Automated Smart Grid Planning considering Flexibility Options and Voltage Regulating Assets

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ABSTRACT

Due to the growing number of distributed energy resources (DERs) and new loads, such as electric mobility, distribution system operators (DSOs) are facing an increasing complexity. Manual processes based on basic planning principles are confronted with new and potentially cost efficient technology options in the context of smart grids. These smart grid options comprise voltage regulating assets as well as flexibility options, such as flexible loads or planned DER curtailment. Their consideration implies the need for more elaborate planning and evaluation methods. In order to cope with these options, this paper presents a newly developed automated planning tool which can be incorporated into DSOs' existing processes and IT infrastructure. The planning tool uses an optimization algorithm to handle the increased complexity and to provide an automated support for planning decisions of DSOs. The exemplary application in a real case study demonstrates the significant potential for cost reductions.

INTRODUCTION

The number of distributed energy resources (DERs) in Germany and worldwide is continuously increasing. Distribution system operators (DSOs) are facing the challenge of integrating these DERs into their grids. Conventional grid expansion measures are no longer the only option to cope with this challenge [1], [2]. There are a number of alternatives emerging that enable a more efficient use of existing grid infrastructure by employing smart grid components and flexibility options [3]. Numerous research demonstration projects have already proven the technical feasibility of such concepts [4]. However, an efficient approach to integrate these new options into grid planning procedures in DSOs' daily operation does not yet exist.

Traditionally, grid planning in distribution grids is characterized by manual approaches using basic planning guidelines. Grid models are manually adjusted by grid planners and analyzed using commercial power flow calculation software (cf. Fig. 1) [5]. These manual procedures are no longer feasible with an increasing number of DERs and more changes in load patterns, caused e.g. by electric mobility. A more automated approach is needed.

Furthermore, novel smart grid options cannot be incorporated in basic planning guidelines. They demand a more extensive consideration of grid operation already at the planning stage, since new operational degrees of freedom are introduced by e.g. storage systems, voltage regulating transformers or DER curtailment.

The objective of this paper is to present and demonstrate a newly developed planning tool for smart grids addressing these challenges. In order to achieve the objective this paper uses the following structure. The available technology options for smart grid planning are analyzed in a first step. Secondly, the grid planning tool, the associated software environment and its optimization algorithm are introduced in detail. Finally, the planning tool is applied to a real case study in a medium voltage (MV) grid in Southern Germany for demonstration purposes.

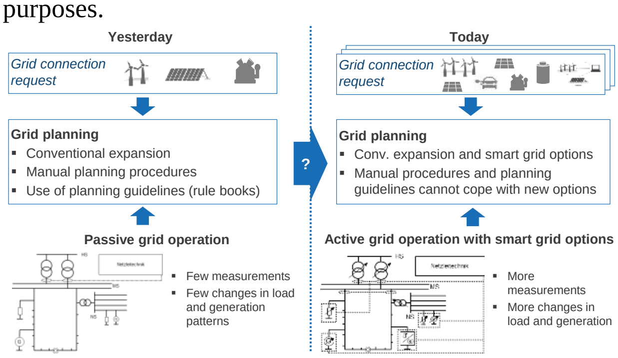

Figure 1: Challenges for planning and operation of DSOs

CONSIDERED TECHNOLOGY OPTIONS

In the context of smart grids, the number of available technology options for DSOs to cope with congestions in their grids increases [1]. Consequently, the following technology options have to be considered in order to enable a holistic representation of planning decisions:

- Conventional grid expansion measures as e.g. the reinforcement of lines, replacement or addition of transformers
- Storage systems with the associated decision on a grid optimal siting and sizing of energy capacity and installed power [6]
- ICT connection of DER to a grid management system in order to enable the planned use of curtailment with a limited annual energy[1]
- ICT connection of flexible loads to a grid management system to enable load management

[1]e.g. in Germany, DER curtailment is to be considered as an option in the long term planning of grids, but with a limited annual amount of 3% of the total DER generation in a given grid [7]

- Installation of voltage regulating distribution transformers and other voltage regulating assets, e.g. reactive power control

In particular the consideration of time coupling components such as storage systems and flexible loads implies the need for using a time series based evaluation approach in the intended planning tool. Existing commercial power flow calculation software cannot handle this complexity efficiently.

INTELLIGENT GRID PLATFORM

The newly developed gird planning tool is part of a larger software environment for DSOs called Intelligent Grid Platform (IGP).

Solution approach

The IGP uses a holistic solution approach for the existing challenges of DSOs with regard to grid planning and operation. The IGP's three core pillars are digitalization, automation and optimization (cf. Fig. 2).

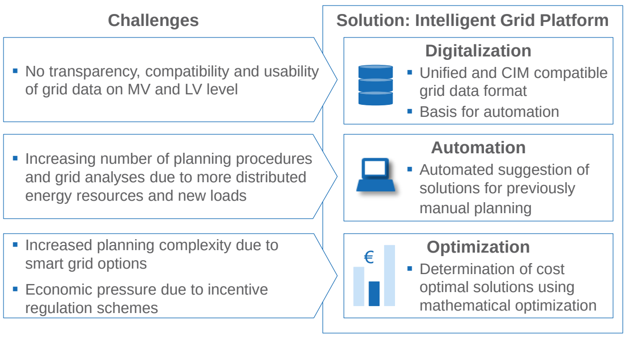

Figure 2: Solution approach of the Intelligent Grid Platform

Digitalization is based on a unified grid data model and the efficient combination and integration of existing data sources within the organization of a DSO. The availability of a digital database is the key enabler for automation, which is needed to cost efficiently cope with the increasing number of grid connection requests in distribution grids.

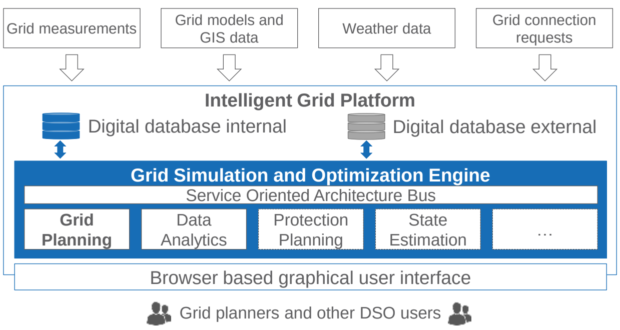

Figure 3: Grid planning tool as part of the IGP

The software uses different applications within the Grid Simulation and Optimization Engine, which provide automated solutions for previously manual planning and data analysis procedures (cf. Fig. 3). The grid planning tool presented in this paper is one of these applications.
In order to enable automated solutions, optimization algorithms are employed within the applications. Mathematical optimization as the methodical approach helps to handle the decision complexity under consideration of smart grid options and the given incentive regulation schemes for DSOs (cf. Fig. 2).

Optimization algorithm for grid planning

Figure 4 presents the grid planning algorithm used in the automated IGP application. It consists of three major steps (cf. Fig. 4).

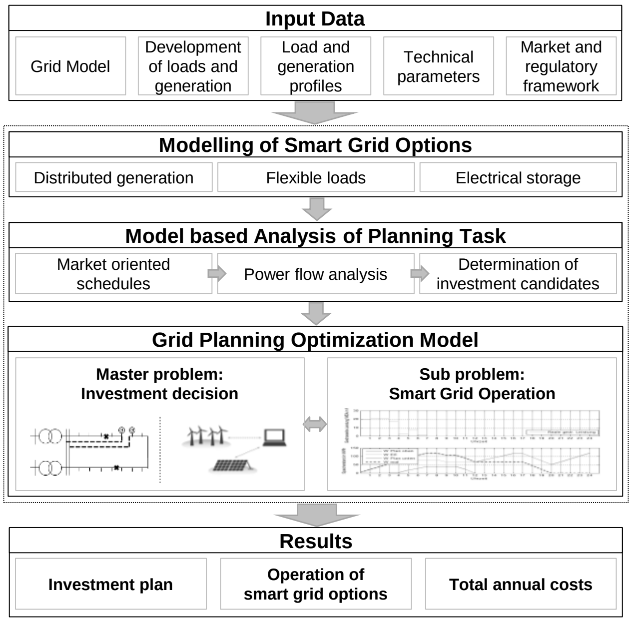

Figure 4: Grid planning algorithm [8]

The first step comprises the modelling of all available smart grid options in a given grid. Technology specific submodels are adapted based on the technical parameters and given grid situation (e.g. available flexible loads or locations for storage deployment).
A model based analysis of the planning task is executed as a second step. This step includes the determination of market oriented schedules for all flexibility options to provide a benchmark for the evaluation of costs associated with flexibility usage by DSOs. Based on the market oriented schedules, the expected future power flow situation is analyzed. Finally, investment candidates are determined based on resulting congestions and voltage limit violations. This automated determination of investment candidates can be complemented by user-defined additional expansion options for the given grid.
The third and final step of the overall algorithm comprises the optimization model. Due to the size and complexity of the optimization problem, an iterative decomposition approach based on Benders Decomposition (cf. [9]) is used to solve the problem. The decomposition approach splits the overall problem into

an investment master problem and an operational sub problem. At the same time, a coordination mechanism using Benders Cuts ensures that the solution converges to the optimal solution of the original optimization problem without decomposition [8].

Investment master problem

All investment candidates from the model based analysis in step two of the algorithm are considered as decision variables x in the investment master problem. The considered technology portfolio comprises all available options in a smart grid (cf. section 2).

The investment master problem is formulated as a mixed-integer linear programming model which minimizes the total annual costs consisting of capital expenditures (CAPEX) and operational expenditures (OPEX) associated with the planning solution:

$$min\ C^{Total} = C^{CAPEX}(x) + \widetilde{C^{OPEX}}$$

The CAPEX depend directly on the chosen investment decision variables of the model. The OPEX on the other hand are only represented by the approximated additional variable $\widetilde{C^{OPEX}}$ in the master problem in order to decompose the overall problem. The exact OPEX are determined in the separate operational sub problem.

As part of the Benders Decomposition approach, the variable $\widetilde{C^{OPEX}}$ is additionally constrained by a new Benders Cut per iteration until the master problem converges to the optimum of the problem without decomposition. The Benders Cuts are determined based on the results of the operational sub problem [8].

Operational sub problem

The operational problem assesses the impact of investment decisions on grid operation using a mixed integer linear optimization model. It tries to resolve grid congestions while minimizing the annual costs for grid operation, consisting of the costs for grid losses and costs for using flexibility options. The latter costs result from compensations which the DSO has to pay to DER owners in order to achieve a grid compatible generation or load pattern based on DSO interventions.

The decision variables of the operational problem include all operational degrees of freedom associated with the considered smart grid options:

- Curtailment of photovoltaic, wind as well as redispatch of combined heat and power plants
- Load management of power-to-X applications (heat, cooling, gas, chemicals) and flexible production processes
- Charging and discharging of electrical storage systems and electric mobility

The operational problem is restricted by two major sets of constraints. On the on hand, the use of flexibility options is limited by technology-specific technical restrictions, e.g. storage power and capacity limits, limited thermal storage capacities of power-to-heat applications or limited availability of electric vehicles.

On the other hand, the operational problem needs to consider the grid constraints, i.e. thermal ratings of grid assets and limits on acceptable voltage deviations at all grid busses. The consideration of grid constraints implies modelling of the nonlinear power flow equations. In order to limit the mathematical complexity and enable the use of Benders Decomposition, the power flow equations are approximated with a linearized approach [8], [10].

CASE STUDY AND RESULTS

The developed planning tool is demonstrated for a real MV case study in Southern Germany.

Exemplary MV case study

The exemplary MV grid comprises 121 secondary substations and is supplied by a 25 MVA HV/MV transformer. The given planning task is characterized by an intended generation capacity of 28 MW of wind and approx. 21 MWp of photovoltaic power plants. In addition, there are flexible loads with an installed capacity of approx. 13 MW in the grid.

Without any expansion measures, the model based analysis of the planning algorithm determines the congestions and voltage limit violations as indicated in Figure 5. The congestions are found in three feeders of the grid. The HV/MV transformer is also overloaded.

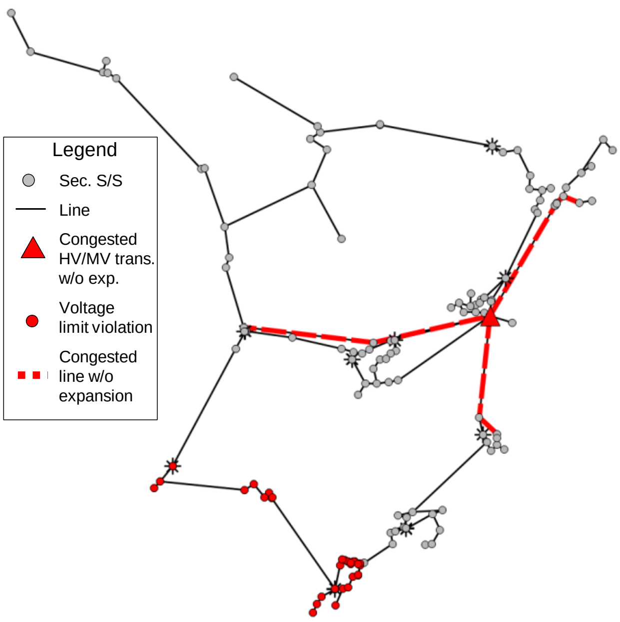

Figure 5: Congested grid situation without grid expansion

In order to solve the given planning task, the optimization model is provided with different options in five scenarios (cf. Table 1). Scenarios 1 to 4 analyze the optimized application of isolated measures. Scenario 5 considers the entire technology portfolio. The relevant cost assumptions for all scenarios are provided in the appendix.

	Grid expansion	DER curtailment	Flexible loads	Battery storage
S1	X			
S2		X		
S3		(X)[2]	X	
S4				X
S5	X	X	X	X

Table 1: Available DSO options per scenario

Optimal expansion portfolio

The optimization algorithm determines the cost minimal expansion portfolio for each of the five scenarios. The solution for the most complex scenario S5 is presented in Figure 6. It includes a combination of grid expansion, curtailment and flexible load management. Electrical storage systems are not chosen as part of the cost optimal solution.

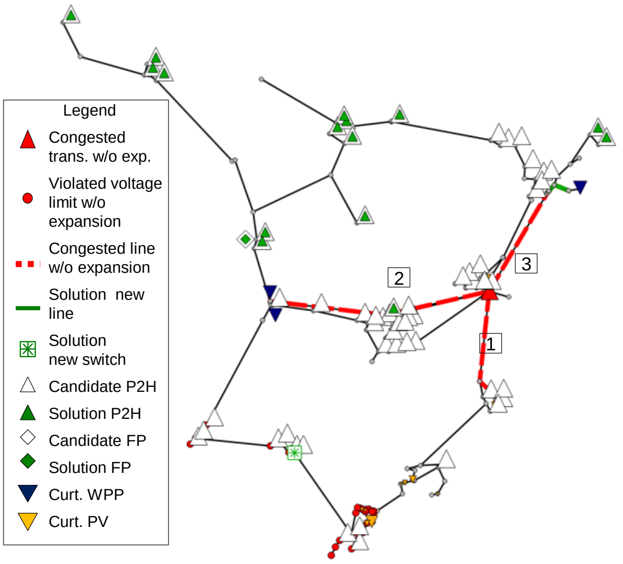

Figure 6: Optimal expansion solution in S5 [8]

The conventional grid expansion measures determined by the algorithm comprise the partial reinforcement of feeder 3 and a new sectioning switch in feeder 1.
Curtailment is applied for wind and PV power plants in feeders 1 to 3. The amount of curtailment needed is shown in Table 2 and amounts to only 0.6% of annual generation in the given grid (the limit was set to 3%).
The ICT connection of flexible loads in feeders 2 and 3 is the final component of the optimal expansion portfolio. The loads are connected to a grid management system to enable a flexible load management. The associated OPEX are evaluated in the operational problem of the algorithm.
The key figures of the solution (cf. Table 2) indicate an increase in grid losses compared to using conventional grid expansion in scenario S1 by 53%. This increase is caused by higher grid utilization in scenario S5. However, the total costs of scenario S5 are 45% lower than in scenario S1 despite the increase in grid losses and curtailment. The optimal smart grid portfolio avoids the majority of expansion measures in comparison to S1.

Solution key figures	
Curtailment in MWh/a	438.8 (0.6% of annual gen.)
Grid losses in MWh/a	1009.7 (+53% compared to S1)
Total annual costs in k€/a	118.9 (-45% compared to S1)

Table 2: Key figures of solution S5

Expansion costs and regulatory implications

Figure 7 presents the comparison of total annual costs across the five scenarios. The consideration of all expansion options leads to the cost minimum in scenario S5 (45% lower costs than in S1). However, also the isolated application of curtailment (S2) and load management (S3) result in cost reductions compared to the conventional expansion portfolio of 37% and 29%, respectively. Using only storage systems to solve the given planning task (S4) is not cost efficient and leads to significantly higher costs[3].

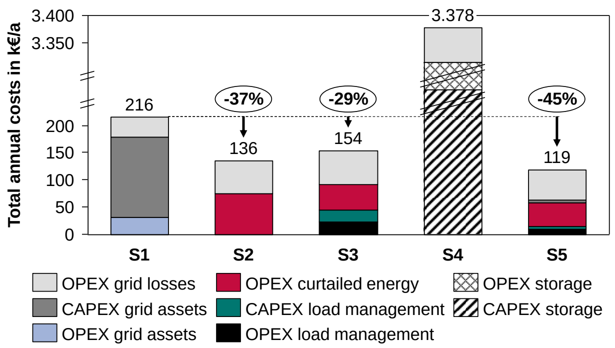

Figure 7: Total annual costs S1-S5 [8]

The cost structure differs significantly between the conventional planning scenario S1 and the more cost efficient scenarios employing smart grid options. Whereas total costs are dominated by CAPEX due to new grid assets in scenario S1, the total costs in scenarios S2, S3 and S5 comprise mainly OPEX including costs for curtailed energy and flexible load management.
This cost structure shift has also regulatory implications for DSOs. The updated German incentive regulation provides the possibility to adapt the individual revenue cap annually to cope with expansion investments [10]. Thus, a CAPEX based solution can be beneficial in a

[2] Curtailment is only used, if load management cannot solve all generation-driven congestions

[3] However, a storage system cost reduction of approx. 35% combined with a multifunctional storage operation can achieve cost parity [8].

short term perspective. However, DSOs with more expensive grid structures (e.g. using solutions like S1) will be in an inefficient position in the efficiency benchmarking for the next regulatory period. This effect is compounded by the newly introduced "efficiency bonus" which rewards the most efficient DSOs. Consequently, planning approaches considering smart grid options and exploiting the cost reduction potentials are becoming increasingly important.

SUMMARY AND CONCLUSIONS

This paper has introduced a novel automated planning tool for distribution grids which considers smart grid options. The planning tool is part of a larger software environment called Intelligent Grid Platform, which enables the integration with and the automation of existing DSO planning processes. It uses the three pillars of digitalization, automation and optimization to cope with existing challenges for DSOs in the context of the energy transition.

Centerpiece of the developed planning tool is an optimization algorithm, which determines cost optimal solutions for the planning decision of DSOs. The algorithm uses Benders Decomposition as the modelling approach to enable the solvability of real-sized grid planning problems while ensuring mathematical optimality at the same time.

In order to correctly evaluate smart grid options, e.g. storage systems or flexible load management, the algorithm enables an extensive consideration of grid operation already at the planning stage. The operational sub model optimizes the degrees of freedom given by smart grid technologies in order to adequately evaluate the benefits and limits of these options.

The algorithm's exemplary application for a planning task in a real MV grid shows that expansion costs can be reduced by approx. 45% compared to conventional grid expansion, if smart grid options are considered as an alternative in grid planning. The cost optimal solution includes a limited amount of curtailment, the integration of flexible loads and some conventional expansion measures.

The developed planning tool thus for the first time provides an option to assess smart grid expansion comprehensively and individually for real grids. In addition, the surrounding Intelligent Grid Platform ensures that the planning tool can be incorporated into existing DSO planning procedures and IT infrastructure, while combining und utilizing a unified digital data base.

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APPENDIX

Cost and equipment lifetime assumptions [1]	
Interest rate	5,49%
Costs for DER curtailment	100 €/MWh
Costs for grid losses	55 €/MWh
Investment costs MV cables	105 €/m
Annual OPEX MV cables (% of invest)	1%
Lifetime MV cable	40 a
Investment costs 40 MVA transformer	1 Mio. €
Annual OPEX 40 MVA transformer (% of invest)	2%
Lifetime 40 MVA transformer	30 a
Investment costs ICT connection	450 €/unit
Annual OPEX ICT connection	30 €/a
Lifetime ICT connection	5 a
Installed power specific investment costs for stationary battery	175 €/kW
Installed energy capacity specific investment costs for stationary battery	500 €/kWh
Annual OPEX stationary battery (% of invest)	1%
Lifetime stationary battery	15 a