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Integrating Agent-Based Control for Normal Operation in Interconnected Power and Communication Systems Simulation

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***Abstract*—Power grids must be stable and reliable, but the growing importance of intelligent control in smart grids creates new challenges due to the increasing dependence on communication networks. This paper investigates the influence of communication on power systems in a future scenario. The simulation environment contains a power grid of a medium-sized city in northwest Germany, in the year 2035, where the normal operation of the power system is disturbed by increased communication traffic. The power and communication networks are integrated into a co-simulation environment, that implements smart grid services in an agent-based control structure. In a case study, multiple scenarios are compared that differ in the configuration of the communication network, to show how the simulation environment can be used to study the interactions between power and communication networks.**

***Index Terms*—smart grids, information and communication technology, simulation, agent-based control, COHDA**

I. INTRODUCTION

Changes in the context of the energy transition create new requirements for the operation of existing power grids. Integrating generators at lower voltage levels requires advanced control mechanisms [1]. In contrast to centralized power generation, small generators produce energy at many different locations and are not necessarily close to large consumers like industry or densely populated areas. Consumers are becoming prosumers, generating power with for example photovoltaic (PV) systems [2]. In the case of power grid congestion, a redispatch request is made by the grid operator, to avoid bottlenecks. By adjusting active power feed-in, the total feed-in remains unchanged, relieving the power grid at certain points. Increased integration of decentralized generation systems like PV systems in low-voltage ranges utilizes the available voltage band, increasing the probability of exceeding or undershooting permissible voltage [3]. Low-voltage power grids must be planned for sufficient generation plants, necessitating costly reinforcement measures [4]. As a result, small generators and consumers will be held more accountable for grid stability. To abstract from specific applications like redispatch, we introduce the term ”Smart Grid Service (SGS)”. SGS serves as an umbrella term encompassing various applications in power systems that rely on communication and impose requirements on the communication system. With respect to SGSs, an important challenge in maintaining a smart grid is that the communications network has to be designed for critical infrastructure like a reliable power supply [5]. Dedicated communication networks, such as the planned Long Term Evolution 450 (LTE450) technology are used, to implement such a system [5]. LTE450 is a variation of the common LTE technology but operates at a frequency of 450 MHz, allowing better obstacle penetration and long-range communication [5]. Furthermore, through the expansion of the power and communication networks, disturbances like slowdowns through traffic generation, in the operation of the communication network must also be considered, as a failure in communication can generate significant consequences for the power grid [6]. The characteristics and behavior of the underlying communication system (including communication network topology, protocols, communication latency, bandwidth, information security, and reliability issues) influence the connected power system [7]. Because of this dependency, failures in the communication system can also lead to misbehavior in the power system, thus jeopardizing the reliable operation of a smart grid [7]. Agent-based control structures provide a promising solution for power grid management in the energy transition [8], enabling dynamic redispatch strategies to optimize power feed-in and ensure grid stability amidst evolving generation and consumption patterns.

The objective of this paper is to investigate the dependencies between communication and power systems in a suitable power and communication network scenario under an increased network load. For that we use the communication network simulator OMNeT++ [9], the power system simulator pandapower [10], and various individual simulators integrated in a co-simulation with mosaik [11]. The paper is structured as follows. We first give an overview of related works. Subsequently, we describe the scenario, going more into detail on the implementation of the SGSs, as well as the simulation of the power and communication network. Next, we present a case study, where we evaluate the influence of communication traffic on the power system in the proposed simulation environment. Finally, we present our results, then conclude by discussing them.

II. RELATED WORK

The interdependencies between power and communication system can be analyzed formally, e.g., regarding the effects of time delays on the performance of Cyber-Physical Energy System (CPES) [12], the effects of Information and Communications Technologies (ICT) infrastructure failures [13] or degradation of ICT-performance [14]. Another approach to analyzing these interdependencies is to use (co-)simulation, where a communication simulator is used to model a realistic network for static link latency determination [15], [16]. Several of the integrated power and communication system simulations are very limited in terms of scalability abilities (less than 15 hosts), which can be caused by integrated real-time components such as OPAL-RT [17], [18], the modeling complexity in power system simulators like DIgSILENT PowerFactory [19], [20] or PSLF/PSCAD2/EMTDC [21], [22] or network-in-the-loop simulations [20], [23]. Simulations using ns-3 for communication simulation, OpenDSS for power system simulation, and HELIX as a co-simulation framework address the grid scalability but lack performance due to fixed synchronization points [24]. Similarly, the communication simulator OMNeT++ can be integrated as a simulator for simulations with the co-simulation framework mosaik [25]. This coupling was able to simulate 50 interconnected hosts representing Distributed Energy Resource (DER) utilizing discrete-event simulation capabilities of mosaik and OMNeT++. So far, no power grid simulation has been integrated or investigated yet. To sum up, various approaches exist for conducting a combined communication and power system analysis. Most integrated co-simulation approaches are often applied to small networks or lack the integration of a power system simulation.

ICT scenarios are modeled in various forms. For the Cigre-MV grid, an ethernet-based ICT system can be modeled with adjusted link bitrates [26]. For wireless ICT systems, (pseudo-) dedicated networks like LTE-A or CDMA450 can be modeled by locating base stations regarding the communication range [15] or by geospatial relations based on public data for public cellular networks like GSM, UMTS, and LTE [27] or arbitrary for 5G networks [28]. To our knowledge, there are no approaches that address the modeling of LTE450 networks for distribution networks.

The robustness of Multi-Agent System (MAS)-based SGSs can be analyzed regarding degraded communication performance. SGSs, such as power grid restoration [16], power demand and supply [29], or fault location [30] can be studied towards communication impairments like delay or packet loss. The MAS-based optimization of operational schedules for ancillary services was analyzed regarding base-station failures, jammer and increased traffic [15]. However, those mentioned robustness analyses are focussing only on one SGS. Multiple SGSs with agent-based control can be considered under Quality of Service (QoS) like a required maximum latency. This has yet only been done in a small network [20], [26] or on a formal level [31].

Overall, none of the above approaches considers a complete integration of communication and power system simulation, including the possibility of using LTE450 while considering multiple agent-based SGSs and allowing for investigating impacts from communication on the power system.

III. SCENARIO DESCRIPTION

In the simulation environment presented here, the communication network is modeled using OMNeT++ [9], the power system is modeled in pandapower [10] and these and other simulators are integrated in the co-simulation framework mosaik [11]. The northern German city of Bremerhaven was depicted as a model in a future scenario for the year 2035. Bremerhaven was used because another research group already built its energy grid model on top of mosaik [32]. The power grid model has been presented by Veith et al. [33]; however, the conventional power plants were replaced by wind parks to consider only renewable energy sources [32]. In the power grid modeling, a large number of heterogeneous grid participants were represented at different grid levels, such as PV systems and household loads at the low-voltage level and industrial loads at the medium-voltage level. However, the research emphasis lies on the investigation of the interactions between the power grid and the communication network on the low-voltage level, since an increasing number of intelligent control units can be expected here due to the anticipated integration of decentralized generation units in 2035. The simulators implemented in the mosaik framework reflect the loads and supplies imposed on the power grid by households and larger power producers based on real data. The household loads and generators are controlled by a MAS in which frequent communication is required to enable real-time monitoring of, e.g., load levels or supply-demand imbalances as well as control through prompt adjustments and interventions necessary to ensure reliable operation of the power grid. Decentralized agent-based approaches are increasingly being proposed for applications in modern power grids, such as controlling load flows, dealing with overloads, or ensuring voltage stability [20]. According to Dehghanpour et al. [8] the idea is that agents in a MAS can evaluate their local situation, determine a local best solution to a problem given by the agents' goals, and communicate the intended action to their neighbors. In that way, the agents may represent the objectives of the individual assets. In addition, such a structure offers the advantage of reacting dynamically to error cases and controlling the plants through the agents.

Therefore, the simulation of the communication network using the technology LTE450 is integrated by using cosima, which extends mosaik by integrating the communication simulator OMNet++ into mosaik. This allows for the analysis of the occurring traffic regarding the agents' behaviour. As the main objective of the conducted simulations in the described simulation environment was the investigation of the influence of non-perfect communication (section III-C) on agent behavior in the power system in case of voltage control and redispatch (optimization of power generation and distribution to ensure grid stability and meet demand, see section III-A), increased

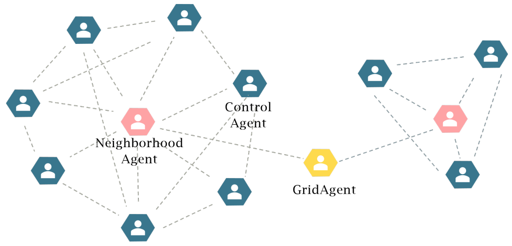

Fig. 1. Agent-based control structure

network traffic in the communication network was modeled by integrating it into the network in OMNeT++. This type of non-ideal communication, exemplified by the choice of traffic (as many SGS have time-critical requirements [15]), was deliberately selected as an example.

A. Implementation of the SGSs

In this project, centralized approaches were combined with decentralized approaches. Figure 1 shows an overview of the system, including the different types of agents. Local asset agents, the so-called `ControlAgents`, represent a set of generators and consumers, such as a household with a PV plant. Schedules generated by the connected simulators represent the flexibility of the assets in a simplified way. The `ControlAgent` can adapt the choice of schedules of its assets. As a central entity, the `NeighborhoodAgent` represents and coordinates a neighborhood. Neighborhoods are used as a construct to coordinate a set of `ControlAgents` in the federation. The `GridAgent` assumes the coordination of several `NeighborhoodAgents` and is thus, for example, in the role of a grid operator. This agent-based control structure allows decentralized control of distributed energy assets in various SGSs in modern power grids, such as voltage control on the low voltage level and the integration of small-scale power plants into the redispatch process, by enabling autonomous agents to make individual decisions based on local information for achieving the desired objectives collectively. According to the definition of the German Federal Network Agency [34], the term *redispatch* refers to interventions in the generation output of power plants to protect line sections from overload, whereby the latest, future version will also include small plants at household level in the processes.

The two SGSs were modeled in a simplified way in the simulation environment described here to be able to evaluate a source of agent communication and its impact on the power grid in the scenario.

1) Voltage control: In a research project conducted in the period from 2010 to 2013 [4] system concepts for the implementation of (intelligent) voltage control at low voltage levels were presented. The implementation chosen here is based on the system concept *Intelligent substation* (free translation from German). The principle involves reducing the active power of distributed plants to induce a deliberate voltage drop along the line. The communication between the distributed generation units and the control and operation management unit further expands this level of control. The transmitted measuring points are utilized to gather information regarding the current state of the network. Fig. 2 shows the steps to realize the SGS. The process is as follows: (1) measured values such as the power and voltage at the facilities (2) are sent to the local grid station (represented by the `NeighborhoodAgent`) (3) and used for intelligent control by the `NeighborhoodAgent` checking the values for voltage band violation and (4) potentially requesting (5) and receiving grid information from the `GridAgent`, and then (6) sending control information to the `ControlAgents` so that they can (7) optimize the grid feed-in of their assets.

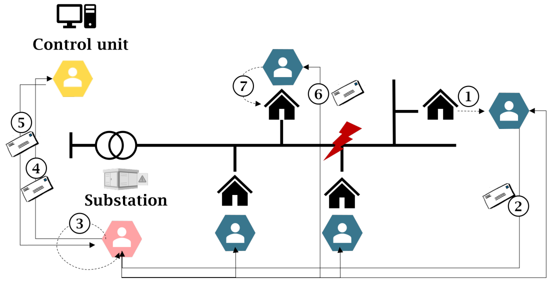

Fig. 2. Overview of steps in voltage control

2) Redispatch: Implementing the redispatch process with the integration of small-scale units, the so-called Redispatch 3.0, which is currently discussed [35], is also based on the agent-based control structure. Therefore, in this SGS implementation, the `GridAgent` sends the initial instruction regarding the intervention to adjust the power feed-in by the (simulated) (small-scale) plants to the `NeighborhoodAgent`. The agent triggers a decentralized optimization of the feed-in by its `ControlAgents` in the neighborhood using the Combinatorial Optimization Heuristic for Distributed Agents (COHDA).

According to [36] COHDA is a fully distributed scheduling heuristic, where both the global objective as well as arbitrary individual local objectives of the agents can be represented. In COHDA each agent searches in its search space, constrained by local constraints, for the partial solution that satisfies the global optimization objective, considering all other plants involved. The resulting aggregated schedule represents an agreement among all plants [36]. In COHDA, information is disseminated via message exchange between agents in a MAS, resulting in asynchronous communication in the simulated environment [36]. The goal of the distributed optimization is to minimize the error between the agents' aggregated schedules and the active power product, which is to be achieved by performing the redispatch.

B. Simulation of the power grid

The publicly available power grid model from the midas repository [32] is the basis for modeling in pandapower [10]. It includes a high voltage (110 kV) and medium voltage (20 kV), as well as a low voltage (0.4 kV) network modeled via aggregated endpoints in the city of Bremerhaven in Germany.

The modeled low-voltage sections include houses in three low-voltage strings and are connected via two substations to the medium-voltage grid. The houses are represented as loads in pandapower [10]. The positions for each house were estimated based on OpenStreetMap [37] data as a basis for the wiring in the low-voltage network. It is assumed that the modeled households have different sizes and types of energy units. To be able to represent this, simulators with different configurations in terms of loads and generators are connected to each other. Therefore, in addition to the household simulator, each household can have further simulators such as a PV system, wallbox (Electric Vehicle (EV) simulator), energy storage and a heat pump. For the household simulator, a data set with 74 high-resolution and representative household load profiles of single-family homes in Germany is used [38]. Based on the measured global radiation from the German Weather Service in Bremerhaven, the energy yield from the calculated roof area of the households is simplified. The storage was modelled in a simplified way and integrated with the help of a given charging/ discharging power, the internal capacity as well as the current State Of Charge (SOC). The EV simulator is quite similar, only the charging rate is limited by 22 kW for a wall box and no discharging is possible at the moment. Based on the configurable annual energy requirement of a household in kWh (130 kWh per square meter [39]), a load profile for the required heat output for the heat pump is calculated based on standard heat profiles [40]. This heat output is converted to the required electrical output using a configurable conversion factor Coefficient of Performance (COP). With the help of stored profiles, corresponding alternative schedules are provided to shift electrical demands as needed.

C. Simulation of the communication network

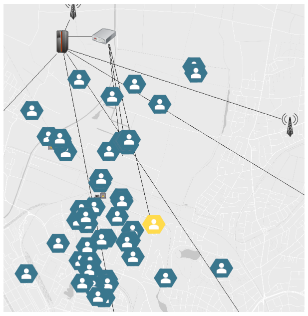

Fig. 3. Part of the modelled communication network

The modeling of the communication network is based on the coupling of the (communication) system simulator OMNeT++ [9] to the co-simulation framework mosaik using cosima [25]. Through cosima, it is specified that all communicating simulators (the agents in this scenario) in mosaik are interconnected by a communication simulator and represented by modeled end devices in OMNeT++. The communication between the simulators in mosaik is then simulated in OMNeT++ to be able to represent the communication parameters such as the message delay.

The LTE450 communication technology was modeled in OMNeT++ using the Simu5G library, in which models for LTE are also available in addition to those for 5G [41]. Six antennas are modeled roughly based on real existing and future locations so that the entire network area of Bremerhaven is covered. To make the simulation as realistic as possible, the tallest buildings were also modeled as obstacles to represent shielding effects. The parameter assignments used to adapt the modeling to LTE450 technology can be found in Table III-C.

Parameter	Value
channel control - carrier frequency	450 MHz
channel control - signal attenuation threshold	20 dBm
channel control - path loss coefficient	40
channel control - num channels	4
channel control - propagation model	RayleighModel
user equipment - tx power	100
user equipment - antenna gain	0
eNodeB - tx power	100
eNodeB - antenna gain	2.15

1) Traffic to mimic state estimation: As motivated before, the influence of non-ideal communication on SGSs in the power system will be investigated exemplary utilizing increased communication traffic in the modeled communication network. For this purpose, it is assumed that a set of secondary substations also act as communication participants and send monitoring information to mimic state estimation behavior during the simulation. With cosima, additional communication traffic can be configured in the co-simulation in mosaik so that corresponding packets are sent in the simulated network in OMNeT++ in addition to the actual information exchange. In this way, it is possible to investigate the impact of increased network utilization on the SGS described earlier in Section III-A. The additional traffic in this scenario was configured in a way that ten modeled secondary substations send packets of 1000 bytes to five different `ControlAgents` each at an interval of one second. The configuration of the additional network traffic here is chosen rather arbitrarily in such a way that effects on the simulation can be seen, but there is no severe disruption of the network.

IV. CASE STUDY ON THE INFLUENCE OF COMMUNICATION TRAFFIC ON POWER SYSTEM USE CASES

A case study was carried out as an exemplary scenario in the simulation environment described in Section III. The simulation environment allows the combined analysis of the communication and the power grid, and thus the investigation of non-perfect communication on metrics such as the execution time of SGSs in the power grid. The case study can be seen as an example of an application of the simulation environment, and it can be adapted by the user for various purposes.

All simulated scenarios consist of the execution of a negotiation for the provision of a redispatch product with 20 agents, which starts immediately at the beginning of the simulation and a one-time execution of the process of intelligent voltage control at the low-voltage level, which is executed after one minute of simulation time. The total simulation duration is two minutes, as this is the time span in which the communication

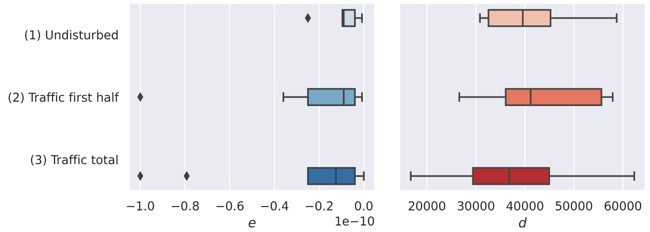

Fig. 4. Comparison of the negotiation metrics in different communication scenarios

arising from the two SGSs can be observed.

Three scenarios are carried out with 20 repetitions each and by means of these, the above-mentioned mutual influences between the power and communications network are investigated. The three scenarios consist of examining (1) a scenario with undisturbed communication, (2) a scenario with communication affected by additional network traffic in the first half (first half assumed simplified with 15.9 seconds) of the redispatch negotiation, and (3) a scenario with communication affected by additional network traffic throughout the entire redispatch negotiation. The exact configuration of the network traffic can be found in the previous section III. In the following, the negotiation duration d and the MSE e of the final solution candidate in the negotiation for redispatch are investigated. The mean percentage reduction r in the feed-in power of the plants controlled by the agents through control commands during voltage control is examined.

Figure 4 shows the results regarding the redispatch negotiation. On the left side, the Mean Squared Error (MSE) between target and aggregated schedules is shown. The optimum is zero, i.e., the complete match of the aggregated schedules. It can be seen here that, especially in the scenario with traffic during the entire negotiation, on average the solution quality was worse regarding the median MSE between the target and the solution. Regarding the duration of negotiations, shown on the right, there is also an influence of communication traffic on the negotiation. On average, the negotiations in the traffic (first half) scenarios take longer than, for example, in the overall disturbed scenario.

The resulting schedules by the simulated plants are impacting the power grid simulation. Due to different solutions and negotiation durations in the different communication scenarios, the effects on the power grid also differ, which in turn can be seen in the following case of voltage control. Figure 5 illustrates the mean total feed-in power decrease per agent due to control commands. It can be seen that especially in the scenario with the worst solution quality regarding the median in the redispatch process, the strongest interventions in the feed-in power of the plants occur in voltage control. The simulation results may appear arbitrary due to the simplified implementation of the SGSs, but they also demonstrate the potential for simulating and analyzing interactions. This opens up practical applications such as designing energy information and communication systems, optimizing smart grid communication behavior, and advancing grid performance. These insights foster the development of more efficient and resilient operation of power systems.

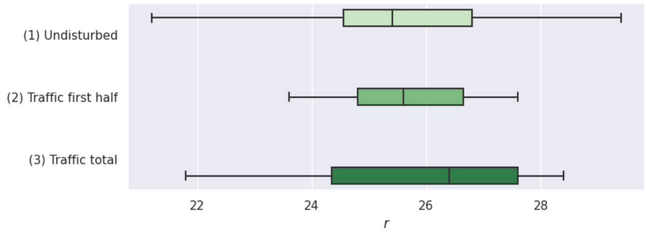

Fig. 5. Comparison of the decrease percentage in voltage control in different communication scenarios

	e	d	r
(1)	$-8.8 \times 10^{-12} \pm 7.48 \times 10^{-12}$	40050±7741	25.4±2.07
(2)	$-1.5 \times 10^{-11} \pm 2.17 \times 10^{-11}$	43410±10239	25.6 ± 1.11
(3)	$-2.3 \times 10^{-11} \pm 2.78 \times 10^{-11}$	38270±11356	26.4 ± 1.97

V. CONCLUSION

In this paper, a combined power and communication network simulation environment was presented, and three different scenarios were examined in a case study regarding the influence of increased communication traffic on the normal operation of the power grid. As exemplary SGSs of normal operation, redispatch, and voltage control have been modeled using an agent-based control structure. We were able to demonstrate in the case study that non-ideal communication influenced the agents' behavior and therefore the operation of the power grid.

In conclusion, the proposed simulation environment with combined communication and power grid simulation based on a real-world system allows the investigation of the effects of communication on the power grid. The scenario presented here represents a starting point for future work, in which additional communication disturbances and technologies can be evaluated regarding the simulated power grid. Furthermore, the simulation environment can be extended to investigate the effects of power grid disturbances on the communication network and further SGSs can be implemented to analyze mutual interdependence. Especially for agent-based control in the power grid, different heuristics may also be implemented to study the influences of communication parameters such as message delay and packet loss on the heuristics' performance indicators.

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CODE AVAILABILITY

The simulation code can be found on the cosima website: https://cosima.offis.de/pages/publications.

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