OPTIMAL DISTRIBUTED HYBRID-STORAGE AND VOLTAGE SUPPORT OF PHOTOVOLTAIC SYSTEMS

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ABSTRACT

Due to climate change and limitations of fossil energy sources, political goals that lead towards a massive increase in renewable and distributed generation, e.g. photovoltaic (PV), wind power, etc. have been proposed. However renewable generation units increase the volatility of electricity production, are only conditionally controllable and are characterized by low full load hours. These negative aspects challenge the integration of renewable energy sources into the electrical grid. Remedial measures that can be applied are the integration of hybrid energy storage in the existing energy system and the use of installed PV systems for voltage support. Hybrid energy storage balances deviations in generation and load. By providing reactive power, PV systems can limit the increased voltage level, which can be observed especially in weak grids in case of a reversed load flow due to a high power production. This paper is going to describe how to achieve a decentralized generation-load-balance by coupling the existing infrastructures (electrical, gas and thermal networks), using decentralized hybrid storage, enabling a massive integration of renewable energy sources into electrical distribution systems, as examined in the project "Symbiose". Parallel to the work of "Symbiose", benefits of voltage support by PV systems in the German distribution network will be presented.

INTRODUCTION

The energy supply networks for power, gas and heat form the backbone of the current energy supply system. Traditionally, the energy flow of these networks is determined hierarchically, based on a top-down principle. This means that in most of the cases, energy flows from upper levels to lower levels of existing energy infrastructures. Currently the gas and electrical infrastructure are only coupled in one direction, with energy flowing from the gas network to the electrical one via power generation from gas turbines. Gas, electrical and thermal grids are connected through power and heat generation by combined-cycle plants.

Due to the increased installation of renewable energy sources, especially into the electrical distribution grids, load flow issues such as load flow inversions, increase in voltage and overloading are occurring. Renewable generation can exceed the local electrical demand during a period of high renewable supply. This results in the inversion of the load flow to the upper voltage level. Compared to this, during night hours and periods of a low or no renewable supply, the power to cover the electrical demand is delivered from the upper voltage levels. The inversion of the electric flow loads additionally the electric lines and results in an uncertain electrical supply. Another issue, caused by the integration of renewable energy sources, is elevated voltages, due to the high share of renewable power production in weak grids.

To enable stable grid operation, the generation-load balance has to be even at any time step. Currently, the uneven generation-load balance is partly being equalized by large-scaled electrical storage systems (pumped storage power plants and storage power plants). Within the project "S4MG" [1], it was determined that the potentials of Austrian pumped storage power plants are not sufficient to enable long term storage of electricity, if Austrian electrical supply would consist of 100% renewable generation. The lack of needed electrical storage capacities requires innovative solutions to enable a large-scaled, flexible and long-term storage of electricity. A possible solution that can be introduced is coupling the existing energy infrastructures. Based on this, the project "Symbiose" was conceived. The idea of the project "Symbiose" is to examine whether the described problems of the electrical grid, caused by the inclusion of renewable energy sources, can be solved via decentralized hybrid storages by bidirectional coupling of the existing energy supply infrastructures. The hybrid storage couples different infrastructures throughout a transformation process of different energy carriers. The work on the project "Symbiose" will be presented in this paper. It is complemented by the work of the company Energynautics GmbH, where the benefits of different control options for voltage support of PV systems are evaluated.

REPRESENTATIVE MODEL REGIONS

The main work in the project "Symbiose" is performed on two representative model regions (a typical urban and a typical rural region). The corresponding electrical and gas distribution systems of these regions have been chosen by our project partner "Voralberger Kraftwerke AG" (an Austrian energy supply company). Based on these distribution networks, coupling of existing infrastructures for different grid configurations is evaluated.

Energy Infrastructures

The relevant electrical grid parameters have been provided by our project partner. Both model regions are operated radially. The rural electrical grid is operated with a supply voltage of 27.4 kV and the urban electrical grid with the supply voltage of 10.3 kV. The investigated rural region consists of 94 nodes (transfer points) and the urban region of 66 nodes, which feed the low voltage (LV) grid, in the case of low decentralized generation. The residential areas of the representative model regions are being fed over these transfer points. The direction of the load flow can reverse, during particular time slots, in case of a surplus of decentralized generation. The electrical demand, of both representative regions, is modelled according to real measured data from the outgoing lines of a distribution station. The maximum load, summed over the outgoing lines, is 12.1 MW in the rural region and 17 MW in the urban region. The future demand increase is modelled according to three scenarios with a demand increase rate of 0.5 %/a to 1.5 %/a. The already existing decentralised power generation is included in the electrical model, based on the provided generation profiles. Currently there is just one decentralised power producer in the representative urban region with an apparent power of 120 kVA. The rural area consists of 27 decentralised power plants. Six small hydro power plants feature a peak generation of 100-960 kW.

The gas grid parameters of the provided model regions have been provided by our project partner. The reference pressure of the provided gas grid varies from 0.045 - 3.8 bar. The gas grid is represented in the Symbiose optimization model by coupled nodes, where an interface between electrical and gas grid is possible. According to the requested quality of injected gas, an intersection of these two infrastructures can only occur in the high or medium pressure grid. The natural gas flow in the distribution grid is lower during the summer period than during the winter period. In addition to that, the natural gas flow in high pressure grids is higher and more evenly distributed over the year than the gas flow in low and middle pressure grids. Hence, an intersection of electrical and gas grid is preferred in the high pressure grid, in order to satisfy the quality of the gas mixture. Therefore one coupled node between the electrical and gas grid is modelled in the rural region and 3 coupled nodes in the urban region.

The representative model regions do not feature area-wide distribution district heating networks. Thus a residential area heat demand is modelled to underline the synergy-effects of different energy infrastructures. The modelled thermal demand is supplied by existing heat plants or by the waste heat of different storage technologies or transformation processes.

Potential of renewable power generation

A full description of the accomplished work regarding the potential of renewable power generation in the provided model regions is given in [2]. The maximum PV potential that can be installed is 11.5 $\mathrm{MW_{peak}}$ in the urban model region and 33.7 $\mathrm{MW_{peak}}$ in the rural region. The wind potential is investigated just for the rural model region. The maximum wind potential that can be installed varies from 5 -10 MW. The potential of biomass is calculated for the rural model region. A biomass potential of 13.4 GWh/a is calculated. This energy corresponds to 670 kW of electrical power, if a biomass power plant, characterized with an efficiency of 30% and 6000 h full load hours, is operated.

Energy versus Power

The maximum potential of renewable energy sources of the urban region equals to 11.5 $\mathrm{MW_{peak}}$ of photovoltaic power. With this installed capacity 11.5 GWh of energy can be produced, representing 14% of the overall annual electrical demand of the urban model region. The average electrical demand, calculated from the annual electrical demand, equals to 9 MW. That means 123% of installed photovoltaic power is required, in order to achieve the 14% renewable energy coverage. The situation in the rural area is much more critical. The maximum potential of renewable energy sources in the rural region sums up to 47 $\mathrm{MW_{peak}}$ of photovoltaic, wind, hydro and biomass power.

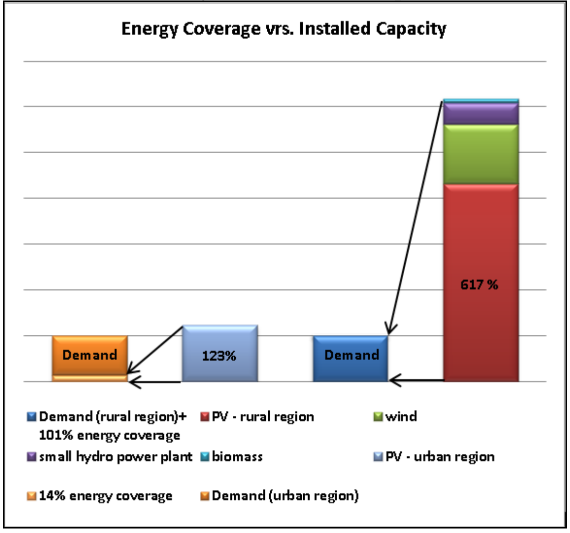

Figure 1: Referenced regenerative generation capacity and demand for model regions

This power contributes 67.4 GWh of energy. In this case, 100% of annual electrical demand is covered by this generation. The average electrical demand equals to 7.6 MW. That means 617% of installed renewable power is required in order to achieve the 100% renewable energy coverage. A referenced comparison between the average electrical demand and the required renewable capacity is reproduced in Figure 1. It is obvious that significant renewable capacity is required to be installed in order to cover the necessary energy demand. The potential of renewable generation in the rural region is much higher than in the urban model region, because of the geography, which enables a much bigger use of renewable sources.

OPTIMAL DECENTRAL STORAGE TECHNOLOGIES

Storage technologies are required to enable the capping of surplus renewable energy. The following optimisation methods are developed in order to determine adequate storage technologies for different model regions.

Technological-topological optimization

A pre-optimization model is implemented to determine topologically where storage technologies for representative electric model regions are required. The pre-optimization model is implemented via a bidirectional interface between the software tools PSS©SINCAL and MATLAB©. The electrical load flow calculations, based on times series of residual loads (future demand consumption minus renewable production), are calculated using PSS©SINCAL. First residual load calculations and load flow calculations show that significant energy surplus is achieved and that load flow inversions to the upper voltage grid are occurring. A cumulated residual load flow in the rural model region for the characteristic summer week is presented in Figure 2. The model does not represent an in terms of power self-sufficient MV-grid.

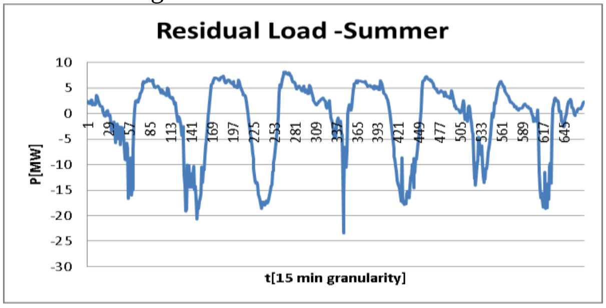

Figure 2: Cumulated residual load in the rural model region for the representative summer period

Via the bidirectional interface between MATLAB© and PSS©SINCAL an optimal position and size of a storage portfolio (storage demand) is determined. The model horizon of the pre-optimization model is one week with a time granularity of 15 minutes. The pre-optimization is performed for three representative time periods (summer, transition period and winter) for each year between 2012 and 2025. Capping residual loads with minimum cost is the defined objective function for the technological-topological optimization model. In addition to that, the defined constraints of the model have to be fulfilled at each time step, especially the constraint of allowed loading of power lines. If overloading of power lines occurs, the optimization starts positioning and sizing the storage portfolio properly. Each storage portfolio is modeled with a fix cost function and each storage activity contributes to the overall objective function of the model.

The load flow calculations lead to the result that overloading of lines of a radial aligned grid rises with decreasing distance to the high voltage transfer points. This behavior correlates with the storage demand of the model region. The reason for that lies in the radial alignment of the model regions. Such an alignment of the electrical grid leads to the correlation of renewable generation, due to the geographical proximity of renewable producers.

Hybrid storage technologies

Hybrid storage couples different infrastructures through a transformation process of different energy carriers. The investigated storage technologies for the representative model regions are pictured in Figure 3. Characteristics of examined storage technologies are not described in this paper, but the use of different storage technologies in the project "Symbiose" will be explained.

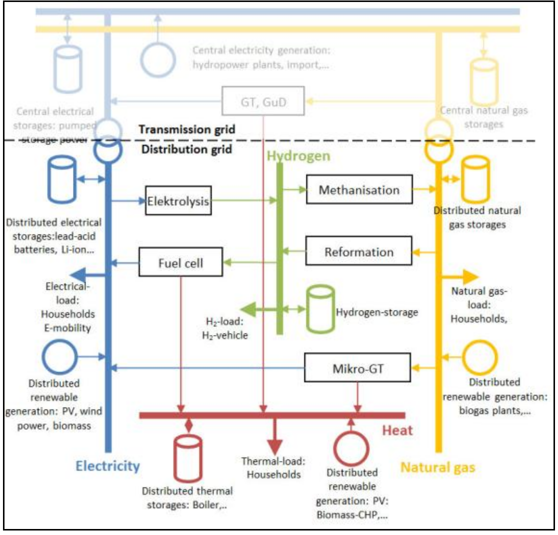

Figure 3: Coupling existing energy infrastructures through distributed hybrid-storage systems

Some storage technologies behave similarly, therefore a common denominator between characteristic parameters of all storage technologies is found in order to realize a consistent modelling of storage technologies. A consistent modelling of storage technologies is mandatory to realize an acceptable optimization time for the main optimization model. Hybrid storage is modelled in the programing tool MATLAB©. The hybrid storage model consists of parameters such as efficiency, power, energy content (initial and maximum) and costs. The storage activity is additionally determined by special charge and discharge characteristics. This means, for example, that the storage activity of a battery is modelled according to characteristic charging curves of an IU charger. The hybrid storage model delivers the following output parameters: the available storage content with respect to the previous time step, alternative material flows, such as heat, H_2 or synthetic gas and minimum and maximum storage power for the next time step with respect to the current storage content in dependency of the characteristic charge/discharge characteristics. Based on the technological-topological optimization, a required storage capacity for each time step of the model horizon and for each MV/LV node of the representative model region is defined. Before the optimal distribution of required storage capacity is identified, a basic storage portfolio of possible storage technologies for each grid node is defined. The basic storage portfolio for each grid node is determined by the required storage size and infrastructure requirements for each grid node. The portfolio of hybrid storage technologies is more flexible in the urban region, because of the available grid infrastructures. Hence the coupling of different infrastructures for the rural region is limited. After the definition of a basic storage portfolio, an optimal distribution of storage capacity within the storage portfolio is calculated. The required storage capacity from the technological-topological optimization functions as an input parameter. The optimal distribution of the storage capacity is again performed via an interface between PSS$^{\copyright}$SINCAL and MATLAB$^{\copyright}$.

PV SYSTEMS FOR VOLTAGE SUPPORT

As already mentioned in the introduction chapter, an increasing amount of renewable power generation is not just driving the distribution lines and transformers to their thermal limits, but also increases the voltage along the lines, which might lead to a voltage rise outside the allowed boundaries (typically plus/minus 10 % of nominal voltage). This can be especially observed in weak grids in the case of reversed power flow. A possible solution for that could be to use the installed PV systems for voltage support.

To investigate this issue and the voltage support possibilities of PV systems, a PV model has been developed by the company Energynautics GmbH [3]. The model is built in DIgSILENT PowerFactory and can be used to simulate dynamically the behavior of the PV System in combination with the electrical distribution grid. Three typical German distribution systems have been selected for this evaluation. The first one is characterized by a typical situation in the countryside where a few farms are supplied by insulated overhead lines. Based on an evaluation of the typical roof areas, the installed PV capacity is set to an average 25 kW$_{\text{peak}}$ per connection point. The second category is a small village, where underground cables are used, the distance between the houses is lower and the average PV system size amounts to 20 kW$_{\text{peak}}$. The final category is a distribution grid in a suburb. The house distance is again lower and the average PV size amounts to 10 kW$_{\text{peak}}$.

These three categories are simulated for different voltage support options, not only for what is required in the German LV grid code, but also for other options, such as Q-control, voltage control, and droop control. The simulation results of Energynautics are in line with the results of the “Symbiose” project: the biggest problems arise in the countryside, as the lines are rather long and the PV systems very large. Depending on the overall amount of PV, voltage support of the PV systems can help to reduce the voltage problem. However, a high reactive current is created, which puts additional loading on the cables and thus increases the losses on the lines.

The best results can be achieved when applying a coordinated Q-control, however this would lead to high communication needs, which are too expensive from a cost-benefit perspective. The second best control scheme turned out to be the power factor control depending on the power output. This is a fairly easy system to install and therefore from a practical point of view the best solution. In the category “village” the benefits of voltage support are also recognizable. In the category “suburban” the voltage problem, due to shorter lines, arises together with overloading problems, which cannot be solved with reactive power control. In this case voltage support cannot help to avoid or postpone a grid upgrade or the use of storage.

CONCLUSION

The surplus of renewable energy sources is more present in the rural region than in the urban region. On the other hand, the coupling of nodes of different energy infrastructures is placed rather in the urban region than in the rural region. The overloading of electric lines in a radially aligned grid rises with decreasing distance to the high voltage transfer points, due to the concurrency of renewable generation. For the next phase of the project “Symbiose”, an optimal distribution of storage portfolio and storage capacity within the storage portfolio will be calculated. Hence more results about the allocation of different coupling nodes are expected. Further on the region-based results will be scaled to the dimension of a nationwide area structure. Regarding the voltage support, best results are achieved in the model regions “country side” and “village”. The PV systems do not solve the voltage issues in the region “suburban”. Therefore other measures such as hybrid storage have to be considered.

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