Design of Smart Grid Test Lab Infrastructure

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AGENDA

- Background/Motivation for Smart Grid testing
- General Design Criteria
- Application Areas of SG Test Labs
  - Component Testing for Certification
    - Power Hardware
    - Information and Communication Technologies (ICT)
  - System Testing and Demonstration
    - Hardware-in-the-Loop Testlab
    - Hybrid System Test Platform
- Conclusions and Outlook

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Background/Motivation for Smart Grid testing

- Challenges for pure lab /field testing of SG components:
  - Increasing complexity of cyber-physical energy systems (CPES)
  - New components (RES, EV, heat pumps, etc.) and fields of applications (e.g. power & heat supply, transport)
  - System services of RES and conformity assessment are now mandatory (EU Network Code – “Requirements for Generators” RfG)
  - New business models (VPP)
  - Digitalization of power systems (Remote control, smart metering)
- Advantages of an Integrated lab based validation approach (incl. RT simulation and Hardware-In-the-Loop (HIL) test setups)
  - Testing of realistic fault conditions or rare network events
  - Flexibility in changes of grid and component parameter
  - De-risking field testing by well adapted testing environment and conditions

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General Design Criteria

- Standards or Features to be tested (Scope)
- Equipment under Test (EUT) Voltage Level (LV, MV, HV, EHV)
- EUT Rated Power Range (W, kW, MW)
- EUT Types (Loads, Generators, Power grid components, controller, communication devices, measurement or protection equipment)
- Auxiliary supplies (Electrical power supply, prime mover, gas/fuel supply, heat sink, exhaust gas pipe)
- Lab infrastructure automation, control and measurement systems
- Mechanical Dimensions, Weight and Climate Conditions
- Number of independent, parallel tests / testbeds

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General Design Criteria
- Two examples of EUT

Grid Protection Device (according to AR-N 4105)

- Automatic disconnection device between a generating plant and the public network
- Voltage protection: U<> and U>
- Frequency protection functions f<> and f>
- Islanding detection df/dt (ROCOF), etc.

Source:
LINETRAXX® VMD460-NA | Bender GmbH & Co. KG

Battery Inverter

- Rated power 3.4 – 3.95 MW,
- Bidirect. DC input: 1003 V - 1500 V, 4750 A
- AC output: 552 V - 759 V, 3320 A

Source:
SUNNY CENTRAL STORAGE UP - Battery inverter for large-scale storage systems (sma.de)

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Application Area: Component Test for Certification – Power Hardware Testing Introduction

- Before installation and connection of Power Generating Plants (PGP) and other devices, the conformity of these PGPs to national Grid Codes must be shown.
- In Germany e.g. VDE-AR-N 4120 describes general “Technical Requirements for the connection and operation of customer installations to the high voltage network”. It is applicable to all „grid users“ (demand facilities, power generating plants, storage units, mixed and charging installations for EV).
- Lab- or onsite-Testing is necessary for two different certificates
  - Power Generating Unit / Component certificates
  - Individual verification certificate of PGP

November 2018

VDE-AR-N 4120

VDE

FNN

Dies ist eine VDE-Anwendungsregel im Sinne von VDE 0022 unter gleichzeitiger Einhaltung des in der VDE-AR-N 100 (VDE-AR-N 4000) beschriebenen Verfahrens. Sie ist nach der Durchführung des vom VDE-Präsidium beschlossenen Genehmigungsverfahrens unter der oben angeführten Nummer in das VDE-Vorschriftenwerk aufgenommen und in der „etz Elektrotechnik + Automation“ bekannt gegeben worden.

Vervielfältigung – auch für innerbetriebliche Zwecke – nicht gestattet.

ICS 29.240.01

Ersatz für
VDE-AR-N 4120:2015-01 und
VDE-AR-N 4120 Berichtigung 1:2017-02
Siehe Anwendungsbeginn

Technische Regeln für den Anschluss von Kundenanlagen an das Hochspannungsnetz und deren Betrieb (TAR Hochspannung)

Technical requirements for the connection and operation of customer installations to the high voltage network (TAR high voltage)

Exigences techniques pour la connexion et l'opération des installations des clients au réseau à haute tension (TAR haute tension)

Gesamtumfang 215 Seiten

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VDE-Vertr.-Nr. 0100493

Source: VDE-AR-N 4120 Anwendungsregel:2018-11 - Standards - VDE Publishing House (vde-verlag.de)

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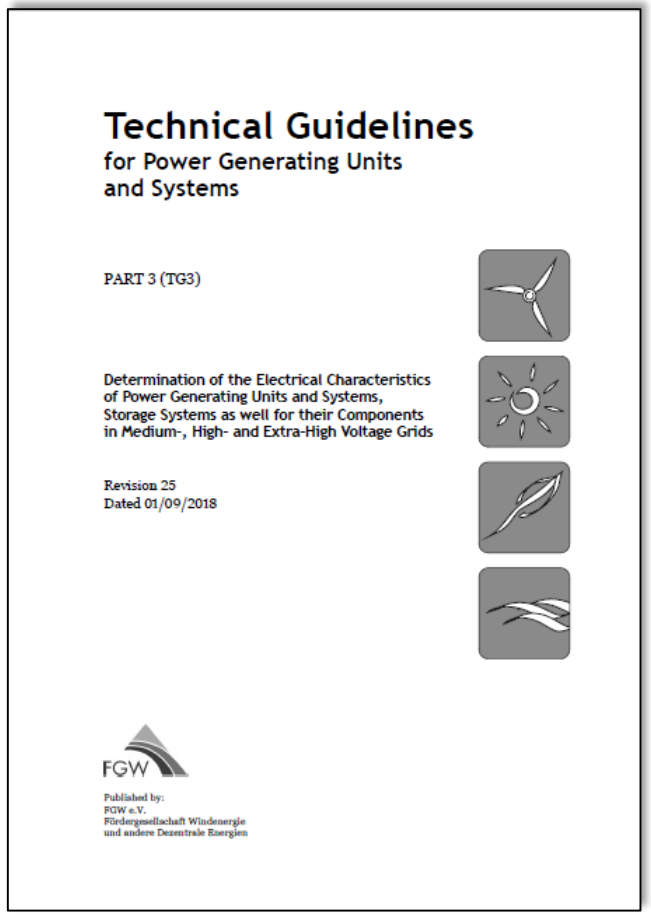
Application Area: Component Test for Certification – Power Hardware Testing Standards Example

- FGW TG Part 3 (TG3) describes measurement methods and test procedures for approval of the grid behavior of PG Units, PG Plants and their components according to the German MV-/HV-/EHV-Grid Codes VDE-AR N 4110/ 4120/ 4130);
- FGW TG3 is applicable to Generating Units of all technologies (Wind, PV, Hydro, CHP, etc.) and their components as well as Storage systems. Originally developed only for WTG Measurements and tests similar to IEC 61400-21
- FGW TG 3 Guideline covers following Tests:
  - Type Tests for PGU
  - Type Tests for PGP components (e.g. Windfarm controller)
  - PG Plant Tests for determination of harmonic emissions
  - PG Plant Tests for Individual Verification Procedure (Certificate C)
- Accreditation (IEC 17025) is required for the test institute / laboratory



Source: https://wind-fgw.de/wp-content/uploads/2018/11/TG_Part3_Rev25_EN_preview.pdf

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Application Area: Component Test for Certification – Power Hardware: Functional Overview

- Major Lab-infrastructure components for testing electrical power EUT:
  - Flexible (f, U) power grid connection or grid emulation
  - Configurable test busbars for EUT connection
  - Primary energy supply of EUT (Gas, Fuels, DC power, etc.)
  - Auxiliaries (Heat sink, exhaust gas system)
  - Controllable RLC loads
  - Suitable Measurement and control system

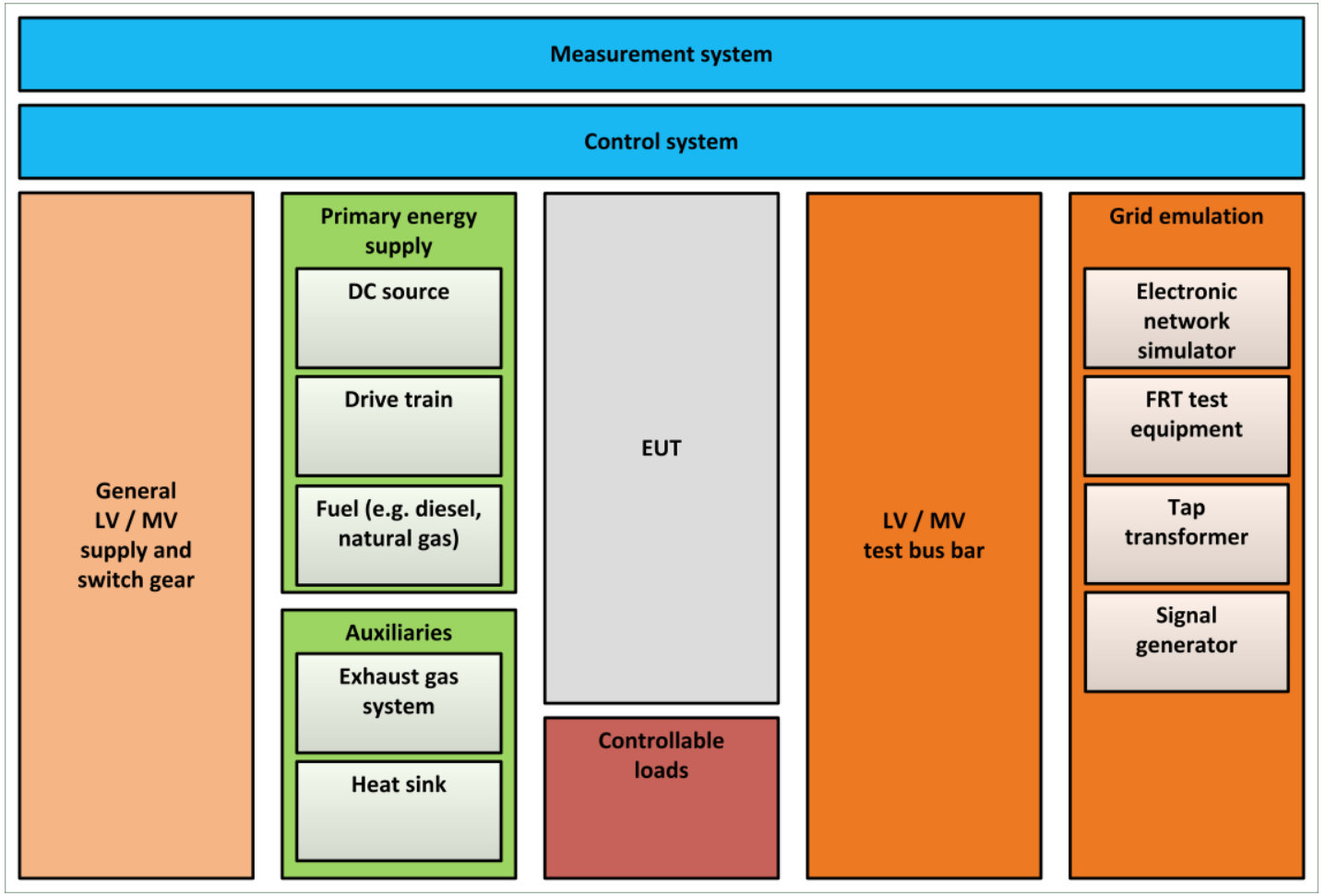

Diagram: T. Degner, Fraunhofer IEE

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Application Area: Component Test for Certification – Power Hardware: Fraunhofer IEE SysTec test lab for grid integration (PNI)

- Public Grid Connection: 20 kV, 50 Hz, 80 MVA
- Mobile 20 kV UVRT test container and
  20 kV OVRT test container up to 6 MVA rated power
- LV test busbar: 3200 A, 1000 V
- MV/LV tap transformer: 1.25 MVA, 254…690 V ± 5x 1%
- LV AC grid simulator: 1 MVA, 100...900 V, 45...65 Hz
- Programmable DC sources (PV Emulator): 3 MW,
  100...1000 VDC @ 3000 ADC
- Programmable RLC loads, 600 kW & ± 600 kvar @ 400 V
- Natural gas connection: 2700 kW@ 90 mbar

Photos: Frank Hellwig

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Application Area: Component Test for Certification – Power Hardware Testing: PGU Type test procedures on Limited Frequency Sensitive Mode (LFSM-O)

- LFSM-O test procedure of FGW TG3 Rev. 25
- Stepwise variation of network frequency value
  1) Rated frequency (50.00Hz) ± 0.05Hz
  2) Rated frequency +0.30Hz (50.30Hz) ± 0.05Hz
  3) Rated frequency +1.40Hz (51.40Hz) ± 0.05Hz
  4) Rated frequency +0.90Hz (50.90Hz) ± 0.05Hz (only for Windturbines)
  5) Rated frequency +0.30Hz (50.30Hz) ± 0.05Hz
  6) Rated frequency (50.00Hz) ± 0.05Hz
- Specific variation of network frequency is at real, interconnected networks not possible
  → For PGU-Tests: Change of network frequency parameter in the PGU control system or
  Tests on programmable grid emulator (AC Source) with sufficient power

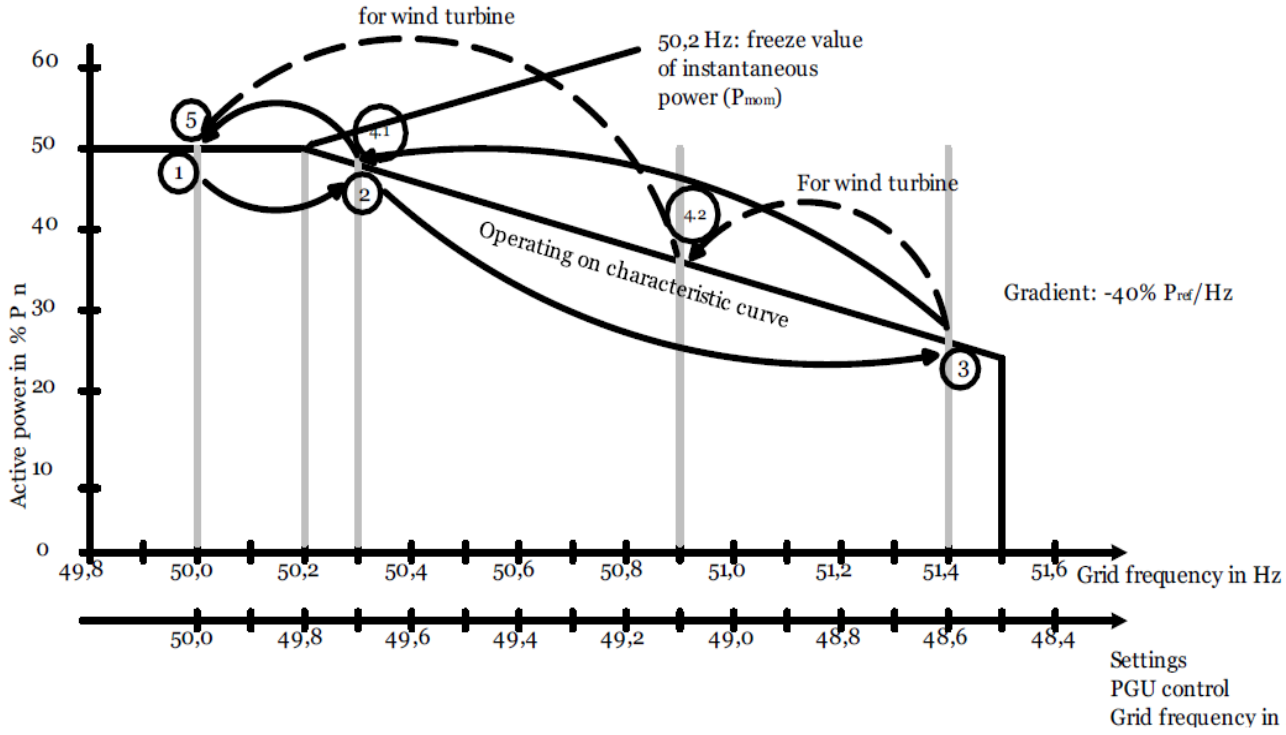

Fig. 4–4: Illustration of active power response for overfrequency and rated power

Source: FGW TG Part 3 Rev.25

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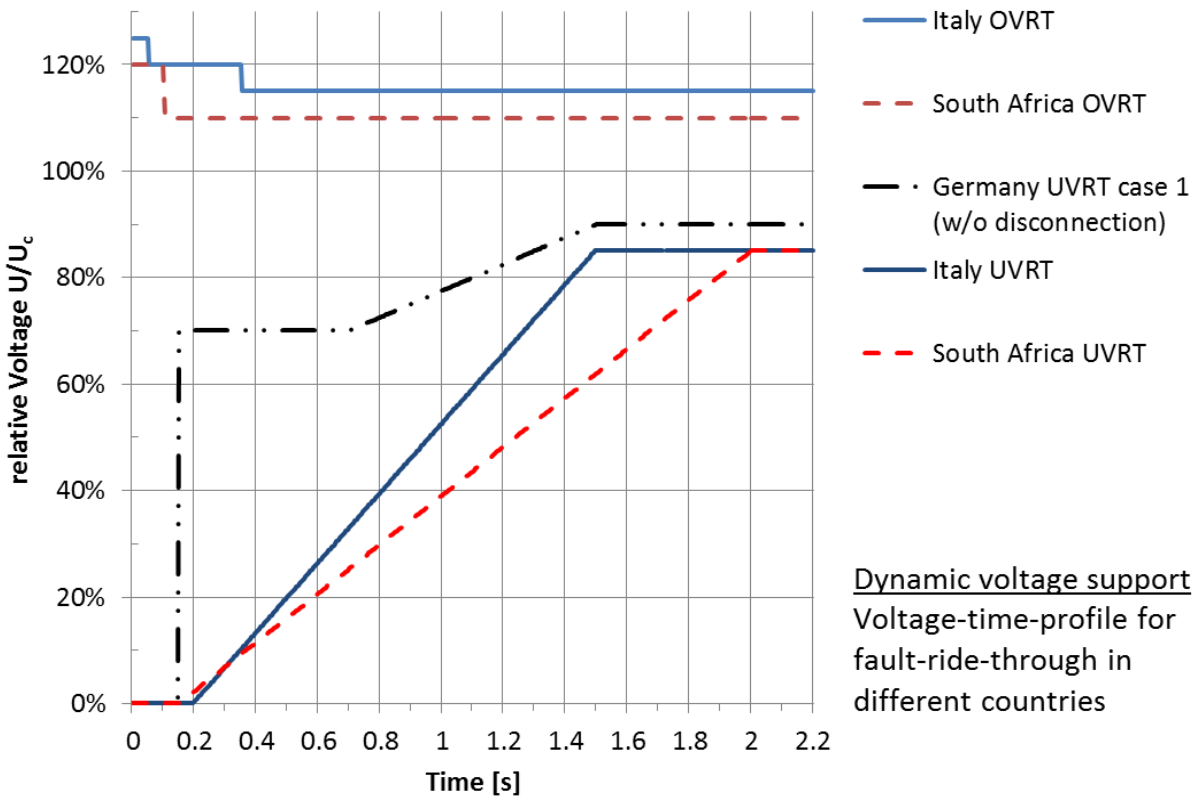
Application Area: Component Test for Certification – Power Hardware Testing: PGU Type test procedures on Under Voltage Ride Through (UVRT)

- Proof of PGU capability to continue operation (& injection of reactive current) during transient events like voltage sags (UVRT)
- UVRT-Requirements of FGW TG3:
  - 4 / 5 different voltage depths
  - Different fault durations
  - 3-ph and 2-ph faults
  - Different PGU setpoints (full load, part load, cosphi = 1, cosphi ≠ 1)
  - Different k-factor settings (for converter based PGU)
- Evaluation of magnitude, build-up and settling time for supply of (additional) reactive current
- After fault clearance: Return to pre-fault values of P and Q within few seconds (1…10s)



Dynamic voltage support
Voltage-time-profile for fault-ride-through in different countries

Source: Schäfer, Arnold, Heckmann: Grid code compliance testing of renewables – New requirements and testing experiences; 1st international conference on Large-Scale Grid Integration of RE in India, New Delhi, 6 - 8 Sep. 2017

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Application Area: Component Test for Certification – Power Hardware Testing: Under Voltage Ride Through (UVRT) test plan for Type 2 PGU acc. to FGW-TG3 Rev. 25

Voltage depth U/U_C in p.u.	Fault duration in ms	Fault Type	Active Power Operating Cond.	Reactive Power Setting Q/P_n	K-Factor-setting	Test-case No.
≤ 0.05 (only for AR-N-4120/ -4130)	Type 2: ≥ 150 (U = 0) Type 2: ≥ 318 (U = 0.05)	3-phase	Full Load (Lab: P ≥0.98 P_n) / (Open air: P ≥0.90 P_n)	0 to ≤ ± 10%	K = 2	0.1
			Part Load (0.10 P_n ≤ P ≤ 0.50 P_n)			0.2
	Type 2: ≥ 220 (U = 0) Type 2: ≥ 406 (U = 0.05	2-phase	Full Load			0.3
			Part Load			0.4
0.20 – 0.30 (only for AR-N-4120/ -4130)	Type 2: ≥ 821 (U = 0.20) Type 2: ≥ 1156 (U = 0.30)	3-phase	Full Load	0 to ≤ ± 10%	K = 2	25.1
			Part Load			25.2
	Option: Multiple Fault test sequence	3-phase	(P > 0.70 P_n)			25.3
	Type 2: ≥ 962 (U = 0.20) Type 2: ≥ 1332 (U = 0.30)	2-phase	Full Load			25.4
			Part Load			25.5
0.45 – 0.60	Type 2:: ≥ 1659 (U = 0.45) Type 2:: ≥ 2162 (U = 0.60)	3-phase	Full Load	0 to ≤ ± 10%	K = 2	50.1
			Part Load			50.2
	Type 2:: ≥ 1888 (U = 0.45) Type 2:: ≥ 2444 (U = 0.60)	2-phase	Full Load			50.3
			Part Load			50.4
0.45 – 0.60 (only for AR-N-4110)	Type 2:: ≥ 1371 (U = 0.45) Type 2:: ≥ 1982 (U = 0.60)	3-phase	Full Load	0 to ≤ ± 10%	K = 2	50.5
	Type 2:: ≥ 1610 (U = 0.45) Type 2:: ≥ 2395 (U = 0.60)	2-phase	Full Load			50.6
0.70 – 0.80	Type 2: ≥ 2498 (U = 0.70) Type 2: ≥ 2833 (U = 0.80)	3-phase	Full Load	0 to ≤ ± 10%	K = 2; K = 4 (75.5)	75.1
			Part Load	0 to ≤ ± 10%, max. underexcited, max. overexcited		75.2, 75.3, 75.4, 75.5
	Type 2: ≥ 2815 (U = 0.70) Type 2: ≥ 3000 (U = 0.80)	2-phase	Full Load	0 to ≤ ± 10%	K = 2; K = 4 (75.8)	75.6
			Part Load			75.7, 75.8
0.75 – 0.85 (only for AR-N-4110)	Type 2: ≥ 2593 (U = 0.75) Type 2: ≥ 3000 (U = 0.85)	3-phase	Full Load	0 to ≤ ± 10%	K = 2	80.1
	Type 2: ≥ 3000	2-phase	Full Load	0 to ≤ ± 10%	K = 0	80.2
0.85 – 0.90	Type 2: ≥ 60000	3-phase	Part Load (P ≥ 0.10 P_n)	0 to ≤ ± 10%	K = 2	85.1

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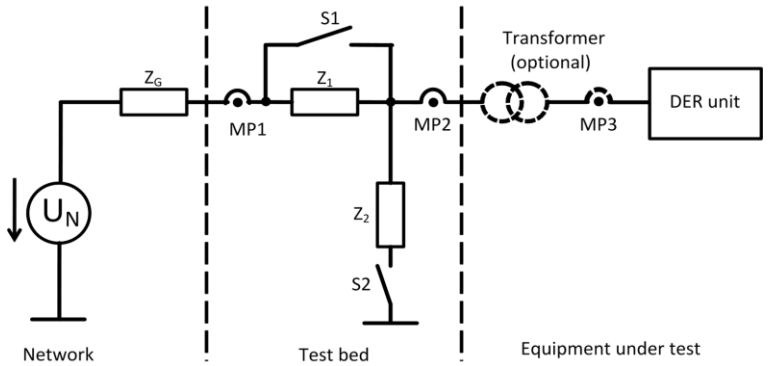
Application Area: Component Test for Certification – Power Hardware: Mobile Test Equipment for PGU Type tests on UVRT

- Data of mobile Fraunhofer IEE UVRT test container:
  - Power range: 0.25 MVA to 6 MVA
  - Voltage levels: 10 kV, 20 kV
  - Frequency: 50 Hz
  - Short-circuit power range: 80 MVA to 350 MVA
  - Ambient temperature:-25 to +60 °C
  - Operating temperature: 0 to +50 °C
  - 40-feet sea container



Photos: G. Arnold, Fraunhofer IEE; F. Hellwig

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Application Area: Component Test for Certification – Power Hardware: Mobile Test Equipment for PGU Type tests on OVRT

- Data of mobile Fraunhofer IEE OVRT test container:
  - Power range: 0.25 MVA to 6 MVA
  - Voltage levels: 10 kV, 20 kV
  - Frequency: 50 Hz
  - Short-circuit power range: 80 MVA to 350 MVA
  - Ambient temperature:-25 to +60 °C
  - Operating temperature: 0 to +50 °C
  - 40-feet sea container
- Generation of over voltages of up to 1.4 p.u.

Photos: Fraunhofer IEE

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Application Area: Component Test for Certification - Information and Communication Technologies (ICT)

- Compliance testing
  - Test specification (and beyond)
  - Compliance
  - Certification
- Simulation / HIL / CHIL tests
  - Communication robustness testing
  - Positive and negative tests
  - Stress tests
- Protocol implementation robustness testing
  - Tests against cybersecurity attackers and misbehavior

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Application Area: Component Test for Certification - Information and Communication Technologies (ICT)

- Major Lab-infrastructure components for ICT testing:
  - Test System Computer with suitable (software based) testing tools
  - ICT Interfaces (e.g. ETH or RS 485 based)
  - Physical ICT network (cabling, switches, hubs etc.)
  - Power amplifier, test signal generator (for HIL testing)
  - RTU simulator (e.g. PLC)

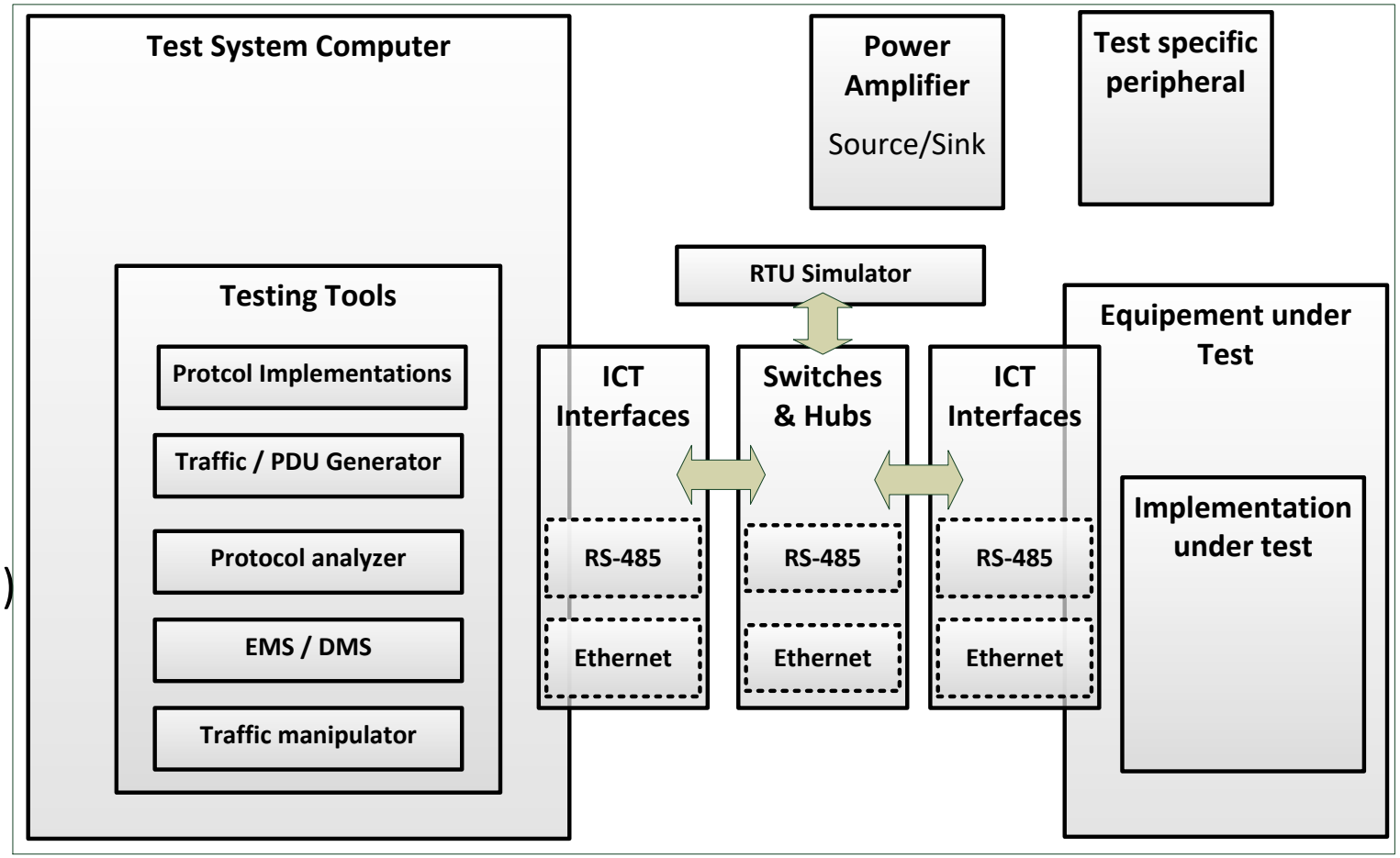

Diagram: P. Hasse, Fraunhofer Fokus

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Application Area: Component Test for Certification - Information and Communication Technologies - Example

- PGU Controller for CHP units with gas-engine and synchronous generator
- Proof of compliance acc. to pre-defined Grid Code (e.g VDE AR-N 4110)
- PGU controller is equipped with various interfaces (AIN, AOUT, DIN, DOUT, RS485, USB, CAN, ETH) to communicate with other PGU components (gas engine, generator, circuit breaker, GUI etc.)

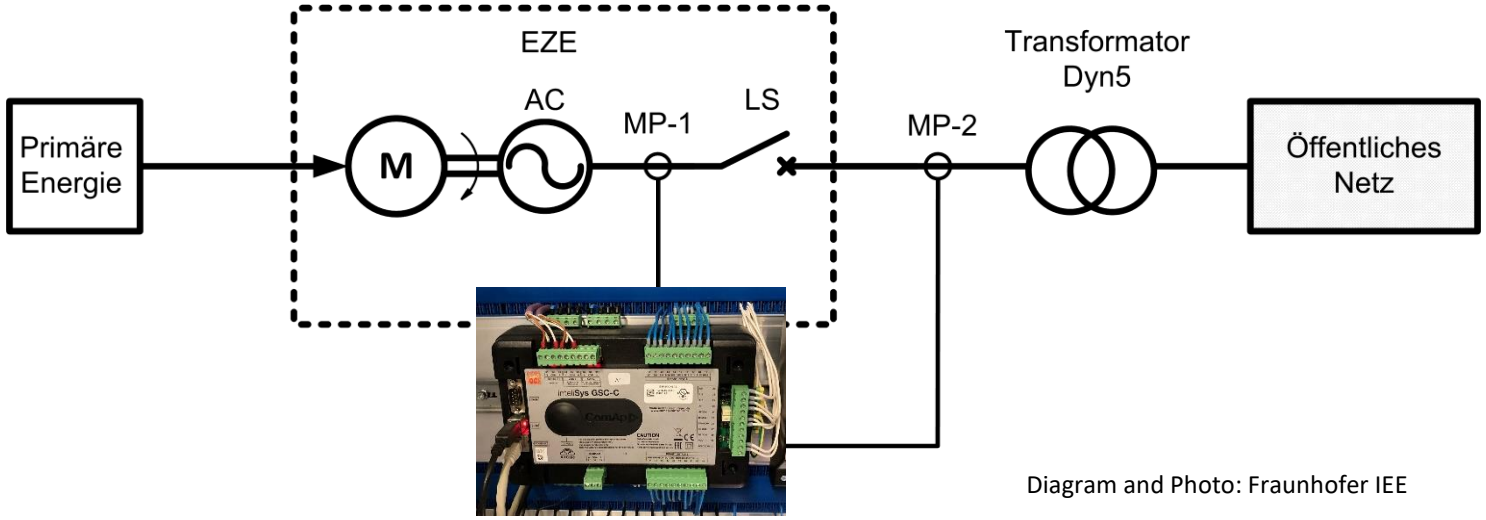

Diagram and Photo: Fraunhofer IEE

M.O.E. GmbH
Certification body
Accredited by
DIN EN ISO/ IEC 17065: 2013
DAkkS registration number: DE-ZE-12005-01-00

M.O.E. MOELLER OPERATING ENGINEERING
CERTIFICATION · MEASUREMENT · INSPECTION

Component certificate

No.: MOE 19-EZE-0041-02
Revision: 2.0

Manufacturer	ComAp a.s.
Type of component	PGU controller for Type 1 generating units
Technical specifications	refer to Table 2-1
VDE code of practice	VDE-AR-N 4110:2018-11 "TAR Mittelspannung"
Certification programme	FGW Technical guideline part 8 Rev. 9
Applicable standards and guidelines	FGW Technical guideline part 3 Rev. 25

The PGU controllers as stated above conform to the requirements of **VDE-AR-N 4110:2018-11 "TAR Mittelspannung"** (medium voltage).
The following restrictions and deviations apply: refer to Restrictions
Table 5-1
The manufacturer has demonstrated certification of the quality management systems of their production facility according to ISO 9001.

This certificate contains the following information:
- Technical specifications of the PGU controller and valid software versions
- block diagram of the PGU controller
- summary data about the properties of the PGU controller;

This certificate comprises 14 pages and the following annexes:
- **Annex I: Evaluation report MOE-19-EZE-0041-01, Rev. 2.0**

This certificate is valid until 2025-01-30.

Itzehoe, **2020-02-20**

20.02.2020 — **Dipl.-Ing. (FH) Michael Voß** — **Head of the certification body**
20.02.2020 — **Dr. Rainer Zimmermann** — **Senior expert of the certification body**

M.O.E. GmbH certification body, Fraunhoferstraße 3, D-25524 Itzehoe, info@moe-service.com

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Source:
https://www.comap-control.com/productfile/525b45a4-12bd-4dce-ab01-a957211b6c2a

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Application Area: System Testing and Demonstration – Hardware-in-the-loop (HIL)

- Hardware-in-the-loop (HIL) is a testing methodology combining Real-Time (RT) simulators and hardware components.
- Depending on the hardware under test, one can distinguish between
  - Power Hardware-in-the-loop (PHIL) → Connected to RT simulator via analogue and digital In- and Outputs and a power amplifier
  - Controller Hardware-in-the-loop (CHIL) → connected to RT simulator either via communication protocols or analogue and digital In- and Outputs
- Advantages of HIL testing
  - Testing of realistic fault conditions or rare network events
  - Flexibility in changes of grid and component simulation models and its parameters

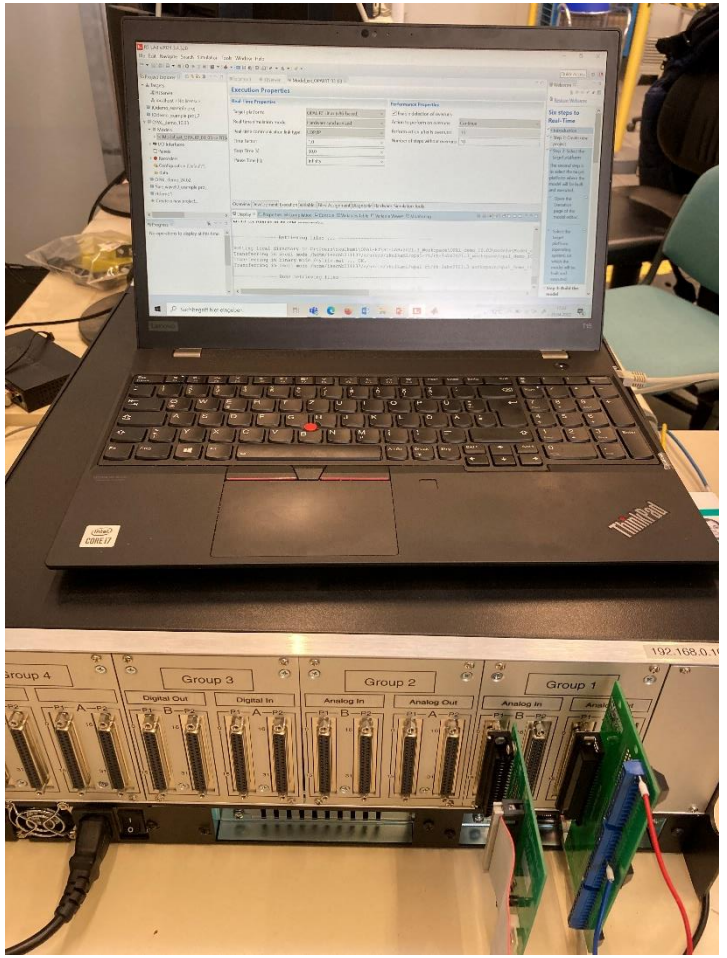

Photo: G.Arnold, Fraunhofer IEE

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Application Area: System Testing and Demonstration – Hardware-in-the-loop (HIL): Functional Overview

- Major Lab components for HIL testing:
  - Real Time (RT) Computer / RT Simulator
  - RT Simulation Environment (RMS and/or EMT mode)
  - Suitable ICT interfaces and protocols (Co-Simulation – SIL)
  - Input and Output Converter with Analog IO and Digital IO (CHIL and PHIL)
  - Power Amplifier and measurement probes (PHIL)

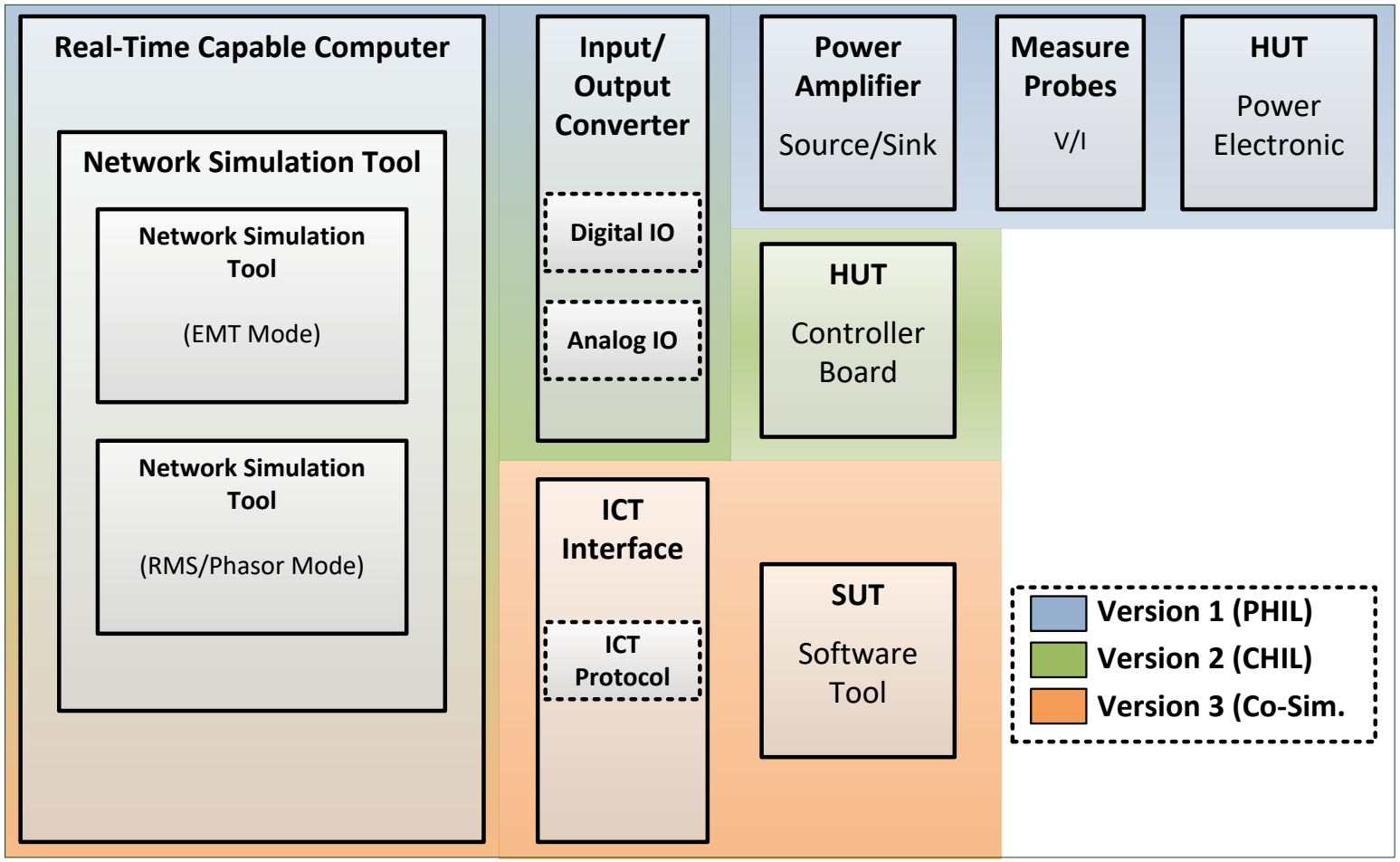

Diagram: R. Brandl, Fraunhofer IEE

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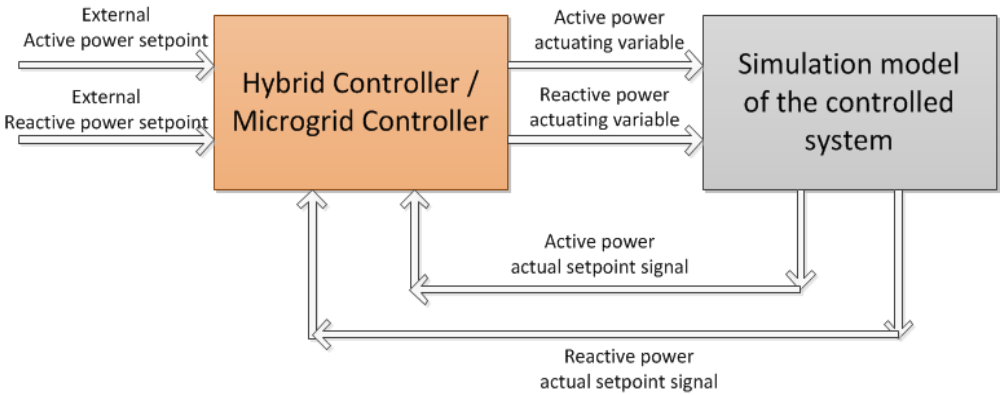
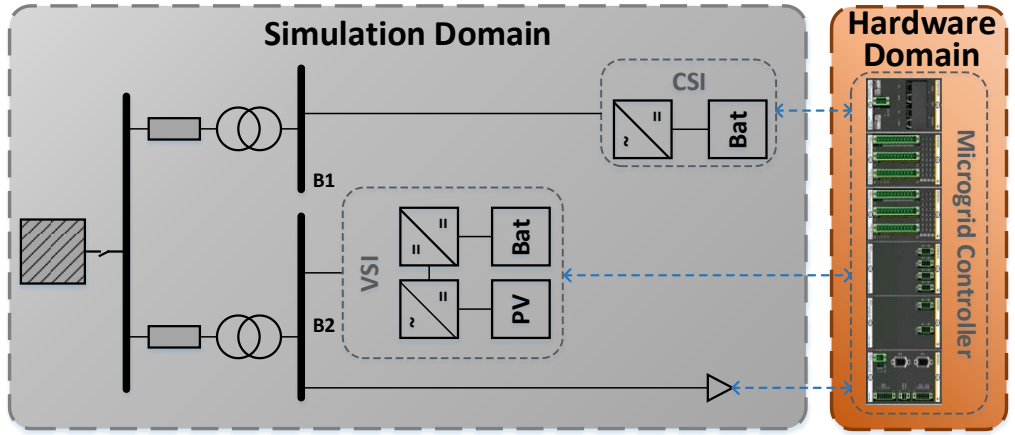
Application Example: Controller Hardware In the Loop (CHIL) tests for Hybrid Controller

- Test procedure based on German technical guideline FGW TG3 Rev.25
- Determination of Hybrid Controller behaviour under following conditions:
  - Active power setpoints
  - Frequency changes
  - Reactive power setpoints
  - Voltage changes
  - Different setpoints at two interfaces
  - Controller malfunction (e.g. loss of communication, faulted power supply)





Source: Brandl, Nuschke, Montoya, Strauss-Mincu: Towards Holistic Testing: Development of a Microgrid Controller

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Application Area: System Testing and Demonstration – Hybrid System Test Platform

- Main Goals
  - To demonstrate the operational behaviour of smart grid components at real distribution network segments (MV, LV)
  - To investigate and analyse interactions between various (smart) grid components in a realistic environment
- Interoperability tests could be performed using products of different manufacturers
- Long term tests with various environmental conditions (temp., humidity, solar irradiation, etc.) are possible e.g. for determination of ageing effects

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Application Area: System Testing and Demonstration – Hybrid System Test Platform: Functional Overview

- System under Test is complex and often part of the Lab
  - Lines, Line emulation
  - MV, LV Switch gear
  - Transformer
  - Controllable loads
- Other major Lab components for hybrid system testing:
  - Power grid connection or emulation
  - Primary energy supply (Fuels, DC power, etc.)
  - Auxiliaries (Heat sink, exhaust gas)
  - Measurement and control system

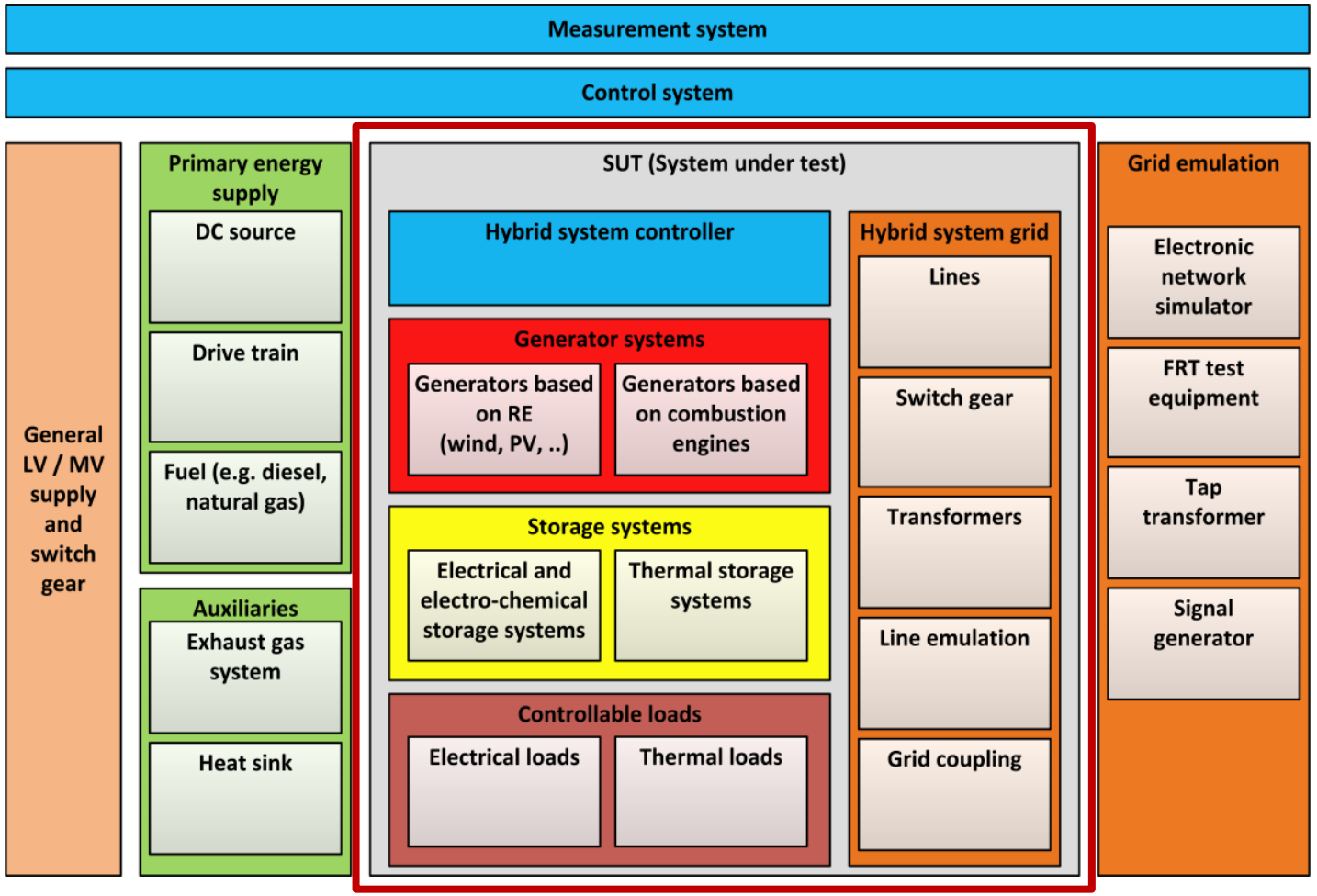

Diagram: T. Degner, Fraunhofer IEE

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Fraunhofer IEE Hybrid Test-Lab

- Fraunhofer IEE- SysTec:
  Medium voltage (20kV) test grid and outdoor test bed for hybrid systems and micro grids

Photo: T. Degner, Fraunhofer IEE

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Fraunhofer IEE SysTec – Smart Grid Low Voltage Feeder (SLGV) components

- Scale 1:1 low voltage grid
- 630 kVA MV/LV transformer with On-Load Tap Changer (OLTC)
- Representation of households / test houses
  - 3 small buildings with roof-top integrated PV
  - electrical storage, heat pump, different household loads, charging stations for electric vehicles
  - 1 flexible test container (bring your own device)
- Power quality measurement equipment
- Configurable grid topology with different cable cross sections

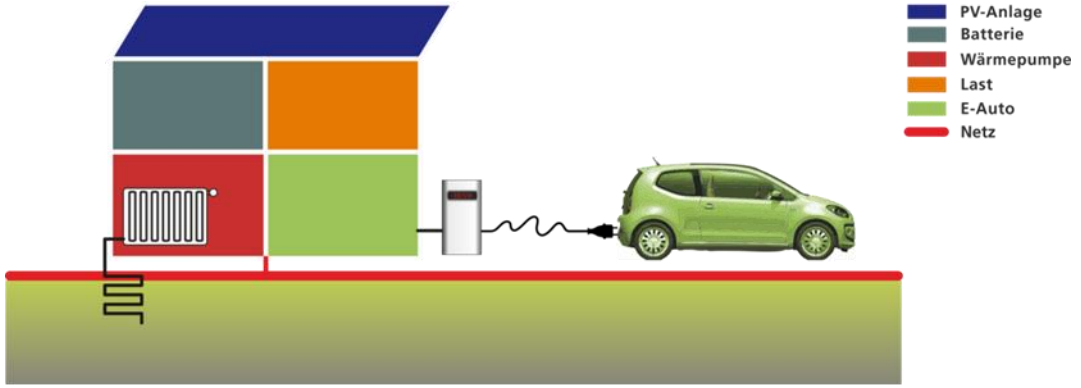

Diagram and Photo: Fraunhofer IEE

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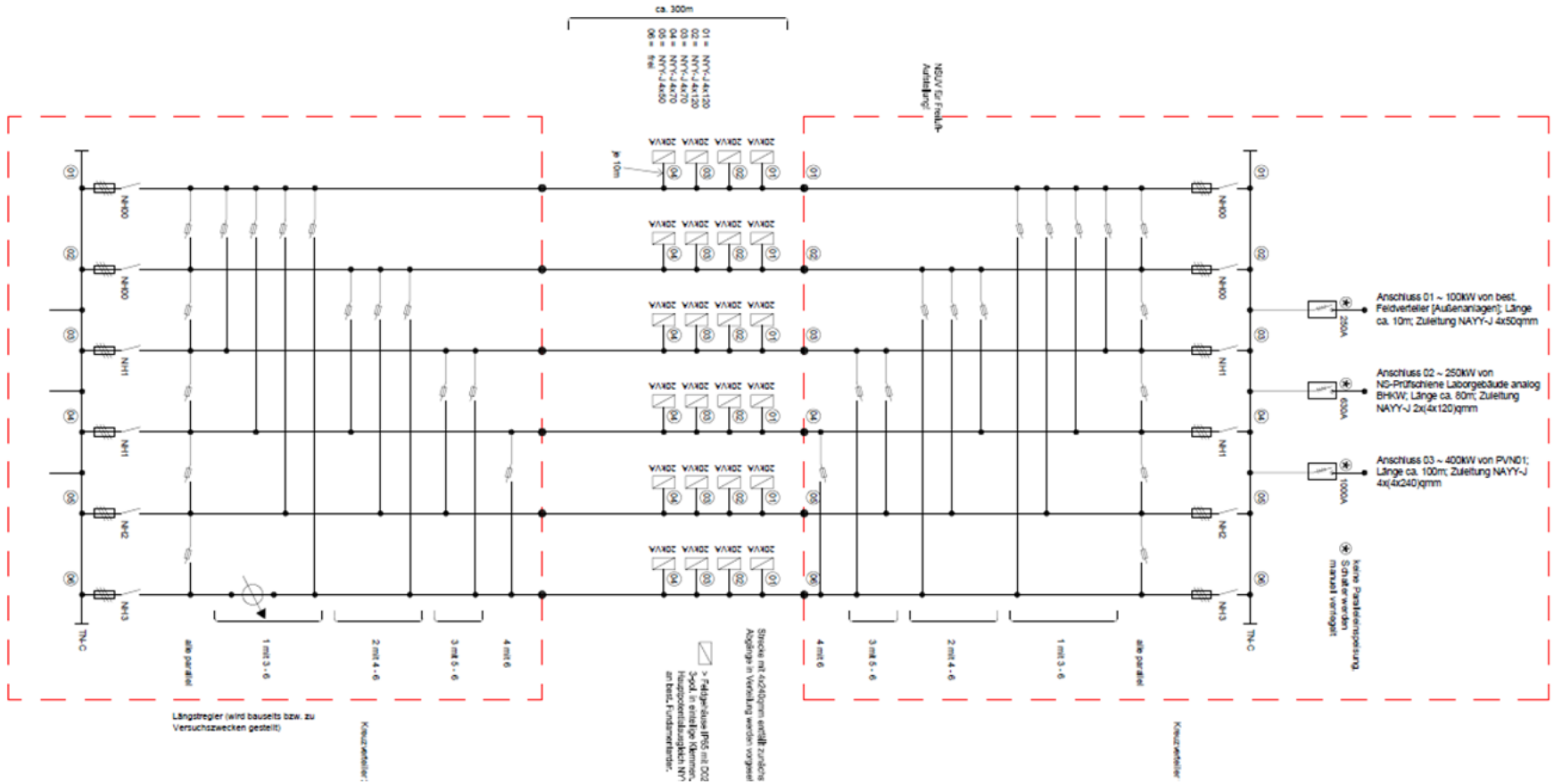
Fraunhofer IEE SysTec – Smart Grid Low Voltage Feeder (SLGV) grid topology

- 5 LV lines (ca. 300 m)
  - Different cross sections (120/120/70/70/30 mm²)
- Each of the 3 test houses can emulate up to 5 housing connections



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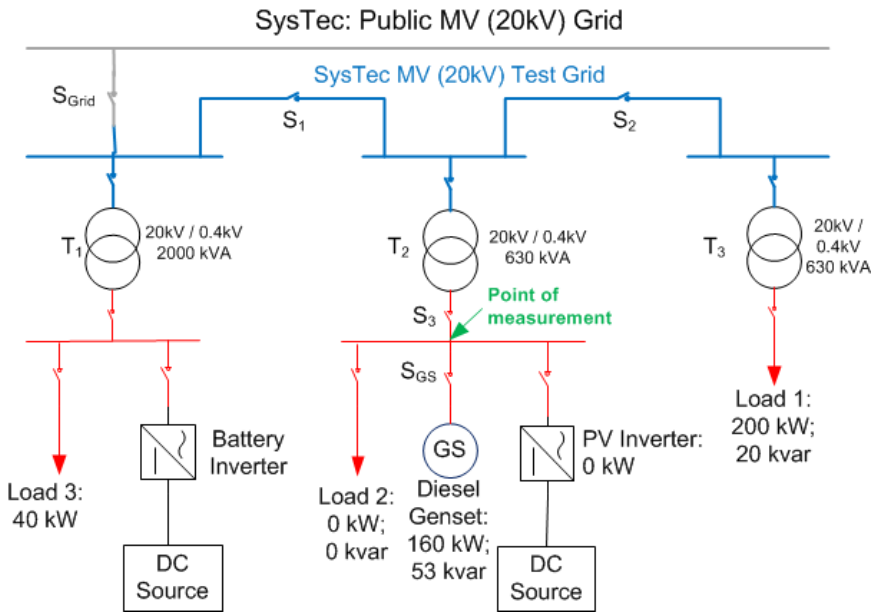
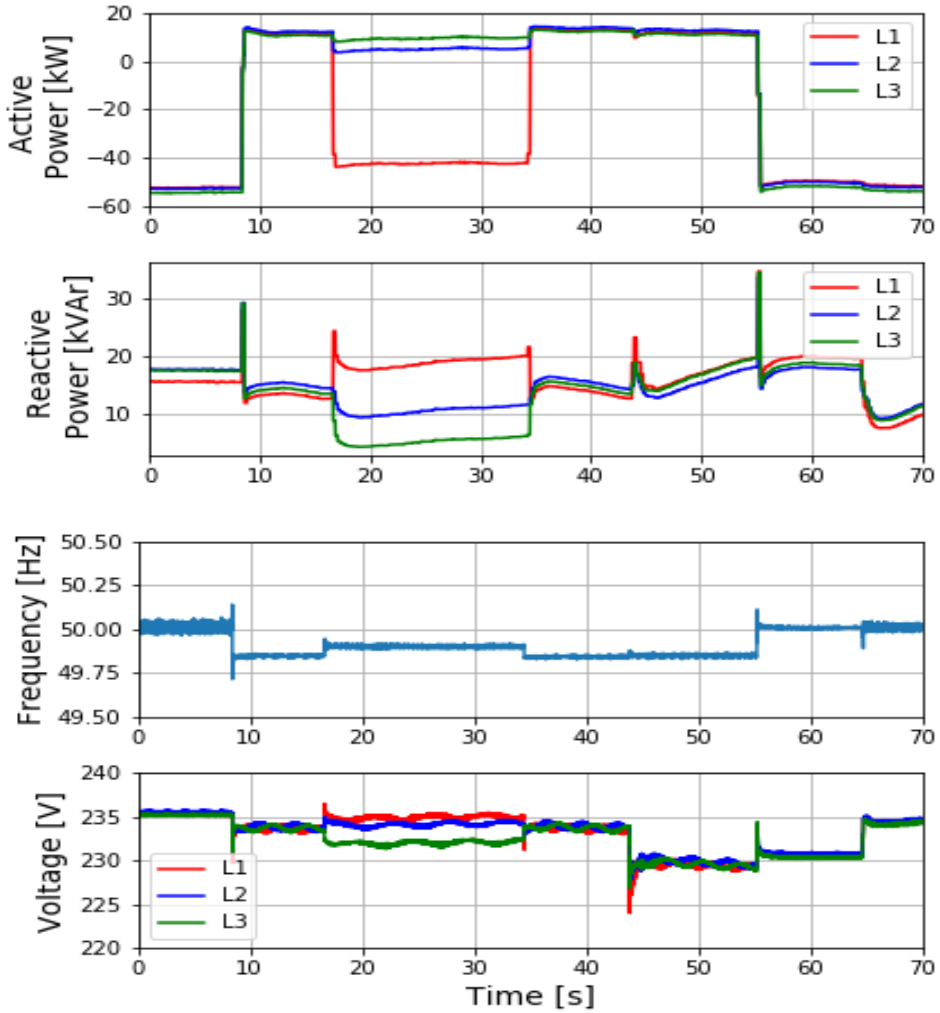
Application Example: System Tests - Island operation of Diesel genset & Battery Inverter





- Joint island operation of Diesel Gen-set; Battery Inverter, Loads and PV inverter
- Battery inverter responsible for freq. and voltage control; f-droop setting: 2 Hz/P_R; P_R = 2200 kVA
- Diesel operated at a fixed P value; RLC Loads with stepwise variations

Source: Arnold G., Niedermeyer F.: Lab Testing of Hybrid Power Systems; EPGC Industry Seminar; Singapore, 12 Nov. 2018

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Testing and evaluation of results
What is essential for all (compliance) test procedures?

- Clear definition of / requirements on:
  - Test setup (e.g. field measurement vs. test lab, measurement quantities, environment. conditions)
  - Measurement system & conditions (e.g. sampling rates, meas. uncertainties)
  - Methods of testing and test plan
  - Operating conditions of the Equipment Under Test (EUT)
  - Set point values and/or characteristics
  - Test sequences and necessary repetitions
  - Evaluation process (e.g. processing of measurement data, definition of tolerances for reaching set point values etc.)
  - Test report (also incl. information like calibration certificates of used equipment)
- **Objective: Comparability and Reproducibility of test results!**

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Overview of DIN EN ISO/IEC 17025:2018-03: General requirements for the competence of testing and calibration laboratories

- DIN EN ISO/IEC 17025 specifies general requirements for the competence, impartiality and uniformity of laboratory procedures.
- This standard contains requirements for laboratories to demonstrate that they work competently and are capable of achieving valid results… .
  It requires the laboratory to plan and implement measures to address risks and opportunities. Dealing with both risks and opportunities provides a basis for increasing the effectiveness of the management system, achieving improved results and avoiding negative effects. The laboratory is responsible for deciding which risks and opportunities need to be addressed.
- Clients of laboratories, authorities, organisations and programmes using peer evaluation, accreditation bodies and others can use this standard to confirm or recognise the competence of laboratories.

Table of Contents

Few forewords, Introduction, General requirements for the competence of testing and calibration laboratories

1. Scope
2. Normative references
3. Terms and definitions
4. General requirements
5. Structural requirements
6. Resource requirements
7. Process requirements
8. Management system requirements

Annex A: Metrological traceability (informative)

Annex B: Application of this International Standard for processes and services (informative)

Bibliography (informative)

Source: https://www.beuth.de/en/standard/din-en-iso-iec-17025/278030106

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DIN EN ISO/IEC 17025: Requirements for lab personnel

- Criteria for selection and use of lab personnel
  - Competent qualified appropriately on basis of
    - Professional education (Qualified Electrician, Bachelor, Master, Dipl.-Ing. of electrical engineering)
    - Regular (internal and external) Training (different topics, e.g. testing procedures, operation of lab infrastructure such as MV switchgear, measurement devices, lab safety, first aid …)
    - Testing experience (how often and deep involved in certain testing projects)
    - demonstrated skills
  - Persons, interpreting test results or reviewing test reports should have additional qualifications
- Policy to identify training needs
- Effectiveness of training shall be evaluated
- Authorize specific staff for specific work (Different functions and responsibilities)

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Conclusions and Outlook

- For design of smart grid lab infrastructure different criteria (testing scope, EUT types, EUT ratings, mechanical dimensions, climate conditions, number of parallel testbeds, etc.) needs to be considered in detail
- Especially for compliance and hybrid system testing a flexible lab infrastructure is very important
  - Large variety of EUT types (e.g. PV inverter or CHP units with differing rated power and operating ranges) from different manufacturers
  - Differing grid code requirements in various countries
  - Grid code requirements are increasing due to several reasons (new technologies, high RE penetration)
- Quality assurance measures (e.g. accreditation acc. to ISO/IEC 17025 , regular calibration of measuring systems, participation in standardization, etc.) mandatory for grid compliance testing
- Hardware in the Loop testing methodologies (SIL, CHIL, PHIL) are very flexible tools for different technologies, EUT setups and ratings, different grid configurations and various test cases.
- Not only the investments but also the operational and maintenance costs should be taken into account
- Well and continuously trained as well as highly motivated lab personnel should be also considered as key factor for a smart grid lab infrastructure

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