Impact of incentive-based demand response on urban low-voltage grid operation

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Abstract

Within the European project Smart House / Smart Grids (SH/SG), contemporary technologies for automated demand response (ADR) in private smart houses and automated load and generation control were developed and tested. At the same time, impacts of ADR and distributed generation (DG) on low-voltage grid operation were researched by means of software simulations in a real urban network. Research questions included whether ADR can be used for lowering grid losses, voltage control and increasing the accommodation ceiling of DG. The paper at hand shortly introduces the basic energy management concept as well as simulation goals. It then presents and discusses simulation results regarding operation of an ADR system with high amounts of DG in a grid area in the city of Mannheim.

Keywords:

Low-voltage grid operation, Distributed generation, Automated demand response

1 Introduction and Problem Statement

Distribution grid operation and planning is nowadays facing a fundamental system change due to growing amounts of distributed and fluctuating generation (DG). The transition of electric networks into smart grids is proposed by various research projects and initiatives [1] and driven by European policy [2]. Albeit many aspects that could play a role in the coming smart grid are already well known, it is not yet clear how the resulting energy system will precisely look like. With this background, the task of grid planning – which includes procurement of assets with lifetimes of 30 years and more – can at best be called a big challenge. At the same time, the beginning transition influences everyday grid operation and maintenance of grid stability.

One well-known supporting tool for smart grids is a decentralized energy management system (EMS) for the low-voltage network (LV). In the project Smart House / Smart Grid (SH/ SG), three contemporary EMS are bundled to form an amalgamated smart grid service architecture applying demand response (DR) and control of distributed generation (DG) e.g.

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in private smart homes [3]. One of these systems is the "Bidirectional Energy Management Interface" (ISET-*BEMI+*®), which automatically controls the operation of electric loads due to day-ahead tariff incentives given from a higher-order level [4].

This system is field tested in the city of Mannheim within private homes [5]. The field trial aims at introducing a new software and hardware platform for energy management in smart houses as well as testing installation procedures and investigating customer reactions. At the same time, grid operation impacts are researched by means of software simulations. These focus on grid operation with high amount of DG. Prior simulations using fictional networks indicate that incentive-based DR can have positive effect on line and transformer loads as well as line losses, energy efficiency increase due to efficient use of renewable energy sources and finally raising the accommodation ceiling for these sources [4]. Hence, the network simulated in SH/SG model is a real urban grid area in the settlement Mannheim-Wallstadt. A schematic view is shown in figure 1. The grid nodes A, B and C depict connections to the medium voltage (MV) level, each equipped with LV-MV breakers. The MV was modelled as external grid with voltage set-point of 1.01*20 kV. The LV grid was not connected to neighbouring LV grid cells, as is the standard operation case.

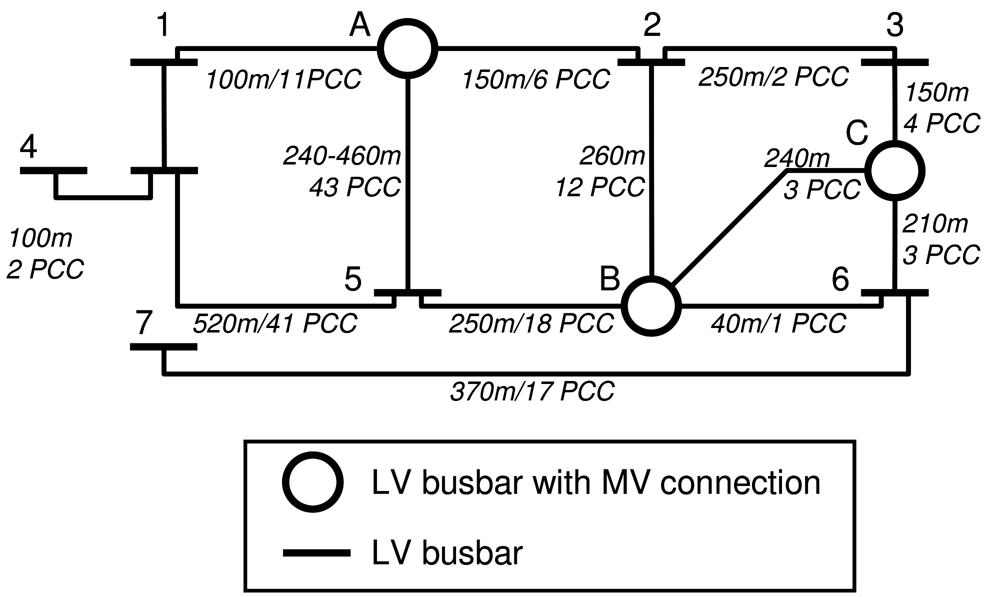

Figure 1: simplified schematics of simulated urban grid area

Within this network there are 168 public connection points (PCC) supplying a total of 309 private households. Each household is assumed to be equipped with a typical selection of controllable household devices. The device operation is automatically controlled and optimized according to day-ahead variable tariffs. In addition, each connection point is assumed to be equipped with a PV generator, adding up to 350 kWp installed PV power within the network. The used tariffs are fictional and are basically designed for giving the best possible match between overall generation and load.

Complementary to this, grid measurements and simulations are carried out in Mannheim for researching the impact of high amounts of DG on grid operation. The results are expected to identify effects and problems arising when implementing DG into the network. In combination with the results from the SH/SG simulations, this again allows for better evaluation of the possible benefits of DR measures in conjunction with grid maintenance planning. There, the question to which extent DR can contribute to avoiding network reinforcements or even allow for network deconstructions with high amounts of DG is of high interest.

Altogether, the work is especially addressing determination of technical constraints (e.g. loading of lines, voltage violations) and minimizing grid losses. By consideration of grid deconstruction scenarios, it is expected that conclusions for future grid planning and design can be derived from the results.

2 Software Simulation of ADR benefits on grid operation

2.1 Simulation system and setup

For simulation of ADR in the Mannheim-Wallstadt network as shown in fig. 1, a software system developed by Fraunhofer IWES was used. The system setup is schematically shown in fig. 2. It is a discrete steady-state simulation with equidistant simulation step-width of at least 1 second that models the behavior of ISET-*BEMI+* equipped smart houses in the electric distribution network. The simulation modules include a Smart House simulator capable of modeling individual Smart Houses independently and an interface to the professional grid calculation software Power Factory from DIgSILENT. The former module contains models for unmanaged loads and loads that are managed by ISET-*BEMI+* original EMS algorithms. Each of the households was equipped with controllable appliances and energy consumption attributed to the devices as shown in table 1. Parameters of the devices, e.g. maximum switch-on and off times, were derived using preliminary results from the SH/SG field trial in Mannheim. Customer usage of the devices was modeled using basic statistical approaches which ensure that many individual household load profiles add up to known standard profiles. Photovoltaic in-feed was modeled using solar irradiation data measured in Kassel. An in-depth description of the models can be found in [6].

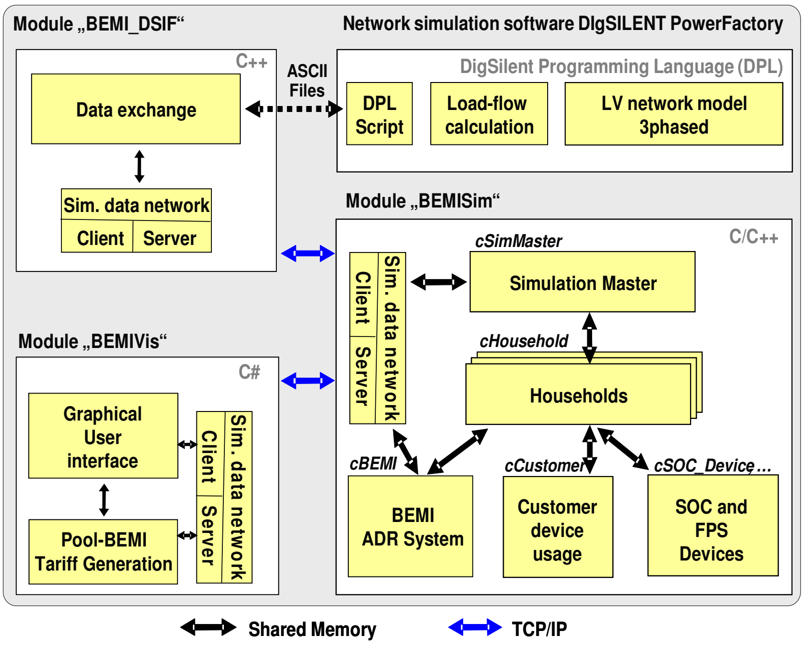

Figure 2: Simulation module schematics

Application	Relative Consumption	Average Consumption [kWh/a]
Fridges	11 %	363
Freezers	11 %	363
Washing Machines	7 %	231
Dish Cleaners	7 %	231
Tumble Dryers	10 %	330
Non-controllable	54 %	1.782
Sum	100 %	3.300

Table 1: assumed smart house energy consumption

The network calculation software was used to calculate steady-state grid operation parameters, namely node voltages, line and transformer loads and losses within the considered grid area, considering only active power load and DG. Simulations were done for three different grid topology scenarios (cf. figure 1):

Top 1) LV-MV breakers A, B and C closed

Top 2) LV-MV breakers A and C closed

Top 3) LV-MV breakers B and C closed

Top 2 and 3 can thus be considered as network deconstruction scenarios. The simulation goal was now to quantify the influence of tariff-based ADR onto the grid operation parameters. Hence, two fictional tariffs were chosen:

1. A “flat tariff” of a constant 20 €ct/kWh
2. A “PV tariff” which would offer lower prices of 15 €ct/kWh between 11:00 – 13:59 at each day

By pre-simulations, the PV tariff was designed such that the resulting load transient would show high correlation with the PV in-feed while at the same time reducing line loads during high PV in-feed times. With this setup, 6 subsequent days in summer were simulated with step-with of 5 minutes.

Figures 4 and 5 show resulting load and generation transients for these days for flat tariff and PV tariff, respectively. The load shift to times of high PV in-feed observed in fig. 5 can be attributed to the tariff changes.

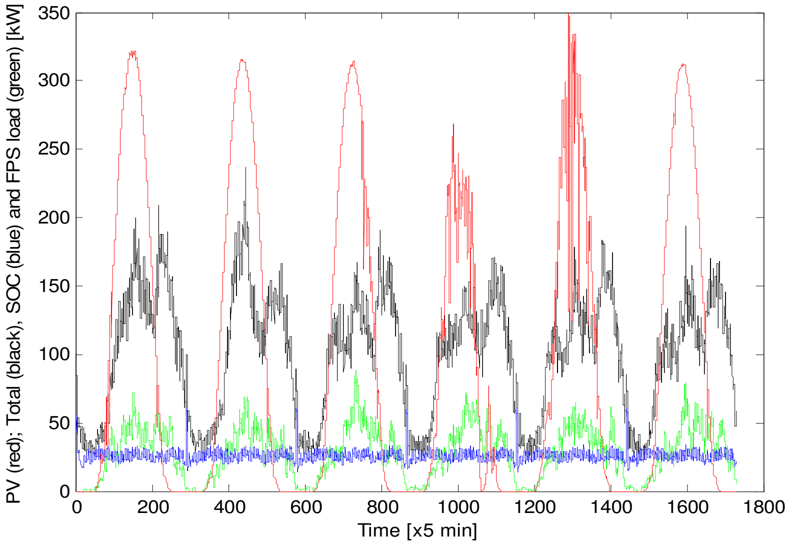

Fig. 4: PV in-feed (red) vs. total (black), SOC (state-of-charge blue) & FPS (fixed-program-schedule, green) load for a flat tariff

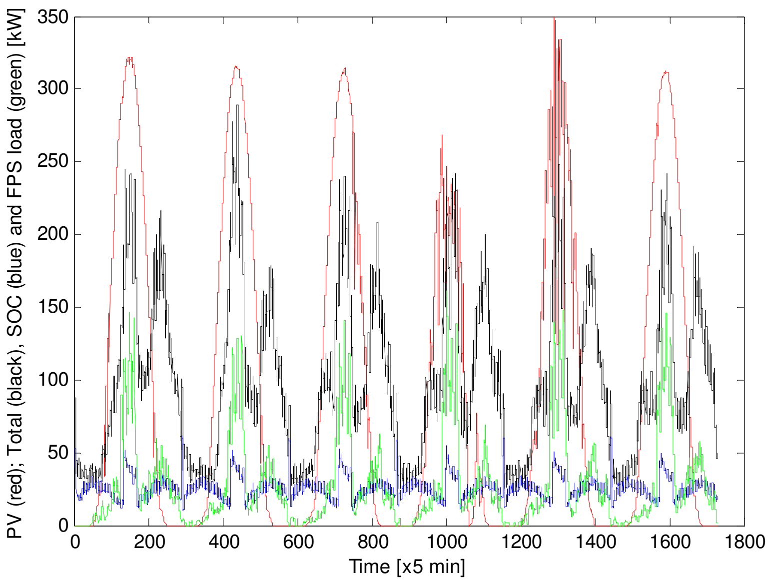

Fig. 5: PV in-feed (red) vs. total (black), SOC (state-of-charge blue), FPS (fixed-program-schedule, green) load for a PV tariff

3 Simulation Results

For quantification of the results, several characteristic values were defined. It was found that none of the grid operation parameters exceeded critical limits in any topology case.

Table 2 contains the following result values for the three topologies considered:

- overall energy consumption E_{cons}, generation E_{gen} and imported energy to the grid area E_{imp} (all timesteps sum)
- exported energy from PV installed within the grid area E_{PVexp} and the locally used energy from PV E_{PVcons} (all timesteps sum)
- total active power losses over distribution lines E_{Lloss} (all timesteps sum)
- total active and reactive power losses over distribution transformers E_{Tloss} (all timesteps sum)
- the node n amongst nodes 1,4,5 and 7 (cf. fig. 1) where the maximum voltage absolute occurs (over all timesteps)
- the peak voltage $U_{n,maxPV}$ at node n during 11:00-13:59 (low price time)
- the peak voltage $U_{n,maxother}$ at node n at all other times (high price time)
- the average voltage $U_{n,avgPV}$ at node n during 11:00-13:59 (low price time)
- the average voltage $U_{n,avgother}$ at node n at all other times (high price time)
- the peak line loading L_{LPVmax} and transformer loading L_{TPVmax} during 11:00-14:00 (low price time)
- the according peak during all other times $L_{LPVother}$ and $L_{TPVother}$
- the average low-voltage distribution line loading L_{LavgPV} and transformer loading L_{TavgPV} during 11:00-14:00 (low price time)
- the according averages during all other times $L_{Lavgother}$ and $L_{Tavgother}$

The results are discussed in the following sections.

Energy Consumption

Comparing the consumed energy in flat vs. PV tariff cases shows deviations of 0.8 % or less. Thus, observed effects on other values can not be attributed to the tariff incentive changing energy consumption, but instead causing temporal load shifts.

Usage of locally generated energy

In any network topology, introduction of the PV tariff does increase the locally used PV and decrease energy imports into the network area. However, yet these changes can be attributed to the tariff change, they are merely marginal: in average over all topologies, the import savings are 3.7%, PV export decreases by an average of 5% and locally consumed PV increases by average 3.7%. This small effect can be attributed to the fact that the used tariff has only got a short low-price time, which was chosen to reach a higher effect on grid losses.

Grid losses

The PV tariff is reducing network line active power losses in any topology case. The line loss savings are about 8% (Topology 1), 8% (Topology 2) and 9% (Topology 3). It should be noted that line losses are a result of integration over the whole simulated time period. Hence, the savings in line losses achieved during low-price times are not over-compensated by additional losses that were observed to be caused by load switch-off during high-price times.

	Topology 1		Topology 2		Topology 3	
	Flat tariff[2]	PV tariff	Flat tariff	PV tariff	Flat tariff	PV tariff
$\mathbf{E_{cons}}$ [kWh]	14,464 (±72)	14,585	14,401	14,424	14,451	14,516
$\mathbf{E_{gen}}$ [kWh]	14,397 (±0)	14,397	14,397	14,397	14,397	14,397
$\mathbf{E_{imp}}$ [kWh]	6,188 (±46)	6,032	6,226	5,964	6,206	5,925
$\mathbf{E_{PVexp}}$ [kWh]	6,137 (±42)	5,844	6,223	5,937	6,149	5,806
$\mathbf{E_{PVcons}}$ [kWh]	8,260 (±42)	8,553	8,174	8,460	8248	8,590
$\mathbf{E_{Lloss}}$ [kWh]	37.1 (±0.4)	34.0	50.6	46.6	94.3	85.5
$\mathbf{E_{Tloss}}$ [kWh]	267.0 (±0.2)	265.8	190.8	188.9	190.3	188.2
n [node Nr.]	4	4	4	4	4	4
$\mathbf{U_{n,maxPV}}$ [V]	235.7 (±0.2)	234.9	236.2	235.4	237.8	236.4
$\mathbf{U_{n,maxother}}$ [V]	235.5 (±0.1)	235.7	236.0	236.2	237.3	237.9
$\mathbf{U_{n,avgPV}}$ [V]	235.3 (±0.1)	234.4	235.7	234.7	237.1	235.3
$\mathbf{U_{n,avgother}}$ [V]	232.9 (±0.01)	233.0	232.9	233.0	232.7	232.9
L_{LmaxPV} [%]	12.8 (±0.6)	9.6	14.0	10.6	18.9	13.4
$L_{Lmaxother}$ [%]	13.6 (±0.6)	13.7	14.2	14.6	18.5	19.7
L_{LavgPV} [%]	10.8 (±0.5)	7.6	11.7	8.2	16.0	9.8
$L_{Lavgother}$ [%]	6.2 (±0.1)	6.3	6.7	6.8	8.5	8.9
L_{TmaxPV} [%]	20.2 (±0.8)	13.8	28.1	20.4	27.4	19.3
$L_{Tmaxother}$ [%]	20.0 (±0.3)	21.6	28.1	29.8	27.1	29.1
L_{TavgPV} [%]	17.2 (±0.7)	10.1	23,6	14.7	23.4	13.7
$L_{Tavgother}$ [%]	9.1 (±0.1)	9.7	12.7	13.2	12.4	13.0

Table 2: Characteristic values derived from the simulation results

[2] This simulation run was carried out six times with unchanged parameters in order to quantify the stochastic variations.

On the downside, the savings in transformer active power losses are <1% (Topology 1), 1% (Topology 2) and 1.1 % (Topology 3). Though marginal, they can be considered to be caused by the tariff change. Even if no-load transformer losses are disregarded, remaining loss savings do not exceed 1.3 % in any topology. Since transformer losses exceed line losses by factors between 2 (Topology 3) and 8 (Topology 1), the overall active power loss reduction results in 1.4 % (Top. 1), 2.4 % (Top. 2) and 3.8 % (Top. 3).

Grid node voltages

Node voltages are increased due to PV in-feed; maximum values observed were around 238 V (phase-to ground, top. 3). Node 4 shows highest voltages for any simulation run. There is significant voltage decrease at this node due to the PV tariff during low-tariff times. The PV tariff reduces the maximum/average value by 0.8 V/1.1 V (Topology 1), 0.8 V/1 V (Topology 2) and 1.4 V/1.8 V (Topology 3). Up to 0.2 V hereof are uncertain to be caused by the tariff change. However, load switch-off during high-price times seems to cause slight increases in voltage of up to 0.3 V for the average value (Topology 3) during these times.

Line and Transformer loadings

Maximum values for the line loadings are not necessarily observed during high PV in-feed times in the first place. Hence, the PV tariff is unable to reduce overall maximum line and transformer loadings, but instead increases them by up to 1.2 % (max. line loads, Topology 3) resp. 2% (max. transformer loads, Topology 3). However, during the low-tariff times of the PV tariff, a significant reduction both in line and transformer loads was observed ranged from an absolute 3.4 % (Topology 1) to 5.5 % (Topology 3) for the line loads resp. 6.4 % to 8.1 % for the transformer loads. For the average values during low price times, the reductions here reach an absolute 3.2 % to 6.2 % (average line loads) resp. 7.1 % to 9.7% (transformer loads). It should be noted that the loading rates are far too low to cause any network problems in all scenarios. However, the results also show that tariff incentives are an appropriate measure to lower average and maximum line and transformer loadings during a restricted time (for a period of 3 hours in the simulations) at the cost of slight increases during other times. This could be used to counteract a short term overload using a specifically designed tariff or an intraday tariff change.

4 Conclusions and Outlook

The results show that ADR is a possible tool to stabilize grid operation with high amount of DG by increased demand. This could contribute to reduced grid investments and maintenance costs. However ADR offers more, as with the help of ADR demand can be shifted also for better load and procurement planning.

The ADR simulations indicate that day-ahead tariffs can be used to control grid operation parameters if tariffs are specifically designed to meet the wanted goals. The simulation results indicate that weaker grids benefit more from the ADR effects. However, ADR potential is limited by physical parameters of the controlled loads. Thus, it will be of high interest to model loads with higher potentials, as electric vehicles or heat pumps, in future work.

The question if introduction of load management to the chosen devices is economically feasible under these conditions is out of the scope of this simulation. However, it should also be kept in mind that the simulations indicate that the tariff incentive influences a broad range of network operation parameters, thus enabling a whole lot of applications. Additionally, the ADR hardware used also offers other functionalities, e.g. smart house building automation, enabling additional values.

Still, the limited potential of day-ahead ADR indicates that it can only be part of the solution for smart grid operation. It also has to compete against alternative technical options, e.g. on-load tap changers, PV inverter reactive power control, agent-based intraday ADR or direct load control. These are all well-known technologies even today, but the problem of combining them in a technically, ecologically and economically optimal way is yet to be solved. This question yet defines the next leap in smart grid research and development. According simulations are currently prepared within the German project Modellstadt Mannheim [7].

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