Integration of Simulations and MAS for Smart Grid Management Systems

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ABSTRACT

In this paper we describe the ILIas framework for development and testing of smart grid simulations and management systems. The framework consists of a simulation environment, an agent based management system, a monitoring tool for human operators, and a physical testbed for testing the management system and its effects on communication networks. The advantage of this approach is that the management system can be tested and optimized with the simulation environment and the simulations can be later used by the management system in order to make forecasts about the behavior of the electricity grid.

Categories and Subject Descriptors

H.4 [**Information Systems Applications**]: Miscellaneous

General Terms

Management, Experimentation

Keywords

Agents, Smart Grid, Simulation

1. INTRODUCTION

Most of today's power grid infrastructure has been in use for decades. The networks and management infrastructures of the grid have grown and evolved over the years, driven by both, technology and expansions. As a result, the current infrastructure is very heterogeneous in both, structure and technology. However, the ways in which the power grid is used are changing drastically. Renewable energy sources add many small scale producers which are distributed all over the networks. The production capacities of these producers vary depending on weather, thus putting more strain on the network.

The changes have already begun. For instance, the amount of renewable energy rose form 4% in 1996 to 20% in 2011, from which 8% are wind energy and 3% photo-voltaic [3]. However, the amount of energy that is produced varies considerably depending on weather, i.e. wind and sunlight. Additionally, if you take Germany as an example, the production of wind energy is located in the northern regions, while most of the demand by industry concentrates on the southern parts. Thus, the changes in production from wind energy also put a large strain on the transport networks that run across the country.

At the same time, the increasing prevalence of smart meters, time dependent tariffs, and electric vehicles introduces entirely new types of consumers, which not only increase the total demand but may also make existing consumption profiles obsolete. And last but not least, the construction work that will be required for the changes and increasingly necessary renovation of the grids will result in frequent and dynamic changes in topologies. Overall, the technical demands on the network as well as the complexity of the energy market will increase dramatically in the coming years. However, at the same time these changes represent a potentially huge market for the electronics industry [22].

All of these changes pose difficult challenges for both, the hardware of networks and producers, and for the software and personnel that manage the grid. Especially, the management will require more support and automation by software systems, in order to allow the human operators to concentrate on the important issues. This software needs to support the transition of the grid infrastructure to new hardware as well as the changing and dynamic demands of the new producers and consumers.

We envision the management of the future electricity grids to be a decentralized system that is able to operate within local subgrids and at the same time coordinate energy exchange between multiple such subgrids. The system has the capabilities to decide about changes in grid autonomously and is supervised by human operators. Furthermore, such a system needs to support lifecycle and management functions that are common with modern software systems, such as remote management, upgrades and modifications at runtime. The installation and activation of new functions and workflows are as important as stability and fault tolerance.

The foundation of the management systems needs to be software platform that allows continuous development. It has to be flexible and provide some basic attributes like distribution concepts, autonomous components, self-healing mechanisms and the ability to add new functionalities at runtime, among others. It needs to be able to interact with infrastructure simulations in order to allow the evaluation of new implementations prior to testbed or real life deployments. These simulations have to be able to reflect the complex and multifaceted interactions smart grids have to deal with, as these can only be marginally tested in real physical testbeds. The smart grid management systems have to behave similar in simulated and real environments. Such a system allows short development cycles, enabling faster integration of new management functionalities in order to keep up with the development of other smart grid components.

In the remainder of this paper, we will describe an approach to the development of such a system. The outstanding feature of our approach is the integration of the management system with a simulation environment for smart grids, which allows us the efficient testing and evaluation of management approaches and strategies. In Section 2 we give an overview over current research on smart grid simulations and smart grid management systems. Section 3 describes our simulation system (*NeSSi²*) and the management system called SmaGriM (**Sma**rt **Gri**d **M**anagement). Section 4 presents an example scenario that we have implemented and tested with both systems, followed by a conclusion in Section 5.

2. RELATED WORK

In this section we give an overview over current research on both, smart grid simulations and smart grid management systems. We start by analyzing existing approaches for smart grid simulation environments. In the next subsection, we give a brief overview over current research approaches on agent based grid management. The third part of this section analyzes whether approaches to combine agent based management systems and simulations exist.

2.1 Smart Grid Simulations

Simulating smart grids is a challenging task. As mentioned before, the most important point for smart grids is the enhancement of power networks with information and communication technology (ICT). This means, we need to consider power as well as communication networks for a simulation. For simulators, this is commonly realized with federation mechanisms, e.g. [13]. To stay synchronized with the simulation, SmaGriM should be able to join this federation, too. Therefore, we have analyzed existing tools based on this focus.

In 2009 Molderink *et al.* realized a simulation environment to analyze control algorithms for energy efficiency [16]. Therefore, they modeled micro-generators, energy buffers and appliances. They continued their work and published an extended version of their model in 2010 [1]. The simulator was written from the scratch and considered different resource streams like energy, heat or gas and the conversion between them. As they did not model a detailed grid, the effects of topology are neglected. But the biggest drawback is that neither implementation details nor source code are available.

In 2010 Bergmann *et al.* analyzed large scale aspects of ICT management frameworks in a smart grid environment [4]. Therefore, they coupled PSS/NETOMAC[1] with the network simulator ns-2. NETOMAC can be used to analyze the dynamics of power networks. It is a part of the commercial Power System Simulator (PSS) product suite from Siemens. The network simulator ns-2 is a well known simulation tool, heavily used for communication network analysis.

Also in 2010 Godfrey *et al.* analyzed how distributed storages behave in case of voltage drops of photovoltaic arrays caused by clouds [9]. They realized this with a co-simulation, i.e. they fed the output of one simulator into a second. This was done with the aforementioned ns-2 and the Open Distribution System Simulator (OpenDSS)[2]. Initially developed by EPRI but now available under an open source license, the tool allows simulations of distribution networks with a focus on the integration of distributed energy resources and grid modernization efforts.

In 2011 Sanches *et al.* developed a model for a remote measurement environment [20]. They focused on the agent aspect i.e. their environment was implemented according to the IEEE FIPA specifications. The underlying power network simulation is based on Brazilian consumption profiles. Unfortunately, neither implementation details nor source code are available.

Also in 2011, Chinnow *et al.* published a simulation environment for smart measuring scenarios[15]. It was used to analyze the stability of the power networks in case of incidents in the measuring infrastructure. The underlying simulator *NeSSi²* is open source and easy extensible to other smart grid scenarios. Additionally, the simulation environment uses agent technologies.

From the analyzed simulation environments, *NeSSi²* has the most advantages. It is available under an open source license, allows federated simulations and uses agent technology. Therefore, we used it as simulator for our experiments.

2.2 Agent-based Grid Management

The domain of electricity grid management has been very popular among agent researchers. In 2003, Jennings et al. described an agent-based decision support system that analyzes the state of the electric grid and generates recommendations for a human operator [14]. This system however only monitored the electricity grid but was unable to actually control it. An actual approach to control electricity grids was given in [11] by Hines et al. This work describes two approaches for the management of the transmission and distribution networks. The first approach tries to minimize cascading failures by applying intelligent load shedding strategies. The second approach tries to perform restoration within local distribution circuits.

Especially the second subject, the management of localized subgrids which potentially have local power generation, has been extensively evaluated in [17] and [10]. Both approaches describe a system that manages low voltage grids that have a high availability of distributed generators, and possibly *Vehicle to Grid electricity*. Saleem et al. state that this is a rather likely scenario in e.g. Denmark, as this country does already have a very decentralized electricity infrastructure. An interesting result of their work is that — given adequate management systems — such subgrids with local power generation can continue operation in islanding scenarios, i.e. when the power transmission from the transportation network is interrupted.

[1] http://www.energy.siemens.com/hq/de/services/stromuebertragung-verteilung/power-technologies-international/software-solutions/pss-netomac.htm

[2] http://sourceforge.net/projects/electricdss/

In [7], Catterson et al. analyze the potential that agent technology provides for future smart grid management systems. The authors focus especially on condition monitoring as a means to manage the electricity grid, but also give some interesting ideas about system architecture.

Another interesting work is that of Saleem et al. in [19, 18]. In this work they describe a system that is able to detect fault locations in electricity networks. The problem they address is that traditional methods for detecting a fault location in an electricity network assume, that the current flows only in one direction, i.e. from the power plant to the consumer. However, distributed power generators create multi-directional current flows and therefore the fault location is hard to detect.

In [20], Sanches et al. present a more practical approach for remote measurement of smart grid components with a multi-agent system. This approach shows the feasibility of collecting and aggregating smart grid data via agents. On a similar level, Wang et al. introduce an interesting approach to the management of micro-grids [24] for buildings or small areas.

As this overview over agent based grid management shows, the subject is approached from many different directions. However, what is clearly missing is an integrated approach for evaluating and optimizing management and control algorithms. Furthermore, we have not yet found an approach in which agents utilize a simulation environment at runtime in order to evaluate the future behavior of the smart grid.

2.3 Combining MAS and Simulations

Typical combinations of multi-agent systems (MAS) and simulations rely on agent based simulation environments, where agents execute simulations of different models. This approach is useful in applying helpful attributes of MAS (e.g. scalability, autonomy, etc.) in the often resource intensive and complex simulations to be realized. The herein presented approach relies on a slightly different concept. The MAS is not the basis for the simulation execution but a standalone MAS that is tested by interacting with a simulated environment. Similar approaches are used in e.g. robotics, where control components are trained in simulated environments and then transferred to real physical robots in a tested and trained state [2].

3. THE ILIAS FRAMEWORK

In this section we describe the concepts and components of the ILIas framework.[3] First we describe the simulation environment that is used for simulating the smart grid. Following that, we describe structure and operation of the management system. Finally we describe the integration of both systems and explain how the monitor for the human operator visualizes the operation of the management system.

3.1 Simulation Environment

We used the Network Security Simulator ($NeSSi^2$) as our simulation environment. The primary focus of the simulation tool was network security related scenarios in IP networks [21]. But it was also used to simulate DSL access networks based on flow models [6]. In this context, it was even extended to a decision support system [5]. Furthermore, in 2011 $NeSSi^2$ was used to realize a security analysis of a smart measuring scenario through a federated simulation [8].

We continued this federation approach and implemented a federate for mapping simulated entities to agents. Thereby, one agent knows the complete state of one power network entity e.g. voltage, voltage angle, real and reactive power. Additionally, an agent can issue commands to the simulator. A more detailed overview is given in the next section. By mapping the entity to a communication network, an agent can also access the functions of the telecommunication network simulation e.g. send and receive packets.

An other problem is that the simulation time differs from the wall-clock time. As the simulation time may run faster than the agents could communicate, i.e. one hour in one second, we had to synchronize it with the agent system. Therefore, we stopped the time advance in the simulator until we received feedback from all agents. This could be either a steering command or just an acknowledgement.

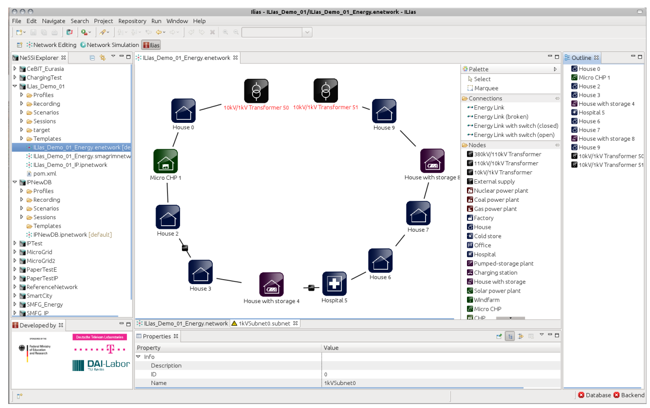

Figure 1: Screenshot of the $NeSSi^2$ GUI

Figure 1 shows the graphical user interface of $NeSSi^2$. It can be used to create and modify network topologies and specify the behavior of network elements. It is further used to define the mapping of network elements and therefore also the agents. After the creation of a scenario, a simulation can be started.

3.2 Agent-based Smart Grid Management

Our approach to smart grid management is based on an agent based solution. In order to implement that solution, we used the JIAC V framework [12]. JIAC V features a flexible communication approach, this allows the agents to employ various communication patterns such as simple messages, services, or protocols. Furthermore, JIAC V agents can be based on different agent models, such as simple reactive agents or BDI agents. This allowed us to efficiently engineer the smart grid management system according to the needs of the domain.

The design objectives of the SmaGriM system were to create a flexible and robust control system for the management of smart grids. In detail this includes:

- Observation and aggregation of information about the current state of the network.
- Detection of failures and overstressing, including fore-

[3] The full name of the project is: "Intelligent Solutions for Protecting Interdependent Critical Infrastructures"

casts on the behavior of the smart grid based on common consumer profiles.

- Management and control of the smart grid infrastructure, preferably after consulting the human operator of the network — but also autonomously if necessary.

- Focus on stability and fault tolerance, especially in connection with the projects main objective of handling interaction between electricity and telecommunication networks in case of a failure.

In order to satisfy the last requirement, we settled for a hierarchical approach in the control and communication flow of the SmaGriM system. Our analysis of the topology of the electricity grid showed that a local subnetwork is typically build as a loop, that contains two or more transformation substations (in order to provide redundancy). The transformation substations are together responsible for the supply of the subnetwork and can do so interchangeably. However, in order to avoid the occurrence of unnecessary impedance, the loop is usually open. Thus each substation supplies only one part of the loop at any given moment.

As a result, we can assign each node in the smart grid, i.e. each consumer, producer, storage, or other device, to exactly one transformation substation at any given time. Consequently, the node sends its current data about voltage, power flow, and status to all substations within its local subgrid (typically only two substations), but only the nearest substation that is currently connected is responsible for the control of the node. Should the setup of the subgrid change, i.e. the node is being switched so that it is connected to the second substation in the subgrid, the second substation becomes responsible. But as it already received all past data about the node, it can easily adopt that control.

This approach allows our SmaGriM system to operate on a local level. For example, in case of an islanding scenario, or if communication with the operator is interrupted, the local substation agents can control their subgrids independently and try to ensure the supply of their local consumers with any means available. Given the current trend of installing local capacity in the form of photovoltaic and wind energy producers, such scenarios are feasible in the future, and need to be covered by a management infrastructure.

On a wider scope, the substations that are responsible for the local subgrids may negotiate about their current and expected power loads, and either provide surplus capacity to other subgrids or satisfy their shortage with their power. With this approach, the SmaGriM system can also cope with islanding scenarios, in which multiple subgrids are disconnected from the main power supply network.

Based on this general structure, the SmaGriM system currently consists of two types of agents: Simple reactive agents on the device nodes of the network and more capable agents on the transformation substations which are responsible for managing the network.

All nodes in the smart grid are controlled by the simple reactive agents that monitor their node, forward the information about the node to the responsible transformer agents, and provide a set of services that allow the management of the node. The services currently available are:

- Shed / unshed the node: The node can be disconnected from the power grid if the stability of the power grid is in danger. This is a standard procedure in electricity networks.

- Turn switches on / off: Typically, all power lines in the networks can be activated or deactivated via switches. A node agent can control all switches on lines connected to its node.

- Increase / decrease Production: For producers, the agent can control how much energy the producers are allowed to inject into the network.

- Store / consume stored energy: For nodes which are able to store electric energy (e.g. capacitors), the agent can control if energy is stored or injected into the grid.

All these operations are available as services for the agents on the transformation substation agents. These substation agents analyze the state of their subgrid and determine which actions are necessary. In order to do this, they use an exchangeable evaluation function that calculates the current state of the network, and can also be used to determine the effect of changes on the network. Currently we use a simple function for testing purposes that allocates points for active nodes, active prioritized nodes (such as hospitals or industry consumers), surplus capacity of producers, and stored energy in capacitors. However, in the first stage of the project we focused more on the general operation of the SmaGriM system. This, the mechanism for the integration and invocation of an evaluation function is in place and has been tested with some simple functions. In our future work we will determine a set of suitable evaluation functions for different applications.

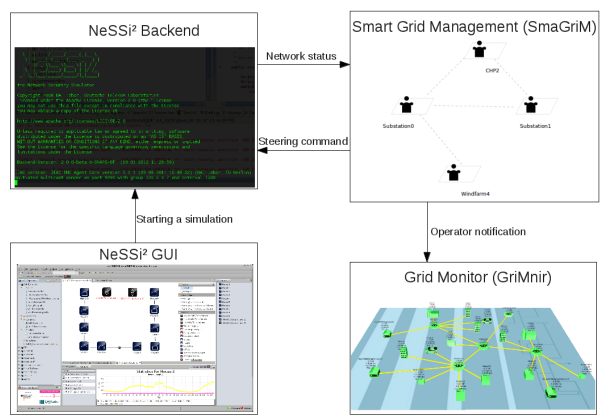

Figure 2: Overview over the ILIas framework.

Furthermore, the substation agents are able to negotiate with other substation agents for power. This can happen via service calls or with the help of negotiation protocols. In order to enable flexible and dynamic negotiations, we rely on the ability of the JIAC V framework to dynamically deploy services into an agent at runtime. An operator or system administrator will be able to model and exchange the strategies and algorithms that control the substation and thus influence the operation of the smart grid.

3.3 ILIas System Integration

In order to cover all aspects of the project, the complete ILIas system consists of four different components as can be seen in Figure 2.

These components are:

- The *NeSSi*^{2} GUI, which enables the modeling of electricity networks and simulations, including the behavior of the individual nodes.
- The *NeSSi*^{2} backend, which allows the execution of simulations. These may either be coupled with the SmaGriM system, or run standalone for simple evaluation of the electricity network.
- The actual SmaGriM management system, which can be coupled with a simulation or run with real smart grid devices.
- A monitoring tool named GriMnir (Grid Monitor) that supports a human operator.

If the SmaGriM system is used together with the simulation environment, the agents of SmaGriM have special connectors that interact with the *NeSSi*^{2} backend and have *NeSSi*^{2} simulate each device of the smart grid individually. Thus the SmaGriM agents are able to retrieve data from the simulation and issue commands as if the devices in the simulation were real. Each device is handled by a dedicated component in the *NeSSi*^{2} backend that handles the communication with SmaGriM and interacts with the simulation.

The advantage of this approach is, that the devices of the agents can be exchanged at any time, without affecting the performance of the agents. An example of this are the device wrappers for our physical testbed. In this testbed we can use the power information of network equipment and notebooks in order to evaluate the power consumption behavior of communication networks.

Another result of the ILIas project is the ability of the SmaGriM system to deploy so called *online simulations* at runtime. For this, the SmaGriM system has a special agent that is able to generate and deploy new simulations for an existing network. These online simulations have no special events such as disasters or other unexpected failures — they just simulate the behavior of the given network in the future, using standard profiles for consumers and producers. The results of the simulation are stored in a database and the SmaGriM simulation agent evaluates them afterwards. This allows the SmaGriM system to forecast the behavior of the electricity grid in the near future. The results of this forecast can be used for example to optimize energy storage and production, or to switch of consumers preemptively in order to avoid hard shedding.

In order to support the operator in monitoring the network and making decisions, we developed a monitoring tool called *GriMnir* for our smart grid management system based on the multi-agent system monitor ASGARD [23]. This monitor is able to visualize the state of the electricity network and allows the human operator to review and acknowledge the decisions of the SmaGriM system. All agents in the SmaGriM system can create notifications and warnings for the operator which are send to the responsible substations. The monitor can listen to those messages and show them to the operator as necessary. Furthermore, the current evaluation of the managed smart grid, as well as all decisions by the system, are visualized on the monitor in order to provide the operator with a complete overview.

4. EXAMPLE SCENARIO

In order to test and demonstrate the performance of the SmaGriM system, we implemented an example scenario. This scenario, which is depicted in Figure 3, consists of one power plant, one connection to the regional transport network, and five subgrids, each with 2 transformation substations.

In total, there are 50 consumers distributed over the 5 subgrids, some of which have the ability to store surplus energy or can act as local producers. Furthermore, two of the consumers are classified as prioritized consumers, e.g. hospitals, which should be kept online as long as possible.

During the course of the simulation, the behavior of the consumers is simulated over the course of approximately twelve hours according to commonly used energy consumption profiles. The gas power plant and the wide area transportation network provide enough energy for the operation of the grid and thus the power network is stable. The SmaGriM system collects the information from all nodes and the substations evaluate the state and forward the evaluation to the GriMnir monitor.

In order to test the management system, we introduced power failures on the wide area transportation network. This results in a shortage of energy in the simulated grid shown in Figure 4. Consequently, we let the simulation perform the automatic shedding that is used in today's electricity grids. Afterwards, the SmaGriM system detects that there is an energy shortage and that some nodes have been shed. SmaGriM analyzes the situation and tries to reorganize the grid in order to maximize its utility function. The result from this is that some low priority consumers are disconnected and the prioritized consumers are reconnected, utilizing the power from the local power plant as can be seen in Figure 5. When the connection to the transportation network is reestablished, SmaGriM detects that more energy is available and reconnects all nodes of the simulated grid.

Our proof of concept scenario showed that both, the *NeSSi*^{2} simulator and the SmaGriM management system perform as expected. The simulation environment is able to simulate a smart grid with all necessary parameters and can generate additional events that allow the simulation of extended scenarios. The management system on the other hand is able to use the simulation data for monitoring and control of the network. It is able to make intelligent decisions based on the evaluation function that is used and is able to execute these decisions.

5. CONCLUSIONS

In this paper we present the ILIas framework that combines a powerful and flexible simulation environment with an agent based smart grid management system. The advantages of this approach are threefold:

- The grid management system can be evaluated within various scenarios in a very efficient manner.
- The devices that the grid management system would connect to can be exchanged with simulated components without any changes on the actual management system, thus giving a clearer picture of the systems performance.

Figure 3: Overview of the demonstration scenario as shown by the GriMnir tool. Green nodes are operating normal. The nodes with the grey pedestals are prioritized consumers.

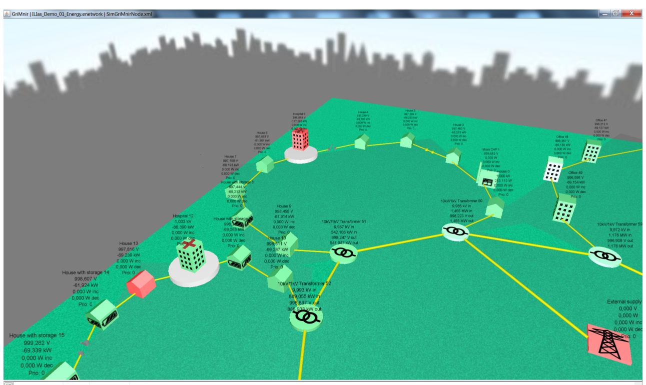

Figure 4: Power failure as shown by the monitoring tool. The red nodes are disconnected and have no electricity.

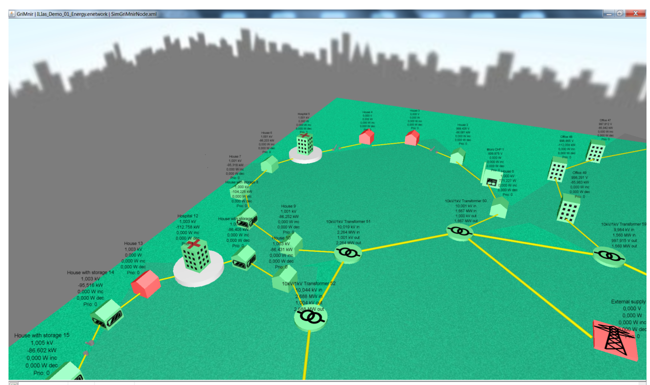

Figure 5: The network after SmaGriM has reorganized the consumers. The prioritized consumer at the top is reconnected and has enough power again. The two nodes to its right have been disconnected by the smart grid system in order to free the electricity for the prioritized consumer.

- Due to the close integration of the two systems, the management system can use the simulation environment to make forecasts about the electricity networks behavior.

In the related work section, we analyzed various approaches to both, smart grid simulation and smart grid management. Our system uses aspects from both fields, but the combination of the two approaches is something we have not yet found in current research. Therefore we deem our approach a useful next step in the development of agent based management systems.

In Section 4 we describe a first scenario we have implemented as a show case for the CeBIT 2012. In this scenario, all parts of the system, i.e. the simulation environment, the management system and the monitor have performed well. Our future work will be dedicated to creating more simulation scenarios and testing different evaluation functions for optimization of the management system.

Acknowledgments

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