Impact Study of Smart Grid Technologies on Low Voltage Networks with High Penetration of Renewable Generation

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Abstract- The evolution of technology brings many innovative solutions due to higher visibility and controllability in systems. Smart grid technologies have many advantages, while bringing integration and use case formulation challenges in the meanwhile. In this paper the effects of renewable generation, energy storage, controllable inverters and demand side management (and combinations of previous solutions) were analyzed to form operation and control based on real network information and conditions. Several scenarios are examined (weekdays vs. weekend profiles), different penetrations of distributed generation were considered for a detailed analysis of network losses and voltage conditions on a low voltage network. A stochastic approach was used to handle the uncertainties of the elements. The contribution of this research is a smart grid technology comparison from a distribution system operator point of view to enhance the integration of renewable energy sources. Effective voltage control is feasible with inverter control from the distributed generation. However, reactive power strategies do not suit the network with a high R/X ratio. Different scenarios showed that the storage and demand side management strategies must consider locality for efficient operation.

Keywords Smart Grid, Renewable Integration, Energy Storage, Demand Side Management, Inverter Control.

1. Introduction

Nowadays, the electric power system is changing significantly due to increasing renewable-based energy source installation to the grid, superseding conventional energy producers [1]. These energy sources are usually not connected to the transmission network – contrarily to conventional ones –, but to the distribution system; therefore, they are increasing the ratio of the so-called distributed energy resources [2]. The necessity for this change comes not only from the distribution system operator (DSO), but rather from the whole energy industry to renew the methodology, the modelling and the long-term planning process, which primarily take distributed energy resources into consideration [3]. System designers face new challenges, as they need to take effects and potential advantages of the so-called prosumers into account [4]. In addition to the least cost principle and the reliable quality of the electricity service (acceptable voltage levels, no overloading and outages), the management of uncertainty and volatility of renewable energy sources are only some of the aspects to take into consideration during the design of a distribution network [5].

However, if used in an appropriate manner, smart grid technologies have the opportunities to present viable technical solutions to the DSO in the integration process [5–6]. One of the most important aspects in smart distribution systems is active voltage control [7]. There are numerous technological possibilities, such as the deployment of online tap changing transformers [8–12], inline voltage regulators [13–15] as close to the conventional grid elements as possible. Further approaches include demand side management (DSM) possibilities for coordination in active distribution networks [16], rural areas [17], as well as integration of end-user storage devices [18]. Electric vehicles also offer a large amount of controllable load [19], while autonomously operated distribution network parts – including prosumers – can also offer a wide range of supply quality improvements [20]. Advanced Home Load Management Systems can integrate residential buildings with RES, energy storage and electric vehicles, while data clustering methods can optimize their operation [21]. Microgrids can also integrate multiple energy carriers – e.g. natural gas, heat and power - and current state of research shows great potential in the optimal operation planning [22]. Microgrids also offer an important aspect in the decentralized, non-synchronous inertia generation integration with advanced frequency control [23] [24].

The key to effective utilization of DSM is finding the right incentives for customers to participate [25]. DSM could have a great effect in the integration processes [26] besides all of the aforementioned values; therefore, it is widely considered as an indispensable part of smart grids. Energy storage systems (ESSs) constitute another crucial element [27] with a wide-range of uses, such as renewable integration at a low voltage level [28], solutions for overloading challenges [29], and nowadays viable business cases [30–33] in an evolving regulatory environment. Another option toward smart distribution grids is the control if distributed generators that offers advantages in voltage control [34–37], network loss reduction [37–39] and hosting capacity increase [40] in the presence of a high share of distributed generation. This controlling method is often referred to as active network management (ANM) and could be considered as a network reinforcement alternative [41-42].

This study focuses on the effects of smart grid technologies – namely DSM, energy storage and ANM – through a real-life test case from Hungary. The Hungarian low voltage (LV) network mostly consists of overhead lines with a high R/X ratio and the infrastructure is quite old. Photovoltaic (PV) generation is increasing quickly, as well as the system load. This environment is challenging for the Hungarian DSOs, and with conventional grid reinforcement techniques the investment costs would become unacceptably high. Therefore, DSOs examine the possibilities of smart grid technologies as alternatives, to find the most effective alternatives from technical and economic points of view. The paper is organized as follows: Section 2 introduces the methodology for stochastic grid simulation studies, PV, DSM, storage and ANM effect consideration and defines the study cases. Section 3 presents the simulation test cases and results, while Section 4 summarizes the main conclusions of the research.

2. Methodology

To test the technical effects of smart grid solutions, load flow simulations were carried out on the low voltage grid model of a selected Hungarian MV/LV transformer supply area. Different scenarios were created with chosen smart grid technologies and with different load and local renewable penetration. The main focus of the studies was the effects of PV generation to the network, especially analysing and handling the effects on grid voltage: with inverter control, indirectly with energy storage in the public network or with DSM. In the following sections the methodology and the examined grid will be presented.

2.1. Simulation framework

Stochastic load flow simulations were performed with scripts created in DIgSILENT PowerFactory. This approach uses probability distribution functions characterized by stochastic variables; it can determine given probability events in the event space. In the case of stochastic models, a projection is created based on random variables. As the number of simulations grows, it increases the number of the projections while giving different results. These can also be characterized by some probability distributions (that can be either empiric or some common probability distribution). Then with the help of distributions, it is possible to determine the highest probability and extreme events with an in-depth understanding of the behavior of the analyzed system.

In the presented research the modelled low voltage grid had both deterministic and stochastic parameters. Deterministic (and in our case constant) parameters are grid impedances, grid topology (including the 3 PVs that are already installed), voltage of the feeder network (which is based on a measurement carried out by the local DSO and handled as an input variable to make the simulation more realistic and include the switching effects of medium voltage (MV) network, e.g. HV/MV transformer tap changes), number and power of consumers (except for the controllable units). Stochastic parameters are the time series, active and reactive power data of consumers and PV (which also has a partly varying location), which is based on previous measurements collected by the authors.

For stochastic simulations, it is necessary to run an adequate number of simulations to be able to replicate the whole event space. 100 simulations were run by each scenario to have the proper amount of data. The script executes the following steps in each run:

- Reading the unique consumer power,
- Assigning load profile to individual consumers,
- Assigning power factor to individual consumers,
- Assigning the power of PV units in distributed locations to individual consumers,
- Assigning generation profile to PV units,
- Running symmetric AC Load-Flow, storing results,
- Executing (based on target value or control function) control tasks (DSM, energy storage),
- Running Load-Flow, storing results,
- Step by a quarter hour in time.

2.2. Grid parameters

The low voltage grid model of the chosen pilot area was created in DigSILENT Power Factory 2018 software environment. Figure 1 shows the non-scaled one liner topology of the case study area, with the fuse ratings, line length and diameters (inside brackets), and nodes (inside brackets).

To assign the loads in the model, the initial data were voltage drop, current records and one-week long measurements (LV terminal voltages and currents, endpoint voltages) from DSO. According to this data, a maximal load corresponding initial state was created. Symmetric three-phase constant power loads corresponding to the consumer number were created. The known number of customers were assigned with uniform distribution along the lines, since the only information about the point of connections was the number of customers on each circuit. This is a usual solution in practice for load assignment. The profile databases had both weekday and weekend profile baselines, which were used in different scenarios during the simulations. Compared with the one-week measurements, the model described the characteristics of the location.

The transformer – which has an apparent power of 400 kVA, and a utilization factor of 66.38% – of the settlement supplies 4 circuits, with a cumulative number of 142 consumers. The known installed household-sized power plants (8.5kWp between node 2 and 4, and 2.85 + 7kWp between node 2 and 3) were built in. In certain simulation cases these data were used as well. Table 1 summarizes the used data. The PV penetration was calculated based on the yearly consumed energy (e.g. 50% PV penetration means that the cumulative production of the PV systems equals to the half of the energy usage of all loads). Then – with the assumption that 1 kW installed PV produces 1100 kWh of energy, which is a commonly used number in Hungary – the PVs were assigned to the customers randomly with different nominal powers, which were generated by a uniform distribution in the range [0; 2*PV_{peak}]. Then, measurement-based profiles were added to customers where PV was assigned by the algorithm. On the line between node 2 and 3, a DSO operated energy storage system was installed with 10 kW nominal power (the capacity is assumed to be sufficient). The placement of the storage system was a given parameter, the DSO already installed it at that point. While it is not the optimal place for voltage control (as it will be analyzed in Section 4.4), the scope of the DSO pilot has other objective functions (energy management etc.) and had to keep in mind the construction constraints, so this point was considered acceptable from every viewpoint.

Table 1. Electrical parameters of the location

Circuit	Total length [m]	Number of customers [-]	Nominal current [A]	Maximum Voltage drop [V]
1	581	42	116.6	16.1
2	358	21	92.7	13.2
3	617	38	148.5	12.0
4	896	41	157.3	27.3

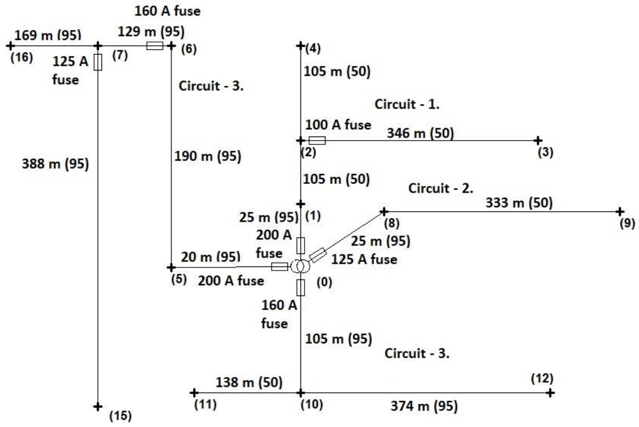

Fig. 1. Grid topology of the location.

3. Simulation Cases

During the analysis, 4 different main scenarios (and within these several options) were ran on the prepared model. These were the following:

- Scenario #1 – Initial state: loads unchanged, known PV units and energy storage device connected to the network but not in operation.
  - Option #1 – Weekday load profile, PV units are not producing, energy storages are not in operation.
  - Option #2 – Weekend load profile, PV units are not producing, energy storages are not in operation.
- Scenario #2 – Examining effects of household-sized power plants. Consumer loads unchanged, known PV units and energy storage devices are not connected to the network.
  - Option #1 – Weekday load profile, PV units producing, energy storages are not in operation, 50% penetration.
  - Option #2 – Weekday load profile, PV units producing, energy storages are not in operation, 25% penetration.
  - Option #3 – Weekday load profile, PV units producing, energy storages are not in operation, 12.5% penetration.
  - Option #4 – Weekend load profile, PV units producing, energy storages are not in operation, 50% penetration.
  - Option #5 – Weekday load profile, PV units producing, energy storages are not in operation, 25% penetration.
  - Option #6 – Weekday load profile, PV units producing, energy storages are not in operation, 12.5% penetration.

- Option #7 – Weekday load profile, PV units producing, energy storages are not in operation, PV units used in voltage control according to constant cos(φ) = 0.95.
- Option #8 – Weekday load profile, PV units producing, energy storages are not in operation, PV units used in voltage control according to the German Verband der Elektrotechnik, Elektronik und Informationstechnik (VDE) standard 4105.

- Scenario #3 – Examining DSM to achieve voltage control. Consumer loads unchanged, known PV units and energy storage devices connected to the network.
  - Option #1 – Weekday, PV units producing, energy storages are not in operation, 50% penetration. Control triggered by voltage problem on the low voltage side of MV/LV transformer, DSM comes from every circuit.
  - Option #2 – Weekday, PV units producing, energy storages are not in operation, 50% penetration. Control triggered by voltage problem at the end of the low voltage grid, DSM cones from every circuit.
  - Option #3 – Weekday, PV units producing, energy storages are not in operation, 50% penetration. Control triggered by decreasing load of low voltage grid below limit, DSM only comes from related lines.
- Scenario #4 – Applying energy storage to achieve voltage control. Consumer loads unchanged, known PV units and energy storage devices connected to the network.
  - Option #1 – Weekday load profile, PV units are not producing. Voltage control with energy storage device according to values of low voltage busbar and the end of the circuits. Maximum allowed differences are +8%, -7% (planning limits in Hungary).
  - Option #2 – Weekday load profile, PV units producing, 50% penetration. Voltage control with energy storage device according to values of low voltage busbar and the end of the lines. Maximum allowed differences are +8%, -7%.
  - Option #3 – Weekday load profile, PV units producing, 50% penetration. Voltage control with energy storage devices according to values of its own busbar. Maximum allowed differences are +8%, -7%.

The created stochastic simulation is suitable for running in any similarly built scenarios different from the above if needed. Previously, the technologies and methodologies were presented that can be critical in installing, operating, controlling smart grids, at the same time those can help realize assumed and expected technical and economic advantages. The different scenarios were put into two categories: the first group examines the cases and replicates and simulates effects of technologies, while the second focuses on the solutions given to these effects. As the grid model and the examining methods cannot be checked manually due to the complexity, validation of the baseline model and simulation scenarios is a necessary and inevitable task during the process.

Table 2. Summary of every scenario

Scenario	Case	Day	DSM	PV pen Δ [%]	Storage	U control
1	1	Wday	-	0	0	-
1	2	Wend	-	0	0	-
2	1	Wday	-	50	0	-
2	2	Wday	-	25	0	-
2	3	Wday	-	12,5	0	-
2	4	Wend	-	50	0	-
2	5	Wend	-	25	0	-
2	6	Wend	-	12,5	0	-
2	7	Wday	-	50	0	cos fi
2	8	Wday	-	50	0	VDE
3	1	Wday	MV/LV point	50	0	-
3	2	Wday	end point	50	0	-
3	3	Wday	Trigger is the circuit	50	0	-
4	1	Wday	-	0	LV U trigger	-
4	2	Wday	-	50	LV U trigger	-
4	3	Wday	-	50	local U trigger	-

4. Results of Selected Scenarios

In this section, the results of the simulations and deductions will be presented. As numerous simulations were performed, not all results of the scenarios will be presented: the focus will be on the cases that offer research interest.

In the initial state, the present behavior of the grid was examined by focusing on the voltage ratios at specific load branches. According to the load profiles, it is important to distinguish the weekdays and weekends due the characteristic differences that are present in customer behavior. In further examination cases, effects of specific technological solutions are discussed through the comparison of scenarios to each other and/or to the initial state.

4.1. Baseline case – Scenario #1

In this case no new unit is connected to the grid, even the already installed PVs are neglected. Based on the simulation results, it can be stated that voltage can decrease significantly due to real power consumption on longer lines, while real power production would increase voltage. A grid with higher load voltage changes will follow this trend, while the electrical losses will appear more significantly as well. It is not surprising, since as a result of higher current, greater loss will be present on the electrical network. During the check of the initial state, not only weekdays but also weekend loads were examined (higher load and different curves). According to the assumptions, correlation between voltage, load and electrical losses remained, the only difference from weekdays was that the profile had the ordinal weekend load pattern. Fig. 2 depicts the per unit voltage around the different branches of the network during the day (C is the circuit, N is the node as defined in Fig. 1).

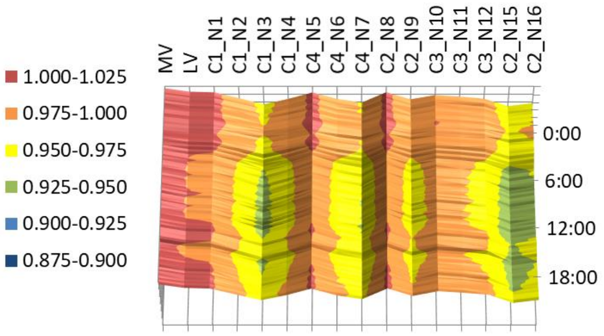

Fig. 2. Voltage value "heat map" at different branches of the topology throughout the day.

The most critical part is the furthermost endpoint, the end of the feeding line of node 15. Here voltage drop reaches 6% during the peak load phase at around 18:00, which lies close to the 7% limit of the guaranteed service restriction of the DSO (service quality limit), though it does not exceed this limit. Based on the results, a potential settlement development or further electrification with high power devices may lead to voltage problems. Therefore, the initial state itself carries possibilities for smart device pilot projects as network development alternatives for conventional solutions.

4.2. Effects of PV generation and ANM – Scenario #2

After an overview of the initial state, the increasing household size power plant penetration was analyzed, as in the future gradual PV penetration increase can be projected on the site. The household size power plant produces a different percentage of annual electricity demand of consumers connected to a given node in different scenarios. With 25% penetration, the voltage increasing effect of producing appears. However, the highest increase does not reach the peak of decrease (~6) caused by the load, its peak is 4% at 12:00. The loss is similar to the 12.5% penetration case. An interesting observation is that here a loss minimum appears during the day, due to the decrease of currents because of the local consumption of produced electricity that are smaller than dawn hour (low load) values. With 50% penetration (Fig. 3), the household size power plant generation significantly exceeds the voltage increase limit of the guaranteed service, goes above even 13% at peak. This kind of spread modifies voltage behavior of the grid basically, as the voltage increases could stay continuously beyond 7% in the 8 A.M to 4 P.M. 8-hour interval, during the hours of the PV production. About the losses, the current infeed of the generators becomes dominant (the direction of power flow changes on the MV/LV transformer during the daytime), compared to previous cases the losses grow significantly. So, in general, the spreading of PV systems decreases the network losses up until a dedicated point (over 25% of penetration), but after that threshold, the losses start to increase at the MV/LV transformer area level. Voltage increase is most critical at the end of circuit 1 (node N3). At nodes N2-N4, N15 violation of guaranteed service would happen during peak production, so voltage problems can be detected at different line sections, not only at endpoints.

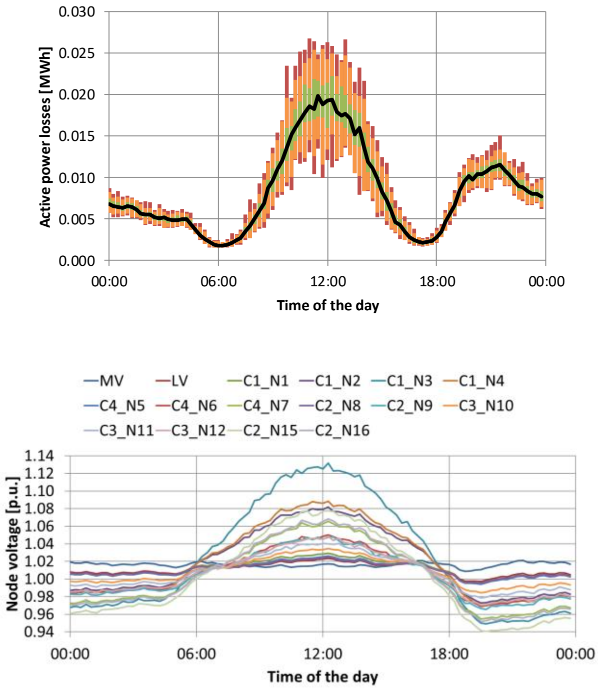

Fig. 3. Losses (upper graph) and node voltages (lower graph) in the case of high PV penetration.

In general, voltage drop is more significant during peak load periods (~1%, difference) in weekend profiles, voltage increase due to household-sized power plants is very similar to weekday profiles, no significant difference can be observed. Network loss is higher in weekend profiles, in different scenarios it exceeds around 14–21% the weekday cases, the main reason for that is the profile difference.

The spread of household-sized power plants certainly leads to significant voltage problems in the grid. However, these can be handled by integrating the PV to the controlling. As a first solution, we examined how the voltage differences changed in weekday profiles with 50% penetration by adjusting the cosφ value to 95%.

The first remarkable difference is the loss increase by 43% compared to the weekday profile with 50% penetration. The reason of this is the increasing current due to reactive power control. Compared to this, the effect on voltage is not so significant, the mostly affected area is the end of line No. 1. where voltage is increased by 12%, control meant only 1% voltage decrease in this case. At end point N15, a positive effect can be observed, where voltage increase is reduced by

3% (5% peak value instead of 8%), so this line is not as close to the limit of guaranteed service (this is the most critical line according to voltage drop; therefore, this control reduces voltage variance in this simulation case). The reason for the reduced efficiency of reactive power control is caused by the impedance relationships of the grid , the high R/X ratio: the network is highly resistive, so active power has the most significant effect on voltage, while reactive power control – though its positive effect can be detected – has lower effects in this environment compared to either high or medium voltage networks. If we take into consideration the increased electrical losses due to the reactive current component increase, using this type of simple characteristic either in Hungary or in any network with similarly high (even around 10) R/X ratio low voltage overhead power line network is not an appropriate solution from the technical point of view. As an alternative, the current inverter control solutions in Germany was implemented, which is defined by VDE 4105 as it can be seen in Fig. 4 [41]. It was observed with weekday profiles and 50% penetration.

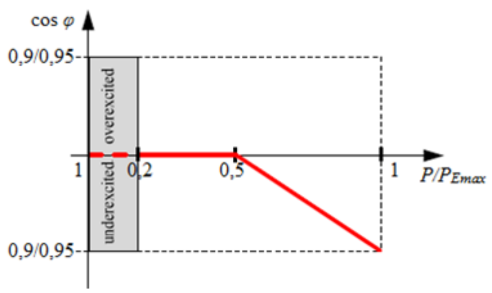

Fig. 4. VDE 4105 voltage control characteristic.

For systems with apparent power below 3.68 kVA, the power factor can be set between +/- 0.95 according to the DIN EN 50438. If the apparent power is between 3.68 and 13.8 kVA, a cosφ(P) characteristic can be defined by the DSO between +/- 0.95 power factor, while over 13.8 also a characteristic can be applied, but the range is between +/- 0.9 for the power factor, as Fig. 4 depicts. This control approach reduces the losses significantly (by around 11% in a day, the curve is similar to Fig. 3, see Fig 8 in the following section for network loss comparison), but still not enough to solve all the voltage increase issues. Figure 5 depicts the reactive power consumption of the MV/LV transformer area.

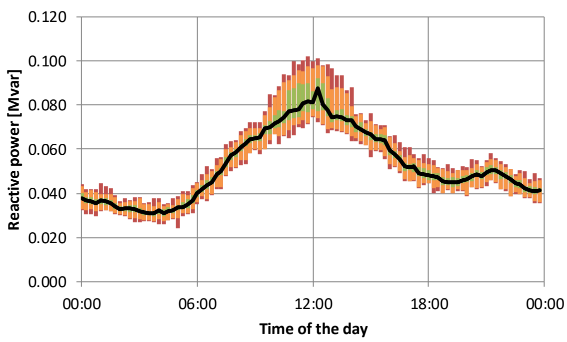

Fig. 5. Reactive power consumption of the location (MV/LV substation area) during the VDE 4105 control

4.3. DSM – Scenario #3

DSM was in the scope of the next scenario. It is practical to evoke the basic problem: new technological solutions appear on the distribution network, increasing load, producer units, so integration issues came up. Therefore, tasks will appear primarily to keep the voltage in the range of predefined limits. This can be changed either directly or indirectly. One of the most widespread solutions is the indirect control through the load, known as DSM. The actual way of the implementation – either by technical or economic incentives – is not the subject of this research, the purpose is to analyze the effects of this controlling possibility. (It is important to know that it is not a new method, as Ripple Current Receiver and Tone Frequency Receiver systems provide more decades of experience for DSOs in this field. New technologies imply the value added by feedback, as due to the setpoint changes the realized interaction will be recognized by the DSO. Indirect control can be a tariff incentive, having its best practices as well, though being analyzed in detail here.) Loads behave according to the predetermined and assigned profiles on the analyzed part of the grid, while the PV systems have the profiles from a database. The loads reduce the power consumption in the case of voltage limit violation (measurement and control assumed to be available). The actual flexibility constraints are not considered here, as it is not the scope of this technical impact research, but the activations do not curtail much power in this case study.

At the first running sequence weekday data was assigned, the energy storage was neglected (only active in Scenario #4), while PV units are producing to the network. In this case, PV penetration is 50%. DSM is available, though it was not applied due to the control method. The DSM activation was based on the voltage problems on the low voltage terminal of the transformer. Since voltage was in the range of the standard limits, no operation took place.

In the next option, the energy storage was still neglected while the level of household sized power plant penetration was 50%. DSM was activated by the circuit's endpoint voltage (C1_N3) exceeding the allowed upper threshold. Consumers taking part in load control were chosen evenly distributed from the whole service area, which means that only part of them were connected to the circuit, where voltage limits were violated. Figure 6 depicts the results. The heat map of node voltages shows that during peak production hours, endpoint voltage of the weakest node (C1_N3) could be kept at constant level (1.08 p.u.), thus limits of guaranteed service were not violated. To achieve this, varying level of load control had to be applied between 6:30 AM and 4:30 PM. The average maximal power that had to be considered for DSM activity in the service area was ~150 kW, but in certain cases it has reached more than 320 kW. This clearly indicates that choosing the controlled loads in a uniform (evenly distributed) way is not the most efficient option. If adequate measurements and means of communication are available, individual addressing of controllable loads would results in the involvement of fewer consumers, thus limiting the active power that has to be controlled.

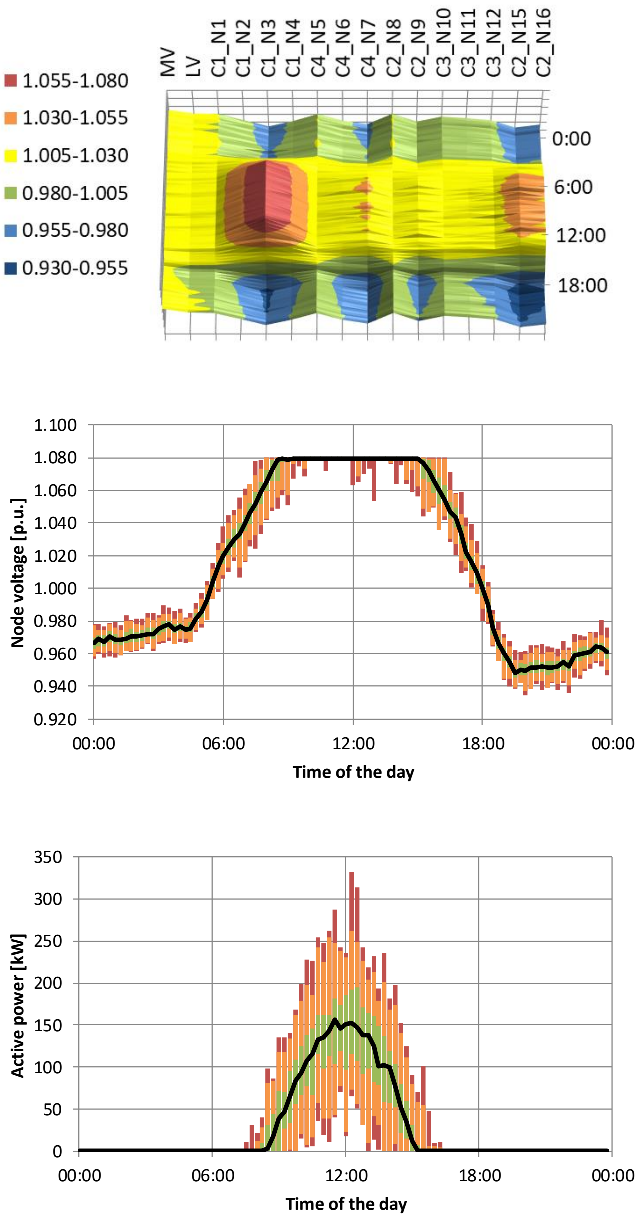

Fig. 6. Results of the DSM (Scenario #3)

4.4. Energy storage – Scenario #4

In the following part, the effects of the operating battery storage system were analyzed, which has a voltage control target function (P(U) droop control with deadband), in three different scenarios. In all cases, weekday profiles were used for modelling the load. The connection point of the device is fixed near node 2, while it has 10kW nominal power.

In the first case, no household sized power plant is connected to the grid, the storage observes voltages on the low voltage busbar of the transformer and at the end of the lines. Based on its target function, the ESS attempts to keep voltages in the range of +8% and -7%. Losses on the grid decreased in this case (see Fig. 8. in the following section for comparison). Like the baseline cases before, there was no violation of the guaranteed services (only small voltage values of node 15 get close to the limit during peak load periods), using storage device in this scenario has no significant effects, there is no need for direct voltage control.

As the second storage scenario, 50% penetration is assumed with similar control method to the previous one (low voltage busbar of the transformer and line end points, with limits of guaranteed service). The results are depicted in Fig. 7. The greatest difference is 13%, which still means violation of the guaranteed service. At problematic nodes (node N2-N4, node N15) which are further from the storage, no significant change can be observed in voltage peak values. Electrical losses decreased insignificantly compared to the reference case (PV with 50% penetration). With this control strategy, the storage unit operates more, since more voltages are given as an input. The placement of ESS obviously has effects on the efficiency of voltage control – the placement here was set according to the DSO preliminary calculations, which considered many objective functions and circumstances (construction, available area etc.).

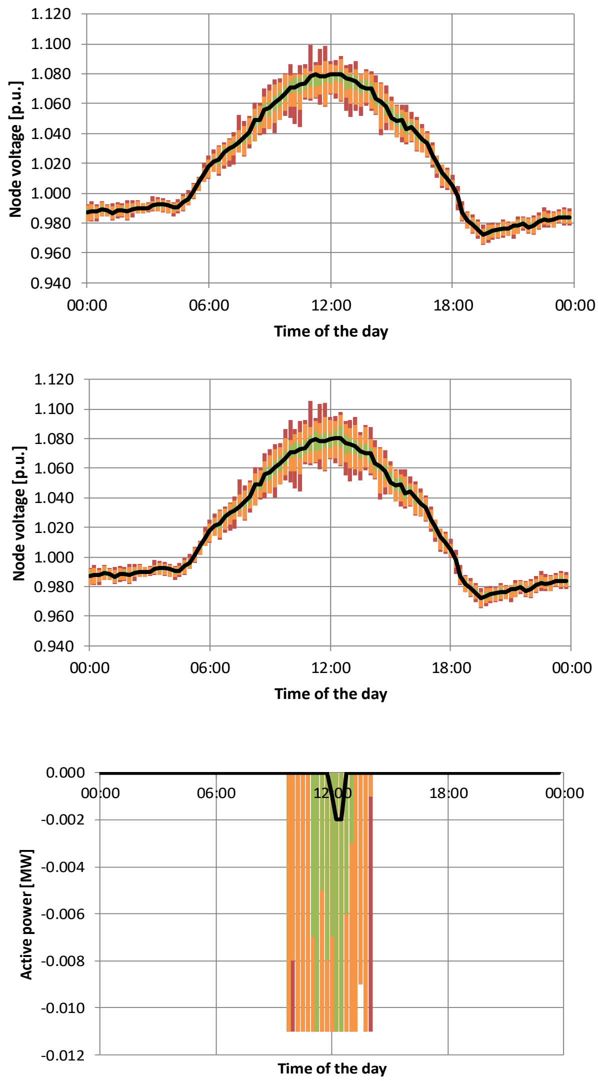

Fig. 7. ESS operation results at the connection node (near N2): voltage without ESS, with ESS operation, active power curve respectively – Scenario #4

In the third case, the storage controls based on the measured voltage of its own connection point and keeps this in the range of +8% and -7%, with 50% household sized power plant penetration. Results are similar to the previous scenario; storage unit does not optimize the voltage near critical nodes. However, these values are not available at the setting of working point, the device observes only its connection point. As a result, its utilization is worse, and no effects can be observed on other circuits. Therefore, the preliminary placement and the nominal power of the ESS should be recalculated by the DSO – this was a practical result of these simulation studies, because the DSO deployed a 25 kVA, 140 kWh system based on the conclusions since then. Combining Scenario #3 and #4, namely DSM and storage, would have great potential, but in this case study – mainly due to the placement of the storage – would not provide further valuable results; therefore, this case is not analyzed here.

5. Evaluation and Conclusions

The In this research, simulation studies were conducted with the main purpose of presenting the effects of new, smart grid technologies on a real-life distribution network. It can be assumed that these opportunities, solutions will not appear suddenly at once on the grid, but rather with a varying steepness, but continuous transition. Owing to that, there is both time for preparation and practical analysis of the assumed effects. Both of those have a great significance: change and technical development are inevitable due to the changing environment, where the distribution network becomes active. Impact studies can have significant value on strategic planning level, to identify pilot projects and have an adaptive approach on the internal and external effects.

Based on the simulation studies, some conclusions can be made that can foster future operation, investment support and design:

The survey confirmed that household sized power plant production can have beneficial effects on grid voltage and electrical losses to a certain penetration level. However, from a dedicated point, it generates significant control necessity and the increased currents from the generators also lead to higher losses. This limit depends on the parameters of the grid, strength of the the grid and the overall power of the consumers; therefore, giving a general limit that is either inaccurate or misleading. Simulation tools have the ability to carry out an appropriate analysis. The stochastic approach proposed in this study is feasible for in-depth analysis to calculate the effects and plan the proper development – also considering smart technologies.

Curtailment of renewable production can be justified from a technical point of view in some extreme load cases, though it is a sensitive topic from the energy policy point of view – renewable generation should be maximized, while here the customers – who should be in the centre of the whole energy industry after the energy transition – should be remunerated for the curtailed energy. It is advisable to analyze the extreme cases and to prepare to facilitate renewable production with the least cost principle on a system level, considering network constraints, customer preferences and every technical option. If necessary, with properly sized storages and/or with DSM.

Regarding grid losses, distributed production has an indirect positive effect at first, but a steep increase can be observed with the growing penetration levels. Table 3. summarizes the relative changes in network losses in the introduced scenarios and options. This behavior is important from an attitude forming point of view and can contribute to improving corporate culture and acceptance in DSOs. There is one risk factor to be noted: with the inclusion of indirect loss reduction caused by the household sized power plants, an improved acknowledged cost (used in Europe to remunerate DSOs for the network loss procurements) calculation method with several assumptions and natural inaccuracies is needed, due to the measurement deficiencies. It would be beneficial to draw the regulators' attention to this problem to prevent DSOs to face disadvantageous situations beyond their own fault.

Table 3. Comparison of network losses in each scenario

Scenario of the simulation	**Option of the simulation**	**Relative losses compared to the base case (p.u.)**
Scenario #1	Option #1	0.923
	Option #2	1.020
Scenario #2	Option #1	0.798
	Option #2	0.484
	Option #3	0.593
	Option #4	0.908
	Option #5	0.586
	Option #6	0.693
	Option #7	1.140
	Option #8	0.892
Scenario #3	Option #1	0.799
	Option #2	0.595
	Option #3	0.679
	Option #4	0.877
	Option #5	0.768
	Option #6	0.798

Concerning PV production, it can be stated that with 12.5% penetration, the load defines the loss curve during the day, so effects of production cannot be recognized either in profiles or in voltage values. With 25% household sized power plant ratio effects in loss reduction is significant with around 4% voltage increase at the most critical nodes. At 50% penetration, guaranteed service violations appear at 3 nodes, 13% voltage increase was observed in the case of extremes. Results confirm that the distributed production has a positive effect on grid relations to a certain extent, beyond this extent negative effects are increasing by calculations as well.

It is important to note that PV production does not affect the highest voltage decrease values due to load, since it appears in the evening peak period. However, this can cause a problem at the line of node 15 – the difference from the nominal voltage is around 6%-7%, but there could be a raise by 5% as well, so the variability is high. The temporality – as in the case of consumption/production concurrency index – can significantly affect the gird relationships, as sometimes it means opposite effects, which should be taken into account through time series load flow simulations. The first type inverter control, reactive power provision with a fixed power factor is an often-recurring suggestion as a control option. An important experience from simulations is that with these high R/X ratios it is not efficient, increasing losses and it cannot restore voltage below the guaranteed service limits. Voltage based active power control methods could lead to solutions, but the curtailed energy remuneration should be taken into account in the planning of such service.

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