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Smart Grids Co-Simulation Research

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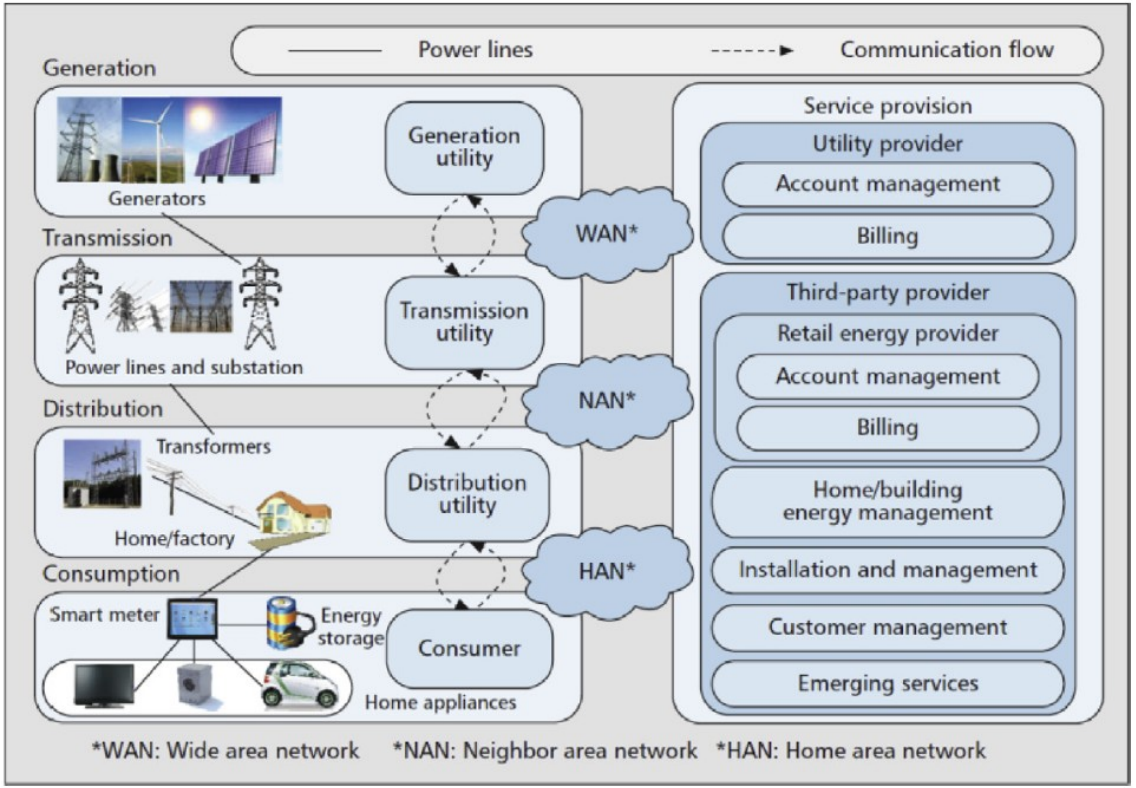
Smart Grid



A Smart Grid can be seen from multiple points of view:

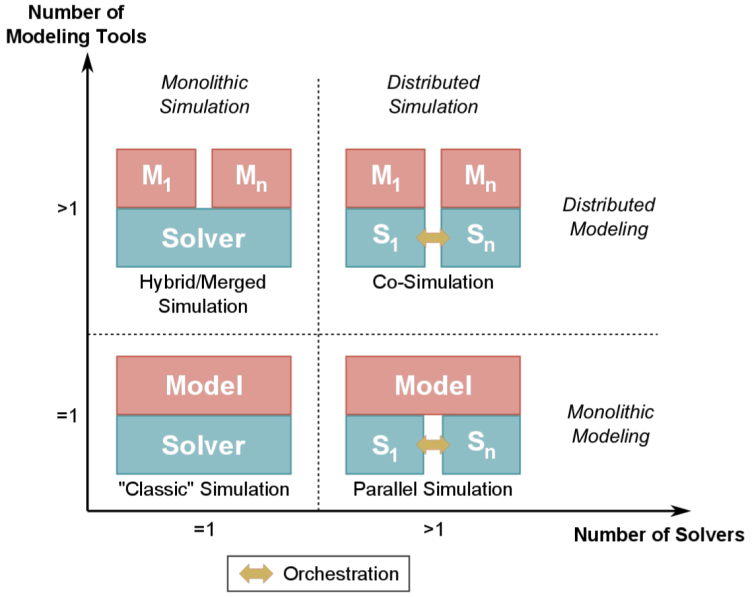
From one side, it can be seen as the integration of different devices, communication and IT infrastructure to provide an economically **efficient, sustainable power system**

From another side, it can be seen as **Collaborative Services Ecosystem**

Li, Weilin, and Xiaobin Zhang. "Simulation of the smart grid communications: Challenges, techniques, and future trends." Computers & Electrical Engineering 40.1 (2014): 270-288.

What are co-simulations?

"**Co-simulation** is defined as the coordinated execution of two or more simulation models that differ in their representation as well as in their runtime environment"*



Common terminology

→ **Emulation** (integrated or co-simulated): emulated component mimics the the real world hardware counterpart

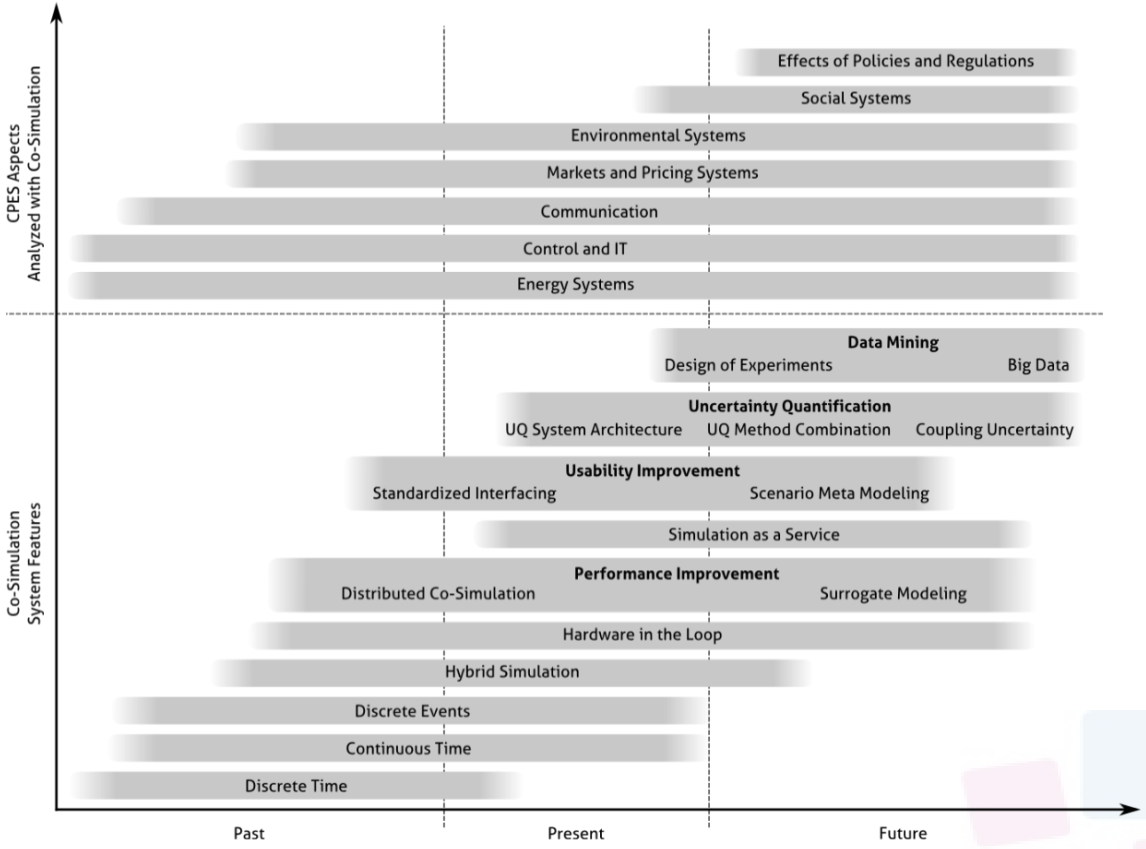
→ **Co-simulation**: orchestrate simulations running by different means

→ **Real-time simulations**: the real time expectation that the simulator needs to fulfill to interact with external components (hardware or software)

→ **Hardware in the loop (HiL)**: used to develop complex real-time embedded systems in which some components are real hardware, whereas others are simulated

* Steinbrink C, Schlögl F, BabazadehD, Lehnhoff S, Rohjans S, Narayan A. Future perspectives of co-simulation in the smart grid domain. In: 2018 IEEE International Energy Conference (ENERGYCON) IEEE; 2018.

Co-simulations research needs



* Steinbrink C, Schlögl F, BabazadehD, Lehnhoff S, Rohjans S, Narayan A. Future perspectives of co-simulation in the smart grid domain. In: 2018 IEEE International Energy Conference (ENERGYCON) IEEE; 2018.

Our High Level Research Goals / Results

RG: Support the SG infrastructure by means of tests/simulations/experiments

→ we reviewed different testing process frameworks that could be applied to the context of SG (e.g. ISO/IEC/IEEE 29119);

→ we looked at different aspects of simulations (co-simulations) by means of several frameworks that can be adopted;

→ we worked on a software platform (SGTMP) that could allow management of SG tests/simulation/experiments (including both hardware and virtualized devices)

→ we reviewed existing co-simulation studies in terms of frameworks adopted, results achieved

→ we started looking into fine-grained changes to one of the frameworks (Mosaik) to allow for *“what-if”* scenarios

Initial prototype

Smart Grids Co-Simulations with Low-Cost Hardware

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***Abstract*—Smart Grids have nowadays gained wide diffusion and relevance. Due to the complexity of the grid, many Smart Grids laboratories have emerged over the years to provide partially virtualized environments for testing and co-simulation testbeds for the modern grid. However, the costs for setting-up Smart Grids laboratories are substantial, representing a barrier for newcomers and for educational purposes. In this paper, we propose an hardware-in-the-loop (HIL) architectural solution based on Arduino and Raspberry PI boards, supported by the Mosaik framework to simulate different Smart Grids scenarios on a small and cost-effective scale. We highlight the educational benefits that the solution can bring for understanding simulations and HIL in an affordable & effective way in an easy-to-deploy environment.**

***Keywords*-Smart Grids, Smart Meters, Hardware in the Loop, Co-Simulations, Cyber-Physical Systems.**

I. Introduction

A Smart Grid has been defined as a form of electricity network that enables "intelligent" integration of all the actions and behaviours of the connected actors, to efficiently deliver sustainable, economic and secure electricity supplies [1], [2].

While modern Smart Grids have ambitious aims, they also pose several challenges, mainly due to the multidisciplinary nature of the area, ranging from power equipment to needs in terms of data analysis to increase the "smartness" of the power grid. As such, communication between the different involved roles is fundamental, to the point that the education of students to several aspects of the grid is seen as one of the main challenges in the area [3]. For this reason, a recent trend is the emergence of Smart Grids laboratories that can serve not only to test Smart Grids software and devices, but also to educate students to the real needs of large-scale Smart Grids in a controlled environment [4].

However, average costs of setting-up a Smart Grid laboratory are in the order of €2M, reaching €30M for larger laboratories [4]. Such values represents a serious barrier for setting-up new laboratories for educational purposes. For this reason, in this paper we propose a virtualized and low-cost environment that students can use to test and validate different Smart Grids scenarios. Such environment can be a first step for looking into hardware-in-the-loop (HIL) and co-simulation environments—environments that are focused on orchestrating several simulations running on different devices, combining also software simulations [3], [5]. The importance of simulations is relevant in the area of Smart Grids due to the complexity of the different layers and sub-systems involved. Simulations can help in tackling away some of the complexity, by having simulation models that run in their own runtime environment.

The proposed solution is based on the Raspberry Pi and Arduino platforms that can be used to test a co-simulation environment for Smart Grids. We focus in particular on two scenarios that can be relevant for the presented prototype: i) sunlight level scenario, to simulate sunlight levels, and ii) a load scenario to predict power usage over time.

The paper is structured as follows. Section II presents the related works, in terms of other low-cost hardware-software solutions that have been proposed to simulate the Smart Grids infrastructure. Section III presents the details of building the prototype integrating hardware devices (Raspberry Pi and Arduino), software components (Mosaik) and the proposed architecture. Section IV proposes examples of usages with two main scenarios. Section V presents evaluation and discussion and Section VI concludes the paper.

II. Related Work

The usage of low-cost hardware/software for Smart Grids testing and validation has acquired more interest in recent years, mainly due to the availability of cheap devices that can be used for the purpose.

Commodity Hardware for Smart Grids—typically Raspberry Pis and Arduinos—has been used for a wide range of applications, for example to enable Smart Meters readings (voltage and users' power consumption) to be remotely transmitted [6], to test self-healing capabilities for multi-agent based approaches [7], or for network reconfiguration in secondary substations [8].

Aurilio et al. (2014) deployed a Raspberry Pi as data concentrator in a low-cost solution for the management and control of a power network based on power meters, monitoring connected loads by communicating with a data concentrator (Raspberry Pi) via Power Line bus [9].

However, while commodity hardware has been used in different parts of the Smart Grids infrastructure, our work is more focused in the area of co-simulations.

Armendariz et al. (2014) developed a platform for co-simulation based on a real-time power system simulator (OpalRT), and a communication network emulator (OPNET). Rasp-

Smart Grids Co-Simulations with Low-Cost Hardware

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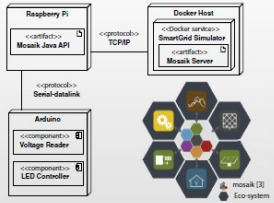
Project Context

We showcase a low-cost environment that students can use to test and validate different Smart Grids scenarios. Such environment can be a first step for looking into hardware-in-the-loop (HIL) and co-simulation environments - environments that are focused on orchestrating several simulations running on different devices, combining also software simulations. This solution can be used for understanding simulations and HIL in an affordable and effective way in an easy to deploy environment [1].

Goals

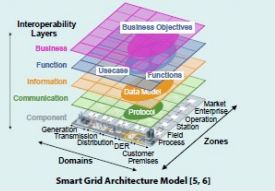
- Education of students in co-simulation concepts using easily accessible and hands-on training in Smart Grids technologies
- Creating ways for cheaper hardware prototyping of Smart Grids by having low-cost simulation nodes

Architecture



Smart Grids & Lasaris

- The Smart Grid can be regarded as an electricity network that benefits both from two-way cyber-secure communication technologies and computational intelligence for electricity generation, transmission, substations integration and consumption to reach the goals of a safe, secure, reliable, resilient, efficient, and sustainable infrastructure [4].
- Lasaris is involved in research on Smart Grids with industrial partners:
  - Supporting Smart Grids testing/simulation infrastructure
  - Data analysis for Smart Grids (load control, anomalies detection)



Smart Grid Architecture Model [5, 6]

Scenarios

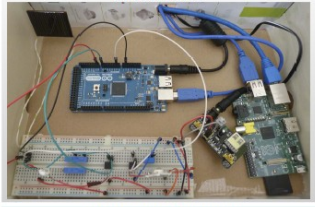
a) Sunlight Levels for a Location

- Uses past weather data to estimate sunlight levels
- Allows evaluating different PV panel deployments
- Each node represents a PV power station in the grid

b) Power Grid Load

- Knowing whether the power grid can meet the current or near future requirements becomes necessary as more intermittently available renewable resources are added to the power grid [2]
- The amount of power produced is compared to expected grid load to determine power deficiencies when using only renewable resources
- Used to determine when power plants need to be switched on to supplement renewable energy sources
- Predicting the required production capacity can be beneficial for the Smart Grid stability

Simulation Node



Project Results

- We created a platform for Smart Grid deployment prototyping
- Students can easily setup their own Smart Grid environments and test them under various changing conditions
- Test cases include: Smart Grid deployment, interoperability, stability
- Our future goal is a full power grid simulation using only commodity hardware

Hardware Node Components

- Photo-voltaic (PV) panel:
  - Produces power proportional to the illumination levels
- LED array:
  - Generates multiple illumination levels
- Arduino Mega:
  - Controls the LED array and reads the voltage level from a PV panel
  - Sends measured data and receives control commands
- Raspberry Pi:
  - Data collection and network communications

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SGTMP Smart Grids Testing Management Platform

applied sciences

MDPI

Article

Smart Grid Testing Management Platform (SGTMP) †

Martin Schvarcbacher [1], Katarína Hrabovská [2], Bruno Rossi [2,*] and Tomáš Pitner [2]

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Abstract The Smart Grid (SG) is nowadays an essential part of modern society, providing two-way energy flow and smart services between providers and customers. The main drawback is the SG complexity, with an SG composed of multiple layers, with devices and components that have to communicate, integrate, and cooperate as a unified system. Such complexity brings challenges for ensuring proper reliability, resilience, availability, integration, and security of the overall infrastructure. In this paper, we introduce a new smart grid testing management platform (herein called SGTMP) for executing real-time hardware-in-the-loop SG tests and experiments that can simplify the testing process in the context of interconnected SG devices. We discuss the context of usage, the system architecture, the interactive web-based interface, the provided API, and the integration with co-simulations frameworks to provide virtualized environments for testing. Furthermore, we present one main scenario about the stress-testing of SG devices that can showcase the applicability of the platform.

Keywords: smart grid testing platform; smart meter; ISO/IEC/IEEE 29119 software testing standard; hardware in the loop; co-simulation frameworks

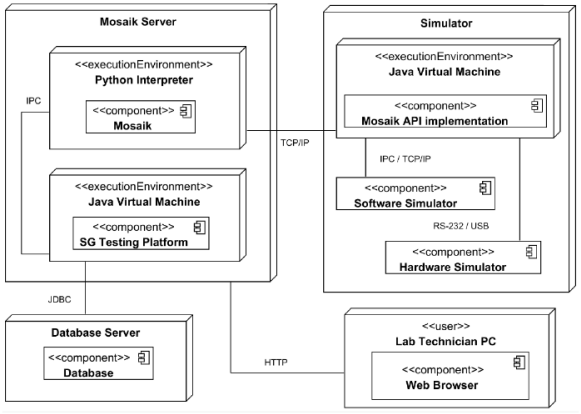
1. Introduction

Traditional power grids distributed and managed energy from a centralized system in one direction, from the energy provider to the customers [1]. With growing demands for reliability and efficiency of the grid operation, there has been a necessity to develop a more interactive, interconnected, and dynamic grid model [2]. As a result, smart grids (SGs) improve electricity management by involving advanced two-way communications and operational capabilities, which allow one to deliver electricity in a more efficient, reliable, sustainable, and safer way [3,4]. The SG technology regulates smart devices at consumers' home and buildings with the aim to save energy and decrease costs [5].

Software testing plays a relevant and significant role in today's society, to provide reliable and safer systems [6–8]. However, testing in the context of SGs is extremely complex due to the multi-layer structure of the overall infrastructure. Many layers need to coexist, each one responsible for different areas such as communication protocols, information exchange, and service provision [9]. Each of these layers has to be tested separately and as a whole system to ensure faultless and reliable energy supply [10]. Furthermore, the nature of SGs as a cyber-physical system involves integration with hardware devices, making use of modeling and simulations highly relevant to discovering integration issues at scale [11,12].

Many SG testing/simulation platforms have emerged over the years, focusing on simulating part of the complexity within SGs, both at the power and at the communication network level [13]:

→ Java + REST API + HTTP GUI server
→ Supporting Mosaik via Inter-Process Communication (IPC)
→ Hardware simulators via a hardware interface (e.g., RS-232, Ethernet, USB)



Key aspects

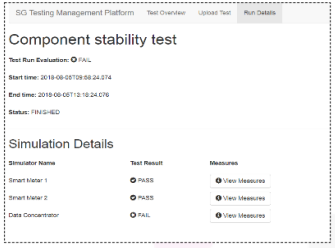
→ Allows testing of Smart Grid components

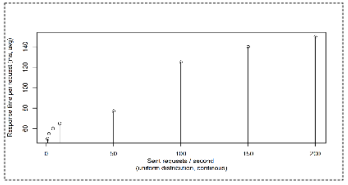
→ User defines Smart Grid topologies, simulator data flows, initial configuration

→ Java based API for simulators (can be HiL/RT/software) – Mosaik takes care of synchronization

→ Users have to implement interfaces to hardware simulators and translate requests between hardware and Mosaik

→ UI allows to manage the definition of testing scenarios to run and collect reports





Executed tests pass/fail → Detailed view with JSON logs → Simulation visual results

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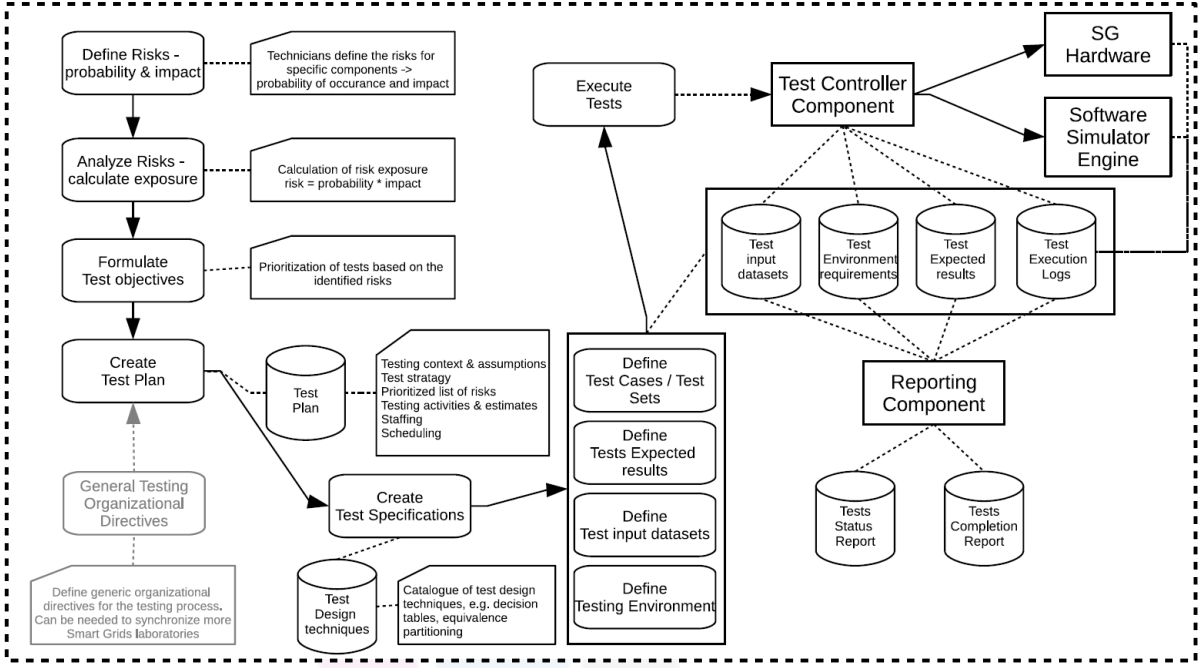

Testing Process Models

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Software Testing Process Models Benefits & Drawbacks: a Systematic Literature Review

Katarína Hrabovská, Bruno Rossi, and Tomáš Pitner
Faculty of Informatics
Masaryk University, Brno, Czech Republic

Abstract

Context: Software testing plays an essential role in product quality improvement. For this reason, several software testing models have been developed to support organizations. However, adoption of testing process models inside organizations is still sporadic, with a need for more evidence about reported experiences.
Aim: Our goal is to identify results gathered from the application of software testing models in organizational contexts. We focus on characteristics such as the context of use, practices applied in different testing process phases, and reported benefits & drawbacks.
Method: We performed a Systematic Literature Review (SLR) focused on studies about the application of software testing processes, complemented by results from previous reviews.
Results: From 35 primary studies and survey-based articles, we collected 17 testing models. Although most of the existing models are described as applicable to general contexts, the evidence obtained from the studies shows that some models are not suitable for all enterprise sizes, and inadequate for specific domains.
Conclusion: The SLR evidence can serve to compare different software testing models for applicability inside organizations. Both benefits and drawbacks, as reported in the surveyed cases, allow getting a better view of the strengths and weaknesses of each model.

1 Introduction

Software testing is a key phase of the software development process, as it represents the process of quality validation and verification of a software product [79]. Such phase is even more crucial nowadays, as software has become increasingly complex, mission-, safety- critical, and essential in daily activities, calling for an increase in quality [12, 46, 59].

Testing models and standards emerged over time to more clearly define a testing process with formalized criteria to make the whole process repeatable and reproducible [44]. Testing standards play a supportive role in reaching the desired quality level, allowing for a more systematic and structured way for further analysis and improvements [8].

Over time, several software testing standards and models have emerged to fulfill various requirements of organizations for a testing process [3, 23, 27]. The number of models can allow organizations to adopt the one that mostly satisfies organizational needs, even though full adoption of testing standards by organizations has been found to be sporadic [25, 35].

The goal of this paper is to identify existing testing models and their characteristics such as domain, context of application, aspects improved, advantages and drawbacks, important models' practices in the industrial context, by complementing existing reviews of Garcia et al. [23], Afzal et al. [3], and Garousi et al. [27]. Information from the review can help practitioners in selecting the most appropriate model for a context.

There is a huge variety of methods that can be applied for literature reviews in the context of Evidence Based Software Engineering (EBSE) [14, 38]. In this paper, we conduct a Systematic Literature Review (SLR) [36, 37]. The review contributes to the area of testing models by identifying and analyzing the most popular models published in empirical studies. Compared to previous reviews in the area ([3, 23, 27]), our focus is more on experiences from empirical studies, by providing models characteristics which can be crucial for organizations in the selection process of an appropriate model. In our review, we focus on the following contributions:

- the list of the most used testing models applied in empirical studies published in the literature, with the indication of the application domains;

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Smart Grids and Software Testing Process Models

Katarína Hrabovská, Nikola Šimková, Bruno Rossi, *Member, IEEE,* and Tomáš Pitner

***Abstract*—A Smart Grid (SG) is a Cyber–Physical System (CPS) idealized with the ultimate goal to reach optimal energy efficiency, a key enabler for the Smart City concept. SG reliability needs to be ensured by an in-depth testing process, involving software/hardware components, network communication, together with quality concerns such as security of the overall infrastructure. While there are many models for modelling/designing SGs (e.g., SGAM), there is no specific testing process model customized for the SGs needs. As such, the aim of this paper is to identify a set of software testing process models developed over the years and investigate their adaptability to SG testing requirements. To reach the goal, we categorize SG requirements from related works with the help of a concept map. Afterwards, the most popular testing process models from literature are discussed in the context of the identified requirements. From a list of 17 main testing models, six testing models (TPI Next, TMMi, Test SPICE, TIM, ISO/IEC/IEEE 29119, and MTPF) are considered as potentially adaptable to the SG domain.**

***Index Terms*—Software Testing Process Models, Smart Grids**

I. Introduction

Cyber–Physical Systems (CPS) have become one of the most important IT concepts, nowadays. CPS deal with the real interaction between the physical and computer levels (i.e., mostly software-based) systems. The CPS concept merges "Cyber" resources (sensing, computing, and hardware/software communication) as a discrete, logical, and switched part, together with "Physical" objects (natural and human-made systems) governed by the laws of physics and operating in continuous time [1]. The ultimate purpose of using a cyber infrastructure is to intelligently monitor (from physical to cyber) and control (from cyber to physical) our physical world [2]. Therefore, CPS are becoming more and more demanding in the various fields of industry. A typical CPS is a Smart Grid (SG), a key enabler for the Smart City concept [3], allowing to integrate renewable energy sources and smart services within Smart Cities [4].

Designing and building SGs can be extremely challenging, costly, and must be carefully planned due to their lifetime, which spans not years but decades corresponding to the lifetime of its power components such as wiring, cabling, switches, etc... Any mistakes in the architecture, design or implementation can have fatal consequences, resulting in delays, significant additional costs, or in the worst case, complete collapse of the entire power distribution system.

Thus, appropriate tests are necessary to evaluate reliability, integration, and performance of different layers of these systems [5], [6], [7]. However, there is no ad-hoc process model for SG testing, a model that can take into account the peculiarities of the domain. For this reason, the aim of the paper is to present SG testing requirements and describe testing models that have been developed over the years for generic or other specific domains, to see how such models can comply with SG testing requirements.

The rest of the paper is structured as follows: Section II describes the background of SGs together with the importance of improving software quality through testing models. Section III presents specific requirements and aspects of SG testing. Section IV provides a discussion about the selection of six representative software testing models to be applied in the context of SG. Section V provides the conclusions.

II. Smart Grids

The development of Information and Communication Technology (ICT) has brought changes in all sectors of the economy, including the energy sector. This sector influences significantly the economic growth in each country and contributes to its greater efficiency. The key factor for optimum energy efficiency together with an energy-efficient economy is at the basis of the development and adoption of SGs [8].

SGs can be defined from different points of view. On the one side, a SG is an electricity network that can intelligently integrate the behavior and actions of all users to ensure sustainable, economic, and secure electricity supply (European Union definition) and on the other hand, SG uses digital technology to improve reliability, security, and efficiency of the electricity system (US Department of Energy definition) [9]. Nevertheless, the fundamentals remain the same—the application of ICT in power grids. SGs use metering, communications and control technologies for generation, transmission lines, substations, feeders (circuits), meters and in-premise technologies [10], [11]. This generation, transmission, and distribution system for energy allows more renewable resources to engage with the energy infrastructure [12]. In today's society, it is important to know how to use renewable resources in each sector of the economy, especially in the energy sector where the trend is particularly appealing and fast progressing together with the growth of electromobility and photovoltaic installations that need control and regulation in near real time, thus demanding a reliable CPS architectures including communication technology.

The reorganisation of the energy sector in terms of SG involves data collection and messaging at both supply and demand ends of the grid, which is the critical requirement in the maintenance of an appropriate supply of energy [13].

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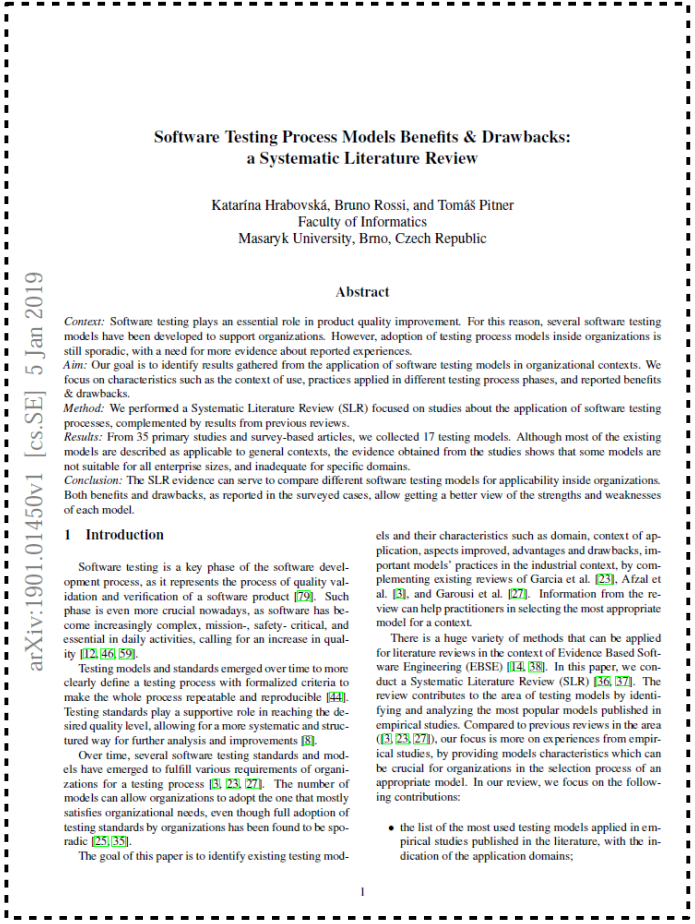
Testing Process Models



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Abstract

Context: Software testing plays an essential role in product quality improvement. For this reason, several software testing models have been developed to support organizations. However, adoption of testing process models inside organizations is still sporadic, with a need for more evidence about reported experiences.
Aim: Our goal is to identify results gathered from the application of software testing models in organizational contexts. We focus on characteristics such as the context of use, practices applied in different testing process phases, and reported benefits & drawbacks.
Method: We performed a Systematic Literature Review (SLR) focused on studies about the application of software testing processes, complemented by results from previous reviews.
Results: From 35 primary studies and survey-based articles, we collected 17 testing models. Although most of the existing models are described as applicable to general contexts, the evidence obtained from the studies shows that some models are not suitable for all enterprise sizes, and inadequate for specific domains.
Conclusion: The SLR evidence can serve to compare different software testing models for applicability inside organizations. Both benefits and drawbacks, as reported in the surveyed cases, allow getting a better view of the strengths and weaknesses of each model.

1 Introduction

Software testing is a key phase of the software development process, as it represents the process of quality validation and verification of a software product [79]. Such phase is even more crucial nowadays, as software has become increasingly complex, mission-, safety- critical, and essential in daily activities, calling for an increase in quality [12, 46, 59].

Testing models and standards emerged over time to more clearly define a testing process with formalized criteria to make the whole process repeatable and reproducible [44]. Testing standards play a supportive role in reaching the desired quality level, allowing for a more systematic and structured way for further analysis and improvements [8].

Over time, several software testing standards and models have emerged to fulfill various requirements of organizations for a testing process [3, 23, 27]. The number of models can allow organizations to adopt the one that mostly satisfies organizational needs, even though full adoption of testing standards by organizations has been found to be sporadic [25, 35].

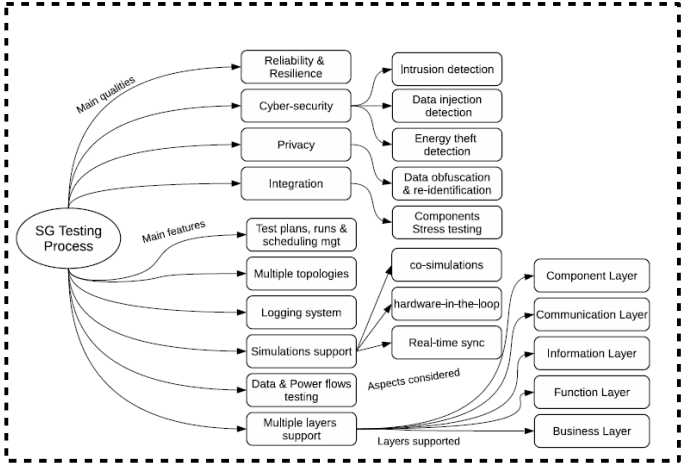
The goal of this paper is to identify existing testing models and their characteristics such as domain, context of application, aspects improved, advantages and drawbacks, important models' practices in the industrial context, by complementing existing reviews of Garcia et al. [23], Afzal et al. [3], and Garousi et al. [27]. Information from the review can help practitioners in selecting the most appropriate model for a context.

There is a huge variety of methods that can be applied for literature reviews in the context of Evidence Based Software Engineering (EBSE) [14, 38]. In this paper, we conduct a Systematic Literature Review (SLR) [36, 37]. The review contributes to the area of testing models by identifying and analyzing the most popular models published in empirical studies. Compared to previous reviews in the area ([3, 23, 27]), our focus is more on experiences from empirical studies, by providing models characteristics which can be crucial for organizations in the selection process of an appropriate model. In our review, we focus on the following contributions:

- the list of the most used testing models applied in empirical studies published in the literature, with the indication of the application domains;

ID	Testing Approach	Abbreviation	Domain	Maturity Model	Model Base	Model Type	Reference
TM1	Testing Maturity Model	TMM	General	✓	CMM	Model	[8, 50]
TM2	Test Maturity Model integration	TMMi	General	✓	TMM	Model	[9, 10, 61]
TM3	Test Process Improvement	TPI	General	✓	SPICE, TMap	Model	[32, 62]
TM4	Embedded Test Process Improvement Model	Emb-TPI	Embedded software	✓	TPI	Model	[31, 40]
TM5	Test SPICE	Test SPICE	General	✗	ISO 15504 part 5	Model	[68]
TM6	Brazilian Maturity Model for Testing	MPT.BR	Small Organizations	✓	ISO/IEC 29119, TMMi	Model	[21]
TM7	Ministry of National Defense-Testing Maturity Model	MND-TMM	Military systems	✓	TMM	Model	[58, 62]
TM8	Software Testing Standard ISO/IEC/IEEE 29119	ISO/IEC/IEEE 29119	General	✗	ISO	Standard	[4, 34]
TM9	Test Improvement Model	TIM	General	✓	TMM	Model	[34]
TM10	Observing Practice	-	Automation or telecommunication	✗	None	Approach	[72]
TM11	Meta-measurement approach	-	General	✗	Evaluation theory	Approach	[18]
TM12	Plan-Do-Check-Action (PDCA) based software testing improvement framework	-	Third party testing center	✗	PDCA	Framework	[78]
TM13	Metrics Based Verification and Validation Maturity Model	MB-VV-MM	General	✓	TMM	Model	[30]
TM14	Evidence-based Software Engineering	-	Automotive software	✗	None	Approach	[33]
TM15	Self-Assessment framework for ISO/IEC/IEEE 29119 based on TIM	-	General	✓	ISO/IEC 29119, TIM	Model	[34]
TM16	Test Process Improvement Model for Automated Test Generation	ATG add-on for TPI	Automated Testing	✓	TPI	Model	[28]
TM17	Minimal Test Practice Framework	MTPF	Small Organizations	✗	None	Framework	[32]

Testing Process Models



ID	Testing Approach	Main Characteristics
M1	Test Process Improvement Next (TPI Next) [38]	Practice-based. Defines a path for testing improvement (areas/checkpoints) with maturity levels (initial, controlled, efficient, optimizing). Includes areas for testing process automation and design of test cases (test strategies, test case design, metrics, reporting). Can be adapted to different domains.
M2	Test Maturity Model integration (TMMi) [39]	Covers all levels of structured testing (static, dynamic, component, integration, system, acceptance testing, etc...). Supports test process maturity levels (initial, managed, defined, measured, optimized).
M3	Test SPICE (Test SPICE) [40], [41]	Includes processes for business analysis and test execution / automation, useful in the SG domain. Test SPICE can be adapted to other domains with the definition of customized process categories, process groups and processes.
M4	Test Improvement Model (TIM) [42]	Supports testing process maturity levels (initial, baselining, cost-effectiveness, risk-lowering, optimising). Focuses at the high level of the testing process management. Less ad-hoc customizations compared to other models.
M5	Software Testing Standard (ISO/IEC/IEEE 29119) [43]	Strongly focused on a risk-based approach, provides support for quality characteristics and specifies test techniques for different aspects (e.g., data flow testing). Can be adapted to different domains.
M6	Minimal Test Practice Framework (MTPF) [44]	Light-weight model that can be adapted to limited SG deployments (like small SG testing laboratories). Divided into different areas/phases, can be adapted to the needs the complexity of the overall process. Not many adaptations of the generic model to other domains exist.

SMART CITIES SYMPOSIUM PRAGUE 2019

Smart Grids and Software Testing Process Models

Katarína Hrabovská, Nikola Šimková, Bruno Rossi, *Member, IEEE,* and Tomáš Pitner

***Abstract*—A Smart Grid (SG) is a Cyber–Physical System (CPS) idealized with the ultimate goal to reach optimal energy efficiency, a key enabler for the Smart City concept. SG reliability needs to be ensured by an in-depth testing process, involving software/hardware components, network communication, together with quality concerns such as security of the overall infrastructure. While there are many models for modelling/designing SGs (e.g., SGAM), there is no specific testing process model customized for the SGs needs. As such, the aim of this paper is to identify a set of software testing process models developed over the years and investigate their adaptability to SG testing requirements. To reach the goal, we categorize SG requirements from related works with the help of a concept map. Afterwards, the most popular testing process models from literature are discussed in the context of the identified requirements. From a list of 17 main testing models, six testing models (TPI Next, TMMi, Test SPICE, TIM, ISO/IEC/IEEE 29119, and MTPF) are considered as potentially adaptable to the SG domain.**

***Index Terms*—Software Testing Process Models, Smart Grids**

I. Introduction

Cyber–Physical Systems (CPS) have become one of the most important IT concepts, nowadays. CPS deal with the real interaction between the physical and computer levels (i.e., mostly software-based) systems. The CPS concept merges "Cyber" resources (sensing, computing, and hardware/software communication) as a discrete, logical, and switched part, together with "Physical" objects (natural and human-made systems) governed by the laws of physics and operating in continuous time [1]. The ultimate purpose of using a cyber infrastructure is to intelligently monitor (from physical to cyber) and control (from cyber to physical) our physical world [2]. Therefore, CPS are becoming more and more demanding in the various fields of industry. A typical CPS is a Smart Grid (SG), a key enabler for the Smart City concept [3], allowing to integrate renewable energy sources and smart services within Smart Cities [4].

Designing and building SGs can be extremely challenging, costly, and must be carefully planned due to their lifetime, which spans not years but decades corresponding to the lifetime of its power components such as wiring, cabling, switches, etc... Any mistakes in the architecture, design or implementation can have fatal consequences, resulting in delays, significant additional costs, or in the worst case, complete collapse of the entire power distribution system.

Thus, appropriate tests are necessary to evaluate reliability, integration, and performance of different layers of these systems [5], [6], [7]. However, there is no ad-hoc process model for SG testing, a model that can take into account the peculiarities of the domain. For this reason, the aim of the paper is to present SG testing requirements and describe testing models that have been developed over the years for generic or other specific domains, to see how such models can comply with SG testing requirements.

The rest of the paper is structured as follows: Section II describes the background of SGs together with the importance of improving software quality through testing models. Section III presents specific requirements and aspects of SG testing. Section IV provides a discussion about the selection of six representative software testing models to be applied in the context of SG. Section V provides the conclusions.

II. Smart Grids

The development of Information and Communication Technology (ICT) has brought changes in all sectors of the economy, including the energy sector. This sector influences significantly the economic growth in each country and contributes to its greater efficiency. The key factor for optimum energy efficiency together with an energy-efficient economy is at the basis of the development and adoption of SGs [8].

SGs can be defined from different points of view. On the one side, a SG is an electricity network that can intelligently integrate the behavior and actions of all users to ensure sustainable, economic, and secure electricity supply (European Union definition) and on the other hand, SG uses digital technology to improve reliability, security, and efficiency of the electricity system (US Department of Energy definition) [9]. Nevertheless, the fundamentals remain the same—the application of ICT in power grids. SGs use metering, communications and control technologies for generation, transmission lines, substations, feeders (circuits), meters and in-premise technologies [10], [11]. This generation, transmission, and distribution system for energy allows more renewable resources to engage with the energy infrastructure [12]. In today's society, it is important to know how to use renewable resources in each sector of the economy, especially in the energy sector where the trend is particularly appealing and fast progressing together with the growth of electromobility and photovoltaic installations that need control and regulation in near real time, thus demanding a reliable CPS architectures including communication technology.

The reorganisation of the energy sector in terms of SG involves data collection and messaging at both supply and demand ends of the grid, which is the critical requirement in the maintenance of an appropriate supply of energy [13].

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SG Co-Simulations Survey and Research Directions

Smart Grids Co-Simulations: Survey & Research Directions (Draft)

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Abstract

Smart Grids (SG) constitute a substantial advancement over traditional electric power grids, allowing real-time power generation, distribution, and transmission with two-way information flow. However, the integration of renewable sources, communication and power networks with information and communication technologies increases the complexity of large-scale testing. For this reason, the coupling of simulators is commonly used to dynamically test several aspects of the SG infrastructure, in the so-called co-simulations. The focus of this paper is to review the research of co-simulations in the context of Smart Grids: i) research areas and research problems addressed by SG co-simulations, ii) specific SG co-simulation aspects focus of research, iii) architectural styles adopted for SG co-simulations, iv) typical coupling of simulators in SG co-simulation studies. To reach this goal, we conduct a semi-formalized review of co-simulations research for SGs, mapping 81 articles to previously defined nine SG research areas and open research problems. Based on the results, we discuss research directions of future co-simulation research in each of the identified areas.

Keywords: co-simulations, Smart Grids, Survey Research

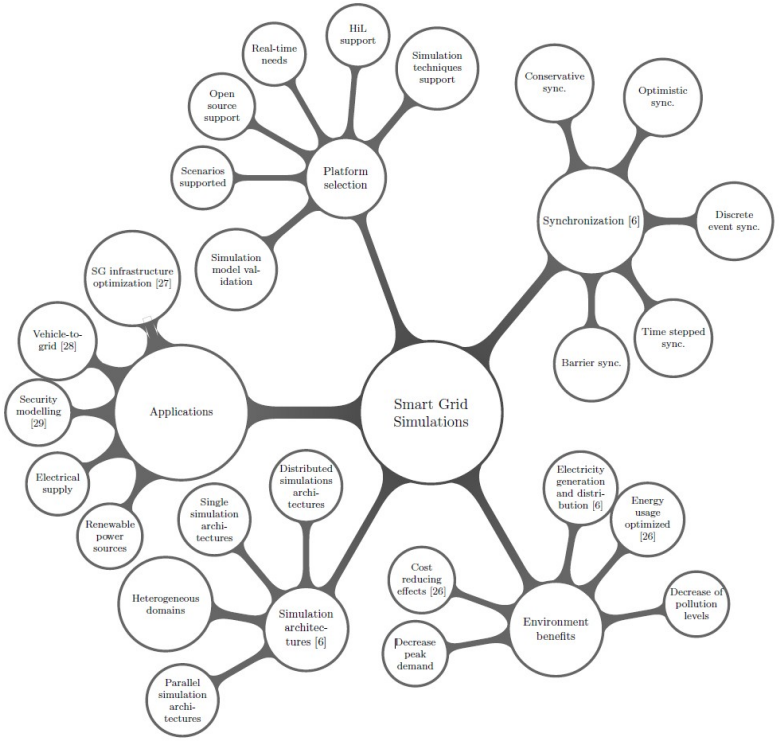
1. Introduction

The complexity of the modern smart power distribution network, the Smart Grid (SG), presents key challenges for systems being developed. The plethora of technologies, communication protocols, and algorithms, requires naive approaches for system development, testing and validation [1, 2]. One solution to tackle such complexity is to use simulations to evaluate several parts of the SG infrastructure and interactions with the environment (such as renewable sources or the energy market). However, single simulations alone are not enough to address all the needs of each underlying system and represent dynamic behaviors and interplays between different aspects: coupling of multiple simulation environments involving both software and hardware devices are necessary to create realistic scenarios [3, 4].

In the SG context, both the power and the communication domain can be modelled concurrently to understand a phenomenon under evaluation, often with some hardware-in-the-loop (HiL) support [5]. Such coupling of different simulators poses several challenges in time-synchronization between different simulators, being some simulators based on discrete events, such as network simulators, while others on the solution of differential equations, such as power simulators [4]. Furthermore, such simulations have to be contextualized to SG testbeds experiments [6], large infrastructures for testing of SG components in terms of both functional and non-functional requirements. To conduct such large-scale experiments, multiple locations can be used and thus be part of the experiment [1]. Communication across large distances and multiple hardware / software solutions, brings even more stringent real-time and synchronization challenges [1].

The coupling of different simulators, each one running in its own runtime environment, is commonly defined as *co-simulation*. A co-simulator allows the connection of multiple different simulation software and hardware to enable a single unified simulation scenario [4]. In this way, multiple domains can be tested and simulated transparently as being part of a single system. Connecting multiple simulators presents many challenges, which are addressed in different ways by the various co-simulation frameworks, such as the mentioned time-synchronization, and the type of architecture for orchestrating the simulators.

Co-simulations in the SG context have been used to combine both power and communication aspects of the grid, but also to integrate other views, such as market pricing simulations or vehicle-to-grid aspects. Co-simulations have been useful for many research goals in the SG area, such as modelling power failures and recovering capability of the power network, investigating device failures, simulating electrical vehicles charging for demand / response management, simulating the impact of communication packets loss on the power network, as well as different forms of data injection attacks. The goal of this paper is to provide a review providing an aggregated view about all these aspects in the area of SG co-simulations: i) research areas and research problems addressed by SG co-simulations, ii) specific SG co-simulation aspects focus of research, iii) architectural styles adopted for SG co-simulations, iv) typical coupling of simulators in SG co-



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Areas

A1. Reliability and wide-area awareness
A2. Consumer energy eciency
A3. Energy resources distribution
A4. Grid energy storage
A5. Transportation of energy
A6. Advanced Metering Infrastructure
A7. Management of distribution grid
A8. Cybersecurity
A9. Network communications

Problems addressed by co-simulations	A1	A2	A3	A4	A5	A6	A7	A8	A9
[R2] Modified radial-distribution network for power failures recovery.	●						●		
[R3] Reliability of the Wide Area Monitoring and Control systems of electric power network with data by phase measurement units.	●						●		
[R4] Reliability of the ICT network of the smart distribution network.	●								
[R1] The effect of communication failures as a function of the radio frequency (RF) transmission power level.	●						●		●
[R5] Protection relays evaluated with simulations.	●						●		
[R6] Power and communication devices failures.	●								●
[R7] Wide area control : agent-based remote relay protection.	●						●		●
[R8] Wide area control: communication-based backup distance relay protection	●						●		●
[R9] Studying mutual effects of communication, network, power levels for wide-area monitoring, protection and control.	●								●
[R10] Latency and bandwidth for control and protection applications, congestions between PMU and PDC systems, cyberattacks.	●						●	●	●
[R11] Power systems monitoring and control applications: feeder reconfiguration algorithms	●						●		
[R12] Identify bad data measurements and states to predict impact on power systems operation.	●							●	
[R13] Agent-based fault location, isolation, and service restoration.	●								
[R14] Reliability of the control strategies in a SG.	●								●
[R15] Testing different operation, control and aggregation strategies on a power network model with multiple voltage levels.	●								●
[R16] Evaluate scenarios in voltage control of photovoltaic stations.	●			●			●		
[R17] Simulating Cascading Failures in SGs.	●							●	
[R18] Reconfigure loads in power systems in case of faults and analyze reactive power control and optimization.	●	●							●
[R19] Power monitoring & control application.	●	●				●			
[R20] Control algorithms for demand and supply load balancing.	●	●	●						
[R21] Voltage control for smart distribution power grid: coordination of photovoltaic inverters.	●	●	●						
[R22] Distribution network model with centralised load control.		●			●		●		
[R23] Power distribution network events, packet loss simulation.		●							●
[R24] Flattening the voltage profile and improving the power factor		●					●		
[R25] Modelling users power consumption behaviour.		●							
[R26] Control strategies for the management of the interaction between SG and active prosumers. Testing of a distributed storage with vehicle-to-grid management system.		●		●	●				
[R27] District level optimization techniques modeling the interaction between a smart electric grid and buildings for energy saving.		●		●					
[R28] Low voltage grids with residential loads simulated by several load curve simulation tools.		●					●		
[R29] Co-simulation environment for thermostatically controlled loads.		●							
[R30] Modelling a grid consisting of producers and loads.		●	●						
[R31] Studying demand response and energy pricing.		●				●			●
[R32] Integration of low-cost hardware in the loop with software simulators for household power consumption with PV panels.		●	●			●			
[R33] Proof-of-concept evaluation of future power system control applications (e.g., voltage control).	●	●	●						
[R34] Home energy management and time-to-use tariffs.		●	●			●			
[R35] Smart grid market application for calculation of the energy price.			●			●			
[R36] Real-time market-grid coupling, to analyze the mutual influence between the market and the grid.			●			●			
[R37] Transmission and distribution networks integration.			●				●		
[R38] Voltage regulation in distribution networks.			●		●				
[R39] Simulations of power load and market pricing.			●			●			
[R40] Control algorithms for distribution networks.	●		●		●				
[R41] Medium voltage DC microgrid system for power supply to offshore production platforms.			●				●		
[R42] Control the dispatch of three power-balancing diesel generators in the isolated grid.	●		●	●					
[R43] Electric Vehicles charging events simulation.				●	●				
[R44] Wireless mesh network and sensor technologies to support charging of plug-in electric vehicles to stabilize the voltage.				●	●				●

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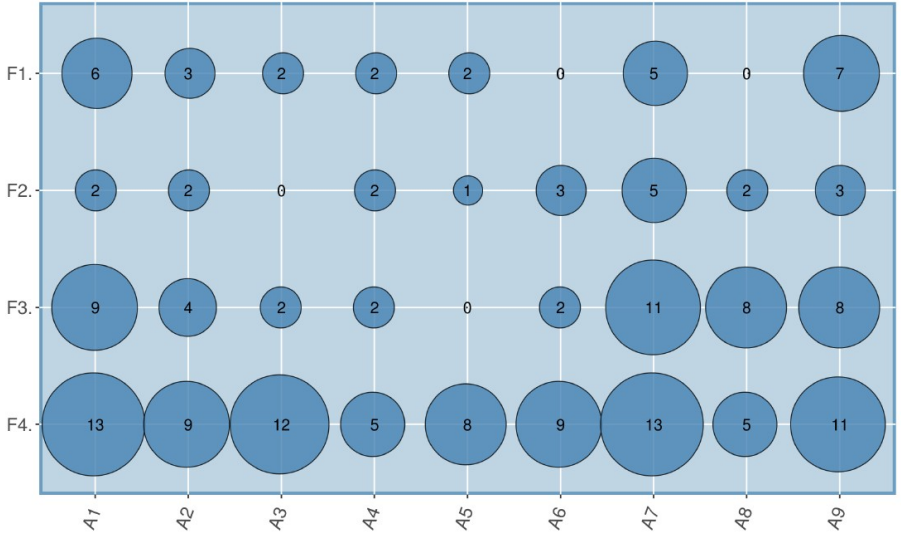
Research Aspects
F1. Approaches for time and objects synchronization in co-simulations
F2. Real-time monitoring and testing
F3. Integration of power and communication simulators
F4. Co-simulation architecture



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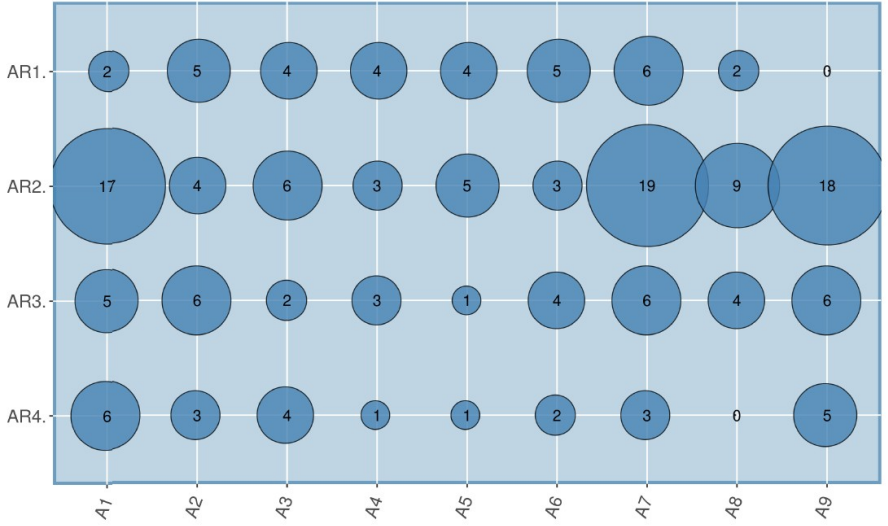
In the SG context, both the power and the communication domain can be modelled concurrently to understand a phenomenon under evaluation, often with some hardware-in-the-loop (HiL) support [5]. Such coupling of different simulators poses several challenges in time-synchronization between different simulators, being some simulators based on discrete events, such as network simulators, while others on the solution of differential equations, such as power simulators [4]. Furthermore, such simulations have to be contextualized to SG testbeds experiments [6], large infrastructures for testing of SG components in terms of both functional and non-functional requirements. To conduct such large-scale experiments, multiple locations can be used and thus be part of the experiment [1]. Communication across large distances and multiple hardware / software solutions, brings even more stringent real-time and synchronization challenges [1].

The coupling of different simulators, each one running in its own runtime environment, is commonly defined as *co-simulation*. A co-simulator allows the connection of multiple different simulation software and hardware to enable a single unified simulation scenario [4]. In this way, multiple domains can be tested and simulated transparently as being part of a single system. Connecting multiple simulators presents many challenges, which are addressed in different ways by the various co-simulation frameworks, such as the mentioned time-synchronization, and the type of architecture for orchestrating the simulators.

Co-simulations in the SG context have been used to combine both power and communication aspects of the grid, but also to integrate other views, such as market pricing simulations or vehicle-to-grid aspects. Co-simulations have been useful for many research goals in the SG area, such as modelling power failures and recovering capability of the power network, investigating device failures, simulating electrical vehicles charging for demand / response management, simulating the impact of communication packets loss on the power network, as well as different forms of data injection attacks. The goal of this paper is to provide a review providing an aggregated view about all these aspects in the area of SG co-simulations: i) research areas and research problems addressed by SG co-simulations, ii) specific SG co-simulation aspects focus of research, iii) architectural styles adopted for SG co-simulations, iv) typical coupling of simulators in SG co-

Architectural style
AR1. Power simulator + coordination component
AR2. Power simulator + communication simulator + coordination component
AR3. Power simulator + communication simulator + hardware interfaces + coordination component
AR4. Message bus + simulators



SG Co-Simulations Survey and Research Directions

Smart Grids Co-Simulations: Survey & Research Directions (Draft)

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Abstract

Smart Grids (SG) constitute a substantial advancement over traditional electric power grids, allowing real-time power generation, distribution, and transmission with two-way information flow. However, the integration of renewable sources, communication and power networks with information and communication technologies increases the complexity of large-scale testing. For this reason, the coupling of simulators is commonly used to dynamically test several aspects of the SG infrastructure, in the so-called co-simulations. The focus of this paper is to review the research of co-simulations in the context of Smart Grids: i) research areas and research problems addressed by SG co-simulations, ii) specific SG co-simulation aspects focus of research, iii) architectural styles adopted for SG co-simulations, iv) typical coupling of simulators in SG co-simulation studies. To reach this goal, we conduct a semi-formalized review of co-simulations research for SGs, mapping 81 articles to previously defined nine SG research areas and open research problems. Based on the results, we discuss research directions of future co-simulation research in each of the identified areas.

Keywords: co-simulations, Smart Grids, Survey Research

1. Introduction

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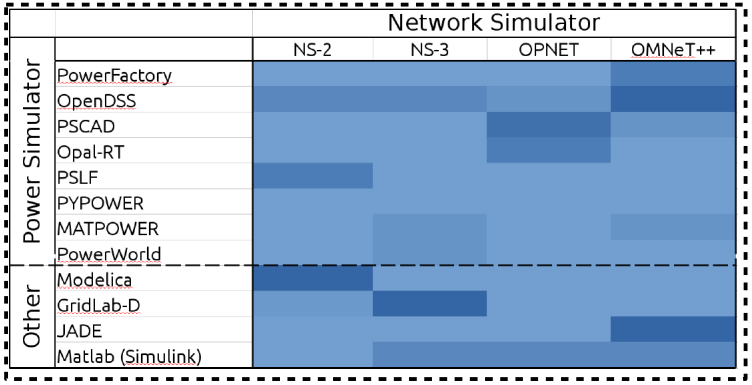

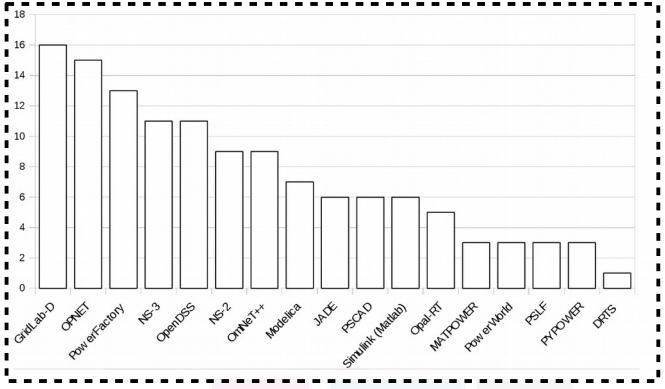

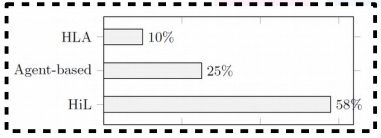

Power consumptions simulations with Mosaik

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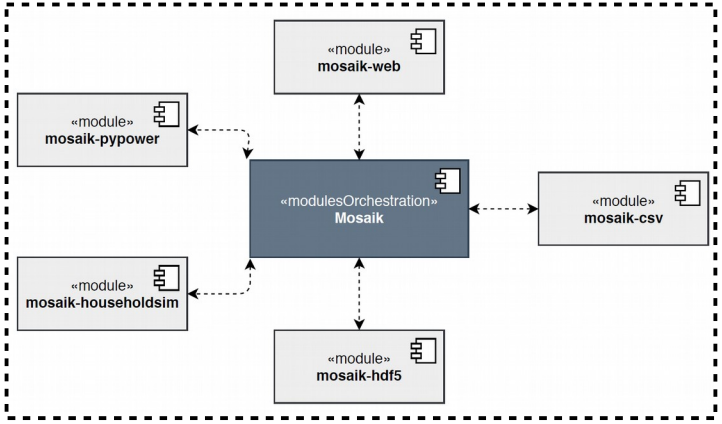
Modelling Smart Grids Operations via Simulations

Master's Thesis

Peter Mihal

Brno, Spring 2019



- `init()`

  Method called exactly once after the start of simulator. It initializes the simulator and applies additional parameters sent by mosaik.

- `create()`

  Method is called in order to initialize a simulation model. It takes file containing a grid as a parameter

- `step()`

  Method tells simulator to perform a simulation step. It is called periodically

- `get_data()`

  Method allows other simulators to get the values of the attributes of certain models.

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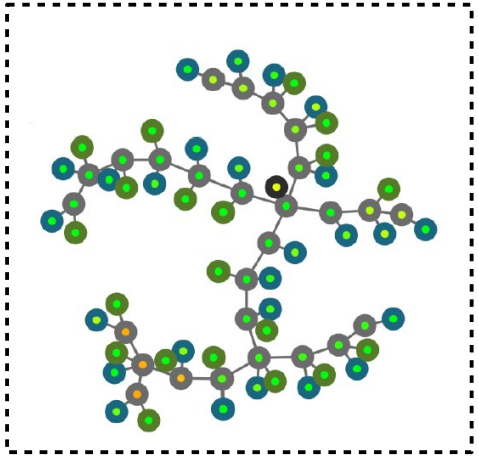


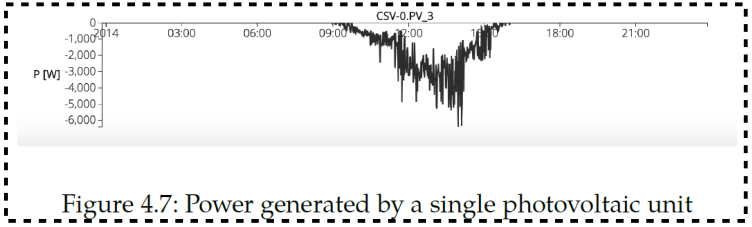


Figure 4.7: Power generated by a single photovoltaic unit

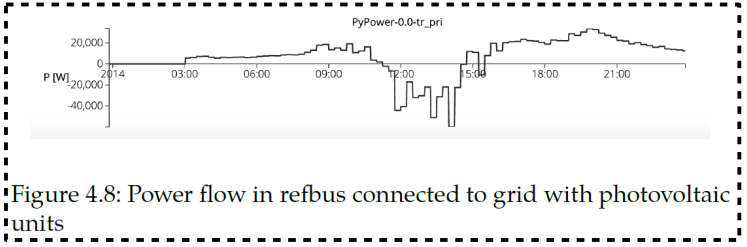


Figure 4.8: Power flow in refbus connected to grid with photovoltaic units

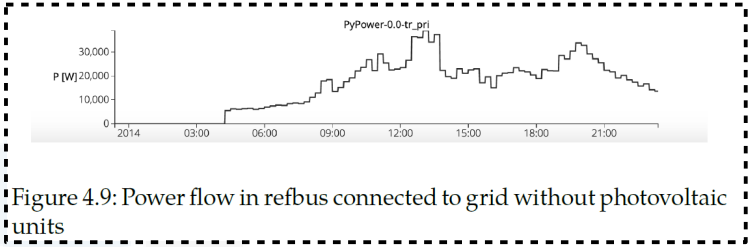
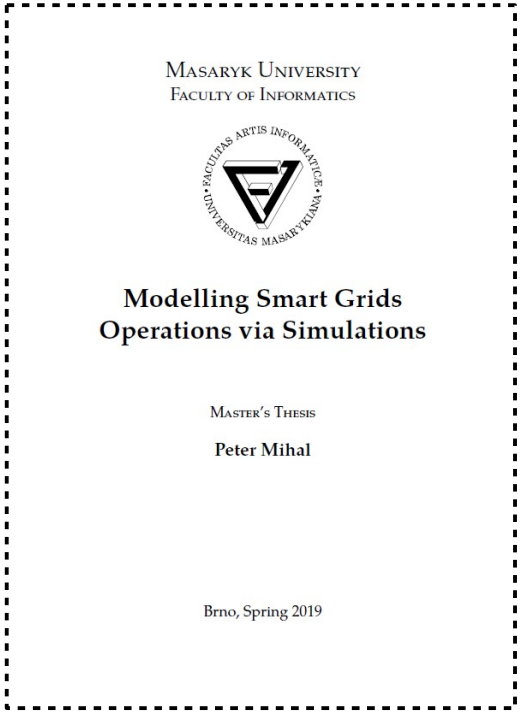


Figure 4.9: Power flow in refbus connected to grid without photovoltaic units

Power consumptions simulations with Mosaik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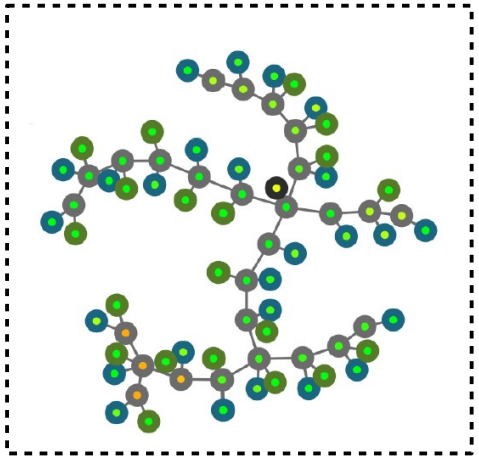

Research Goal: adjusting dynamically the topology

Benefits:

- studying “what-if” scenarios:
  - * e.g. what happens when one node goes down/is attacked
  - * optimizations of power loads

Main published material

→ M. Schvarcbacher, K. Hrabovská, B. Rossi, T. Pitner (2018). *"SGTMP: Smart Grid Testing Management Platform"* (submitted to journal, not yet available)

→ HRABOVSKÁ, Katarína, Nikola ŠIMKOVÁ, Bruno ROSSI and Tomáš PITNER. Smart Grids and Software Testing Process Models. In Ruzicka, J. 2019 Smart City Symposium Prague (SCSP). New York: IEEE, 2019. p. 1-6, 6 pp. ISBN 978-1-72810-497-3. doi:10.1109/SCSP.2019.8805718.

→ Schvarcbacher, M., Rossi, B. (2017). *"Smart Grids Co-Simulations with Low-Cost Hardware"*, in 43rd Euromicro Conference on Software Engineering and Advanced Applications (SEAA) 2017, IEEE, DOI: 10.1109/SEAA.2017.43. [download]

→ LAMBA, Vikas, Nikola ŠIMKOVÁ and Bruno ROSSI. Recommendations for Smart Grid Security Risk Management. Cyber-Physical Systems, Taylor & Francis, 2019, vol. 5, No 2, p. 92-118. ISSN 2333-5777. doi:10.1080/23335777.2019.1600035.

→ GE, Mouzhi, Stanislav CHREN, Bruno ROSSI and Tomáš PITNER. Data Quality Management Framework for Smart Grid Systems. In Proceedings of the 22nd International Conference on Business Information Systems. : Springer, 2019. 12 pp. Doi:10.1007/978-3-030-20482-2_24.

→ MIHAL, Peter, Martin SCHVARCBACHER, Bruno ROSSI, and Tomáš PITNER. Smart Grids Co-Simulations: Survey & Research Directions. Submitted to Elsevier Computers in Industry.

Theses:

→ Schvarcbacher M. (2018). *"Smart Grid Testing Management Platform"*, BSc Thesis Masaryk University, Brno [download]

→ Hrabovská K. (2017). *"Supporting a Smart Grids Laboratory: Testing Management for Cyber-Physical Systems"*, MSc Thesis Masaryk University, Brno [download]

→ Mihal P. (2019). "Modelling Smart Grids Operations via Simulations" MSc Thesis Masaryk University, Brno [download]