Towards more realistic co-simulation of cyber-physical energy distribution systems

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Abstract: The increased integration of information and communications technology at the distribution grid level offers broader opportunities for active operational management concepts. At the same time, requirements for resilience against internal and external threats to the power supply, such as outages or cyberattacks, are increasing. The emerging threat landscape needs to be investigated to ensure the security of supply of future distribution grids. This extended abstract presents a co-simulation environment to study communication infrastructures for the resilient operation of distribution grids. For this purpose, a communication network emulation and a power grid simulation are combined in a common modular environment. This will provide the basis for cybersecurity investigations and testing of new active operation management concepts for smart grids. Exemplary laboratory tests and attack replications will be used to demonstrate the diverse use cases of our co-simulation approach.

Keywords: Co-Simulation, Cyber-Physical System, Smart Grid, Cybersecurity, Multi-Use Flexibility

1. INTRODUCTION

In distribution grids, progressive digitization is leading to increasing integration of Information and Communications Technology (ICT). This provides enhanced grid transparency through more opportunities for real-time monitoring of the grid and also offers opportunities for active control of individual assets of the overall system. This opens up new potential in the area of active operational management at the distribution grid level.

In particular, flexibility resources provided by new types of (distributed) generation and consumers at this grid level should be used in an optimizing manner, both market- and grid-related. Multi-use concepts developed for this purpose are the subject of current research (Truong, Cong Nam et al., 2018).

In addition to the acquisition of new potentials, the increasing inclusion of ICT in grid-relevant operations also requires the fulfillment of fundamental requirements for cyber-resilience and cybersecurity of the overall system. Malfunctions in the ICT domain can have a direct impact on the security of supply. In particular, adequate measures are needed to prevent cyberattacks to counter the increased attack surface. This requires providing communications data from attacks patterns that can be used to develop, validate, and test such measures. However, such data is not publicly available (Zuech, Richard et al., 2015).

Both the development of new operational management concepts and the investigation of domain-specific cybersecurity measures require tailored development environments that share essential requirements in terms of their scalability, realism (e.g., digital twin), and flexibility.

This paper presents our ongoing work on a framework for the co-simulation of cyber-physical energy systems. For this, we present the goals and added values of the environment in Section 2. Section 3 gives an overview of the environment and its main components. The focus of the paper is on the presentation of two exemplary use cases in Section 4, which we implement with the help of the environment. This includes the replication of cyberattacks to provide a development environment for countermeasures, e.g., for intrusion detection, and the use of the environment as a digital twin for practical testing of operational concepts for flexibility management.

2. BACKGROUND & RELATED WORK

In this section, we introduce the important parts of a Smart Grid (SG) infrastructure to be considered in a simulation environment for our use case and derive the requirements. First, we give a brief overview of SGs and their simulation, and then their cybersecurity.

Usually, the SG infrastructure is divided into different zones. Each component of the energy system refers to one of those zones. The important zones for our work are Primary Technology, Operational Technology (OT), Information Technology (IT) and Operation. Primary Technologies are power grid equipment, such as transformers, switches, loads, and generation units. Those assets are connected to the OT network to control them or to retrieve information/measurements. The IT section represents the communication infrastructure used by the OT components



Fig. 1. Overview of the utilized co-simulation environment and its major components. Depending on the use case, the respective components can be modeled in different degrees of abstraction.

for the communication with operators, such as a Distribution System Operator (DSO).

A simulation environment needs to meet specific requirements for the appropriate modelling of the SG infrastructure proposed before. First, mutual dependencies between the zones need to be considered. Second, we need a modular, component-based infrastructure model. Hereby, separate models with different detail level should be considered.

There are already various approaches in current research that depict SGs both using hardware within laboratories and software in the sense of a simulation. Veith, Eric et al. (2020) utilize a Software-in-the-Loop co-simulation for the preliminary testing of SG software rollouts. In Wermann, A. G. et al. (2016) a co-simulation is used to simulate cyberattacks in SGs. As part of our developments, we needed a common environment in which we could flexibly connect both hardware and software components. Only in this manner can we investigate all use cases and interactions relevant to us.

Despite a variety of preventive measures such as strict user management, password policies, access control, and network segmentation, intrusion detection capabilities are still needed to meet the high-security requirements in SGs. A holistic security concept, consisting not only of preventive measures but also of detective and reactive measures, can provide options for counteracting intruders even in cases where they are not prevented. Several approaches address the analysis of cybersecurity by investigating cyberattack scenarios, e.g., denial-of-service attacks, false data injection, or a physical system disruption technique, using mathematical modeling or cyberattack trees (Falco, Gregory et al., 2018). In addition, several co-simulation approaches are being explored that consider hardware-inthe-loop co-simulation or a synthetic framework to simulate attack scenarios in SG applications to generate normal and attack data (Albarakati, Abdullah et al., 2018). Our approach leverages isolated and real-time co-simulation so that we can perform a variety of services and vulnerabilities that allow us to simulate a dynamic, multistage attacker exploring the network and exploiting found vulnerabilities in a virtual, as well as a cyber-physical, environment.

3. CO-SIMULATION FOR SMART GRIDS

This Section introduces the overall environment we use to model the relevant use cases for smart distribution grids. Section 3.1 provides an overview of this environment. In Section 3.2 we describe the environment components.

3.1 Environment Overview

Our work is based on a co-simulation environment and a SG laboratory van der Velde, Dennis et al. (2021). The framework *mosaik* is used as a modelling tool (Steinbrink, Cornelius et al., 2019). It allows the connection of various independent simulators. The *mosaik* framework schedules the time-discrete proceeding of each simulator and manages the data flow of connecting simulators. Therefore, a dynamic interconnection of those simulators is possible. In this way, the data flow as abstracted communication is considered explicitly. In addition, we can connect real components of our SG laboratory to the environment. Therefore, it is possible to use both simulated and real components. Although, parts of the laboratory can be combined with simulated parts. Figure 1 shows a general overview of the co-simulation environment.

As mentioned before, the different zones Primary Technology, OT, IT and Operation are considered in our work. The depth of implementation of the components in each zone can vary depending on the use case. In our work, there are two aspects that we primarily focus on. On the one hand, we focus on attack replications. For this use case, the zones at the lower level are more abstracted while operation processes and IT are modelled in detail. On the other hand, we focus on flexibility coordination processes for smallscale Decentralized Energy Resource (DER). Therefore, we implement a bottom-up modelling approach for flexibility units and operation technologies at the household level. In addition to those use case-specific implementation, we use general implementations for all use cases. These implementations are axillary functions for the preparation of time series data and grid topologies, data collection, and a power flow simulation based on *PandaPower* (Thurner, L. et al., 2018).

3.2 Components and Functionality

In the following, the functionalities of the most important components of the deployed environment for the use cases discussed in the paper are explained in more detail.

To map the IT and OT networks and their components such as switches, routers or firewalls, we use the emulation environment Containernet (Peuster, M. et al., 2016). The nodes of the communication networks are containerized here and enable flexible deployment of the various components. Deployment and synchronization with the overall environment is done via an interface with *mosaik*.

virtual RTU (vRTU)s can also be deployed within the nodes. These enable communication with real Supervisory Control and Data Acquisition (SCADA) protocols (IEC 60870-5-104). The data points of the protocol can be logically linked and additional services (SSH, SNMP, ...) can be added. These services can also be specifically equipped with vulnerabilities that serve as initial access for the replication of cyberattacks.

We use the concept of Virtual Edge Device (VED) for modelling Smart Homes. Using this concept, we explicitly consider well-defined interfaces of Smart Homes for the communication with external actors as well as for the control of behind-the-meter assets like Battery Storage and Photovoltaic systems. An Energy Management System bundles retrieved data implements the operation logic and sends new control commands for connected assets. Within the lab, the communication with inverters is via Modbus. The option of using real-world communication protocols both between OT-layer and operational layer and between OT-layer and primary technology allows flexible use of either simulated or real components on each of the layers. This allows us to use components from our SG Laboratory on all layers if required. This includes a control system, several Remote Terminal Units (RTUs) and measuring systems concerning the ICTs and a flexible distribution grid with medium/low-voltage substations and flexibilities such as controllable loads, storage systems, and photovoltaic plants.

4. USE CASES AND FRAMEWORK INTEGRATION

Based on the environment previously introduced, various investigations can be performed. In this paper we focus on the two use cases replication of cyberattacks (cf. Section 4.1) and the development and testing of operational management concepts for grid flexibilities (cf. Section 4.2).

4.1 Cyberattack Replication in Smart Grids

Based on our previous work (Sen, Ömer et al., 2021), an example multi-stage attack scenario is demonstrated using a simulated medium/low voltage distribution grid equipped with networked assets such as edge switch, Master Terminal Unit (MTU), RTU, DER, etc. (cf. Figure 2). Here,



Fig. 2. Illustration of the simulated attack replication scenario performing an exemplary multi-stage attack (Sen, Ömer et al., 2021): network scan (S1), RCE (S2), PE (S3), and data manipulation (S4).

the RTU components are equipped with vulnerabilities that allow non-legitimate remote control via attack vectors such as Remote Code Execution (RCE) and Privilege Escalation (PE). The concept of these vulnerabilities is based on providing simple running network services such as a web interface, SSH server, or Telnet service that allow executing commands on the computer system. After gaining remote access via RCE vulnerabilities, the Simulated Attacker Model (SAM) then attempts to escalate its privileges on the infiltrated, e.g., Linux-based, host systems by exploiting PE vulnerabilities such as set-user-ID (SUID) or a sudoers-enabled script that allows the execution of administrative commands without authentication.

For further illustration, the automatically executed phases of the attack process within the co-simulation are shown using terminal executions and the effects of the attack are shown by plotting the measurements across the simulation steps. In the first phase of the sequence, the SAM scans the SCADA network and identifies the connected device, e.g., a RTU on a secondary substation transformer with its open TCP ports indicating configured services such as SSH, Telnet, and Nginx web server. Based on the collected information, in the next phase, SAM executes a RCE over the identified vulnerable web interface on port 80 equipped with a command execution script by specifying the command 'whoami' as a parameter, which issues the executing user 'www-data'. Since the user 'wwwdata' has no administrative privileges, the SAM extends its privileges through PE by exploiting a found SUID vulnerability. In the final phase, the SAM manipulates the measured load, active and reactive power data from the secondary substation and transmits it to the MTU. This demonstration illustrates the capabilities of SAM to manipulate process data remotely. With intelligent manipulation strategies based on False Data Injection (FDI) techniques (Sayghe, Ali et al., 2020), SAM could even disrupt grid operations over the long term.



Fig. 3. Exemplary results of operational management strategies in the SG Laboratory.(Hacker, Immanuel et al., 2021)

4.2 Testing of Operational Management Concepts

One of the biggest challenges of future active distribution grids is coordinating behind-the-meter flexibility. This is all flexibility on the customer premise like heat pumps, electric cars, and battery storage systems. Our work on operational flexibility mainly focuses on multi-use strategies and the cyber-resilience of these connected systems. Different stakeholders are interested in using this operational flexibility, mainly the owner of the asset who wants to use the primary purpose with minimal costs, the DSO who wants to optimize the grid operation, and market actors like Virtual Power Plant (VPP) who want to monetize the flexibility. The goal of multi-use strategies is to find an optimal solution to balance the interests of the different stakeholders. These systems require a high degree of networking, so cyber-resilience is essential. Energy Management System (EMS) are at the core of this concept, they implement the optimization logic and take over the control of the assets and the communication with external platforms. In (Hacker, Immanuel et al., 2021) we showed how the development of EMS logic could take place in a digital twin and then be transferred to our laboratory grid.

Figure 3 shows the results of using different logic in the SG Laboratory integrated by the VED (cf. Section 3.2). In addition to the modular exchange of the connection with the assets, coordination platforms can also be abstracted, or prototypes of real platforms can be used. This allows the future analysis of the cyber-resilience of different IT-Architectures.

5. CONCLUSION

In this paper, we present our co-simulation environment used for the investigation of domain-specific use cases such as cybersecurity and SG operation concepts. Our proposed modular approach is used for simulative evaluation and evaluation in our SG Laboratory. This allows adjusting the level of abstraction of all components depending on the use cases. We have shown that the environment can be used productively for both of the use cases presented. Regarding attack replication, we have shown how we can perform manipulations of data traffic. In future works, we can use this to generate attack data that can be used to develop countermeasures such as intrusion detection. In addition, we have also shown how we can integrate operational management concepts for controlling decentralized flexibilities into the environment. For us, this forms the basis for further developments in the area of multi-use strategies and the cyber-resilience of such networked systems.

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