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Automated Grid Planning for Distribution Grids with Increasing PV Penetration

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***Abstract*— Grid integration studies try to assess the impact of future developments on large scale network areas, e.g. nation-wide, state-wide or DSO-wide. Goals can be to support strategic alignment in the regulatory framework or to adapt the grid planning principles of DSOs. This paper presents pandapower, an open source software framework that was developed by Fraunhofer IWES together with University of Kassel and that was used in several grid integration studies so far. pandapower's high suitability of automation together with a novel automated grid planning approach allows for analysing large number of real distribution grids with respect to different technologies and possibly many scenarios. This assures a high accuracy and informative value of the grid integration study. Exemplary case study results are presented, with a focus on PV integration studies. The integration studies were performed in cooperation with different major distribution system operators and cover varies research tasks. Furthermore, benefits and challenges of the proposed approach are discussed.**

Keywords: PV integration; network planning, grid integration study, automated simulations, smart grid technologies

I. INTRODUCTION

A. Future Distribution Systems

The goal of distribution system operators (DSO) is to provide a secure, reliable and cost-effective grid infrastructure. The increasing share of renewable energy sources (RES) as well as the introduction of new electrical consumers (e.g. electric vehicles (EHV), heat pumps, storage systems) in the distribution network bring about new challenges in this task. At the same time, innovative power grid components (e.g. ICT infrastructure, new control strategies, additional voltage regulators) become a possible option in the network development [1]. With evolving supply tasks, new technological possibilities and a rapidly changing regulatory framework, it is increasingly difficult for DSOs to plan and operate distribution networks efficiently. Planning principles that have been developed and validated over a long period of time might no longer apply for future power systems. DSOs and researchers are therefore working together to develop strategies on how to cope with these challenges.

B. RES Grid Integration Studies

The anticipated changes in distribution systems bring forth questions about the potential of different smart grid technologies, optimal development paths of different distribution systems and overall expected costs for RES integration. In the recent years, various system-wide grid integration studies (e.g. nation-wide, state-wide, DSO-wide) have been published in Germany [2]-[6], which mainly focus on:

- Determination of the maximum RES hosting capacity of distribution grids
- Estimation of RES integration costs in the distribution system based on different RES installation scenarios
- Technical and economic assessment of innovative equipment and control strategies

Such system-wide grid integration studies can support the strategic alignment in the regulatory framework as well as help to adapt the grid planning principles of the DSOs. Due to the huge amount of data, the big efforts for data preparation and partly the lack of relevant data, system-wide grid integration studies in the MV and LV level are usually performed on representative networks, which are chosen on the basis of parameters like residents per km^2, expected RES installation or length of feeders. The representative networks are either built as generic grid models to resemble real networks based on the network parameters [2] or representative real networks are chosen based on a cluster analysis of the network parameters [3]-[6]. The network study is then carried out on the chosen representative networks and the results are extrapolated on a system-wide perspective according to a suitable allocation formula.

Despite the advanced approaches for the development and/or selection of characteristic grid models in recent grid integrations studies, the application of characteristic grid models and the extrapolation of the results on a system-wide perspective is a significant simplification and potential source of error in these grid integration studies. Previous studies at the Fraunhofer IWES with a high number of real distribution grids show a large variation in the results and the obtained findings. Especially the technical and economic assessment of different technical measures in the grid planning process (e.g. grid reinforcement and expansion) show a high local or regional diversity, which can hardly be covered by characteristic grid models. Furthermore, relevant network parameters for the development and/or selection of characteristic grids can strongly differ between different objects of investigation. The inaccuracy of these simplifications is rather difficult to estimate since there is no comparative data available. A high sample size is therefore crucial for the accuracy of the results in RES grid integration studies.

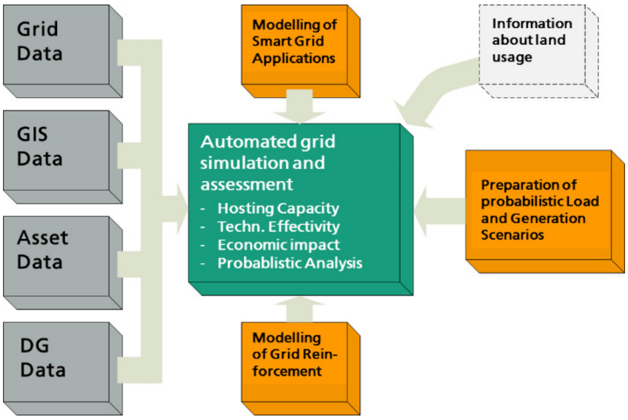

Fig. 1 IT-Framework for automated grid integration studies at Fraunhofer IWES [7]

C. *Automation in RES Grid Integration Studies*

To obtain representative results in system-wide grid integration studies, it is crucial to avoid data selection or simplification wherever possible. Detailed analysis of a large number of network models is however only possible with a high degree of automation. Fig. 1 shows an IT-framework for automated grid integration studies. Data import, analysis of the research objective and export of the results all have to be automated, so that the whole process can be carried out without manual engagement. The reason that many state of the art studies rely on generic or simplified data and semi-automated approaches, is that there are several challenges in the automation of this process:

1) Tools for automation: network data is mostly available at the DSO in commercial network calculation software. While these tools provide some possibilities of automation, they are primarily developed and suited as GUI applications. Directly processing data in these tools has additional drawbacks: licensing might limit or completely rule out parallel computing and developed algorithms cannot be applied to network models in other programs. For these reasons a common approach is to convert the data into an open source load flow solver, most prominent of which being MATPOWER [8], to carry out automated analysis. The data conversion however always comes with a loss of information, since MATPOWER and other available solvers use a bus-branch model that allows neither differentiation between different branches (e.g. lines and transformers) nor preserve secondary information like line length, transformer short circuit voltages or standard types. These information are however relevant in the network planning process. Furthermore, open source solvers usually offer less functionality than commercial network calculation tools, such as topological searches, short-circuit calculation or the modelling of switches.

2) Incoherent or incomplete data: network integration studies rely on a large amount of data from different data sources. Some data, such as low voltage network data, might not even be available in machine-readable form. It is a challenge to automatically import and intersect network data, geographical information, prognosis data etc.

3) Complexity of network planning: network planning is carried out by experienced experts who use their experience to balance economical and technical goals and constraints. It is a challenge to automate this complicated process without significant simplifications in the actions that can be taken by the network planner or in the considered boundary conditions.

In this paper, an approach is presented on how to cope with these challenges in automated network studies. First, the open source software *pandapower* is introduced, which allows comfortable automation as well as detailed modelling of distribution networks (Chapter II). Second, methodologies for the automated evaluation of hosting capacity (Chapter III) and evaluation of network reinforcement and expansion costs are introduced (Chapter IV). Both approaches are based on pandapower and allow a detailed modelling of network optimisation, reinforcement and expansion measures as well as a flexible consideration of different boundary conditions. These methods have been successfully applied in several studies and projects in cooperation with different DSOs, some of which are presented in Chapter V.

II. PANDAPOWER

A. *What is pandapower?*

pandapower is a Python based open source module that combines the data analysis library pandas[1] and the power flow solver PYPOWER[2] to create an easy to use network calculation framework[3]. *pandapower* is aimed at automation of power system analysis and optimization in distribution and sub-transmission networks. The software is a joint development of the University of Kassel and the Fraunhofer

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[1] http://pandas.pydata.org

[2] a port of MATPOWER to the python programming language, see https://pypi.python.org/pypi/PYPOWER

[3] http://www.uni-kassel.de/go/pandapower

IWES and was hitherto applied in numerous grid integration studies.

The *pandapower* data structure is centred on electric elements, such as lines, transformers, loads, external networks, generators etc. The information for each element is saved in separate pandas tables, where it can be handled more comfortably than in a matrix-based data structure as used by PYPOWER. To calculate the load flow *pandapower* combines the relevant data into a PYPOWER case file and uses PYPOWER to solve the load flow problem. The results are then processed and written back into the *pandapower* result tables (see Fig. 2).

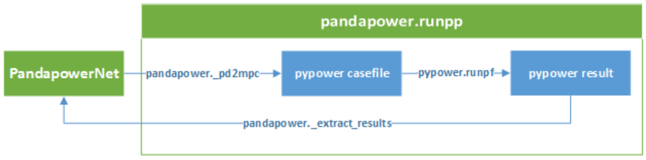

Fig. 2 pandapower load flow structure [9]

B. Advantages of pandapower

pandapower includes several additional and improved features compared to PYPOWER [2]:

1) Electric Models: pandapower comes with static equivalent circuit models for lines, 2-Winding transformers, 3-Winding transformers, ward-equivalents and more. The input parameters are commonly used nameplate parameters, such as line length and resistance per kilometer for lines or rated power and short-circuit voltages for transformers.

2) Switch Model: pandapower includes a switch model which allows modelling of ideal bus-bus switches as well as bus-line / bus-transformer switches.

3) Datastructure: since variables of any datatype can be stored in the pandas dataframes, electric parameters (integer / float) can be stored together with names (strings), status variables (boolean) etc. The variables can be accessed by name instead of the column number of a matrix. All inherent pandas methods can be used to access, query, statistically evaluate, iterate over, visualize any information that is stored in the pandapower dataframes - be it element parameters, load flow results or a combination of both.

4) Results: the load flow results do not only contain basic load flow results, such as bus voltages and branch power flows, but also processed result information like utilization rate and losses for lines and transformers.

5) Network Creation: To create new elements one can add and edit new rows in the respective element tables directly. However, *pandapower* also provides specific functions to add new elements. This allows for checks on the consistency of input parameters as well as the automized step-by-step construction of networks. A standard type library allows simplified creation of lines, 2-Winding transformers and 3-Winding transformers.

6) Topological Searches: pandapower networks can be translated into networkx[4] multigraphs for fast topological searches. All native networkx algorithms can be used to perform graph searches on pandapower networks. Additionally pandapower provides some search algorithms specialized on electric power networks.

7) Plotting: geographical data for buses and lines can be stored in the pandapower datastructure and plotted using matplotlib[5]. If no geographical information is available, generic coordinates can be created through a python-igraph[6] interface to plot structural network plans.

III. ASSESMENT OF HOSTING CAPACITY AND EVALUATION OF SMART GRID TECHNOLOGIES

A. Determining PV hosting Capacity

The term PV hosting capacity relates to the maximum PV capacity which can be connected to a specific distribution grid, while complying with relevant grid codes and grid planning principles. However, it is hard to reflect the PV hosting capacity of a grid by a single value. The reason is that the distribution of PV systems within the grid, e.g. the points of PV interconnection and the rated power of the PV installations, has strong impact on the maximally installable PV capacity.

To cope with this uncertainty we use probabilistic Monte-Carlo simulations to simulate a large number of different future PV installation scenarios. Here a scenario consists of PV systems of particular sizes connected at particular interconnection points that are installed in a particular order. The resulting statistical distribution of maximally installable PV systems represents the additional hosting capacity of the grid. An exemplary distribution of maximum installable PV systems for a specific low voltage grid is depicted in Fig. 3. The results were generated by simulating 50 different possible future PV deployment scenarios. As can be seen, the hosting capacity varies between 9 and 14 additionally installable PV plants. A boxplot can visualize the resulting distribution and helps to understand the behaviour of the grid when additional PV systems will be installed. It shows the minimum as well as the average of additionally installed PV systems at which to expect that first problem occurs.

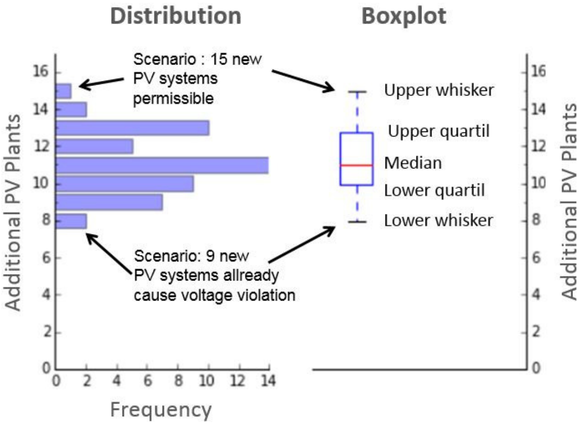

Fig. 3 Permissible additional PV systems for a grid (left: statistical distribution, right: boxplot)

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[4] https://networkx.github.io

[5] http://matplotlib.org

[6] http://igraph.org/python

The automated analysis of the hosting capacity of a large number of grids as part of PV integration studies can answer questions like:

- Are the distribution grids overall well dimensioned for future PV deployment?
- Which or how many distribution grids require additional measures for PV integration?
- When will additional measures for PV integration be required?

B. Assessing the effectiveness of Smart Grid Technologies

Nowadays, several technical solutions are available to improve RES integration and to increase the PV hosting capacity of a distribution grid, for example advanced PV inverter functions, advanced control strategies of voltage regulators, additional voltage regulators (e.g. on-load tap changer (OLTC) of MV/LV transformer, line voltage regulators), active power control or additional storage systems. However, the selection of suitable measures can be difficult and technical and economic assessment of smart grid applications can support the strategic alignment in the grid planning process. Clearly, the effectiveness of the different measures depends on the specificities of the considered networks. Therefore, the results gained with the simulation of a small number characteristic grids might be misleading. Rather the automated analysis of different technologies applied to a larger number of grids and load scenarios would allow for well-founded strategic decisions.

Multifaceted research questions can be considered regarding the smart grid applications. Further case study results with different smart grid technologies were presented in [1]. Typical research question for smart grid application are for example:

- What is the maximum PV hosting capacity for different smart grid applications?
- What is the cost saving potential of different smart grid applications?
- Which smart grid application is most cost efficient for different grid conditions or characteristics (e.g. PV penetration level)?
- Which combination of smart grid applications is beneficiary?
- What are effective operational strategies of active grid components (e.g. reactive power characteristics of PV inverters)?
- What are suitable grid planning principles for the application of smart grid technologies?

IV. AUTOMATED NETWORK PLANNING

To estimate the cost of RES integration and to be able to economically compare different technologies / planning principles, it is necessary to have means to calculate the cost of classic grid expansion and reinforcement measures like, for example, the reconfiguration of feeders, the increase of diameters of lines or the exchange of transformers. Some grid integration studies rely on the help of experienced network planners who plan the necessary grid reinforcement for selected representative networks. However, in the scope of the proposed automation of grid integration studies the cost for grid expansion must be estimated in an automatized fashion, too.

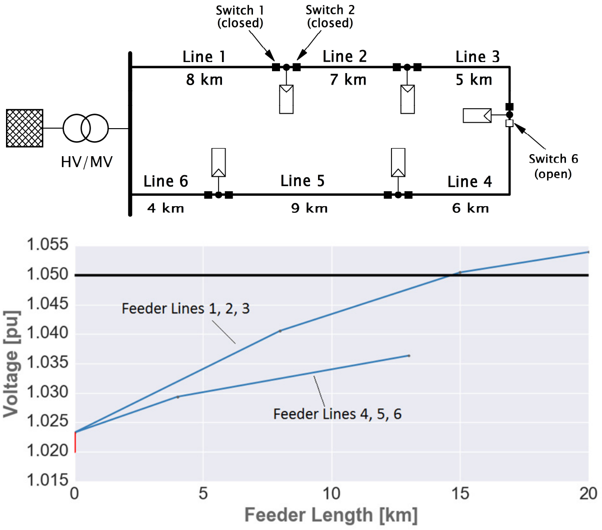

Fig. 4 Medium voltage line ring (6 lines, 5 MV/LV stations and 10 load-break-switches) with corresponding voltage profile

The task of automatic network reinforcement is to find a combination of possible optimisation, reinforcement and expansion measures that ensures safe operation of the network while being as cost-efficient as possible. The formalisation of this problem results in a highly complex combinatorial problem. In the following an optimization approach is presented that is applicable to real network data without loss of information and preserves all degrees of freedom a network planner would have.

A. Line Replacement

The proposed approach is explained with the help of the simplified example network detailed in Fig. 4. Since the bus voltage exceeds the voltage limit at several stations, the network is not valid in its current state. To ensure its safe operation, the network has to be optimized, reinforced or expanded so that all constraints are complied with.

Each possible action that can be taken by the network planner is represented by one network reinforcement measure. In a first step, we consider network reinforcement, which means the measures consist of replacing the lines in the network with a new line with higher diameter. The set of possible measures M is then given as:

$$\mathrm{M} = \{ \text{'replace\_line\_1'}, \ldots \text{'replace\_line\_6'} \}$$

Each of the $2^{|M|} = 2^6 = 64$ combinations of these measures is defined as a solution s. The goal of the network reinforcement is to find a network state that complies with the voltage constraints at minimal cost. Each of the measures m is assigned an individual cost function c(m). Here we assume that the costs are equal to the length of the replaced line.

The cost of one solution s is then defined as the sum of the costs of all measures in the solution:

$$\mathrm{c(s)} = \sum_{\mathrm{m} \in \mathrm{s}} \mathrm{c(m)}$$

To ensure compliance with the constraints, penalty costs are added to the cost function:

$$\tilde{c}(s) = \sum_{m\in s} c(m) + c_{penalty}$$

The penalty cost $c_{penalty}$ is added for solutions that violate operational or topological constraints, to ensure that found solutions comply with all constraints.

The problem has now been formalised as a single-objective combinatorial optimisation problem. Metaheuristics such as Iterated Local Search (ILS) [10], Tabu Search [11], Genetic Algorithms (GA) [12], Evolutionary Algorithms (EA) [13] or Ant Colony Optimization (ACO) [14] have been proven to be suitable to solve this class of optimisation problem. Here, we use an ILS algorithm to find the most cost efficient feasible combination of measures $\tilde{s}$, which results in the solution:

$$\tilde{s} = \{\text{'replace\_line\_2'}\}$$

This solution corresponds to a network state where line 2 with the length of 7 km is replaced with a new cable with higher diameter and subsequently the voltage constraints are complied with (see Fig. 5).

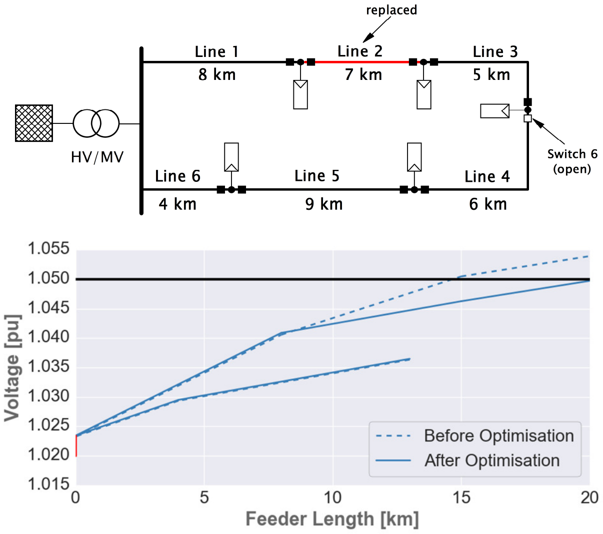

Fig. 5 Example network complies with voltage constraint after replacing Line 2

B. Network Reconfiguration and Line Replacement

The optimisation can now be expanded to include switching operations. This is done by simply defining the opening of each switch as a new measure, which yields the collections of measures:

$$M = \{\text{'open\_switch\_1'}, \ldots \text{'open\_switch\_10'}, \text{'replace\_line\_1'}, \ldots \text{'replace\_line\_6'}\}$$

For these 16 possible measures there are now 2^{16} or over 650,000 possible solutions. Since the sectioning point in the current network is located at switch 4, the starting network state is codified as:

$$s_{start} = \{\text{'open\_switch\_4'}\}$$

In addition to the voltage limit, the optimisation has to consider radiality and supply constraints. The radiality constraint ensures that the network is not meshed, the supply constraints ensures that busses are not cut from power supply. The ILS optimisation now yields the solution

$$\tilde{s} = \{\text{'open\_switch\_3'}, \text{'replace\_line\_6'}\}$$

The optimisation has found a solution with only 4 km of line replacement by moving the sectioning point from switch 4 to switch 3 (see Fig. 6).

In this simple case, we know that every feasible solution will always include exactly one switch measure that guarantees the radial structure. Using this kind of problem specific knowledge is important to restrict the optimisation problem especially in more complicated problems, since the solution space grows exponentially with the number of measures.

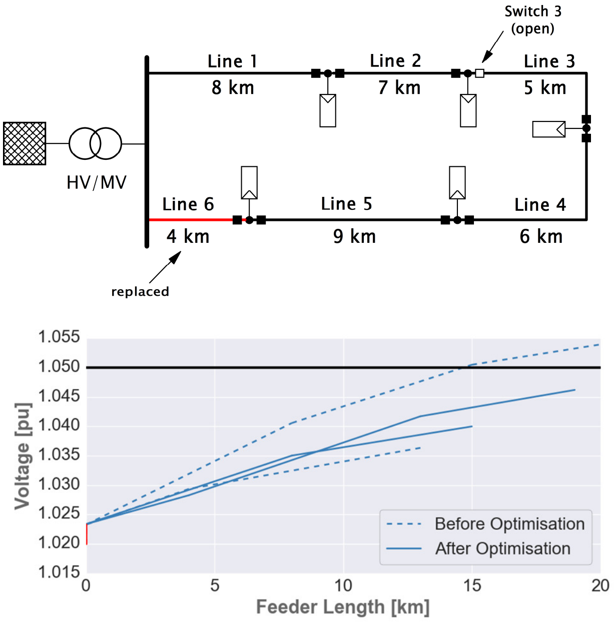

Fig. 6 Example network complies with voltage constraint after moving sectioning point to Switch 3 and replacing Line 6

C. General Application

The example above focused on optimization of line replacement and network reconfiguration. The network planning framework is however implemented in a modular way that allows flexible combination of measures, target functions and boundary conditions to reflect different objects of investigation.

Measures that have already been implemented in different studies include:

- Replacing existing lines or transformers
- Changing the switching configuration
- Adding parallel lines to existing line trails
- Finding new line trails between stations
- Deploying controllers for transformers or PV systems
- Replacing transformers with OLTC transformers

In the same way, the constraints for network planning can be individually specified. Constraints that have been considered in different studies include:

- radiality, supply, n-1 and other topological constraints
- load flow constraints (bus voltage, line loading, transformer loading) for several worst-case scenarios, e.g. high load or high generation
- load flow constraints for n-1 operation with optimal resupply
- reliability constraints for outage times (ASIDI / SAIDI)

The implementation of the framework allows for a flexible introduction of new measures and constraints. The combination of different measures with different constraints facilitates a multitude of studies with different goals and boundary conditions.

V. CASE STUDIES

In this Chapter exemplary case study results are presented, with a focus on PV integration studies. The PV or grid integration studies were performed in cooperation with different major distribution system operators.

A. *PV hosting Capacity in Low Voltage Networks*

Within the scope of a PV integration study carried out for the Swiss distribution system operator Romande Energie, the hosting capacity of 111 LV networks were evaluated and compared to different PV forecast scenarios provided by the DSO. Fig. 7 shows a comparison of the PV hosting capacity (green boxplots) and the expected PV installations 2035 (red boxplot) in the most progressive scenario for the LV level. The expected PV capacity 2035 exceeds the determined PV hosting capacity only in a very few LV grids. Therefore, the LV grids are mostly well dimensioned for the expected additional PV installations and additional measures for PV integration are just expected in a few LV grids.

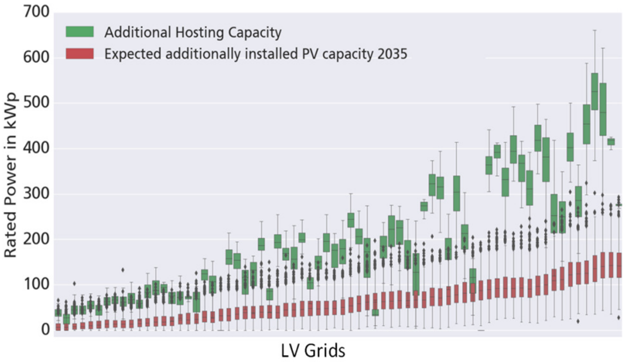

Fig. 7 Comparison of PV hosting capacity and expected PV installations for several LV grids (courtesy of Romande Energie)

B. *Inverter Control Strategies in MV Networks*

Contrary to the LV network, the analysis of the PV hosting capacity in the MV network showed need for network reinforcement. It was therefore further investigated how control strategies can mitigate the expected reinforcement cost. This was done by automatically calculating and comparing network reinforcement costs under different boundary conditions. The considered control strategies are:

- Constant CosPhi: reactive power provision by PV plants with a constant power factor

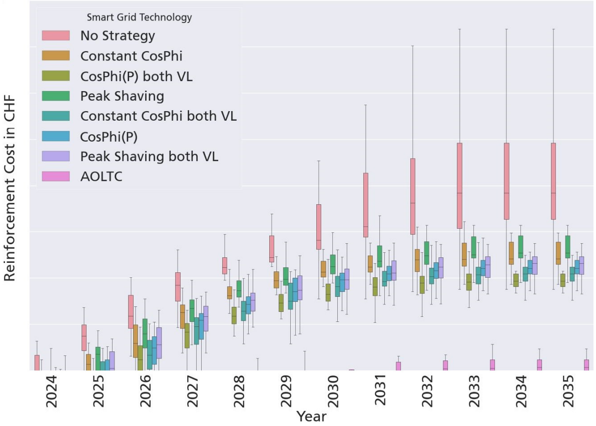

Fig. 8 Evaluation of cost savings in network reinforcement with control strategies. Inverter Strategies are either applied on the MV Level or on both MV and LV level (appendix "both LV")

- CosPhi(P): reactive power provision by PV plants with a power factor depending on active power provision
- Peak Shaving: active power curtailment of PV plants
- AOLTC: advanced on-load tap changer control of the HV/MV transformer, where the voltage set point of the transformer control is adapted to the active power flow over the transformer

Exemplary results are shown in Fig. 8. Note that for different distributions of PV systems in the grid also different expected cost are calculated. The distribution of these cost is shown as a boxplot.

It is clearly visible that all studied autonomous voltage control strategies are capable of reducing the expected reinforcement costs considerably. The possible costs savings directly correlate to the increase of the hosting capacity by the different strategies. Due to the specific structure of the investigated MV level network mainly voltage rise is the limiting factor for the hosting capacity. Therefore, increasing the allowed voltage band by using an AOLTC has a significant effect on the expected reinforcement cost.

C. *Technical and Economical Assesment of MV/LV OLTC transformer*

In LV grids the application of an OLTC for the MV/LV transformer (rONT[7]) is a promising technical solution to increase the PV hosting capacity. In a grid integration study in cooperation with Bayernwerk the technical and economic potential of the rONT was analysed for 84 real LV grids. A

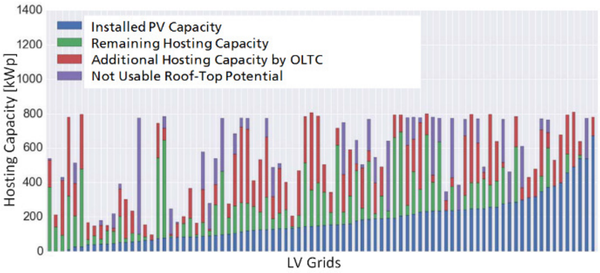

Fig. 9 Increase of PV hosting capacity (median value) by rONT application for 84 real LV grids (courtesy of Bayernwerk) [7]

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[7] rONT: regelbarer Ortsnetztransformator (in German)

simplified analysis of the PV rooftop potential forms the basis of this PV integration study. Fig. 9 shows the technical effectivity of the rONT to increase the PV hosting capacity. The blue bars show the installed PV capacity, the green bars show the additional PV hosting capacity without further measures and the red bars indicate the additional PV hosting capacity with rONT. The rONT can significantly increase the PV hosting capacity for a large number of real LV grids. However, in some LV grids the rONT do not permit grid integration of the complete PV rooftop potential (purple bars). This affects especially LV grids, there loading constraints of grid assets are the limiting factor for PV integration. Furthermore, the required grid reinforcement and the grid reinforcement costs for PV integration are determined with and without rONT application. Fig. 10 shows a comparison of the avoided grid reinforcement costs by rONT application and the rONT investment costs for the LV grids. The rONT application is a cost-effective measure for PV integration for a large number of LV grids. It should be noted, that a high PV penetration scenario was investigated (PV rooftop potential) and that the operational cost are not considered in this example.

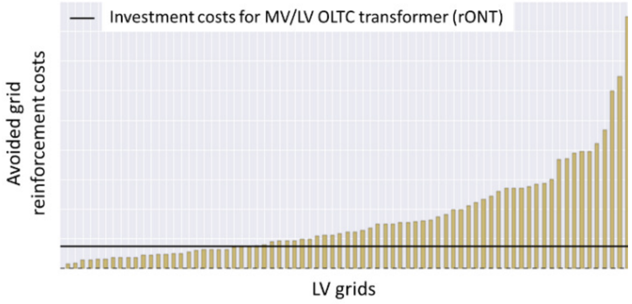

Fig. 10 Comparison of avoided grid reinforcement costs by rONT application for 84 LV grids and rONT investment costs (courtesy of Bayernwerk) [7]

D. Network Topology Optimisation

A goal in strategic network planning can be to renew specific network elements, for example elements of a particular type (e.g. overhead lines or cables with a specific insulation) or elements that will have exceeded their life expectancy at the planning horizon. Consequently, sometimes large parts of a network area are to be renewed. In such a case it can be more cost efficient to find a network structure with new line trails than simply maintaining the existing structure by renewing old line trails.

Fig. 11 shows an example of an automated topology optimisation in a 10 kV network of the DSO Westnetz GmbH that has been developed in the scope of the project ANaPlan[8]. The lines that are to be renewed in the target network are shown as dashed lines in the Fig. 11 a). Fig. 11 b) shows the possible new line trails that are considered in the optimization. Each line trail is modelled as one network reinforcement measure as explained in Chapter IV. The line length of a new trail is assumed to be equal to the airline distance multiplied with a factor of 1.5 to account for obstacles. Additionally, switch measures are considered in the optimisation to allow a reconfiguration of the feeder partitioning and ensure radial network structure. In this example, 232 line trail measures and 605 switching measures have been considered, which results in a solution space of $2^{232+605} \approx 9 \cdot 10^{252}$ possible network configurations. With this kind of complexity, it is important to use problem specific knowledge (like switches on stubs can never be opened, two switches on the same feeder sections can never be opened at the same time etc.) to restrict the optimisation problem. The network optimisation is then used to find a solution that requires a minimum amount of cabling while complying with all defined constraints. In this example, the constraints consist of topological and operational constraints. The topological constraints ensure the radial structure of the network and possibilities of resupply in case of line faults. The operational constraints ensure the compliance with voltage band and maximum line loading in worst-case situations. The worst-case is modelled by one low load and high RES scenario and one high load and low RES scenario. By applying a prognosis for load development and RES installation at the planning horizon, the methodology can be used to find cost-efficient network structures for future power systems. The best solution that is found by the optimisation can be seen in Fig. 11 c). The feeder configuration in Fig. 11 d) shows that the radiality of the network is maintained. The optimized network structure leads to about 25 km of new line trails, while a renewal of

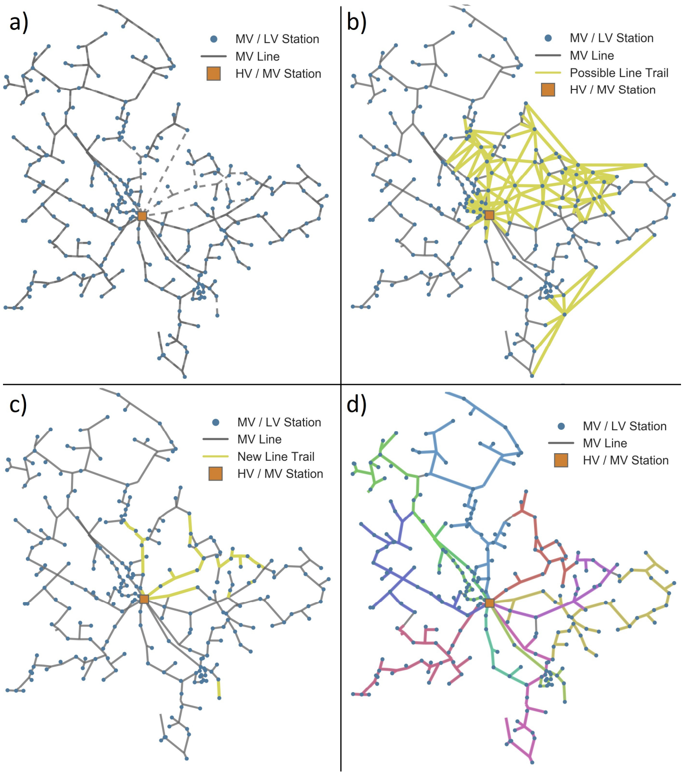

Fig. 11 a) Initial network with lines to remove (dotted), b) line trails considered for new network structure, c) optimized network structure, d) feeder sectioning in optimized network structure

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[8] http://forschung-stromnetze.info/projekte/automatisierte-netzausbauplanung-im-verteilnetz

the old line trails would have resulted in about 31 km of cabling. The optimisation was therefore able to find a more efficient structure that still complies with topological and operational constraints considering load and RES development.

Possible research questions that can be tackled with a network structure optimisation include:

- Integration of network reinforcement and asset management
- Validation of planning principles by optimising network structures with different boundary conditions
- Possible savings in grid reinforcement cost by using certain smart grid technologies
- Supporting the network planning process with an automated network planning approach

VI. CONCLUSION

This paper introduces approaches for automatic network analysis and optimisation. All implementations are carried out in the network calculation software *pandapower,* which is also introduced in this paper. The automatic network optimization allows a calculation of network reconfiguration, reinforcement and expansion with detailed network models. Since no data reduction or simplification is necessary, results of the automated grid planning approach can be directly compared to real solutions of experienced network planners to validate the results and improve the algorithm. This increases the transparency of RES grid integration studies and permits direct conclusions regarding the grid planning principles of the DSO. A further benefit of the approach is the possible application of probabilistic load and generation scenarios in the grid integration study, which further increases the robustness and informative values. The grid integrations studies can be performed for a large number of real distribution grids, which avoids inaccuracies in the application of characteristic grid models and their projection on a system-wide perspective. Therefore, the approach covers the complete diversity of the investigated distribution grid and allows conclusion for the grid planning process of the individual grid sections. The case studies presented in this paper highlight the need for detailed investigations, since results vary greatly in different case studies with different DSOs.

There are two main challenges for automated network studies. The first is the availability of data: quality and the informative value of the RES grid integration studies are strongly dependent on the provided data base. Since a detailed knowledge of grid conditions will become increasingly important in active distribution networks, most DSOs are actively working on improving data maintenance and standardisation to facilitate automated data analysis. It is therefore to be expected, that the quality and availability of data will improve in the future.

Another challenge is the complexity of the grid planning optimisation problem, which rises exponentially with the number of considered measures. Metaheuristic optimisation has been shown to find good solutions even in heterogeneous problems with several hundred measures.

The presented algorithms have been validated and improved with the feedback of network planning experts of several DSOs. In the future, the algorithm could not only be used for studies but also applied as a direct supporting tool in the grid planning process.

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