Applied Energy 222 (2018) 67–78

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

A survey and statistical analysis of smart grid co-simulations

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HIGHLIGHTS

- Definition of state-of-the-art co-simulation and provision of recent trends.
- Review of 26 different Smart Grid simulation frameworks and their applications.
- Analysis of several parameters: research topic, computational effort & problem size.
- Correlation of different application, showing trends in simulation tools.

ABSTRACT

Smart Grids consist of multiple actors and physical phenomena, which are often difficult to capture in one single simulation framework. Therefore, researchers increasingly couple distinct simulators to form novel “co-simulations”. In this paper we present a literature survey of 26 smart grid co-simulation frameworks. First of all, we present our understanding of a co-simulation. We then classify the 26 frameworks on multiple characteristics, such as simulation tools, synchronization methods and research topics. Finally, we present correlations between different key characteristics, analyze possible research gaps and discuss possible trends and future development areas in the field of smart grid co-simulations.

1. Introduction

Electric power grids are complex dynamic systems, which are continuously perturbed by multiple actors: grid operators measure and control distinct areas of the power system, energy traders plan and dispatch generators, and substations are increasingly equipped with smart controllers responding to changes in power flow or voltage. The integration of renewable energies adds a further degree of complexity; such power sources are less predictable than conventional power plants and may be installed at many decentralized locations in the grid [1]. To measure and coordinate the renewable in-feed, grid operators may implement more information and communications technology (ICT) solutions and create a “Smart Grid”. The electric power system may interact with gas and heat networks as well, e.g. when excess renewable feed-in is converted into other forms than electric energy (for example [2] or [3]). However, the term “Smart Grid” also dictates an increased communication need amongst the actors of the power system. For example, the “2017–2026 research and innovation roadmap” by ENTSOE [4] focuses on network constrained market simulation tools, interactions between various regulatory frameworks and joint Transmission System Operator (TSO) and Distribution System Operator (DSO) activities, to name a few.

In research, a common practice to test smart grid concepts is by means of simulations. However, due to the above described complexity, modelling a smart grid is far from simple. Simulators often do not capture both the physical power grid, the ICT components, the decisions from multiple grid operators and market actors, as well as heat, power and gas networks. Instead of tackling all these factors by one simulation, researchers develop so called “co-simulations”, which consist of multiple simulators, coupled together by a software interface. Each simulator may cover a different aspect of the smart grid. Together, the simulators allow researchers to analyze complex interactions and dynamics in more detail.

Rehtanz and Guillaid [5] describe a co-simulation as “hybrid simulation models and different representations which are executed in individual runtime environments”, with a particular challenge to synchronize this complex setup. The focus of their work is real-time simulation for hardware in the loop (HIL) and electromagnetic transient (EMT) simulations.

The work by Mets et al. [6] surveys power grid and communication

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https://doi.org/10.1016/j.apenergy.2018.03.123

Received 20 September 2017; Received in revised form 23 February 2018; Accepted 27 March 2018

0306-2619/

network co-simulations. Their approach to co-simulation is motivated by the fact that creating a new simulation environment, which simulates power and ICT network, is "potentially time-consuming and expensive". Hence the survey provides an in-depth look at existing simulations and presents a classification of different co-simulation environments. In the author's opinion, the main challenge is, "to connect, handle and synchronize data and interactions between both simulators using their respective simulator interfaces".

A recent survey by Cintuglu et al. [7] provides a systematic study for smart grid cyber-physical testbeds, being testing environments for novel smart grid concepts. Amongst the four testbed categories are simulations, HIL environments, real-time simulators and hardware-based platforms. Co-simulations are addressed as part of the first category, though they are not the primary focus of the survey. A broad view on co-simulation in power systems is outlined by Schloegl et al. [8]. In this work the authors presents a morphological box with eight different categories of simulators. However, this box is subsequently applied to only one particular co-simulation.

Building on these recent works, our goal is to provide a more general survey of 26 smart grid co-simulations, focusing on features such as involved simulators, research topics, open source availability as well as the mechanism for synchronizing different simulators.

The structure of our paper is as follows: Section 2 gives a common understanding about the term "co-simulation" and its implications. Section 3 explains the methods of our survey, e.g. the search and classification procedure. Section 4 contains the results of the survey and Section 5 provides an in-depth discussion and analysis of the results.

2. A common understanding of co-simulation

In this work, simulations are addressed which are applied to smart grid relevant topics; examples can be found in Refs. [9,10] or [11] and an introduction to smart grids can be obtained from Refs. [12] or [13]. In this section, our understanding of a co-simulation in the context of smart grids and its required components is presented.

2.1. Definition of co-simulation

A co-simulation is a special kind of simulation in which multiple simulations are coupled together. We first investigate the essential parts of a co-simulation:

- Simulation models (B)
- Simulation solvers (C)
- Runtime infrastructure (D)
- Simulation synchronization (E)
- Different types of simulations (F)

2.2. Simulation models

Simulation models are mathematical models describing a real world phenomenon through mathematical rules and language. There exist many categories of mathematical models: for instance, one can categorize models according to temporal (static versus dynamic) and spatial properties (e.g. ordinary versus partial differential equations). Electric power systems for example are commonly simulated with models such as *algebraic, statistical* and *(partial, delay) differential equations* [14–16]. Communication networks, on the other hand, are commonly simulated as *discrete event systems* [17]: this is a model where state changes (events) occur at discrete instances in time and an event takes zero time to happen. Lastly, some models are described via parameters or measured curves.

2.3. Simulation solvers

We refer to "solvers" as the mathematical/computational solution method that is applied to either exactly solve a model or approximate its solution with sufficient numerical accuracy. Power system models, for example, are commonly solved by numerical methods, e.g. [18,19]. Communication network models, on the other hand, are solved by computational loops, which process upcoming events (e.g. the sending of a data package) in a causally correct fashion. The loops are stopped when all scheduled events are processed or a certain computation time limit is reached [17].

Solvers are not necessarily limited to solving only one model, they can solve different models or they can be able to solve many instances of the same model with different parameters.

2.4. Runtime infrastructure

"Runtime infrastructure" refers to the underlying architecture which orchestrates, coordinates and exchanges information in the simulation (often called "communication infrastructure"). Such infrastructures may not be needed for every simulation setup, but are important in co-simulations. They rely on a central coordinator (e.g. INSPIRE and VPNET), whereas others, such as HLA, Mosaik or OpSim rely on a more complex system (see Table 2). In his book [20], Fujimoto classifies computers in two groups, which define the communication infrastructure:

(1) Parallel Computers, e.g. symmetric multiprocessor, are tightly coupled systems which often share the same memory and are able to do inter process communication. Their communication latency is typically less than 100 µs.
(2) Distributed Computers are often composed of several computers from different manufacturers. Normal network technology is often used to interconnect these machines, creating a typical latency of around 10 ms (for LAN Networks) up to seconds for radiofrequency or satellite based communications.

These two groups require different programming strategies and therefore present their own challenges to the runtime infrastructure.

2.5. Simulation synchronization

Simulation synchronization describes the way in which time stamped data is exchanged between simulation solvers. The topic of time and data synchronization is often solved by the runtime infrastructure (see [21,20,22] or [23]). In Ref. [20] p. 51 it is cited that "*Errors resulting from out-of-order event processing are referred to as causality errors, and the general problem of ensuring that events are processed in a time stamp order is referred to as the synchronization problem.*" It implies that very tight limits for the simulation infrastructure are required. Parallel computers might handle this, but distributed computers present a major challenge requiring special attention, due to their latencies discussed in the previous subsection.

The first major class of algorithms for solving this problem is called "*conservative synchronization*", where each simulator strictly processes events in a time stamp order. For example, a dynamically defined barrier for all simulators, which only allows a next simulation iteration after all simulators have finished. It is referred to as "*barrier synchronization*".

The next class is called "*optimistic synchronization*", wherein errors are detected during the simulation and different mechanisms are used to revert them. For example, a pre-defined number of events are stored and in case of an out-of-order event, the simulation is reversed to a time before this event and executed again with this event in order; hence it is called "Time Warp". The name "*optimistic*" comes from "optimistically", assuming that there are no causality errors.

The third class is *"web-based"* and uses web-services such as REST or SOAP. It focuses on model reuse and providing a better interoperation between different simulators. In addition, cloud computing has