ON THE SIMULATION OF SMART GRID ENVIRONMENTS

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ABSTRACT

The electrical grid is transitioning towards a so-called Smart Grid (SG), which facilitates advanced management and control mechanisms through the integration of Information and Communication Technology (ICT) but also introduces novel challenges resulting from cyber-physical interdependencies. Therefore, this transition requires a transformation of the system's structure and control mechanisms to meet the requirements for future SGs. However, examining and thoroughly testing those novel approaches is mandatory to enable a safe and smooth system change. These tests need to be conducted in a safe environment to avoid system failures, which may result in monetary losses and ultimately threaten human lives. Modeling and simulation is an established technique for testing and evaluating critical systems in a safe environment. Therefore, the paper aims at providing an overview of current modeling and simulation tools related to future SGs, by presenting them alongside challenges for simulating ICT, electrical grids and combined cyber-physical approaches.

Keywords: cyber-physical systems, smart grid, survey

1 INTRODUCTION

The advances of the electrical grid towards transitioning into a distributively organized system, fueled by Renewable Energy Sources (RESs), requires fundamental changes in its structure and control mechanisms (Farhangi 2010). However, the grids' size and the ubiquity of electricity significantly increases the difficulty of introducing such modifications. Moreover, changes may cause erratic system behavior, which can have devastating consequences ranging from monetary losses caused by damaged equipment, to threatening human lives. Additionally, the increasing introduction of Information and Communication Technology (ICT) and the resulting interconnection between the grid and different sectors further complicates matters. Therefore, thorough testing and examination of novel developments in a safe environment are of utmost importance. However, conducting tests in the real electrical grid is not a safe option due to the high potential for causing disturbances in the continuity of electricity supply. Modeling and Simulation is a prominent technique to assess novel approaches in a virtual and safe environment. For the current electrical grid, a variety of sophisticated tools exist that allow for the examination of electrical phenomena and for the simulation of electrical grids. However, those tools were mostly developed for the old electrical grid and are not suited for the upcoming changes (Amin 2011). To address this problem, novel tools need to be developed that adequately represent the properties of the future grid and provide capabilities to test new developments in a safe environment (Salvadori et al. 2013).

Supporting the development of novel tools, our work provides an overview of the capabilities of state-of-the-art tools that fulfill requirements related to their applicability for future electrical grids. In particular, we provide an overview of commonly used tools for simulating digital communication networks, which become increasingly important in future grid control. Additionally, we elaborate on established calculation and simulation tools for electrical phenomena and electricity grids to address the physical aspects of Smart Grids (SGs). Finally, we discuss recent work that aims at implementing integrated cyber-physical simulation tools and combined approaches based on co-simulation. The goal of this work is to highlight simulation tools and key aspects that indicate their suitability for adequately supporting the development of future SGs.

The remaining paper is organized as follows. Section 2 provides an overview of ICT-network simulation tools that are commonly used in energy grid research. Section 3 addresses the calculation programs and simulation environments for representing physical properties. Subsequently, Section 4 covers the current approaches that aim to simultaneously address cyber-aspects and physical properties. In Section 5 identified requirements and open issues are discussed. Finally, Section 6 concludes the paper.

2 SIMULATION OF CYBER ASPECTS

Simulating data networks is a challenge that has been present for many years. Simulation tools aim at supporting the design and planning of networks to speed up development processes and save money. The SG is envisioned to be tightly coupled to an ICT infrastructure, forming a so-called Cyber-Physical System (CPS). This coupling results in strong interdependencies, which need to be assessed in a safe environment. Therefore, simulation tools need to be capable to represent them adequately. In this section, simulation tools for ICT networks in the SG domain are presented. Note that this section is focused on tools that are related to SG research and, therefore, does not provide a comprehensive overview of general network simulators (Mehta, Sulatan, and Kwak 2010; Monika and Shekhar 2014).

OMNeT++. The *OMNeT++* framework is one of the most prominent general-purpose network simulation platform tools, which is strongly utilized in scientific work for the SG domain (Dede et al. 2015, Bhor et al. 2014). It is platform independent and was developed for modeling communication networks, but it allows modeling a wide variety of additional concepts like wireless distributed networks, multiprocessor communication and sensor network simulations. *OMNeT++* provides a component-based architecture for system models. Components of these models (modules) can be developed using the C++ programming language and can subsequently be combined to form a network model.

NS-3. This discrete-event network simulator is another prominent general purpose simulator (Henderson et al. 2008). It is the successor of the *NS-2* simulator (Mhatre 2007) and was also developed to support network research activities and for this, it enables the simulation of a variety of technologies. It can function as a network emulator, which allows its integration into real systems. Furthermore, this simulator is an open-source project actively used for research activities in the SG domain (Kim et al. 2012).

OPNET. The Optimized Network Engineering Tool (OPNET) (Chang 1999) was developed by OPNET technologies and is now a commercial network simulator, which is maintained by Riverbed Technology (Riverbed Technology 2019). This tool consists of several tool-sets that support the development and evaluation of large scale networks. For this, OPNET enables a GUI based network generation, provides detailed process and protocol configuration capabilities and also supports the analysis of the network simulation. It is a hierarchically structured tool, where higher level modules can use the modules on lower levels, facilitating efficient network development.

J-Sim. This tool is an open-source Java-based simulation framework for the development and assessment of wireless sensor networks (Sobeih et al. 2006). It is structured in a modular fashion facilitating easy extension and the integration of new technologies. This is done by extending one of the four main components of *J-Sim*, namely, *sink nodes, target nodes, sensor nodes*, or *sensor channels*.

Special Purpose Simulators. Aside from the general purpose tools, other ones address specific aspects in the domain of SGs. Among those is, for instance, a framework that provides capabilities for modeling attack scenarios and detection mechanisms for ICT networks (Egert et al. 2017). Another work is concerned with analyzing the effects of the network topology on the scalability of different communication technologies for SG applications (Müller, Georg, and Wietfeld 2012). This tool uses *OMNeT++* to combine the generation of large scale networks with the distributed execution of services. *NESSI*[2] (Godfrey et al. 2010) is another simulation framework for SGs that encompasses electrical components, ICT and the simulation of attack scenarios. As described in (Chinnow et al. 2011), it mainly concerned with the simulation of some basic attacks on the smart metering infrastructure.

In the future SG, digital networks are going to be combined with the physical grid. This combination of the discrete cyber-domain and the continuous physical domain represents a challenging problem for simulating ICT systems. Therefore, the capability for integrating the additional requirements into simulation environments is of utmost importance.

3 SIMULATION OF PHYSICAL ASPECTS

The main part of the SG simulation is the realistic representation of the physical properties and behavior of the electrical grid and its components. For the modeling and analysis of electrical phenomena, a wide variety of tools is available (Bam and Jewell 2005). However, the electrical grid is in a process of fundamental change, which introduces additional challenges, like the introduction of RES and the grids extension by an ICT infrastructure. To support the development towards a SG, sophisticated simulation tools are required. The currently available tools range from open-source solutions to commercial solutions and special purpose simulators. In the following, tools from the context of modeling and simulation of electrical phenomena and electrical grids are presented.

3.1 Commercial and Closed-Source Tools

APT-EMTP. It is a commercial simulation tool for electromagnetic transient phenomena (Europan EMTP-ATP users group 2019), which is capable of simulating real power system dynamics and allows to continuously monitor the system state. This allows the tool to be widely utilized by the power industry for system planning and design purposes.

PSCAD/EMTDC. The *PSCAD/EMTP* simulation environment is one of the most established tools for electricity-related calculation and simulations (Gole et al. 1996). It provides a variety of device models and enables the generation of large scale electricity networks in a drag and drop manner. Additionally, a large set of analysis tools are provided, including real-time visualization of the electrical phenomena.

NEPLAN. It is a commercial tool for modeling electrical grids. It is a standalone simulation environment that allows modeling electrical grids on different hierarchical levels, ranging from high voltage grids to distribution grids. Additionally, NEPLAN provides detailed component models and a large variety of analysis functionalities (NEPLAN AG 2019).

ETAP. The Electrical Transient Analyzer Program (*ETAP*) is a tool for designing, modeling and analyzing electrical systems (Brown et al. 1990, ETAP/Operation Technology, Inc. 2019). It is developed by

ETAP/Operation Technology Inc. and claims to be the top electrical power system software. It provides a suite of different software applications that enable a comprehensive network generation, simulation of the modeled system, detailed analysis functionalities and also live-monitoring.

PSLF. The tools is a general purpose tool for modeling and analyzing the electrical grid on different levels (General Electric Company 2019). It is a standalone software developed by GE and is tailored to be understandable and to provide diverse plotting and visualization functionalities. Additionally, it supports positioning analysis and visualization using the google earth application. The modeling capabilities are very detailed and allow for a realistic behavior modeling of electricity grids.

Power Factory. This tool is a commercial calculation and simulation software developed by DIgSilent (DIgSilent - Power Factory 2019). Similar to the *NEPLAN* software, it provides very sophisticated modeling and analysis tools for the electrical grid. Additionally, it supports its own programming language DPL, which can be leveraged to automate tasks for the software and enables the interaction with the network model.

Modelica-based Tools. Two prominent representatives for Modelica-based simulation tools are *Dymola* (Dassault Systemes 2019) and *OpenModelica* (Open Source Modelica Consortium 2019). These simulation tools allow modeling a wide variety of scenarios with a focus on industrial applications. These tools use very basic building blocks that allow their reuse in different scenarios, but, nonetheless, makes the manual building process of complex systems complicated and error-prone for the user.

3.2 Free and Open-Source Tools

GridLAB-D. The *GridLAB-D* toolbox (Chassin, Schneider, and Gerkensmeyer 2008; Nasiakou, Alamaniotis, and Tsoukalas 2016) is an agent-based simulation tool for electrical grids. It allows to create models of distributively organized grids and conduct a variety of analyses. Additionally, the simulation can be executed for arbitrary time frames.

Matpower. *Matpower* is a high-level open-source package for the Matlab environment, which was developed by the authors of (Zimmerman et al. 2011). It enables the modeling and simulation of power flow problems and provides corresponding solvers. The *Matpower* tool is tailored to be easily extensible for modifications of power flow problems support research and education in this area.

OpenDSS. *OpenDSS* was developed in 1997 by Electrotek Concepts, Inc. and it is used for the modeling and analysis of electrical distribution systems (Electric Power Research Institute 2019). It is inherently script-based, which facilitates strong extensibility by combining it with other programming languages. However, this limits usability since programming in the script language is required.

Special Purpose Simulators. A special purpose simulation environment called *HOLEG*, is presented by the authors of (Egert et al. 2017). This tool enables the simulation of simplified electrical distribution grids structured as a holarchy. It allows to model appliances down to individual in-house components but does not provide electrical phenomena calculation. The main purpose of the tool is the application of algorithms for control and optimization of the grid and visualization of their consequences. Another special purpose tool developed by Siemens (Siemens AG 2019). It allows designing requirements for electricity distribution on different levels and supports the automatic scaling of components. Additionally, it supports the calculation and testing for common problems in electrical grids. A real-time large scale power system and power electronics simulation platform is developed by Opal-RT Technologies, Inc. (Bélanger et al. 2007). *eMegaSim* is based on *Matlab/Simulink* and aims at testing real security and control equipment for electrical grids. For this, the tool is based on the *RT-LAB* technology to conduct high-performance simulations and provides FPGA controlled connections to integrate real equipment.

4 SIMULATION OF CYBER-PHYSICAL ASPECTS

The future smart grid is envisioned as a CPS and, therefore, combined simulation approaches that adequately represent both aspects are mandatory. The most prominent work from the domain of co-simulation and integrated simulation are presented in the following.

EPOCHS. This time-discrete simulation framework is based on the High Level Architecture (HLA)-standard and combines three standalone tools *PSCAD/EMTDC*, *PSLF* and the *NS-2* simulator (Hopkinson et al. 2006). The combination is implemented as a co-simulation using the Application Programming Interfaces (APIs) of the individual tools. The tools are organized as collaborative agents, which are synchronized to combine realistic network communications with electric power components.

Hybrid HLA-based simulator. Another simulation tool based on the HLA standard is presented by (Müller et al. 2012). It allows simulating hierarchical aspects of power grids using the *DIgSilent Power Factory* tool. Additionally, ICT communication aspects are incorporated using the *OPNET* network simulator. This setup enables the development of distributed simulation environments. It is used to evaluate wide-area monitoring, protection and control aspects in different smart grid applications.

INSPIRE. INtegrated co-Simulation of Power and ICT-systems for Real-time Evaluation (INSPIRE) is a tool, which is based on the HLA standard and combines *OPNET* for ICT simulation with *DIgSilents Power Factory* for the underlying physical network simulation (Georg et al. 2013). In their work, the authors strongly focus on the reduction of transmission time between the two simulators and the corresponding time synchronization. For this, the framework uses a conservative time synchronization approach, which guarantees that the current state of the co-simulation can be processed without the interference of the individual simulators. However, this approach may reduce the simulation speed.

GECO. It is an event-driven co-simulation framework for power systems and communication networks (Lin et al. 2012). In their work, the authors propose a scheduler that handles all events from the individual processes and uses a global time-scale. This concept aims at solving the problem of synchronization window-sizes between processes, which is common in HLA-based solutions. The standalone simulators used for their evaluation are *PSLF* and *NS-2*.

OMNeT++-based Simulator. The authors of (Mets et al. 2011) propose an integrated simulation framework that supports the simulation of both cyber and physical aspects of large scale electricity networks. It is organized in a modular fashion based on *OMNeT++*, where modules are used for implementing cyber, physical and cyber-physical objects. In particular the *INET* framework (INET - Framework 2019) is used for ICT and a *Matlab* implementation of a distribution grid is used for the electricity network.

ORNL Power Simulator. It is a discrete-event simulator for modeling of the dynamics of electromechanical components (Nutaro 2011). For this it provides a discrete approximation for the continuous dynamics of electrical components. Subsequently, this event-based simulation is then combined with other standalone ICT simulation tools to provide a cyber-physical co-simulation model. To facilitate interoperability, *ORNL* provides an API to incorporate additional simulators like *OMNET++* or *NS-2*.

Mosaik. In contrast to synchronizing specific standalone tools *Mosaik* aims for combining arbitrary standalone simulators in an event-based manner (Schütte, Scherfke, and Tröschel 2011). The input and output behavior of these simulators is handled as discrete events and is then coordinated and combined by *Mosaik*. Despite the large potential of combining arbitrary tools, this limits its applicability since the matching between all simulator combinations needs to be defined.

5 DISCUSSION

On the basis of the conducted analysis of modeling and simulation tools, several important requirements have been identified, which can be used to assess a tool's applicability for supporting developments in the domain of future SGs. Many of them are not limited to a specific domain but can be attributed to tools concerned with the development of connected systems. The identified requirements are listed in the following:

1) *Architecture Support*: A simulator's capability for supporting various system architectures, like centralized, decentralized and hybrid ones. The SG is envisioned to be more decentralized than the current grid, consisting of multiple (semi-)autonomous systems, which are able to collaborate.
2) *Scalability*: The energy grid nowadays encompasses hundreds of thousands of interconnected electrical components, which will increase with the integration of ICT. Simulation environments need to be able to handle a high number of devices.
3) *Extensibility*: The ongoing transition of the grid may yield the development of novel concepts and components, which need to be integrated into simulation environments. It is important for simulators to be extensible to integrate novel technologies, without requiring significant changes.
4) *Interoperability*: The future grid will be strongly coupled to different sectors like industries or smart homes through an ICT infrastructure. Therefore, the collaboration with special tools from such related sectors can support the quality of the overall system simulation. Simulators should provide means to facilitate such a collaboration.
5) *Usability*: As different sectors will be connected to the future SG, experts from those domains will be increasingly involved in collaborative development processes. To support development, simulation tools should provide good usability for people with limited IT background. This allows people to get involved in SG-related development and understand inter-connections between sectors.
6) *Interactivity*: Failures and attacks are an imminent threat in connected systems like a SG. To prepare for such situations, analyzing the system while facing threats is essential. Simulation environments should encompass capabilities for interactivity that allow inducing system failures and attacks during simulation to examine their consequences.
7) *Time Management*: Thorough system analysis requires the adequate simulation of short-term behavior and long-term behavior alike. Therefore, future grid simulators should be capable of conducting simulation scenarios with a flexible time horizons.

For the subsequent comparison, the following notation is used throughout this section. If a tool fulfills a requirement, it is indicated with a check-mark ✓. For not fulfilling a requirement the ✗-symbol is used. Additionally, if tools do not completely fulfill a requirement, but are designed to allow extending them in order to do so, it is marked with (✓). Finally, if such an extension is possible, but only with significant effort or profound expert knowledge, it is marked as (✗).

ICT Simulation. Tools for simulating ICT networks are very sophisticated and facilitate the development of a variety of networks. Table 1 provides an overview of the requirement coverage of the presented tools.

(1) Different system architectures in ICT networks mainly differ in the availability of information for individual system participants and the communication behavior between those participants. Since communication is taking place in a digital environment and in a time-discrete fashion, adaptions to the behavior and knowledge distribution can be made quickly, facilitating a fast application of novel technologies. Therefore, simulation tools incorporated such modifications quickly. For special purpose simulators, this is usually not the case, because many of them were built to evaluate very specific components or situations and do not require building complete networks or specific architectures. (2) *Scalability* aspects are considered by the

Table 1: Overview of the cyber aspect simulation tools and their coverage of the identified requirements for their future application in SG simulations.

Simulator\Requirement	1	2	3	4	5	6	7
OMNeT++	✓	✓	✓	✓	(✗)	(✓)	✓
NS-3	✓	✓	✓	✓	(✓)	(✓)	✓
OPNET	✓	✓	(✗)	✓	✓	(✗)	✓
J-Sim	(✓)	✓	(✗)	✓	✓	(✗)	(✓)
Special Purpose (ICT)	✗	(✓)	(✗)	✗	(✓)	(✓)	(✗)

majority of the presented simulators. To adequately represent the large variety of components and the scope of digital networks (e.g., parts of the internet), general purpose simulation tools quickly managed to simulate large scale scenarios. In contrast, special purpose tools often do not need to represent larger systems but are scalable in terms of speeding up tasks (e.g., parallel simulation of specific problems). (3) Most of the simulators are *extensible*, which is important to incorporate novel developments made during the transitioning process towards a SG. Some are built in a modular fashion or are *extensible* through a corresponding programming language, like *NS-3* and *OMNeT++*. (4) The importance of *interoperability* is mostly covered by providing specific APIs to operate with external hardware or programming languages. However, many special purpose tools lack this capability, since they were designed for a very specific purpose. (5) The *usability* varies significantly among the presented simulation environments. Moreover, this aspect is often related to *extensbility* and *scalability* aspects, where increased *extensbility* is often achieved using programming languages, which, simultaneously, may lead to *usability* limitations, especially for non-expert users. (6) Many simulators lack *interaction* capabilities during simulation for introducing failures and attacks to analyze the system facing hazardous situations. However, highly extensible tools can incorporate this functionality, but this often requires additional modifications. (7) Finally, the *time management* is mostly not restricted and simulations environments are capable of real-time and long term simulations.

Physical-Aspect Simulation. The presented simulation tools were developed for a variety of different applications related to the electrical grid. For them to be applicable for future grid applications, they should address as many of the previously mentioned requirements as possible. Table 2 provides an overview of the presented physical simulation tools and their coverage of the identified requirements.

(1) Despite their development for the hierarchically organized legacy grid, most of the tools are capable of representing different network architectures like distributed and hybrid approaches. (2) Additionally, the simulators provide good *scalability*, since the well-known electrical phenomena can be efficiently calculated. (3) The extensibility of the simulators varies. It is often limited for commercial tools since they mostly rely on updates provided by their organizations. Additionally, their development was based on assumptions for the old electrical grid. Consequently, this limits the *extensibility* towards future developments. However, most of the simulation tools provide a possibility to incorporate novel developments through updates or special scripting languages. (4) The capability to operate with third-party tools is often very limited. Many tools support restricted APIs for special programs or provide simple data exports. In contrast, only a few tools enable full access to the model of the current simulation. (5) The majority of the simulators provides good *usability* through a General User Interfaces (GUIs), but a fine-grained configuration often requires programming capabilities. (6) The introduction of failures or attacks is limited to common electrical problems. However, introducing faults and attacks during the simulation was not considered during the development of most of the tools, but extensible ones can be modified to enable such interaction. (7) The *time management* of the electrical simulation environments is mostly short-term and rarely allow for long-term simulation.

Table 2: Overview of the physical aspect simulation tools and their coverage of the identified requirements for their future application in SG simulations.

Simulator\Requirement	1	2	3	4	5	6	7
APT-EMTP	(✗)	(✓)	✗	✗	✓	✗	(✗)
PSCAD/EMTDC	✓	✓	(✓)	✗	✓	✗	(✗)
NEPLAN	✓	✓	(✓)	✓	✓	(✓)	(✗)
ETAP	✓	✓	(✓)	(✓)	✓	(✓)	✓
PSLF	(✓)	✓	✓	✓	✓	(✓)	(✓)
Power Factory	✓	✓	✓	✓	✓	(✓)	✓
Modelica tools	✓	✓	✓	(✓)	✗	(✗)	(✗)
GridLAB-D	✓	✓	(✓)	(✗)	✗	(✓)	(✓)
Matpower	(✓)	✓	✓	(✗)	(✓)	✗	✗
OpenDSS	✓	✓	✓	(✓)	(✓)	✗	(✗)
Special Purpose (power)	✗	(✓)	(✓)	(✗)	✓	✗	(✗)

Cyber-Physical Simulation. Approaches for the integrated simulation of cyber and physical aspects are envisioned to provide novel insights into SG behavior and support the development of future applications. Most of the presented approaches orchestrate the execution of standalone simulation environments to provide a cyber-physical simulation. More rarely, this is done by using techniques that allow modeling of both aspects in an integrated way. Table 3 provides an overview of the tools presented in this work and their coverage of the identified requirements.

The presented tools can be divided into two categories. First, tools for general purpose modeling and simulation and second, simulators that attempt an integrated approach, or use co-simulation. In the following the tools suitability with regard to the identified requirements is discussed.

General purpose tools. In this work one technology for cyber-physical simulation was presented that can be considered as general purpose tools, which is the tool that uses the *OMNeT++* framework. (1) *OMNeT++*-based tools are capable of representing different architectures, due to the concept of using programming languages. (2) This also yields a strong *scalability* due to fast execution of code written in *C#/Java*. (3) Simultaneously, the support for programming languages allows *OMNeT++* to be freely *extensible*, which; however, requires additional effort, since all parts and their connections have to be programmed. (4) *Interoperability* also is correlated to a tools *extensibility*. Programmed models can be exported and APIs can be defined to work with different third-party tools. (5) One severe drawback is the reduced *usability*, due to programming languages, which makes it difficult for inexperienced users to get started. (6) *Interactivity* is a requirement which is in general not considered, but can be integrated, since *OMNeT++* is extensible. (7) Similar to the *interactivity* requirement, *OMNeT++* benefits from many established modules that allows integrating different *time behavior* for short-term and long-term simulations.

Co-Simulation tools. The most advanced among the presented cyber-physical simulators use co-simulation to achieve cyber-physical simulation. Therefore, fulfilling the identified requirements strongly depends on the standalone tools chosen for co-simulation. One of the main problems is the orchestration of the standalone tools and the exchange of information. Handling this synchronization is a challenging task, which is often addressed by using the HLA standard, which allows defining standalone simulations

Table 3: Overview of the cyber-physical simulation tools and their coverage of the identified requirements for their future application in SG simulations.

Simulator\Requirement	1	2	3	4	5	6	7
Mosaik	(✓)	✓	✓	✓	✓	(✓)	(✓)
ORNL Power Simulator	✓	✓	(✓)	✓	✗	(✗)	(✗)
EPOCHS	✓	✓	✓	✓	(✓)	(✓)	(✓)
GECO	(✓)	✓	✓	✓	(✓)	(✓)	(✓)
Hybrid HLA-based Simulator	✓	✓	✓	✓	(✓)	✓	✓
INSPIRE	✓	✓	(✓)	✓	✓	(✓)	✓
OMNeT++-based	(✓)	✓	✓	(✓)	✗	(✓)	(✓)

and organizes data-exchange and time behavior between them. Tools that use this approach are *EPOCHS*, *INSPIRE* and the *Hybrid HLA-based* simulation frameworks. They combine tools, fulfilling the requirements identified in this work, which indicates their strong suitability for cyber-physical simulation and their applicability in future SG developments. However, a problem that needs to be investigated is the issue of choosing the time window for simulation synchronization, which is a known problem in HLA-based approaches. In contrast to the HLA approach, *GECO*s time synchronization is handled by a scheduler that uses a global time-scale to coordinate the *PSLF* tool and the *NS-2* simulator. In contrast to the tools using the HLA standard, the developers of *GECO* avoid common synchronization errors by avoiding fixed synchronization point. In particular, they solve the physical simulation in a time-discrete manner and combine these events with events from the ICT domain, which are then sorted according to a global time scale. Aside from the tools that combine specific standalone simulators two approaches were identified that aim combining arbitrary standalone tools. First, the *ORNL Power Simulator* provides physical component simulation using *Toolkit for Hybrid Modeling of Electric power systems (THYME)*, which is a collection of modules for simulating electric power systems. Additionally, *ORNL Power Simulator* uses *adves* for facilitating the interoperability with other tools in a time-discrete fashion. This enables the information exchange with different other standalone tools for ICT simulation like *OMNeT++* and *NS-2*. Second, the *Mosaik* tool aims at enabling the automatic composition of discrete-event simulation processes. This is done by coordinating the input and output of interfaces, which have to be provided by the simulation processes. Additionally, a semantic description has to be provided for matching information between the interfaces. This is addressed by an easy-to-extend dataflow reference model, which handles datatypes and corresponding units.

Both presented tool categories are important for future SG design and development. Specific simulator combinations may currently be more sophisticated but are limited by the respective standalone tools. In contrast, tools that aim at simplifying the process of combining multiple tools enable the interconnection of multiple sectors, ultimately providing simulations adequately reflecting the dependencies of a future SG.

6 CONCLUSION

The integration of novel developments for the future SG into real systems requires thorough testing to avoid failures that may damage equipment and can threaten humans lives. Due to the importance of continuously supplying electricity, modeling and simulation is an established technique for conducting tests in a safe environment. However, tools developed for the old electrical grid have to face novel challenges, which emerge from the grid's transition towards a SG. In this work, we provided an overview of tools, related to electrical grids and indicated their suitability for the simulation of future SG developments. For this, we presented and discussed tools, for simulating ICT, electrical grids and cyber-physical approaches. Interesting and necessary future investigations should aim at resolving challenges in timing and coordination of multiple simulators to adequately represent the interdependencies between the cyber and physical domain. Additionally, the future coupling of multiple systems, like in the context of smart cities, needs to be investigated, which may require the combination of a variety of tools from different sectors.

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