A NOVEL METHODOLOGY FOR MULTI-YEAR PLANNING OF LARGE-SCALE DISTRIBUTION NETWORKS

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Summary - This paper presents a new optimization procedure for multi-year distribution network planning based on dynamic programming, local network concept and mixed integer model. By introducing principles of dynamic programming and local network concept the multi-year planning problem of real-size networks is divided into sequences of sub problems with significantly reduced dimensions, enabling application of complex mixed integer programming model in each sub problem. The results obtained on several real-life distribution networks have shown that suggested procedure enables more efficient use of existing capacities and reduction of future expansion costs.

1. INTRODUCTION

Deregulation and competitive marketplace enforced completely new conditions in power industry. Even though a distribution company may still operate within regulatory framework, it is faced with financial pressures and noticeable decrease in available capital budgets. In such conditions distribution planning process becomes business-driven (rather than engineering driven) with the aim of reducing capital costs of future enhancements and changes in distribution networks. In this sense, there is a strict demand for efficient planning tools that enable maximal utilization of existing capacities in distribution network, i.e. finding a way to work around operational limitations [1].

The main difficulty in developing of a high quality planning tool is large dimension of distribution networks and the fact that this problem is highly constrained. Necessity to include dynamic in solving planning problems makes it even more complex. For solving planning problems several approaches are used: 1) optimization methods [2-8]; 2) heuristic methods [9-12]; 3) artificial intelligence (AI) based methods [13,14]. The main feature of optimization methods is the convergence to the global optimal solution. However, these methods can hardly be applied to real-size networks because of convergence problems and extensive computer processing. The heuristics algorithms can obtain “good” solution for real-size problems, but global optimal solution cannot be quarantined. Although AI methods have several advantages (they are robust, flexible, do not require “well behaved” objective functions, can be easily applied for multi-objective optimization), they do not provide any assurance that the best solution will be found and do not handle constraints well.

In this paper is proposed a new decomposition procedure for multi-year planning of large-scale distribution networks based on dynamic programming, local network concept and mixed integer model. The proposed procedure is developed in order to overcome above-mentioned problems.

Based on the principle of dynamic programming the multi-year planning problem is embedded within a family of similar one-stage problems. Furthermore, according to the local network concept the whole network at each stage is divided into a number of local networks (subproblems). In this way dimension of the overall problem is drastically reduced enabling application of sophisticated and time-consuming mixed integer model at each subproblem. This model minimize capital costs of future design, i.e. determines optimal reinforcements of existing feeders as well as location and size of new feeders (decision variables) taking into account switching (load transfer) capabilities and operational constraints in each local network (subproblem). Thus, the optimal one-year network design is obtained by sequential solving of a number of defined (obtained) local networks while the optimal multi-year planning scenario is obtained by sequential solving of a number of obtained one-stage problems.

A software package, based on proposed procedure, has been developed and tested on several real-life distribution networks. Obtained results prove that suggested procedure is a powerful planning tool which can significantly improve utilization of existing capacities and minimize future expansion costs.

2. PLANNING PROCEDURE

Multi-year distribution network planning problem can be stated as an allocation problem in which “available recourses” (budget) have to be allocating among the “activities” (reinforcements and new facilities in each year in the considered planning period) in such a way that present worth expansion costs in the considered planning horizon (objective function) are minimized while operational constraints are satisfied. The dynamic programming based procedure for
solving the above allocation problem in distribution networks is described in the following sections.

2.1. Determining one-stage planning scenarios

In the first step of the procedure the planning problem for the network is solved for each year in the considered planning horizon. The starting state of the network for determining planning scenarios in each year is the network configuration of the year \( t=0 \) (base year), as it is shown in Fig. 1. The set of obtained reinforcements and enhancement in year \( j \) are named \( \text{PSC}_t \).

![Fig. 1. Determining one stage planning scenarios](image_url)

After determining planning scenarios for each year, three possible cases may arise:

a) the set of reinforcements and enhancement obtained for year \( t \) is the subset of the set of reinforcements and enhancements obtained for year \( (t+1) \), starting from the first year \( (t=1) \) and up to the last year \( (t=n) \) in the planning horizon \( \text{PSC}_t \subset \text{PSC}_{t+1} \subset \ldots \subset \text{PSC}_n \),

b) the previous statement is fulfilled for only first \( m \) years in the planning horizon i.e., the set of reinforcements and enhancements obtained for the first \( m \) years is common for all years that follow year \( m \),

c) neither of the previous statements are fulfilled.

In the first case the \( n \) separately obtained one-stage planning scenarios represents the optimal solution of multi-year planning problem. In the second case optimal planning scenario for the first \( m \) years is obtained as in the first case. In this way the multi-year planning problem is reduced from \( n \)-year problem to \( (n-m) \)-year planning problem. In this case as well as in the third case the dynamic programming based procedure is applied for obtaining the best multi-year planning scenario.

2.2. Dynamic programming procedure

In order to visualize dynamic programming procedure, the solution of the above-mentioned allocation problem is presented in the form of decision tree. For the sake of clarity, an example of a three year distribution network planning problem that is considered. The decision tree for this case is shown in the Fig. 2.

Sequential solution of planning problem for each year is depicted with empty circle and numbered with Roman numbers in the Fig. 2. Each path in the decision tree defines one possible solution for the multi-year planning problem. These solutions are obtained by different sequence of solving planning problems for all years in the planning period. In order to clarify the proposed procedure three characteristic cases (paths) will be analyzed in more details.

Path \((1,2,3)\) define that planning problem is first solved for year \( t_1 \). The obtained solution (obtained set of reinforcements and enhancements) becomes the starting state of the network and on the basis of that solution the planning problem for year \( t_2 \) is solved. Afterwards, based on the solution for the year \( t_2 \), the planning scenario for the year \( t_3 \) is obtained. In this way path \((1,2,3)\) define one possible solution for three-year planning problem (marked as DSPSC1 in the Fig. 2). This way of solving multi-year planning problems is well-known as forward concept (forward fill-in) \[1\]. The next path which will be analyzed is \((3,2,1)\). In this case the planning problem is first solved for the year \( t_3 \). The obtained set of reinforcements and enhancements in this case is restricted as \( \text{PSC}_3 \). After that a planning procedure for year \( t_2 \) is solved taking into account that available (feasible) set of reinforcements and enhancements in this year is restricted to \( \text{PSC}_3 \). It leads to the solution in which obtained set of reinforcements and enhancements in this year is restricted to \( \text{PSC}_3 \). The obtained set of reinforcements and enhancements in this year is restricted to \( \text{PSC}_3 \). The solution of the planning problem for the year \( t_2 \) is obtained in the similar way, bearing in mind that available set of reinforcements and enhancements in this case is restricted to \( \text{PSC}_3 \). Thus, path \((3,2,1)\) define another possible solution for three-year planning problem (marked as DSPSC6 in the Fig. 2) which is known as backward pull-out \[1\].

The rest of the paths are very similar regarding to the way of obtaining multi-year planning scenarios. Because of that only one of them, path \((2,3,1)\), is thoroughly analyzed. In this path the planning problem is first solved for the year \( t_2 \). Afterwards, based on that solution, the solution of the planning problem for the year \( t_3 \) is obtained. Finally, bearing in mind that everything which is done in the year \( t_1 \) must also be in operation in the year \( t_2 \), the planning problem for year \( t_1 \) is solved by restricting available set of reinforcements and enhancements to \( \text{PSC}_1 \).

Maximum number of paths in the decision tree, i.e. number of different multi-year planning scenarios, for overall network is \( n! \), where \( n \) is the number of one-stage problems (number of considered time intervals (years)). However,
some paths will lead to the same multi-year planning scenarios. Thus, the number of different dynamic planning scenarios could be much smaller than \( n! \).

One-stage planning problem for the whole network in each path is solved by inclusion of the local network concept [15]. According to this concept the whole network is divided into a number of local networks (subproblems). In this way dimensions of the original one-stage problem are significantly reduced, enabling application of time-consuming mixed integer model for solving planning problems for each local network (subproblem). Thus, the optimal network design for one-stage problem is obtained by sequential solving of a number of defined subproblems, i.e. the dynamic programming concept is also applied in this case as it is presented in details in [8].

Ranking of obtained multi-year planning scenarios as well as obtained one-stage planning scenarios and selection of the best one is done by applying minimum expansion costs criterion, i.e. planning scenario with minimum expansion costs is selected as the best expansion design.

3. APPLICATION

Proposed procedure is applied on solving three-year planning problem for medium voltage network shown in the Fig. 3. The network consists of 4 feeders, 17 existing branches (solid lines), 6 possibly new branches (dashed lines) and 1 possibly new tie (dash-dot-dot-dash line). Thermal capacities of all branches are shown in p.u. with bold numbers. The lengths of branches that are longer than 1 km are shown in the Fig. 3. All other branches are 1 km long. It is assumed that there is a switch in each branch. Normally opened switches are marked with "X" in the middle of branch where they are located. The 15 existing demand nodes are depicted with empty circles while 2 future demand nodes are shown as full circles. Demand node XVII will appear in second year while demand node XVI will appear in third year. The original loads in the base year for all demand nodes are presented in p.u. Based value for thermal capacities and demand loads is 10 MVA. The load growth rate is 3% by year for all demand nodes. Cost of building new lines as well as reinforcing existing lines is 0.145 million$/km while discount rate is assumed to be 9%.

In the first step, the one-stage planning problem for each year in the planning horizon is obtained. After analyzing the obtained set of reinforcements and enhancements in each year, it is found that \( PSC_t \not\subset PSC_{t+1} \not\subset PSC_{t+2} \). Decision tree for this case is the same as the one shown in the Fig. 2. In this case only three different multi-year planning scenarios are obtained. These scenarios and corresponding present worth expansion costs are given in the Table 1.

<table>
<thead>
<tr>
<th>Dynamic planning scenario</th>
<th>Present worth expansion (fixed) costs (million $)</th>
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<tbody>
<tr>
<td>DPSC1=DPSC2</td>
<td>0.8480</td>
</tr>
<tr>
<td>DPSC3=DPSC4</td>
<td>0.6905</td>
</tr>
<tr>
<td>DPSC5=DPSC6</td>
<td>0.7226</td>
</tr>
</tbody>
</table>

The best three-year planning scenario that leads to the minimal present worth expansion costs is DPSC3. The obtained planning scenario for the first year is shown in the Fig. 4, for the second year in the Fig. 5 and for the third year in the Fig. 6. In these figures, obtained reinforcements and new constructions in each year are presented with bold lines, so the total number of reinforcements and new constructions in the three-year period is the “sum” of all bold lines.
4. CONCLUSION

In this paper is proposed an optimization procedure for multi-year planning of large-scale distribution networks. The goal of the proposed procedure is to maximally utilize existing capacities and minimize present worth expansion costs while satisfying operational constraints (voltage and thermal constraints). This goal is achieved through application of dynamic programming principles, local network concept and mixed integer model. It is shown that proposed procedure is a powerful decision-making tool for multi-year expansion planning of real-life distribution networks and can considerably improve efficiency and reduce expansion costs in the modern (deregulated) distribution systems.

5. REFERENCES