RECENT RESEARCH TRENDS IN ENGINEERING AND VALIDATING CYBER-PHYSICAL ENERGY SYSTEMS

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OUTLINE

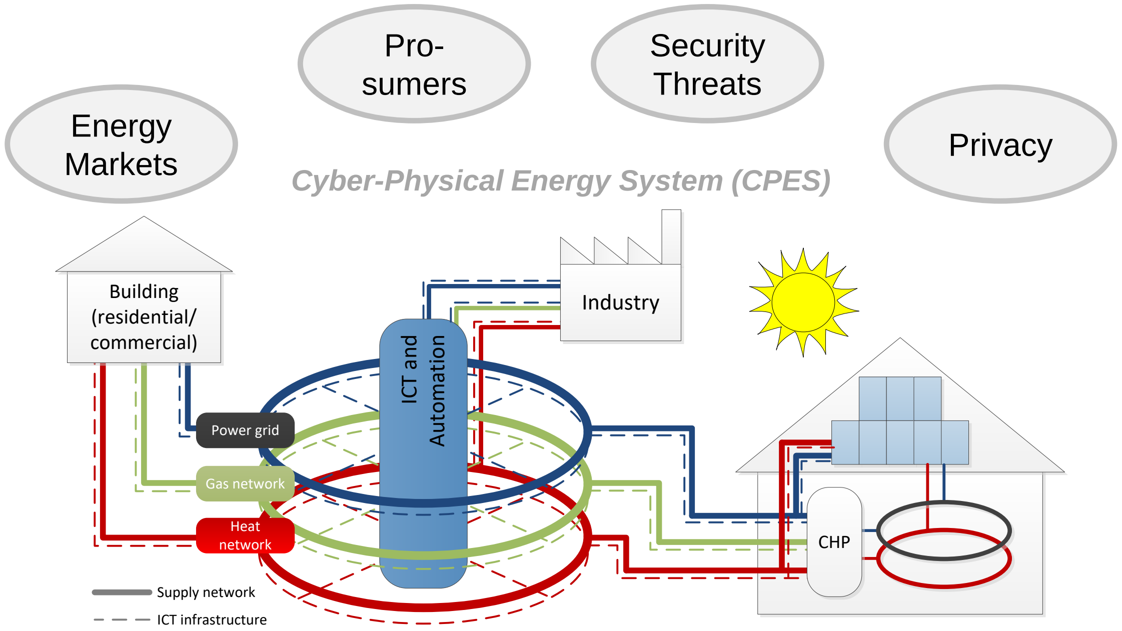
- Higher complexity in cyber-physical energy systems
- Engineering problems and needs
- Status quo in research and development
- Validating controllers for cyber-physical energy systems
- Example Demo
- Conclusions and outlook
- References

HIGHER COMPLEXITY IN CYBER-PHYSICAL ENERGY SYSTEMS

Webinar “Recent Research Trends in Engineering and Validating Cyber-Physical Energy Systems”

HIGHER COMPLEXITY IN CYBER-PHYSICAL ENERGY SYSTEMS

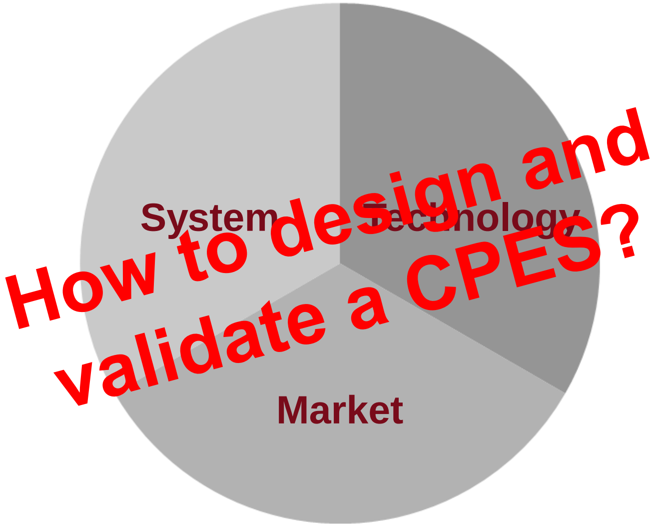
- Planning and operation of the energy infrastructure becomes more complex
  - Large-scale integration of renewable sources (PV, wind, etc.)
  - Controllable loads (batteries, electric vehicles, heat pumps, etc.)
- Trends and future directions
  - Digitalisation of power grids
  - Deeper involvement of consumers and market interaction
  - Linking electricity, gas, and heat grids for higher flexibility and resilience



Source: AIT

HIGHER COMPLEXITY IN CYBER-PHYSICAL ENERGY SYSTEMS

- 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
- Engineering and validation of power and energy systems characterized by
  - Lots of manual engineering steps
  - Partly missing integrated view on sub-domain’s (power, ICT, etc.)
  - Usage of less formalized approaches and tools (compared to other areas)



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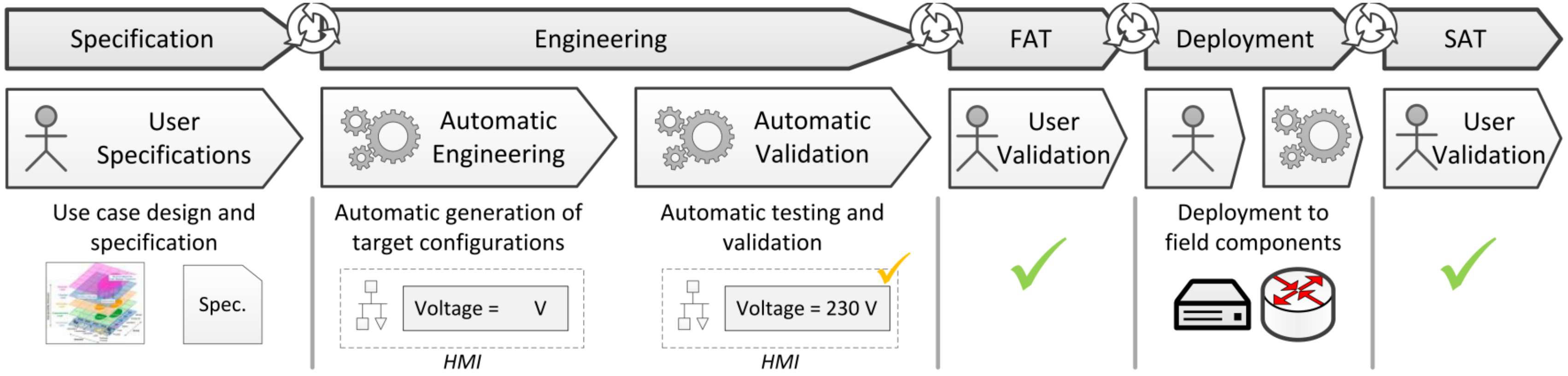
ENGINEERING PROBLEMS AND NEEDS

Webinar “Recent Research Trends in Engineering and Validating Cyber-Physical Energy Systems”

ENGINEERING PROBLEMS AND NEEDS

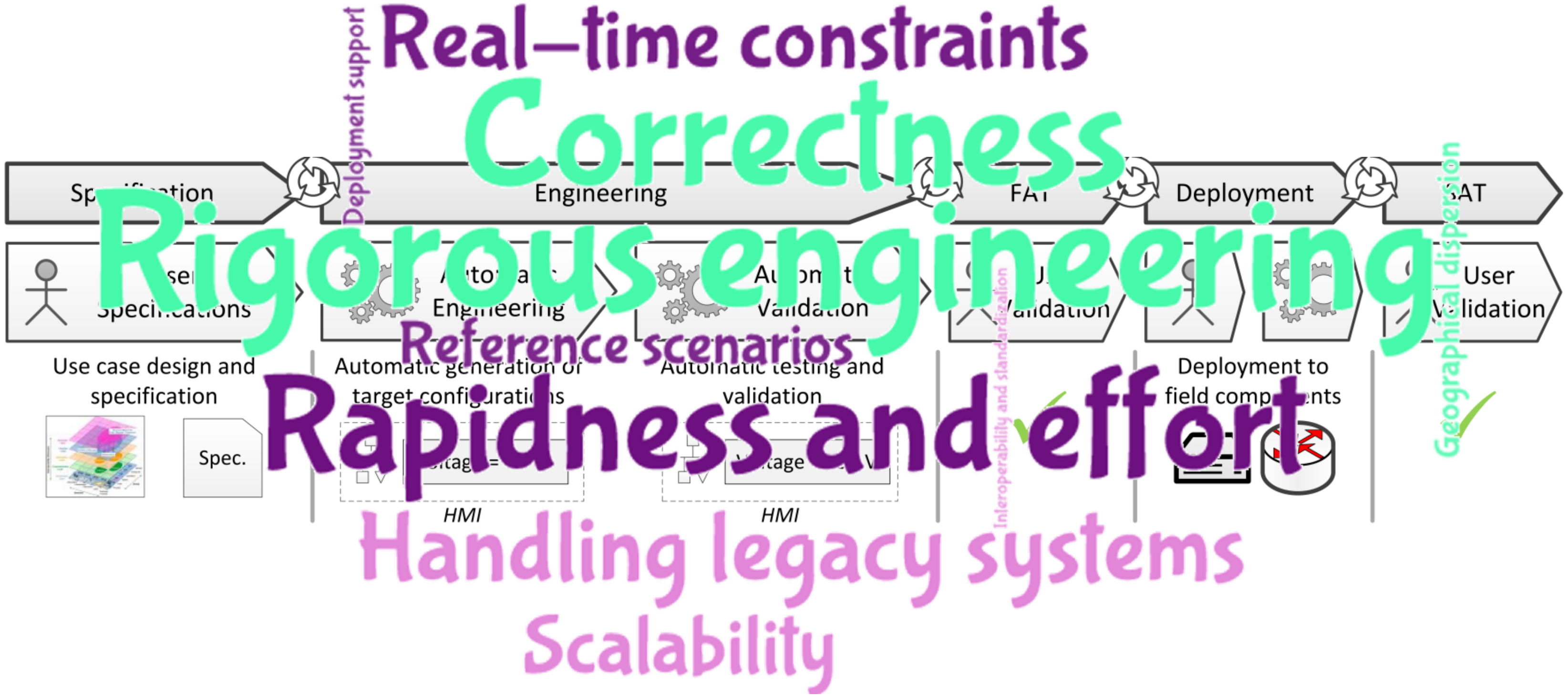
- Background and motivation
  - Reduction of manual steps necessary to handle complex CPES configs
  - Reduction of potential error sources due to manual steps and improvement of application/software quality required
  - Faster application development needed due to market behaviour and trends
- Providing support from design to implementation and installation



Source: AIT

FAT: Factory Acceptance Test
SAT: System Acceptance Test

ENGINEERING PROBLEMS AND NEEDS



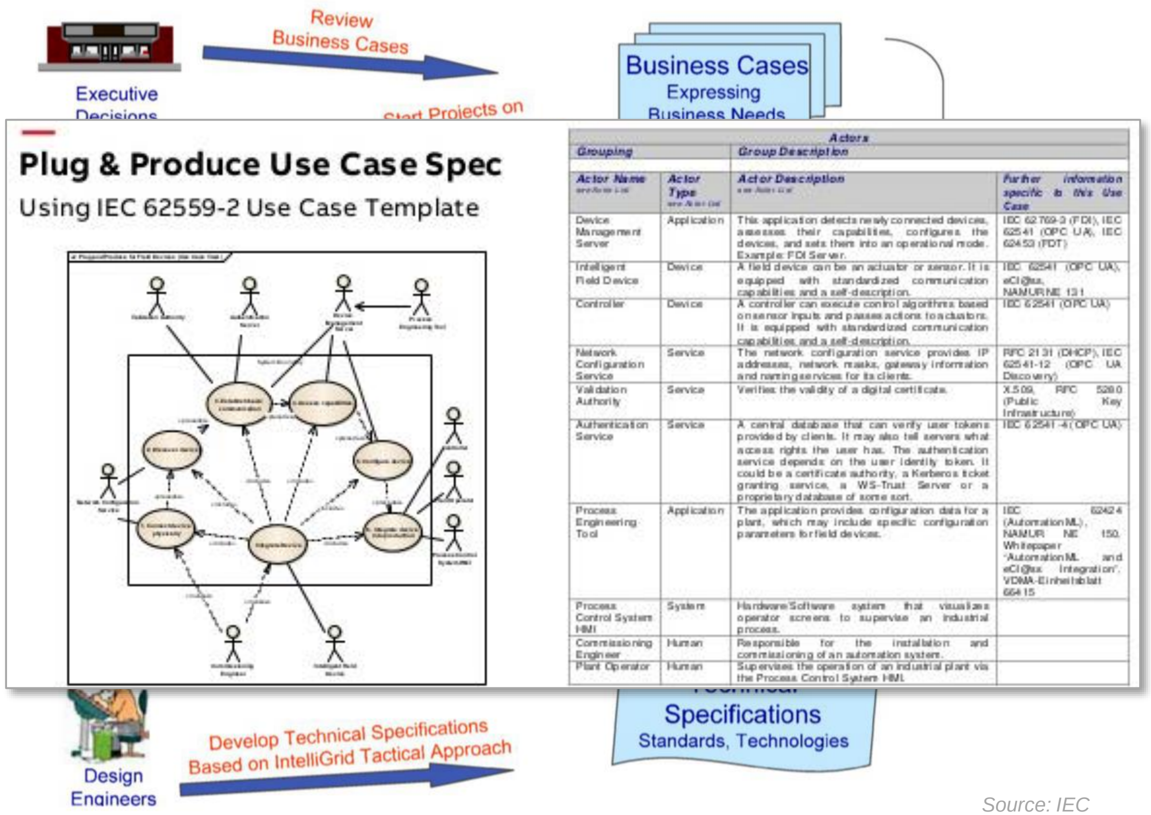
STATUS QUO IN RESEARCH AND DEVELOPMENT

Webinar “Recent Research Trends in Engineering and Validating Cyber-Physical Energy Systems”

STATUS QUO IN RESEARCH AND DEVELOPMENT

Specification

- IntelliGrid (IEC 62559) use case engineering approach
  - Structured process for specifying smart grid related applications
  - Identification of requirements and needs
  - Provision of use case templates

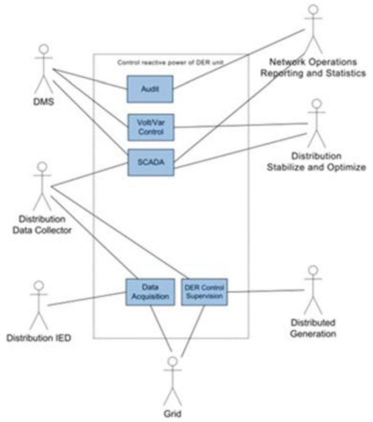


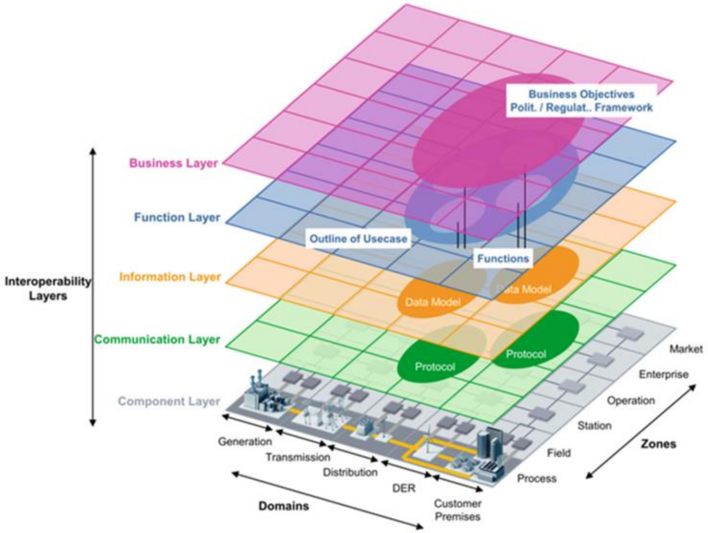
Source: IEC

STATUS QUO IN RESEARCH AND DEVELOPMENT

Specification

- Smart Grid Architecture Model (SGAM)
  - Supports the specification of smart grid applications
  - Provides a structured process linking use cases into system architectures





Use Case Description → Business Layer Analysis → Function Layer Analysis → Component Layer Analysis → Information Layer Analysis → Communication Layer Analysis

Source: IEC

STATUS QUO IN RESEARCH AND DEVELOPMENT

Engineering

- Power System Automation Language (PSAL) model-based engineering for smart grids
  - Model-Driven Engineering (MDE) of smart grid applications will reduce the amount of manual work needed to describe information in multiple models
  - Integrated MDE approach covering the whole engineering process to handle the multi-domain aspect of smart grids

Holistic approach

An approach that combines design, implementation, validation, and deployment is missing

Model-based

Model-based engineering concepts for smart grids are missing or only partly available

Multidisciplinarity

The multi-domain character of smart grids is not covered by existing approaches

→ *Domain-specific approach Power System Automation Language (PSAL)*

STATUS QUO IN RESEARCH AND DEVELOPMENT

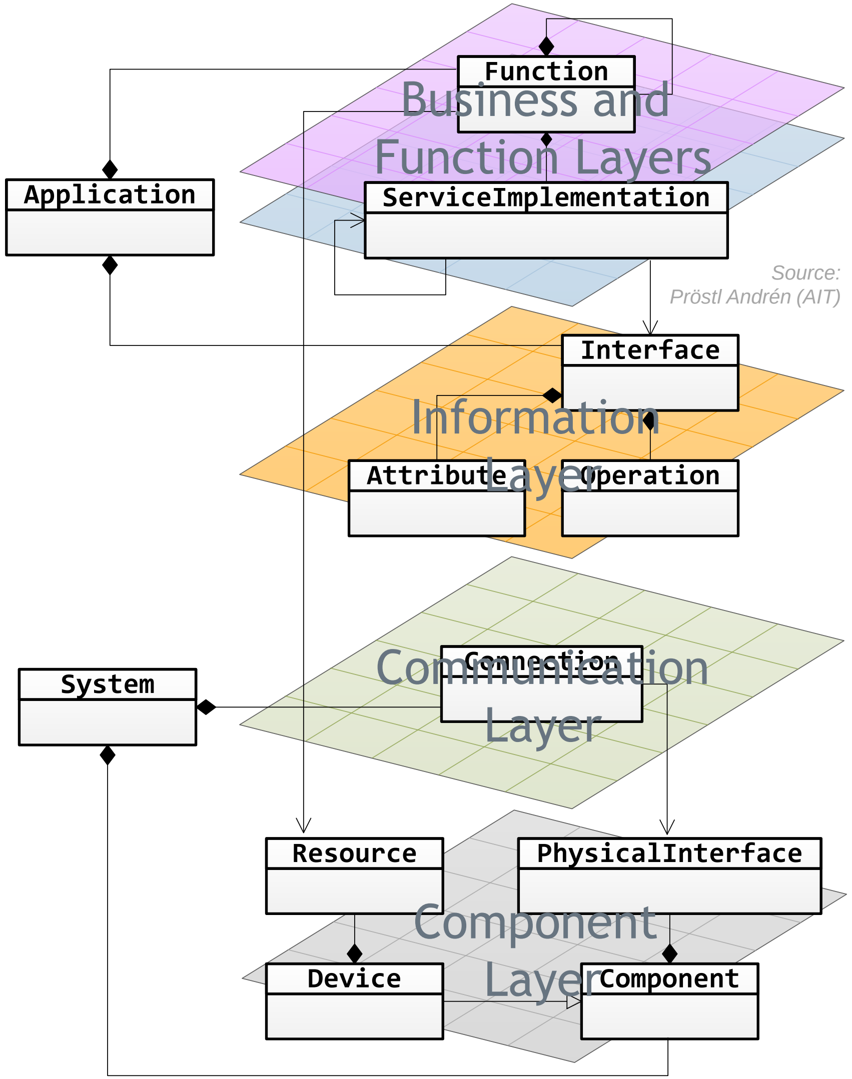
Engineering

- PSAL model-based engineering for smart grids
  - Based on SGAM

```
application VoltageControl {
  function VoltVArCtrl at DSOComputer.VoltVAr {
    requests Field.Controls fieldControls
  }
  module Field {
    interface Controls {
      attribute float32 activePowerSetpoint
}}}
```

```
system DistributionSystem {
  device DSOComputer {
    ethernet eth0 {ip = "10.0.0.1"}
    resource VoltVAr
  }
  router StationRouter
  generator DER

  connect DSOComputer.eth0 with StationRouter
}
```



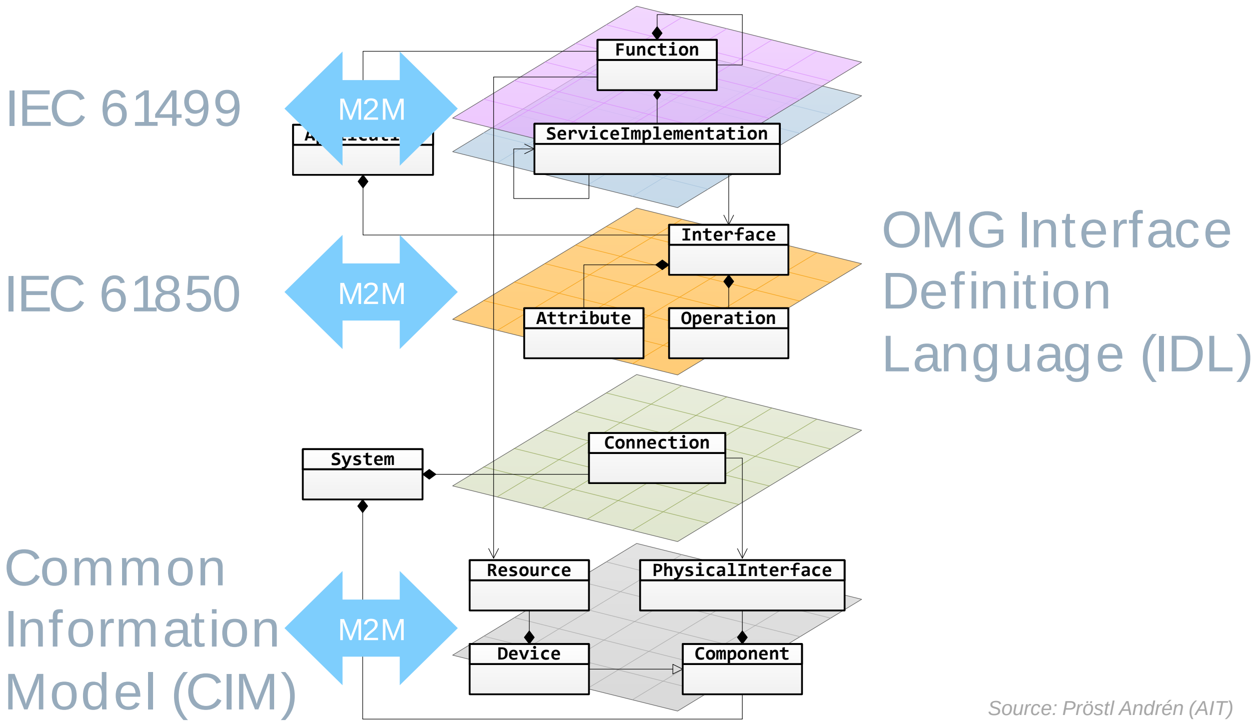
Source: Pröstl Andrén (AIT)

Engineering

STATUS QUO IN RESEARCH AND DEVELOPMENT

- PSAL model-based engineering for smart grids
  - Basis for PSAL

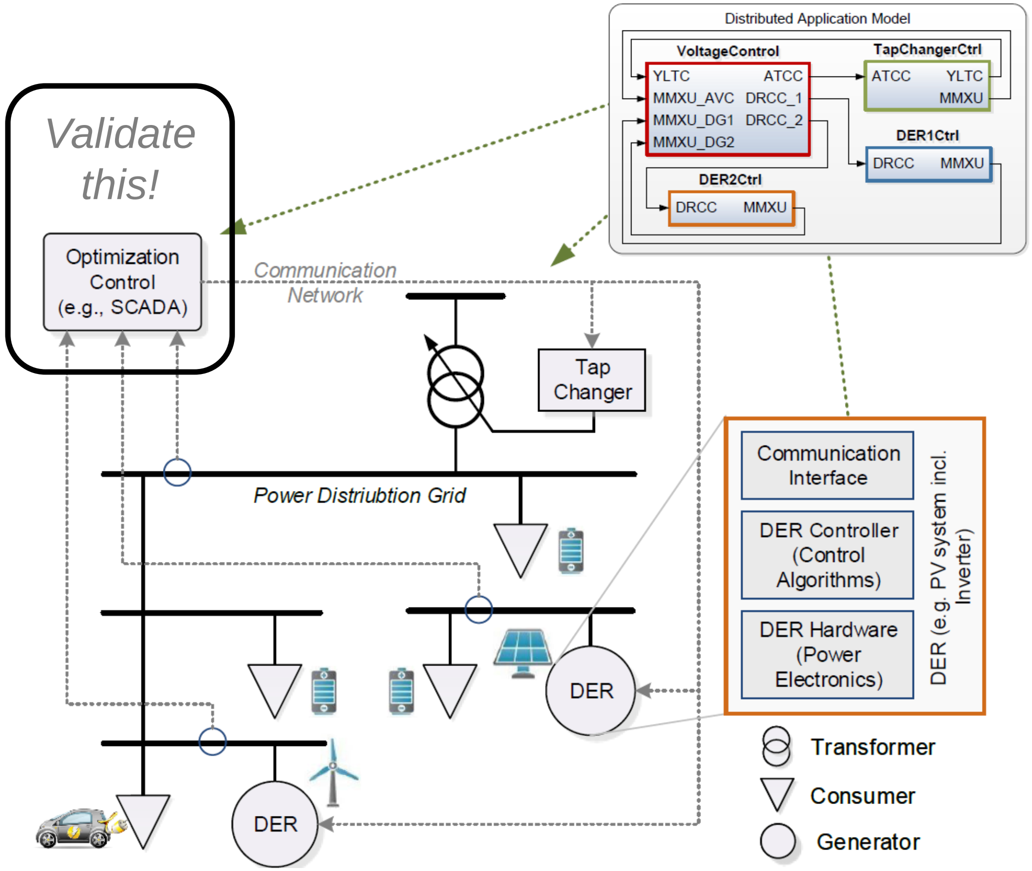
SGAM for the approach



Source: Pröstl Andrén (AIT)

STATUS QUO IN RESEARCH AND DEVELOPMENT

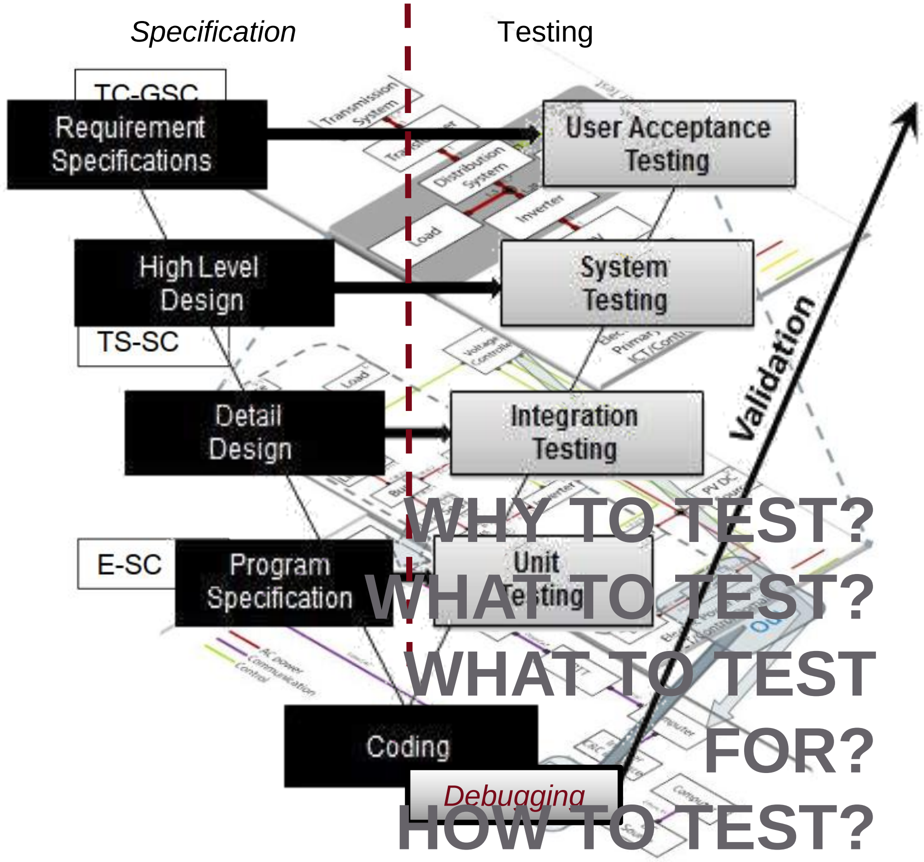
- ERIGrid holistic testing approach for smart grid systems
  - Testing of CPES components and concepts
  - Many domain involved (holism)
  - Setups and workflows differ across Research Infrastructures (RI)
    - Experiments are often hardly reproducible
    - Often limited by RI capabilities



Source: ERIGrid

STATUS QUO IN RESEARCH AND DEVELOPMENT

- ERIGrid holistic testing approach for smart grid systems
  - Formalize testing process
    - Testing → documented and reproducible
    - Basis for knowledge exchange
  - Formal process covering all stages of test planning
    - Overview of resources
    - Consider state-of-the-art
    - Operationalize, refine

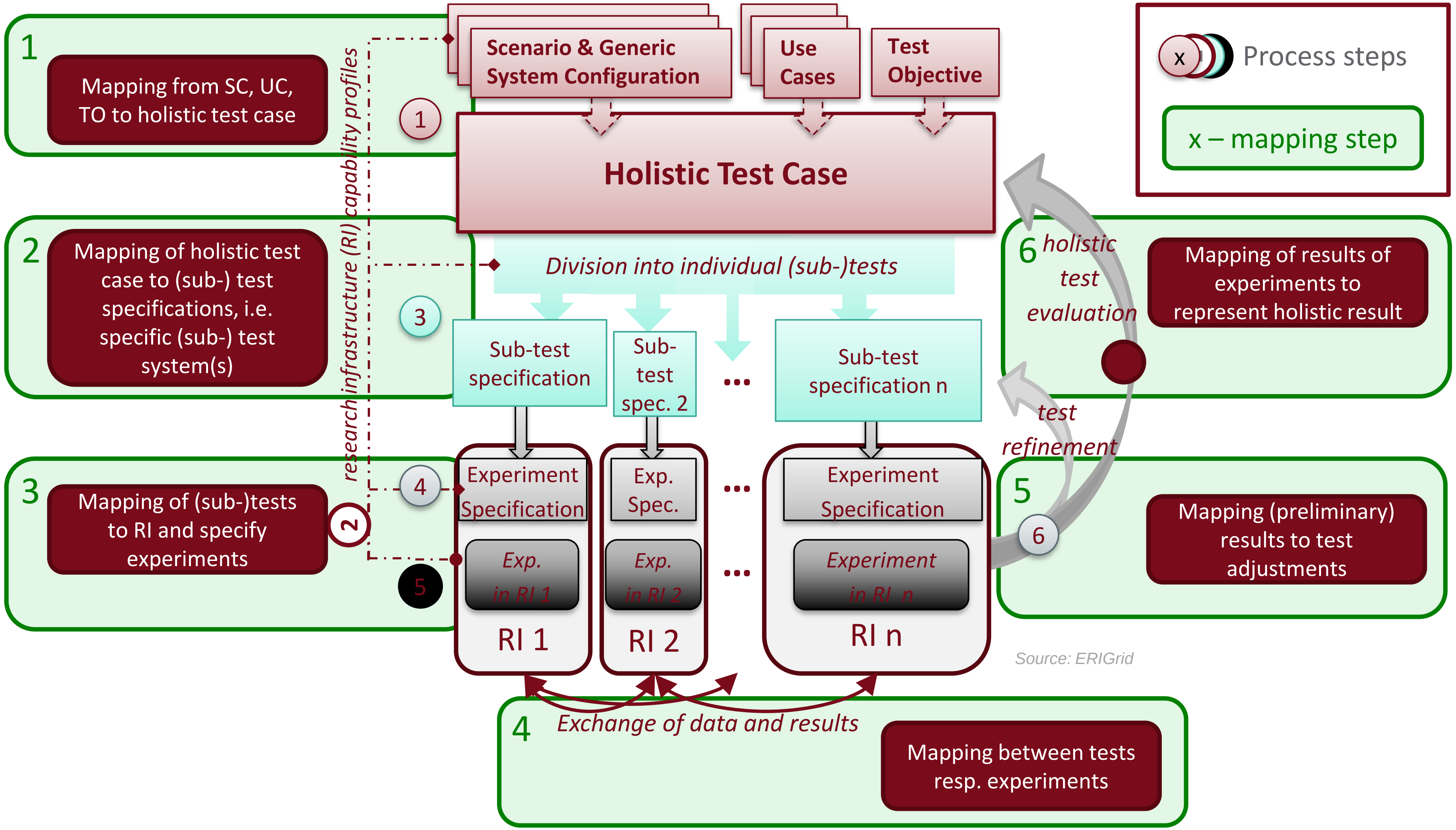


Source: ERIGrid

STATUS QUO IN RESEARCH AND DEVELOPMENT

Validation & Testing

- ERIGrid holistic testing approach for smart grid systems

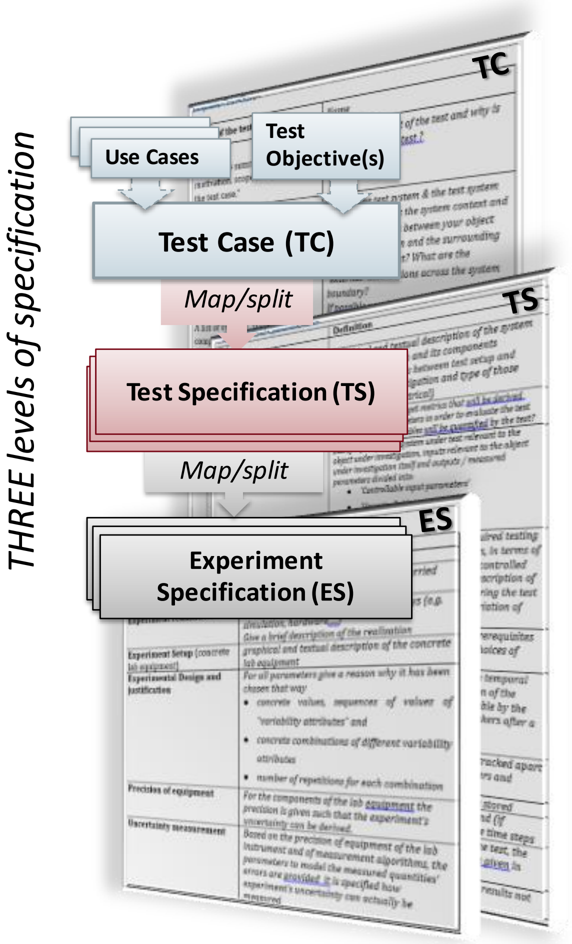


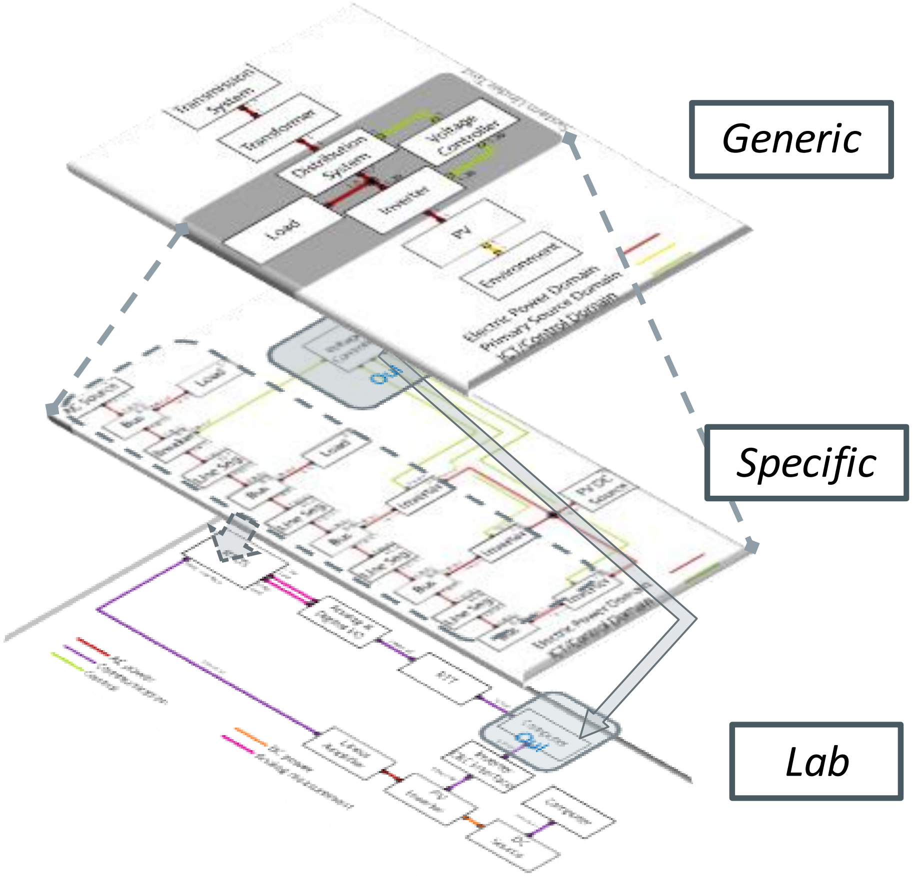
Source: ERIGrid

STATUS QUO IN RESEARCH AND DEVELOPMENT

Validation & Testing

- ERIGrid holistic testing approach for smart grid systems





Source: ERIGrid

VALIDATING CONTROLLERS FOR CYBER-PHYSICAL ENERGY SYSTEMS

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VALIDATING CONTROLLERS FOR CYBER-PHYSICAL ENERGY SYSTEMS

Increased complexity and dynamics in the electrical energy system

- Massive deployment of volatile Distributed Energy Resources
- Paradigm change in terms of planning and operation of the distribution system

Increased engineering and validation costs

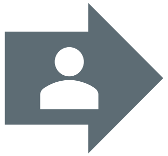
- Traditional engineering and validation methods were not intended to be used for applications of this scale and complexity

Possible countermeasures

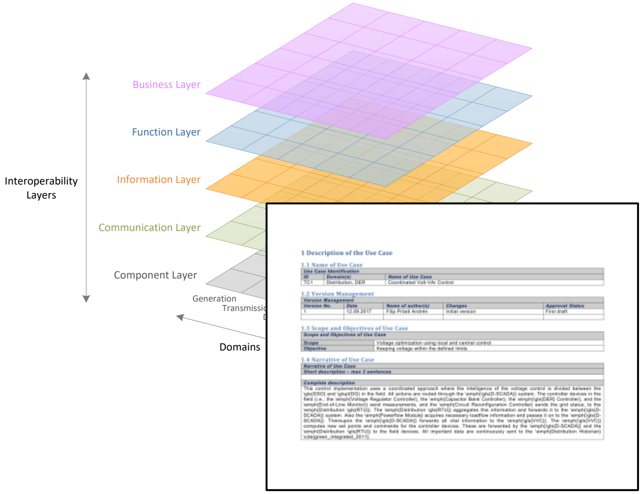
- Automation and control systems
- Automated engineering and validation
  - Exhaustive testing is manually time consuming and error prone
  - Formalized use case and requirements engineering
  - Automated setup of cyber-physical test-beds
  - Speed up iterations between testing and development

VALIDATING CONTROLLERS FOR CYBER-PHYSICAL ENERGY SYSTEMS

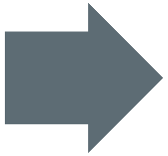
- Use case design and requirements



Smart Grid Architecture Model (SGAM)



Use Case Method (IEC 62559)



Power System Automation Language (PSAL)

```
application VoltageControl {
  function VoltVArCtrl at DSOComputer.VoltVAr {
    requests Field.Controls fieldControls
  }
  module Field {
    interface Controls {
      attribute float32 activePowerSetpoint
}}}
```

```
system DistributionSystem {
  device DSOComputer {
    ethernet eth0 {ip = "10.0.0.1"}
    resource VoltVAr
  }
  router StationRouter
  generator DER

  connect DSOComputer.eth0 with StationRouter
}
```

Specification → Engineering → Validation → Deployment → Operation

VALIDATING CONTROLLERS FOR CYBER-PHYSICAL ENERGY SYSTEMS

- Implementation according to design

```
application VoltageControl {
  function VoltVArCtrl at DSOComputer.VoltVAr {
    requests Field.Controls fieldControls
  }
  module Field {
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}}}
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```
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  device DSOComputer {
    ethernet eth0 {ip = "10.0.0.1"}
    resource VoltVAr
  }
  router StationRouter
  generator DER

  connect DSOComputer.eth0 with StationRouter
}
```

```
y = f(x) { ... }
```

```
eth0 mac 00:0c:…
     ip4 192.168…
     ip6 fe80::…
```

Code and configurations

Specification | Engineering | Validation | Deployment | Operation

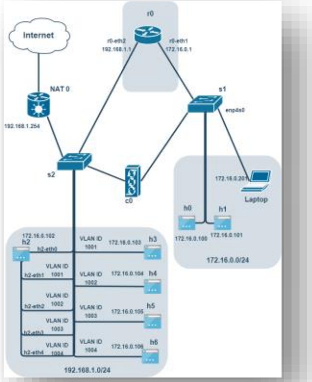
VALIDATING CONTROLLERS FOR CYBER-PHYSICAL ENERGY SYSTEMS

- Testing and validation of requirements

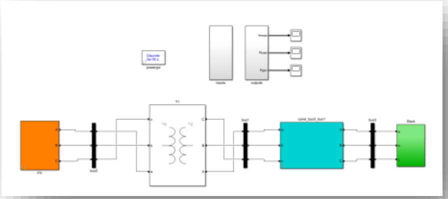
```
application VoltageControl {
  function VoltVArCtrl at DSOComputer.VoltVAr {
    requests Field.Controls fieldControls
  }
  module Field {
    interface Controls {
      attribute float32 activePowerSetpoint
}}}
```

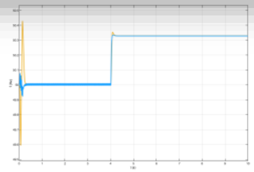
```
system DistributionSystem {
  device DSOComputer {
    ethernet eth0 {ip = "10.0.0.1"}
    resource VoltVAr
  }
  router StationRouter
  generator DER

  connect DSOComputer.eth0 with StationRouter
}
```



Communication Emulation





Power System Simulation

Simulations/Emulations

Specification → Engineering → Validation → Deployment → Operation

VALIDATING CONTROLLERS FOR CYBER-PHYSICAL ENERGY SYSTEMS

- Deployment to specific platforms

```
application VoltageControl {
  function VoltVArCtrl at DSOComputer.VoltVAr {
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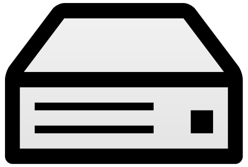
  }
  module Field {
    interface Controls {
      attribute float32 activePowerSetpoint
}}}
```

```
system DistributionSystem {
  device DSOComputer {
    ethernet eth0 {ip = "10.0.0.1"}
    resource VoltVAr
  }
  router StationRouter
  generator DER

  connect DSOComputer.eth0 with StationRouter
}
```

```
- #include <winsock.h>
+ #include <socket.h>
```

Platform specific code



Field device
(DER Controller)

Specification → Engineering → Validation → Deployment → Operation

VALIDATING CONTROLLERS FOR CYBER-PHYSICAL ENERGY SYSTEMS

- Common approach to validation of CPES controllers

Standard software tests

- Unit tests
- Code-completion tests

→

Controller-in-the-Loop tests

- Software-in-the-Loop
- Hardware-in-the-Loop
- Factory Acceptance Test (FAT)

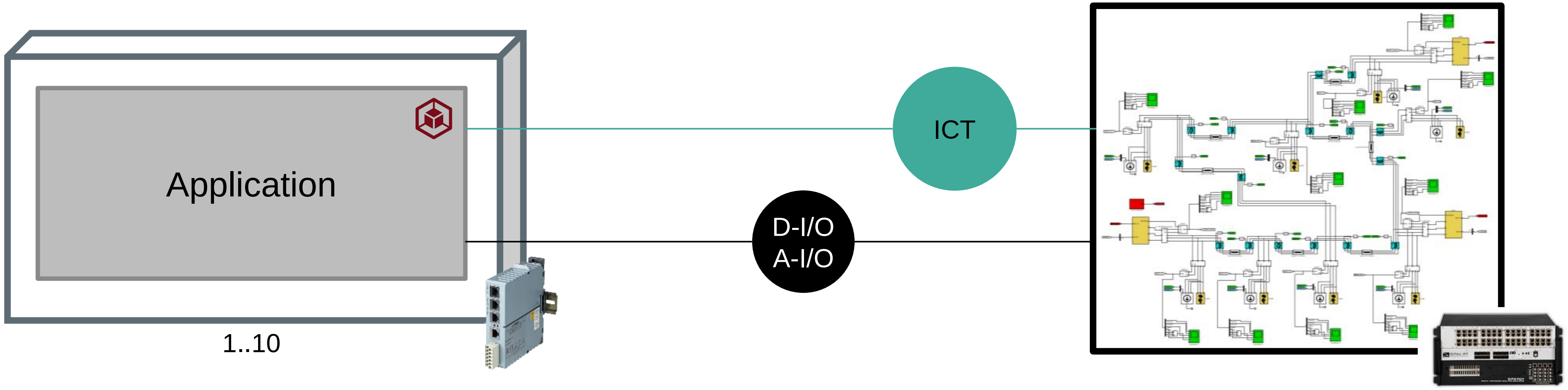
→

Tests on-site with real system

- Site Acceptance Test (SAT)

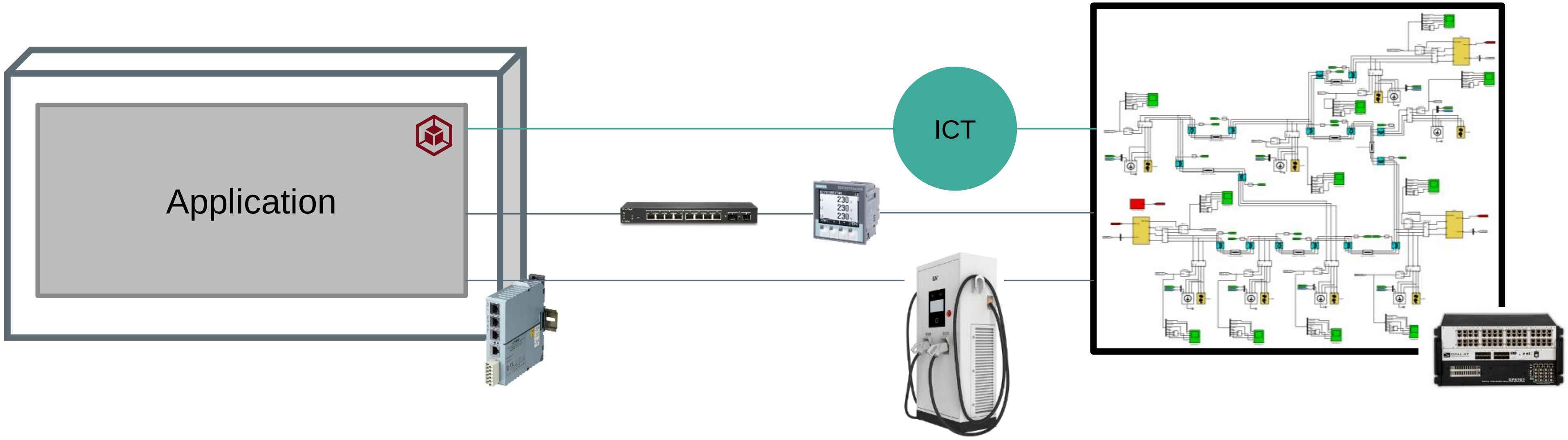
VALIDATING CONTROLLERS FOR CYBER-PHYSICAL ENERGY SYSTEMS

- Controller Hardware-In-the-Loop (C-HIL)
  - C-HIL tests with dedicated controller hardware
    - Deploy software on dedicated industrial hardware
  - Purpose
    - Validation on selected electrical networks



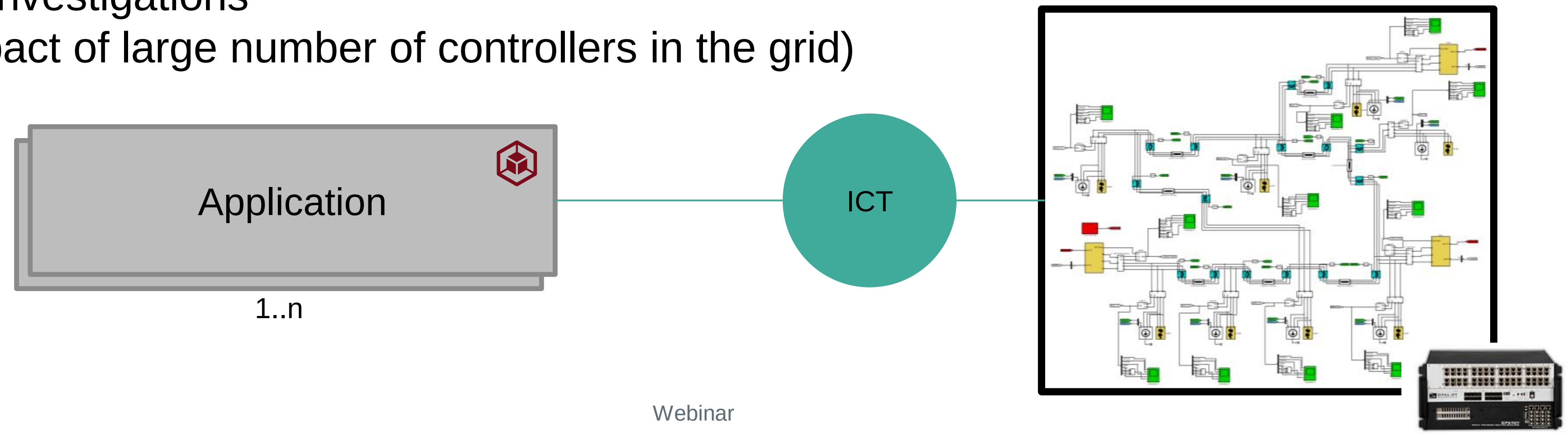
VALIDATING CONTROLLERS FOR CYBER-PHYSICAL ENERGY SYSTEMS

- Controller and Power Hardware-in-the-Loop (PHIL)
  - C-HIL and P-HIL interaction tests
    - Deploy software on industrial hardware
  - Purpose
    - Validation + interaction between controller and key components (charging stations, metering, etc.)



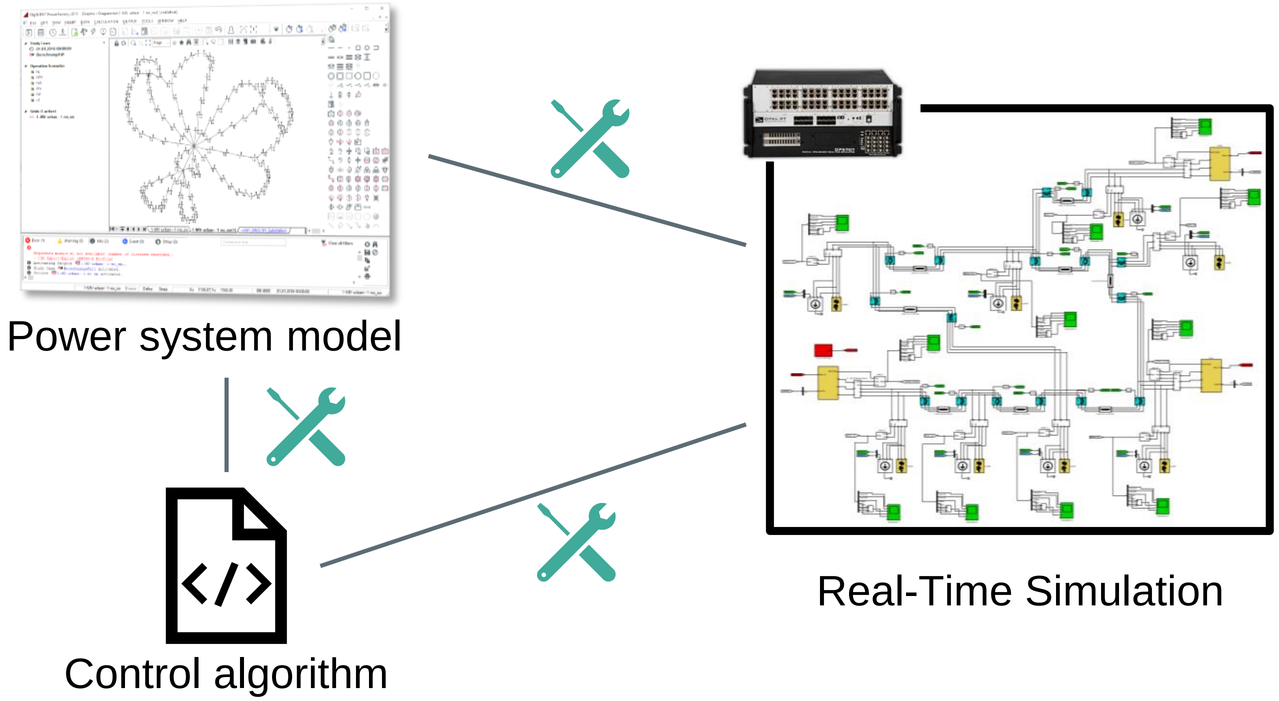
VALIDATING CONTROLLERS FOR CYBER-PHYSICAL ENERGY SYSTEMS

- Software-in-the-Loop (SIL)
  - Software tests without dedicated hardware
    - Software is connected to the real-time simulation using a communication protocol
  - Purpose
    - Development and optimization of control applications
    - Automated validation using multiple grids from grid operators
    - Stability investigations
      (e.g., impact of large number of controllers in the grid)



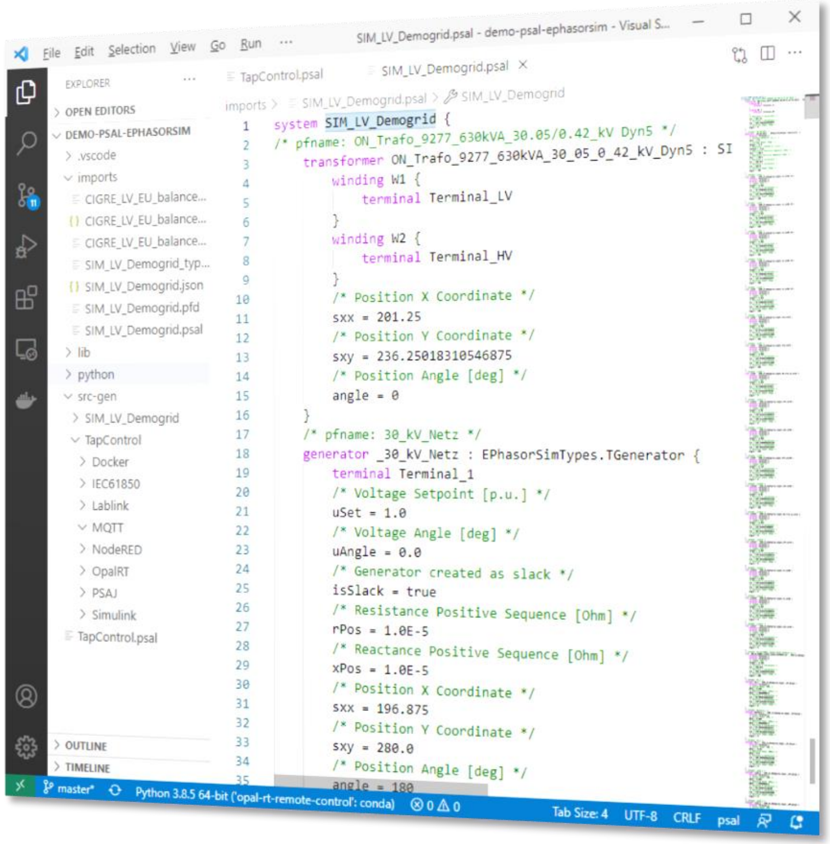
VALIDATING CONTROLLERS FOR CYBER-PHYSICAL ENERGY SYSTEMS

- Setup of a SIL experiment



VALIDATING CONTROLLERS FOR CYBER-PHYSICAL ENERGY SYSTEMS

- Automated SIL setup using PSAL



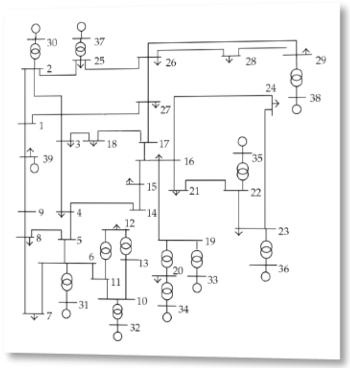
PSAL-IDE

- Formalized, domain-specific language
- SGAM compatible use case design
- Specifically targeted at rapid generation of code and configurations
  - Communication configurations
  - Simulation models
  - Deployment configurations

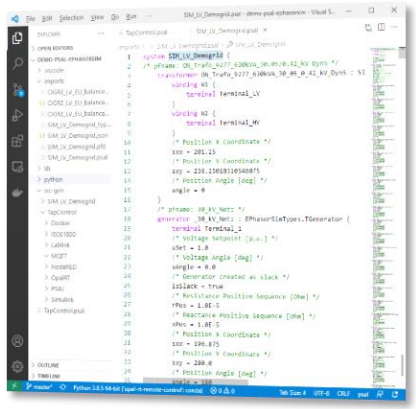
VALIDATING CONTROLLERS FOR CYBER-PHYSICAL ENERGY SYSTEMS

- Automated SIL setup using PSAL

Power system model

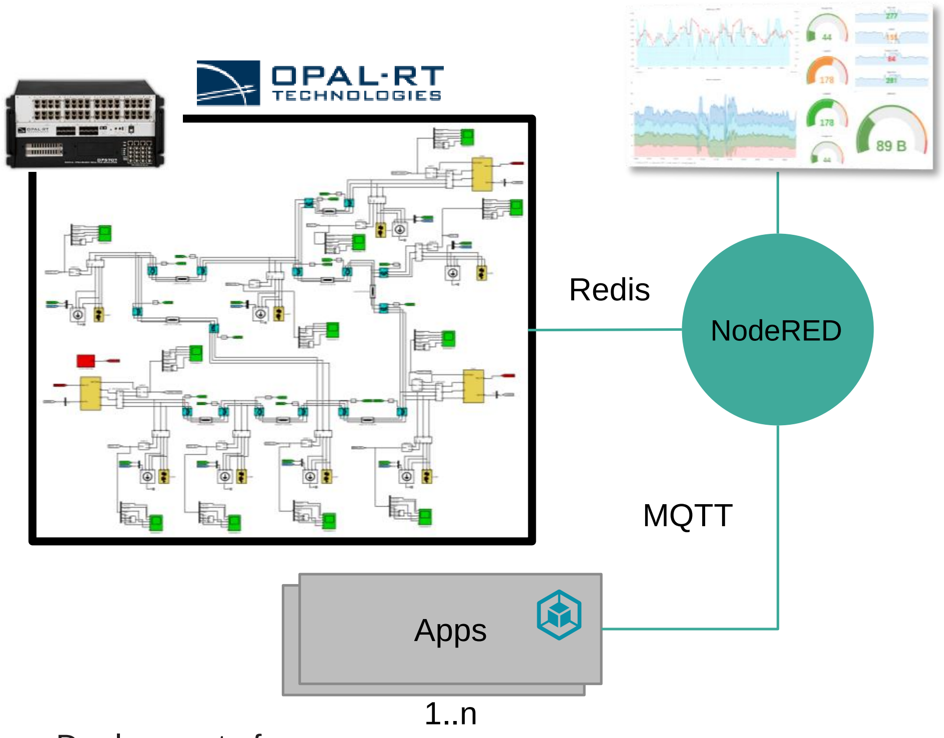


PSAL-IDE



Control algorithm

Additional specification
- Control architecture
- ICT setup



Deployment of
- Real-time simulations in ePHASORSIM
- NodeRED for
  - Data layer
  - Visualizations

EXAMPLE DEMO

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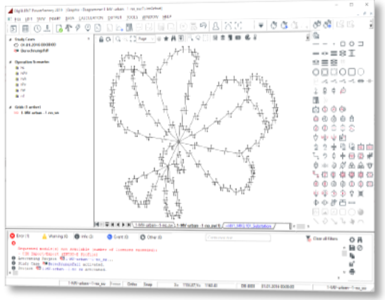
EXAMPLE DEMO

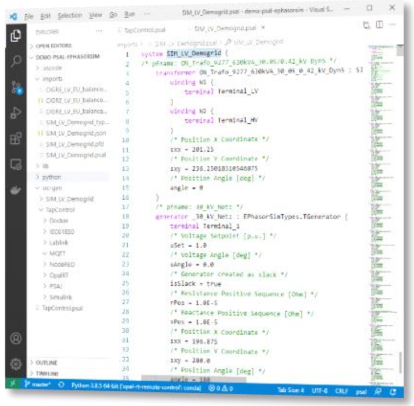
- Rapid validation of a tap controller developed in Python

PowerFactory model
LV network

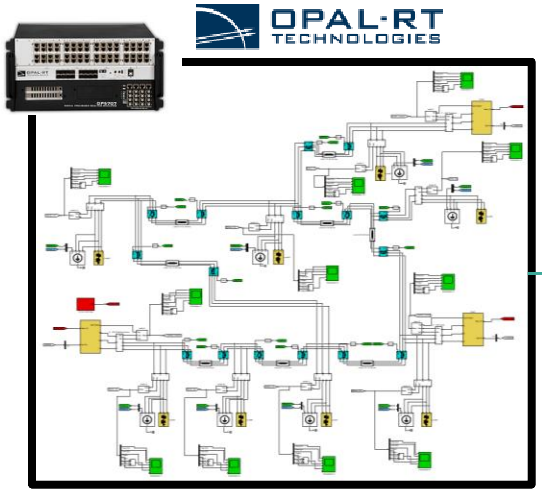


1.

PSAL-IDE



3.

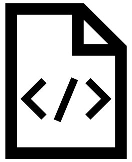


Redis

NodeRED

MQTT

tap_ctrl.py



tap_ctrl.py
Voltage control using
tap changer

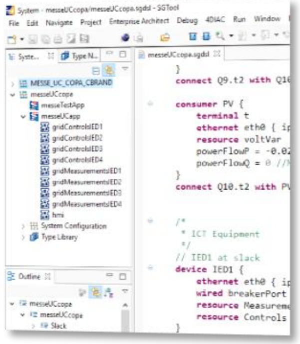
2.

Specify control application
- Connect control algorithm with simulation

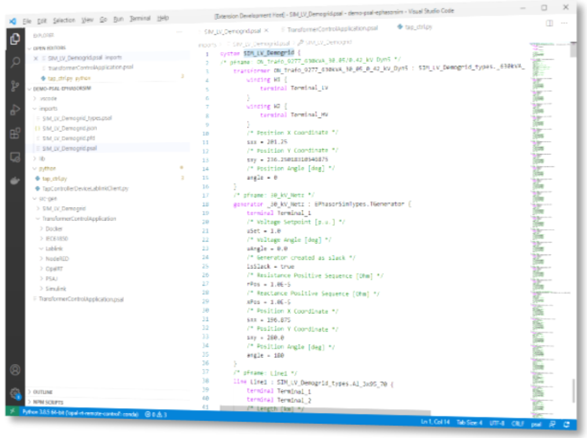
Deployment of
- Real-time simulations in ePHASORSIM
- NodeRED for
  - Data layer
  - Visualizations

PSAL-IDE

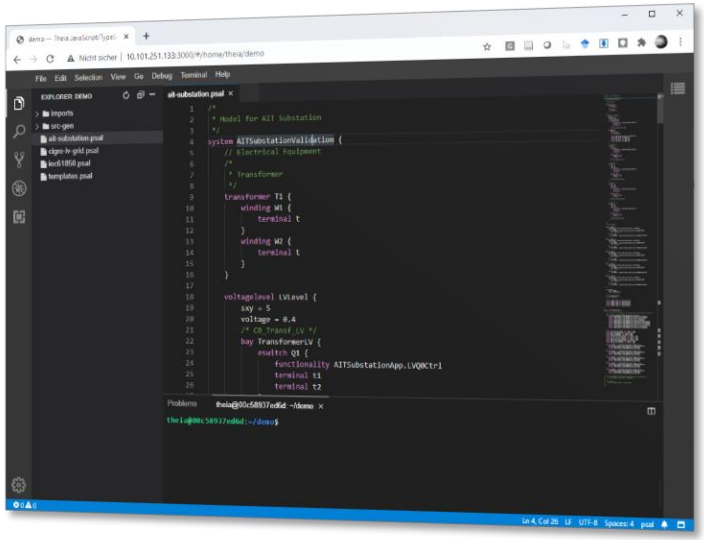
PSAL-IDE
Eclipse



PSAL-IDE
Visual Studio Code



PSAL-IDE
Theia Browser



Available soon through
ERIGrid 2.0 Virtual Access
https://erigrid2.eu/lab-access/

CONCLUSIONS AND OUTLOOK

Webinar “Recent Research Trends in Engineering and Validating Cyber-Physical Energy Systems”

CONCLUSIONS AND OUTLOOK

- Formalized processes and approaches for CPES development necessary
- Integrated analysis of power and ICT needed
- Methods for system-level testing required
- Integrated analysis of power and ICT needed
- Several solutions available but several points still partly solved
  - Harmonization of existing approaches
  - Large-scale examples and scenarios
  - Integration with traditional engineering approaches
  - Introducing new abstractions and modelling options

phase / approach	design					proof	impl.	rapid prot.
	function	inform.	comm.	comp.	inconst.	function	function	
UML	😐	✗	✗	✗	✗	✗	👎	✗
SysML	😐	👎	✗	✗	✗	✗	👎	✗
IntelliGrid	👎	✗	✗	✗	✗	✗	✗	✗
SGAM-TB	😐	✗	👎	👎	✗	✗	👎	👎
PSAL	😐	😐	✓	✓	✗	✓	✓	😐
MATLAB	😐	👎	✗	👎	✗	✓	✓	😐
IEC 61499	😐	👎	✓	✓	✗	✓	✓	✗
IEC 61131-3	😐	👎	✓	👎	✗	✓	✓	✗
EMSOnto	😐	✓	✗	✗	✓	✓	✓	✓

Source: AIT

CONCLUSIONS AND OUTLOOK

Source: ERIGrid 2.0

REFERENCES

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AUSTRIAN INSTITUTE OF TECHNOLOGY

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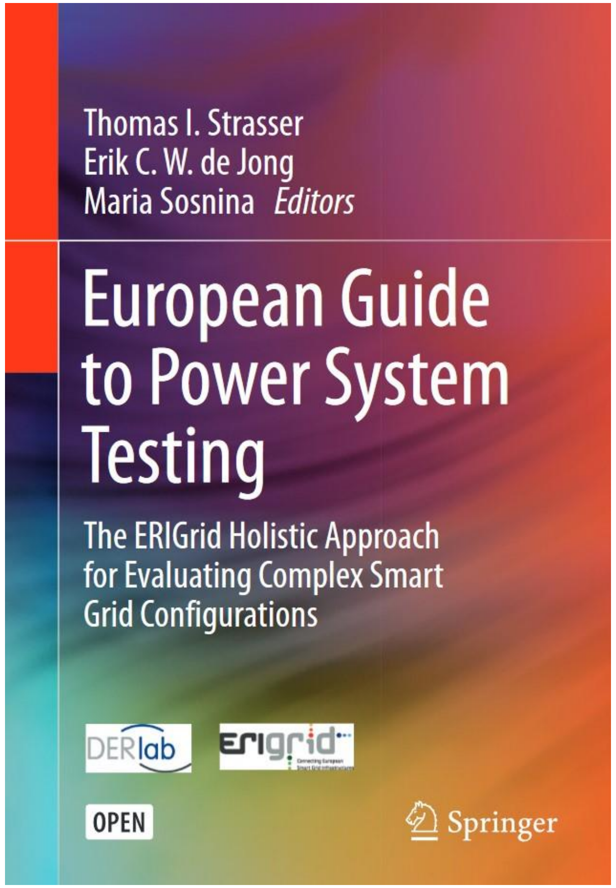

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