MULTI-TEMPORAL ROBUST EXPANSION PLANNING OF DISTRIBUTION GRIDS CONSIDERING UNCERTAINTIES AND CURTAILMENT OF RES

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ABSTRACT

This paper focuses on the rising complexity of network expansion planning due to different sources of uncertainty and the transformation into a smart grid environment. Both have to be considered in the process of determining the optimal multiannual expansion plan. Due to long life-spans and high investment cost of the grid assets robust investment decisions avoiding sunk-cost are crucial. Thus a stochastic, multi-step optimization program has to be solved.

This paper presents a new hybrid-heuristic optimization approach to derive optimal multiannual investment decisions considering the uncertainty of the RES-development and flexibility options on the example of a RES-curtailment. .

INTRODUCTION

Due to the rising share of renewable energy sources (RES) many electrical networks need to be expanded in order to integrate all RES without violating any technical constraint. Furthermore the ending life-time of grid assets requires new investment decisions. Within the process of network expansion planning the distribution system operator (DSO) has to derive the economically optimal multiannual expansion plan, which determines for each year of the middle-term planning horizon which new grid assets are necessary. Due to long life-spans and high investment cost of the grid assets robust investment decisions avoiding sunk-costs are crucial.

Nowadays the DSO faces new challenges within the planning process and its complexity rises. The future network usage, especially the development of the installed capacity of RES is highly uncertain and has to be taken into account. With the transformation into a smart-grid world the conventional grid assets to resolve technical violations are supplemented with new technologies and planning strategies that offers flexibility. Due to the rising complexity of the planning problem the application of computer-based optimization methods is helpful [1].

Therefore this paper presents firstly the description of the optimization problem for the task of distribution network expansion planning followed by the detailed description of the new optimization approach. Afterwards the planning task of connecting new wind generation units into an existing medium voltage network is shown as an exemplary application to demonstrate the functionality of the optimization algorithm and to provide a deeper understanding of the heuristic approach.

NETWORK EXPANSION PLANNING

Scope of consideration

The paper focuses on high (HV, the 110-kV-area) and medium voltage networks (MV, the 10-, 20-, 30-, 60-kV area) due to the higher investment cost and the more standardized planning process compared to low voltage networks. As Figure 1 shows, the relevant time frame for the expansion planning can be subdivided in three different intervals. For the years of the planning interval A explicit investment decisions have to be taken and their realization process starts. These decisions must consider the follow-up costs which are given by the choice of investment decisions in the years of interval B, which are determined within the optimization. For interval C it is assumed that the network usage is constant (process of RES-integration completed) and therefore eternal cost of the periodic renewal have to been considered. The whole process is applied periodically.

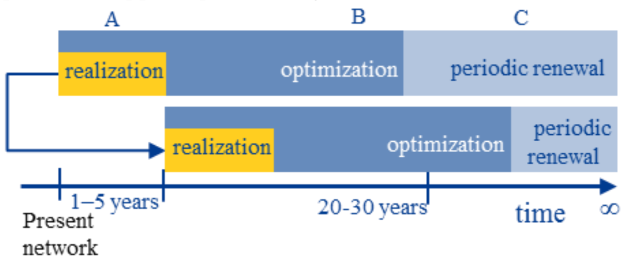

Figure 1: Time frame of network expansion planning

Problem statement

As stated above the task of network expansion planning is a complex optimization problem. Figure 2 illustrates that first of all an adequate model for the uncertainty of the network usage (development of RES and load) is necessary. Then the three standard aspects (degrees of freedom, constraints, objective function) of an optimization problem are modelled according to the requirement of the network expansion planning.

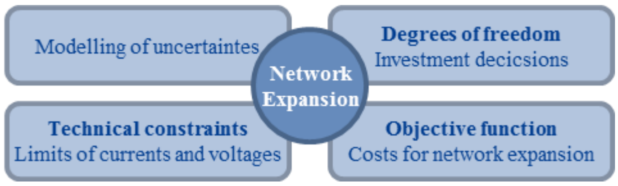

Figure 2: Overview – Network expansion planning

Uncertainty of the network usage

Many contributions such as [2] use multiple scenarios to model the uncertainty. Each scenario represents one possible development but is completely unrelated to all other scenarios, in other words they have not a joint development. The weakness of this approach is that optimal and unambiguous investment decisions which have to be taken “now and at once” cannot be derived. Either the single scenarios are individually optimized and then lack in the ability to give one joint decision or the so-called robust decision are derived either as a fat solution (feasibility for all scenarios at higher costs) or as a solution that is feasibility only for a percentile. This paper introduces a scenario tree approach [3] to model the uncertainty. As illustrated in Figure 3 this is advantageous, as robust investment plans with an optimal joint decision for the “now and at once” investments can be derived.

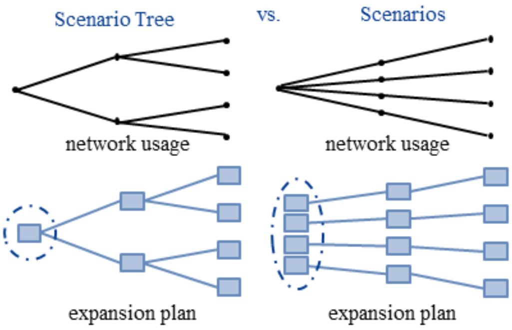

Figure 3: Advantages of the scenario tree approach

This approach also includes the multi-stage character of the expansion planning. Where in many contributions [4,5] the models are only one-stage, e.g. the present network is expanded to match the network usage at on future point of time T, in this paper the scenario tree models the development of the network usage for different stages from “now” to a future T.

Objective function

The objective function is the minimization of the expected costs $\mu(C)$ which are capital expenditures (CAPEX) and operations expenditures (OPEX), including the costs of curtailed energy. Costs of each part of the network expansion plan (each point of time and each scenario) are balanced. Due to different time frames of the investment decision cash-values are used. Minimization of the expected value $\mu(C)$ corresponds to a risk-neutral decision strategy. For risk-averse optimization an additional measure R can be integrated. Then, the objective function is $f = f(\mu, R_1, R_2, \ldots)$. Example for risk-averse objective functions are $f = \mu + \alpha_1 \cdot \rho$, with the semi-variance ρ as the average of the squared derivations of values (costs) that are bigger than the mean, or $f = \mu + \alpha_2 \cdot CVaR$ with $CVaR$ as conditional value at risk.

Technical constraints

To prevent damages of the assets, operational constraints for the branch current I_b are defined for each branch in the system. To ensure an adequate voltage level for customers and to prevent damages of assets due to over or under voltages, the nodal voltage V_n has to stay within the range defined by the standard EN 50160 (for MV-networks) and within operational limits for HV-networks [6].

Furthermore it has to be ensured that the minimum and maximum short-circuit currents stay within the admissible range. The N-1-criteria has to be fulfilled in order to guarantee a sufficiently reliability. In MV-networks interruptions are allowed if the load can be reconnected with switching measures. In HV-networks the reconnection must be guaranteed by remote-controlled automatic switches.

Degrees of freedom

Overview

Table 1 sums up the degrees of freedom that are considered in the presented network expansion algorithm.

Degree of freedom	HV	MV
Build / Rebuild / Degradation of overhead lines, cables and transformers		
Use of high temperature electrical conductors		
Use of overhead transmission line monitoring		
Build of new transformer stations (MV/HV, HV/EHV)		
Integration of voltage regulated transformers (standard in HV)		
Use of flexibility options provided by generators and loads, if accessible by DSO		

Table 1: Degrees of freedom in network expansion planning

Consideration of RES-curtailment strategies

Since 2016 the curtailment of RES can be considered in the network planning process. Then, the planner does not expand the network for theoretically hosting the full installed capacity and is allowed to curtail the feed-in within a certain range. Therefore in network planning an optimal balance between curtailment (and remuneration of the producer for the energy curtailed) and investing in conventional grid assets (e.g. new line to reduce overloading) must be derived in order to determine the optimal annual expansion plan.

OPTIMIZATION ALGORITHM

The main characteristic of the algorithm for network expansion planning is the multi-step optimization, that is capable of finding optimal investment decisions for the planning interval of realization (see Figure 1 A) considering the follow-up costs of intervals B (optimization) and C (endless renewal). Nowadays many approaches exist for the strategic planning referring to a certain point in time and giving optimal target networks. These are the cost-minimal network configurations for a given network usage (loads and generators to be integrated) [7]. Target network planning approaches do neither consider the status quo network configuration nor any potential cost of rebuilding or degradation for the transformation of the present network into the target network. Although this is a common model for the network expansion optimization algorithm, forcing the realization of this transformation is not the optimal way to do due to additional costs. But as the target network planning gives useful ideas for investment decisions to be taken along the network expansion process, it is still a good way to incorporate this as one part of the optimization algorithm.

To solve the presented optimization task a hybrid heuristic approach combining a genetic algorithm (GA) and a particle swarm optimization (PSO) is used. Hybrid approaches of GA and PSO are well-known in power system applications [8]. This paper adapts a hybrid approach from ongoing research activities to derive robust switching states for an application in transmission system operation [9]. The approach consists of a master and subproblem, where the subproblem defines the solution space of the master problem. Here, the subproblem is the task of performing target-network planning for each relevant network usage and derives a predefined number of possible target-networks. This is done using an algorithm based on GA. The master problem selects the overall optimal solution from the candidate solutions using PSO.

Multi-step approach with time-couplings

To begin with, the genetic algorithm (GA) for the target network planning is applied to all points in time (not only the end of the planning horizons) and provides a local optimization for each point of time. But as the series of the optimal solutions (target network TN) of each GA is not optimal in respect to the objective function of the expansion planning which includes the costs of rebuild and degradation, a communication process between the independent GA is introduced (see Figure 4).

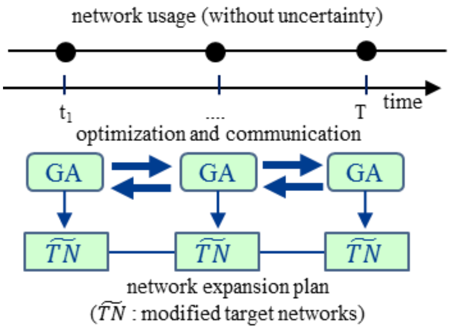

Figure 4: Optimization with different time-steps

Then the local optimization solutions provide candidate solutions $\widetilde{TN}$ that are modified in a way that a series of $\widetilde{TN}$ can be found which is optimal in respect to the global optimization function of the network expansion planning. Figure 5 illustrates that under uncertainty the communication process takes place between each part of the scenario tree.

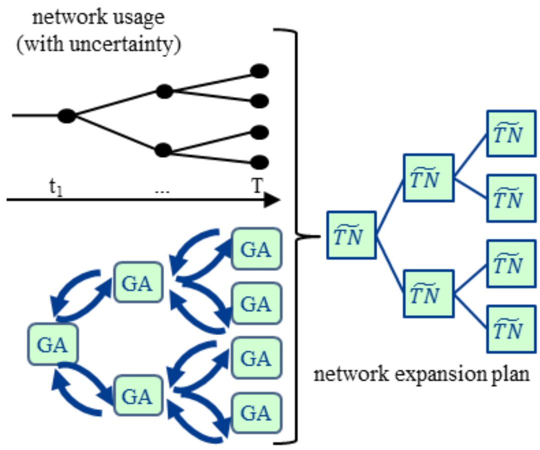

Figure 5: Optimization under uncertainty

Subproblem

This paper uses an existing algorithm of target-network planning based on a genetic algorithm [7] as a starting point. As stated above, the task of the subproblem is to define the solution space for the master problem. For this, the fitness function of the GA (evaluation of each individual) is set on the difference of costs between the current individual and a given network configuration. To begin, this given configuration is the present network and it will then be updated periodically by the master problem. Network configurations resulting of the GA have to fulfil all technical constraints. Therefore existing algorithms for load-flow calculations and security constrained optimal power flow (SCOPF) [10] to determine optimal curtailment strategy are integrated.

Master problem

The master process collects the candidate solutions $\widetilde{TN}$ of each GA, calculates the corresponding value of the global target function and gives back information to each GA about how the local optimization process should be adopted in order to improve the global optimization result. This is done by updating the given network configuration of each GA which is the reference for the calculation of costs within the GA. These given networks are the result of one master problem optimization and therefore include information from all GA. Thus, the communication between the different GA is performed via the master problem and the new given networks. The fitness function of the master problem is the objective function of the network expansion planning problem as described above.

Overview of the optimization algorithm

Figure 6 gives an overview of the complete optimization process. For each node of the scenario tree the modified genetic algorithm is started, trying to derive the optimal network configuration relative to the given configuration. In the first iteration the given configuration is equal to the present network. In the following iterations the present network is updated by the master-process. Within the GA load-flow analyses SCOPF algorithm is used to address branch currents and nodes voltages and to determine the energy to be curtailed so that no technical limits are violated.

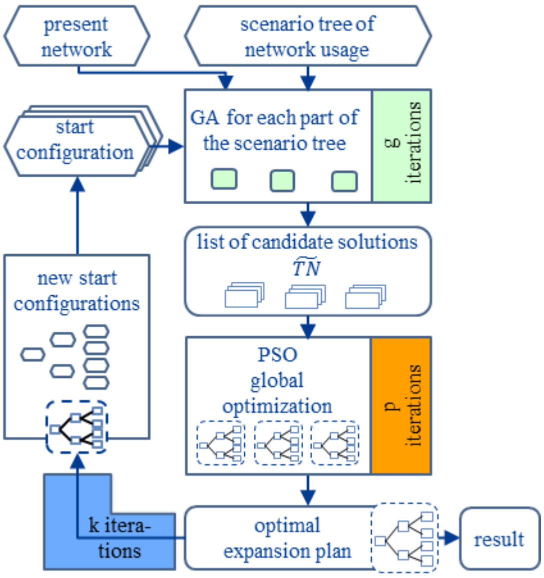

Figure 6: Overall optimization algorithm

After g iterations within the GA, the candidates are sent to the master optimization (PSO). The PSO evaluates within p iterations different combinations of investment strategies (each given as one GA candidate for each part of the scenario tree) and determines the optimal one. For each part of the scenario tree the investment decisions corresponding to the optimal configuration found within the PSO are given back to the slave process in order to start a new GA iteration with a new network configuration as starting point. After k iteration the final result of the PSO optimization is taken as the final optimization result.

The investment decisions within the time frame A (realization) should be realized. They are optimal and robust decision regarding to all possible developments and to all follow-up costs given by the scenario tree.

EXEMPLARY RESULTS

To prove the functionality of the presented optimization algorithm a part of a 10-kV-network is investigated (see Figure 7). To model the uncertainty of the development of the wind-power a scenario tree with 2 scenarios and two possible realisations is considered. Depending on the scenario 9 MW (sum = 12 MW) or 15 MW (sum=18 MW) of installed wind power must be connected to the network in addition to the 3 MW already existing.

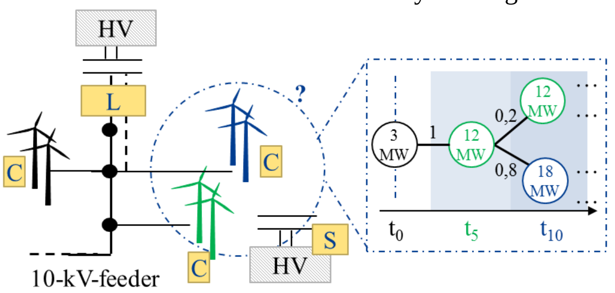

Figure 7: Present network and uncertainty of network usage

The degrees of freedom are shown in Table 2. The costs for investment and RES-curtailment are chosen based on standard values but without need to be realistic, as the paper focuses on the demonstration of the functionality of the presented approach [5].

L	Investing in new lines/corridors (6 MVA)
S	New transformer station (31.5 MVA)
C	RES-curtailment

Table 2: Exemplary results – Degrees of freedom

The optimization is performed for the five different cases presented in Table 3. In case N°1 all degrees of freedom are available without limitations. In contrast, in N°2 the amount of annual energy curtailed may not exceed 3% of the annual energy feed-in, as it is required in Germany since 2016. N°3 is the optimization based on the precondition that line enforcement has to be chosen in t_5. Optimization N°4 is equal to N°3 with the additional limitation that no curtailment at all is possible. N°5 is the optimization without curtailment but with free choice of the network configuration in t_5.

N°	description	L	S	C
1	without further limitations	x	x	x
2	**l**imitation of energy curtailed	x	x	x (l)
3	line enforcement in t_5 **r**equired	x (r)	x	x
4	line enforcement in t_5 **r**equired	x (r)	x	-
5	without further limitations	x	x	-

Table 3: Evaluated cases of optimization

Results

The results in Figure 8 show the optimal network expansion plans for the presented cases of optimization. Each is given as a scenario tree with investment decisions and its value of the global objective function (cash-value of expected costs) - differentiated in capital expenditures (CAPEX) and operational expenditures (OPEX). All costs are presented in a relative way and are all referred to the solution of case N°1.

With the assumed relations of costs for investments and RES-curtailment for case **N°1** the optimal investment plan is given by a permanent RES-curtailment over the optimization time frame and with endless repetition.

Given the presented limitation for the energy curtailed, **N°2** shows that curtailment is still chosen in t_5 and in the upper scenario of t_{10} because it offers a "wait and see" approach. Given the uncertainty of the development of the network usage violations of technical limits can be solved with curtailment until in t_{10}, depending on the scenario that will occur, the necessary investment decision (station) can be taken without risks.
In the case that line enforcement is required in t_5, **N°3** shows that the existing line must be enhanced with a parallel one. The follow-up cost may be zero (upper scenario with 12 MW) or consists in the cost for the energy curtailed. In N°4 a further line enforcement is necessary in t_{10} and scenario 2 because curtailment is no longer considered as degree of freedom.
N°5 demonstrates that without the possibility of RES-curtailment the optimal solution is the immediate investment in the new transformer station. Then all new generation units are connected to the new station and now overloadings occur on the existing line.

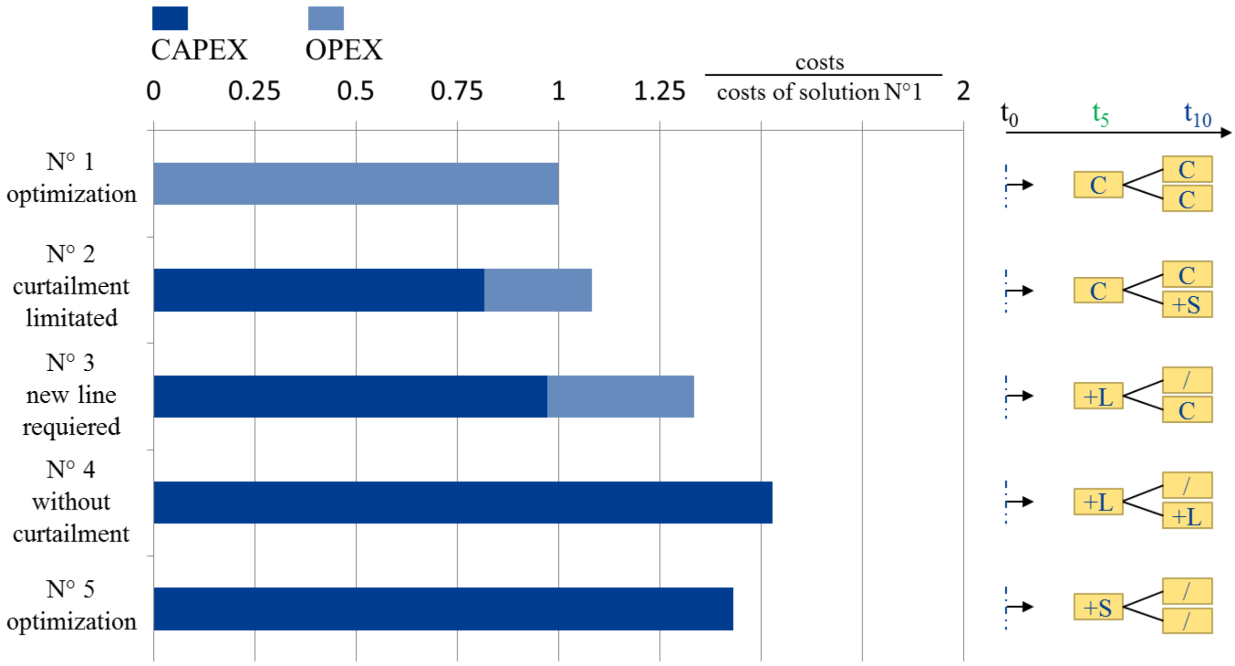

Figure 8: Exemplary results

REFERENCES

[1] Ziegeldorf et al, 2016 „Optimale Ausbauplanung von Verteilnetzen unter Berücksichtigung von Unsicherheiten und innovativen Betriebsmitteln", *EnInnov - 14. Symposium Energieinnovation*, Graz
[2] Bongers et al, 2016, "Robust High Voltage Network Expansion Plannig Considering Multiple Future Renewable Scenarios", *Energycon - IEEE International Energy Conference*, Leuven
[3] Grüwe-Kuska, Heitsch, Römisch, 2003, „Scenario Reduction and Scenario Tree construction for Power Management Problems", *IEEE Power Tech Proceedings*, Bologna
[4] Bongers et al, 2016, „Impact of Curtailment of Renewable Energies Sources on High Voltage Network Expansion Planning", *PSCC - 19th Power Systems Computation Conference*, Genova
[5] Ziegeldorf et al, 2015, „Innovative Planning Method for Deriving New Rules for Future Network Planning," *Paper 1394, 23rd International CIRED Conference*, Lyon
[6] Verband der Netzbetreiber - VDN – e.V. beim VDEW, 2007, „TransmissionCode 2007: Netz- und Systemregeln der deutschen Übertragungs-netzbetreiber"
[7] Maurer, 2004, „Integrierte Grundsatz- und Ausbauplanung für Hochspannungsnetze", *Aachener Beiträge zur Energieversorgung. Bd. 101, Klinkenberg*
[8] Del Valle, Y. et al, 2008, „Particle Swarm Optimization: Basic Concepts, Variants and Applications in Power Systems", *IEEE Transactions on Evolutionary Computation*
[9] Moormann et al, 2015: "Robust Switching States for an Application in Transmission System Operation", International ETG Congress 2015: Die Energie-wende - Blueprints for the new energy age, Bonn
[10] Eickmann et al, 2015, „Security-Constrained Optimization Framework for Large-Scale Power Systems Including Post-Contingency Remedial Actions and Inter-Temporal Constraints", *International Symposium on Energy System Optimization*; Heidelberg (DEU)