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**Gehrke, Oliver; Ziras, Charalampos; Heussen, Kai; Jensen, Tue Vissing; Bindner, Henrik W.**

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# TESTBEDS FOR ACTIVE DISTRIBUTION NETWORKS: CASE EXPERIENCE FROM SYSLAB

Oliver Gehrke, Charalampos Ziras, Kai Heussen, Tue V Jensen
and Henrik W Bindner

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**Abstract**

Active distribution networks integrate controllable energy resources into new coordinated operational strategies based on distributed or centralised control schemes. Especially for new and innovative players in the field, laboratory testing serves to identify integration needs and reveals real-world technology issues that cannot be recognized in simulated environments. Industrial and certification laboratories address such needs for component-level tests, however, new types of facilities are required for system-level testing, accommodating the interactions of both physical and cyber-infrastructures. This paper reflects on case studies of recent integrated system experiments carried out in the integrated test facility SYSLAB. These cases are used to observe evidence for the evolving testing needs, and extended laboratory requirements are distilled.

## 1 Introduction

In recent years a number of developments are transforming the traditionally passive distribution networks into what is commonly known as active distribution networks (ADNs) [1]. These include the wider adoption of information and communication technology (ICT) and means of increased observability and controllability of the networks by distribution system operators (DSOs). The increase of the penetration of controllable distributed energy resources (DERs) and the need for their secure integration in the power system call for a more active role from the DSO side [2].

This transformation of the distribution networks and the large-scale DER integration require testing and validation. However, electrical power systems do not easily lend themselves to field trials of new and unproven technology. While small sections of the grid can be taken out of operation, for example for the deployment of a new type of generator, the power system as a whole is a continuously operating, critical infrastructure. Any breakdown has a large societal and economic impact. Research and development in the area of power system control has always been required to make extensive use of simulation technology as a primary feedback element when maturing a new concept.

Pure software-based simulation is the first step in evaluating new technology such as coordinated control strategies in large-scale systems. In recent years, real-time hardware-in-the-loop (HIL) technology is increasingly adopted to directly incorporating physical control devices (C-HIL) and power components into a simulated environment [3, 4]. Such simulation-based technologies overcome the challenges of cost, scalability and ease of use. However, established simulation tools struggle to reflect properties and behaviour of ICT systems which form an integral part of ADNs [3]. Likewise, established power system simulation tools cannot serve to mature concepts such as energy sector coupling. Coupling of mature tools by means of co-simulation is a promising approach for research purposes [5, 6, 7]; however, the present state of technology causes these setups to be developed ad-hoc. They therefore lack the validation credentials of the established tools.

New types of experimental facilities can fill this gap of proof-of-concept testing and model validation. As such a test facility, SYSLAB enables the testing of cyber-physical smart distribution systems in a holistic manner by allowing the integration of the different interoperable layers of ADNs such as ICT, physical grid and control strategies under different testing scenarios.

The goal of this paper is to outline the emerging system testing needs of future power systems and present four case studies from recent experiments in the integrated test facility SYSLAB, as examples of the evolving testing and validation requirements.

# 2 Emerging System Testing Needs

The power system is becoming increasingly more complex as more roles are defined due to the unbundling of the sector. New types of equipment are being deployed and more advanced monitoring and control functions are developed and put into operation regardless whether a centralized or distributed design approach is taken. In recent years, this complexity has created a demand for more formal design methodologies to ensure safe and secure operation [8]. These grid architecture tools cover the physical system as well as the associated communication and control infrastructure, and capture the physical behaviour as well as actor interaction and coordination between controllers. The interaction between physical components and controllers and the overall coordination is very complex and it is necessary to perform tests to validate and develop the design models.

From a bottom-up perspective, the power system is seeing the deployment of components with extended functionality, such as secondary transformers with on-load tap changing (OLTC), building management systems and heat pumps that can participate in managed portfolios for providing flexibility, and new sensors including low-cost phasor measurement units used to augment smart meter data to provide better visibility of the network [9]. These will be integrated in advanced distribution management systems, the active management of the network and the other business processes of the DSO such as planning and asset management [10]. Sources of customer-side flexibility such as electric vehicles (EVs) and heat pumps will be actively managed according to energy prices and the demand for ancillary services. This development calls for pre-integration tests of components to validate their behaviour in normal and extreme situations and for the validation of control algorithms for large portfolios of flexible units before deployment.

# 3 Case studies on Integrated System Experiments

This section studies the laboratory requirements of four recent industry and research experiments carried out in SYSLAB.

## 3.1 HOLISTICA

In this test, SYSLAB hosted the performance assessment of a distribution-level voltage controller coordinating an OLTC transformer and the reactive power of multiple DERs, in both rural and urban grid configurations (Fig. 1). For this experiment the lab was required to: 1) accommodate an OLTC transformer, 2) be configurable to several realistic feeder topologies, 3) integrate a commercial smart controller, and 4) control multiple loads, DERs and EVs, in both deterministic and realistic free-wheeling power flow scenarios [11].

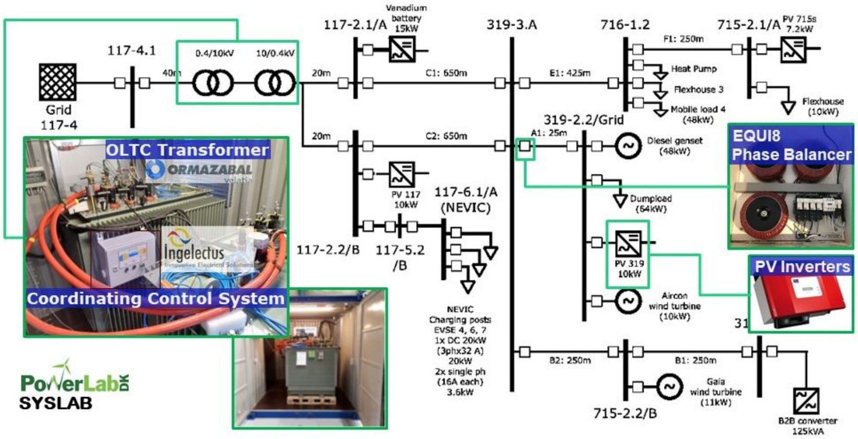

Figure 1: Physical setup of the HOLISTICA experiment.

After 4 days of system integration and configuration, the high automation level at SYSLAB enabled about 120 experiments in 6 days, which included experiments in three different grid topologies [13, 12]. The control technology and

OLTC transformer were thereby validated in both controlled and operational environments, lifting the control solution significantly closer to market-readiness[1].

To enable these experiments, SYSLAB offered remote interfaces for 14 controllable DERs (photovoltaics (PVs), EVs, battery, back-to-back converter, 3-phase and 1-phase controllable loads), as well as real-time measurements on all connection points. As external hardware two OLTC transformers in back-to-back configuration in a container, as well as a phase-balancing device were integrated. Prior to the experiments, a PowerFactory model of the laboratory allowed the pre-deployment testing of the control systems. The rollout and testing was then accelerated by laboratory automation, simplified/adaptable DER communication interfaces and design support via a low-voltage network model. Unique features required in this experiment were:

- the need for in-line integration of power components in realistic grid configurations and real DERs;
- the laboratory use both for operational validation (TRL7), and deterministic characterization environment in the same facility (TRL4-6).

## 3.2 Team-VAR

This project aimed at the physical validation of a novel type of optimizing distributed control algorithm [14, 15]. It involved two separate testing sessions with a gap of over one year [16, 17]. The first session concluded without validation but with important learnings for algorithm improvements and deployment strategy [16]. The second session resulted in the successful validation of two algorithm variants, reported in [18, 19]: a centrally computed variant [18] and a physically distributed control system [19]. The test scenario required a deterministic setup in which several controllable inverters are located along a long radial, as illustrated on Fig. 2.

By producing active power at the end of the radial, and consuming power close to the upstream connection, voltage first drops and then rises, causing an overvoltage at the far end. As the authors demonstrate, a droop control (in fact, any decentralized non-communicating control) scheme would be unable to restore an optimal voltage profile under this scenario, and the proposed control scheme is able to optimally restore the system using the proposed primal-dual iteration scheme, as reported in [18, 19]. In the fully distributed variant [19], local computers control the voltage and reactive power, perform simple computations and communicate with peers along the physical network topology.

The requirements for the lab infrastructure regarding this experiment [19] were:

- software platform for distributed deployment of local asynchronously communicating controllers without shared memory [20];

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[1] cf. "HOLISTICA success story", online at ERIGrid.eu.

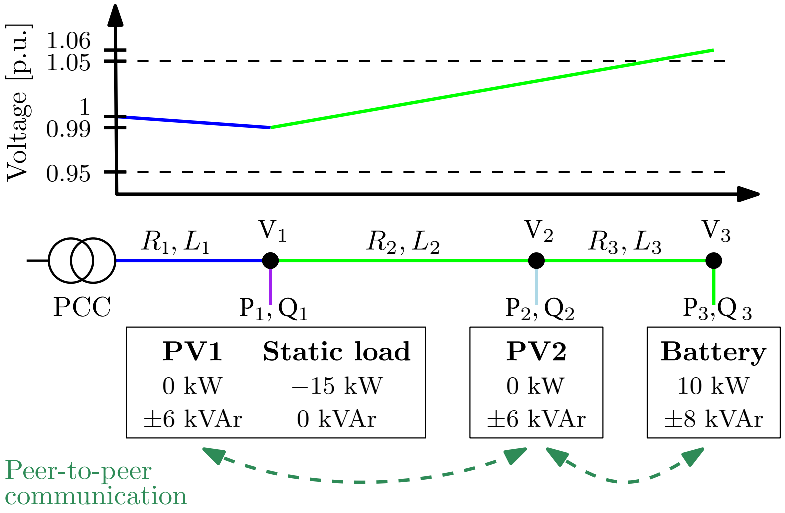

Figure 2: Test setup for Team-VAR experiment. Figure reproduced with permission from [19].

- a physically distributed computing infrastructure requiring non-local communication patterns.

Lab testing revealed gaps between the theory and application of the algorithm design [16], such as the need for distributed anti-windup schemes for distributed integrators [19]. Testing also led to algorithm improvements and minor adjustments during the second session, enabled by the lab's testing platform [20], providing validation (TRL4, controlled environment) of the improved design.

## 3.3 DREM

The DREM project proposed and developed a trade permission system (TPS) as a mitigating solution for congestion in distribution grids caused by insufficient coordination between DSOs and other actors in the energy system. A primary focus of the project was the conflicts of interest between DSO operation and transmission system operator (TSO)-level services delivered by flexible units in the distribution grid, facilitated by aggregators (AGGs) and balance responsible partys (BRPs). The experimental setup is shown in Fig. 3.

In one of the concrete test cases, an AGG responds to a TSO activation by ordering a consumption increase for a number of flexible loads on a distribution feeder. This creates a congestion issue for the DSO. The proposed TPS provides a mechanism for the DSO to anticipate these situations and to indicate the presence of grid capacity constraints to the affected AGGs/BRPs without, for reasons of competition, needing to know their identity. The project executed a number of laboratory tests to validate the correct system integration between

TPS, AGG/BRP, flexible units and an (emulated) DSO prior to a field test. This resulted in the following requirements for the lab infrastructure:

- the ability to replicate a real-world DSO feeder. The test required a long split-loop feeder with multiple distributed loads and generation which could be reconfigured to a single-ended supply during the test;
- a high degree of automation, specifically the possibility for 3rd-party remote control of all flexible assets and the ability to emulate the operation of a DSO (grid monitoring and automatic breaker control);
- the ability to integrate laboratory assets and local control infrastructure with 3rd-party control systems located outside of the laboratory, in closed-loop, real-time operation.

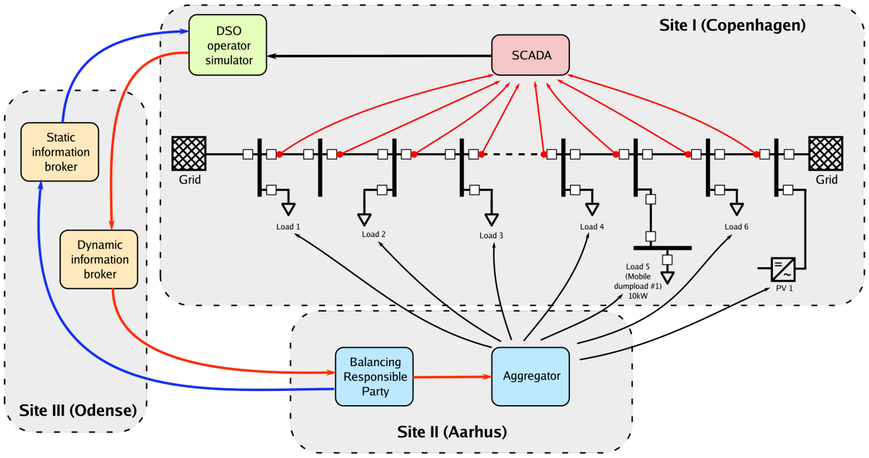

Figure 3: Physical setup for the DREM experiment.

The experiment showed that the proposed TPS was able to resolve the actor conflict by allowing the DSO to communicate capacity limits to the AGG. It demonstrated that the system is able to mitigate congestion caused by flexible assets. During laboratory testing, several issues were found relating to mismatched information models between the individual subsystems developed by different entities. Being able to easily detect these issues due to the richer instrumentation of the laboratory, and being able to mitigate the issues with a short turn-around cycle provided the primary value of the laboratory test.

## 3.4 Direct Load Frequency Control

A series of experiments [21] were conducted with the purpose of verifying a novel tuningless direct load frequency control scheme. The experimental setup is shown in Fig. 4. This scheme relies on increased observability, which is to

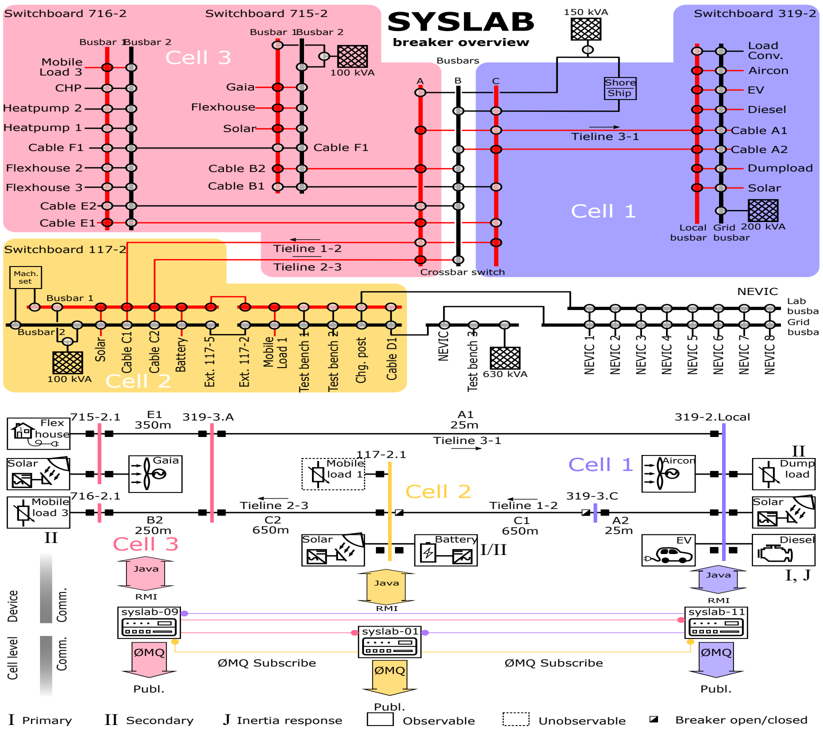

Figure 4: Overview of SYSLAB and experimental setup for the Direct LFC experiments - figure adapted from [21].

be expected in future power systems, to replace the traditional load frequency control (LFC) which has the drawback of requiring very careful tuning.

After the proposed control framework was tested via simulations, experiments were also conducted in SYSLAB, to provide a real-world verification by including a variety of factors whose behaviour cannot be precisely captured in a simulation setup, such as system frequency dynamics, delays and communication-related aspects of the controllable units, response dynamics, etc. The ability of the control scheme to regulate frequency under various disturbances, imperfect parameter knowledge, partial observability and controllability and other uncertainties was demonstrated.

The experimental work confirmed the applicability of the theoretical algorithm design, where only a low-pass filter was added to the original peer-to-peer asynchronous algorithm design. The experiments, resulted in the following requirements for lab infrastructure:

- sufficient amounts of automated DER units dispersed across the grid and wide network (re-)configuration options, allowing for the operation of the electrical system in a multi-cell setup;
- islanded operation, representing a multi-cell system, using physical and

virtual parameters for coordination;

- reconfiguration capabilities;
- ability to operate units with a flexible communication setup for truly distributed control (local intelligence);
- controllers designed from the ground up to handle working with asynchronous message-based coordination which is independent from the continuous physical coordination.

# 4 Discussion

We note that the case studies reported above allow the definition of sets of laboratory properties and features which were crucial for achieving the intended objectives. Some of these properties and features are specific to the needs of one individual case study while some others are critical for multiple cases and a few appear as universal enablers across all case studies.

The two dominant topics in the broadest category of universal enablers are *flexibility in the physical configuration of the system* and *a high degree of automation*. The former includes

- a flexible, reconfigurable grid topology, with multiple supply points, which allows for the emulation of different kinds of real-world grid topologies, such as long rural feeders, branched urban networks, islanded networks etc.
- a diverse array of controllable off-the-shelf energy resources distributed across the network.

The latter includes

- a high degree of automation of all assets, including the grid and energy resources.
- availability of external application programming interfaces for monitoring and control of assets, to allow third party control systems (both on-site and remotely) to access the automation capabilities of the laboratory in closed-loop, real-time operation.

The list of enabling features for multiple, but not all cases includes

- a physically distributed computing infrastructure requiring asynchronous, non-local communication between control entities without shared memory;
- a flexible, reconfigurable communication network allowing control topologies to be defined independently of the grid setup;

- "plugs everywhere": optional connection points for additional power equipment, e.g. series-connected optional impedance, auxiliary loads, or compensation devices.

Finally, the following enabling features were found to be specific to a single case only:

- available single-phase and unbalanced loads for study of unbalanced grid conditions;
- a controllable grid interface to ensure controlled or islanded grid conditions;
- the availability of standardized interfaces to enable high-TRL tests.

While the small number of presented case studies cannot claim to be a comprehensive cross-section of ADN-related testing needs, a pattern of broadly useful features clearly emerges. Of particular note is that these requirements are not addressed by typical power HIL setups, which seek to accurately reproduce the electrical response of a simulated system to the action of a unit under test. Instead, these aspects focus on the separation of functional, control and physical layers, on the ability to host generic external controls, and on the ability to provide sufficient actuation vectors for both controllers and testing signals to engage with.

# 5 Conclusion

This paper reviewed recent system experiments as carried out in an advanced research and testing facility for smart energy systems. Driven by the validation needs of smart grids and ADN solutions, we observe a trend to increasingly integrated system testing. Here, the "system" comprises an increasing number of active and communicating grid elements as well as DERs, where also the production and consumption behaviours and control are of concern. As multiple domains of engineering and computation are involved, such experiments are difficult to fully materialize in simulated environments.

We identify how these trends lead to specific features being required of laboratory infrastructure that are not found in more conventional power systems testing laboratories. Our analysis of the experiments identifies several specific requirements: integrating controls into the lab, multiple controlled devices, communication among controllers in the field, and modifiable and realistic power system topologies.

Event though such analysis is based on specific experiments, it can be expected that these requirements will be more commonly sought after from laboratories in the future.

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