QUALITY OF SUPPLY AS A BOUNDARY CONDITION OF COST-EFFICIENT DISTRIBUTION NETWORKS

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ABSTRACT

In liberalized and regulated electricity markets, realising cost-efficient network structures is becoming more and more important for network system operators. In many incentive regulation schemes, quality of supply is considered as an output variable of network operation or treated as a technical standard that needs to be fulfilled. Thus, quantitative quality of supply indices need to be considered during network planning. Until now, this was not possible due to high computational effort of both network optimization and quality of supply analysis. In this paper, a newly developed approach for integrating the quality of supply analysis into an existing network optimization algorithm is presented. Despite cost-efficient network structures under quality of supply constraints, the coherence between quality of supply and network costs can be analysed subjectively for the first time.

BACKGROUND INFORMATION

Due to the impending incentive regulation of electricity networks in Germany, the pressure on network system operators to develop cost-efficient network structures has increased significantly over the last years. Because of that, network operators have already started to search intensely for procedures that improve the efficiency of their networks. For this, a convenient method is to optimize the network structure in order to supply energy to all network customers with minimum costs [1]. However, since the amortisation period of assets in distribution networks can amount for several decades, this approach does only lead to a reduction of costs in very long periods. For calculating cost-efficient network structures, more and more computer-based methods are used. Those determine the structure and dimensioning of the optimal network fulfilling the (n–1)-criterion with respect to the characteristics of the supply area and network customers. Despite the calculation of long-term target networks, numerous applications of those methods like the calculation of reference networks for measuring the efficiency of network system operators have proved the functionality of those algorithms [2, 3].

One of the key issues in the incentive regulation process is to ensure an adequate level of the quality of supply for network customers. For this it is inevitable to assure that a reduction of costs does not lead to a reduction of necessary investments and maintenance schemes and thereby to an inadequate worsening of the quality of supply. Thus, the incentive regulation in Germany will consist of one additional module for regulating the quality of supply in distribution networks as well. This may be done by defining quality standards depending on the supply area that need to be fulfilled and by implementing penalties for violating those standards.

Because of that, taking the quality of supply into account during the network optimization process is becoming more and more important. Until now, this could only be done by defining empirical criteria like the (n–1)-criterion that could easily be tested during network optimization. Following the optimization process, quantitative indices like the System Average Interruption Duration Index (SAIDI) were calculated for the network structures with minimum costs by applying a probabilistic quality of supply analysis. In case those indices exceeded a given value, modified network structures were taken into account. This led to a time-consuming iterative optimization process and not necessarily to the overall optimal solution. In order to consider the quality of supply as a boundary condition in a more adequate way, it seems reasonable to consider boundary conditions regarding quantitative quality indices during the computer-based network optimization process.

This paper describes the integration of a probabilistic quality of supply analysis into an existing network optimization method for meshed distribution networks. With this implementation it is now possible to treat quantitative quality indices as a boundary condition during network optimization. Despite the calculation of cost-efficient network structures with respect to those constraints, the coherence between the quality of supply and network costs can be analyzed with this method as well. Finally, penalties for violating quality of supply boundary conditions may also be considered as part of the objective function during optimization and can therefore be evaluated as to whether they assure an adequate quality of supply for network customers.

DEVELOPED METHOD

When calculating optimal cost-efficient distribution networks, the individual impact of a single planning decision like the number of lines used on a specific route or the dimensioning of equipment on system-wide quality of supply indices cannot be described by a mathematically exact formulation. Under consideration of constraints for those indices the optimization task can therefore not be solved with exact optimization methods like Mixed Integer Programming.

Hence, the proposed method is based on the heuristic optimization approach of *Genetic Algorithms* [4]. It has been developed at the Institute of Power Systems and Power Economics (IAEW) at RWTH Aachen University [5] and calculates multiple network structures with similar costs, known as the *population* of the optimization process, in an iterative manner. For all possible solutions—referred to as *individuals*—the compliance to technical boundary conditions as the (n–1)-criterion, voltage and short circuit current limits and quality indices in particular is assured in each iteration. The algorithm used for testing technical boundary conditions is described later on. New individuals are created by combining and mutating attributes of those individuals that comply to all constraints with minimum costs. Individuals with higher costs are replaced by the newly created individuals when moving to the next iteration. Thus, the whole population converges against the optimal solution with an increasing number of iterations.

For evaluating quantitative quality indices of the various network structures, the algorithm for probabilistic quality of supply analyses RAMSES, which has also been developed at IAEW, is used [6]. This method determines the System Average Interruption Frequency Index H_U (SAIFI), the Customer Average Interruption Duration Index T_U (CAIDI) and the System Average Interruption Duration Index Q_U (SAIDI) based on the failure rate of the equipment in the network, which can be derived from statistical data. Boundary conditions regarding the quality of supply at different substations or the whole system can therefore be described by maximum allowable values for those indices.

If one or more technical boundary conditions are violated by an individual during the optimization process, actions are taken that transfer the individual solution into the valid solution space. Those actions are chosen by heuristic rules that have been implemented into the developed algorithm. For example, improvements in the quality of supply may be achieved by adding additional circuits to the network or by changing switching station concepts, as when replacing a branch connection by a busbar concept.

Choosing adequate actions in order to repair the violation of boundary conditions has crucial impact on the computing time and on the quality of the best solution found. To find the optimal action, failures that lead to an interruption of customers in the individual network structure are analyzed at first. In this step, the influence of the type of equipment used, the dominating reasons for failures and the topology of the network are considered. Second, actions that lead to the largest improvement of the quality of supply for most customers are identified and chosen. If more than one optimal action exists, new individuals for which alternative actions are chosen are created and added to the population.

EXEMPLARY RESULTS

The functionality and capability of the developed method is proved by solving a typical optimization problem for 110 kV networks. Additionally, the influence of quantitative boundary conditions regarding the quality of supply on network structure and costs is analyzed.

Figure 1 shows the considered 110 kV supply area including the useable routes for 110 kV overhead lines. On all lines, one or two 110 kV circuits may be installed.

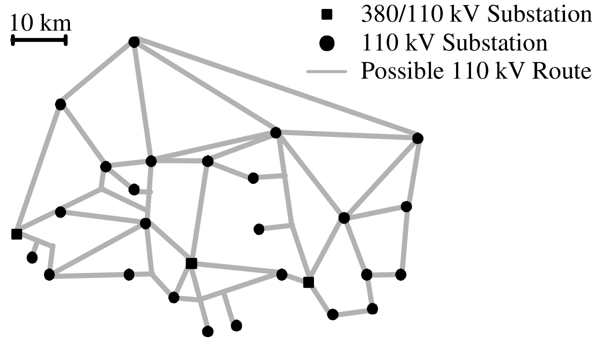

Figure 1: 110 kV supply area

The 380/110 kV substations in the supply area have to be realized as inherently safe by installing two 300 MVA transformers in each substation. The type of overhead conductors used is Al/St 265/35 mm^2. Degrees of freedom are therefore given by the choice of routes to be used, the number of circuits to be installed on those lines and the switching station concepts. Basically, switching stations may be realized as branch, loop or busbar concepts, but the choice of concept may be restricted due to the number of lines that have to be connected at this switching station.

As a quantitative quality of supply index, the SAIDI Q_U for each customer is considered in the following. At first, the network structure with minimum costs is calculated for the supply area from figure 1 considering only the (n–1)-criterion without regarding quantitative constraints as a reference. This network is shown in figure 2 and dyed according to Q_U at each substation. The annuity network costs of this solution amount to 12 Mill. €/a. The probability of an interruption at the substation with the worst quality of supply is almost 12 min/a.

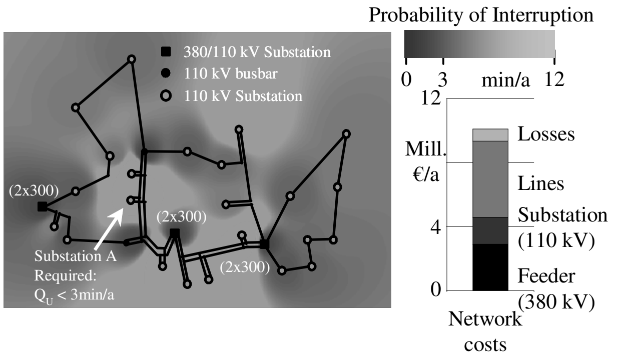

Figure 2: Cost-efficient network structure considering only the (n–1)-criterion

The relatively high probability for an interruption at some substations in this network is caused by the intensive use of cost-efficient branch line connections. In case all circuits on one route have to be switched off because of a common-mode failure, several substations are disconnected from the network simultaneously. Thus, the additional costs for improving the quality of supply at those substations by using more cost-intensive loop connections have to be analyzed and evaluated.

As an example, for substation A in figure 2 a maximum allowable value for Q_U of 3 min/a is claimed. Under this additional constraint, the optimal network structure shown in figure 3 is calculated.

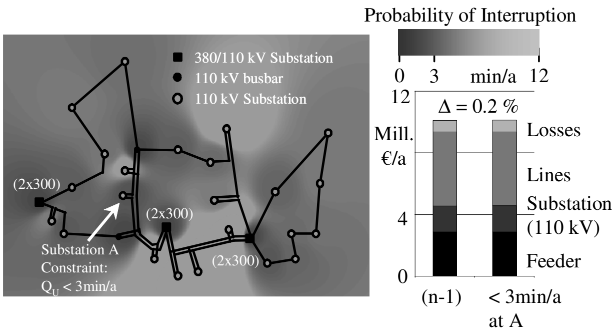

Figure 3: Cost-efficient network structure under the constraint $Q_U \leq 3$ min/a at substation A

This network structure differs from the one shown in figure 2 only by the loop instead of branch connection at substation A. Through this, not only the quality of supply for the customers connected in substation A but also for those connected at substations close to this area is improved. This is due to the significantly smaller protection zone. The annuity network costs are only 0.2 % higher than in the cost-efficient network fulfilling only the (n–1)-criterion. This shows that in this case the quality of supply can be improved significantly with only small financial effort.

Additionally, the impact of a system-wide maximum allowable value of 3 min/a for Q_U is analyzed. The network structure considering this additional constraint is shown in figure 4. It differs significantly from the structures analyzed so far.

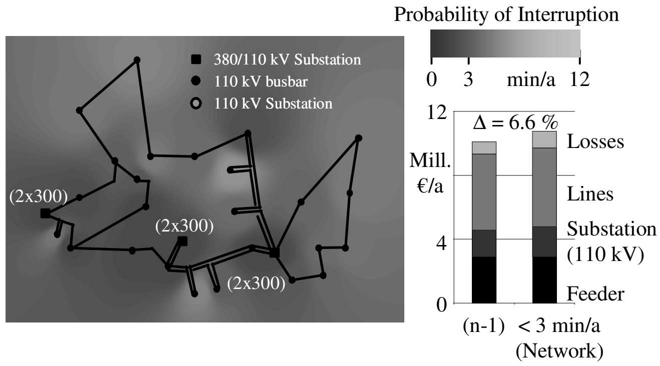

Figure 4: Cost-efficient network structure with $Q_U \leq 3$ min/a for all customers

The improvement in the quality of supply is mainly achieved by replacing double circuits with more single circuit lines. Therefore, the impact of common-mode failures on the quality of supply is reduced. In addition to this, more busbar switching stations are used instead of simple branch and loop connections. However, the additional costs required for this network amount for 6.6 % of the costs associated with the cost-efficient network considering only the (n–1)-criterion.

As this results prove, the newly developed method is able to quantify the coherence between network costs and quantitative boundary conditions regarding the quality of supply.

In figure 5, the results of a systematic analysis of this coherence are shown. For this, the system-wide maximum allowable SAIDI has been reduced step by step, starting at 15 min/a. For each solution of the optimization process, network costs have been calculated and compared with the costs of the network with the worst quality of supply.

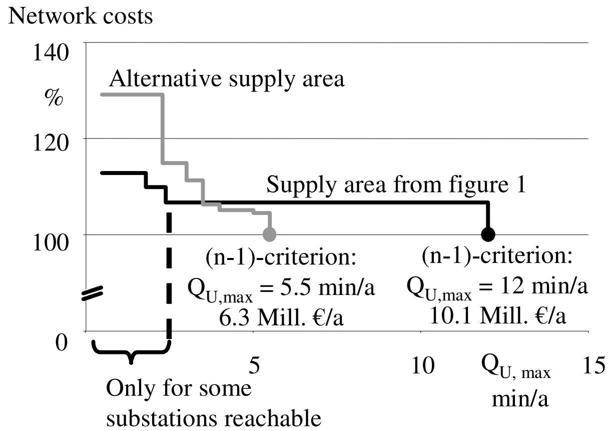

Figure 5: Coherence between network costs and the quality of supply

The following effects can be identified through these results:

- The System Average Interruption Duration Index cannot be reduced to any value. For example, in the supply area which has been described in detail above, no network structure ensuring a SAIDI less than 2.4 min/a for every customer exists. In order to improve the quality of supply further, additional routes have to be used.
- Quantitative indices regarding the quality of supply of different networks fulfilling the (n–1)-criterion can differ significantly. For an alternative supply area similar to that from figure 1, the network costs depending on the required quality of supply are also shown in figure 5. As can be seen, the maximum SAIDI of the network considering only the (n–1)-criterion is only 5.5 min/a.
- With increasing demands regarding quality of supply, network costs do not increase continuously. Instead, discontinuous points appear as soon as a network structure does not meet those demands any longer.
- For different supply areas, different coherences between network costs and the quality of supply are observed. Thus, no general value for the additionally required costs can be associated with certain demands regarding quality of supply.

Economical incentives for following boundary conditions regarding quality of supply can be defined by penalties that have to be paid if given limits are violated. From the network operators point of view, those penalties have to be treated as additional network costs and are therefore part of the objective function during network optimization. Thus, the developed method allows the integration of penalties into the objective function that has to be minimized.

In the following, a maximum allowable SAIDI of 3 min/a is defined. For every substation that exceeds this boundary value, penalties proportional to the exceedance have to be paid. Thus, in case of high penalties, the network operator is obliged to invest in more reliable equipment with higher costs in order to increase the quality of supply. In case of low penalties, paying for violating the given boundary values is economically reasonable. Therefore, the quality of supply that is provided by the network with minimum costs depends on the penalties that have been defined. In figure 6, the maximum SAIDI in the system depending on the penalties is shown for the supply area from figure 1 and the alternative, similar supply area.

It can be seen that

- improvements in the quality of supply that can be reached without large financial effort are already attained with low penalties (compare to figure 3), although the required value of 3 min/a is only reached with very high penalties (500 thousand euro per year per min/a exceedance);
- different penalties for exceeding given boundary values have different impacts depending on the characteristics of the supply area. Therefore, adequate penalties have to be chosen individually for each network.

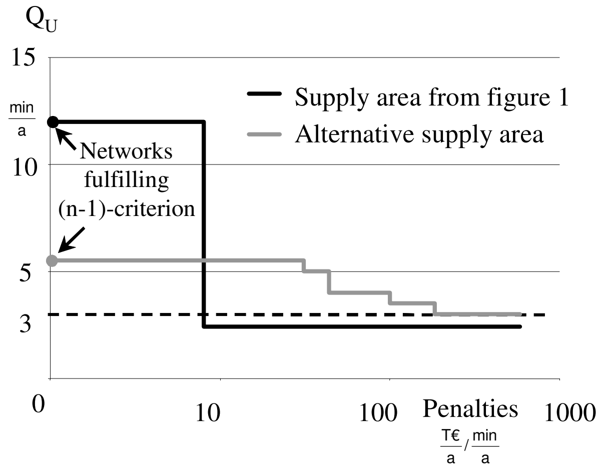

Figure 6: Maximum SAIDI of the cost-efficient network structure depending on penalties

SUMMARY

This paper describes a computer-based optimization method for planning distribution networks that allows considering quantitative boundary conditions regarding the quality of supply during optimization for the first time. With this method, the impact of such constraints on the network structure and network costs can be quantified. Additionally, the coherence between network costs and the quality of supply can be analyzed. Likewise, the impact of penalties for violating given standards defining the quality of supply can be evaluated with this algorithm.

REFERENCES

[1] K. Steinbrich, L. Bendel, 2005, „Neukonzeption eines städtischen Versorgungsnetzes zur Optimierung des Netzbetriebs“, *ew* vol. 104, 48-53.

[2] P. Wolffram, Ch. Maurer, 2003, „Ermittlung langfristig optimaler Strukturen für 110-kV-Netze unter Berücksichtigung der Stationskonzepte“, *Annual Report 2003 of the Institute of Power Systems and Power Economics*, Aachener Beiträge zur Energieversorgung, vol. 92.

[3] Ch. Maurer, K. v. Sengbusch, P. Wolffram, 2004, „Netzvergleich mit Referenzverfahren“, *Energietechnische Tagesfragen*, vol. 54, 436 – 438.

[4] V. Nissen, 1997, *Einführung in evolutionäre Algorithmen: Optimierung nach dem Vorbild der Evolution*, Vieweg Verlag, Braunschweig, Germany.

[5] Ch. Maurer, 2004, *Integrierte Grundsatz- und Ausbauplanung für 110-kV-Netze*, Dissertation, Klinkenberg Verlag, Aachen, Germany.

[6] H.-J. Haubrich, 1996, *Zuverlässigkeitsberechnung von Verteilungsnetzen*, Klinkenberg Verlag, Aachen, Germany.