Combining power and communication network simulation for cost-effective smart grid analysis

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***Abstract*—Today's electricity grid is transitioning to a so-called smart grid. The associated challenges and funding initiatives have spurred great efforts from the research community to propose innovative smart grid solutions. To assess the performance of possible solutions, simulation tools offer a cost effective and safe approach. In this paper we will provide a comprehensive overview of various tools and their characteristics, applicable in smart grid research: we will cover both the communication and associated ICT infrastructure, on top of the power grid. First, we discuss the motivation for the development of smart grid simulators, as well as their associated research questions and design challenges. Next, we discuss three types of simulators in the smart grid area: power system simulators, communication network simulators, and combined power and communication simulators. To summarize the findings from this survey, we classify the different simulators according to targeted use cases, simulation model level of detail, and architecture. To conclude, we discuss the use of standards and multi-agent based modeling in smart grid simulation.**

I. INTRODUCTION

TODAY'S electricity grid is transitioning to a so-called *smart grid*. This is driven by the objective of making electricity delivery more reliable, economical and sustainable. Given the reliance of critical services (e.g., transportation, communication, finance) on the power grid, demand for a resilient and self-healing grid is high. The challenge to realize it is complicated by the ever increasing penetration of renewable and distributed energy, adding an extra uncertainty dimension and thus the need for efficient responses to not only varying customer demand, but also to varying (and less controllable) production levels: demand-side management (DSM), in particular demand response (DR) is increasingly important to keep the grid operation economically viable (i.e., feasible without excessive infrastructure investments). Indeed, the power grid since its inception was designed to deliver power from large centralized generation units unidirectionally over transmission networks towards the consumers connected to distribution nets. To make it more economical, distributed sources could help reduce the distance between production and consumption (thus limiting transmission losses, which typically amount to 8% [1]). Further, DSM/DR approaches can help to reduce required generation capacity to deal with peak demand only (for which around 20% of current generation capacity is deployed [1]).

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While the smart grid transition happens at the various grid levels (i.e., generation, transmission and distribution), much research attention is going to the distribution grid, where today limited control is available. Also, typically the roots of power system issues trace back to this distribution level [1].

Central to the smart grid concept, is the convergence of information and communication technology with power system engineering. Modern monitoring, analysis, control, and communication capabilities are being added to the aging infrastructure of the electricity grid, to more accurately get insight in the current grid state and use that knowledge to operate it more efficiently. The latter also implies environmental constraints, which are an important underlying motivation for the smart grid evolution, as exemplified by e.g., the European Union's "Climate and Energy Package" definition of the famous 20-20-20 targets, to be met by 2020: (i) 20% of energy supply should stem from renewable energy sources, (ii) reduce greenhouse gasses with 20%, (iii) 20% increase in energy efficiency.

Undeniably, aforementioned challenges and associated funding initiatives have spurred great efforts from the research community to propose innovative smart grid solutions. Smart grid technology typically results in an increased complexity of the power grid, and implies uncertainty (to be dealt with by, e.g., stochastic control models). To assess the performance of possible solutions, simulation tools offer a cost effective approach. In this paper, we will provide a comprehensive overview of the various tools and their characteristics, applicable in smart grid research: we will cover both the communication and associated ICT infrastructure, on top of the power grid.

The aim of our work is to assist (i) smart grid *researchers* looking for tools that target a certain use case, as well as (ii) smart grid simulator *developers* that wish to gain insights and learn more about simulator paradigms, architectures, standards, etc. However, it is not our intention to provide a detailed implementation guide for smart grid simulators.

The remainder of this introduction outlines the main power grid challenges and indicates how they call for communication infrastructure to be added. In Section II in general, and more specifically in Section II-A, we motivate the choice for a simulation approach in the domain of smart grids. Section II-B points out possible pitfalls to aspiring developers of a smart grid simulator, through an overview of the related design challenges. From a researcher's perspective, the same overview of design challenges can serve as a guide whether to develop custom simulation tools, or rather aim to reuse existing tools where possible. A general overview of smart grid simulation paradigms is given in Section III. Specifically, Section III-A provides insights into the two main approaches used to achieve combined simulation of communication networks and power grids, and Section III-B goes into more detail regarding the differences in modeling time in both domains. Although this survey is focused on software based simulation, we briefly discuss the related concepts such as emulation, real-time simulation, and hardware-in-the-loop in Section III-C. Next, we will discuss the three types of simulators in the smart grid area: power system simulators in Section IV, communication network simulation tools in Section V, and combined power and communication simulation in Section VI. From a researcher's perspective, these respective overviews can help to assist in the tools to select for a particular task, while for a developer it might be worthwhile to select one (or more) as a starting point (resp. building block(s) in a co-simulation approach, see further). We will finally provide a summarizing discussion in Section VII and conclude in Section VIII.

A. The role of communication networks in smart grids

Communication networks already play an important role in the power system. However, from a communication perspective, existing power grid networks suffer from several drawbacks [2], such as: (i) fragemented architectures, (ii) a lack of adequate bandwidth for two-way communications, (iii) a lack of inter-operability between system components, and (iv) the inability to handle increasing amount of data from smart devices. As we will show in the next sections, communication networks will play an even more crucial role in the development of smart grids, and hence are subject of many research efforts, studying the most efficient topology of the communication network, physical media, protocols, etc. [3]. To gain a better understanding of the type of communication networks present in smart grids, the overall smart grid communications layer is often considered to consist of three types of networks, each having a distinct scale and range:

- *Wide Area Networks (WAN)* provide communication between the electric utility and substations, and as such operate at the scale of the medium voltage network and beyond. WAN are typically high-bandwidth backbone communication networks that handle long-distance data transmission.
- *Field Area Networks (FAN), Neighborhood Area Networks (NAN), and Advanced Metering Infrastructure (AMI)* provide communication for power distribution areas (low voltage network). FAN/NAN/AMI interconnect WAN and the Home/Building/Industrial Area Networks (HAN/BAN/IAN) of the end-users.
- *Home Area Networks (HAN), Building Area Networks (BAN), and Industrial Area Networks (IAN)* provide communication between electrical appliances and smart meters within the home, building or industrial complex.

Various smart grid applications have specific (challenging) communication requirements (see [4]), and in the next subsections we present some high level examples showcasing the need for communication for both measurement/monitoring and control. The latter calls for combining accurate models of information and communications technology (ICT) components as well as power networks, e.g., allowing the impact of such control on power system transients [5]. In the context of such smart grid applications, some examples of communication requirements and performance metrics are [2], [4]:

- *Latency* requirements are concerned with the time required to send data from a source to a destination. Certain applications, such as real-time state estimation using PMU data requires very low latency (few tens of ms). For applications such as smart meters data collection or demand response the latency requirements are less critical (up to seconds).
- *Data rate* requirements are concerned with the speed at which data can be sent, i.e., the data volume that can be sent within a certain period of time. For example, video data used in wide area monitoring and control requires high data rates, whereas data rates for AMI can be low.
- *Reliability* requirements deal with ensuring the communication system remains available and is able to send data. Remote protection applications require a very reliable communication network to ensure the safe operation of the grid.
- *Security* requirements aim to protect the system from a wide range of attacks. Concepts related to security are confidentiality (i.e., prevent the disclosure of information to unauthorized parties), integrity (i.e., maintain and assure the accuracy and consistency of data over its entire life-cycle), availability (i.e., the information must be available when needed), authenticity (i.e., validate that parties are who they claim to be), and non-repudiation.

Power line communication (PLC) reuses existing power wires for data communication. i.e., the power grid itself becomes the communication network. Different types of PLC technology exist [6]: (i) ultra narrowband PLC technology operating in 300 to 3000 Hz range with very low bit rate (100 bps), (ii) low data rate (few kilobits per seconds) narrowband PLC operating in the 3-500 kHz range, (iii) high data rate narrowband PLC (500 kbps), (iv) broadband PLC operating in 1.5–30 MHz range and data rates up to 200 Mbps.

Narrowband PLC technologies that operate over the medium voltage or low voltage power grids have been proposed by e.g., PRIME [7], PLC G3 [8], and IEEE 1901.2 initiatives. Targeted applications include monitoring (e.g., AMI), grid control, etc. Broadband PLC is being used for e.g., home multimedia services. However, PLC is challenging because the communication channel, i.e., the power grid, was not designed for that purpose.

B. Advanced metering and demand response

Distribution grids have limited monitoring and control capabilities and today in practice still depend largely on manual actions. As part of the efforts to transition to more automated solutions, advanced metering infrastructure (AMI) has been the focus on the distribution system level. It provides distribution system operators not only with system state information, but also provides remote control capabilities. AMI systems originate from automated meter reading (AMR) systems capable of remotely reading consumption and production records, alarms and status information from the customer. However, AMR is limited by one-way communication capabilities and does not enable control actions based on received information. AMI on the other hand provides two-way communication, and therefore supports control over the demand: AMI is considered as a possible basis for distributed command and control strategies [1]. Note that AMI will need to scale to very large number of participants (e.g., every electricity meter).

Indeed, energy demand levels and their patterns over time are undergoing changes as a result of emerging technologies such as electric vehicles, heat pumps, μ-CHP, etc. Demand response (DR) technologies aim to adapt the energy demanded over time. A classic example of DR is a dual tariff scheme for energy consumption, i.e., an expensive peak hour tariff, and a cheap off-peak hour tariff. In such a scheme, consumers are provided an incentive to modify their energy consumption patterns. Communication technologies such as AMI will enable much more fine-grained levels of control using variable pricing or even real-time pricing. Electric appliances that are equipped with a smart grid interface could react automatically to these price signals (thus relieving the consumer from having to take manual actions based on the changing prices).

One particular area of specific interest in the DR sphere is the charging of plug-in (hybrid) electric vehicles (P(H)EV), which show great promise for the transport sector in reducing the associated emissions and costs (esp. if the energy is supplied by renewable sources). However, such vehicles represent a significant new load to the power grid, especially for distribution grids that are already operating near their limits. The load stemming from uncontrolled EV charging (which for full-electric EVs amounts to the same order of magnitude of a complete household!) thus may require substantial (distribution) grid infrastructure investments. Hence the importance of applying DR-like techniques to avoid overloading the grid. On the other hand, electric vehicles also present new opportunities for utilities. For example, the vehicle batteries could be used for so-called vehicle-to-grid (V2G) applications [9], [10]: provide peak power, or cope with the intermittent behavior of renewable energy sources by storing excess energy and feeding it back into the grid when needed. Intelligent management (based on ICT technology in the power grid) of these vehicles will be essential to deal with these challenges and to benefit from the opportunities.

C. Distributed renewable energy sources (DRES)

Another major cause of the smart grid challenges stems from distributed renewable energy sources (DRES): their large scale deployment has a significant impact on the power system, since the output of solar and wind power is difficult to control given its dependence on variable local weather conditions. Therefore, the effect of such distributed generation (DG) units on system stability is less predictable than on-demand sources such as coal or hydroelectric. As such, large amounts of distributed energy sources have to be monitored and managed [11] to ensure optimal integration. Demand and supply must be in balance in the power grid. As a result, large shares of renewable energy require stand-by controllable generation or the presence of storage to cope with sudden changes in power output. Small controllable energy sources can be aggregated in so called virtual power plants. Distributed algorithms must be developed to make decisions on power system state and control actions [3]. In this context, communication protocols, standards and data formats will be essential to make these components inter operable. Therefore, it is essential that these are evaluated in detail before deployment [3], [11]. Also, DRES may be located in regions where no communication infrastructure is currently available and possibly difficult to deploy. For example, DRES located in mountainous terrain or offshore may require wireless or power line communication based solutions due to the complexity and cost of deploying alternative wired solutions (e.g., fiber).

D. Wide-Area Monitoring, Protection & Control (WAMPAC)

To prevent instability and collapse of the system (e.g., because of DG behavior), control and protection schemes are essential. Traditional protection schemes depend on local measurements sent to a central control system that is part of the supervisory control and data acquisition (SCADA) system [12], and which sends adjusting (low bandwidth) control signals over dedicated communication networks. However, modern protection and control schemes measure and send information at a much higher rate: e.g., measurement and communication of coherent real-time data is considered an enabling technology for improving monitoring and control of the power grid [13]. Synchronized phasor measurements (synchrophasors), representing both magnitude and phase angle of voltage or current waveform at particular points in the grid, are obtained by phasor measurement units (PMU) devices and further collected by phasor data concentrators (PDC). This offers real-time state information with microsecond time accuracy, thanks to synchronization using Global Positioning System (GPS) clocks. Such PMU data supports detailed and accurate state estimation, and enables multiple applications including distributed wide area control, protection, wide-area situational awareness, post-event analysis, etc. While such PMU networks initially were considered in the context of transmission networks, today PMU applications are considered to also improve the observability of the distribution grid. These safety- and time-critical applications clearly need fast communication networks, with requirements beyond best-effort internet technologies. Therefore, there is a need for modeling the communication network and evaluating its impact on modern protection and control schemes [14], [15].

II. Motivation

To study aforementioned smart grid innovations, simulation is considered an important tool. However, writing a new simulation engine from scratch is complex, costly and time consuming [3], [14], especially if we consider the interdisciplinary nature of the smart grid comprising both power system engineering and ICT as key components. The alternative, i.e., reuse existing (off-the shelf, commercial) simulation environments as is, or combine them into a (distributed) simulation environment, may have the benefit of better reliability and scalability [3]. However, the interdisciplinary nature of the smart grid complicates the assurance of the model validity for both power and communication networks, requiring extensive expertise of the most appropriate tools (and their settings) for both domains.

As such, the primary objective of this survey is to provide a comprehensive overview of existing simulation tools in the individual fields of power systems and communication networks, and the interdisciplinary field of smart grids combining power and ICT simulation. To assist in selection of the right tool for the job, this survey provides a detailed overview and classification of existing tools and their capabilities, illustrated by example use cases. .

Although reusing existing simulation tools offers many benefits, it is sometimes necessary to design custom tools, e.g., due to missing features. Therefore, the secondary objective of this survey is to give insights in the design and implementation of smart grid simulators, indicating common pitfalls, lessons learned from earlier experiences, and methods to integrate different simulators.

Next we first motivate the use of simulation tools for smart grid research, and continue by pointing out the most apparent challenges in designing such tools.

A. Why simulation?

Historically, simulation is an important tool for the design of power systems [16]–[18] as well as communication networks [19]. Communication network simulation environments are used to develop and evaluate new ICT architectures and network protocols, while similarly power system engineers use simulation environments for power system planning and operations. In a smart grid context, simulators allow to study complex interactions between these interconnected systems and the monitoring and control elements on top of them [20]. Motivations for resorting to simulation has both economical and practical origins. Simulation is used to reduce the costs associated with upgrades to the power system and communication network infrastructures: costs related to performing the upgrades (installation, testing, etc.), but also to the potential loss of service that can occur as a consequence. Indeed, upgrades can have severe economic and social impacts, even for a short period of time [21]. Simulation reduces these risks, enabling the design and evaluation of different solutions before actually deploying them the in the field, and moreover in a fully controlled environment. The latter implies that future power systems or communication networks can be studied under varying conditions and for different scenario's [20]. Another benefit is that simulation can happen faster than real-time, depending on the complexity of the simulation model [22]. This can reduce the time required to develop new technologies. Therefore, simulation offers much more flexibility compared to studies that depend on real-life deployments. Simulation is also considered an important tool for educational and research support [17].

B. Smart grid simulator design challenges

In this section, we further motivate the need for smart grid simulators, and also discuss the challenges associated with the design and development of smart grid simulators. The provided information not only assists developers in the development process, but also enables users to evaluate the different solutions. We discuss (i) the need for combined simulation of the power system and ICT infrastructure, (ii) selection of the appropriate abstraction level for simulation models, (iii) requirements for simulation scenario's, (iv) differences in modeling time, and (v) practical considerations such as user friendliness, flexibility, etc.

The underlying challenge associated with smart grid simulation is that it requires combined simulation of both the power system and the ICT infrastructure, as well as the applications (e.g., control algorithms) running on top of them, especially considering the large scale those systems [17], [18]. As pointed out previously, the operation of the power grid increasingly depends on ICT [21] and it is therefore crucial to understand the impact of the performance of the communication network on the operation of the power grid [17], [23]. The smart grid, comprising many heterogeneous communicating devices, thus needs to deal with issues such as safety, security (including protection against potential cyber attacks [17]), interoperability, and performance [24]. Yet, current power grid simulators typically do not model the network communication protocols, or even traffic patterns involved in such a smart grid [14], [24]. On the other hand, the operating mode of the smart grid has an impact on the traffic in the communication network [23]. Thus, integration of power and ICT components in the operational power grid also requires similarly integrated simulation frameworks [17].

A first main challenge that thus arises is to decide on the appropriate abstraction level for smart grid simulator models, that should cover the power grid, and ICT components ranging from the communication network, middleware (e.g., [13], [25]), control strategies (which constitute the key smart grid innovations, see Section I), etc. One of the key challenges is the different time resolution (see below) and fidelity of the simulation [20]. Furthermore, the simulator should allow flexible specification of varying scenarios [20], and possibly definition of the level of detail (e.g., time resolution). In this respect, scalability is an important concern: simulators should scale to support the complexity of modern large scale smart grid scenario's, e.g., when considering nation wide smart grids. As such, deciding on the level of modeling detail has to account for computational efficiency [17]. Furthermore, simulations should not only aim to achieve technical objectives, but also consider financial and business criteria as dictated in industry standards [26].

On the modeling part, it should be noted that traditional simulation tools will need to be extended with models specific of the advanced smart grid scenarios. On the power side, this includes appropriate characterization of renewable sources:

dealing with their intermittent and stochastic behavior is a crucial research topic [17]. In view of the DR approaches, correct modeling of the user behavior [26], and especially the flexibility of his load (e.g., time shifting of appliance usage, state-of-charge and charging deadlines for EVs), is crucial. Such models should be accompanied by explanatory meta-data to allow correct application of the models, respecting the assumptions under which they were constructed.

Another complexity stems from different models of time by various simulators: continuous simulation is common in power systems, whereas communication network simulators typically are discrete event simulators [3], [15], [20], [27]. Thus, when combining such tools in so-called co-simulation approaches (see Section III), synchronizing the time of different co-simulation components is a recurring topic [3], [14], [22], [28]. Clearly, the synchronisation of various simulation model constituents has to be carefully managed, as we will explain in Section III-B.

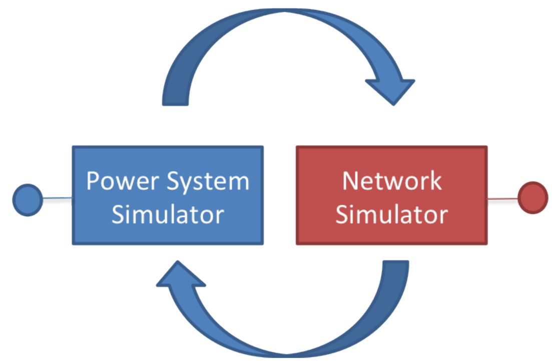
Beyond aforementioned technical aspects, the design of a smart grid simulator should also take into account more practical aspects, including user friendliness. Not only is simulation is an important tool to support education and research [17], [29], [30], consumer involvement in smart grid simulation is also considered [17], [30]. As such, a smart simulator should be an open and flexible environment, that supports user-defined models [17], and easy reuse of already established and validated models. The latter suggests that possible integration with different programming languages could give such support to a broad audience [17], [20]. To achieve this, the use of a common simulation interface and existing communication methods (e.g., web services) is suggested, as to enable integration of existing models, independent of the programming language or simulation tools used [20]. Related to this is the use of data formats for input/output: simulators should limit the dependency on proprietary input formats, operating systems or third party libraries. Ideally, a smart grid simulator should be able to incorporate actual power system components, i.e., hardware in the loop simulations [17], [18], [23]: thus, existing components can be tested in a controlled environment, or used as building blocks to speed up development. However, this requires real-time operation of the simulator and hence appropriate modeling of time.

III. Smart Grid Simulation Paradigms

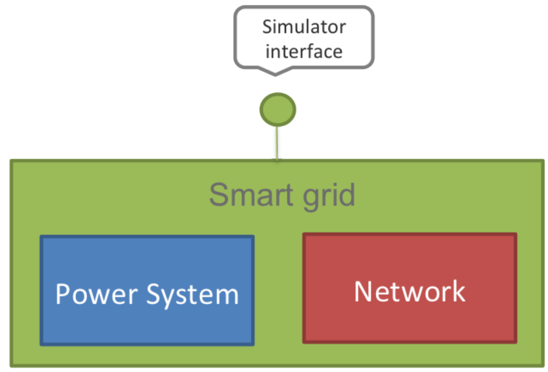
In the following sections we will present simulation environments that are used for simulating power systems, communication networks, as well as their combination in the context of smart grids. First however, we will discuss the overall simulation paradigms they are built on. After sketching how to combine power and ICT simulation constituents, we will outline specific time modeling approaches and the complexity of combining them.

A. Combined simulation of power and communication systems

We briefly discuss the combined simulation of the power system and communication network. Although power system or communication network simulators are being used extensively in both domains, it is the combined simulation of the power system and communication network that has recently attracted more attention due to rising interest in smart grid from governments, industry, and academia. It can be achieved using a variety of approaches, of which two will be discussed in more detail: (i) co-simulation, (ii) comprehensive or integrated simulation.



(a) Co-simulation



(b) Integrated simulation

Fig. 1. Conceptual approaches to combining power and communication network simulation: (a) *Co-simulation*: Multiple simulators with specialized tasks, each having their own simulation interface for data input/output, control, etc. The arrows indicate that interaction between the simulators is required. (b) *Integrated or comprehensive simulation*: One combined simulator provides an integrated environment for combined simulation of power system and ICT.

Constructing a new combined simulation environment is potentially time-consuming and expensive. Therefore, a *co-simulation* approach combines existing specialized simulators. In the context of smart grid co-simulation, a co-simulator would consist of a specialized communication network simulator (e.g., OMNeT++) and a specialized power system simulator (e.g., OpenDSS). Figure 1(a) illustrates the co-simulation approach. Multiple simulators are used, each having their own distinct simulation interface for data input, configuration, result output, control, etc. Therefore, the main challenge is to connect, handle and synchronize data and interactions between both simulators using their respective simulator interfaces. Especially time management between both simulators is challenging, because each simulator manages their simulation time individually. Nonetheless, the main advantage is that existing simulation models, algorithms, etc. that have already been implemented and validated can be reused. Indeed, the majority of the development effort is put into modeling of additional, smart grid specific components: systems such as photovoltaics, wind turbines, etc. and composite sub-systems such as low or medium voltage power grids [20]. Hence, a co-simulation approach reduces development time and the risk of errors.

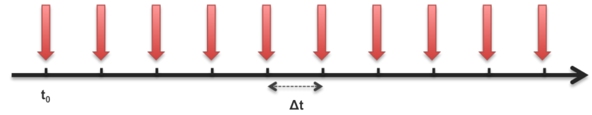
Notwithstanding the development advantages, running the simulators separately and the necessary synchronization likely will imply performance penalties. E.g., in [31] the authors present an example in the context of video streaming where synchronization overhead accounted for 90% of the total simulation time. To further illustrate potential performance examples, we consider a co-simulation approach in which each simulator is run in sequence. For each simulation run, the simulation environment must be loaded (i.e., start-up time is the performance penalty), configured and input data must be provided (i.e., reading and processing configuration and input data is the performance penalty). Next, the simulation model is executed and results are gathered and output. Data input/output often requires intermediaries to store the data, e.g., files on a file system, a database, web services, etc., in which case the access time and the time required to read the data will incur a performance penalty. Also, input/output data must be pre-processed before using it in a next step (e.g., due to different file formats used), introducing pre-processing delay.

An alternative for co-simulation is an *integrated* or *comprehensive* approach to simulation, in which both the power system and communication network are simulated in one environment. Figure 1(b) illustrates the concept. A single simulation interface is provided, instead of having distinct interfaces for each simulator. Another advantage of this tightly coupled approach is that the management of time, data, and power/communication system interactions can be shared among the simulator constituents. Hence, no performance penalty due to synchronization is expected. However, the main challenge is the combination of both models in one environment. The main challenge is to provide a simulation interface that provides sufficient level of detail for the different aspects of the smart grid simulation model. A possible implementation approach to integrated simulation is to select a communication network, power system or other platform as the basis for the smart grid simulator, and implement the other components from scratch or link existing libraries or tools.

B. Continuous time and discrete event simulation models

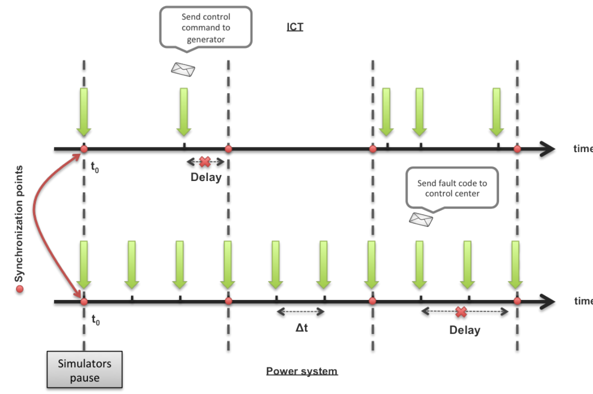
As stated earlier, power system and communication network simulators tend to adopt different modeling approaches. Dynamic power system simulation commonly uses continuous time modeling, where state variables are described as continuous functions of time. Thus, power system element dynamics are expressed by differential equations defining the relations between continuous state variables. However, some discrete dynamics are introduced by circuit breakers, relays, etc. Hence, a time stepped approach is used: since exactly solving the equations analytically is only possible for trivial cases, numerical algorithms using discrete time slots are used. This leads to the time model illustrated in Fig. 2(a).

Communication networks typically are packet switching networks (cf. IP based technologies), which are adequately modeled as discrete event systems characterized by events such as sending and receiving of packets, expiration of timers, etc. Such events occur unevenly distributed in time. This is clearly different from the time stepped approach commonly used for power system dynamic simulation, where a fixed interval between events is selected. An event scheduler is responsible for maintaining a time-ordered list of all scheduled events, and simulation time progresses from event to event as sketched in Fig. 2(b).



(a) Continuous time simulation

(b) Discrete event simulation



(c) Synchronisation issues

Fig. 2. Continous time vs discrete event simulation: (a) Time stepped simulation of a continuous time simulation model. (b) Discrete event simulation (DES). (c) Example of simulation errors in an approach based on predefined synchronization points.

One approach to combine both approaches is the use of predefined synchronization points, indicated by the dashed lines in Fig. 2(c). Each simulator pauses when their simulation clock reaches a synchronization point. After each simulator is paused, information is exchanged. This however can lead to simulation inaccuracies: messages that need to be exchanged between both simulators are delayed if they occur between synchronization points. A solution to this problem is to reduce the time step between synchronization points (and possibly refining the timescale used for the continuous time simulator), yet this clearly degrades performance. Thus, co-simulation needs to strike the right balance between accuracy and simulation speed. Also, not all time instants at which communication between the different simulators must occur are known a priori.

C. Emulation, Real-Time Simulation and Hardware-in-the-Loop Simulation

So far we only considered pure software-based simulation approaches, i.e., both power grid and ICT infrastructure are

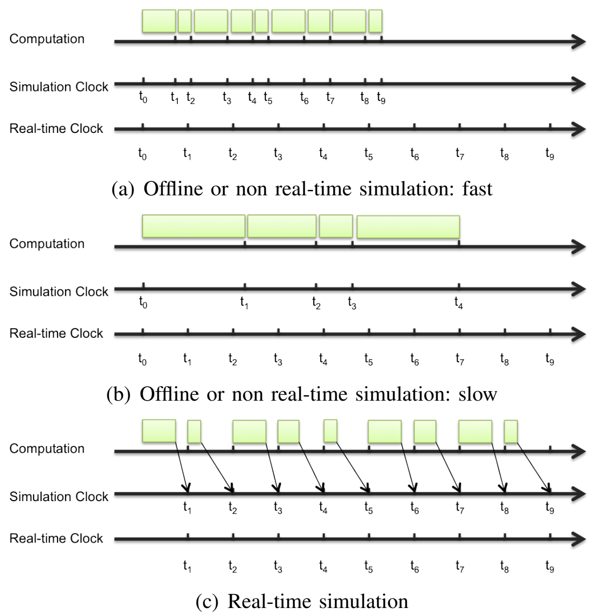


Fig. 3. Non real-time (offline) simulation and real-time simulation: (a) Non real-time simulation in which computation takes less time than the simulated event: simulation clock progresses faster than the real-time clock. (b) Non real-time simulation in which computation takes more time than the simulated event: simulation clock progresses slower than the real-time clock. (c) Real-time simulation: simulation clock and real-time clock are synchronized.

simulated: the physical world components are abstracted as software models. However, some approaches aim for a more realism and therefore provide support for emulation, real-time simulation, and/or hardware-in-the loop experiments. In this section, we provide an introduction to these concepts.

In an *emulation* approach (integrated or co-simulation), the emulated component more closely mimics the real world in hardware. For example, a network emulator such as Emulab [32] can be used instead of simulators such as ns-2/ns-3 or OMNeT++, resulting in a more realistic but still controllable environment: i.e., Emulab allows specifying an arbitrary network topology, resulting in a controllable, predictable, and repeatable environment. To provide an even higher level of detail, it is possible to use actual smart grid components, e.g., GridSim [18] uses the GridStat [33] communication middleware platform.

Next, we discuss *real-time simulation*. The difference with non *real-time or offline simulation* is illustrated in Fig. 3. Figure 3(a) and Fig. 3(b) illustrate two possible scenarios for non real-time simulation: the simulation clock can progress either faster than the real-time clock (i.e., time in the real world) or slower. However, in a real-time simulation approach, the simulation clock and real-time clock are synchronized as illustrated in Fig. 3(c). For these examples, we have assumed a simulation model with discrete time and constant time step (see also Section III-B). Note that techniques exist for supporting variable time steps, but they are less suitable for real-time simulation [34]. Put more formally, a real-time simulator must accurately produce the internal variables and outputs of the simulation model within the same length of time as its real-world counterpart would. I.e., the correctness of a real-time model not only depends upon the numerical computation, but also on the timeliness with which the simulation model interacts with external components (hardware or software). Applications of real-time simulation include testing of physical control and protection equipment.

Hardware-in-the loop (HIL) simulation is a technique used to develop complex real-time embedded systems (e.g., in the domain of power electronics) in which some components are real hardware, whereas others are simulated. Components may be simulated because they are unavailable, or because experiments with the real components are too costly, time consuming, or are too hazardous. Typically, a mathematical model of the simulated system is used to provide electrical emulation of sensors and actuators that are connected to real hardware.

IV. POWER SYSTEM SIMULATION

In this section we discuss power simulation, mainly targeting readers with an ICT background: we introduce different power simulation types, and an overview of existing power simulators, in terms of their main features, example studies, and options for integration of external tools.

Simulators for power system analysis have been extensively used by professionals for network planning, operations and price forecasting. Over-voltages, harmonics, short circuits, transient stability, power flow, and optimal dispatch of generating units are examples of important power system phenomena that need to be captured and parameterized in the simulations. Power system simulations are usually classified into one of these two categories:

1) Steady state simulations form the basis for power grid network planning studies. Researchers and engineers perform "what-if" studies to measure the impact of modifications in the power system. The system is analyzed in a stable equilibrium state, and focus lies on checking whether the power system variables are within proper boundaries (e.g., validation of voltage limits). The different simulators specialized in steady state studies offer a full range of analysis methods, from power flow studies, load estimation and load balancing, to fault analysis or optimal capacitor placement. Steady state simulations also cover optimal power flow studies. In these studies, the system conditions that minimize the cost per kW/h delivered are analyzed using linear optimization. Other optimal power flow methods that incorporate Artificial Intelligence (AI) techniques are described in [35].

2) Transient dynamics simulations study transitions between equilibrium points due to a major changes in the power grid configuration, e.g., disturbances. A major goal of such studies is to determine if the load angle reaches a new optimal steady state. Simulations performed include electromagnetic transient studies with finer time granularity (in the order of microseconds to milliseconds) than the steady state ones. In these simulations, time varying and short term signals are studied. If the equilibrium is lost due to continuous small disturbances, dynamic stability simulations, also known as small-signal stability simulations, are needed. Simulators specialized in transient dynamic power characteristics enable to model the

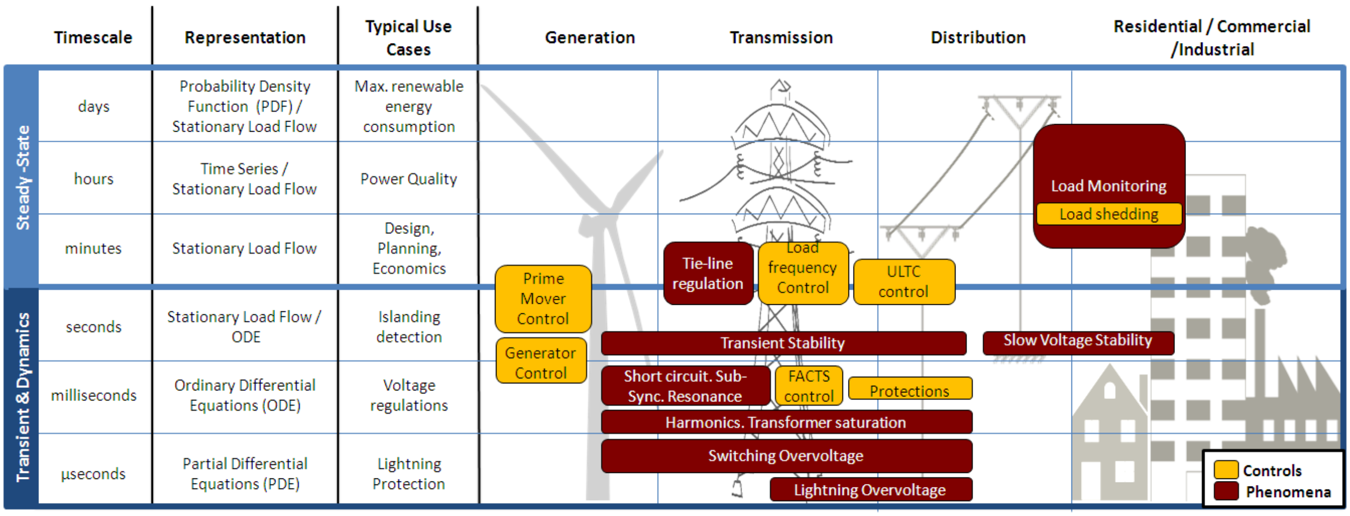


Fig. 4. Time scales of different power phenomena and power control: depending on the time scale, different model representations are adopted. The time scale considered depends on the use case, which typically is related to a particular part of the grid (generation, transmission, distribution, etc.).

network at circuit level, reproducing the time domain wave forms of state variables at any point in the system.

In addition to the "steady state" vs "transient dynamic" classification, power system simulations usually focus to one of the hierarchical power grid domains: Power Generation, Transmission, Distribution or Utilization (residential, commercial and industrial loads). Depending on the domain of interest and the power phenomena, the time steps of the simulation would vary. Figure 4 gives an overview of the timescale for different phenomena and control strategies in power systems. Phenomena that require higher frequency studies (transients) would require a smaller duration of calculation time steps. Note that such smaller time steps would deliver more accurate results, but come at the price of increasing the total simulation runtime [11]. Figure 4 also captures the different power system domains, example studies and the mathematical representation of the various power phenomena. The top part of the diagram focuses on steady-state analysis, while the bottom groups the transient dynamics.

As pointed out in Section II-B, smart grids pose specific challenges, such as high penetration of renewable DG units and microgrid operation, implying importance of energy storage and decentralized energy management. In energy transmission and distribution, the increment in sensing and communication capabilities enables new automation and control strategies for remote condition monitoring or blackout prevention. Moreover, new intelligent consumption strategies are possible thanks to more frequent meter readings, demand response plans and smart appliances with different load management features. These all need to be appropriately modeled. In the following subsections, we present an overview of the main simulators found in research literature and illustrative applications thereof in smart grid studies. We also indicate interfaces offered by the simulation tools to expand its functionality, and e.g., link with other components to realize co-simulation.

A. PSCAD/EMTDC

PSCAD/EMTDC is a commercial simulation tool for the Power System Computer Aided Design and Electromagnetic transients for DC. An example of PSCAD/EMTDC simulations of power system control in a smart grid context is [36], where Fazeli et al. present a novel integration of wind farm energy storage systems within microgrids. PSCAD/EMTDC can be coupled with external tools like Matlab, as exemplified in [37], where Luo et al. combine PSCAD/EMTDS's electromagnetic transient simulation capability and with advanced matrix calculations in Matlab for testing a new network based protection scheme for the power distribution grid. Similarly, Mahmood et al. have designed a three-phase Voltage Source Converter (VSC) for distributed generation, developed their linear model in Matlab and validated it using a detailed switching model in PSCAD/EMTDC [38].

B. DigSilent - PowerFactory

DigSilent Power Factory allows the modelling of generation, transmission, distribution and industrial grids, and the analysis of their mutual interactions. Load flow, electromechanical RMS fluctuations and electromagnetic transient events can be simulated. Thus, both transient grid fault and longer-term power quality and control issues can be studied. As an example of power flow studies using DigSilent, Coroiu et al. evaluate the continuity of power supply using the comparative methods of the probabilistic load flow and the stochastic load flow [39]. Transient studies is performed by e.g., Chen et al. , who studied the transient stability of a micro-grid supplied by multiple distributed generators [40]. Models of voltage controllers, generators, motors, dynamic and passive loads, transformers, etc. are part of DigSilent's built-in electrical components library, but the algorithms inside these models are not accessible. However, users can create models using the DigSilent Simulation Language (DSL). An example of such a study on dynamic wind models can be found in

Table I
CLASSIFICATION OF POWER SIMULATORS

	Simulation Type		Power Subsystem - Domain			License	
Simulator	Steady State (min, hours, days)	Transient Dynamics (s, ms, μs)	Generation	Transmission	Distribution + RCI loads	Commercial	Open Source
Cymdist	x		x		x		
DigSilent	x	x	x	x	x	x	
EMTP-RV		x		x	x	x	
ETAP PSMS	x	x	x	x	x	x	
EuroStag	x		x	x	x	x	
homer			x			x	x (v.2.68Beta)
ObjectStab		x	x	x			x
OpenDSS	x	x	x		x		x
PowerWorld	x	AO		x			
PSCAD/EMTDC		x		x	x	x	
PSS®E	x	x	x	x		x	
PSS®Sincal	x	AO	x		x	x	

RCI: Residential, Commercial and Industrial loads **AO**: Add-on

[41]. In addition, DigSilent supports the exchange of power data with external tools. For example, in [42] Andren et al. combine DigSilent with Matlab andt present a framework for the simulation of power networks and their components, using an Open Process Control (OPC) interface for exchanging data between simulators.

C. Siemens PSS®

The Power Systems Simulator (PSS®) product suite includes several software solutions targeting different domains and time scales. Among others, PSS includes PSS SINCAL and PSS E. PSS SINCAL targets utility distribution system analysis: it is a commercial (with special licenses for research and education) network planning and analysis tool with capability to perform, among others, power flow, load balancing, load flow optimization and optimal branching simulations. PSS SINCAL's COM-server interface facilitates the integration into existing IT architectures. The COM interfaces can be exploited in Smart Grid simulations, where PSS SINCAL can be used in the analysis of distributed generation and smart meter data. As an example of such studies, Chant et al. investigate the impacts on integrating photo voltaic panels on the utility grid in terms of harmonic distortion, voltage fluctuation and load rejection issues [43]. PSS SINCAL allows users to link each Smart Grid equipment model (e.g., e-cars, micro-turbine, smart meter, etc.) with their correspondent generation and load profiles [44]. For transmission system planning, the PSS E tool allows users to perform load flow analysis and transient analysis. For example, Mohamad et al. use PSS E for transient stability analysis [45].

PSS E can interact with user scripts using the Python scripting language. Such integration is used by Hernandez et al. : modeling Synchronous Series Compensators (SSSC) in Python, they simulate the control of power flow through transmission lines [46].

D. EMTP-RV

EMTP-RV is a commercial software for simulations of electromagnetic, electromechanical and control systems transients in multiphase electric power systems. For instance, Napolitano et al. use transient modeling using EMTP-RV software to model the MV feeder response to indirect lightning strokes [47]. Other potential uses of EMTP-RV include studies in insulation coordination, switching surges, capacitor bank switching, motor starting, etc. Users can develop customized modules and interface them to EMTP-RV via dynamic-link library (DLL) functionality.

E. PowerWorld

PowerWorld Simulator is an interactive, visual-approach, power system simulation package designed to simulate high voltage power system operation on a time frame ranging from several minutes to several days. PowerWorld's add-on SimAuto allows to control the simulator from external applications. SimAuto acts as a Component Object Model (COM) object for interfacing with external tools, such as Matlab or Visual Basic. Such combination is illustrated by Roche et al. , who combine PowerWorld with external artificial intelligence (AI) decision making tools to realize smart grid simulations studying feeder reconfiguration and large-scale demand response [48].

F. ETAP PSMS

ETAP PSMS is a real time power management system. ETAP software has more than 40 modules for load flow analysis, short-circuit analysis, device coordination analysis, motor starting analysis, transient stability analysis, harmonic analysis, etc. In [49], Mehra et al. applied principal component analysis (PCA) to simulated phasor data, generated by ETAP software.

G. Cymdist

Cymdist is designed for planning studies and simulating the behavior of electrical distribution networks under different operating conditions and scenarios. It offers a full network editor and it is suitable for unbalanced load flow and load balancing studies. The software workspace is fully customizable. The graphical representation of network components, results and reports can be built and modified to supply the level of detail needed. Furthermore, the CYME COM module allows different environments to communicate with the CYMDIST software for accessing different pre-defined functions and calculations. An illustrative distribution system modeling study using Cymdist can be found in [50].

H. EuroStag

EuroStag is a power systems dynamics simulator developed by Tractebel Engineering GDF SUEZ and RTE (electricity system operator of France). It allows a range of transient and stability studies. Supplementary tools, such as Smart FLow, enable load flow calculations. An example of such studies can be found in [51], where Asimakopoulou et al. compared various load control scenarios for the power system in the island of Crete, using EuroStag as the basis for their simulations.

Table II
CLASSIFICATION OF MATLAB-BASED POWER SIMULATORS

Package	PF	CPF	OPF	TD	EMT	SSA
DCOPFJ			x			
EST	x			x		x
INTERPSSS	x	x	x	x		
MatEMTP				x	x	
MATPOWER	x		x			x
PAT	x			x		x
PSAT	x	x	x	x		x
PST	x	x		x		x
PYLON	x		x			
SIMPOWER	x			x		
SPS	x			x	x	x
TEFTS	x			x		
VST	x	x		x		x

PF: Power Flow **CPF**: Continuation Power Flows
OPF: Optimal Power Flow **TD**: Time Domain
EMT: Electromagnetic transients **SSA**: Small-signal Stability Analysis

I. Homer

HOMER is a power generation simulator. It can be used for designing hybrid power systems containing a mix of energy sources: conventional generators, combined heat and power, wind turbines, photo voltaics, batteries, etc. Both grid tied or standalone systems can be simulated. In addition, green house calculations are also possible. An illustrative micro grid sizing and dynamic analysis study using Homer and EuroStag is presented in [52].

J. OpenDSS

OpenDSS is an open-source distribution system simulator developed and maintained by EPRI. It is designed to support power distribution planning analysis associated with the interconnection of distributed generation to the utility system. Other targeted applications include harmonic studies, neutral-earth voltage studies, volt-var control studies, etc. Co-simulation interfaces (e.g., COM and scripting interfaces) are provided and users can define their own models [53]. OpenDSS is considered a suitable platform for smart grid research as it supports the analysis of intermittent and stochastic processes associated with renewable energy sources [17].

K. ObjectStab

ObjectStab [54] is an open source power system library with capabilities to perform power system transient simulations. It is based on Modelica, a general purpose object oriented modeling language. An example of high voltage DC (HVDC) power transmission studies can be found in [55], where Meere et al. designed optimised power system models for variable speed wind turbine machines with a HVDC link for grid interconnection. The electrical performance of the system is verified using ObjectStab.

L. Real-time hardware-based simulation

Opal-RT [56] develops real-time digital simulators and hardware-in-the-loop testing equipment. eMEGAsim from Opal-RT is a real-time hardware-based simulator that has been developed to study, test, and simulate large power grids, industrial power systems, etc. It supports simulation of very large power grids with a time step as low as 20 microseconds. It can also be used for simulation of power electronics found in distributed generation (e.g., wind farms, photo voltaic cells) and Plug-in Hybrid Electric Vehicles (PHEV). RT-LAB [57] is the core technology behind eMEGAsim and enables distributed real-time simulation and hardware-in-the-loop testing of electrical, mechanical, and power electronic systems, and related controllers. ARTEMIS is a suite of fixed-step solvers and algorithms that optimize real-time simulation of SimPowerSystems [58] models of electrical, power electronic, and electromechanical systems. Opal-RT products are fully integrated with MATLAB/SimuLink.

The Real-Time Digital Simulator (RTDS) [16] from RTDS Technologies [59] is a power system simulator that solves electromagnetic transient simulations in real-time. It supports high-speed simulations, closed-loop testing of protection and control equipment, and hardware-in-the-loop applications. Parallel processing techniques enable the simulation of large scale power systems: power system equations are solved fast enough to continuously produce output conditions that realistically represent conditions in the real network. RTDS supports IEC 61850 device testing. As a result, the simulator can be connected directly to power system control and protective relay equipment.

M. Classification

A characterization of the previously mentioned simulators can be found in Table I, which presents a classification of popular power simulators according to the time-scale of the simulations (steady-state vs transient), the domain (power generation, transmission, distribution, consumption) and their licensing (open-source vs commercial).

In addition, simulation platforms based on Matlab/Simulink environments are also widely used. Examples of power system simulators based on MATLAB include Power System Analysis Toolbox (PSAT) [60], Power System Toolbox (PST) [61], Educational Simulation Tool (EST) [62], SimPowerSystem [58], Power Analysis Toolbox (PAT) [63], Voltage Stability Toolbox

(VST) [64] and MATPOWER [65]. Note that although several of these tools are open source, MATLAB is a commercial and closed product. Yet, PSAT can also run on GNU/Octave, which is a free Matlab clone, therefore resulting in a complete open source solution that is freely available. In addition, PYPOWER is a translation of MATPOWER to the Python programming language. Table II summarizes the different MATLAB modules and their capabilities, based on [17], [60], [64]

Note that in addition to the major tools discussed above, additional open source tools are described by Milano et al. in [66]: UWPFLOW (power flow, implemented in the C programming language), TEFTS (transient stability, C), InterPSS (load flow and transient studies, in Java), AMES (whole sale power market, Java), DCOPFJ (DC optimal power flow, Java) and PYPOWER (DC and AC power flow and DC and AC optimal power flow).

V. Communication Network Simulation

In this section, we present an overview of communication network simulators, which are widely used for the development and evaluation of communication architectures and protocols. We present a short overview of the different simulators that have been successfully used in a smart grid context: ns-2/ns-3, OMNeT++, NeSSi and OPNET Modeler®. This section will primarily serve readers with a power systems background, since ICT experts will be presumably be familiar with some of these tools. Yet of particular interest for ICT researchers will be the highlighted sample smart grid use cases for which they have been used. We limit our selection of examples to those that focus on the communication aspects in the smart grid, and as such do not require (detailed) modeling or simulation of the electric behavior of the power grid. Simulators and use cases that focus on the combined simulation of the power system and communication network are considered in Section VI. Note that general purpose tools such as MATLAB have also been applied to study communication networks in a smart grid context [67], [68], but we will not further elaborate on those studies here.

A. Network Simulator (ns-2 and ns-3)

The *Network Simulator version 2 (ns-2)* is a widely used open source discrete event network simulator created for research and educational purposes. It is targeted at networking research, with a strong focus on internet systems. Therefore, it includes a rich library of network models to support simulation of e.g., IP-based applications (including TCP, UDP, etc.), routing, multicast protocols, over wired and/or wireless networks. The *ns-2* core is written in the C++ programming language. Users can create new network models or protocols using the C++ language. Simulation scripts to control the simulation and configure aspects such as the network topology are created using the OTcl language interface. As a result, users can create and modify simulations without having to resort to C++ programming and recompiling *ns-2*. Development of *ns-3*, the successor to *ns-2*, is ongoing: new features include support for the Python programming language as a scripting interface (instead of OTcl), improved scalability, more attention to realism, better software integration, etc. [69]. However, when selecting a specific version of *ns*, it is important to consider that *ns-3* is not backwards compatible with *ns-2*: i.e., existing *ns-2* simulation models must implemented again for *ns-3*. Both are widely used for networking research in general, and unsurprisingly also in a smart grid context both *ns-2* and *ns-3* are adopted in e.g., a co-simulation approach [11], [22], [24], [27], [70], [71]. In [72] a suite of software modules for simulation of PLC networks using ns-3 is presented and source code is made available at [73].The simulation model is based on transmission line theory (TLT), which relies on the knowledge of the topology, wires, and the load characteristics of the power grid underlying the PLC system. This approach supports networks with multiple node-to- node links. An interface to the ns-3 framework is provided, which allows the integration of higher level protocols such as TCP/IP. A GUI is provided that enables users to draw the topology and specify node and line properties, and also noise present in the network.

B. OMNeT++

The open-source OMNeT++ discrete event simulation environment [74] has been designed for the simulation of communication networks (wired and wireless) and distributed systems in general. The simulation environment has a general design (i.e., it is not limited to simulating communication networks) and therefore has been used in various domains, such as wireless network simulations, business process simulation and peer-to-peer networking. However, OMNeT++ is mostly applied in the domain of communication network simulation. A comprehensive set of internet based protocols is provided by means of the INET framework extension which includes support for IPv4, IPv6, TCP, UDP, Ethernet, and many other protocols. Other extensions provide simulation support for mobility scenarios (e.g., VNS), ad-hoc wireless networks (e.g., INET-MANET), wireless sensor networks (e.g., MiXiM, Castalia), etc. Distributed parallel simulation is supported to enable simulation of large scale networks. Additionally, federation support based on the High-Level Architecture (HLA) standard is provided in OMNEST, the commercial version of OMNeT++. An OMNeT++ simulation model consists of simple modules implemented in C++. Compound modules consist of other simple or compound modules, and are defined using the OMNeT++ Network Description Language (NED). Modules communicate by passing messages via gates, which are the input and output interfaces of the modules that are linked to each other by so-called connections forming communication links between modules. Apart from the networking community, OMNeT++ has also received substantial attention from the smart grid community for developing smart grid simulators [5], [29], [75]–[80].

Example use cases that focus on the communication aspect of the smart grid include the design and evaluation of different smart grid communication architectures, performance of smart grid protocols, etc. For example, a demand side management communication architecture based on orthogonal frequency-division multiplexing (OFDM) power line communication

(PLC) is proposed in [76], [77]: the authors test business cases and benchmark overall network performance in a controlled environment, and use OMNeT++ results to iteratively improve the network design. As part of that research, a full simulation model of PRIME protocols has been developed that enables simulation of IP communication over a PLC network. Another PLC simulation model for OMNeT++ is presented in [81]. It is a generic model that does not implement a specific variant of PLC, but provides a toolkit that should enable the user to model the desired PLC variant. Simulation of broadband PLC in a home environment is demonstrated.

Another example is a simulation environment to study geographical routing in multi-hop wireless networks in the context of smart grid energy applications [78]. There, the authors purely focus on communication, i.e., without power system modeling and simulation. That work is extended and a modular and distributed simulation environment is proposed in [79], focusing on scalability analysis of smart grid ICT infrastructures. It allows distributed simulation and provides additional simulation management features (scenario generation, model repository, dependency management, management GUI, etc.). Main research questions include topology-specific influences on the scalability of different technologies and various traffic patterns for smart grid applications.

A last example is related to the evaluation of smart grid standards and protocols. An important standard in smart grids is the IEC 61850 standard, targeted at substation automation. A IEC 61850 simulation platform is described in [29] based on OMNeT++. The platform is designed to support communication network performance analysis, hardware-in-the-loop simulations, and algorithm development and evaluation. An overview of other IEC 61850 simulation platforms that are limited to communication network performance analysis is also presented in [29].

C. NeSSi

NeSSi (Network Security Simulator) is an open source discrete event network simulator developed at DAI-Labor (Distributed Artificial Intelligence Laboratory) and sponsored by Deutsche Telekom Laboratories. We include NeSSI because the primary focus of the tool is on network security related scenarios in IP networks [82]. Features described to support security related scenarios are attack modeling, attack detection, security metrics, etc. Distributed simulation is supported to enable simulation of large scale networks. Example uses in the smart grid domain include a security analysis of a smart measuring scenario through federated simulation [83] and to use an integrated approach for evaluating and optimizing an agent-based smart grid management system [82].

D. OPNET Modeler®

OPNET Modeler® is a powerful commercial discrete event network simulator with built-in, validated models including LTE, WIMAX, UMTS, ZigBee, Wi-Fi, etc. It enables modeling of various kinds of communication networks, incorporating terrain, mobility, and path-loss characteristics in the simulation models. OPNET Modeler has a visual high-level user interface offering access to a large library of C and C++ source code blocks, representing the different models and functions. It comes with an open interface for integrating external object files, libraries, other simulators (co-simulation) and even hardware-in-the-loop.

The Smart Grid Communications Assessment Tool (SG-CAT), introduced in [84], is a simulation, modeling and analysis platform, targeted to utilities that want to develop a holistic smart grid communications strategy. It has been developed to assess the performance of different smart grid applications under various terrains, asset topologies, technologies and application configurations. SG-CAT has been built on top of OPNET Modeler, taking advantage of OPNET's modular design, which allows the exchange and customization of applications, communication technologies, terrain profiles and path-loss models. The same authors also discuss the scale-up concerns when approaching large scale simulations in OPNET, and offer a solutions to these challenges based on the unique characteristics of smart grid scenarios [85].

Furthermore, OPNET is used in multiple co-simulation approaches (see further in Section VI) that consider both the communication network and power system in detail [15], [28], [86]–[88]. Smart grid use cases that focus on the communication network without detailed modeling of the power grid are described in [89]–[91]. The authors of [89] consider a wide area monitoring and control scenario system that uses a WiMAX/IEEE 802.16 network to transport delay-sensitive PMU data: several IEEE 802.16 scheduling services (UGS, rtPS, BE) are evaluated in terms of delay, uplink use and signaling overhead, using a simulation model developed in OPNET. The same authors also propose a heterogeneous WiMAX-WLAN network architecture for advanced metering infrastructure (AMI) communications [90], and compare the performance of the WiMAX-WLAN network architecture to that of a pure WLAN network architecture. In [91], the authors study the performance of a Long Term Evolution (LTE) based networks (frequency- vs time-division multiplexing mode) for up-link biased smart grid communication in terms of latency and channel utilization.

E. Discussion

The communication network simulators discussed in this section have been used successfully in context of smart grid research. OMNeT++ and ns-2/ns-3 are used extensively in academia due to their open-source nature. In terms of supported simulation models, we believe that a wide range of models is available for each simulator, and the choice mainly depends on prior knowledge and preferences of the user regarding modeling language and tools, extensibility and supported programming languages, presence of extensive GUI tools, etc. For example, OMNeT++ and NeSSi provide an integrated development environment (IDE) that includes GUI's for building and configuring simulation models, visualization of topologies, result processing, etc. However, ns-2/ns-3 lacks an extensive set of GUI tools as found in OMNeT++, making it more complex in its usage. OPNET Modeler® on the other hand is a commercial simulator that has a visual high-level interface. Another aspect that may influence the choice of simulator is commercial support, which is available for OMNeT++ (i.e., OMNEST) and OPNET. NeSSi, also an open-source simulator, distinguishes itself from the other tools due to its primary focus being network security.

VI. Smart Grid Simulation

In this section, we present an extensive overview of smart grid simulators, i.e., those that support the combined simulation of the power system and the communication network, and/or model and study higher layers such as market mechanisms (e.g., for the development of demand response algorithms). We will categorize such smart grid simulators in two types, which we dub tools, resp. environments. A smart grid simulation *tool* is defined as providing a combined simulation of the power grid and communication network for a specific use case, i.e., the simulation tool is designed for that specific use case and others are not supported. As such, these tools are used to provide answers to very specific research questions, and are not extensible. On the other hand, smart grid simulation *environments* do not target a specific use case, but their design supports a wide range of use cases. As such, these environments are used to provide answers to a broad range of research questions, and are much more extensible.

A. Specialized smart grid simulation tools

A smart grid co-simulation tool to study the impact of delays in the communication network on the performance of the power grid is presented in [24]. A wireless communication network is simulated. A control strategy uses the wireless network to activate distributed storage units to compensate for temporary loss of power from a photo voltaic (PV) array, a phenomenon called "cloud transient" or "solar ramping"). The tool is used to determine if the distributed storage units can be dispatched quickly enough in case such a cloud transient occurs. A model of an actual distribution feeder is used to which small-scale storage batteries and a large scale PV array are connected. The wireless communication system is based on IEEE 802.11 (Wi-Fi). OpenDSS is employed to simulate the distribution system and the ns-2 network simulator is used to simulate the wireless communication network. Figure 5 illustrates the sequential co-simulation approach that is employed. OpenDSS outputs data regarding the time of the PV ramp event, the geographical coordinates of the storage nodes, and the power output of the storage nodes. Scripts parse this output and configure ns-2 with the storage node topology. Ns-2 then simulates the arrival of the dispatching messages at the storage units. Next, the arrival times of these messages are used to create OpenDSS scripts that are fed back to the OpenDSS environment, which then performs a sequence of power flow solutions. Note that this implies careful synchronization, as discussed in Section III-B.

B. Smart grid distribution system

In this section we discuss (i) the power distribution system simulation and analysis tool GridLAB-D, and (ii) a hardware-in-the-loop test platform for real-time state estimation in distribution networks.We include GridLAB-D in the smart grid simulator overview instead of the power system simulator overview because it focuses on smart grid technologies and aims to incorporate simulation of the communication network.

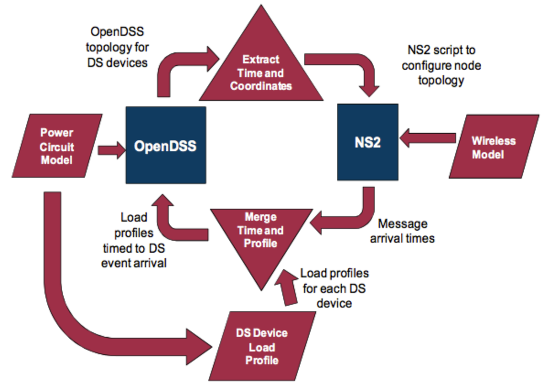


Fig. 5. Example of a co-simulation approach [24].

1) GridLAB-D: GridLAB-D can be considered as a power distribution system simulation and analysis tool [92] targeted at the smart grid. It allows the simultaneous simulation of power flow, end use loads, and market functions and interactions. The software consists of a system core that can determine the simultaneous state of millions of independent devices (each can be described by multiple differential or difference equations) resulting in a detailed and accurate system model. GridLAB-D is designed as a modular system: the system core can load additional modules that add specific functions and models to the simulation environment. Modules can be developed and distributed independently. Basic features provided by these modules include power flow calculations and device control, end use loads and controls, data collection, etc. Additional, more advanced features, such as consumer behavior models (e.g., different types of demand profiles, price response, contract choice), energy operations (e.g., distribution automation, load-shedding programs, emergency operations), and business operations (e.g., retail rate, billing, market-based incentive programs) are also provided or under development [93]. Although the original focus of GridLAB-D was on the distribution system, research into the transmission system is also supported (e.g., the power flow module consists of both a distribution module and a transmission module [93]) as illustrated by [94] in which the influence of distributed energy sources on the transmission grid is evaluated. Although the current version (2.3.1) of GridLAB-D does not support explicit modeling of the communication network, a communication network module and a co-simulation approach are mentioned in the context of the next version (3.0): i.e., a *communications module* will allow users to simulate latency and dropped messages [95], [96]. The addition of such a module will enable users to determine the impact communications systems have on the operations of smart grid technologies. GridLAB-D is is also reported to be used as a basis for other smart grid simulation frameworks [97], [98] (although some raise concerns on the limited flexibility of composing GridLAB-D with other modules [20]). An electricity market simulator and GridLAB-

D distribution system simulator are combined to simulate integrated retail and wholesale power system operation in [97]. In [98] the authors show that demand response resources can be used to maintain a flat and stable voltage profile over the feeder. For this, the authors extended GridLAB-D with a demand response controller, and adapted the existing volt/var controller is adapted to make use of the added demand response controller. Note that no communication network is simulated in [97], [98].

2) Hardware-in-the-loop test platform: A hardware-in-the-loop [99] test platform for real-time state estimation of active distribution networks using phasor measurement units is presented. Active distribution networks refer to electrical grids of which the resources are controlled by an energy management systems (EMS) to perform optimal voltage control, fault detection and management, etc. Such functions are deployed in time frames that vary between a few hundreds of milliseconds (fault management) to few tens of seconds. As such, they require real-time information about the network state. For this purpose, real-time state estimators (RTSE) that use PMU measurements are being developed. However, it is difficult to assess the accuracy of such RTSE in a real operational grid, as the true network state is unknown. Real-time simulators overcome this problem by enabling researchers to reproduce realistic power network conditions in a controlled environment.

The authors use the eMEGASim PowerGrid Real-Time Digital Simulator from Opal-RT to generate three-phase voltage and current analog signals of the monitored network buses, which are captured by a number of PMUs, which encapsulate the processed signals according to IEEE Std. C37.118.2-2011 [100] and send them over a real communication network to a workstation running a Phasor Data Concentrator (PDC) that processes and stores the information. The RTSE, also running on the workstation, uses the information to estimate the network state in real-time.

The real-time digital simulator accurately simulates the electromagnetic transients required by power grid and fast power electronic and converters systems. The true network state is known because it is recorded by the real-time simulator. Therefore, the performance of the RTSE algorithm can be assessed. Also, because a real communication network is used, the impact thereof (e.g., latency and/or data errors and loss) can be evaluated.

C. Electricity Markets

In this section we discuss smart grid simulators that focus on simulation of electricity markets in smart grids. Although these simulators do not explicitly model the communication network, we include them because of they incorporate specific smart grid technologies (e.g., VPP). Also, agent based simulators for electricity markets such as SEPIA could be seen as the predecessors of the smart grid simulators of today. Agent based approaches were gaining attention as a concept for self-healing distributed control of the power grid. Clearly, concepts such as self-healing, distributed control, and agent based system are currently still active research domains in the smart grid. Modeling thereof started with tools such as SEPIA [12] to which additional control strategies would be added. Hence, our reasoning for including SEPIA in this discussion of smart grid simulators.

1) SEPIA: Simulator for Electric Power Industry Agents (SEPIA) [26] is an agent-based simulation approach to modeling and simulation of physical and business operations in an electric power system. SEPIA is aimed to be a proof-of-concept to illustrate an agent-based simulation approach for the power industry. Possible applications targeted by SEPIA relate to the integration of physical and business operations in a power system. A power system structure can be defined by components that represent generators, loads, and business entities. These components are interconnected by links, representing power grid links, ownership, or money flows. Basic AC and DC power flow simulations are supported. SEPIA consists of three main components: (i) a graphical user interface to design, monitor and steer simulations, (ii) domain specific agents, and (iii) a simulation engine. Domain specific agents consist of traditional power system agents (e.g., generators, loads, transmission lines) and ancillary agents (e.g., markets, weather and speculators). Agents can transmit messages to each other. Each message is sent with an associated delivery time, which enables modeling of communication delay. The simulation engine has three major functions: (i) keeping track of simulated time, (ii) managing all communication between agents, and (iii) enforcing constraints set by the model topology. SEPIA supports studying agent learning in a power system by including a learning module that is based on the Q-learning algorithm (for agents to learn actions to take based on their observations of the system state). An example use case considers generator agents that learn how to take price decisions in electricity markets.

2) MASGriP: Similarly to Sepia, the authors of [101] propose a multi-agent based smart grid environment, but explicitly focuses on smart grid use cases e.g., in the context of residential demand response. The simulation environment consists of two parts that are integrated in one environment: (i) the multi-agent smart grid simulation platform (MASGriP), and (ii) the multi-agent system for competitive electricity markets (MASCEM) [102]. Thus, MASGriP considers the technical aspects, whereas MASCEM considers the economical aspects of the smart grid, as discussed in more detail below.

MASGriP models the distribution network and the involved players. Power system entities such as consumers (residential, commercial, industrial) and (distributed) generators are modeled as agents. Each agent represents a physical entity in the smart grid and includes information regarding the electrical properties, location, etc. Additionally, demand response (DR) functions, micro-generation units, and/or electric vehicles can be assigned to these consumer types. These consumer agents establish contracts with aggregator agents: Virtual Power Players (VPP) or Curtailment Service Providers (CSP). Since individual consumers have insufficient flexibility required by for example DR programs, a CSP aggregates the demand response participation from small and medium consumers. CSP tasks include: identifying curtailable loads, enrolling customers, manage curtailment events, and calculate payments

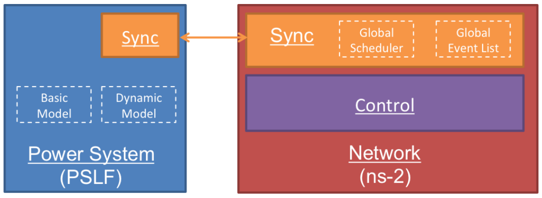


Fig. 6. The GECO Architecture. Power system is simulated by PSLF and state information and control commands are exchanged between PSLF and ns-2 using a bidirectional interface (indicated by *Sync*). Control models (PMU, intelligent agents, etc.) are implemented in ns-2.

and penalties for participators. A VPP manages energy resources (DG, DR, SS, EV) and participates in the energy negotiation process (DR contracts, markets, etc.). Hence, a CSP is responsible for the technical management of energy resources, whereas a VPP is responsible for the economical activities associated with these resources.

MASCEM is a modeling and simulation tool to study complex and restructured electricity markets. Following agents are defined: market operator, system operator, market facilitator, buyer agents, seller agents, VPP agents, and VPP facilitators. Although the focus of MASCEM is on the economical aspects (i.e., electricity markets), technical constraints influence the operation of electricity markets (e.g., supply and demand must be balanced). Therefore, the system operator agent ensures that all constraints are met in the system and is therefore connected to a power system simulator to perform power flow analysis.

D. Wide-Area Monitoring, Protection and Control

Now we discuss three approaches that target use cases related to wide-area monitoring, protection and control: (i) Two co-simulation approaches (GECO [3] and ORNL PSS [27]), (ii) a federated co-simulation approach (EPOCHS), and (iii) A real-time co-simulation approach (GridSim).

1) GECO: A global event-driven co-simulation framework for interconnected power systems and communication networks (GECO) is proposed [3], [70]. It is based on the PSLF (steady state and dynamic power system simulations) and ns-2 (communication network) simulation environments. GECO has been used to evaluate wide area monitoring, protection and control schemes [3], [103].

The GECO architecture is illustrated in Fig. 6. A subcomponent in ns-2 is responsible for managing the co-simulation. It implements a global event scheduler designed as the global time reference and coordinator. A bidirectional interface between ns-2 and PSLF is used to exchange information (e.g., power system data, control commands), which is a tighter coupling than the co-simulation approach of e.g., [24]. Network-based power system control strategies are implemented in ns-2 based on the Application class in ns-2: control models for digital relays, phasor measurement units, and intelligent electronic devices. Agents make control decisions that are communicated using the simulated network and communication protocols based on TCP and UDP. Synchronization of the simulators is based on a global event driven mechanism, therefore it does not exhibit the accuracy problems illustrated in Section III.

An example use case discussed is a communication-based backup distance relay protection scheme. The present distance relay protection framework is extended with an underlying network infrastructure. Distance relays can communicate with each other through their software agents thereby forming a coordinated system protection scheme. The objective of the scheme is to have faster backup relay protection and additional robustness to prevent tripping. Depending on the type of communication, two related protection schemes are discussed: supervisory (master-slave) and ad-hoc (peer-to-peer). Both schemes achieve faster backup relay protection than traditional non-communication based schemes, and also false-tripping (i.e., due to faulty measurements) is avoided.

2) ORNL Power System Simulator: Another example, based on a co-simulation approach using the ns-2 and A Discrete EVent system Simulator (adevs) simulation tools, is presented in [27], and in [5] the authors present a similar approach using OMNeT++ instead of ns-2. In [27], the authors discuss in detail the problem of integrating the discrete event nature of communication systems and the continuous time models of power systems. An approach based on Discrete Event System Specification (DEVS) is proposed to ensure formally that simulation correctness is preserved, enabling an integrated simulation of both domains. DEVS is a formalism to model and analyze general discrete event systems. The Toolkit for HYbrid Modeling of Electric power systems (THYME) is built on adevs and provides power system models (loads, transmission lines, generators, etc.), a power flow model, and a limited model for electro-mechanical transients [5]. A wide area load control use case demonstrates the simulation environment. Example results link the performance of the communication network to the operation of the power system: e.g., network flows affect load shed order and available bandwidth and network latency affects the control behavior.

3) EPOCHS: The electric power and communication synchronizing simulator (EPOCHS) [14], [104] is a platform for agent-based electric power and communication simulation. The main use cases supported by the EPOCHS simulation framework are related to wide area monitoring, protection and control. Example use cases are: (i) evaluation of the benefits and drawbacks of using communication in an agent-based special protection system, (ii) a backup protection system, (iii) monitoring of power system to prevent blackouts caused by voltage collapse. Instead of designing and building a new combined simulation environment, multiple specialized simulation environments (PSCAD/EMTDC, PSLF, ns-2) are linked into a distributed environment (federation).

EPOCHS is a combined simulation environment that links a power system simulator and communication network simulator (“federates”) in a distributed environment (a “federation”). Figure 7 gives an overview of the EPOCHS architecture. The user of the simulation environment has the choice between two power system simulators, depending on the target use case: the PSCAD/EMTDC electromagnetic transient simulator (power system modeling), or the PSLF electromechanical transient simulator (transient timescales). Support for these different power system simulators is required due to the large differences in time scales between the electromagnetic and

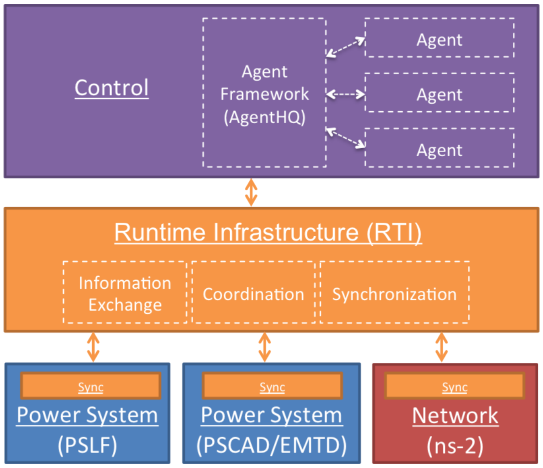


Fig. 7. The EPOCHS Architecture. Intelligent agents implement distributed wide area control and protection schemes. RTI routes all messages between simulation components and manages simulation time.

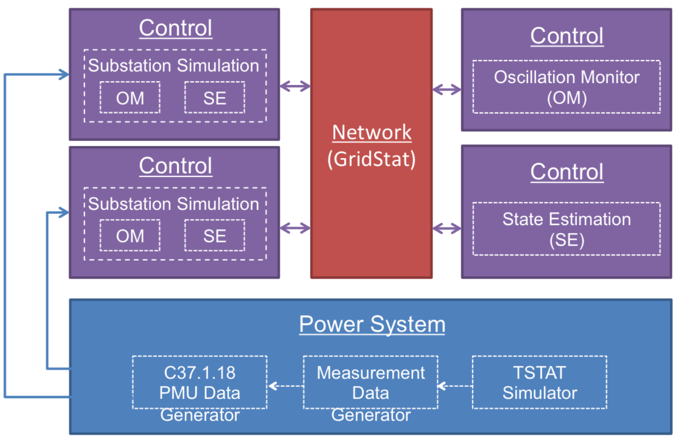


Fig. 8. The GridSim Architecture. The *Power System* component generates PMU measurements that are encapsulated in C37.1.18 data format and forwarded to simulated substations that use real communication middleware (GridStat) to transmit them to OM and SE applications.

electromechanical simulations. The communication network is modeled in Network Simulator 2 (ns-2). The federation is managed by a central component, the runtime infrastructure (RTI). The RTI routes all messages between simulation components and ensures that the simulation time is synchronized across all components. The AgentHQ provides a unified view on the federation and provides a framework for implementation of intelligent agents, for example to implement distributed wide-area control and protection schemes. EPOCHS uses a time stepped synchronization approach as discussed in section Section III and as such may exhibit accuracy problems.

Summarized, EPOCHS is a distributed simulation environment that considers the combined simulation of the power grid and communication network. Supported use cases are related to wide-area monitoring, protection and control.

4) GridSim: simulates the power grid, the ICT infrastructure that overlays the grid, and the control systems running on top of it, in real-time. It focuses on the design and testing of wide area control and protection applications using PMU and other high-rate time stamped data. Distinctive about GridSim is that it operates in real-time to ensure optimal interfacing with actual power system elements, either hardware or software, i.e., it enables hardware-in-the-loop (HiL) experiments.

GridSim provides a flexible simulation framework that supports power system simulation, data delivery, flexible sensor deployments, and integration of actual power system components, protocols, and algorithms. GridSim components can be organized in four groups: power system simulation, substation simulation, communication and data delivery, and control center applications. TSTAT, a transient stability simulator, is used for power system simulation. GridStat, is used to deliver data between the different components in GridSim. GridStat is a wide area data delivery framework based on a publish-subscribe architecture. Examples of control center applications that are included in GridSim are: (i) an oscillation monitor, and (ii) a state estimator, both built using the OpenPDC applications set, which is an open-source software system for collecting and processing PMU measurements.

Summarized, GridSim is a real-time simulator for the power grid, the communication network and the control systems. Real-time operation ensures that actual power system elements can be integrated. Instead of using a communication network simulator, a real communication middleware platform is used.

E. Demand-Response/Demand-Side Management

This section gives an overview of simulators that are used to perform simulations related to demand-response or demand-side management applications. The simulators have been selected because they have distinct features. The IBCN smart grid simulator provides an integrated environment that has been used to evaluate DSM algorithms for electric vehicles. The SGiC simulator for example aims to involve end-users in their simulations, whereas GridSpice demonstrates how cloud technology can be used to enhance smart grid simulation scalability.

1) IBCN Smart Grid Simulator: An integrated smart grid simulator that considers the combined simulation of the power system and ICT infrastructure is proposed in [75]. A case study demonstrates the capabilities of the environment by investigating the impact of control algorithms for distributed generators (i.e., PV panels) has on a distribution grid, i.e., on the voltage profile and load profile of a household. Another area for which the simulator has been used extensively is demand side management of electric vehicles, e.g., [105].

The smart grid simulation environment is designed as layered architecture in which three layers are defined: application, middleware and support layers. The architecture is illustrated in Figure 9. The simulation environment is implemented in OMNeT++ using the INET framework, and power system simulator module implemented in Matlab is integrated into the environment.

The application layer consists of high-level applications or services, for example AMI, DSM/DR, or billing services. The services in the application layer make use of the middleware layer, which provides generic functionality that can be used by any service. This includes a communication interface which can be used to send messages between components independent of the underlying networking technology (e.g., ZigBee

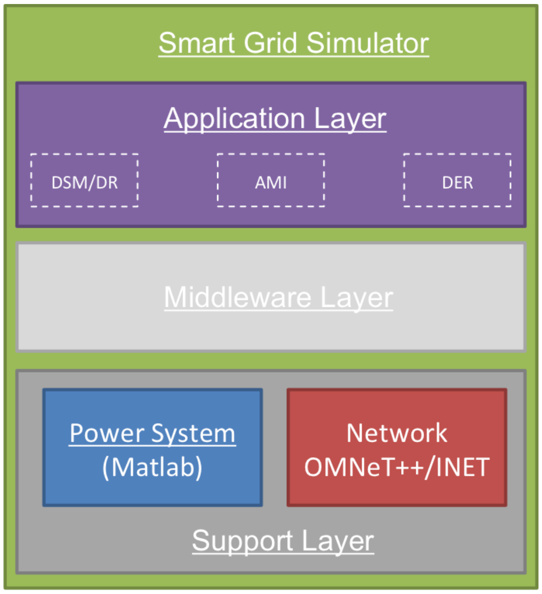


Fig. 9. IBCN Smart Grid Simulator presented in [75]

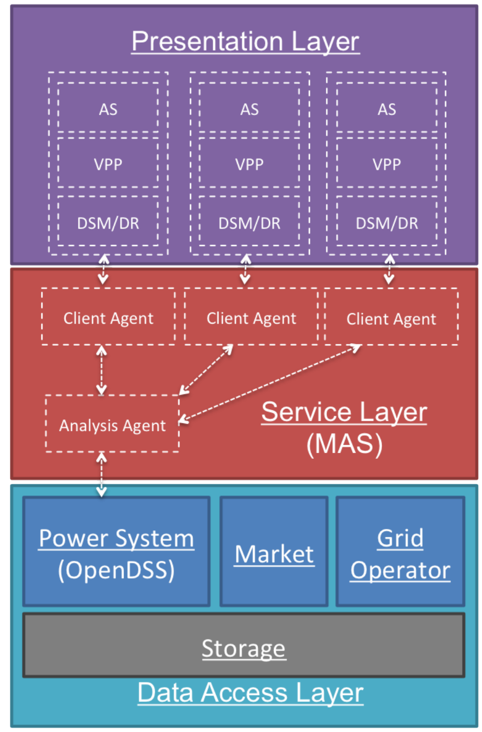


Fig. 10. The layered SGiC architecture [17]. AS: ancillary services, VPP: virtual power plant, DSM: demand side management, DR: demand response, MAS: multi-agent system.

or PLC; TCP or UDP) that is being simulated, discovery of devices or services, etc. The goal of this middleware layer is to support a broad range of applications while reducing the effort required to develop these services to a minimum. The support layer, composed of the network and electrical components, provides support functions for the layers above. Communication between services is simulated by the network component that provides simulation models for multiple types of physical media and communication protocols. The simulation environment must be able to model and interact with (virtual) electrical devices. This is supported by the power system component of the simulator which provides power flow simulations. Basic electrical models are provided (e.g. PV panel, battery, electric vehicle), but the user can add his own models.

2) SGiC: The Smart Grids Information & Communication (SGiC) [17] is web-based software for distributed decision support and performance analysis. Target use cases for the SGiC framework are power routing, power balancing, virtual power plants, or price based control. The software enables active participation of researchers, engineers and customers (residential or commercial). The latter is the unique aspect of this simulation tools. SGiC provides a end-user interface that supports social network interactions, which are considered appropriate incentives for consumers participating in DR, DSM, and virtual power plant (VPP) programs.

The SGiC software has a three-layer architecture, illustrated in Fig. 10: presentation, service, and data access layers. The presentation layer provides web-based services to the end user that assist in participating in VPP, DSM, DR and local balancing programs. Customers are encouraged to share information, in order to obtain information on interesting programs in which to participate. An agent framework is used in the service layer to share information between users, network operators, and markets. Based on input from the users, an analysis agent (based on OpenDSS) will perform power system simulations and send decisions back to the users. Data from network operators, markets, DR participation, etc. is recorded in a common database in the data access layer.

3) GridSpice: is cloud-based simulation package developed to provide a framework to model all interactions of a smart grid, i.e., power flows, communication and market operations, in distribution and transmission networks. Built on top of GridLab-D and MATPOWER, the initial applications it targets are: renewable energy integration, home area control and smart algorithms, electric vehicle infrastructure, distributed energy resources, micro-grids, demand response and distribution operation, and utility scale storage. In [98] the authors use the GridSpice simulation platform to simulate volt/var control, demand response, and distribution automation in order to maintain a flat and stable voltage profile over the feeder.

F. Generic smart grid simulation environment

In this section we discuss generic smart grid simulation environments. Such environments do not target a specific use case, but aim to be general enough to support a wide range of use cases. The coupled simulator presented in [11] uses IEC 61850 to provide standards based distributed simulations. Mosaik [106] is an automatic simulation composition framework for the smart grid.

1) The Coupled Simulator: A coupled power system and communication network simulator is presented in [11]. Example use cases include the monitoring and control of large amounts of distributed energy resources in the context virtual power plants. Nevertheless, the simulator is described as not being limited to specific use cases (e.g., time step can be

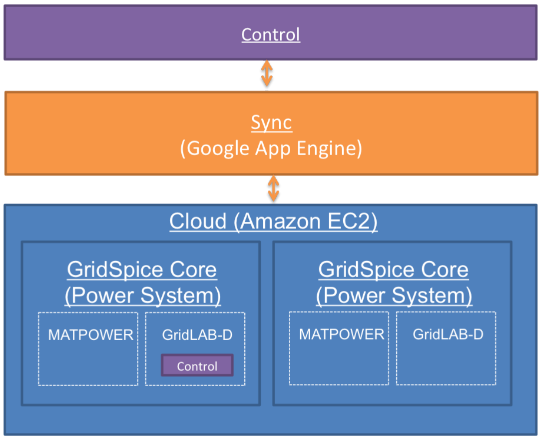


Fig. 11. The GridSpice Architecture

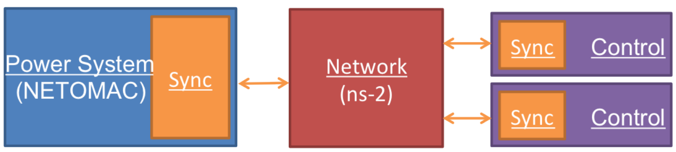


Fig. 12. Architecture of the Coupled Simulator described in [11]

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chosen in function of the phonomena under study). A message format and communication protocol based on the IEC 61850 specification is used to communicate over sockets, enabling a standards based distributed approach.

An overview of the architecture is given in Fig. 12. The authors define the concept of interaction points, which are a subset of the IEC 61850 logical nodes. These nodes are the elements of the data model used for communication. Access (reading/writing) to those interaction points is provided via JNI (Java Native Interface) interfaces. A network simulator is placed between the smart grid applications and the power simulator. All messages are routed through this network. A GUI enables the user to view the topology and simulation results of the simulated smart grid. Real-time simulation is supported enabling real-time testing of hardware.

2) Mosaik: is a modular smart grid simulation framework supporting automatic composition of existing, heterogeneous simulation models for the evaluation of control strategies for heterogeneous DER and loads [106]. As such, the framework aims to provide support for scenario specification, simulation composition and scenario result analysis.

Mosaik adopts a layered approach to the simulation composition problem, which deals with the selection and combination of simulation components into valid simulation systems, according to specific user requirements. The layered architecture is illustrated in Figure 13. The *syntactic level* defines the interactions between the simulation models: i.e., to integrate a simulation model in Mosaik, the modeler has to provide an implementation of a predefined interface (SimAPI – XML/RPC API) that enables Mosaik to progress time of the simulation model and to get and set model data in a uniform way. The *semantic level* uses a reference data flow model to add a semantic description (i.e., data type, units) of the data that can be exchanged using the interfaces defined at the syntactic level. The *scenario level* deals with scenario definition and depends on a scenario meta model which is a formal scenario description. A prototype scenario meta model has been implemented using domain specific language (DSL). The *control level layer* provides a standardized API for the control strategies to analyze and manipulate the system at runtime. The Mosaik prototype consists of two components (both implemented in Python) [20]: (i) Master Control Program (MCP) (ii) simulation interface (SimAPI). The MCP manages the composition of the simulation scenarios and controls the execution of the scenarios. SimAPI must be implemented by the simulation models to integrate with Mosaik. An example use case is presented that composes a variety of simulation models: (i) electric vehicles (Python/SimPy and JADE), (ii) photovoltaics (MATLAB/Simulink), (iii) residential loads (CSV timeseries), (iv) distribution grids (single-phase power flow analyses with Python/Pylon). Although not described, the SimAPI should allow a communication network simulator to be part of the framework. A future resource management component will enable simulations to be distributed over multiple machines thereby enhancing scalability.

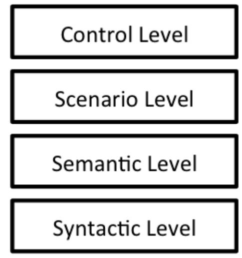


Fig. 13. The Mosaik architecture for the selection and combination of simulation components into valid smart grid simulation systems

G. Summary

Figure 14 displays a classification of smart grid simulators according to their modeling capabilities in terms of communication network and power system. The communication network model level of detail is divided in three parts: (i) no model, (ii) black box communication network model, (iii) detailed communication network model.

Figure 15(a) illustrates the cases where no communication network simulation model is implemented by the smart grid simulator. Information is exchanged without modeling message sizes, bandwidth, delay, errors, congestion, protocols, etc. In other words, an ideal network with infinite bandwidth, zero delay, no errors, etc. is modeled.

Figure 15(b) illustrates a black-box communication network model which provides a simplified and abstract model of the simulated communication network. The example black-box communication network is modeled using two parameters: the delay and errors. For simplicity, we assume a fixed delay, independent of the source, destination, message size, etc. In such a scenario, a source that wants to transmit a message to a destination, forwards the message to the black-box communication network model, which delivers the message

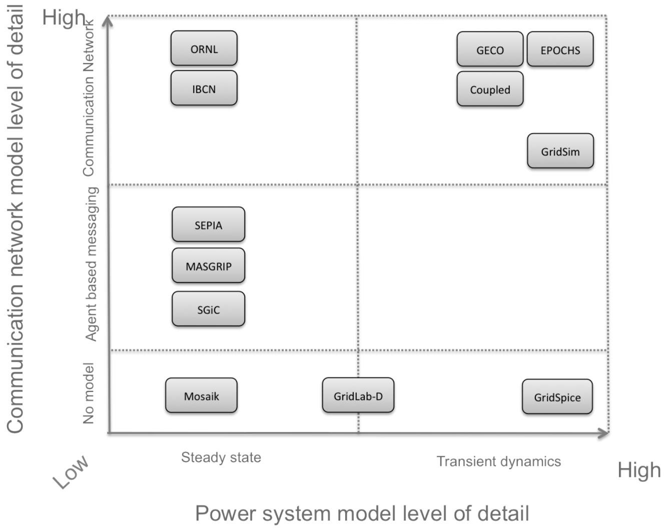
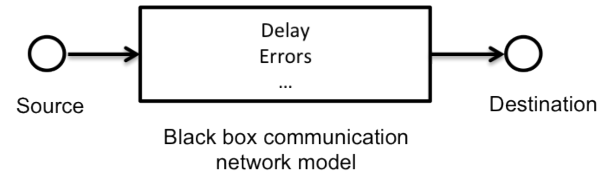
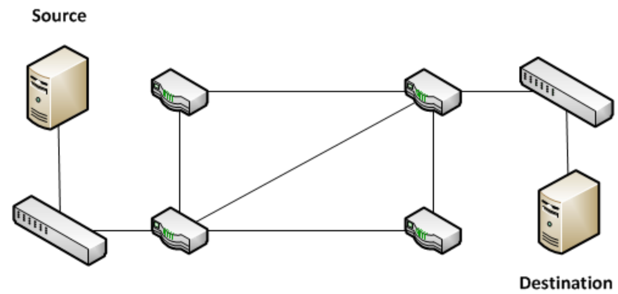


Fig. 14. Classification of smart grid simulators according to supported power grid simulation type and communication network model.

(a) No communication network simulation model



(b) Black-box communication network simulation model



(c) Detailed communication network simulation model

Fig. 15. Level of detail of the communication network simulation model: (a) No communication network simulation model. (b) Black-box: high level abstract simulation model. (c) Detailed communication network simulation model.

to the destination after the specified delay. An example of a possible "error" model could be a given probability that a message is lost in the network, and as a result is not received at the destination. Note that other parameters (e.g., bandwidth, congestion, message sizes) could also be included in the black-box model.

Figure 15(c) illustrates a detailed communication network model which provides a realistic model of the simulated communication network. The example network consists of a source and destination host connected to a switch, which are connected to the core network that consists of multiple interconnected routers. Each communication link may be configured with specific bandwidth, delay, error, etc. parameters. Source and destination hosts contain models for the application, transport, network, link and the physical layers of the network. Switches contain models for the link and physical layers of the network. Routers contain models for the network, link and physical layers of the network.

Summarized, a black-box model does not explicitly model the network topology, links, protocols, background traffic, etc., whereas a detailed communication network model provides support for this

The power system model level of detail is divided in two levels: (i) steady state, (ii) transient dynamics. Summarized, steady state simulations analyze the system in a stable equilibrium state, and focus lies on checking whether the power system variables are within proper boundaries (e.g., validation of voltage limits). Transient dynamics simulations study transitions between equilibrium points due to a major changes in the power grid configuration, e.g., disturbances. We refer to Section IV for more information about these power system simulation types.

VII. Discussion

Above, we presented a survey of power system, communication network and smart grid simulators. In this section, we first synthesize the architectural schemes these smart grid simulators are built on. Next, we will discuss the use of standards, communication protocols, data formats, etc. in smart grid simulators. Finally, we briefly indicate the role of on multi-agent based systems in smart grid simulators.

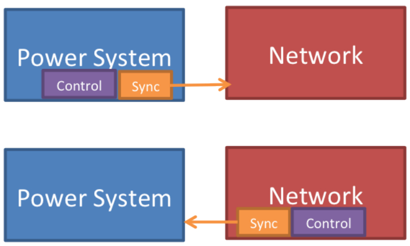
A. Smart grid simulator architectures

In this section we give an overview of the different smart grid simulator architectures, for which we will indicate the relationship between the four high level functional components:

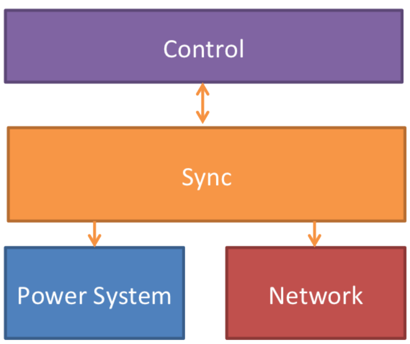
- *Power system* models the power grid.
- *Network* models the communication network.
- *Control* models the smart grid applications (WAMS, DSM/DR, AMI, etc.).
- *Sync* synchronizes time, data and interactions between the different simulator constituents.

As discussed in Section III, in an *integrated simulation* architecture (see Fig. 1(b)) a single simulation environment combines simulation of the power system, communication network and control. Synchronization between the various components in this approach is straightforward, since there is only one core simulation engine keeping track of (simulated) time. This is the approach taken in, e.g., [75], [107].

In a *co-simulation* approach (recall Fig. 1(a)), multiple specialized simulators are used, thus requiring synchronization between them. Therefore, in practice typically one simulator is selected as a master simulator for the synchronization logic, which usually (although not strictly required) is also the one where control logic is implemented: this amounts to a master-slave configuration, as illustrated in Fig. 16(a). Control and synchronization thus are possibly limited by the capabilities of the master simulator. An example of this approach is [22], combining ns-2 (master) and Modelica, which identified possible drawbacks: (i) the master controls the slave model, therefore, sending data from slave to master is not possible (i.e., slave cannot push messages in response to internal events to master) (ii) no parallelism is exploited, both run each in turn. Also, such an architecture does not naturally lend itself to distributed or federated simulation. Other examples that use this approach are GECO [3], the ORNL Power System Simulator [5], [27], VPNET [28].



(a) Master-slave



(b) Dedicated synchronization and control

Fig. 16. Two fundamentally different approaches to co-simulation.

Figure 16(b) illustrates a co-simulation in architecture in which a single dedicated component is responsible for synchronizing and connecting all the different components. Not only does it provide synchronization between the multiple simulators, it also offers a unified interface for the control logic. This approach also lends itself to distributed or federated simulation: dedicated hosts could be used for each individual host. Examples that use this approach are EPOCHS [14] and GridSpice [18], Mosaik, and the HLA-based simulator proposed in [15].

Figure 17 illustrates a layered approach using different synchronization layers between each simulator. An example that uses this approach is [11]. Also, we could consider the co-simulation approach presented in [24] to be of this type. Although the SGiC does not explicitly model the communication network, it also uses a layered approach. Mapping the SGiC architecture [17] to the functional blocks defined in this section (power system, network, control, sync), we could say that network and synchronization layers have been merged in the service layer.

Table III provides an overview of smart grid simulators using an integrated or co-simulation approach. It can be used to identify simulators based on the targeted use case, illustrate different co-simulators that have been used, etc. Emphasis is put on simulators that consider the combined simulation of the power grid and ICT infrastructure. However, certain examples do not consider both components, but are still included due to the specific smart grid applications they target. For each simulator, we indicate the main use case that is being targeted, the power and network communication components, and lastly if the simulator can be used in a distributed setting. The support for distributed simulation can be beneficial the increase the scalability of the simulator, and enables easier integration with other simulators (e.g., based on HLA, see below).

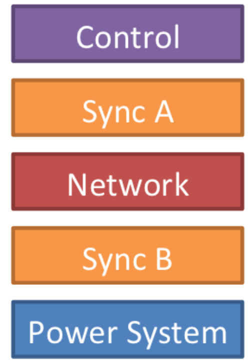


Fig. 17. Layered simulation architecture. *Sync A* is responsible for synchronization between *Control* and *Network* components whereas *Sync B* provides synchronization between the *Power System* and *Network* components. The difference in naming indicates that completely different approaches/technologies may be used.

B. Standards and smart grid simulation

Federation is identified as a common mechanism to co-simulation in this survey and in [82]. The High Level Architecture (HLA) is an open standard developed by the Simulation Interoperability Standards Organization and published in IEEE Standard 1516. It is a technology for developing distributed simulation and describes the components of HLA, their interfaces and properties. Several smart grid simulators use this technology or a similar approach to perform a combined simulation of the power system and ICT infrastructure [14], [15], [83]. A federation consists of a number of simulators (federates) that are connected to a service bus called the Runtime Infrastructure (RTI). Figure 18 gives an overview of a topology of a HLA federation. The RTI provides information, synchronization, and coordination services. Information exchange occurs according to a publish/subscribe paradigm. Synchronization services handle time, synchronization points, snapshots, etc. Coordination services are used to manage the execution of the federation and the different federates. A Federation Agreement is a document that describes how federates are exchanging services. It consists of Federation Object Models (FOM) that contain a description of the data exchange in the federation (e.g., objects, interactions). Main advantages of the HLA are standardized interface specifications and documentation. However, concerns are also raised regarding: (i) added complexity of developing a federated simulation, (ii) the requirement to modify existing simulators to make them HLA conform.

Table III
OVERVIEW OF SMART GRID SIMULATORS.

Reference	Use Case	Power	Communication	Distributed
GridLab-D [92]	Distribution system	-	-	No
GridSim [18]	Wide Area Monitoring and Control	TSTAT	GridStat	Yes
ORNL [5], [27]	Wide Area Monitoring and Control	adevs	ns-2, OMNeT++	No
EPOCHS [14]	Wide Area Monitoring and Control	PSCAD/EMTDC, PSLF	ns-2	Yes
GECO [3]	Wide Area Monitoring and Control	PSLF	ns-2	No
Zhu et al. [87]	Wide Area Monitoring and Control	Matlab/Simulink	OPNET	No
Georg et al. [15]	Wide Area Monitoring and Control	DigSilent	OPNET	Yes
Lugaric et al. [21]	Wide Area Monitoring and Control	PowerWorld	Anylogic	No
Mets et al. [75]	DSM/DR	Matlab	OMNeT++	No
GridSpice [98]	DSM/DR	GridLab-D, MATPOWER	-	Yes
Godfrey et al. [24]	DSM/DR	OpenDSS	ns-2	No
SEPIA [26]	Electricity Markets	MP_2	-	Yes
MASGrip [101]	Electricity Markets	-	-	No
Bergmann et al. [11]	Virtual Power Plants	PSS NETOMAC	ns-2	Yes
Davis et al. [108]	SCADA Security	PowerWorld	RINSE	?
Mallouhi et al. [109]	SCADA Security	PowerWorld	OPNET	?
Liberatore et al. [22]	Networked control	Modelica	ns-2	No
VPNET [28]	Networked control	VTB	OPNET	No
Xiaoyang et al. [88]	Networked control	-	OPNET	No

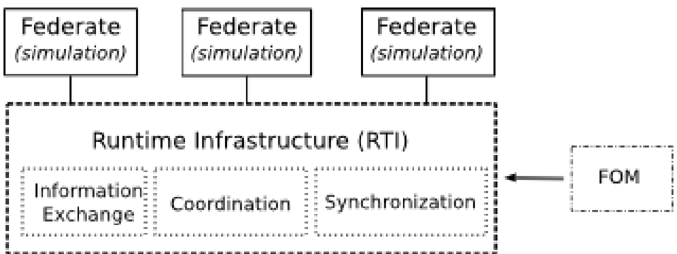


Fig. 18. Topology of a HLA Federation

The smart grid simulators presented in [11], [15] make extensive use of smart grid standards such as *IEC 61970 Common Information Model (CIM)/Energy Management*, *IEC 61968 Common Information Model (CIM)/Distribution Management* and *IEC 61850 Power Utility Automation*. In [15], the power system topology is provided as input to the simulator using CIM, which defines a description language used for the power system topology. Ontology matching is used to convert the CIM topology to the IEC 61850 based model description used internally. Support for both technologies using ontology matching approaches is considered beneficial considering the ongoing CIM and IEC 61850 harmonization. Similarly, Mosaik [20] supports CIM to define the topology of the power system. A message format and communication protocol based on the IEC 61850 specification is used to communicate over sockets between the different simulator components [11]. GridSim [18] uses a communication protocol defined by IEEE C37.118 when simulating the exchange of PMU data. For static power flow analysis, a CIM compliant tool chain for Python has been identified in [110], comprising: (i) PyCIM to import grid topology as CIM XML/RDF file (ii) CIM2BusBranch to convert CIM node breaker topology to the bus branch topology, and (iii) PyPOWER to perform load flow analysis.

Use of standards based approaches (HLA, IEC 61850, CIM, etc.) facilitates the interoperability of different simulators that are acquired or developed over time, as well as the exchange of simulation models. It also adds an extra level of realism to the simulation models. Another advantage is that users can easily select and combine components according to their specific requirements, reducing cost, time and risk.

C. Multi-agent based systems

Agents are a natural way to extend the power system without drastic changes in the architecture of the power system [14]. Main benefits that are associated with agent based approaches are their (i) autonomous nature, (ii) ability to share information, (iii) ability to coordinate actions. Hence, multi-agent based systems are being used in a variety of ways for smart grid applications [111]. For example, protection schemes, demand side algorithms, etc. are being implemented using (market based) multi-agent systems, in which the agents contain the intelligence required to take appropriate actions. As such, the (simulated) multi-agent architecture and the intelligence implemented in the agents could eventually be implemented in the field and thus is not only for simulation purposes. Another example of the application of multi-agent systems is the increased use of agents that is observed in devices deployed in the field such as Intelligent Electronic Devices (IED) [14].

This survey on smart grid simulation has pointed out that also in the context of simulation, agent based approaches play a significant role: i.e., agents are used as a model for simulator components, which would not necessarily correspond to an actual components in the real world. Agent based approaches are typically used in simulators that consider electricity markets such as SEPIA and MASGriP. Examples of other smart grid simulators that use agent models include GECO, EPOCHS and SGiC. The ILIas framework presented in [82] focuses on integration of simulation and multi-agent based management systems. For the requirements analysis for Mosaik, additional emphasis was put on supporting agent based control strategies [106]. In [112] the authors describe a simulator based on software agents that simulates the dynamic behavior of a smart city: heterogeneous devices that consume and/or produce energy, and that are able to act autonomously and collaborate. Agents are also considered to model the human factor within simulations [21].

VIII. Conclusion

Smart grid technology typically results in an increased complexity of the power grid, and implies uncertainty (to be dealt with by, e.g., stochastic control models). To assess the performance of possible solutions, simulation tools offer a cost effective approach. A comprehensive overview of the various tools applicable in smart grid research, as well as their main characteristics, shows they fall into three groups: (i) power system, (ii) communication network, and (iii) smart grid simulators. Power simulation tools broadly are either targeted at steady state analysis (typically power flow studies), or at transient dynamics simulations (typically upon disturbances or sudden system changes). They typically adopt a continuous time model, studying the system state at fixed, equidistant points in time. Communication network simulators on the other hand typically adopt a discrete event simulation approach, where time intervals between successive events (i.e., system changes) can greatly vary. Thus, combining them both into real smart grid simulators requires careful synchronization when a so-called *co-simulation* approach is followed, where models from both domains in different tools are combined. More *integrated* solutions have a tighter coupling between the two domain models, avoiding more tedious model synchronization interactions. In terms of use cases, we found two major types of studies: either on wide-area monitoring, protection and control (WAMPAC), or on demand-response (DR). The latter also imply extensive models studying market-based control, where typically multi-agent system (MAS) approaches are adopted.

Our survey details current state-of-the-art grid simulation approaches, in terms of their use cases, architecture and example studies. We believe this synthesis thus will assist (i) smart grid researchers looking for tools that target a certain use case, as well as (ii) smart grid simulator developers that wish to learn more about simulator paradigms, architectures, standards, etc. To conclude, lessons learned from the current state of the art seem to be:

- Power system simulation is supported by a wide variety of tools that can be classified in *steady state* and *transient dynamic* simulators according to the phenomenon under investigation.
- For well-defined, specific use cases, *dedicated simulation tools* exist in both power and communications domains, but for cross-domain issues, combined simulations are required.
- Combined simulation of power system and ICT infrastructure can be achieved using a *co-simulation* or *integrated approach*.
- *Power line communication (PLC)* technologies transform the power grid into a data communication network, and are being considered for a wide range of smart grid applications. However, support for simulation of PLC networks in popular network simulators is only limited and not available by default.
- Smart grid simulators that offer a combined simulation or focus on applications that characterize smart grids are found for *use cases* related to *active distribution systems*, *electricity markets*, *wide-area monitoring*, *protection and control (WAMPAC)*, and *demand-response/demand side management*.
- *Generic smart grid simulation tools* are being developed that support a wide range of use cases instead of focusing on one specific area. However, most simulators focus on one specific area.
- When power network (resp. communication) details can be highly abstracted, an *integrated* simulator taking a detailed power (resp. communication) simulator as a base seems appropriate.
- When a *detailed simulation* of both domains can be most efficiently (esp. in terms of development effort) realized using a *co-simulation* approach that reuses existing tools.
- However, supporting combined simulation remains challenging because of the need to manage and synchronize actions and state (especially time) of the components.
- *Federated* smart grid simulators are a promising to achieve large-scale and detailed smart grid simulations: distributed simulation is supported and other co-simulator components could be added more easily (e.g., transportation, weather). Use of standards (e.g., HLA, IEC 61850, CIM) may play an important role in this.

References

[1] H. Farhangi, "The path of the smart grid," *IEEE Power and Energy Magazine*, vol. 8, no. 1, pp. 18–28, 2010.

[2] V. Gungor, D. Sahin, T. Kocak, S. Ergut, C. Buccella, C. Cecati, and G. Hancke, "A survey on smart grid potential applications and communication requirements," *Industrial Informatics, IEEE Transactions on*, vol. 9, no. 1, pp. 28–42, 2013.

[3] H. Lin, S. Veda, S. Shukla, L. Mili, and J. Thorp, "GECO: Global event-driven co-simulation framework for interconnected power system and communication networks," *IEEE Trans. on Smart Grid*, vol. 3, no. 3, pp. 1444–1456, Sep. 2012.

[4] K. C. Budka, J. G. Deshpande, T. L. Doumi, M. Madden, and T. Mew, "Communication network architecture and design principles for smart grids," *Bell Labs Tech. J.*, vol. 15, no. 2, pp. 205–227, Sep. 2010.

[5] J. Nutaro, "Designing power system simulators for the smart grid: Combining controls, communications, and electro-mechanical dynamics," in *Proc. IEEE Power and Energy Society General Meeting 2011 (PES '11)*, 2011, pp. 1–5.

[6] T. Papadopoulos, C. Kaloudas, A. Chrysochos, and G. Papagiannis, "Application of narrowband power-line communication in medium-voltage smart distribution grids," *Power Delivery, IEEE Transactions on*, vol. 28, no. 2, pp. 981–988, 2013.

[7] "Prime (powerline intelligent metering evolution) alliance," http://www.prime-alliance.org/.

[8] "G3-plc alliance," http://www.g3-plc.com/.

[9] W. Kempton and J. Tomic, "Vehicle-to-grid power fundamentals: Calculating capacity and net revenue," *Journal of Power Sources*, vol. 144, no. 1, pp. 268 – 279, 2005. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0378775305000352

[10] ——, "Vehicle-to-grid power implementation: From stabilizing the grid to supporting large-scale renewable energy," *Journal of Power Sources*, vol. 144, no. 1, pp. 280 – 294, 2005. [Online]. Available: http://www.sciencedirect.com/science/article/pii/S0378775305000212

[11] J. Bergmann, C. Glomb, J. Gö andtz, J. Heuer, R. Kuntschke, and M. Winter, "Scalability of smart grid protocols: Protocols and their simulative evaluation for massively distributed DERs," in *Proc. 1st IEEE Int. Conf. on Smart Grid Communications 2010 (SmartGridComm '10)*, oct. 2010, pp. 131–136.

[12] S. Amin and B. Wollenberg, "Toward a smart grid: power delivery for the 21st century," *IEEE Power and Energy Magazine*, vol. 3, no. 5, pp. 34–41, 2005.

[13] D. Bakken, A. Bose, C. Hauser, D. Whitehead, and G. Zweigle, "Smart generation and transmission with coherent, real-time data," *Proceedings of the IEEE*, vol. 99, no. 6, pp. 928–951, 2011.

[14] K. Hopkinson, X. Wang, R. Giovanini, J. Thorp, K. Birman, and D. Coury, "EPOCHS: a platform for agent-based electric power and communication simulation built from commercial off-the-shelf components," *IEEE Trans. on Power Systems*, vol. 21, no. 2, pp. 548–558, May 2006.

[15] H. Georg, C. Wietfeld, S. C. Müller, and C. Rehtanz, "A HLA based simulator architecture for co-simulating ICT based power system control and protection systems," in *Proc. IEEE SmartGridComm 2012 Symposium - Performance Analysis and Simulation*, 2012.

[16] R. Kuffel, J. Giesbrecht, T. Maguire, R. Wierckx, and P. McLaren, "Rtds-a fully digital power system simulator operating in real time," in *WESCANEX 95. Communications, Power, and Computing. Conference Proceedings., IEEE*, vol. 2, 1995, pp. 300–305 vol.2.

[17] J. de Haan, P. Nguyen, W. Kling, and P. Ribeiro, "Social interaction interface for performance analysis of smart grids," in *Proc. 1st Int. Workshop Smart Grid Modeling and Simulation (SGMS 2011) at IEEE SmartGridComm 2011*, oct. 2011, pp. 79–83.

[18] D. Anderson, C. Zhao, C. Hauser, V. Venkatasubramanian, D. Bakken, and A. Bose, "A virtual smart grid - real-time simulation for smart grid control and communications design," *IEEE Power and Energy Magazine*, vol. 10, no. 1, pp. 49–57, jan.-feb. 2012.

[19] E. Weingärtner, H. Vom Lehn, and K. Wehrle, "A performance comparison of recent network simulators," in *Proc. IEEE international Conference on Communications 2009*, ser. ICC'09. Piscataway, NJ, USA: IEEE Press, 2009, pp. 1287–1291. [Online]. Available: http://dl.acm.org/citation.cfm?id=1817271.1817510

[20] S. Schutte, S. Scherfke, and M. Troschel, "Mosaik: A framework for modular simulation of active components in smart grids," in *Proc. 1st Int. Workshop Smart Grid Modeling and Simulation (SGMS 2011) at IEEE SmartGridComm 2011*, 17 Oct. 2011, pp. 55–60.

[21] L. Lugaric, S. Krajcar, and Z. Simic, "Smart city - platform for emergent phenomena power system testbed simulator," in *Proc. IEEE/PES Innovative Smart Grid Technologies Conference Europe 2010 (ISGT Europe '10)*, oct. 2010, pp. 1–7.

[22] V. Liberatore and A. Al-Hammouri, "Smart grid communication and co-simulation," in *Proc. IEEE Energytech 2011*, may 2011, pp. 1–5.

[23] F. Ponci, A. Monti, and A. Benigni, "Simulation for the design of smart grid controls," in *Proc. 1st Int. Workshop Smart Grid Modeling and Simulation (SGMS 2011) at IEEE SmartGridComm 2011*, oct. 2011, pp. 73–78.

[24] T. Godfrey, S. Mullen, R. C. Dugan, C. Rodine, D. W. Griffith, and N. Golmie, "Modeling smart grid applications with co-simulation," in *Proc. 1st IEEE Int. Conf. on Smart Grid Communications 2010 SmartGridComm '10)*, 2010.

[25] Y.-J. Kim, M. Thottan, V. Kolesnikov, and W. Lee, "A secure decentralized data-centric information infrastructure for smart grid," *IEEE Commun. Mag.*, vol. 48, no. 11, pp. 58–65, Nov. 2010.

[26] S. Harp, S. Brignone, B. Wollenberg, and T. Samad, "SEPIA. a simulator for electric power industry agents," *IEEE Control Systems Magazine*, vol. 20, no. 4, pp. 53–69, aug 2000.

[27] J. Nutaro, P. Kuruganti, L. Miller, S. Mullen, and M. Shankar, "Integrated hybrid-simulation of electric power and communications systems," in *Proc. IEEE Power Engineering Society General Meeting 2007 (PES '07)*, june 2007, pp. 1–8.

[28] W. Li, A. Monti, M. Luo, and R. Dougal, "VPNET: A co-simulation framework for analyzing communication channel effects on power systems," in *Proc. IEEE Electric Ship Technologies Symposium 2011 (ESTS '11)*, april 2011, pp. 143–149.

[29] J. Juárez, C. Rodríguez-Morcillo, and J. A. Rodríguez-Mondéjar, "Simulation of IEC 61850-based substations under OMNeT++," in *Proc. of the 5th Int. ICST Conference on Simulation Tools and Techniques*. ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2012, pp. 319–326.

[30] R. Podmore and M. Robinson, "The role of simulators for smart grid development," *IEEE Trans. on Smart Grid*, vol. 1, no. 2, pp. 205–212, Sept.

[31] D. Kim, Y. Yi, and S. Ha, "Trace-driven hw/sw cosimulation using virtual synchronization technique," in *Design Automation Conference, 2005. Proceedings. 42nd*, 2005, pp. 345–348.

[32] C. Siaterlis, A. Garcia, and B. Genge, "On the use of Emulab testbeds for scientifically rigorous experiments," *IEEE Communications Surveys Tutorials*, vol. PP, pp. 1–14, 2012.

[33] H. Gjermundrød, D. Bakken, C. Hauser, and A. Bose, "GridStat: A flexible QoS-managed data dissemination framework for the power grids," *IEEE Trans. Power Deliv.*, vol. 24, no. 1, pp. 136–143, Jan. 2009.

[34] J. Blanger, P. Venne, and J.-N. Paquin, "The what, where and why of real-time simulation," in *IEEE PES General Meeting*, Minneapolis, MN, USA, 25–29 July 2010.

[35] S. K.S.Pandya, "A survey of optimal power flow methods," *Journal of Theoretical and Applied Information Technology*, vol. 4, pp. 450–458, 2008.

[36] M. Fazeli, G. Asher, C. Klumpner, L. Yao, and M. Bazargan, "Novel integration of wind generator-energy storage systems within microgrids," *IEEE Trans. on Smart Grid*, vol. 3, no. 2, pp. 728–737, 2012.

[37] C. Luo, J. Yang, Y. Sun, M. Cai, J. Wu, and L. Xu, "A network based protection scheme of distribution system," in *IEEE Int. Conf. on Power System Technology 2012 (POWERCON '12)*, 2012, pp. 1–6.

[38] H. Mahmood and J. Jiang, "Modeling and control system design of a grid connected VSC considering the effect of the interface transformer type," *IEEE Trans. on Smart Grid*, vol. 3, no. 1, pp. 122–134, 2012.

[39] F. Coroiu, C. Velicescu, and C. Barbulescu, "Probabilistic and deterministic load flows methods in power systems reliability estimation," in *Proc. IEEE Int. Conf. on Computer as a Tool 2011 (EUROCON '11)*, 2011, pp. 1–4.

[40] X. Chen, W. Pei, and X. Tang, "Transient stability analyses of microgrids with multiple distributed generations," in *Proc. Int. Conf. on Power System Technology 2010 (POWERCON '10)*, 2010, pp. 1–8.

[41] A. Hansen, C. Jauch, P. Sørensen, F. Iov, and F. Blaabjerg, "Dynamic wind turbine models in power system simulation tool DIgSILENT," Risø National Laboratory, Roskilde, Tech. Rep., 2003.

[42] F. Andren, M. Stifter, T. Strasser, and D. Burnier de Castro, "Framework for co-ordinated simulation of power networks and components in smart grids using common communication protocols," in *Proc. 37th Annual Conference on IEEE Industrial Electronics Society (IECON '11)*, 2011, pp. 2700–2705.

[43] T. Chant, G. M. Shafiullah, A. Oo, and B. Harvey, "Impacts of increased photovoltaic panel utilisation on utility grid operations - a case study," in *Proc. IEEE/PES Innovative Smart Grid Technologies Asia 2011 (ISGT Asia '11)*, 2011, pp. 1–7.

[44] U. Sachs, "Smart grid offering within PSS®SINCAL," Siemens, Tech. Rep., 2012.

[45] A. Mohamad, N. Hashim, N. Hamzah, N. F. N. Ismail, and M. Latip, "Transient stability analysis on sarawak's grid using power system simulator for engineering (PSS/E)," in *Proc. IEEE Symposium on Industrial Electronics and Applications 2011 (ISIEA '11)*, 2011, pp. 521–526.

[46] A. Hernandez, P. Eguia, E. Torres, and M. Rodriguez, "Dynamic simulation of a SSSC for power flow control during transmission network contingencies," in *Proc. IEEE Trondheim PowerTech 2011*, 2011, pp. 1–6.

[47] F. Napolitano, A. Borghettia, M. Paolonea, and M. Bernardib, "Voltage transient measurements in a distribution network correlated with data from lightning location system and from sequence of events recorders," *Electric Power Systems Research*, vol. 81, pp. 237–253, 2011.

[48] R. Roche, S. Natarajan, A. Bhattacharyya, and S. Suryanarayanan, "A framework for co-simulation of AI tools with power systems analysis software," in *Proc. 23rd Int.Workshop on Database and Expert Systems Applications 2012 (DEXA '12)*, 2012, pp. 350–354.

[49] R. Mehra, N. Bhatt, F. Kazi, and N. Singh, "Analysis of PCA based compression and denoising of smart grid data under normal and fault conditions," in *Proc. IEEE Int. Conference on Electronics, Computing and Communication Technologies 2013 (CONECCT '13)*, 2013, pp. 1–6.

[50] Y. Tang, X. Mao, and R. Ayyanar, "Distribution system modeling using CYMDIST for study of high penetration of distributed solar photovoltaics," in *Proc. North American Power Symposium 2012 (NAPS '12)*, 2012, pp. 1–6.

[51] G. Asimakopoulou, E. Voumvoulakis, A. Dimeas, and N. Hatziargyriou, "Impact of large-scale integration of intelligent meters to the operation of the power system of crete," in *Proc. 16th Int. Conf. on Intelligent System Application to Power Systems 2011 (ISAP '11)*, 2011, pp. 1–6.

[52] S. Kreckelbergh and I. Vechiu, “Sizing and dynamic analyses of a micro-grid supplying a harbor industrial area,” in *Proc. 16th Int. Conf. on System Theory, Control and Computing 2012 (ICSTCC ’12)*, 2012, pp. 1–5.

[53] A. Anwar and H. Pota, “Loss reduction of power distribution network using optimum size and location of distributed generation,” in *Proc. 21st Australasian Universities Power Engineering Conference (AUPEC ’11)*, 2011, pp. 1–6.

[54] M. Larsson, “ObjectStab - an educational tool for power system stability studies,” *IEEE Trans. on Power Systems*, vol. 19, no. 1, pp. 56–63, feb. 2004.

[55] R. Meere, M. O’Malley, and A. Keane, “VSC-HVDC link to support voltage and frequency fluctuations for variable speed wind turbines for grid connection,” in *Proc. 3rd IEEE/PES Int. Conf. and Exhibition on Innovative Smart Grid Technologies 2012 (ISGT Europe ’12)*, 2012, pp. 1–5.

[56] “Opal-rt,” http://www.opal-rt.com/.

[57] S. Abourida, C. Dufour, J. Belanger, G. Murere, N. Lechevin, and B. Yu, “Real-time pc-based simulator of electric systems and drives,” in *Applied Power Electronics Conference and Exposition, 2002. APEC 2002. Seventeenth Annual IEEE*, vol. 1, 2002, pp. 433–438 vol.1.

[58] Mathworks, “Simpowersystems,” available at http://www.mathworks.com/products/simpower/.

[59] “Rtds technologies,” http://www.rtds.com/.

[60] F. Milano, “An open source power system analysis toolbox,” *IEEE Trans. on Power Systems*, vol. 20, no. 3, pp. 1199–1206, aug. 2005.

[61] D. Kwok, W. Cheung, and P. J. Chow, “Power system toolbox (PST),” Rensselaer Polytechnic Institute, available at http://www.ecse.rpi.edu/pst/PST.html.

[62] C. Vournas, E. Potamianakis, C. Moors, and T. Van Cutsem, “An educational simulation tool for power system control and stability,” *IEEE Trans. on Power Systems*, vol. 19, no. 1, pp. 48–55, feb. 2004.

[63] K. Schoder, A. Hasanovic, and A. Feliachi, “PAT: a power analysis toolbox for MATLAB/Simulink,” *IEEE Trans. on Power Systems*, vol. 18, no. 1, pp. 42–47, feb 2003.

[64] S. Ayasun, C. Nwankpa, and H. Kwatny, “Voltage stability toolbox for power system education and research,” *IEEE Trans. on Education*, vol. 49, no. 4, pp. 432–442, nov. 2006.

[65] R. D. Zimmerman and D. Gan, “Matpower, documentation for version 4.1,” Power System Engineering Research Center, Cornell University, 2011, available at http://www.pserc.cornell.edu/matpower/.

[66] F. Milano and L. Vanfretti, “State of the art and future of OSS for power systems,” in *Proc. IEEE Power Energy Society General Meeting 2009 (PES ’09)*, july 2009, pp. 1–7.

[67] R. Amin, J. Martin, and X. Zhou, “Smart grid communication using next generation heterogeneous wireless networks,” in *Proc. 3rd IEEE Int. Conf. on Smart Grid Communications 2012 (SmartGridComm ’12)*, 2012, pp. 229–234.

[68] C. Muller, M. Putzke, and C. Wietfeld, “Traffic engineering analysis of smart grid services in cellular networks,” in *Proc. 3rd IEEE Int. Conf. on Smart Grid Communications 2012 (SmartGridComm ’12)*, 2012, pp. 252–257.

[69] T. R. Henderson, M. Lacage, and G. F. Riley, “Network simulations with the ns-3 simulator,” in *Proc. ACM Conf. of the Special Interest Group on Data Communication 2008 (SIGCOMM ’08)*, August 17-22 2008, p. 527.

[70] H. Lin, S. Sambamoorthy, S. Shukla, J. Thorp, and L. Mili, “Power system and communication network co-simulation for smart grid applications,” in *Proc. IEEE/PES Innovative Smart Grid Technologies 2011 (ISGT ’11)*, jan. 2011, pp. 1–6.

[71] J. Kim, D. Kim, K.-W. Lim, Y.-B. Ko, and S.-Y. Lee, “Improving the reliability of IEEE 802.11s based wireless mesh networks for smart grid systems,” *Journal of Communications and Networks*, vol. 14, no. 6, pp. 629–639, Dec. 2012.

[72] F. Aalamifar, A. Schlogl, D. Harris, and L. Lampe. Modelling power line communication using network simulator-3. http://www.ece.ubc.ca/ faribaa/paper.pdf.

[73] ——, “Plc-ns3 module,” http://www.ece.ubc.ca/ faribaa/index_files/Page417.htm.

[74] A. Varga, “An overview of the OMNeT++ simulation environment,” in *Proc. 1st Int. Conf. Simulation Tools and Techniques for Commun., Netw. and Systems (SIMUTools ’08)*, Marseille, France, 3–7 March 2008.

[75] K. Mets, T. Verschueren, C. Develder, T. L. Vandoor, and L. Vandevelde, “Integrated simulation of power and communication networks for smart grid applications,” in *Proc. IEEE 16th Int. Workshop on Computer Aided Modeling and Design of Communication Links and Networks 2011 (CAMAD ’11)*, Kyoto, Japan, 10–11 June 2011.

[76] R. Mora, A. Lopez, D. Roman, R. Sanz, F. Lobo, F. Carmona, D. Mora, A. Cabello, A. Sendin, and I. Berganza, “Demand management communications architecture,” in *Proc. 20th Int. Conf. on Electricity Distribution (CIRED ’09)*, Prague, 2009, pp. 8–11.

[77] R. Mora, A. Lopez, D. Roman, A. Sendin, and I. Berganza, “Communications architecture of smart grids to manage the electrical demand,” in *Proc. 3rd Workshop on Power Line Communications*, Udine, Italy, October 1–2 2009.

[78] C. Müller, S. Šubik, A. Wolff, and C. Wietfeld, “A system design framework for scalability analysis of geographic routing algorithms in large-scale mesh networks,” in *Proc. 3rd Int. ICST Conf. on Simulation Tools and Techniques (SIMUTools ’10)*. ICST, Brussels, Belgium, Belgium: ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2010, pp. 1–7.

[79] C. Müller, H. Georg, and C. Wietfeld, “A modularized and distributed simulation environment for scalability analysis of smart grid ICT infrastructures,” in *Proc. 5th Int. ICST Conf. on Simulation Tools and Techniques (SIMUTools ’12)*, ser. SIMUTOOLS ’12. ICST, Brussels, Belgium, Belgium: ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2012, pp. 327–330. [Online]. Available: http://dl.acm.org/citation.cfm?id=2263019.2263070

[80] J. Tripathi, J. de Oliveira, and J. Vasseur, “Applicability study of RPL with local repair in smart grid substation networks,” in *Proc. First IEEE International Conference on Smart Grid Communications 2010 (SmartGridComm ’10)*, oct. 2010, pp. 262–267.

[81] H. Kellerbauer and H. Hisch, “Simulation of powerline communication with omnet++ in (static) smart grids,” in *Proceedings of the 4th International ICST Conference on Simulation Tools and Techniques*, ser. SIMUTools ’11. ICST, Brussels, Belgium, Belgium: ICST (Institute for Computer Sciences, Social-Informatics and Telecommunications Engineering), 2011, pp. 406–409. [Online]. Available: http://dl.acm.org/citation.cfm?id=2151054.2151126

[82] T. Konnerth, J. Chinnow, D. Grunewald, and S. Kaiser, “Integration of simulations and MAS for smart grid management systems,” in *Proc. 3rd Int. Workshop on Agent Technologies for Energy Systems (ATES 2012) at 11th Int. Conf. on Autonomos Augents and Multiagent Systems (AAMAS ’12)*, Valencia, Spain, June 5 2012.

[83] J. Chinnow, K. Bsufka, A.-D. Schmidt, R. Bye, A. Camtepe, and S. Albayrak, “A simulation framework for smart meter security evaluation,” in *Proc. IEEE Int. Conf. on Smart Measurements of Future Grids 2011*, ser. SMFG ’11. Washington, DC, USA: IEEE Computer Society, 2011, pp. 1–9. [Online]. Available: http://dx.doi.org/10.1109/SMFG.2011.6125758

[84] A. Patel, J. Aparicio, N. Tas, M. Loiacono, and J. Rosca, “Assessing communications technology options for smart grid applications,” in *Proc. IEEE Int. Conference on Smart Grid Communications 2011 (SmartGridComm ’11)*, 2011, pp. 126–131.

[85] J. Aparicio, A. Patel, N. Tas, M. Loiacono, and J. Rosca, “Scalable smart grid simulations in OPNET Modeler,” Proc. OPNETWORK 2011, Tech. Rep., 2011.

[86] T. Sidhu and Y. Yin, “Modelling and simulation for performance evaluation of IEC61850-based substation communication systems,” *IEEE Trans. on Power Delivery*, vol. 22, no. 3, pp. 1482–1489, july 2007.

[87] K. Zhu, M. Chenine, and L. Nordstrom, “ICT architecture impact on wide area monitoring and control systems’ reliability,” *IEEE Trans. on Power Delivery*, vol. 26, no. 4, pp. 2801–2808, Oct.

[88] X. Tong, “The co-simulation extending for wide-area communication networks in power system,” in *Proc. IEEE Asia-Pacific Power and Energy Engineering Conference 2010 (APPEEC ’10)*, March, pp. 1–4.

[89] R. H. Khan and J. Y. Khan, “Wide area PMU communication over a WiMAX network in the smart grids,” in *Proc. 3rd IEEE Int. Conf. on Smart Grid Communications 2012 (SmartGridComm ’12)*, 2012, pp. 187–192.

[90] ——, “A heterogeneous WiMAX-WLAN network for AMI communications in the smart grids,” in *Proc. 3rd IEEE Int. Conf. on Smart Grid Communications 2012 (SmartGridComm ’12)*, 2012, pp. 710–715.

[91] J. Brown and J. Y. Khan, “Performance comparison of LTE FDD and TDD based smart grid communications networks for uplink biased traffic,” in *Proc. 3rd IEEE Int. Conf. on Smart Grid Communications 2012 (SmartGridComm ’12)*, 2012, pp. 276–281.

[92] D. Chassin, K. Schneider, and C. Gerkensmeyer, “GridLAB-D: An open-source power systems modeling and simulation environment,” in *Proc. IEEE/PES Transmission and Distribution Conference and Exposition 2008*, april 2008, pp. 1–5.

[93] K. Schneider, D. Chassin, Y. Chen, and J. Fuller, "Distribution power flow for smart grid technologies," in *Proc. IEEE/PES Power Systems Conference and Exposition 2009 (PSCE '09)*, march 2009, pp. 1–7.

[94] R. Guttromson, "Modeling distributed energy resource dynamics on the transmission system," *IEEE Trans. on Power Systems*, vol. 17, no. 4, pp. 1148–1153, Nov.

[95] GridLAB-D Wiki, "Gridlab-d communications module," http://sourceforge.net/apps/mediawiki/gridlab-d/index.php?title=Communications_module, October 2013. [Online]. Available: http://sourceforge.net/apps/mediawiki/gridlab-d/index.php?title=Communications_module

[96] ——, "Gridlab-d v3 applications concepts: Communications," http://sourceforge.net/apps/mediawiki/gridlab-d/index.php?title=V3_applications_concepts, October 2013. [Online]. Available: http://sourceforge.net/apps/mediawiki/gridlab-d/index.php?title=V3_applications_concepts#Communications

[97] D. Aliprantis, S. Penick, L. Tesfatsion, and H. Zhao, "Integrated retail and wholesale power system operation with smart-grid functionality," in *Proc. IEEE Power and Energy Society General Meeting 2010 (PES '10)*, july 2010, pp. 1–8.

[98] K. Anderson and A. Narayan, "Simulating integrated volt/var control and distributed demand response using GridSpice," in *Proc. 1st Int. Workshop Smart Grid Modeling and Simulation (SGMS 2011) at IEEE SmartGridComm 2011*, Brussels, Belgium, 17 Oct. 2011, pp. 84–89.

[99] M. Paolone, M. Pignati, P. Romano, S. Sarri, L. Zanni, and R. Cherkaoui, "A hardware-in-the-loop test platform for the real-time state estimation of active distribution networks using phasor measurement units," in *Cigr SC6 Colloquium*, Yokohama, Japan, 2013.

[100] *C37.118.2-2011 - IEEE Standard for Synchrophasor Data Transfer for Power Systems*, IEEE Standards Association Std.

[101] P. Oliveira, T. Pinto, H. Morais, and Z. Vale, "MASGriP - a multi-agent smart grid simulation platform," in *Proc. IEEE Power and Energy Society General Meeting (PES '12)*, july 2012, pp. 1–8.

[102] P. Oliveira, T. Pinto, H. Morais, Z. Vale, and I. Praca, "MASCEM - an electricity market simulator providing coalition support for virtual power players," in *Proc. 15th Int. Conf. on Intelligent System Applications to Power Systems 2009 (ISAP '09)*, Nov. 2009, pp. 1–6.

[103] H. Lin, Y. Deng, S. Shukla, J. Thorp, and L. Mili, "Cyber security impacts on all-PMU state estimator - a case study on co-simulation platform GECO," in *Proc. IEEE SmartGridComm 2012 Symposium - Wide Area Protection and Control (WAMPAC)*, 2012.

[104] K. Hopkinson, K. Birman, R. Giovanini, D. Coury, X. Wang, and J. Thorp, "EPOCHS: integrated commercial off-the-shelf software for agent-based electric power and communication simulations," in *Proc. Winter Simulation Conference 2003*, vol. 2, Dec., pp. 1158–1166.

[105] K. Mets, T. Verschueren, F. De Turck, and C. Develder, "Exploiting v2g to optimize residential energy consumption with electrical vehicle (dis)charging," in *Proc. 1st Int. Workshop Smart Grid Modeling and Simulation (SGMS 2011) at IEEE SmartGridComm 2011*, oct. 2011, pp. 7 –12.

[106] S. Schutte, "Composition of simulations for the analysis of smart grid scenarios," Energieinformatik, Tech. Rep., 2011.

[107] A. Awad, P. Bazan, and R. German, "Abstract-based methodology for modeling and simulation of smart grid components," in *Proc. 6th UKSim/AMSS European Symposium on Computer Modeling and Simulation 2012 (EMS '12)*, nov. 2012, pp. 305–310.

[108] C. M. Davis, J. Tate, H. Okhravi, C. Grier, T. Overbye, and D. Nicol, "SCADA cyber security testbed development," in *Proc. 38th North American Power Symposium 2006 (NAPS '06)*, 2006, pp. 483–488.

[109] M. Mallouhi, Y. Al-Nashif, D. Cox, T. Chadaga, and S. Hariri, "A testbed for analyzing security of SCADA control systems (TASSCS)," in *Proc. IEEE/PES Innovative Smart Grid Technologies 2011 (ISGT '11)*, 2011, pp. 1–7.

[110] S. Schütte, M. Tröschel, J. Schoene, C. Develder, K. Mets, and J. Taylor, "Smart grid simulation platform architecture & requirements specification," SG Simulations Working Group - OpenSG, Tech. Rep., 2012.

[111] M. Pipattanasomporn, H. Feroze, and S. Rahman, "Multi-agent systems in a distributed smart grid: Design and implementation," in *Proc. IEEE/PES Power Sys. Conf. and Expo. (PSCE 2009)*, Seattle, WA, USA, Mar. 2009, pp. 1–8.

[112] S. Karnouskos and T. de Holanda, "Simulation of a Smart Grid City with Software Agents," in *Proc. 3rd UKSim European Symposium on Computer Modeling and Simulation 2009*. IEEE, 2009, pp. 424–429.

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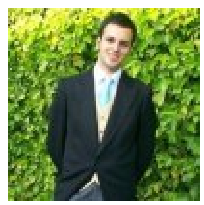

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