TIME SERIES BASED POWER SYSTEM PLANNING INCLUDING STORAGE SYSTEMS AND CURTAILMENT STRATEGIES

Florian SCHAEFER*, Jan-Hendrik MENKE*
*University of Kassel - Germany
<florian.schaefer, jan-hendrik.menke>@uni-kassel.de

Frank MARTEN°, Martin BRAUN*°
°Fraunhofer IEE - Germany
<frank.marten, martin.braun>@iee.fraunhofer.de

ABSTRACT

Compared to the analysis of few loading situations, time series based power system planning methods allow to integrate control strategies of generators and storage systems into grid expansion planning. A novel framework is introduced in this paper, which is able to consider operational options such as the curtailment of distributed generators as well as storage systems in the expansion planning of distribution grids. The framework combines time series simulations and reinforcement heuristics to evaluate expansion planning costs, line loadings, voltages, energy and losses. To reduce computational effort and integrate the single contingency policy into the framework, artificial neural networks are employed.

INTRODUCTION

Static worst case “snapshot” analysis is state of the art in distribution grid expansion planning. However, the rising share of renewable generators requires to investigate time periods to consider their volatility but also their flexibility. As outlined in [3], the German regulatory framework allows to curtail the distributed generators to reduce line loadings and high bus voltages. This strategy is only feasible up to a certain degree under economic and environmental points of view. If, however, enough storage systems are installed in the distribution grid, an alternative to the curtailment of the generators is provided by storing their energy. In the expansion planning phase of the power system, this requires simulating the generator curtailment strategy and the storage system management. In this paper, a method is introduced which allows to take into account the flexibility of control (curtailment, storage systems) in a time series based power system planning approach.

In the section “State of the Art”, the time series based grid planning problem is described. In the section “Method” an overview of the framework, components and control strategies is given. Exemplary results are shown in the section “Results”. In the last section, an outlook is given.

STATE OF THE ART

Grid expansion planning has the objective to find a trade-off between security of supply, economic efficiency and the environmentally friendly supply of energy. Historically, the supply of loads was the main purpose and design criteria of distribution grids. With the rising share of renewable energy resources (RES), the uncertainty of supply steadily increases. In the German jurisdiction, it is the duty of the distribution system operator (DSO) to connect distributed generators (DGs) into their grids. Based on the criteria (1) supply of loads and (2) connection of RES, two static worst-case grid scenarios exist: the “high load” case and the “high generation” case. They are common “worst-case” assumptions to determine the maximum technical limits (voltages, line or transformer loadings) occurring in a specific grid. However, designing the grid based on these worst-case scenarios has several drawbacks. First, time-dependent assets, such as storage systems, or the curtailment of generation can only be integrated to a very limited extent in the planning strategy. Second, in meshed grids simultaneous high load and high generation situations are possible, which may result in higher grid loadings and are not covered in the “worst-case” scenarios. Third, it cannot be determined how often line loading or voltage limits are violated during a year. This information is necessary for asset management and allows the evaluation of erosion caused thermal stress.

These disadvantages are solved with time series based planning strategies [1]. The main challenge of such methods is to find a trade-off between sufficient detail and computational time. Depending on the considered constraints, storage systems are often modelled with linear or mixed-integer linear programming method [2]. Curtailment strategies are modelled through static factors, by calculating power injection limits based on the sorted annual injection curve or with OPF-based optimization [3]. Also, the chosen time series, in terms of weather years, strongly influence the resulting loadings and bus voltages. To cover as many situations as possible, and by that increasing robustness, multiple years / time series should be analysed for a specific grid. This results in even longer simulation times, for which approximations of power flows can provide fast results [4].

After having determined the relevant future load and injection scenarios, for which the power system will be designed, it must be decided which transformers and lines are to be replaced or reinforced. This task can be formulated as a combinatorial optimization problem. Different heuristics exist [5] to solve this problem depending on the grid size and the amount scenarios.

METHOD

In this paper, a novel grid expansion planning framework, which unites time series based simulations and grid reinforcement optimization, is introduced.

Framework

The planning framework consists of four different modules which are shown in Figure 1. In the first module, the input data is converted to a “memory map” format for fast accessing. This data consists of topology (grid) of the power system, the time series for load and generation as well as the chosen control strategy or operation mode. In the second module, the time series simulation of the given time horizon (e.g., 1 year) is performed to identify the critical loading situations during the time frame as well as high and low voltage limit violations. The simulation module is based on [6]. To include the single contingency policy (SCP) or “n-1 security criterion”, an artificial neural network (ANN) is trained to predict power flow results for possible outages of lines. See [7] for details. Based on the results of the time series simulation, snapshots of different grid states (load cases, supply cases) are defined. These cases are the input for the reinforcement module, which is based on the combinatorial heuristic approach described in [8]. In the last module, the results are evaluated: economical and technical criteria are compared. Economic criteria include replacement costs of lines, curtailed energy and storage costs. Technical criteria include the evaluation of voltage limits, thermal limits and the shifted energy during the year.

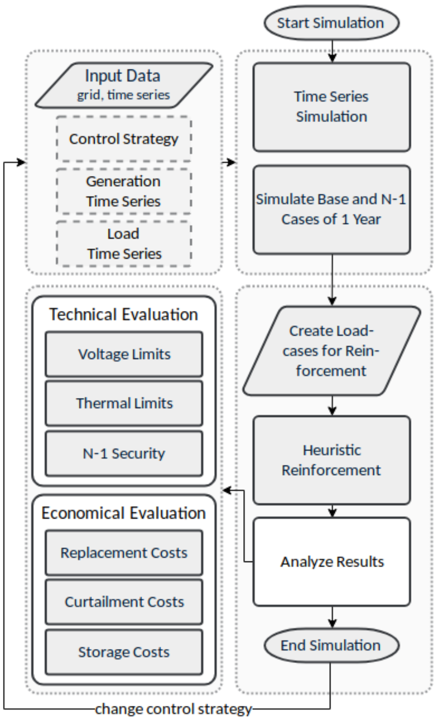

Figure 1: Grid expansion planning framework overview.

Control Strategies

Operational strategies for curtailing DGs and controlling storage systems may allow to mitigate some critical grid loading situations and hence avoid some grid expansion measures. Hence, the following control strategies will be analysed in this paper.

DG P-control – ‘x% curtailment’

This peak shaving method is based on the individually calculated factors approach in [3]. To calculate the maximum allowed active power injection P_{max} of a DG, the expected annual generation of the DG is sorted as shown in Figure 2. The value of P_{max} is calculated by limiting the annual DG energy production (surface under power curve) by x%, in which x is pre-defined (e.g. 3%).

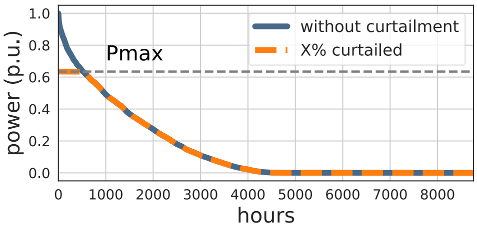

Figure 2: Sorted annual generation curve of a DG. P_{max} is the maximum power injection if x % of the annual energy is curtailed.

DG P-control curtailment – ‘popt’

The “popt”-algorithm is based on the works in [9] and is used to reduce the loading of overloaded lines by reducing the active power of n_{DG} decentralized generators (DGs) in the grid. It can be formulated as an iterative solution to the following bounded quadratic programming problem:

$$\text{minimize} \quad \left\| \frac{\partial \mathrm{L}}{\partial \mathrm{p}} \cdot \boldsymbol{\Delta}\mathbf{p} - \boldsymbol{\Delta}\mathbf{L}_{\mathbf{goal}} \right\|^2 \qquad (1)$$

$$\text{subject to} \quad \frac{\partial \mathrm{h}}{\partial \mathrm{p}} \cdot \boldsymbol{\Delta}\mathbf{p} \leq \mathbf{0} \qquad (2)$$

in which $\boldsymbol{\Delta p}$ is an $n_{DG} \times 1$ vector of active power changes of the DGs, $\boldsymbol{\Delta L_{goal}}$ an $n_L \times 1$ vector of the desired change of contingent line or transformer loading values and $\partial L/\partial p$ is the $n_L \times n_{DG}$ sensitivity matrix which relates $\boldsymbol{\Delta L}$ to changes in $\boldsymbol{\Delta p}$. Moreover, the DG’s active power $\boldsymbol{p}$, grid voltage $\boldsymbol{V}$ and non-contingent line/transformer loading-values $\boldsymbol{L}$ must stay within technical limits. If $\boldsymbol{p^0}, \boldsymbol{V^0}, \boldsymbol{L^0}$ are their initial values prior to optimization, these limits can be expressed as:

$$\mathbf{0} \leq (\mathbf{p^0} + \boldsymbol{\Delta}\mathbf{p}) \leq \mathbf{p_{max}} \qquad (3)$$

$$\mathbf{V_{min}} \leq (\mathbf{V^0} + \boldsymbol{\Delta}\mathbf{V}) \leq \mathbf{V_{max}} \qquad (4)$$

$$(\mathbf{L^0} + \boldsymbol{\Delta}\mathbf{L}) \leq \mathbf{L_{max}} \qquad (5)$$

which are cast into the standard formulation of quadratic programming in (2). The sensitivity matrix $\partial h/\partial p$ relates $\boldsymbol{\Delta p}$ to the changes in $\boldsymbol{\Delta h} = [\boldsymbol{\Delta p}^T, \boldsymbol{\Delta V}^T, \boldsymbol{\Delta L}^T]^T$.

The optimization goal is to achieve a desired loading value (expressed as a loading-change $\boldsymbol{\Delta L_{goal}}$) on all contingent lines and transformers. Also, we aim to keep the active power curtailment of each DG as minimal as possible, hence an additional set point is used to keep $\boldsymbol{\Delta p}$ near with:

$$\boldsymbol{\Delta p_{goal}} = \mathbf{0} \qquad (6)$$

Storage control based on market prices – 'storage'

The storage model is based on [10]. The objective function maximizes the revenue of the storage owner based on the spot market price while considering the maximum line loadings. Inputs to the optimization problem are load and generation time series at the storage bus as well as DC power flow constraints and market price time series.

Single contingency policy

The time series simulation requires a large computational effort, depending on the number of buses in the grid and the resolution of time steps. An hourly resolution requires the calculation of 8760 load flow solutions, further multiplied by the number of possible outages of lines. For realistic power systems and multiple future scenarios, the simulation process can take up to days.
To include the SCP in the planning approach, we use an artificial neural network to predict line loadings and voltage magnitudes of the n-1 cases. The ANN is trained with active (P) and reactive (Q) bus power values and the n-1 configuration as inputs (7) and voltage magnitudes v_m and relative line loadings $i_{\%}$ results as outputs (8). This allows to reduce the calculation time significantly as shown in [7].

$$X = [P, Q, n-1] \qquad (7)$$
$$y = [v_m, i_{\%}] \qquad (8)$$

OpSim

OpSim is a co-simulation environment developed by Fraunhofer IEE and the University of Kassel. It enables users to connect their software to a simulated power system or to test their software in conjunction with other simulations. The core of OpSim is based on a flexible Message Bus (MB) architecture, allowing arbitrary co-simulations scenarios. In these scenarios, several simulators can be coupled. A detailed description of OpSim can be found in [11]. In this paper, OpSim is used to simulate a remotely connected control center, which runs the "DG P-control" curtailment strategy.

Reinforcement Heuristic

Based on the derived grid states (load cases) from the time series simulation, the reinforcement heuristic is started. Its inputs are the loadcases, defined by active (P) and reactive (Q) power of at the nodes, outaged lines, tap positions and switching state of the grid. The optimization goal of the heuristic is to minimize the cost of the necessary reinforcement of lines, subject to multiple restrictions.

$$\text{minimize costs} \qquad (9)$$
$$\text{s.t. voltage limits, line / transformer loadings} \qquad (10)$$

The restrictions include thermal line and transformer loading limits as well as bus voltage limits. Possible reinforcement measures are the replacement of lines and transformers. The optimization algorithm is a hill climbing heuristic, which is further explained in [8].

RESULTS

Analysed grids

Two exemplary distribution grid models are analysed to show the capabilities of the expansion planning framework. In both grids, the installed renewable DGs are scaled up to emulate a future scenario. The dynamics of generation and loads are modelled with ENTSO-E time series data and market prices of one year (2017) from [12]. Some key data of the two grids is summarized in Table 1.

Table 1: Data of analysed grids.

	CIGRE MV	Simbench HV
Voltage level [kV]	20 kV	110 kV
# Buses	15	61
# Lines	15	61
DG [MW]	11	1186
Load [MW]	5	686
Topology	open-ring	meshed

CIGRE medium voltage grid

The CIGRE medium voltage grid [6] is a synthetic grid model, which has typical characteristics of a European 20 kV open ring grid with radially operated feeders. As grid expansion planning criteria, a maximum line loading of 60 % and voltage deviations of 5 % from the nominal voltage is assumed.

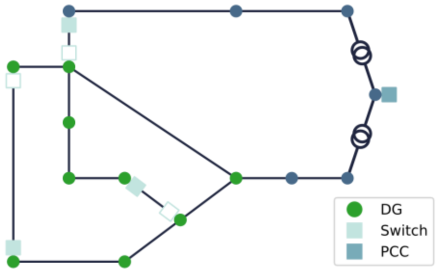

Figure 3: CIGRE medium voltage grid (open ring).

Technical results

Depending on the control strategy, line loadings vary during the year. Figure 4 shows the number of time steps (left) and height (right) of high line loadings. It can be seen that peak curtailment with x=10 % "curtailment 10%", is necessary to reduce the maximum loadings of all lines below 60 %. The optimized P-control strategy (popt) can also reduce the line loading below 60 %. With the assumed storage system configurations and control methods, line loadings exceed the 60 % limit and are not able to reduce the line loading sufficiently.

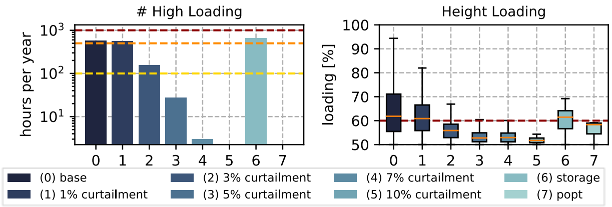

Figure 4: Line loading comparison of different control strategies.

No voltage violations occur during the year, as shown in Figure 5.

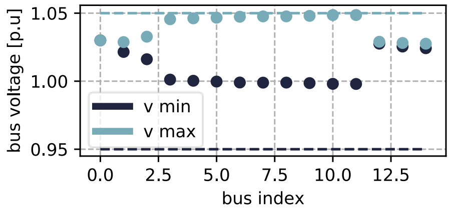

Figure 5: Maximum and minimum voltage per bus.

Figure 6 (left) outlines the curtailed DG energy for the x % peak shaving and the P-control method in comparison to the base values. With less than 3 % curtailment of the annual energy generation, the P-control method (popt) resolves all high line loadings. The storage control method shifts about 1 % of the annual generation but does not resolve the high line loadings. Depending on the control strategy and replacement criteria, different lines must be replaced to maintain the line loading limits, as shown in Figure 6 (right).

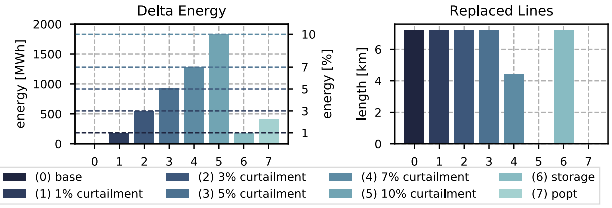

Figure 6: Curtailed energy and stored energy (left). Replaced lines (right).

Monetary results

The resulting costs for replaced lines as well as the power curtailment or energy shift by the storage systems are depicted in Figure 7. The replacement cost of 1 km of a medium voltage line is assumed to be 70.000 Euro [14]. The energy costs are obtained by multiplying the spot market price with the curtailed or shifted energy at the corresponding time step. Values are chosen from scientific data and do not necessarily represent actual costs. A detailed view of the sum of real power values for each bus is shown in Figure 8 (bottom) for exemplary time steps together with the market price. Figure 8 (top) shows the resulting costs for these time steps. The higher the curtailment, the higher the costs. The storage systems can achieve profit by shifting the energy to times of higher market prices.

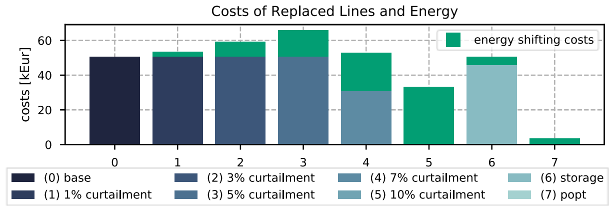

Figure 7: Resulting costs of line replacements (bottom bars), curtailed energy and energy shift of storage systems (top bars).

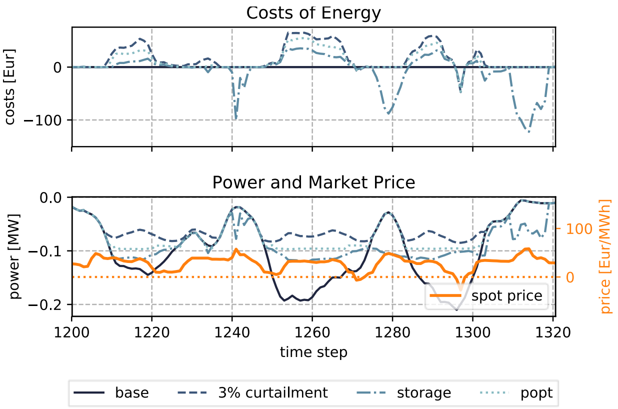

Figure 8: Detailed plot of costs of the curtailment and shifted energy (top). Real power injections and market price (bottom).

SimBench high voltage grid

The SimBench HV grid [13] is developed as a benchmark grid for grid analysis, grid planning and grid operation management. It is a meshed grid with a high share of RES and 3 points of common coupling to the 380 kV level.

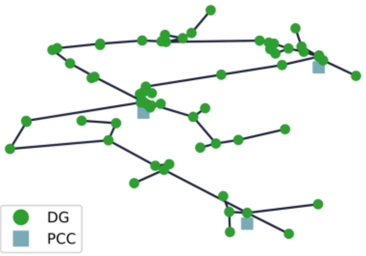

Figure 9: SimBench HV grid.

Technical results

The planning of meshed HV grids requires to consider the SCP. This results in higher computational effort, since each n-1 case must be analysed. For this reason, the ANN was used to predict the loading of each line in every possible outage situation. Exemplary results for the base case in comparison to the P-control strategy (popt) are shown in Figure 10. Without any outages, the line loadings are within 60 % for the P-control strategy. If, however, the SCP is considered, maximum loadings exceed the thermal limits. In this case, the P-control strategy can maintain limits for lines 4, 7 and reduce loadings by up to 10 % for other critical lines.

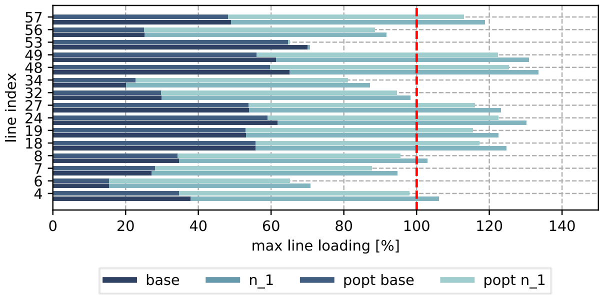

Figure 10: Line loadings for the base case and when using the popt strategy. Predicted n-1 loadings are shown for both.

The maximum and minimum voltage of each bus during the whole year is shown in Figure 11. In the base case, without line outages, the bus voltages are within a 5% limit of the nominal voltage. In the (n-1) cases, the maximum and minimum limits of the bus voltages are violated.

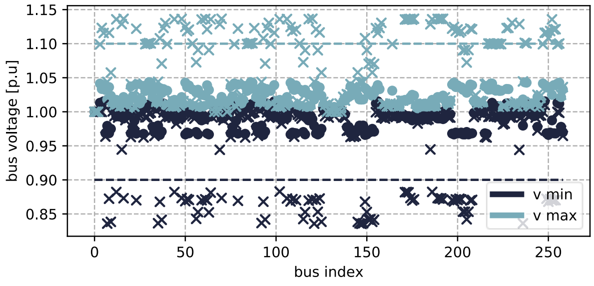

Figure 11: Maximum and minimum voltage per bus for the base case (circle) and n-1 cases (cross).

OUTLOOK / POTENTIAL APPLICATIONS

In this paper we introduced a novel distribution grid expansion planning framework, which combines time series simulations and heuristic optimization. Through the OpSim message bus architecture, diverse grid control strategies can be attached to the framework as well. Additionally, the replacement heuristic is able to consider other criteria, such as aging information of lines, in the optimization step. To demonstrate the framework technical and economic results are shown for two exemplary networks: the CIGRE medium voltage grid and the meshed SimBench HV grid.

Multiple time series must be analysed to increase robustness, since the heuristic solves only the derived loadcases derived from the input time series. Also, in meshed grids violations might occur after reinforcement due to altered power flows and other lines might overload. The simulation therefore must be computed multiple times.

ACKNOWLEDGMENTS

The research is part of the project **OpSimEval** and funded by the BMWi (0325782A,B). The authors are solely responsible for the content of this publication.

REFERENCES

[1] J. Kays, C. Rehtanz, 2016, “Planning process for distribution grids based on flexibly generated time series considering RES, DSM and storages”, *IET Generation, Transmission & Distribution 14, pp. 3405–3412*

[2] H. Saboori et.al, 2017, “Energy storage planning in electric power distribution networks – A state-of-the-art review”, *Renewable and Sustainable Energy Reviews 79, p. 1108– 1121*

[3] VDE | FNN, 2017, “Curtailment – a new degree of freedom in planning”, URL*: https://www.vde.com/de/fnn (07.01.2018)*

[4] A. J. Wood, B. F. Wollenberg, and G. B. Sheblé, 2014, “Power Generation, Operation, and Control”, *3rd ed. John Wiley & Sons*

[5] P.S. Georgilakis, N.D. Hatziargyriou, 2015,“A review of power distribution planning in the modern power systems era: Models, methods and future research”, *Electric Power Systems Research 121, pp. 89- 100.*

[6] L. Thurner, et. al., 2018, “pandapower - an open source python tool for convenient modeling, analysis and optimization of electric power systems,” *IEEE Transactions on Power Systems*

[7] F. Schaefer, J-H. Menke, M. Braun, 2018, “Contingency Analysis of Power Systems with Artificial Neural Networks”, *Proceedings IEEE SmartGridComm’18 conference*

[8] L. Thurner, 2018, “Structural Optimizations in Strategic Medium Voltage Power System Planning.” *kassel university press, Kassel, Hess. Germany*

[9] K. Mamandur and R. Chenoweth, 1981, “Optimal control of reactive power flow for improvements in voltage profiles and for real power loss minimization” *IEEE Trans. Power App. Syst., vol.100, pp.3185-3194*

[10] J. v, Appen, M. Braun 2018, “Strategic decision making of distribution network operators and investors in residential photovoltaic battery storage systems.” *Applied Energy, Vol. 230, pp. 540-550*

[11] Fraunhofer Institute for Energy Economics and Energy System Technology, 2018, “OpSim: test- and simulation-environment for grid control and aggregation strategies'', URL*: www.opsim.net/en (07.01.2018)*

[12] The OPSD project – a free and open data platform for power system modelling, 2018, *URL: https://open-power-system-data.org (07.01.2018)*

[13] SimBench, 2018, “Simulation data base for a consistent comparison of innovative solutions in the field of grid analysis, planning and operation management.” url: www.simbench.net *(07.01.2018)*

[14] K. Heuck, K.-D. Dettmann, D. Schulz, 2010, “Elektrische Energieversorgung” (8th Edition), Vieweg+Teubner, Berlin, Germany