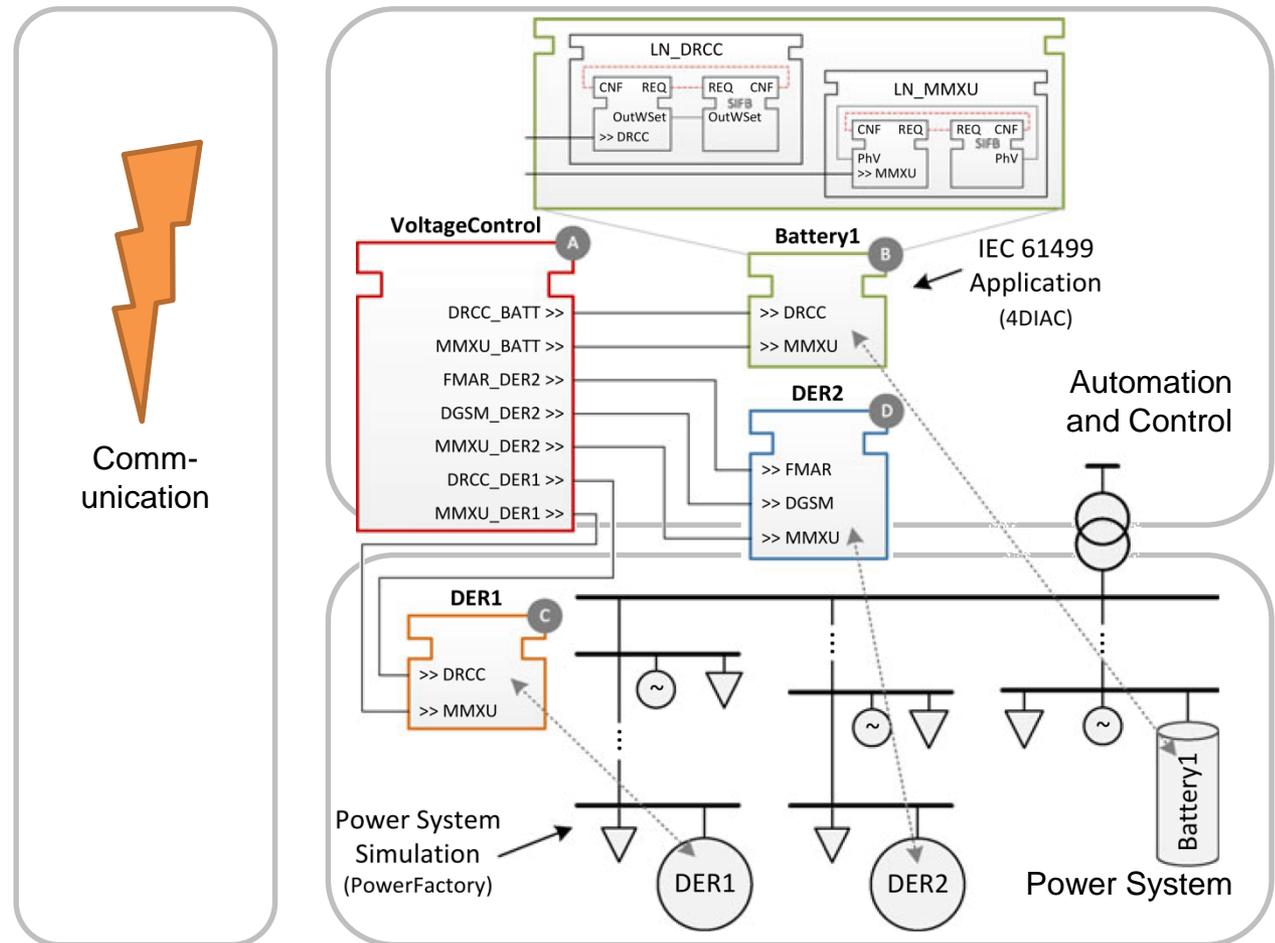
Title	Definition
Ref. Test Spec.	
Research Infrastructure	<i>Specify the RI where the experiment is carried out</i>
Experiment realisation	<i>The setup can be realised in different ways (e.g. simulation, hardware,...) Give a brief description of the realisation</i>
Experiment Setup (concrete lab equipment)	<i>graphical and textual description of the concrete lab equipment</i>
Experimental Design and	<i>For all parameters give a reason why it has been</i>

Experiment Specification
Experiment Design, Experiment setup

Precision of equipment	<i>For the components of the lab equipment the precision is given such that the experiment's uncertainty can be derived.</i>
Uncertainty measurement	<i>Based on the precision of equipment of the lab instrument and of measurement algorithms, the parameters to model the measured quantities' errors are provided, it is specified how experiment's uncertainty can actually be measured.</i>

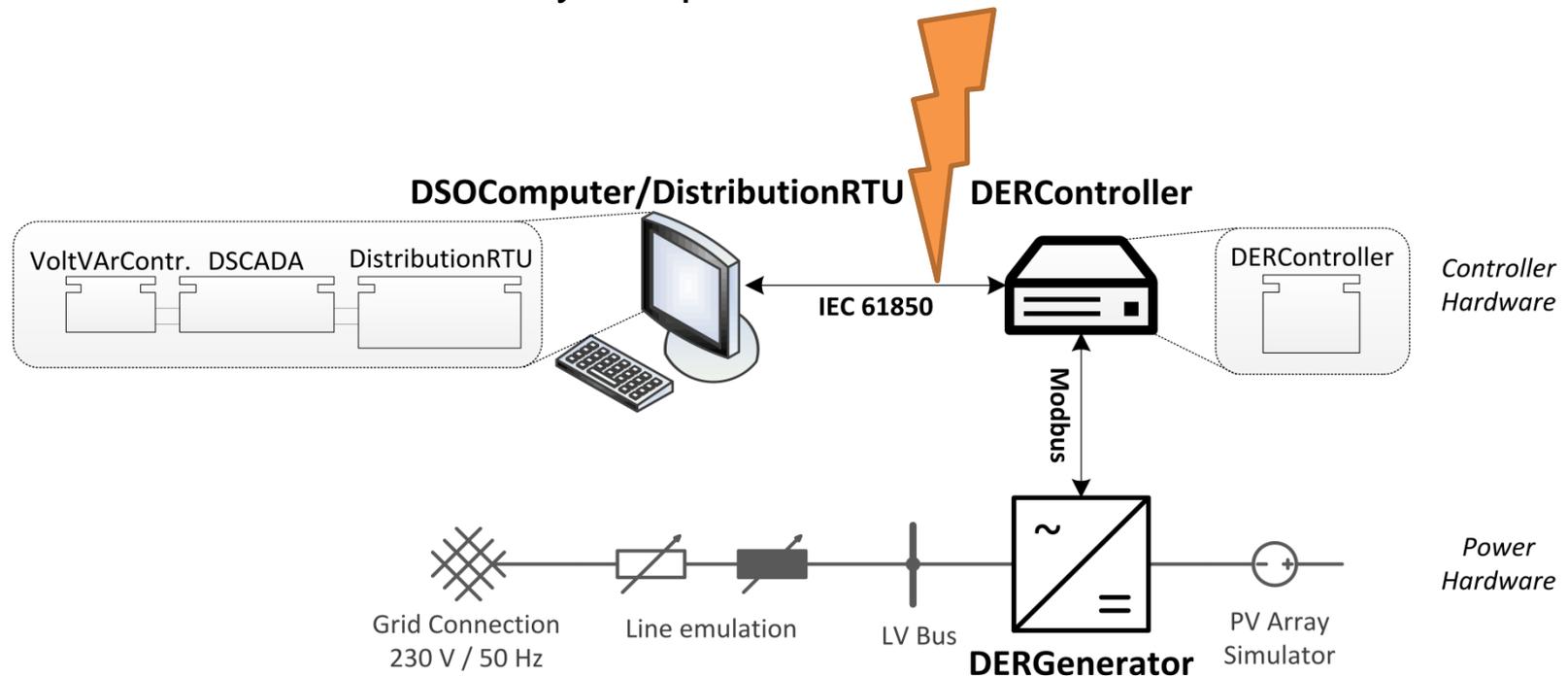
Cyber-Physical Attacks Investigation

- Simulation-based analysis
 - Coupling of different domains (power, ICT, control & automation)



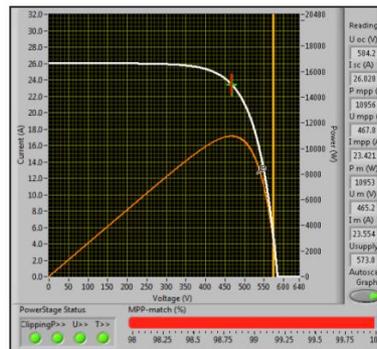
Cyber-Physical Attacks Investigation

- Lab-based analysis
 - AIT SmartEST laboratory setup

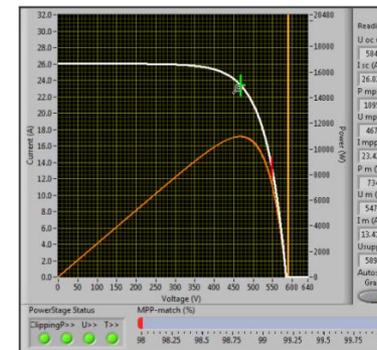


Cyber-Physical Attacks Investigation

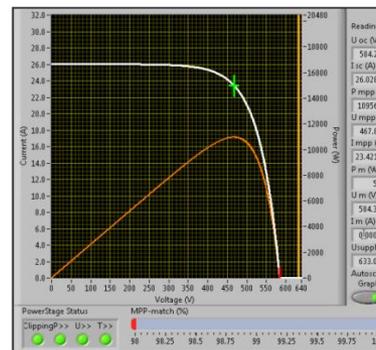
- Lab-based analysis
 - Attack (manipulation) of inverter set-points (active power)



(a) 100% of power limitation by the operator



(b) 60% of power limitation by the operator



(c) 10% of power limitation by the attacker

Discussion, Feedback and Conclusions

SMC 2018 Tutorial

Concepts, Methods, and Tools for
Validating Cyber-Physical Energy Systems



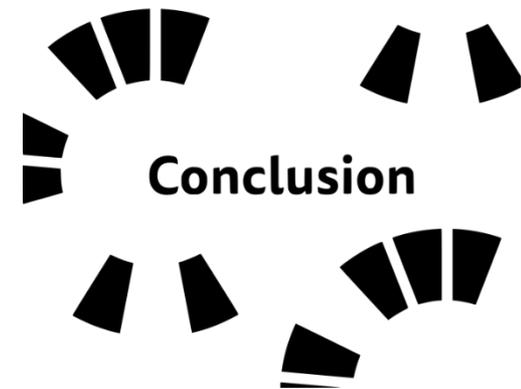
Discussion and Feedback

- Questions?
- Open issues?
- etc.



Conclusions

- A large-scale roll out of smart grid solutions, technologies, and products can be expected in the near future
- New technologies, suitable concepts, methods and approaches are necessary to support system analysis, evaluation and testing issues of integrated approaches
- Advanced research infrastructures are still necessary
- Flexible integration of simulation-based methods, hardware-in-the-loop approaches, and lab-based testing looks promising for overcoming shortcomings



Future Activities and Research

- Improvement and integration of design and validation tools from different domains (power system + ICT + markets + consumer behaviour)
- Development of system level validation procedures and benchmark criteria
- Improvement of research infrastructures supporting system level validation
- Education, training and standardization is also a key factor

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2nd call: 15 March - 15 June, 2017

3rd call: 15 August - 15 November, 2017

4th call: 15 February - 15 May, 2018

5th call: 15 August - 15 November, 2018

6th call: 15 February - 15 May, 2019



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