Uncertainty Quantification in Smart Grid Co-simulation Across Heterogeneous Model Domains

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1 MOTIVATION

The international power distribution grids are expected to undergo fundamental restructuring in the next decades, becoming Smart Grids. Smart Grids are typically defined as power grids enhanced with information and communication technology (ICT). They provide components of the power system with means to send and receive information about current states, energy requirements, load and generation predictions etc. This calls for the development of various new hardware devices and control concepts and thereby for rigorous, systematic testing of the interaction between the new components.

Smart Grids are highly complex systems since their dynamics do not solely depend on classical grid components like generators and consumers anymore, but also on weather predictions, market prices, the utilization of the ICT system, and many other factors. This complexity limits the pool of possible testing procedures. Hardware experiments are too expensive and inflexible to serve as generally applicable means of testing. In the form of field tests they are even potentially dangerous since real infrastructure is involved. Software simulation is considered to be more suitable for the early stages of Smart Grid research since it is generally cheap, flexible and safe. However, monolithic simulation software easily expires in its usability since it does not consider the expendability of the Smart Grid setup. Whenever new Smart Grid components or concepts are introduced, they have to be modeled and implemented by the software developers, which requires high manual effort and sometimes simply is not possible. In order to avoid this overhead, the OFFIS – Institute for Information Technology, has developed the modular Smart Grid simulation tool *mosaik* (Rohjans et al., 2013).

Mosaik is an event-based co-simulation framework that allows the integration of existing Smart Grid component models with the help of a flexible API. The implemented models exchange data with one another via mosaik and may be instantiated and orchestrated to form large-scale simulation scenarios (i.e. scenarios with thousands of model instances). The extensive scenario size is enabled at reasonable computational costs by employing steady-state calculation of the grid utilization in the frequency domain (e.g. PyPower, a port of the MATPOWER package (Zimmerman et al., 2011)). This means that short-term dynamic behavior like electro-magnetic transients is not resolved.

Due to its flexible design, mosaik supports various kinds of simulation processes, e.g. hardware emulation. This is the concept of the Smart Energy Simulation and Automation Laboratory (SESA-Lab) that has been set up at the OFFIS. The central component of the laboratory is the real-time simulator *eMEGAsim* developed by the company OPAL-RT. This high performance computer allows the simulation of network models with μs resolution and provides digital and analogue I/O capabilities that make it a ready-to-use hardware-in-the-loop framework (HIL, see (de Jong et al., 2011)). By combining mosaik and eMEGAsim, the SESA-Lab enables analysis of dynamic transients in precise subsystems of otherwise steady-state large-scale scenarios. The main challenge of this approach is to ensure accuracy of results for this heterogeneous co-simulation system. A schematic overview of the SESA-Lab setup is given in Figure 1.

2 STAGE OF THE RESEARCH

A showcase scenario has been implemented to demonstrate the technical coupling between mosaik and eMEGAsim. The scenario's simulator pool contains 44 low voltage grid nodes, 41 households, and 21 photovoltaic converters. The majority of these instances is managed by mosaik. The included simulators are based on time series and thus ensure power generation and consumption within unproblematic operational conditions. Similarly, no faults or power outages have been modeled. Due to the simplicity of this showcase it is a suitable starting point to systematically study the requirements for accurate coupling

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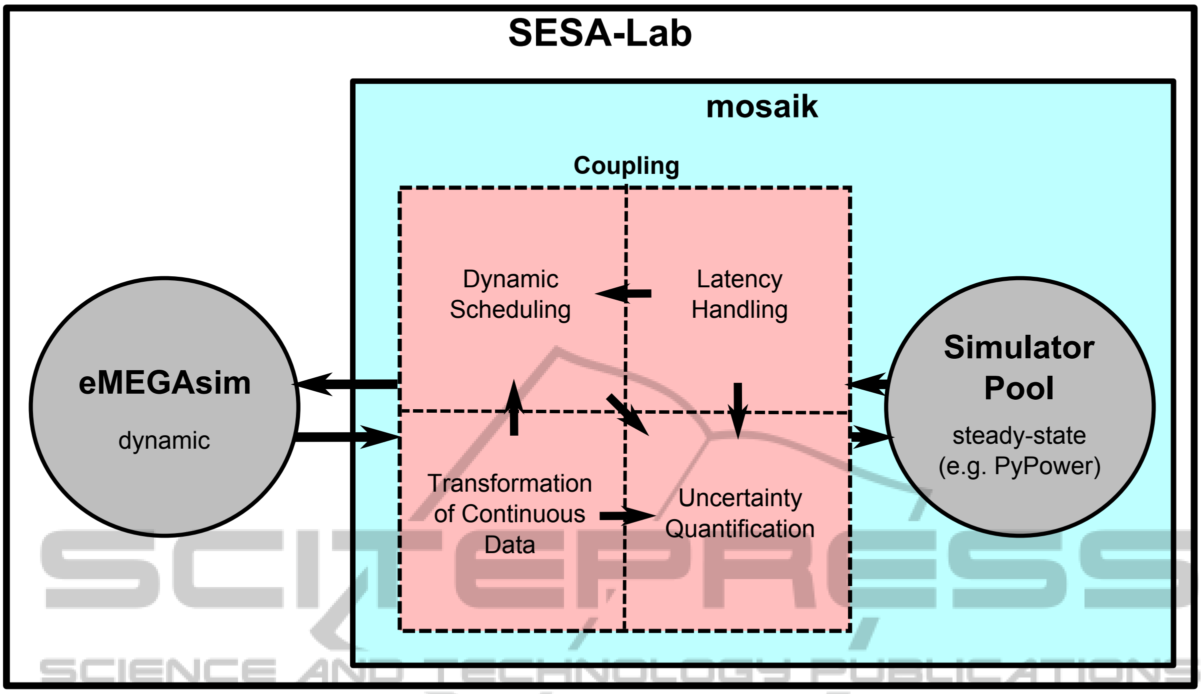

Figure 1: Schematic sketch of the SESA-Lab concept.

between the two systems.

A theoretical list of these requirements has already been set up and is presented in Section 3. The requirement, on which this PhD project is focused, is uncertainty quantification (UQ). It is the common way to assess accuracy of measurements or simulation results. The challenges of designing a flexible UQ system in the Smart Grid context are discussed in Section 4. A systematic design approach has been developed to tackle these challenges. The approach is outlined in Section 6.

3 OUTLINE OF OBJECTIVES

The main objective of the presented PhD project is the improvement of the coupling between eMEGAsim and mosaik. Since the former represents a highly dynamic time domain system while the latter represents a steady-state frequency domain system, information is inevitably lost, which leads to uncertainty in the results. Four requirements have been identified that need to be fulfilled in order to reduce this uncertainty as much as possible and provide a measure for the result accuracy: *information transfer*, *latency handling*, *dynamic scheduling*, and, as mentioned before, *uncertainty quantification*.

The challenge of information transfer focuses on the transformation of data. As already mentioned, eMEGAsim calculates data in the time domain. Thus, frequency domain transformation has to be performed before sending data to mosaik. The simplest way to do this is by calculating effective values of voltage and current, or via Fourier transform. However, more elaborate techniques exist that support the goal of preserving as much information as possible. Notable concepts applied to power system analysis are wavelet analysis (Shariatinasab et al., 2012), machine learning (Wehenkel, 1997), and parameter estimation (Lechtenberg et al., 2012). Choosing the most appropriate method or combination of methods for information preservation is only one part of successful information transfer. It also has to be determined, in which way mosaik (or implemented models) can effectively use this information. E.g. currently, there is no component implemented in mosaik that is able to process information about higher harmonics in the eMEGAsim simulation. However, such components might be integrated in the future. In that case, the coupling between the platforms should provide usable information in a standardized manner.

The issue of latency leads to temporal uncertainty. First tests of coupling between mosaik and eMEGAsim have revealed some transmission latency for data exchange. Since the real-time simulator is a closed-source resource, the transmission paths can not be directly adjusted. However, different possibilities exist to establish the connection between the platforms. Therefore, the first step to latency handling is given by the systematic comparison of the different connection strategies in order to find the one least inflicted with latency. Furthermore, a deterministic character of the latency has to be ensured. Most likely, transmission latency can not be eliminated completely. Instead, the remaining, deterministic latency has to be quantified so that it can be compensated or considered in some other way.

Scheduling is needed for the temporal specification of data exchange between the platforms, i.e. the synchronization. Within mosaik scheduling is event-based. Thus, data is exchanged whenever new values have been calculated through a simulation event. This form of synchronization is very efficient, but it is not directly applicable to the coupling between mosaik and eMEGAsim. After all, the simulation of eMEGAsim is continuous and therefore does not produce distinct events. The simplest alternative synchronization mechanism is time-discrete with a fixed time interval between two “synchronization points”. Lin and colleagues point out that this mechanism is rather inefficient since events that require data exchange do not necessarily coincide with the fixed synchronization points (Lin et al., 2011). If an important event happens in between two synchronization points, the corresponding system has to wait until the end of the interval to send data. This leads to temporal uncertainty. Of course, this uncertainty can be diminished by reducing the time length between two synchronization points. However, this would lead to much higher computational effort. Instead, some previously discussed methods for data transformation may be used to characterize and detect events in the eMEGAsim signal. This would allow for much more efficient and accurate, event-based synchronization between the platforms.

The presented requirements for accurate coupling between mosaik and eMEGAsim are strongly connected (see Figure 1). Elaborate information transfer reduces uncertainty caused by information loss and enables dynamic scheduling. Scheduling itself as well as latency handling reduce temporal uncertainty. Therefore, the three features provide the groundwork for a UQ system that is then used to analyze the remaining influence of uncertainty in the Smart Grid scenarios. Since the design of a UQ system is the focus of this PhD project, the following sections outline the corresponding research process further. The three aforementioned features will be included in the coupling in a rather prototypical fashion and refined in future research projects.

4 RESEARCH PROBLEM

It is challenging to design a general UQ system for a field of application as complex as the SESA-Lab. The main reason for this is that UQ is a multi-step process that requires interaction with the user. Therefore, it can not be fully automated. First, initial information has to be provided about uncertainty of system mechanisms and input values. Then these uncertainties are propagated through the model(s) and finally the calculated uncertainty of the results is presented to the user as a basis for decision-making. Further problems stem from the fact that there exists no single standardized measure to quantify uncertainty. The methods for uncertainty propagation are manifold as well. Nevertheless, some categories exist that are helpful for theoretical conceptualization as well as practical implementation. Uncertainties are typically divided into *aleatory* and *epistemic*.

Aleatory uncertainty is also called irreducible uncertainty. It stems from natural fluctuations in a system that can be statistically described but not diminished. Examples for this are power production of wind farms and solar panels, or power consumptions of households. In practice, knowledge about sources of aleatory uncertainty is typically assumed in the sense that mean value, standard deviation and form of the distribution are known.

Epistemic uncertainty is defined as reducible uncertainty. It stems from the lack of knowledge about parameters, input values or the system in general. Therefore, it can theoretically be reduced when more knowledge is obtained, but it can never be excluded completely, due to the nature of knowledge. Examples for epistemic uncertainty are diverse: simplifications in the model equations, the possibility of intentional attacks against the system, or operation parameters of a power plant. In practice, the knowledge about sources of epistemic uncertainty is by definition sparse. Generally, only interval boundaries or measures from possibility theory are given. The coupling features discussed in Section 3 all contribute to reducing epistemic uncertainty.

Methods for uncertainty assessment and propagation are oftentimes only appropriate to treat one of the two types of uncertainty. Aside from that, they are divided into intrusive and non-intrusive methods. Intrusive methods require the user to adjust the numerical simulation code, e.g. to replace deterministic model equations by stochastic ones. This leads to higher computational efficiency since intrusive approaches are not sampling-based. Non-intrusive methods leave the model code untouched, which is sometimes less efficient but much more flexible.

Since the SESA-Lab is a modular environment, used by many stakeholders and practitioners of different backgrounds, non-intrusive UQ methods are deemed the most appropriate. Intrusive methods would require too much manual effort of the user, and are not applicable at all when closed-source software is used.

Additionally to being non-intrusive, UQ methods must suffice two requirements for the SESA-Lab: they must be computationally efficient in order to be applicable in large-scale scenarios, and they must be applicable for sources of aleatory as well as epistemic uncertainty. Combining these two requirements underlines the challenging character of UQ in Smart Grids. Computationally efficient algorithms typically assume knowledge about the distribution of uncertain values and are therefore only applicable for aleatory uncertainty, see e.g. (Lin et al., 2014). Distribution-ignorant methods, on the other hand, are typically sampling-based, like Monte Carlo Simulation (MCS), which leads to high computational costs in complex systems.

5 STATE OF THE ART

Uncertainty quantification in general is a broad and active research field. Since it is a collection of widely applicable methods, it is of interest for every scientific discipline that is associated with measurement or modeling. Consequently, readily usable tools have been developed to facilitate the application of UQ methods. One of the most noteworthy of these tools is the open-source software DAKOTA (Adams et al., 2014) that has been developed by Sandia National Laboratories. It provides not only functionalities for UQ but also for optimization, parameter estimation and sensitivity analysis. The UQ capabilities of the software include different ways to assess initial uncertainty as well as the most established propagation methods. However, it is not considered suitable to manage mosaik's UQ via DAKOTA by coupling the platforms. The most important argument against the coupling is the fact that the analyzed simulation code has to be started by DAKOTA. This would limit the independence and thereby the modular character of mosaik. Furthermore, DAKOTA is not a domain-specific tool. In the context of Smart Grid research, it provides a large overhead of unnecessary functionalities while those functions are not included that have been specifically developed for the energy domain, e.g. probabilistic load flow (Borkowska, 1974). Nevertheless, DAKOTA has to be considered as an important reference and a possible resource. After all, the open-source character of the software promises to be helpful for individual implementations of selected methods.

Although UQ is a field with a long tradition, its application to power system modeling and especially Smart Grid modeling has only started to gain attention in the recent years. It has often been suggested that large-scale power systems are too complex for classical sampling-based UQ methods like MCS. Instead, new methods are developed and improved, e.g. the approach by Lin and colleagues (Lin et al., 2014). They specifically test their collocation method with a power grid model and demonstrate its computational efficiency in comparison to MCS.

Hiskens and Alseddiqu present a UQ approach specifically focused on dynamic, continuous power system simulations, similar to the ones conducted by eMEGAsim in the SESA-Lab context (Hiskens and Alseddiqu, 2006). They point out the computational efficiency of their trajectory sensitivity approach, stressing the importance of this feature for systems as complex as power grids.

The Smart Grid concept increases the complexity of power systems even more, especially in the context of uncertainty, as suggested by Zio and Aven (Zio and Aven, 2011). They argue that the large amount of determining factors yields different forms of uncertainty due to different states of knowledge. This is problematic since uncertainty propagation methods oftentimes rely on knowledge about the uncertainty sources. Furthermore, they deem it important to consider as much uncertainty sources as possible, but it can be difficult even for experts to assess input uncertainties for some sources, e.g: what is the probability of a fault in a newly developed grid component? Zio and Aven suggest a general framework for uncertainty assessment in Smart Grids, divided into three abstract categories, namely “drivers” (observable targets, e.g. costs), “limiters” (constraints, e.g. limitations in technical deployment), and “effectors” (influencing phenomena, e.g. failures). However, the practical use of such a framework has not yet been tested. In the context of mosaik, it is also unclear whether the framework can be applied to each type of model that is capable of being integrated through the API.

Li and Zio suggest a more practical approach for joint assessment of uncertainties from different sources (Li and Zio, 2012). They combine concepts of probability and possibility theory in order to account for different states of knowledge. However, they use this approach as a first step of MCS that is oftentimes assumed to be unfit for complex, large-scale systems, as stated above. It is questionable whether the joint assessment approach is compatible with more sophisticated propagation methods.

Uncertainty assessment is also the focus of some auxiliary software tools for energy management systems. An example is a tool for the assessment of wind power and load forecast uncertainty developed by the Pacific Northwest National Laboratory (Makarov et al., 2010). It is a complex system in itself and contains various methods for uncertainty assessment, e.g. statistical analysis of error data. Still, it is worth considering to include specialized tools like this or selected underlying concepts into the mosaik UQ framework.

6 METHODOLOGY

The presented approach to set up a UQ system is structured according to the design science framework for information system research established by Hevner and colleagues (Hevner et al., 2004), see Figure 2. They propose a number of guidelines that help to set up the research project. In this sense, the UQ system represents the artifact that is to be designed (Guideline 1). The requirements are established by a specific environment, i.e. users of the SESA-Lab, and a knowledge base, i.e. literature regarding UQ (Guideline 2). Furthermore, means of evaluation of the artifact are needed (Guideline 3). For this, two data and information sets will be set up: an uncertainty taxonomy and a set of test scenarios.

A taxonomy is a common classification scheme in knowledge engineering that enables the practical handling of theoretical concepts, see e.g. (Avižienis et al., 2004). It collects the definitions of the concepts of a certain domain and captures the relations between them thereby facilitating the modeling of said concepts. An uncertainty taxonomy in this sense is a collection of all common uncertainty concepts that illustrates how these concepts are represented and utilized in practice. This establishes standardization and is thus important for all steps of the UQ process that require user interaction.

A second helpful data set consists of test scenarios. Scenario-based design is a popular engineering approach in computer science that provides some benefits like early evaluation of usability of certain concepts (Rosson and Carroll, 2002). In a practical sense, scenario sets furthermore provide different types of boundary conditions for systematic testing of implementations. The approach is typically iterative with rough initial scenarios that become refined through theoretical and practical requirement analysis. Smart Grid scenarios vary in size, types of integrated grid components, and simulated faults. Additionally, SESA-Lab scenarios vary in the size of the subsystem that is modeled in eMEGAsim. The showcase scenario already counts as a first test scenario that now has to be complemented by other setups.

Once the taxonomy and test scenarios are set up, they will be used to design and evaluate the artifact, i.e. a UQ system for the SESA-Lab. A UQ system, as outlined in Section 4, consists of three components: an *assessment framework* for specification of initial uncertainties, a *propagation method*, and *result representation* for the final accuracy assessment.

An uncertainty assessment framework should provide users with the possibility to specify initial uncertainties of different scenario components in a standardized manner. The differentiation between epistemic and aleatory uncertainty is important here. It will be facilitated by the outlined uncertainty taxonomy.

Once the initial uncertainties are assessed, they are propagated through the models via an appropriate method. Since a variety of these methods is available, it has to be researched, which of them are applicable or adoptable in the SESA-Lab context and thus should be included into the UQ system. Furthermore, it is promising to enhance sampling-based UQ methods with practices from the field of Design of Experiments (DoE). DoE provides many techniques that render sampling more efficient and thereby minimize the number of needed samples. DoE minimal sampling methods like Latin Hypercube Sampling (LHS, see (Giunta et al., 2003)) are already well-established in UQ. The set of test scenarios will allow for systematic comparison of propagation methods.

Finally, the calculated uncertainty of the simulation results has to be presented to the user in an efficient and understandable way in order to support interpretation and decision-making. Since this task is related to the assessment of initial uncertainties, the taxonomy will again be helpful.

Validation of the UQ system artifact will be conducted via use of the test scenarios. Uncertainty values may be computed for fixed model compositions a priori, even with methods that are not applicable in the UQ system itself, e.g. intrusive methods. Then these values are compared with the UQ system output in order to evaluate its accuracy. It is reasonable to select well-understood models for the test scenarios so that correct uncertainty values can be identified easily.

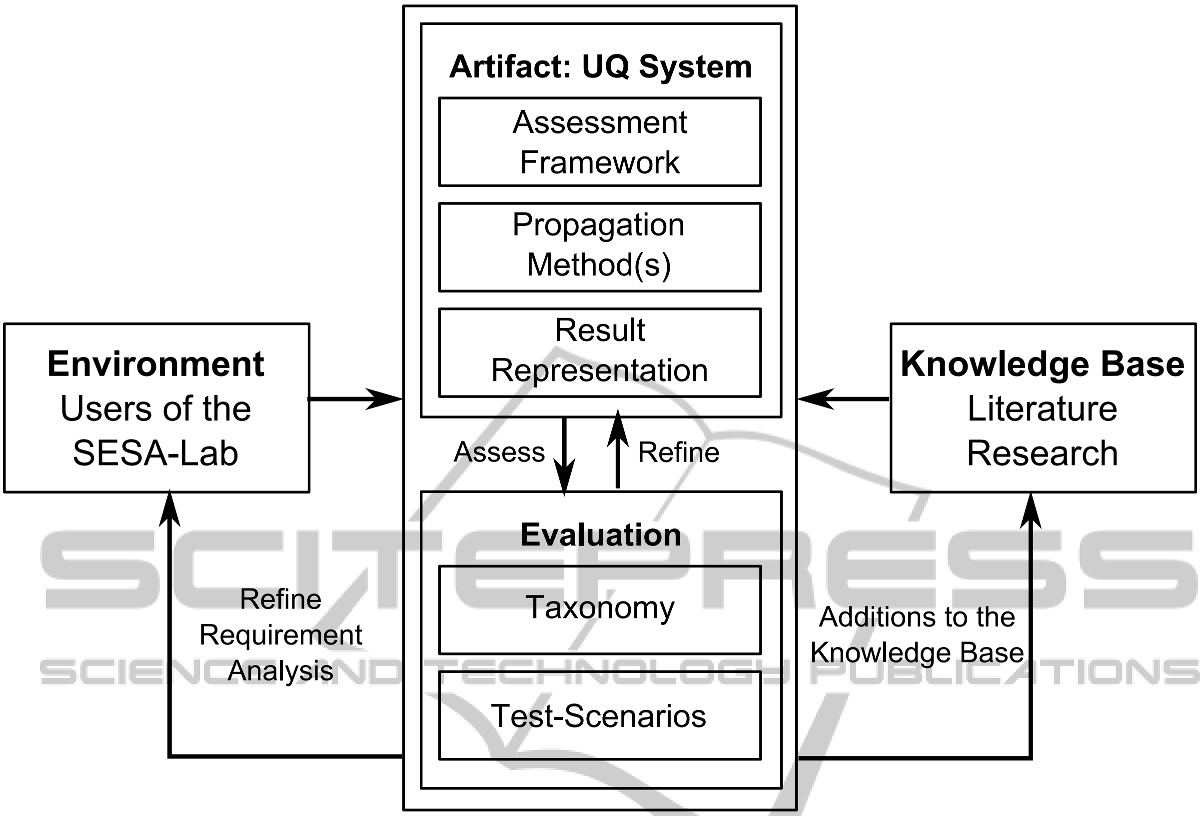

Figure 2: Design process for the uncertainty quantification system analogous to the framework proposed by (Hevner et al., 2004).

7 EXPECTED OUTCOME

The expected outcome of the presented PhD project is a coupling between the simulation platforms eMEGAsim and mosaik with quantifiable accuracy. This will contribute to the development of the SESA-Lab, a setup for software/hardware as well as steady-state/dynamic Smart Grid co-simulation. The coupling ensures accuracy by reducing temporal and data value uncertainty through means of latency handling, dynamic scheduling, and data transformation. The remaining uncertainty is quantified via a flexible UQ system that provides the user with standardized means of interaction and readily evaluated propagation methods.

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