Towards System-Level Validation

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1 Higher Complexity in Future Power Systems

Power system operation is of vital importance and has to be developed far beyond today's practice in order to meet future needs like the integration of renewables or battery storage systems [3]. In fact, nearly all European countries faced an abrupt and very important growth of Renewable Energy Sources (RES) such as wind and photovoltaic that are intrinsically variable and up to some extent difficult to predict. In addition, an increase of new types of electric loads such as air conditioning, heat pumps, and electric vehicles; and a reduction of traditional generation power plants can be observed. Hence, the level of complexity of system operation increases steadily. To avoid dramatic consequences, there is an urgent need for a system flexibility increase [18]. Also the roll-out of smart grids applications and solutions such as Information and Communication Technology (ICT) and power electronic-based grid components is of particular importance in order to realize a number of advanced system functionalities (power/energy management, demand side management, ancillary services provision, etc.) [6, 7, 13, 14].

In such a Cyber-Physical Energy System (CPES)—also denoted as "Smart Grid" in the literature [3]—this also requires distributed intelligence on different levels in the system as outlined in Fig. 1 and Table 1. Flexibility, adaptability, scalability, and autonomy are key points to realize the automation systems and component controllers of CPES [13]. Also, interoperability and open interfaces are important to enable the above described functions on the different levels of intelligence [6]. Hence, such kind

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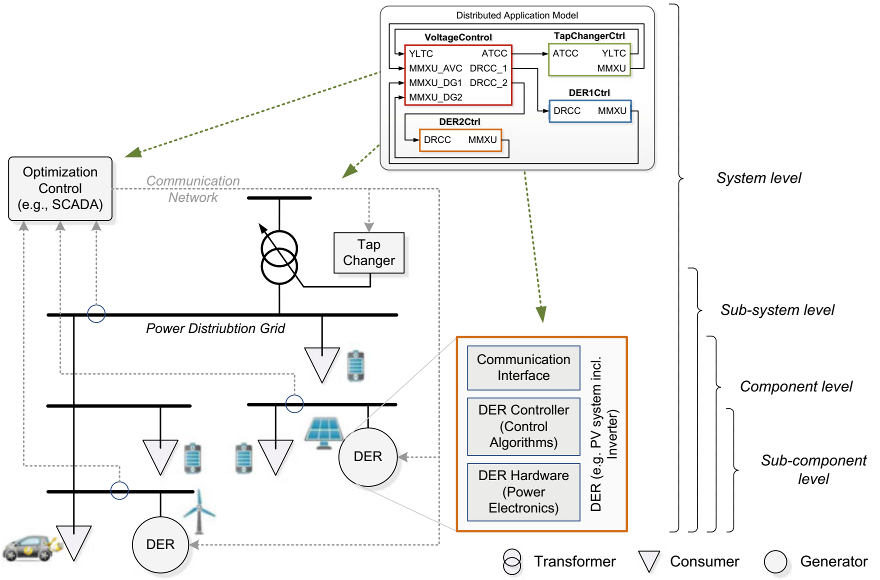

Fig. 1 Intelligence on different levels of smart grid systems [13, 14]

of systems tend to have a much higher complexity compared to traditional power systems [14].

2 Needs for System-Level Validation

2.1 Engineering and Validation Process

Typically, the engineering and validation process of CPES applications and solutions involves several stages depending on the applied design methodology or process model (V-model, etc.). Also, the overall complexity of the system under development usually influences the whole process (e.g., the development of a micro-grid controller is less complex as the supervisory control of a power distribution grid). However, the four main stages are common for the whole process as depicted in Fig. 2 and described in Table 2 [14, 17]. As indicated in the figure a step back to an earlier stage is possible if necessary. This can happen if the requirements are not met in a certain stage and a refinement of the previous one is necessary.

Table 1 Smart grid systems and their elements/components (adopted from [13, 14])

Level	Type of intelligence
System	Power system operation applications like energy management, distribution management or demand-side management are tackled at this level. Services of the underlying sub-systems and components are executed in a coordinated manner
Sub-systems	Control and optimization are the main tasks whereas the corresponding functions and algorithms have to deal with a limited number of components (generators, storages, etc.). Micro-grid control approaches as well as building energy management concepts are typical examples for this level
Components	Distributed Energy Resources (DER)/RES, battery storage systems or electric vehicle supply equipment is covered by this level. Such devices typically provide advanced functions like ancillary services (reactive power and voltage control, inertia and frequency control, etc.). Intelligence is either used for local optimization purposes (device behaviour) or for the optimization of systems/sub-systems on higher levels in a coordinated manner
Sub-components	Intelligence is used to improve the local component behaviour (harmonics, flicker, etc.). Power electronics and their advanced control functions is the driver for local intelligence. The controllers of DER, energy storages and other type of power system equipment (tap-changing transformers, smart breakers, etc.) can be considered as examples for sub-components

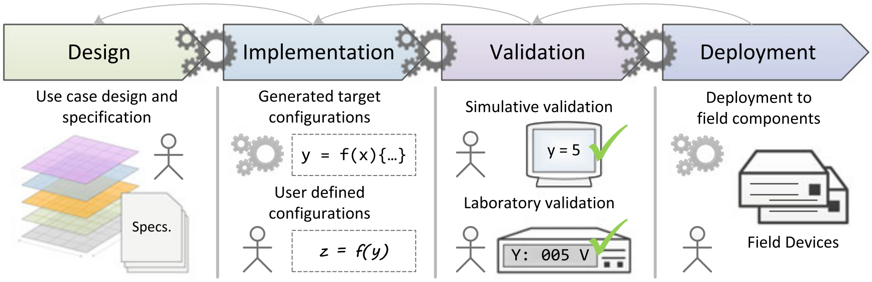

Fig. 2 Overview of the design and validation process of CPES applications [10]

Compared to other domains, the main challenges during the engineering and validation process of CPES applications and solutions can be summarized as [14]: *(i)* the fulfilment of high-reliability requirements, *(ii)* the observance of (strict) real-time requirements, *(iii)* the compliance with national rules, and *(iv)* the interaction with several system integrators/manufacturers. In order to prove the outcomes and results of the different stages proper concepts, methods, and corresponding tools are required. Due to the higher complexity of smart grid systems advanced testing methods are necessary addressing cyber-physical and multi-domain issues.

Table 2 Main design and validation stages for CPES development (adopted from [14, 17])

Process stage	Description of activities
System-level requirements and design	The system-level requirements and application scenarios are being identified (i.e., use cases). In the following a basic design and high-level architecture specification are typically carried out. After the conceptual design has been elaborated a detailed engineering of the system under development is done. Functions and services are also identified and specified
Implementation and prototype development	Usually prototypes are being developed at this stage. The process of transforming a concept into a prototype often introduces issues which were not considered during the design stage(s). Often boundary problems like communication latencies or non-linearities are neglected during the first versions of a basic concept. During the development of a prototype iterative refinements of solutions/algorithm are often necessary
System validation and component testing	After the first prototypes are available they are being tested (often either in simulation or in a laboratory environment). Test are usually carried out at component level first and afterwards integration tests are being performed
Deployment and roll out	Deals with the realization of a product or application as well as the installation/roll out of components and solutions in the field

2.2 *Towards a System Validation Approach*

Validating and testing CPES technologies are tasks which require a holistic view on the overall engineering process. The entire spectrum of future smart grid applications and solutions has to be taken into consideration, but also the whole engineering process (as depicted in Fig. 2). Even more, the whole range of aspects from interest and relevance for a stable, safe and efficient smart grid system has to be regarded [2, 14]. Comparable processes have already been successfully implemented in other application domains like automotive, consumer electronics, mechanical/chemical engineering, albeit on an arguably less complex level [1]. The domain of power and energy system can profit from existing approaches and can adapt them to fulfil needs and requirements of the domain. There is no need to start from scratch.

However, until now there is a lack of an integrated approach for the engineering and validating CPES covering power system, ICT as well as automation and control aspects in an integrated manner. Several mandatory testing approaches are nowadays available, but they are mainly focused on the device-level [2]. Those approaches are usually not sufficient to test a whole CPES configuration on the system level [14]. In order to guarantee a sustainable and secure supply of electricity in a more complex smart grid system as well as to support the expected forthcoming large-scale roll out of new technologies, proper validation and testing methods are necessary. They need to cover the power system in a cyber-physical and multi-domain manner. Therefore, the following needs can be identified [10, 14]:

- *Cyber-physical, multi-domain approach:* System integration topics including analysis and evaluation need to be addressed on the system level in a cyber-physical and multi-domain manner.
- *Holistic validation framework:* A suitable framework which allows the holistic analysis and evaluation of CPES approaches on the system level is required; this also includes the corresponding Research Infrastructure (RI).
- *Standardized procedures:* Harmonized and possibly standardized validation procedures and tools need to be developed.
- *Educated professionals:* Besides the technical validation aspects, engineers and researchers need to be properly educated in order to understand smart grid solutions in a cyber-physical and multi-domain manner. They need to be aware about the main testing requirements.

2.3 Illustrative Example

For a better understanding of future system validation needs a coordinated voltage control in a power distribution grid is introduced [14]. Figure 1 provides an overview of this illustrative smart grid example where an On-Load Tap Changing (OLTC) transformer is used together with reactive and active power control provided by DERs (e.g., photovoltaic generator and small wind turbines) and battery storage systems. The goal of this application is to keep the voltage in the grid in defined boundaries and therefore to increase the hosting capacity of renewables [12]. The corresponding control approach has to calculate the optimal position of the OLTC and to derive set-points for reactive and active power of DER units. Those control commands are usually send over a communication network to the corresponding components.

Before deploying this solution into the field various tests need to be carried out like the validation of the different components (incl. local control approaches and communication interfaces) on the sub-component and component level. Also, the local OLTC control approach needs to be evaluated, too. Nevertheless, the integration of all components and sub-systems is one of the most important issues. The proper functionality of all components is not a guarantee that the whole system is behaving as expected. As outlined above, a system-level testing is required in order to prove that the whole application (addressing power system and ICT topics) is working properly and as expected [14].

This example will be used also later in the book for the explanation of the developed validation methods and corresponding testing tools.

Table 3 Overview of validation and testing approaches (adopted from [14])

Method	Stage			
	Basic design	Detailed design	Prototype	Deployment
Analytics and simulation	+	++	∘	−
Real-time sim. and HIL	−	−	++	+
Lab-based testing	−	−	++	++
Field trials	−	−	−	++

Legend: − …less suitable, ∘ …suitable with limitations, + …suitable, ++ …best choice

3 Existing Approaches and Research Directions

3.1 Suitable Methods and Tools

In the literature there are a several well-known development and validation methods documented which are suitable for the domain of power and energy systems [14, 17]. The most promising approaches are *(i)* analytic analysis and software simulation, *(ii)* real-time simulation and Hardware-in-the-Loop (HIL), *(iii)* laboratory-based testing, and *(iv)* field trials and large-scale demonstration projects. However, they are useful for specific activities and they are not covering all process stages as outlined in Fig. 2 in the same way. Therefore, Table 3 provides an overview where those methods fit best and where not.

Simulation-based approaches are very common in power systems engineering. Individual technological areas (power system, ICT/automation) have been analysed in dedicated simulation tools. Transient stability and steady state simulations are very often used to investigate the behaviour of power systems and their components where various tools are nowadays available [8]. Comparable developments can be observed also in the domain of ICT and automation systems.

Nevertheless, the development of CPES applications urge for a more integrated simulation approach covering all targeted areas. The usage of simulation as development approach gets more of interest. Analysing the behaviour of smart grid systems requires hybrid models combining continuous time-based (physics-related) and discrete event-based (communication and controls-related) aspects. Co-simulation (or co-operative simulation) is an approach for the joint simulation of models developed with different tools (tool coupling) where each tool treats one part of a modular coupled problem. Co-simulation takes under consideration the complexity of the simulated system and influences between different aspects or domains interconnected in the same system [9, 11, 14].

Nowadays HIL-based approaches get more interest from the power system domain. Two different approaches can be distinguished, namely Controller-Hardware-in-the-Loop (CHIL) and Power-Hardware-in-the-Loop (PHIL). The first approach is used to evaluate a controller platform and the corresponding algorithm(s) where the real implementation is available and the power system component is simulated in a real-time environment. Besides that, PHIL provides a more advanced tool for power system analysis, testing and validation by evaluating the actual power device with a real-life system which is simulated in a Digital Real-Time Simulator (DRTS), allowing repeatable and economical testing under realistic, highly flexible and scalable conditions. Extreme conditions can be studied with minimum cost and risk, while problematic issues in the equipment behaviour can be revealed allowing an in depth understanding of the tested device. PHIL testing combines the benefits of numeric simulation and hardware testing and is constantly gaining interest at international level [4, 5, 14].

Laboratory experiments in electrical engineering for testing or certifying single or small setups of components are common practice. However, the decentralization of operation and control as well as the massive deployment of ICT components (and thus introducing shorter innovation and product cycles than hitherto known in energy supply systems) drastically increase the complexity of the system under investigation and easily exceed the scope of existing laboratory setups. In a single laboratory environment, the evaluation of holistic CPES is out of the question leaving simulation (or hybrid co-simulation experimentation incl. HIL) setups as the only viable option. Moreover, flexibility to deploy intelligent algorithms in different locations across the system is also necessary to move towards a laboratory-based testing of integrated power systems. Another issue is that laboratories are often developed for a specific purpose and they cannot be adapted easily (from the technical but also from the financial point of view) [2, 14].

Besides simulation and lab-based validation approaches (incl. HIL) field trials and large-scale demonstration projects are also of importance for the validation of new architectures and concepts. They have the advantage to test industrial-like prototypes and developments under real-world conditions, but a huge amount of preparation and planning work is necessary to realize such kind of field trials. Usually, they are also quite expensive and resource intensive [14].

3.2 Future Research Directions

As outlined above there are a couple of interesting approaches available in the literature which are suitable for validation and testing. However, all of them have in common that they are usually address a specific domain and they are not really developed to cope with the cyber-physical and multi-domain nature of CPES applications and solutions. In order to analyse and evaluate such a multi-domain configuration, a set of corresponding methods, procedures, and corresponding tools are necessary. Usually, pure virtual-based methods are not enough for validating smart grid systems, since the availability of proper and accurate simulation models cannot always be guaranteed (e.g., inverter-based components are some-times very complex to model or it takes too long to get a proper model). Simulation and lab-based validation approaches have to be combined and used in an integrated manner covering the

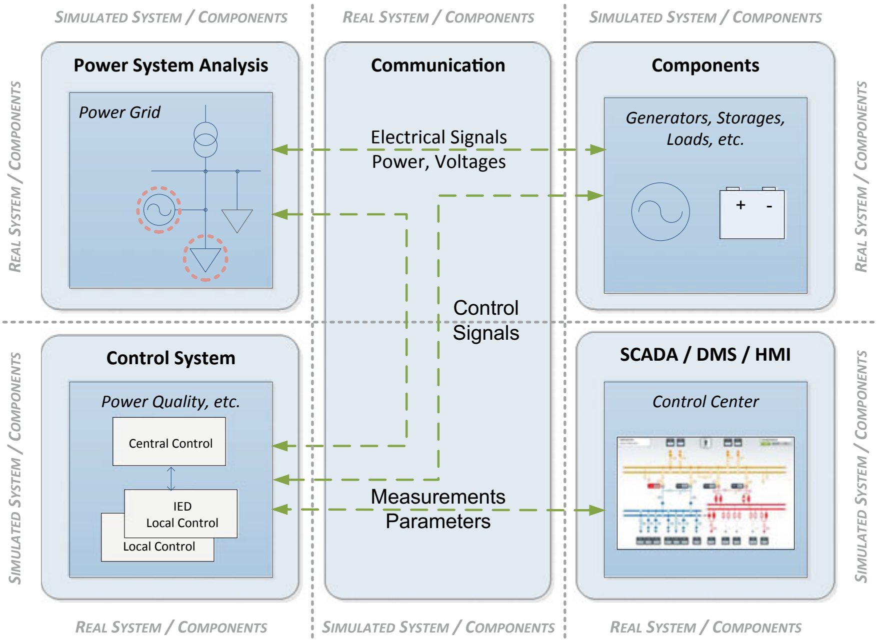

Fig. 3 Integrated CPES validation using virtual and real components (adopted from [14, 16])

whole range of opportunities and challenges. Such an approach is necessary when answering system level integration and validation questions [14].

Figure 3 sketches this idea where a flexible combination of physical components (available in a laboratory environment) and simulation models are combined in a flexible way in dependence of the corresponding validation or testing goal. Such an approach needs the improvement of available methods and tools. In addition, proper interfaces need to be provided as well. There is still space for future research and development related to this topic [14].

Besides that, system-level validation procedures as well as corresponding benchmark criteria are necessary. Moreover, also the linking of existing RIs as well as the establishment of clusters of them should be in the focus of future research. Such an integrated RI should be able to provide advanced validation and testing services fulfilling future validation needs in a cyber-physical manner. Last but not least also the training and education of engineers and researchers active in the domain of power and energy systems need to be educated on CPES topics [14].

4 Overview of the ERIGrid Validation Approach

To overcome the shortcomings in power system evaluation as briefly outlined above the ERIGrid approach has been developed. It addresses the open points by developing a holistic, cyber-physical systems-oriented approach for testing smart grid systems. This integrated European smart grid RI targets the following points [15]:

- Creation of a single point of reference promoting research, technology development, and innovation on all aspects of smart grid systems validation,
- Development of a coordinated and integrated approach using the partners' expertise and infrastructures more effectively, adding value to research projects, and promoting European leadership in smart grid systems,
- Facilitating a wider sharing of knowledge, tools, and techniques across fields and between academia and industry across Europe, and
- Accelerating pre-normative research and promoting the rapid transfer of research results into industrial-related standards to support future smart grids development, validation and roll out.

To realize the above introduced project goals the following main research and development activities have been identified for the ERIGrid project:

- Development of a formalized, holistic validation procedure for testing smart grid systems and corresponding configurations,
- Improvement of simulation and lab-based testing methods supporting the validation activities, and
- The provision of a corresponding and integrated pan-European RI based on the partner's laboratories.

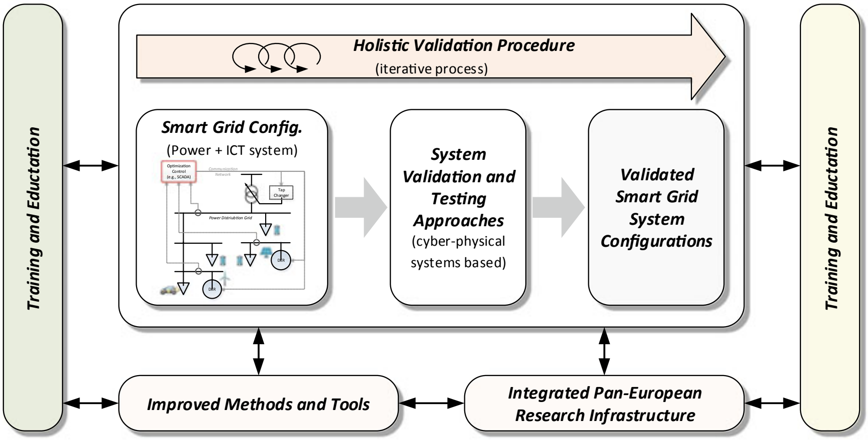

Fig. 4 Overview of the ERIGrid approach [15]

Additionally, training and education concepts are also being developed to support the overall research activities. An interesting point in the ERIGrid approach is to provide free access to the integrated RI (i.e., partner's smart grid laboratories) and the corresponding methods and tools for external user groups from industry and academia as outlined in Fig. 4.

The holistic testing methodology should facilitate conducting tests and experiments representative of integrated smart grid systems by testing and experimentation across distributed RIs, which might not necessarily be functionally interconnected.

In the following chapters main validation concepts and procedures as well as the corresponding tools are introduced and demonstrated on selected scenarios. Lessons learned and educational approaches are discussed as well.

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