ASSESSMENT OF AGGREGATED IMPACTS OF PROSUMER BEHAVIOUR

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ABSTRACT

We present a distribution grid simulation study in which we analyse the aggregated impacts of individual prosumer optimization strategies for the operation of a typical European distribution grid. For this we simulate the individual behaviour of 4'000 prosumer households that have roof-top solar PV and residential batteries. They are using different operation strategies in order to maximize their own benefit with respect to variable residential electricity tariffs as well as their own load consumption and PV power production – for instance via PV self-consumption maximization. We analyse the aggregated impacts of the individual prosumer behaviour on the distribution grid. We show how the choice of the applied rule-set, respectively the economic incentives given to prosumers, is decisive for inducing either grid-friendly or grid-unfriendly prosumer behaviour.

INTRODUCTION

Traditional distribution grid as well as transmission grid planning is usually based on a static load flow computation, a so-called snapshot situation, which takes into account the maximum coincident load to determine the necessary grid infrastructure dimensioning.

With the rise of Distributed Generation (DG), particularly wind and solar PV generation, the snapshot of the maximum coincident generation is also becoming relevant for grid infrastructure dimensioning. The coincidence of load demand and distributed generation in time and space may either reduce or actually impose more stress on the grid than load demand would by itself. Merely considering the grid's overall worst-case load snapshot can lead to highly over-dimensioned parts of the grid infrastructure and rare utilization of the full grid capacity. In fact, the worst-case snapshot approach can also lead to critical under-dimensioning of other parts of the grid infrastructure, as their particular worst-case loading may simple occur at another point in time [1].

SmartGrid technologies are emerging that are able to actively influence electric load and generation profiles in order to improve grid operation and reduce grid loading stress. Studies show that innovative operational measures, such as selective renewable energy curtailments, Demand Response, distributed storage, and reactive power control, can potentially make the transition to high shares of renewable energies more cost-effective by reducing otherwise needed grid upgrade costs [2].

In order to reduce grid infrastructure costs by using one or a combination of several SmartGrid technologies, these SmartGrid technologies need to be considered explicitly at the grid planning stage. However, the respective literature shows that existing grid planning tools do in many cases not support the realistic modelling and simulation of electricity grids with SmartGrid elements, a necessary prerequisite for cost-effective grid planning [3].

In order to overcome these limitations, the SmartGrid time-series based simulation platform DPG.sim is developed and commercialized by ETH Zurich spin-off Adaptricity [4]. The detailed simulations and subsequent grid analytics provide valuable qualitative as well as quantitative decision-support for all aspects of distribution grid operation, e.g. the design and performance analysis of active network management operation strategies, as well as distribution grid planning, e.g. the integration of SmartGrid elements into distribution grid planning.

The main advantages of the DPG.sim simulation platform are threefold: First, its possibility to realistically model and simulate the operation of active distribution grids as well as the temporal evolution of generation, load, storage states, and their operational control algorithms down to the level of individual households and household units. Its unique feature in this respect is its versatile Prosumer modelling approach [5], which allows capturing all relevant modelling details and operational constraints of controllable loads, distributed generation, and storage as well as SmartMeter communication infrastructure (Fig. 1). Second, the ability to perform large-scale time-series simulations and operational (big) data analytics based on heterogeneous sets of grid data as well as end-consumer data sets by tapping into scalable cloud-based computation and data storage resources. Third, data visualization and statistics tools that provide detailed insights into electricity grid operation and enable robust decision support (Fig. 2).

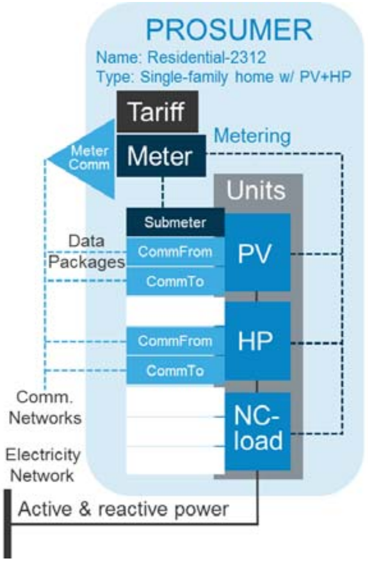

Figure 1: Prosumer Modeling Approach

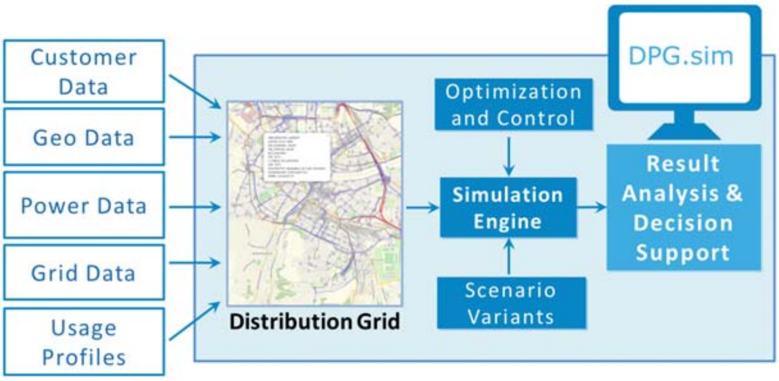

Figure 2: Structure of Simulation Platform DPG.sim

EXEMPLARY DISTRIBUTION GRID

We consider as exemplary electricity grid a rural distribution system in Germany. The considered grid zone includes two medium-voltage (MV) grids (20 kV) as well as the high-voltage (HV) grid connection (110 kV) as depicted in Fig. 3 [6].

Within this grid topology, 4’000 prosumer households were randomly modelled and dispersed. Individual peak load demand of prosumer households is in a band of 5-7 kW, whereas individual PV peak is in a band of 4-7 kW. The household batteries have a rating of 4 kW peak power and 20 kWh energy capacity. The considered distribution grid is only moderately stressed by the given prosumers’ aggregated load and generation patterns. Line loading is at most 60%, whereas transformer loading is at most 30%.

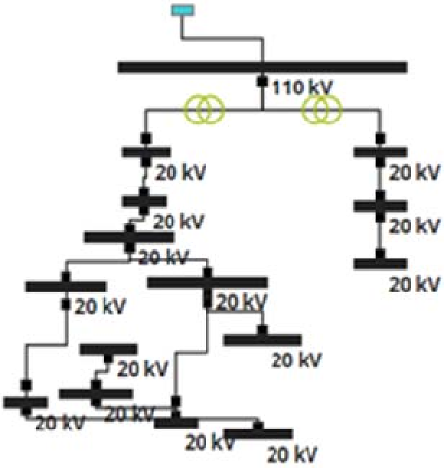

Figure 3: Exemplary MV/HV Distribution Grid

SIMULATION RESULTS

Three plausible prosumer optimization strategies were analyzed: First, the base case, in which the decentralized PV production of prosumer households is released unbuffered to the distribution grid. Second, the PV self-consumption case in which household batteries are used for buffering the PV peak generation. And third, the energy arbitrage case in which the household battery capacity is used for exploiting price differences of end-consumer electricity tariff schemes.

Base Case (unbuffered PV production)

As expected, the unbuffered PV power in-feed to the distribution grid creates clearly visible over-voltage peaks on sunny days of up to 1.07 p.u. at noon (Fig. 4). This may require active PV curtailment in day-to-day grid operation and eventually lead to costly grid upgrades.

PV Self-Consumption Case (battery-buffered)

In this case, household batteries are employed to actively absorb PV production locally and thereby relieve grid stress. This, however, is only the case for as long as the batteries can indeed absorb the PV production.

Depending on the initial State-of-Charge (SoC) of individual household batteries, the particular household’s individual load consumption as well as PV production this may or may not be the case. This complex interdependence leads to acceptable grid behavior, i.e. lower voltage peaks during noon hours, on some days but not on others (Fig. 5). On sunny days the battery capacity is in many households already exhausted by noon and the coinciding PV peak can cause similarly high voltage levels as in the base case.

Energy Arbitrage Case

Even more extreme voltage peaks can arise due to a tariff-driven operation of household batteries. Batteries are charged during night hours, i.e. during the low electricity tariff period, and discharged during daytime, i.e. during the high electricity tariff period (Fig. 6, BESS charging/discharging given in blue).

This creates both under-voltage situations during night-hours as well as very high voltage peaks (> 1.12 p.u.) due to the coincidence of PV and battery power in-feed.

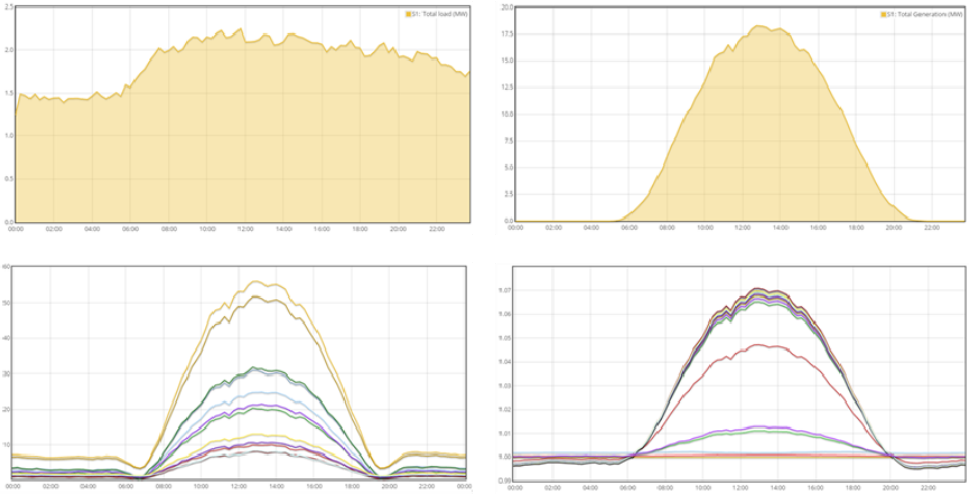

Figure 4: Base Case (unbuffered PV production)
(clock-wise from top left: load demand, distributed generation, voltage profile, line loading)

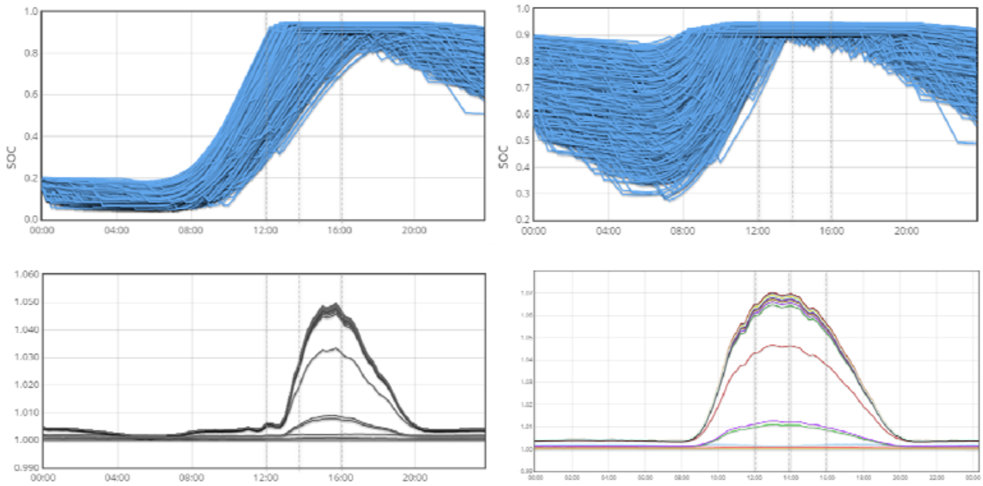

Figure 5: PV Self-Consumption Case (battery-buffered)
(SOCs of individual household batteries and resulting aggregated voltage profile, left-side: day 1, right-side: day 2)

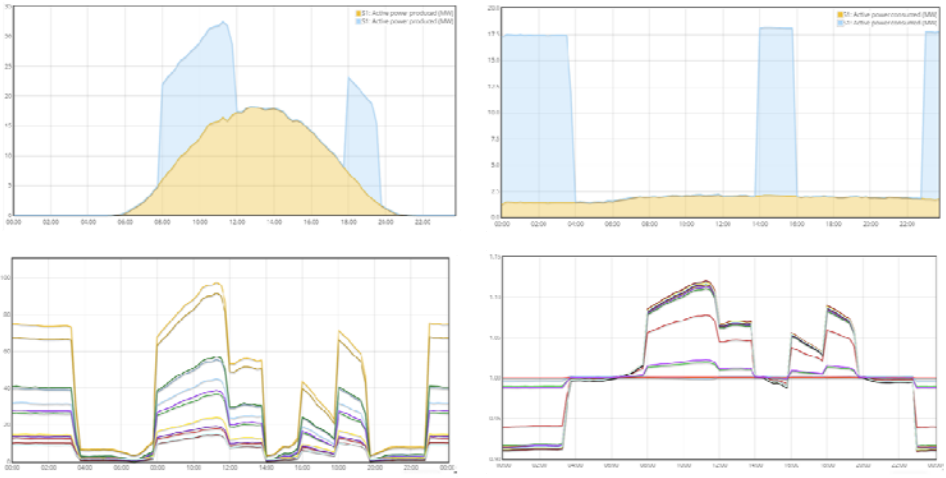

Figure 6: Energy Arbitrage Case
(clock-wise from top left: load, generation with BESS charging/discharging given in blue, voltage profile, line loading)

STATISTICAL ANALYES OF TIME-SERIES-BASED GRID SIMULATIONS

Time-series-based grid simulations by nature create an enormous amount of simulation data, providing rich opportunities for grid analytics that can inform both grid operation and grid planning decisions.

For the following examples, we used grid simulation raw data gathered over a six-month simulation period, i.e. for more than 17’000 time instants. The sum of all operation variables of 4’000 prosumer households as well as for the relevant grid variables of the whole distribution topology as captured over this time-frame lead to several millions of data points. This is an immensely valuable database for data analytics and data visualization methods. It enables for instance the insightful analysis of the frequency and gravity of occurring voltage violations and their relevance for grid upgrade measures via box-plots and histograms of voltage levels (Fig. 7). By looking at these results, notably the voltage band histograms, it becomes apparent that the PV self-consumption case (Fig. 7, middle) does on average perform better than the base case (Fig. 7, top) as the voltage band is *tighter* on average although outliers above 1.08 p.u. do at times occur. Also, the energy arbitrage case (Fig. 7, bottom) shows indeed a highly deteriorated performance, as the voltage band widens with significant over- as well as under-voltage events. Similar analyses can be accomplished for lines and transformer (over-) loading.

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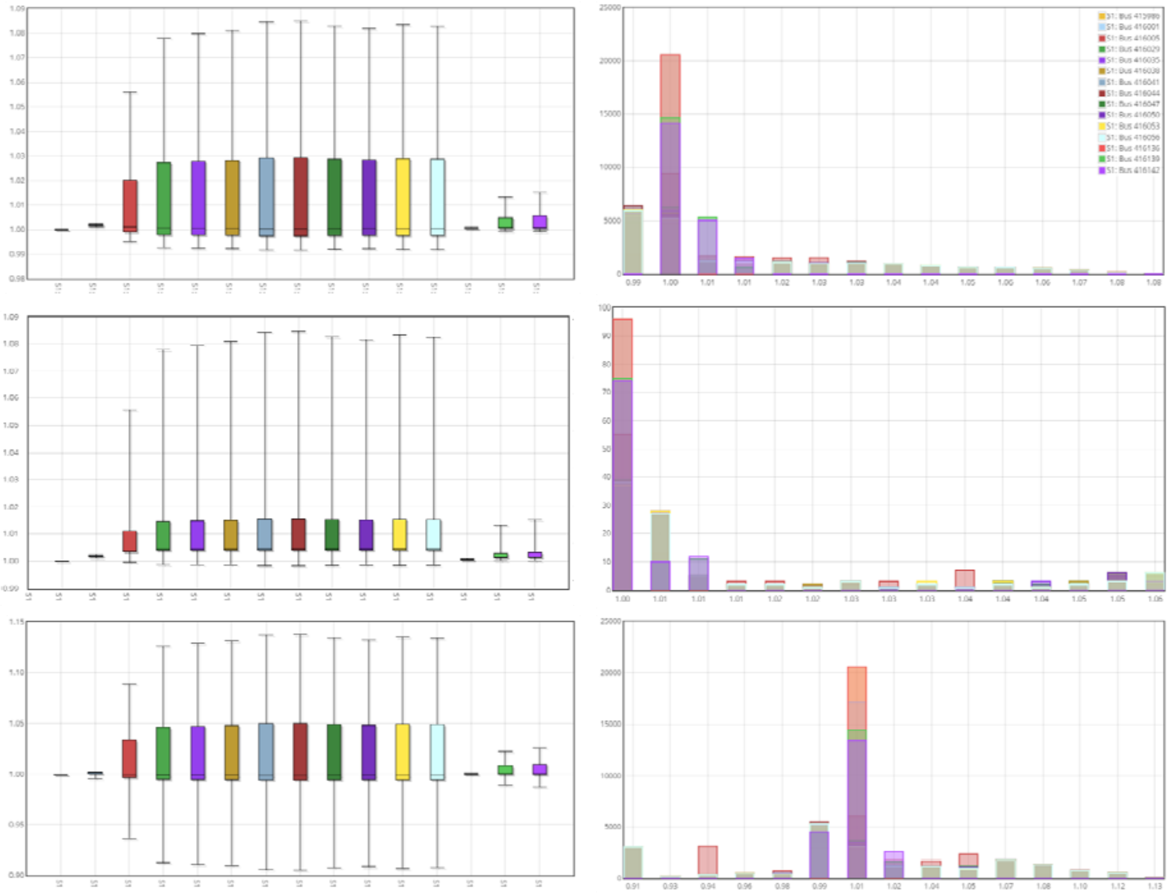

Figure 7: Box-Plots & Histograms of voltage profiles from time-series based grid operation (1/2 year, 15min. samples) (top: base case, middle: PV self-consumption, below: energy arbitrage case)