CONCEPTS, METHODS, AND TOOLS FOR DESIGNING AND VALIDATING CYBER-PHYSICAL ENERGY SYSTEMS

Thomas I. Strasser[1,2]

[1]Center for Energy, AIT Austrian Institute of Technology, Vienna, Austria

[2]Institute of Mechanics and Mechatronics, TU Wien, Vienna, Austria

Keynote Address 3

September 5, 2023 – Mugla, Türkiye

SEST 2023 – September 4-6, Mugla, Türkiye

6th International Conference on Smart Energy Systems and Technologies

BACKGROUND AND MOTIVATION

- Challenges and drivers

- Climate change
- Deep decarbonisation
- Energy transition

- Industrial competitiveness
- Business Innovation
- Digitalisation

- Urban Transformation
- Infrastructure needs
- Societal changes

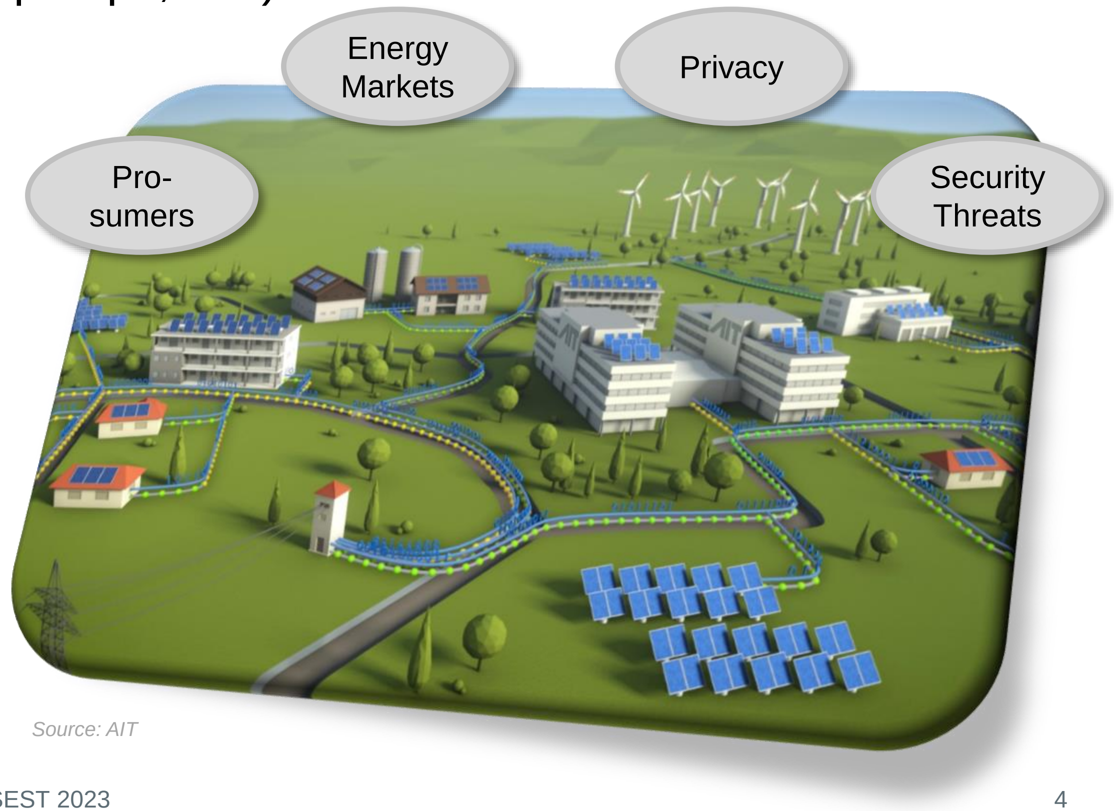
BACKGROUND AND MOTIVATION

- Global policy
  - Paris Agreement (COP21): long-term, limit temperature increase to 1.5°C
  - UN Sustainable Development Goals: pathway for future research and innovation activities
  - Mission Innovation: global initiative to accelerate clean energy innovation
- Europe policy
  - European Green Deal: climate-neutrality by 2050
  - EC Roadmap Low-Carbon Economy 2050: EU GHG emissions towards an 80% domestic reduction
  - EC Hydrogen Strategy and Sector Integration: renewable hydrogen electrolysers

HIGHER COMPLEXITY IN SMART GRID 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

→ *Smart Grid or Cyber-Physical Energy Systems*



Source: AIT

HIGHER COMPLEXITY IN SMART GRID SYSTEMS

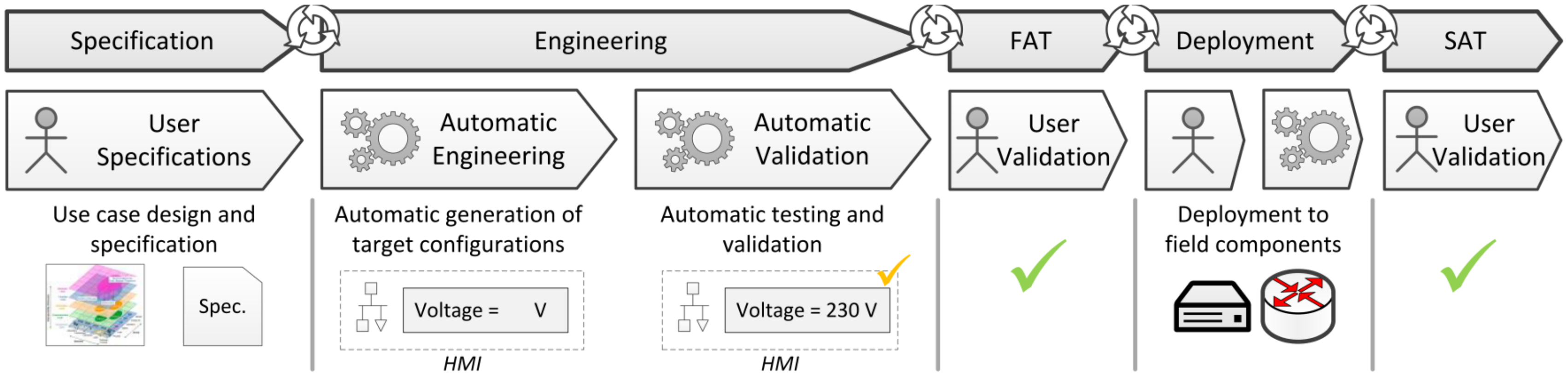
- Key elements of future integrated smart grids and energy systems are
  - Advanced communication, automation, and control systems
  - Power electronics
  - Smart algorithms
  - Monitoring and data analytics
  - Interfaces/interaction with other energy systems
- Design and validation of power and energy systems characterized by
  - Lots of manual engineering steps
  - Partly missing integrated view on sub-domains (power, ICT, etc.)
  - Usage of less formalized approaches and tools (compared to other areas)

Source: AIT

ENGINEERING ISSUES AND NEEDS

- Targets and goals
  - Reduction of manual steps necessary to handle complex smart grid configurations
  - 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

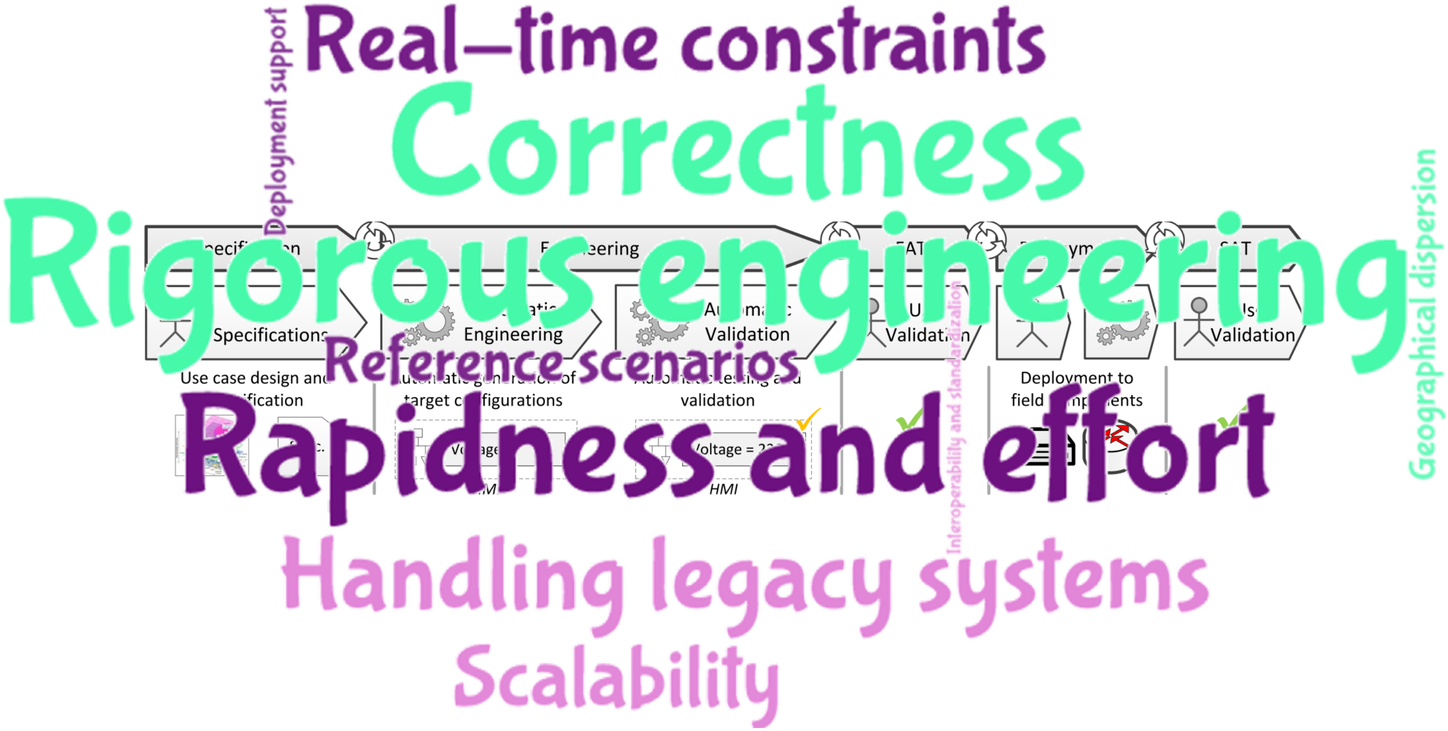
→ Providing support from design to implementation and installation



FAT: Factory Acceptance Test
SAT: System Acceptance Test

Source: AIT

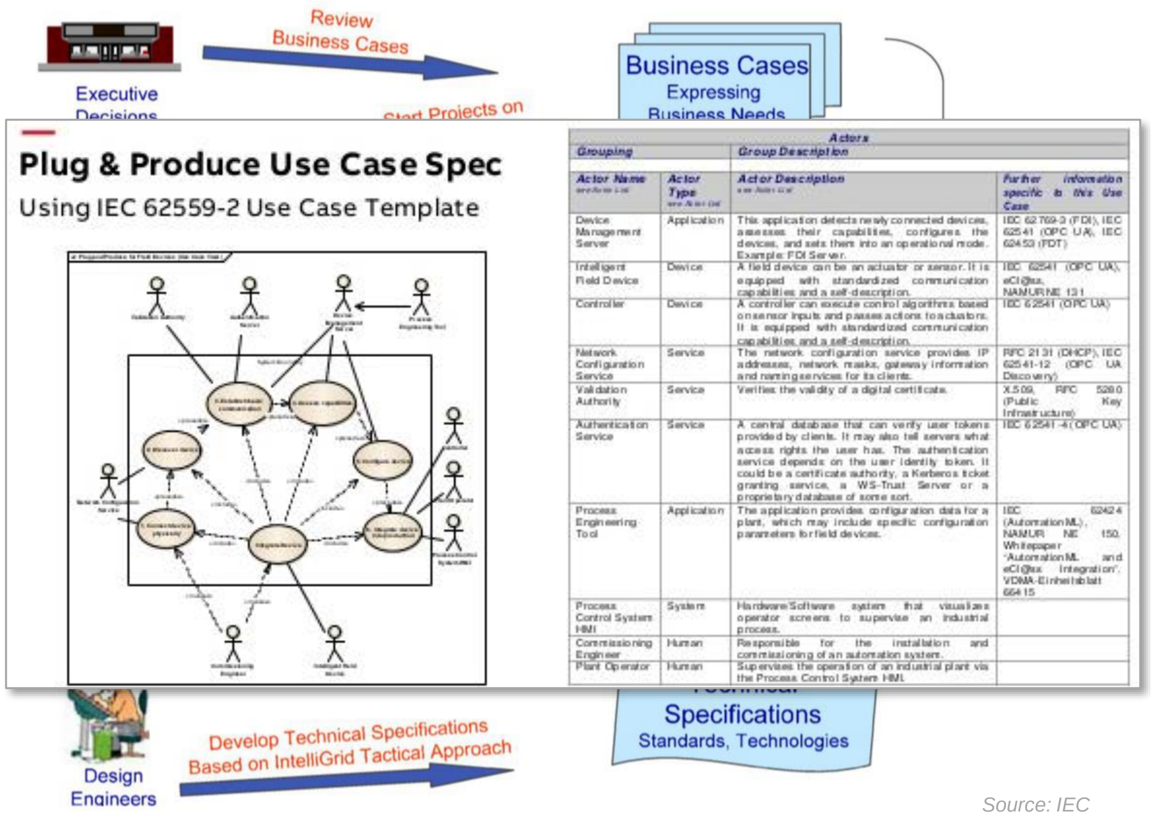
ENGINEERING ISSUES AND NEEDS



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

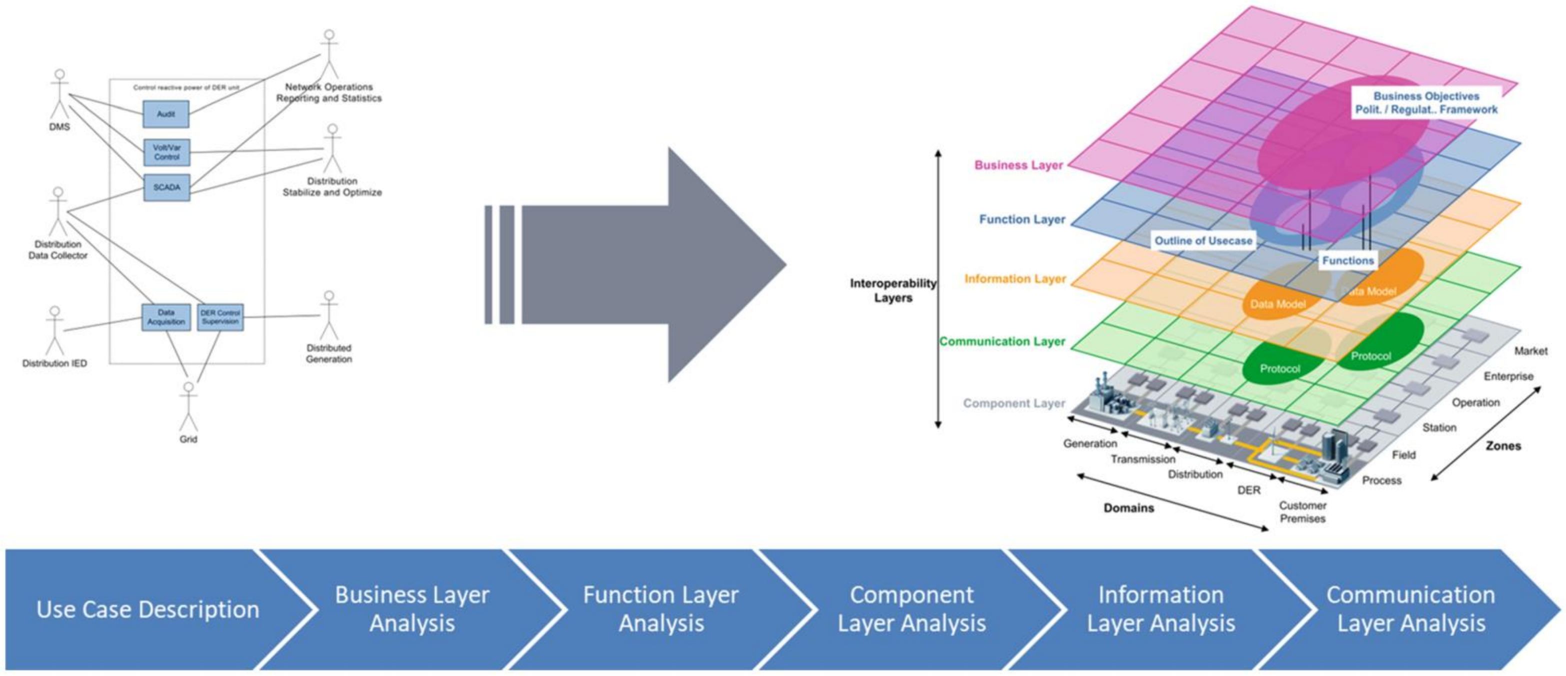


Source: IEC

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



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)*

Source: F. Pröstl Andrén, Model-Driven Engineering for Smart Grid Automation, Doctoral Thesis, TU Wien, supervisor W. Kastner, T. Strasser, 2018

STATUS QUO IN RESEARCH AND DEVELOPMENT

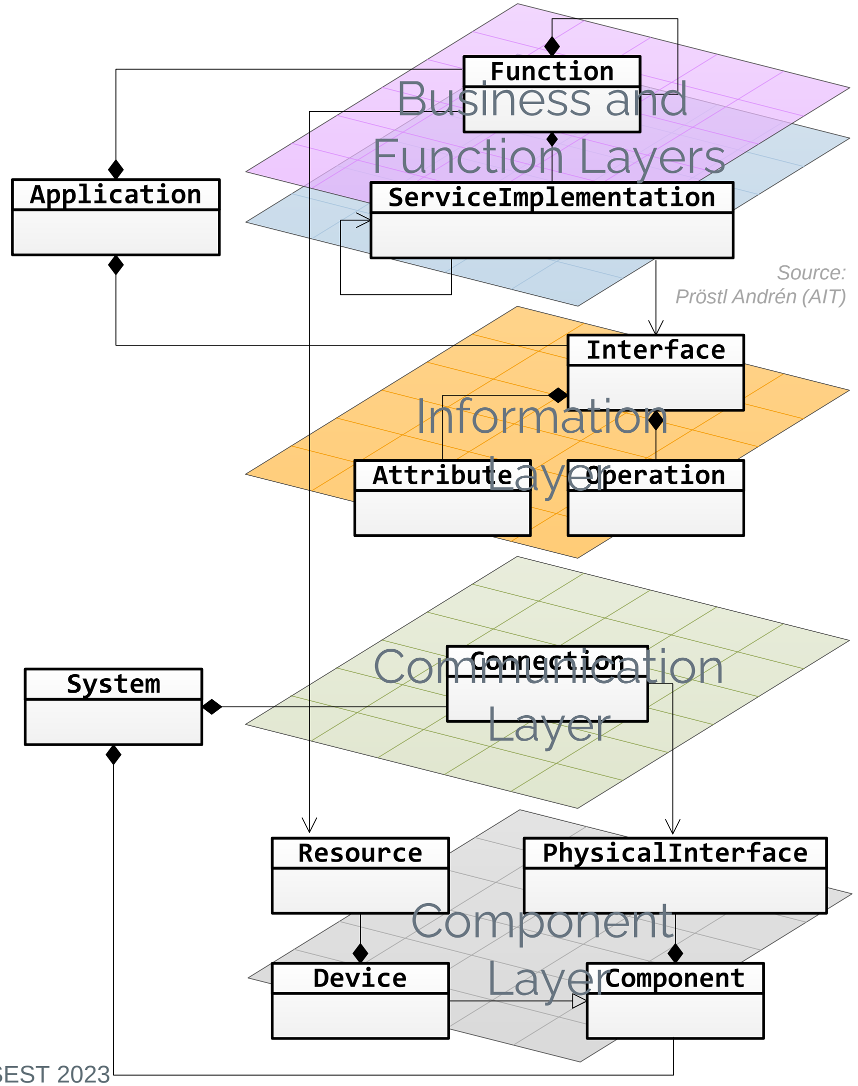
Engineering

- 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
}
```



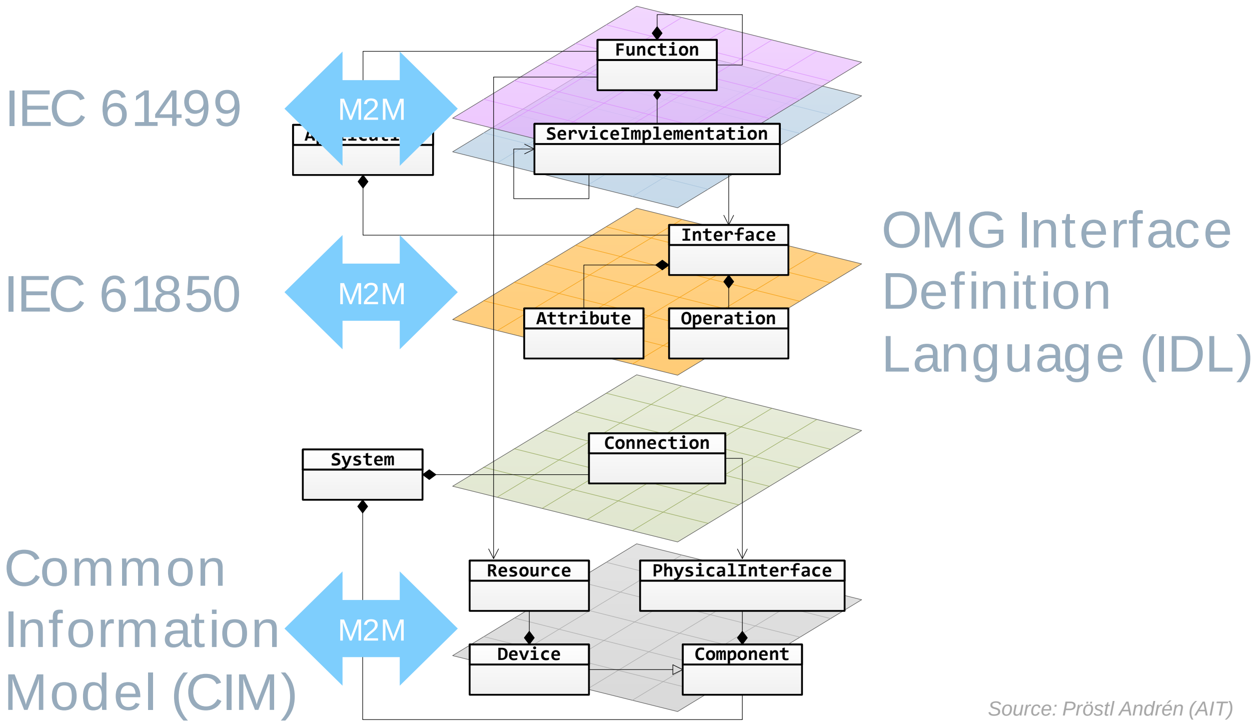
Source: Pröstl Andrén (AIT)

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

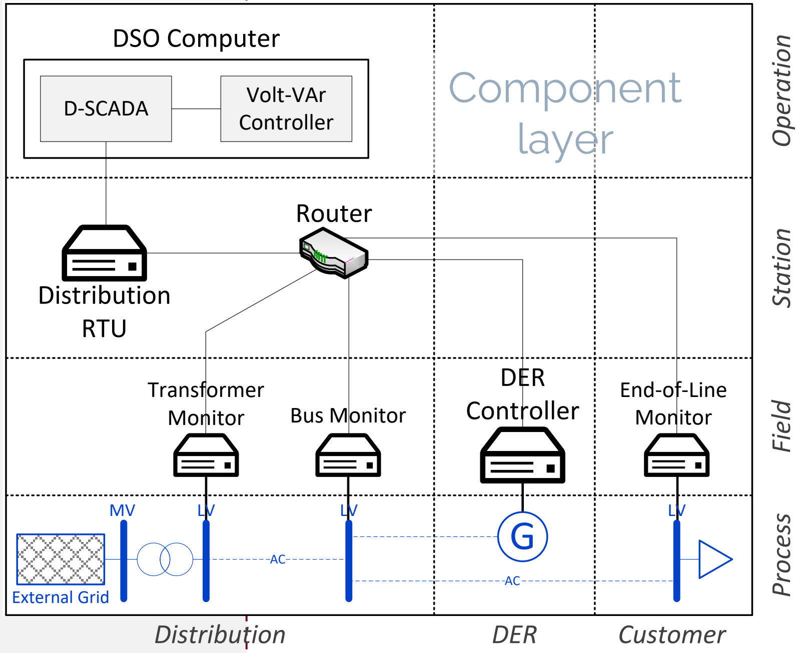
Engineering

- PSAL model-based engineering for smart grids
  - Application example

```
application VoltVArControlCentralized {
  function DERController at DERController.AncillaryServices {
    provides Measurements.GridMeasurements measurements
    requests DERCtrlInterfaces.DERDirectControls derDirectControls
    …
  }
  function VoltVArController {…}
  function DSCADA {…}
  function DistributionRTU {…}
  function DERGenerator {…}
  function TransformerMonitor {…}
  function BusMonitor {…}
  function EndOfLineMonitor {…}

  module Measurements {
    interface GridMeasurement {…}
    eventtype AggregatedMeasurement {…}
  }
  module DERCtrlInterfaces {…}

  connect DERController.derDirectControls
          with DERGenerator.directControls
  …
}
```



Source: Pröstl Andrén (AIT)

STATUS QUO IN RESEARCH AND DEVELOPMENT

Engineering

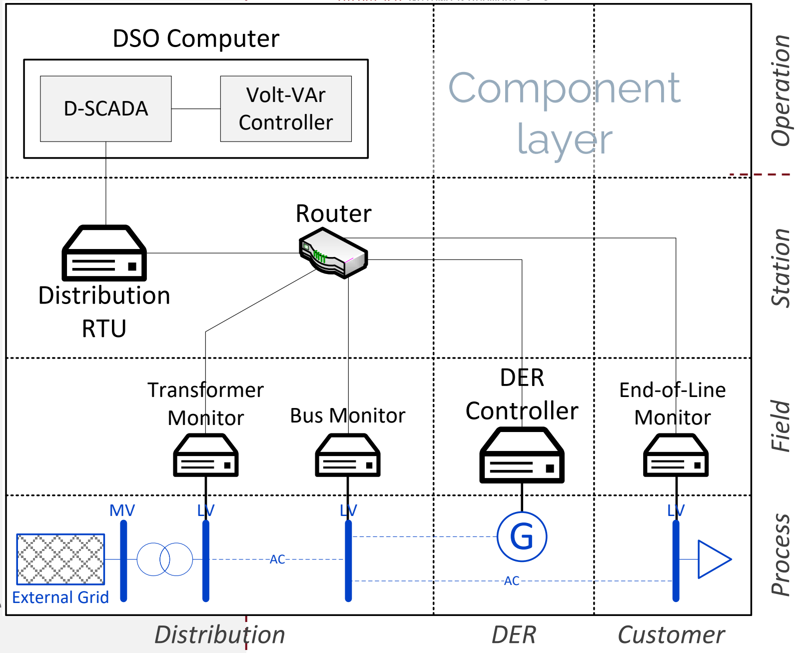
- PSAL model-based engineering for smart grids
  - System example

```
system DistributionSystemVV {
  @DER @Field
  device DERController {
    ethernet eth0 {ip = "10.0.0.1"}
    ethernet eth1 {ip = "192.168.0.2"}
    resource AncillaryServices
  }
  device DSOComputer {…}
  device DistributionRTU {…}
  router StationRouter
  device TransformerMonitor {…}
  device BusMonitor {…}
  device EndOfLineMonitor {…}

  generator ExternalSystem {…}
  busbar MVBus {…} …
  generator DERGenerator {
    ethernet eth0 {ip = "192.168.0.1"}
    terminal LVBus2
    resource DERResource
  }
  …
  connect DERController.eth1 with DERGenerator.eth0
  connect DERGenerator.LVBus2 with LVBus2.DERGenerator
}
```

```
application VoltVArControlCentralized {
  function DERController at DERController.AncillaryServices {
    provides Measurements.GridMeasurements measurements
    requests DERCtrlInterfaces.DERDirectControls derDirectControls
    …
  }
  function VoltVArController {…}
  function DSCADA {…}
  function DistributionRTU {…}
  function DERGenerator {…}
  function TransformerMonitor {…}
  function BusMonitor {…}
  function EndOfLineMonitor {…}

  module Measurements {
```

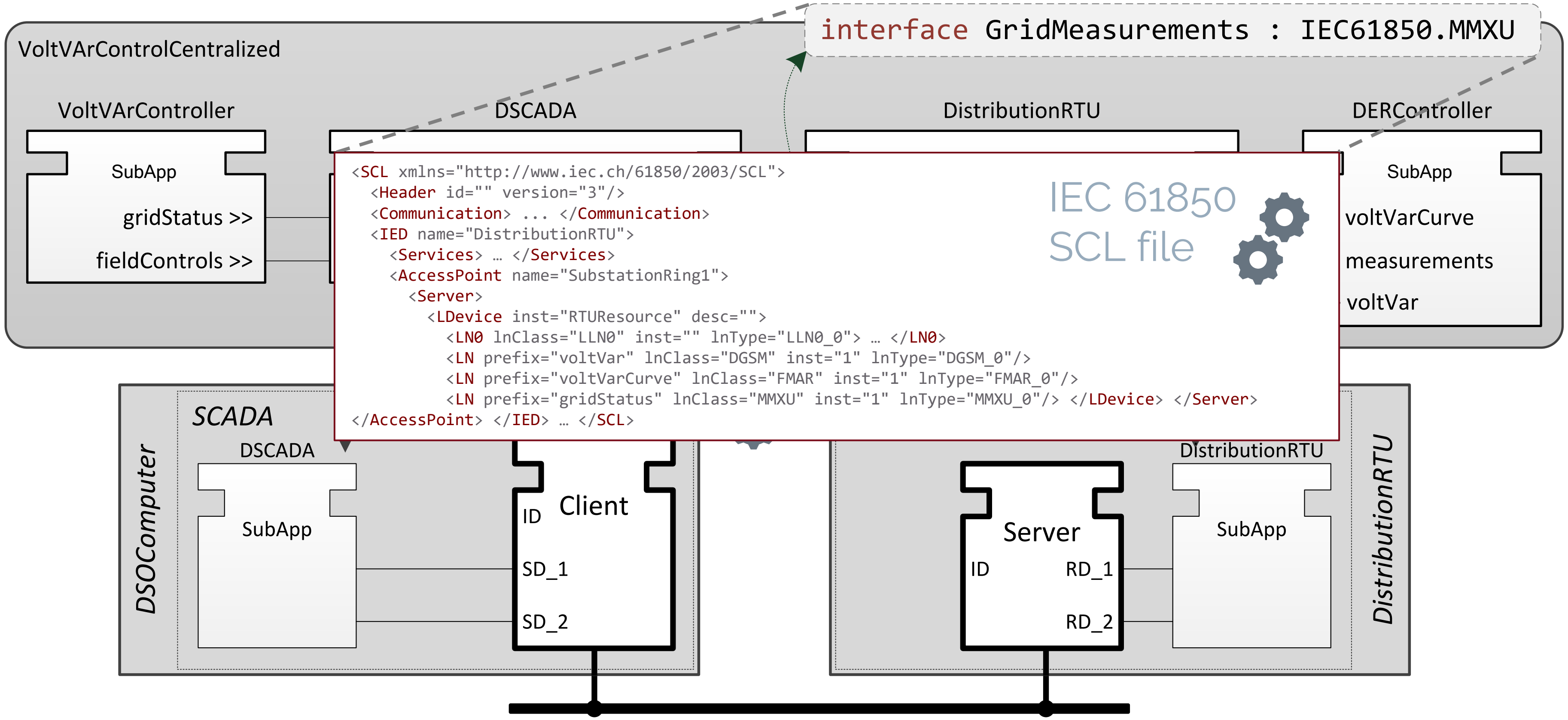


Source: Pröstl Andrén (AIT)

STATUS QUO IN RESEARCH AND DEVELOPMENT

Engineering

- PSAL model-based engineering for smart grids
  - Generation of IEC 61499 code

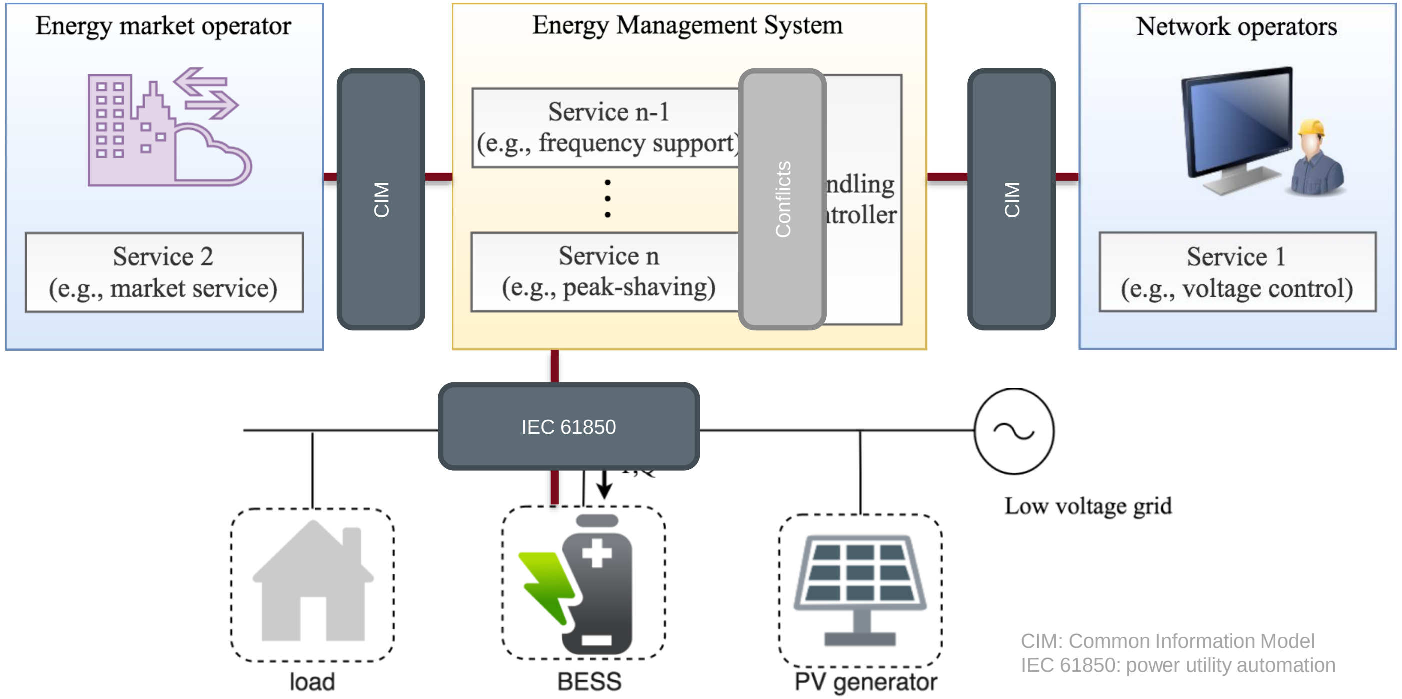


Source: Pröstl Andrén (AIT)

STATUS QUO IN RESEARCH AND DEVELOPMENT

Engineering

- Ontology-based engineering for Battery Energy Storage Systems (BESS)



CIM: Common Information Model
IEC 61850: power utility automation

Source: Zanabria (AIT)

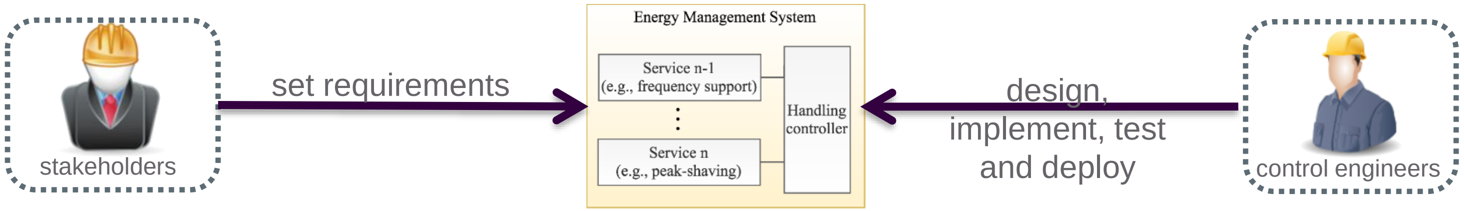
1. Conflicts between services
2. Lack of data interoperability

Source: C. Zanabria, Adaptable Engineering Support Framework for Multi-Functional Battery Energy Storage Systems, Doctoral Thesis, TU Wien, supervisor T. Strasser, 2018

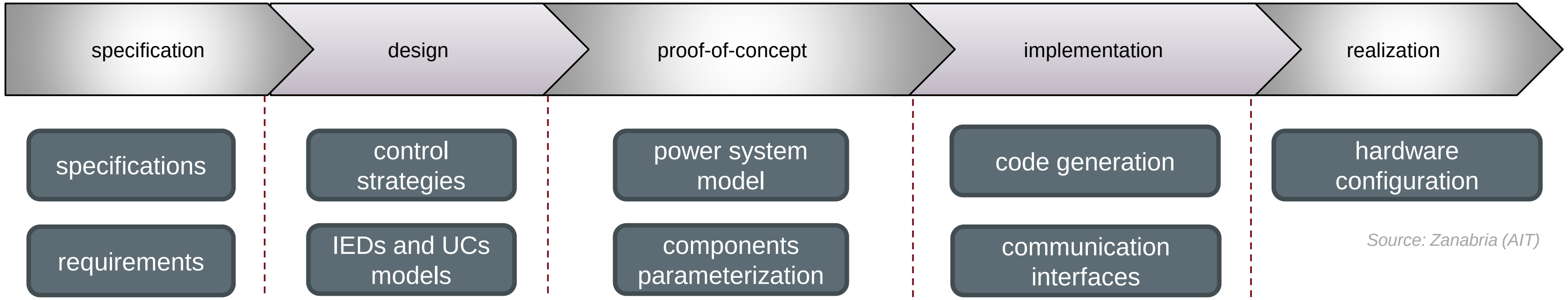
STATUS QUO IN RESEARCH AND DEVELOPMENT

Engineering

- Ontology-based engineering for Battery Energy Storage Systems (BESS)
  - Energy Management System (EMS) core element (multi-functional usage)



  - Complex EMS engineering process



Source: Zanabria (AIT)

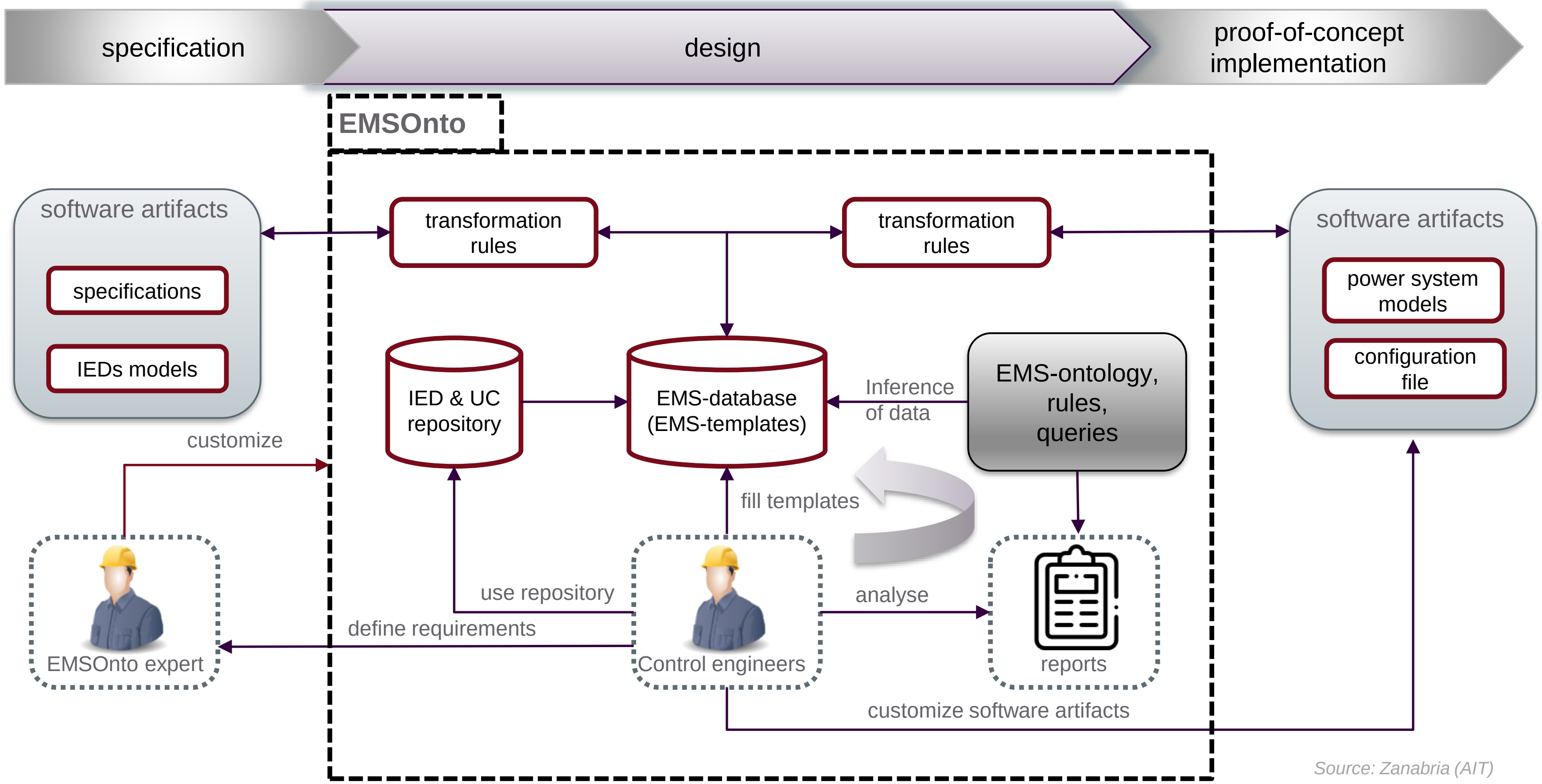
3. Lack of a vendor-independent solution
4. Error-prone engineering process

IED: Intelligent Electronic Device
UC: Use Case

STATUS QUO IN RESEARCH AND DEVELOPMENT

Engineering

- Ontology-based engineering for Battery Energy Storage Systems (BESS)



Source: Zanabria (AIT)

STATUS QUO IN RESEARCH AND DEVELOPMENT

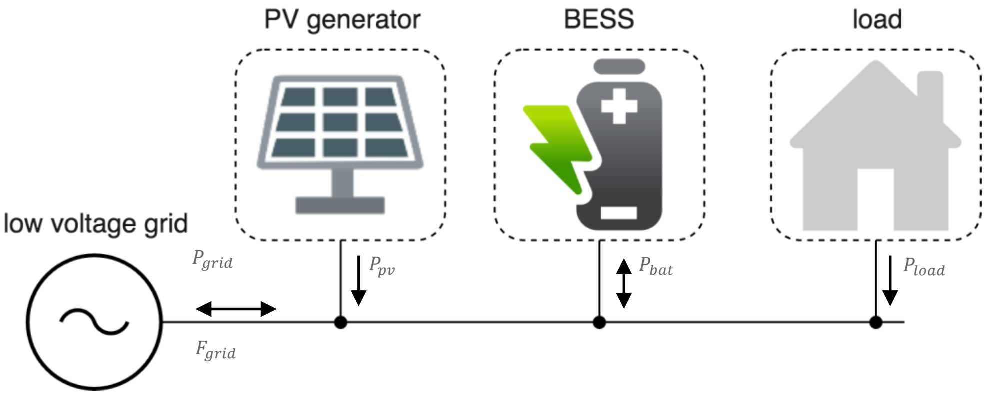
Engineering

- Ontology-based engineering for Battery Energy Storage Systems (BESS)
  - Conflict handling: different types considered

service	*manipulate*	*control*	*control goal*
frequency-watt(FW)	P_{bat}	P_{bat}	$P_{bat} = \gamma F_{grid} + \theta$
self-consumption (SC)	P_{grid}	P_{bat}	$P_{grid} = 0$

Source: Zanabria (AIT)

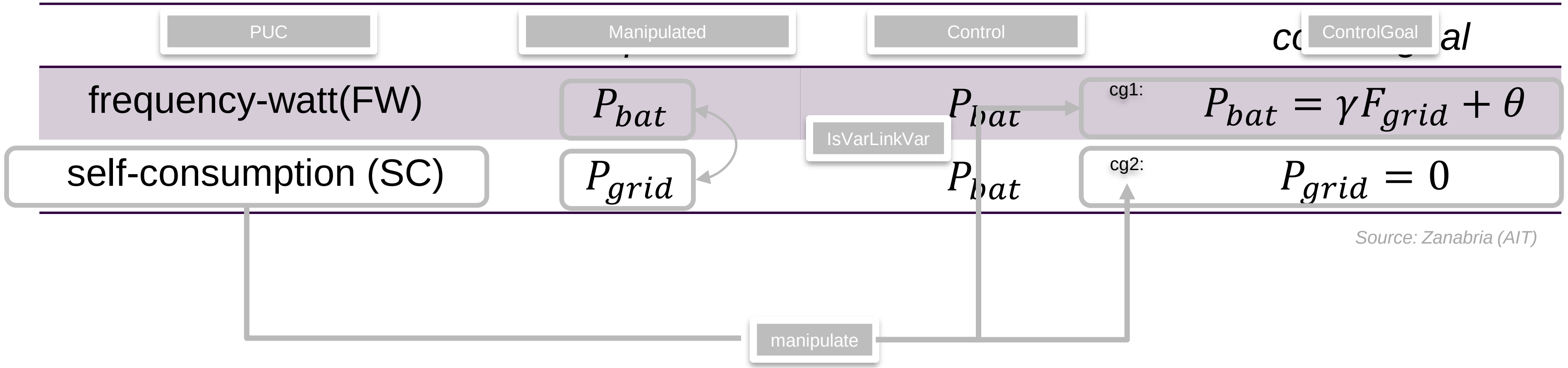
$$P_{grid} + P_{bat} + P_{PV} + P_{load} = 0$$



STATUS QUO IN RESEARCH AND DEVELOPMENT

Engineering

- Ontology-based engineering for Battery Energy Storage Systems (BESS)
  - Conflict handling: ontology-based modelling of engineering conflicts



Source: Zanabria (AIT)

- $Tbox$
  (Terminological component)
- Inferred assertions
- Query to identify a conflict type
- Conclusion

$$hasFctVar \circ IsVarLinkVar \sqsubseteq hasFctVar,$$
$$hasFctVar \circ hasFctVar^{-} \sqsubseteq \text{IsFcLinkFc},$$
$$manipulate \circ IsFcLinkFc \sqsubseteq manipulate$$

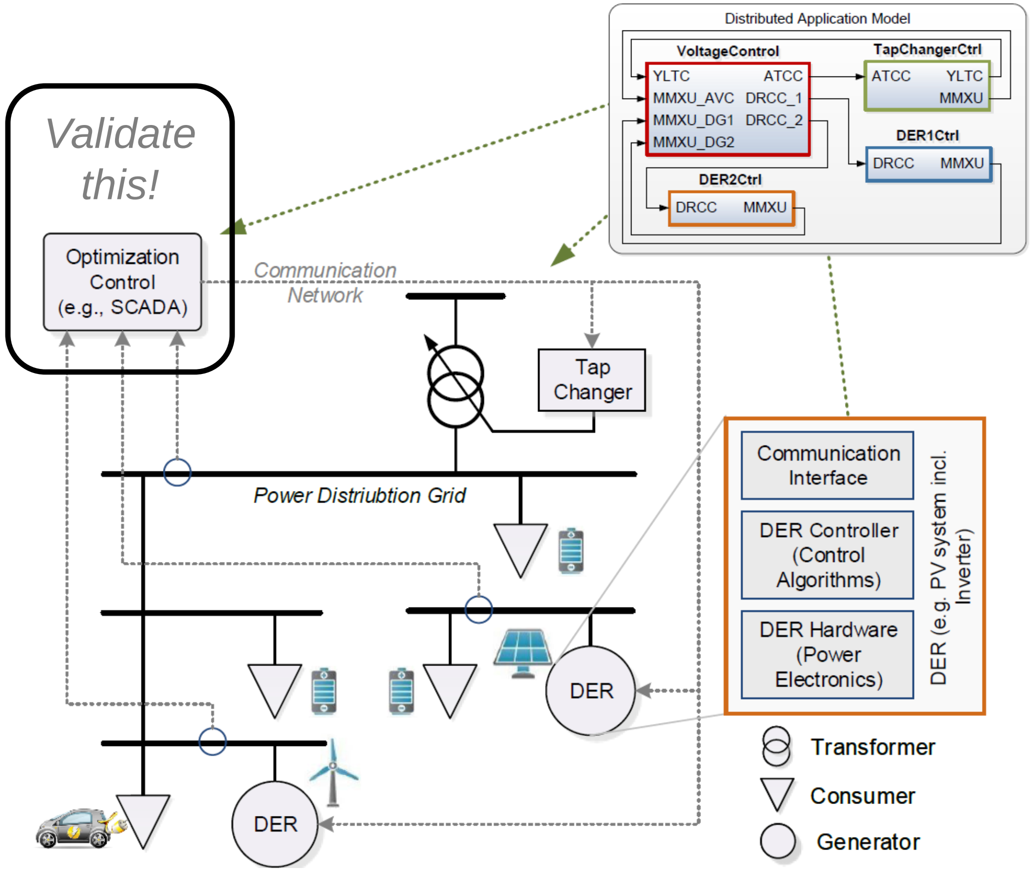
$$manipulate(SC, cg1)$$

$$ControlGoal \sqcap 2manipulate^{-}.PUC$$

FW and SC are in conflict

STATUS QUO IN RESEARCH AND DEVELOPMENT

- ERIGrid holistic testing approach for smart grid systems
  - Testing of smart grid 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

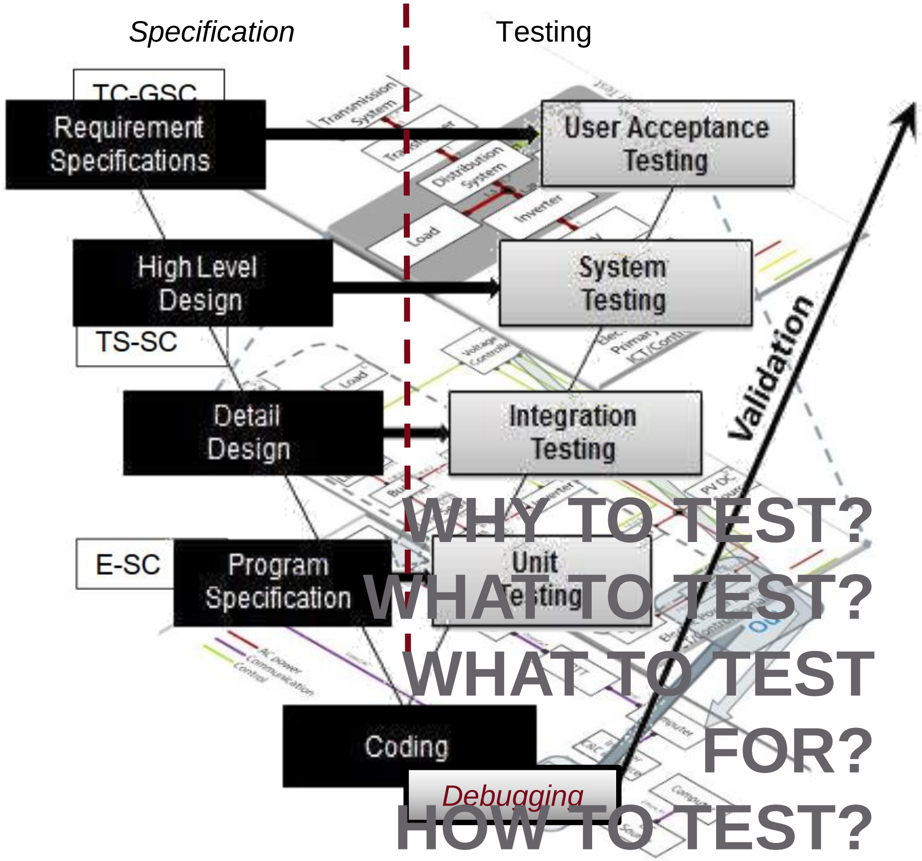


Source: ERIGrid

STATUS QUO IN RESEARCH AND DEVELOPMENT

Validation & Testing

- 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

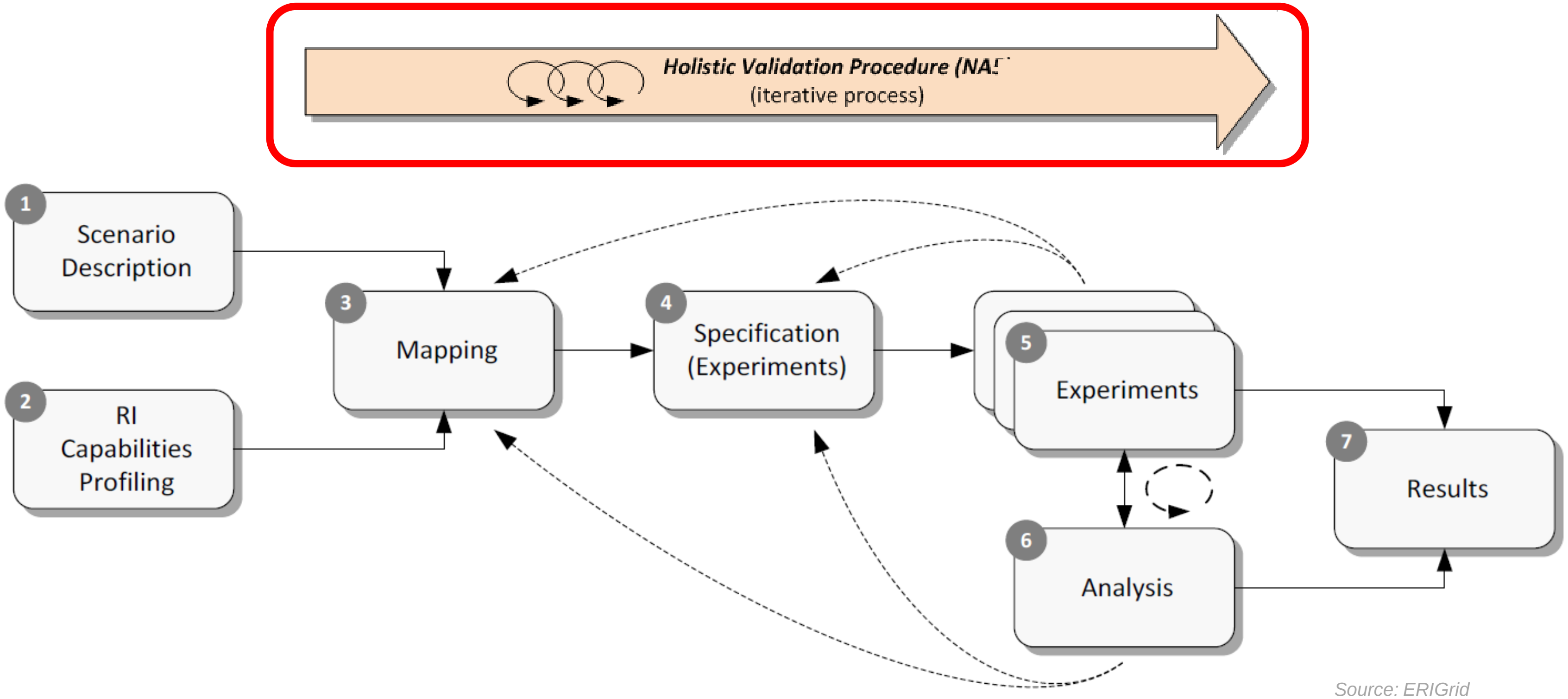


Source: ERIGrid

STATUS QUO IN RESEARCH AND DEVELOPMENT

Validation & Testing

- ERIGrid holistic testing approach for smart grid systems



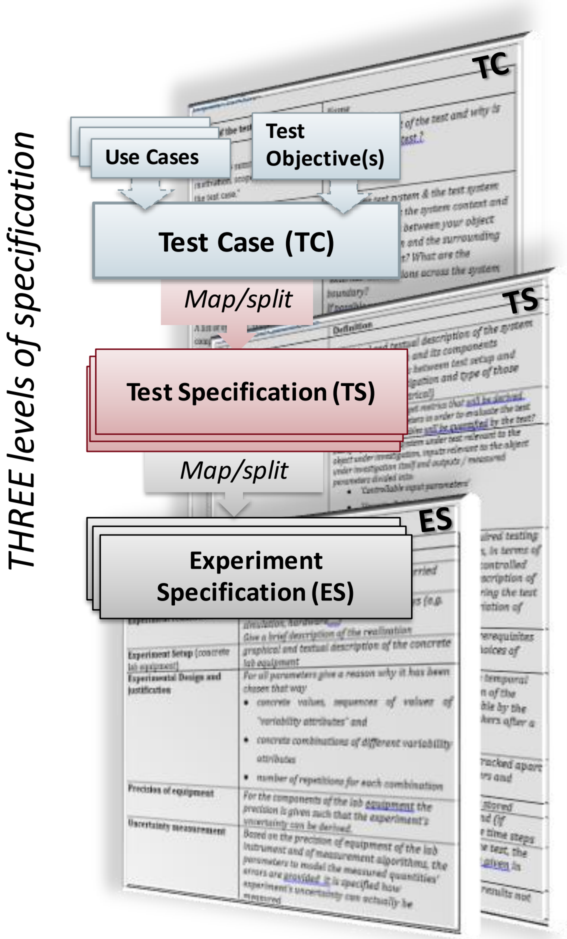
Source: ERIGrid

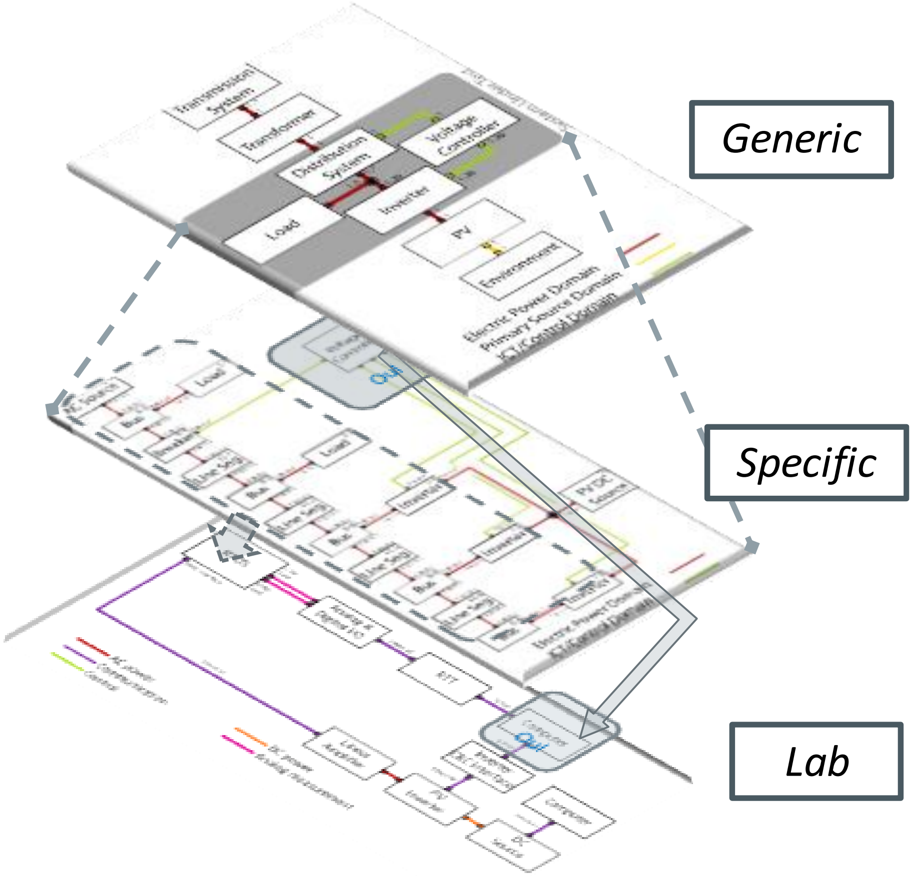
*"**Holistic testing** is the <u>process</u> and <u>methodology</u> for the evaluation of a concrete function, system or component (object under investigation) within its relevant operational context (system under test), corresponding to the purpose of investigation"*

STATUS QUO IN RESEARCH AND DEVELOPMENT

Validation & Testing

- ERIGrid holistic testing approach for smart grid systems



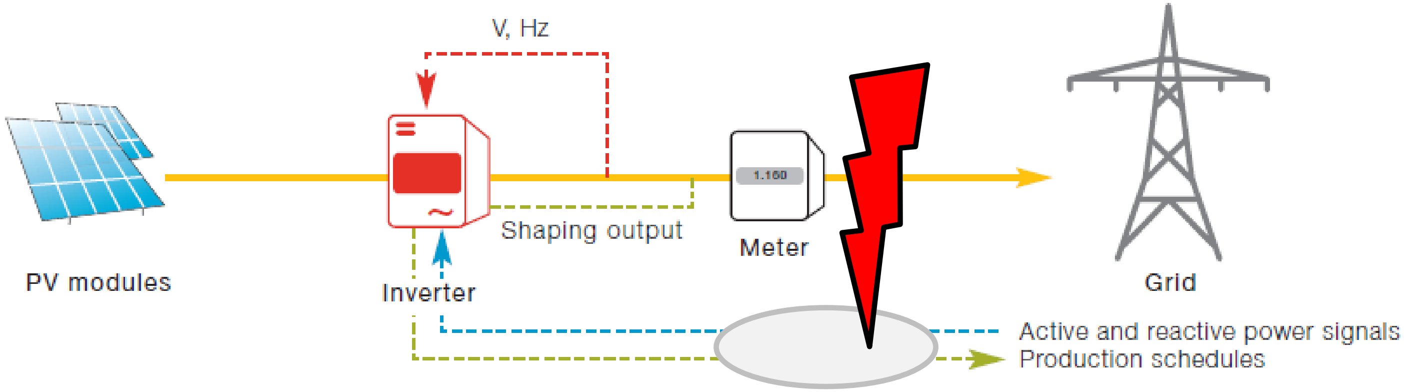


Source: ERIGrid

STATUS QUO IN RESEARCH AND DEVELOPMENT

Validation & Testing

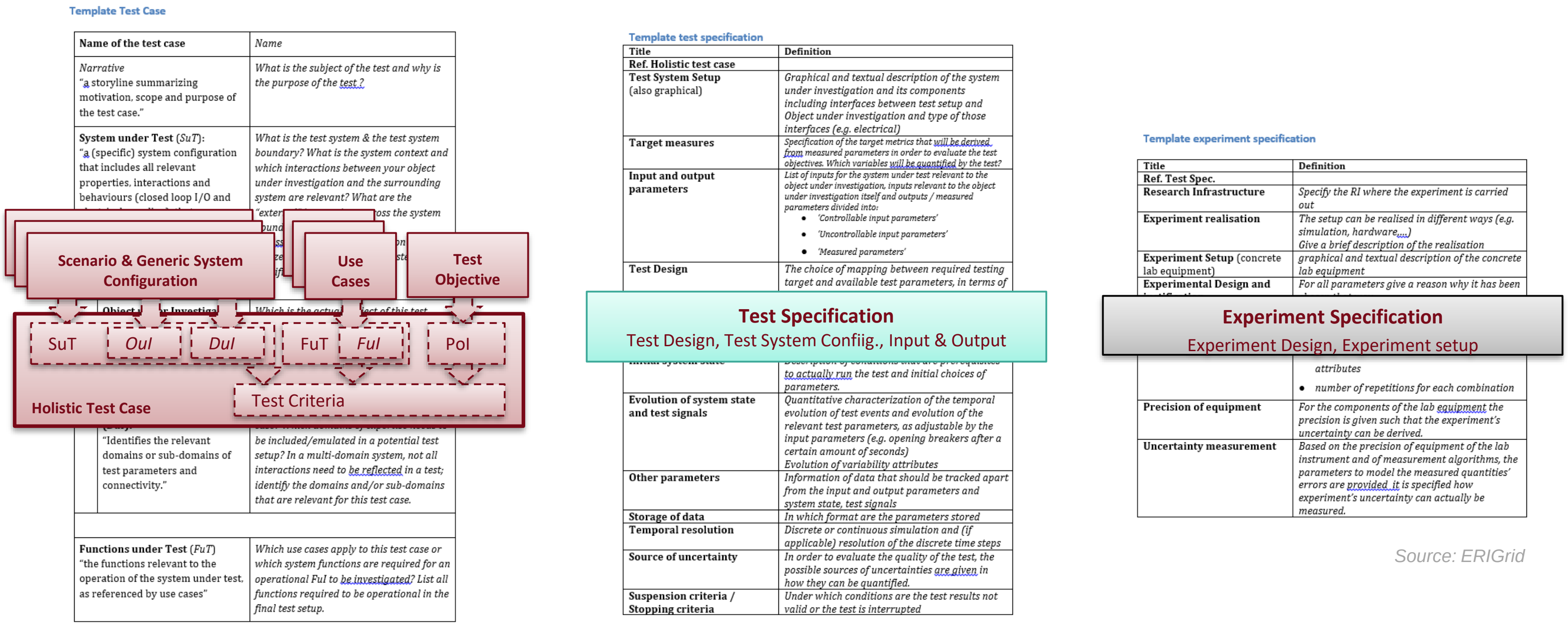
- ERIGrid holistic testing approach for smart grid systems
  - Example: cyber-security analysis
    - Analysing the influence of the attack on the energy infrastructure
    - IEC 61850 remote controlled inverter-based DER
    - Man-in-the-Middle attack scenario



Source: SMA

STATUS QUO IN RESEARCH AND DEVELOPMENT

- ERIGrid holistic testing approach for smart grid systems
  - Example: cyber-security analysis
    - Formalized test case description

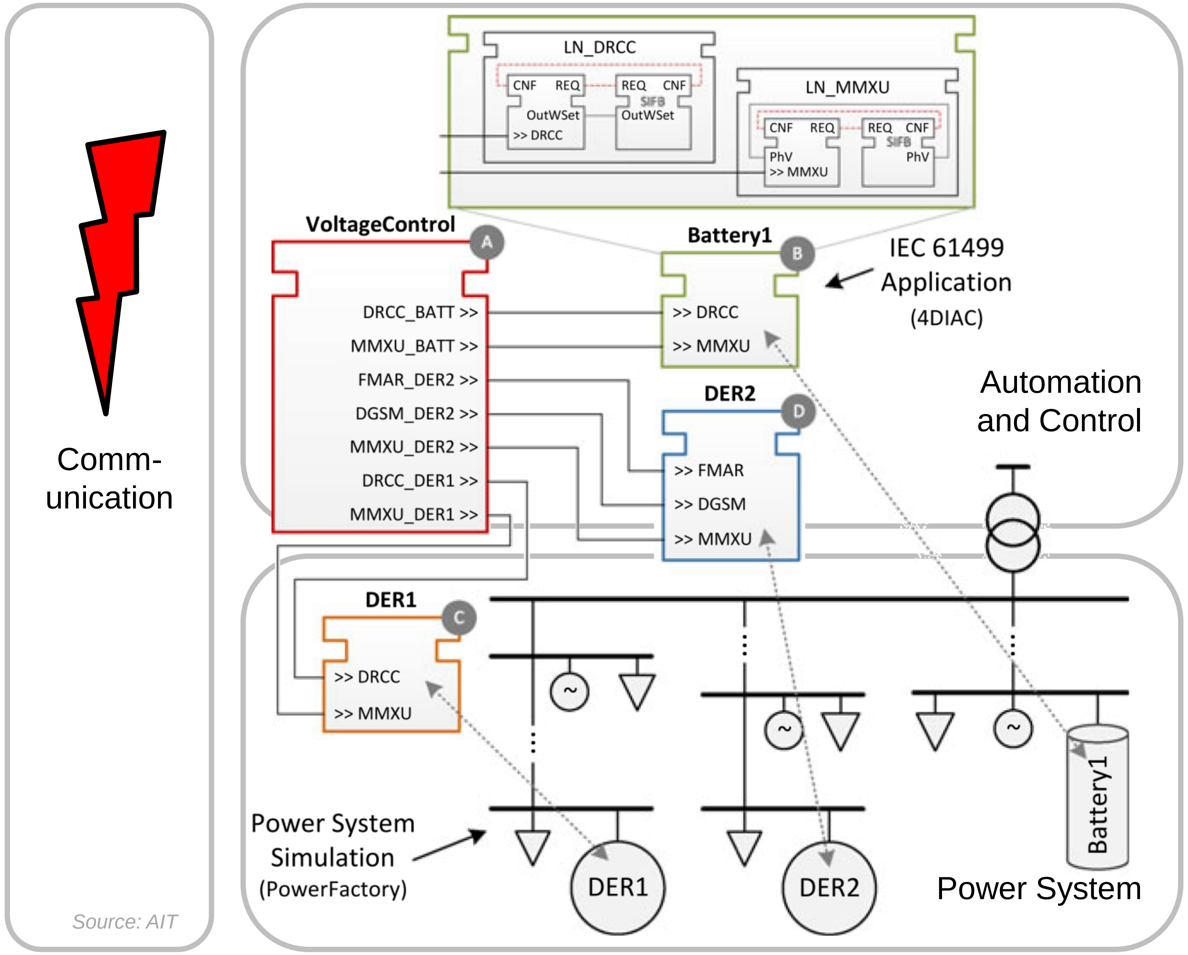


Source: ERIGrid

STATUS QUO IN RESEARCH AND DEVELOPMENT

Validation & Testing

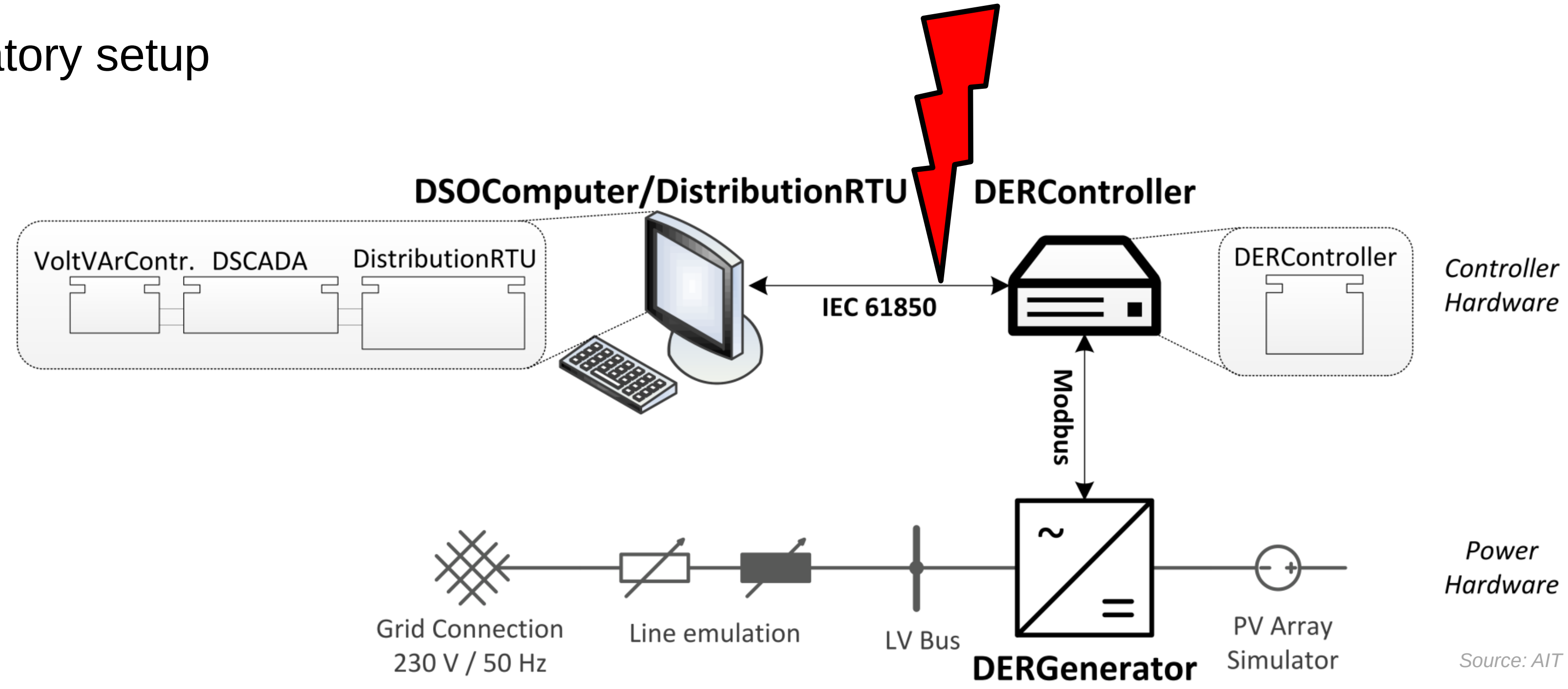
- ERIGrid holistic testing approach for smart grid systems
  - Example: cyber-security analysis
    - Simulation-based analysis
    - Coupling of different domains (power, ICT, control & automation)



STATUS QUO IN RESEARCH AND DEVELOPMENT

Validation & Testing

- ERIGrid holistic testing approach for smart grid systems
  - Example: cyber-security analysis
    - Laboratory setup

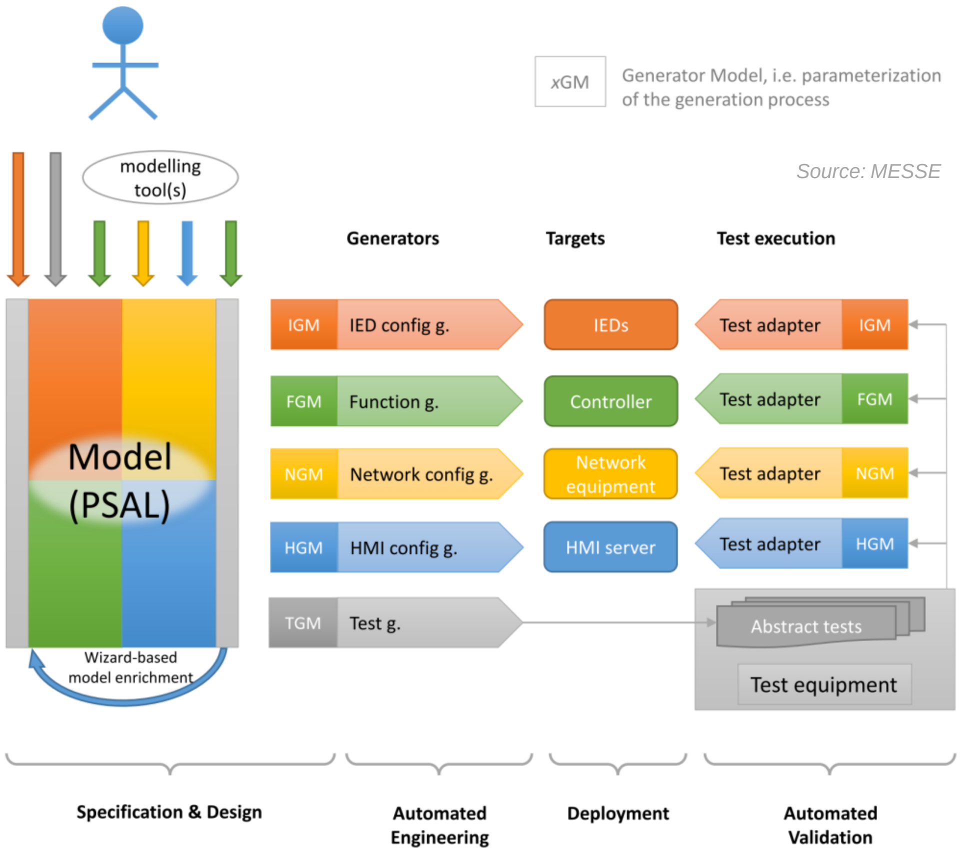


Source: AIT

STATUS QUO IN RESEARCH AND DEVELOPMENT

Validation & Testing

- MESSE holistic engineering, validation, and deployment support system
  - Automation of the engineering and validation process
  - Usage of MDE
  - Covers different domains (power, ICT, HMI)
  - Generation support for
    - Code (PLC, SCADA)
    - Testing scenarios

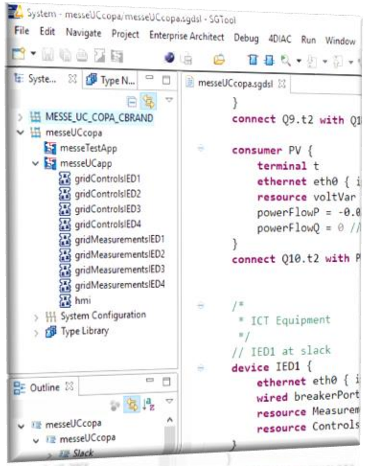


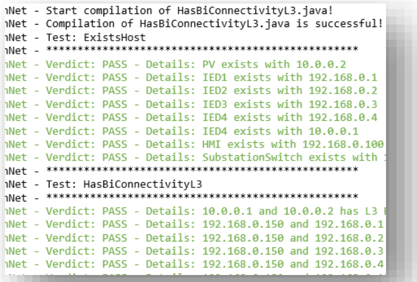
STATUS QUO IN RESEARCH AND DEVELOPMENT

Validation & Testing

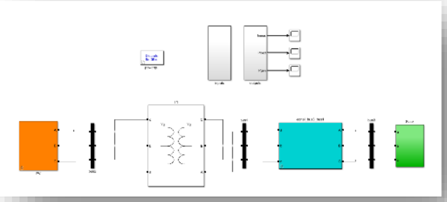
- MESSE integrated engineering, validation, and deployment support system

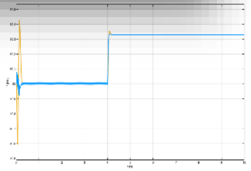
Integrated Development Environment



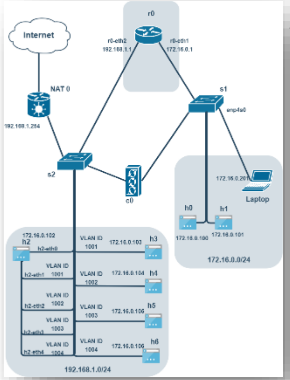


Automated HMI tests

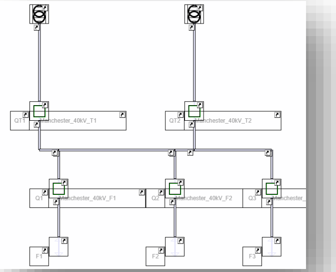




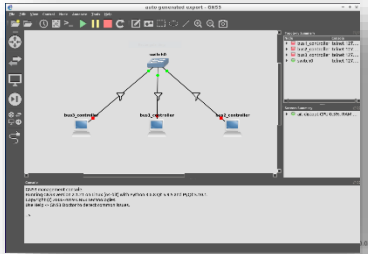
Matlab/Simulink simulation

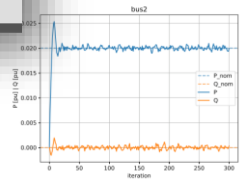


Virtualized communication network (Mininet)



HMI components





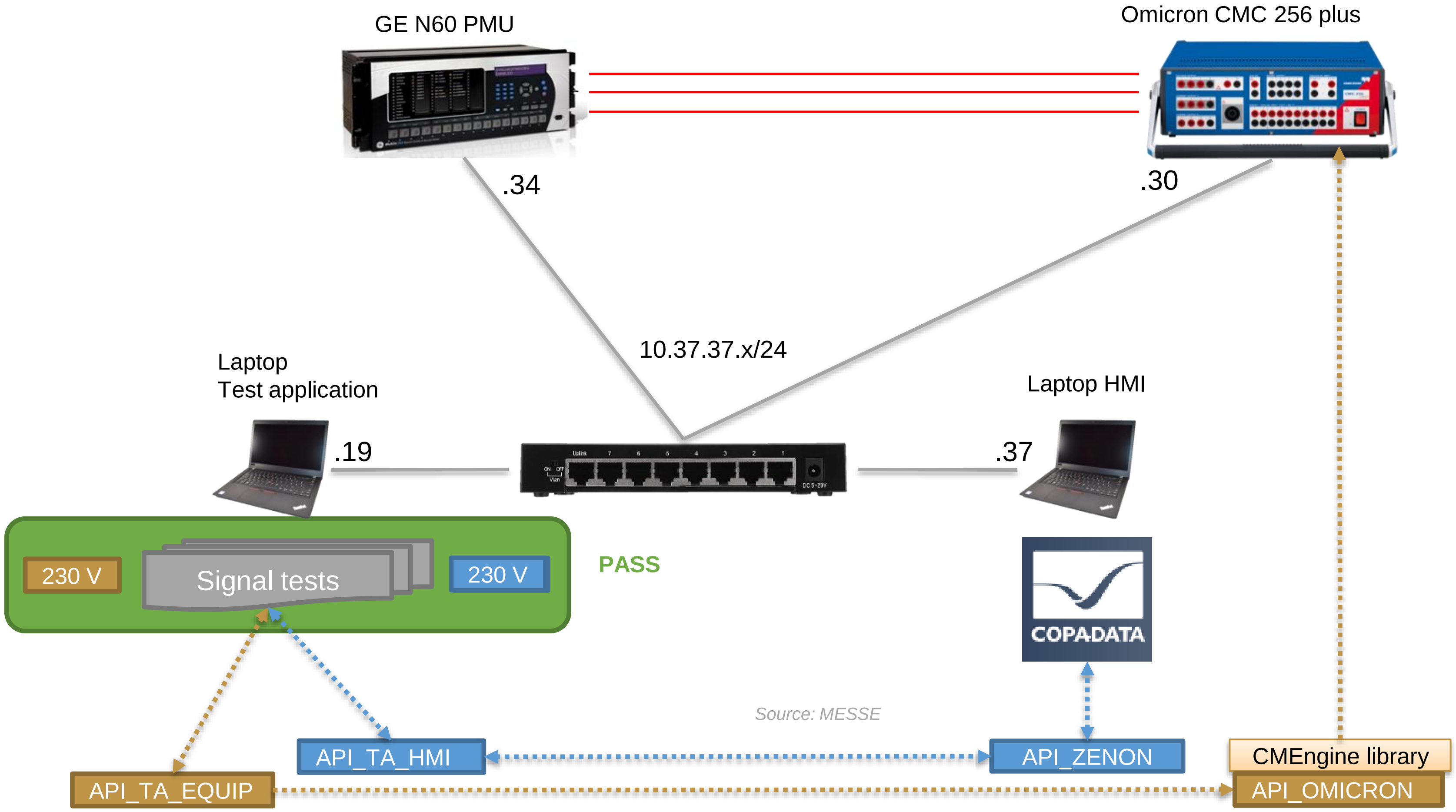
Gns-3 network emulation

Source: MESSE

STATUS QUO IN RESEARCH AND DEVELOPMENT

Validation & Testing

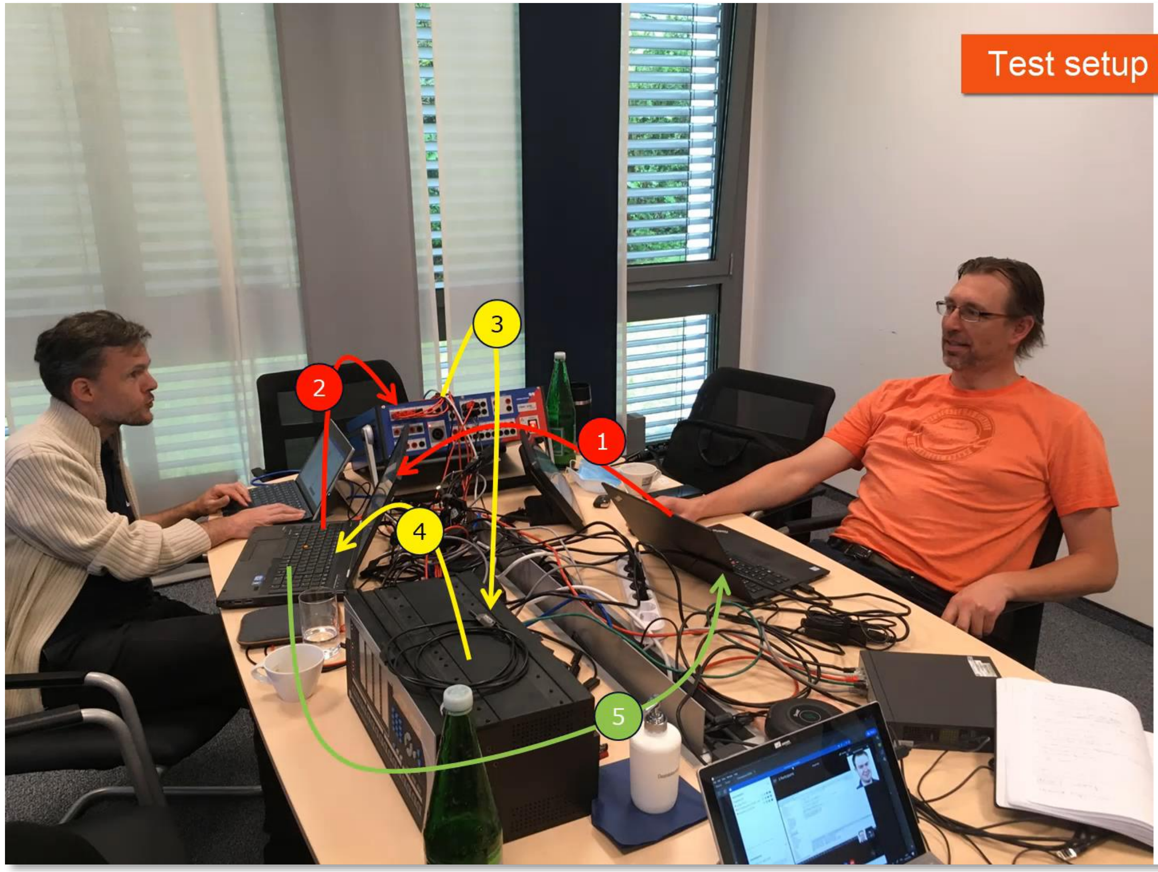
- MESSE integrated engineering, validation, and deployment support system



STATUS QUO IN RESEARCH AND DEVELOPMENT

Validation & Testing

- MESSE integrated engineering, validation, and deployment support system



Test setup in reality

1. Abstract Test triggered by Java test application, triggers Omicron Test Adapter
2. Omicron Test Adapter (using Test Engine) sets Voltage level on CMC-Outputs
3. Omicron CMC provides Voltage on GE N60
4. GE N60 sends values via IEC 61850 to zenon HMI
5. zenon API provides voltage values – read by Test Adapter of Java test application for comparison

CONCLUSIONS AND OUTLOOK

- Formalized processes and approaches for smart grid systems 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: Zanabria (AIT)

CONCLUSIONS AND OUTLOOK

www.erigrid2.eu

@ERIGrid 2.0 Project

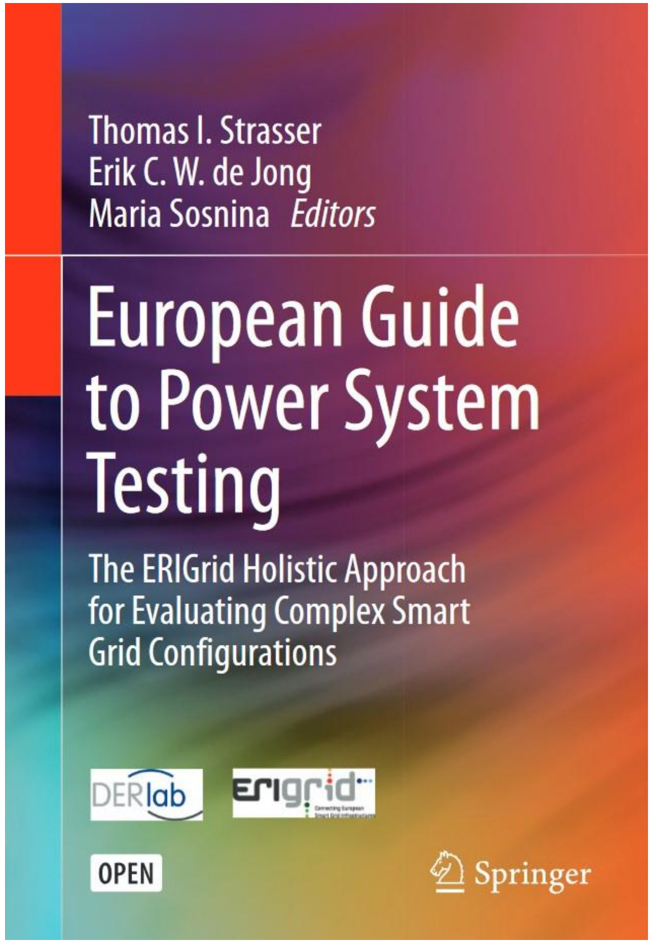
Source: ERIGrid 2.0

ACKNOWLEDGEMENTS

- OpenNES consortium (FFG No. 845632)
- MESSE Consortium (FFG No. 861265)
- ERIGrid/ERIGrid 2.0 Consortia (H2020 GA 654113 and 870620)

REFERENCES

- T. Strasser, E. de Jong, M. Sosnina (ed.): “European Guide to Power System Testing: The ERIGrid Holistic Approach for Evaluating Complex Smart Grid Configurations”; Springer Nature, Cham, Switzerland, 2020, ISBN: 978-3-030-42274-5; 141 pages.
- K. Heussen, C. Steinbrink, I. Abdulhadi, et al.: “ERIGrid Holistic Test Description for Validating Cyber-Physical Energy Systems”; Energies, 12 (2019), 14.
- T. Strasser, S. Rohjans, G. Burt (ed.): “Methods and Concepts for Designing and Validating Smart Grid Systems”; MDPI, Basel, Beijing, Wuhan Barcelona Belgrade, 2019, ISBN: 978-3-03921-649-9; 408 pages.
- F. Pröstl Andren, T. Strasser, W Kastner: “Engineering Smart Grids: Applying Model-Driven Development from Use Case Design to Deployment”; Energies, 10 (2017), 3.
- T. Strasser, F. Pröstl Andren, G. Lauss, et al.: “Towards holistic power distribution system validation and testing-an overview and discussion of different possibilities”; e & i Elektrotechnik und Informationstechnik, Vol. 134 (2017), Issue 1.
- A. Benigni, T. Strasser, G. De Carne, M. Liserre, M. Cupelli, A. Monti: “Real-Time Simulation-Based Testing of Modern Energy Systems: A Review and Discussion”; IEEE Industrial Electronics Magazine, 14 (2020), Vol. 2; 28 - 39.
- C. Zanabria, F. Pröstl Andren, J. Kathan, T. Strasser: “Rapid Prototyping of Multi-Functional Battery Energy Storage System Applications”; Applied Sciences, 8 (2018), 8; 1 - 34.
- C. Zanabria, F. Pröstl Andren, T. Strasser: “Comparing Specification and Design Approaches for Power Systems Applications”; 2018 IEEE PES Transmission & Distribution Conference and Exhibition - Latin America (T&D-LA), Lima, Peru; 2018.



TECHNISCHE UNIVERSITÄT WIEN

AIT AUSTRIAN INSTITUTE OF TECHNOLOGY
TOMORROW TODAY

Privatdoz. DI Dr. Thomas Strasser

Senior Scientist
Center for Energy
Electric Energy Systems

AIT Austrian Institute of Technology GmbH
Giefinggasse 2 | 1210 Vienna | Austria
T +43(0) 50550-6279 | F +43(0) 50550-6390
thomas.strasser@ait.ac.at | http://www.ait.ac.at