AN INNOVATIVE SOFTWARE PLATFORM FOR SIMULATION AND OPTIMIZATION OF ACTIVE DISTRIBUTION GRIDS FOR DSOS AND SMARTGRID RESEARCHERS

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ABSTRACT

In this paper, we present the novel simulation platform DPG.sim (Distributed Prosumer and Grid Simulation). We propose a time-series-based simulation framework for active distribution grids comprising SmartGrid elements. In particular, we focus on the integration of large amounts of Distributed Generation from intermittent Renewable Energy Sources, dynamic Demand Response schemes, energy storage, SmartMetering, and telemetry equipment for communicating with distributed units in the field. The simulation software is server-based and can be accessed through a web browser. The simulation constitutes a valuable basis for the development of SmartGrid operation strategies and the integration of SmartGrid infrastructure into grid planning decisions.

INTRODUCTION

The high growth of renewable energy sources (RES) and the continuously increasing electricity trading volumes tend to push electricity grids towards their boundaries. Up to now, distribution grids were designed such that neither the maximum power generation nor the maximum power consumption leads to an overload of the grid or to a violation of allowed voltage levels [1]. However, with growing intermittent power generation based on RES, accommodating all possible peak events – regardless of their frequency and duration of occurrence – would require a highly over-dimensioned grid [2]. Hence, it is questionable if the currently applied worst-case grid design is suitable for future power systems with high RES penetration.

An efficient grid dimensioning can be achieved by various options which are discussed in the context of *SmartGrids*. Decentralized energy storage, dynamic Demand Response, and controlling the power factor (cos φ) of Distributed Generation (DG) help to reduce grid load. Moreover, a temporary curtailment of wind and PV generation can mitigate short-term congestions and allows the realization of economic trade-offs between required grid extensions and complete usage of in-feeds provided by RES. *SmartMetering* enables energy measurements with a high temporal and spatial resolution. Furthermore, it provides communication interfaces to individual customers which can be used to realize a variety of Demand Response methods.

In order to identify these optimization potentials and to realize them in future grid designs, appropriate new software tools are required. Currently available tools for grid simulation are usually restricted to the analysis of dynamic processes on the order of seconds and to the simulation of individual generation and consumption scenarios denoted as snapshots. However, the analysis of such snapshots is not suitable for modeling the temporal behavior of RES energy generation and RES forecasts combined with the temporal evolution of storage states, temperatures of flexible thermal loads, and control actions. In order to precisely quantify the pros and cons of innovative operation strategies including SmartGrid infrastructure, an accurate simulation of such strategies is indispensable.

Consequently, the main motivation for this work is the *current lack of industry-grade simulation, analysis, and optimization software for SmartGrids*. Although many research projects result in the development of novel methods for SmartGrids and *Active Distribution Network Management*, industrial practice is still lagging behind. Therefore, we are developing innovative software in order to facilitate the practical application of such methods. The software will be brought to the market by the ETH Zurich spin-off *Adaptricity* [3].

MODELING OF PROSUMERS

The proposed solution *DPG.sim* allows the simulation of SmartGrid features in distribution grids and their detailed analysis. The approach is based on a mathematical representation of so-called active *prosumers* in the grid. According to the widely accepted definition, prosumers are characterized by the fact that they can both be *pro*ducers and con*sumers* of electrical power.

In our software, the following models can be assigned to prosumer objects:

- Static and dynamic models of generation, load, and storage units,
- Associated parameter sets, including the possibility to generate them from probability distributions, and associated time series that describe use processes or sources of energy,
- SmartMeter models with various options for measuring electrical quantities on the customer level,
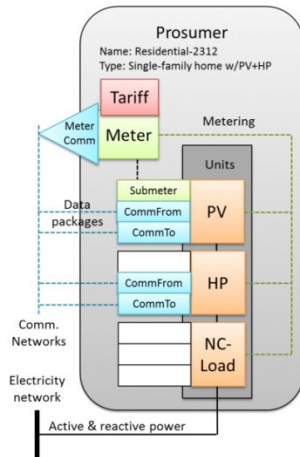
Figure 1: Schematic illustration of a prosumer

- Simplified models of communication interfaces to SmartMeters and physical units, and
- An individual tariff model.

A schematic illustration of an exemplary prosumer is shown in Figure 1.

In *DPG.sim*, prosumers encapsulate the *units* that are present in the grid, i.e., generation, load, and storage devices. This means that a prosumer can represent, e.g., a conventional power plant or a standard household without any generation units.

MODELING OF PHYSICAL UNITS

Parameterizing a Unit Type

In our concept, we distinguish between *static* and *dynamic* units. Static units do not have any intrinsic energy storage, i.e., no internal state that represents an inter-temporal relation between time steps. Static units interact with the grid by a consumption or generation behavior that is determined by time series. Examples for static units are fluctuating generation and non-controllable load units. In contrast, dynamic units have an inner storage state that is determined by a state equation, e.g., a thermal storage with inner temperatures or batteries with a state of charge (SOC). Dynamic units can have associated time series as well.

The performed unit modeling is loosely based on the *PowerNodes* approach [4] with a number of extensions.

Dynamic units can be represented by a standard linear state-space equation of the form

$$\dot{x} = Ax + Bu \qquad (1)$$

or an affine state-space equation of the form

$$\dot{x} = A(x - x_0) + Bu \; . \qquad (2)$$

The variable x denotes the state vector and $\dot{x}$ its time derivative, x_0 is a reference point (e.g., the ambient temperature in a thermal model), and u denotes the system's inputs (which can be controlled by internal controllers or external influences). The matrices A and B are the dynamic and input matrices. The differential equations are subject to the initial condition $x(t=0) = x_0$.

The model for the static unit is a purely algebraic equation of the form

$$Bu = 0 \; . \qquad (3)$$

The outputs that can be measured either by a controller inside the unit or a communication interface to the outside are described by the standard output equation

$$y = Cx + Du \; , \qquad (4)$$

where y is the output vector, C is the state output matrix, and D is the feed-through matrix. Naturally, $Cx = 0$ holds for static units.

In order to determine which variables describe the in-feed into the grid and consumption of electricity from the grid, one of the elements of the u-vector can be flagged as consumption and one as an in-feed variable.

Additionally, the units can have the following attributes:

- Electrical characteristic (constant power, constant current, constant impedance),
- Reactive power characteristic (constant cos φ, $Q(P)$ or $Q(U)$ characteristic),
- Inner controller (hysteresis or PID controller), and
- External control possibilities (e.g., blocking, toggling the switching state, etc.).
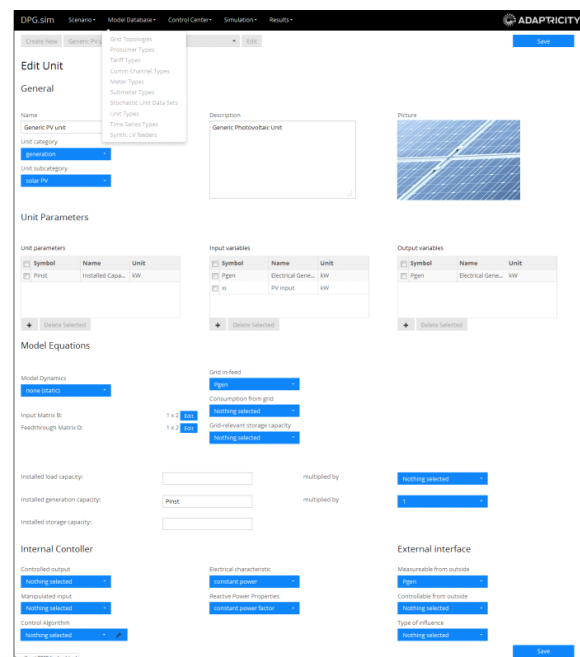

Figure 2: Screenshot of unit parameterization interface

Figure 2 shows the unit parameterization interface of *DPG.sim*. The currently loaded unit is a static unit parameterized as a photovoltaic generator.

In the future, we will also allow for parameter-varying and nonlinear unit models.

Stochastic Parameter Sets

The governing equations of physical units in the grid depend on certain parameters. Similarly, constraints that represent the finite physical nature of a unit connected to the power system are imposed on the variables x and u. For both parameters and constraints of each unit, proper values have to be assigned.

Since parameterizing a multitude of units (up to tens of thousands) by hand is practically impossible, *DPG.sim* provides a framework for drawing parameter and constraint values from stochastic distributions for a population of units.

Time Series Handling and Stochastic Sampling

The time series that are used in the simulation are imported into the program using standard file formats (see Figure 3). Except for SmartMetering data and measurement data from large distinct units in the grid, these time series usually represent aggregate effects in the grid such as aggregate load profiles. In reality, these aggregate profiles constitute the superposition of a large number of stochastic effects, e.g., the individual behavior of many residential loads. Consequently, *DPG.sim* offers various options to de-aggregate imported time series by stochastic sampling techniques, e.g., the top-down load profile generation approach presented in [5].
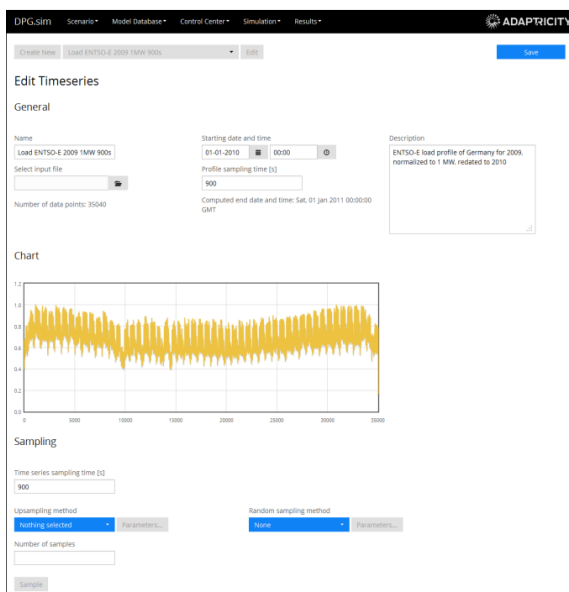
In order to integrate the time series into the simulation, each time series can be associated with an input variable of a certain unit type, determining the value of this input in each time step. This association is also done in the stochastic parameter set dialog.

SCENARIO GENERATION WORKFLOW

In order to assemble a simulation scenario in *DPG.sim*, the following components have to be generated:

- A grid topology (usually by importing from a variety of supported standard formats),
- Sampling times and other simulation settings,
- Prosumer types and corresponding prosumer populations by means of sampling, and
- Assignment of prosumer populations to locations within the grid topology.

In what follows, we present the latter two in detail.

Prosumer Type Definition

In Figure 4, we show the parameterization interface for a prosumer type. It can be considered as a template for the stochastic sampling of a large number of prosumers. As can be seen in the figure, a certain unit type is joined with a stochastic parameter set and possibly communication interfaces as well as a submeter. The prosumer itself possesses a certain meter, a communication channel to this meter, and a tariff type. This procedure implements the concept illustrated in Figure 1.
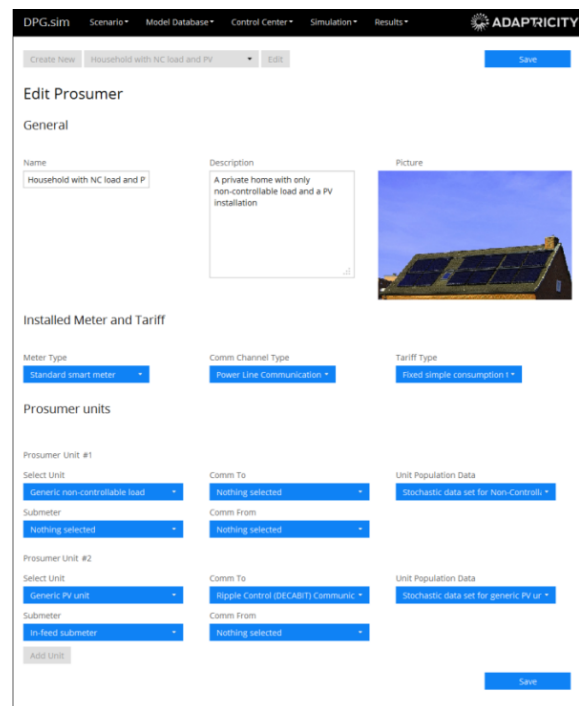

Figure 3: Screenshot of time series import and randomization interface

Figure 4: Prosumer parameterization interface

Prosumer Population Sampling

In order to obtain a number of prosumers with the same basic properties but different unit parameterizations, the sampling of a prosumer population of arbitrary size can be triggered easily within *DPG.sim*. The generation of individual simulation objects for each prosumer and associated assets is then performed automatically. In doing so, a large number of prosumers can be generated without having to parameterize them individually. Consequently, the generated prosumer populations have parameters that are within known bounds and come from known probability distributions.

Prosumer Dispersion on a Grid Topology

The assignment of prosumers to the underlying network topology can be done based on the following criteria:

- Selected grid buses,
- Voltage levels, and
- Uniformly or with statistical variations.

In this way, certain areas in the grid which are known to consist of certain types of prosumers, e.g., a mix of residential and commercial loads, can be populated by corresponding prosumer types in *DPG.sim*.

Matching of underlying sampled data to available measurement time series

In order to create a plausible simulation scenario for a certain part of a distribution grid, it is important to ensure consistency between the stochastic behavior of prosumers and available aggregate measurement data from substations or MV/LV transformer stations. To this end, *DPG.sim* provides the possibility to import measurement time series, attach them to a component in the grid, and match the underlying stochastically sampled individual time series against these aggregate measurements. The matching involves the calculation of a load flow in the considered part of the grid in order to account correctly for grid losses. Naturally, the matching will only act on the stochastically generated parts of load and generation and not on physically-based dynamic models such as thermal load models.

TIME SIMULATION FRAMEWORK

Once the simulation scenario has been assembled, it is executed by a time simulation framework:

- It computes the current state of each prosumer and associated units etc. in each time step.
- It runs a load flow calculation in each time step in order to compute the state of the power system (voltages and angles) and also derived quantities such as line flows and grid losses.
- It executes the appropriate control algorithms.
- It records the selected simulation variables.
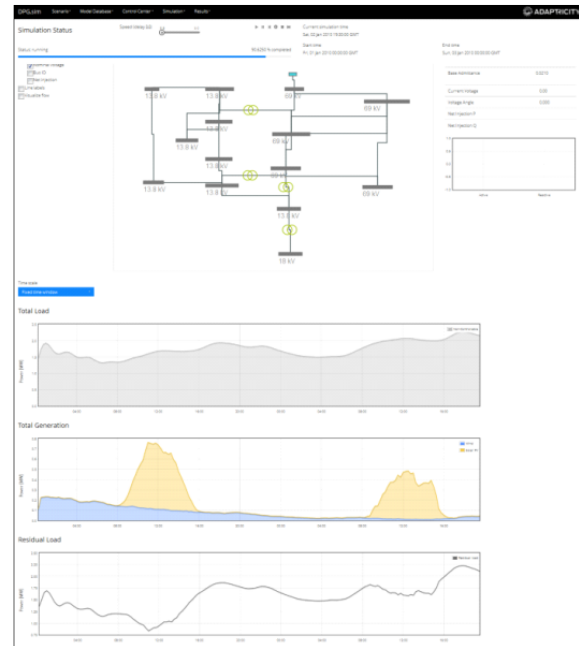
Figure 5: Time simulation interface (aggregated view)

The software supports various simulation types. For instance, it allows the simulation of the medium-voltage level only, which implies that all prosumers that are behind a MV/LV transformer are aggregated to one grid node. Alternatively, the complete low-voltage level can be simulated with each prosumer being connected to a separate grid node. Due to the large number of state variables in the latter case, this type of analysis is more suitable for smaller sub-grids.

The simulation can be executed both interactively, where user inputs and changes can be processed during the simulation run, and non-interactively, where only the numerical results of the pre-defined simulation scenario are of interest. The aggregated view on a running simulation is presented in Figure 5.

AGGREGATION AND CONTROL

DPG.sim offers unique possibilities to aggregate units with certain properties into collections which can then be controlled as a group. We consider a sequence of filters which allow the selection of units according to specific properties. For example, we consider the selection according to

- Unit category (load, generation, storage),
- Unit sub-category (technology),
- Unit type,
- Association to prosumer population,
- Communication interface, and
- Grid buses and voltage levels.

This sequential filtering enables the user to narrow down the selection in order to only capture the desired

units for a specific application. For example, the desired selection may comprise all photovoltaic units below 10 kW in certain low-voltage networks. This selection of units can then be saved in order to subject the group to certain control strategies.

SOFTWARE ARCHITECTURE

DPG.sim is designed as a web application which uses state-of-the-art web frameworks. The Graphical User Interface of the software runs directly in modern web browsers on any operating system. This is advantageous since users do not need to install any additional software on their computer and they are always equipped with the latest version of the simulation software. Moreover, no special hardware is required for the users' computers and multiple users can have access to the same simulation scenario while the simulation is running. Thus, they can observe and analyze the same simulation simultaneously on different computers. All entities such as prosumers, units, scenarios, and results are stored in a common database for easy access and exchange with other users. A permission system allows the definition of various user roles so that users can have individual privileges.

The simulation, algorithms, and database run in the server part of the software. This part can either be run on specific servers within the local company network in order to keep all data in the company. It can also be operated on various cloud computing platforms in order to allow easy operation and scalability without requiring specialized server infrastructure and personnel for server maintenance.

CONCLUDING REMARKS

The main advantage of *DPG.sim* is the possibility to realistically simulate the operation of active distribution grids including SmartGrid elements as well as the temporal evolution of generation, load, storage states, and operational control algorithms. Highly customizable views and data recording options provide deep simulation-based insights into a given distribution system. This helps decision makers to evaluate consequences and outcomes of integrating SmartGrid elements in their system with a high precision.

REFERENCES

[1] VSE, CSRES, VDN, VWEW, 2007: "D-A-CH-CZ Technische Regeln zur Beurteilung von Netzrückwirkungen", available in German, French, and Italian.

[2] International Renewable Energy Agency (IRENA), 2013: "SmartGrids and Renewables – A guide for effective deployment", available online. [URL]: www.irena.org/DocumentDownloads/Publications/smart_grids.pdf.

[3] Adaptricity – Official Homepage. [URL]: www.adaptricity.com.

[4] K. Heussen, S. Koch, A. Ulbig, G. Andersson, 2012: "Unified system-level modeling of intermittent renewable energy sources and energy storage for power system operation", *Systems Journal, IEEE,* vol. 6, no. 1, pp. 140 – 151, March 2012.

[5] C. Bucher, G. Andersson, 2012: Generation of domestic load profiles – an adaptive top-down approach. *Proceedings of PMAPS 2012*, Istanbul, Turkey, June 10-14, 2012.