A HYBRID METAHEURISTIC METHOD FOR THE PLANNING OF MEDIUM-VOLTAGE POWER DISTRIBUTION SYSTEMS

Xiaohu Tao, Hans-Jürgen Haubrich
Institute of Power Systems and Power Economics
RWTH Aachen University, Germany
xiaohu.tao@iaew.rwth-aachen.de

Abstract – The cost pressure on the electric distribution companies has increased after the liberalization of electricity markets. Network efficiency analysis becomes important. Distribution companies carry out network efficiency analysis through benchmarking for the internal controlling. Regulatory authorities use efficiency analysis to check the use of system fees. Today a lot of assets in German distribution systems will reach the end of the useful lifetime within the next twenty years, therefore restructure and renewal measures will be necessary in the coming years. "Green Field" based long-term distribution system planning can provide a reference network for network efficiency analysis and an objective network for the restructure. It is known that the planning problem is a NP-hard combinatorial optimization problem and is normally formulated as a non-linear mixed integer-programming problem. To solve the problem efficiently, we propose a metaheuristic method, which combines guided local search and large neighborhood search. Results of test case show that the proposed hybrid metaheuristic method can provide a high-quality solution of a medium-size problem requiring only some minutes and is therefore especially suitable for efficiency analysis.

Keywords: Hybrid metaheuristic algorithm, medium voltage network planning, guided local search, large neighborhood search

1 INTRODUCTION

After the liberalization of electricity markets the cost pressure has increased not only in the generation sector but also in the transmission and distribution sectors. The regulatory authorities check the use of system fees and put pressure on network companies to improve the efficiency. A lot of assets in German distribution systems will reach the end of useful lifetime within some years, therefore there are needs for restructure and renewal measures. How to restructure and improve the efficiency of the networks is an important problem for the electricity distribution companies.

The "Green Field" based long-term planning of distribution systems can provide an optimal network as reference network for the efficiency analysis or as objective network for restructuring measures.

The requirements of the optimal network planning include: 1) minimization of the capital investment, annual operational cost and annual cost of power losses; 2) consideration of all important technical constraints, such as security of supply and reliability of supply; 3) consideration of the degrees of freedom, for example equipment types, laying multi-feeder in the same trench, and network structures; 4) the solution must be optimal or at least close to optimum; 5) optimization time for the planning of real distribution systems must be acceptable.

Planning of MV distribution systems is a typical combinatorial NP-hard optimization problem, which is generally formulated as a mixed nonlinear integer problem. There are two types of algorithms for the problem, namely heuristic and exact. Boardman and Meckiff [1] and Marshall [2] have applied an exact method, the Branch-and-Bound, for the planning of small-size distribution system. Till today there are still no suitable exact methods to solve it efficiently. Some authors [3-7] have proposed heuristic methods for the problem. The commonly used heuristic methods are Genetic Algorithms, Simulated Annealing and Ant Colony Algorithm. Díaz-Dorado [3] has applied successfully Genetic Algorithms for the planning of real Spanish distribution networks. Gómez [4] has applied the Ant Colony Algorithm for the planning problem and achieved better solutions in shorter time, compared with the results of Ramírez-Rosado [7] via Genetic Algorithms. Burkhardt [6] has applied a simple and fast local search for the problem. Only Burkhardt [6] and Díaz-Dorado [3] have considered the possibility of laying multi-feeder in the same trench to save digging cost, which is generally 5-10 times higher than the cable cost in urban areas. Ramírez-Rosado [7] has applied the multli-objective method for the problem, considering the costs of reliability, and has showed that radial network has high cost of reliability, because it has no reserve lines in case of faults. The ring network structure is chose by Díaz-Dorado [3] and Burkhardt [6]. Study by Kaufmann [8] shows that ring and interconnective networks have high reliability and good economics. We choose the ring and interconnective network structures in this paper.

In this paper we will present an effective hybrid metaheuristic algorithm to get a high-quality solution of the problem within a few minutes. The algorithm combines strengths of the guided local search and large-scale neighborhood into an iterative two-stage procedure. Applications of the guided local search (GLS) for other combinatorial optimization problems, for example Traveling Salesman Problem and Quadratic Assignment Problem [9], show that GLS is competitive with other metaheuristic algorithms, such as Genetic Algorithms. What's more, GLS requires less optimization time than other metaheuristic algorithms. In the second stage of the proposed algorithm large-scale neighborhood search [10] will be used to escape from the local optimum. Experimental tests show that using the newly developed algorithm we can get solutions, most of which are generally 0.1-0.5% to the global optimal solution, in some minutes. Comparing with other work on the medium voltage network planning, this paper has also other important contributions besides less optimization time, including the consideration of laying multi-feeder in the same trench to save digging cost, reliability requirements and other special requirements.

The rest of this paper is organized as follows. Section 2 describes the problem formulation and specifies the notations. Section 3 introduces the proposed method. Case studies based on a real distribution network and comparisons of the proposed method with an exact method are presented in section 4. Section 5 concludes this paper.

2 PROBLEM FORMULATION

The objective of distribution system planning is to minimize the total costs, including capital investment cost of equipments, annual operational cost and cost of power losses under the consideration of all possible degree of freedom and main technical constraints.

2.1 Objective of the planning problem

Objective of the problem can be formulated as sum of capital investment cost of equipments, annual operational cost and annual cost of power loss. With the annuity method, capital investment cost can be traversed into the annual cost, so that we can evaluate the whole cost of each planning project based on the annual cost.

Generally there are two ways to consider the supply reliability in the network planning. One is to take the cost of the supply reliability as a cost part in the objective of the network planning problem to achieve the social economics. The other one is to treat the supply reliability as a constraint.

The electric distribution companies try to reduce network costs in the liberalized electricity markets. However, the regulatory authorities set some supply reliability requirements to prevent the electric distribution companies from reducing the network costs too much so that the supply reliability becomes explicitly worse. Therefore it is reasonable to consider the supply reliability as constraints at present. The way how to quantify the cost of the supply reliability is still under discussion in Germany. If the relationship between network costs and the supply reliability is known, it is possible and meanful to consider the supply reliability as a part in the objective of the network planning problem. The way how to consider the supply reliability as a constraint is described in details in 2.3.

2.2 Degrees of freedom

The degrees of freedom mainly include: 1) type of the equipment; 2) laying multi-feeder in the same trench; 3) voltage level, 10 kV or 20 kV; 4) HV/MV-transformer substation; 5) network structures.

In this paper the considered equipments include switchgears and power lines. In Germany many companies use only two or three standard power lines, for example, 3xAl150mm^2 and 3xAl185mm^2 for power cables. For urban underground distribution networks the trench costs is a big part of total costs. In high load-density areas, such as city center, the trench costs could be more than 30% of the total costs. Normally, the trench costs for laying different number of feeders are not the same. For example, the trench cost for laying one feeder is 100 €/m, for two feeders is 110 €/m, and for any additional feeder is 20 €/m more. So laying multi-feeder in the same trench is very important for minimizing the total costs.

The voltage level, 10 kV or 20 kV, depends strongly on the environment and the company's philosophy. In Germany, 20 kV is often used for rural areas, and 10 kV for urban areas. Planning of HV/MV-transformer substation consists of the maximal capacity and location. In this paper, we will use different scenarios for the HV/MV-transformer substation planning.

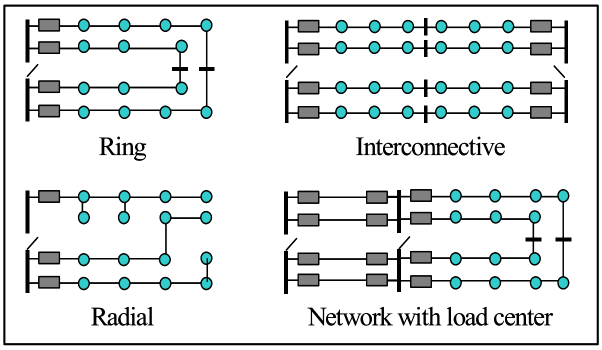

Figure 1: Network structures

The most commonly used electricity distribution network structures are radial, ring, interconnective and the network with load center [8] in Figure 1. The radial network is like a spanning tree. All MS/NS-substations are connected in a tree form. This structure has usually low investment costs, but no possibility of switching loads in case of faults. Such a network configuration is not preferable in some west European countries because of its low reliability. The planning of such a network structure is described in details in papers [4]. Comparing with the radial structure, ring and interconnective structures offer a high reliability of supply because of the capability of switching demands in the feeder with fault to other feeders without fault. To achieve higher supply reliability, some countries also apply the network with load center. In the reality many networks have mesh network structure, because the real networks are mostly historically developed. Although the mesh network structure has lower investment cost, comparing with ring network structure, and the possibility of switching loads in case of faults, the detailed analysis of operational costs of real mesh networks proves that the operational costs of the mesh network structure is much higher than the operational costs of ring network structure. One of the important reasons is that the fault location and the fault clearing of the mesh network strucuture are not as easy as the ring network structure. Further more, the mesh network structure has normally higher costs of power losses. Studies [8] on the network structure show that ring and interconnective network structures have high supply reliability but not so high cost. In Germany ring and interconnective network structures are adapted as the basic network structure by almost all power distribution companies. In this paper, we will consider ring and interconnective network structures.

2.3 Technical constraints

The main technical constraints are: 1) security of supply, including the maximal capacity of the equipments, the (n-1)-criteria and maximal short circuit current; 2) quality of supply, i.e., reliability of supply and voltage quality; 3) other additional special requirements, such as the maximal length of a feeder and maximal number of MV/LV-substations in one feeder.

The security of supply means: 1) the equipments should not be overloaded; 2) all MS/NS substations and demands are connected under (n-1)-criteria with consideration of the switching possibility; 3) the maximal short circuit current in the system should be not higher than a given value. The maximal short circuit current constraint is an important criterion for choosing of the switchgear and type of HV/MV-transformer substation.

Generally the supply quality has three important parts: supply reliability, voltage quality and frequency quality. Because the frequency quality is controlled in the extra-high voltage level, we will not consider it in this paper. From the consumer's point of view the reliability of supply has three parameters: fault frequency, fault duration and fault probability. The fault duration depends strongly on many uncertain factors, such as the fault location strategy and the geographic information of the system, so that it is not meaningful to consider it exactly in the planning step. In this paper we use the estimated values for the fault duration. According to the VDN statistics in Germany, we know that the single fault is the dominating fault type in the medium voltage networks. In this paper, we consider only the single fault. The HV/MV-transformer substations, MV/LV substations and lines cause more than 95% of the faults.

The maximal fault frequency criterion is $H_f \leq H_{fmax}$. With the estimated fault duration we can get the fault probability, i.e., product of fault frequency and fault duration.

The voltage quality consists of static quality (voltage drop) and transient quality. The transient quality is locally treated in the network operation, therefore we will not consider the transient quality in the network planning.

In papers [3, 7] load flow calculation is used to get the voltage drop. Burkhardt [6] shows the possibility of applying a simple method to calculate the voltage drop for ring and interconnective network structures. In this paper we use the simple method by Burkhardt [6]. The voltage drop of the customer in the end of a feeder is calculated with $\Delta U \approx \sum_{i=1}^{n} I_i \cdot (R_i \cdot \cos\varphi + X_i \cdot \sin\varphi)$. The difference of the voltage drop results via simple method and results via exact load flow calculation is negligible.

Other special constraints are the maximal length of a feeder and the maximal number of MV/LV-substations in a feeder. The maximal length constraint is,

$$\sum_{i=1}^{n} L_i \leq L_{max} \tag{1}$$

Where,

L_i: length between two substations in a feeder

L_{max}: the given maximal length of a feeder

3 PROPOSED METHODOLOGY

The proposed hybrid metaheuristic method consists of two main steps. In the first step an initial solution will be generated with the hybrid insertion heuristic of Mester [11] that is a combination of the savings heuristic of Clarke and Wright and the heuristic of Russell. The savings heuristic tries to insert the MV/LV-substations in the loops that have few MV/LV-substations to other loops. The criteria of choosing the MV/LV-substations to be inserted depend on the distance and load of the MV/LV-substations. In the second step the solution will be iteratively improved with the Guided Local Search [9] and Large Neighborhood Search [10]. A simple schema of the two-step method is as follows,

- Step 1: Generation of an initial solution
  - Step 1.1 Each MV/LV-substation forms a loop
  - Step 1.2 Reduction of the loops
- Step 2: Improvement of the solution
  - Step 2.1 Guided Local Search
    1) Local Search with the penalized function
    2) Penalties of the chosen features
  - Step 2.2 Large Neighborhood Search
    1) Reject some MV/LV-substations
    2) Reinsert the rejected substations

3.1 Guided Local Search

Voudouris and Tsang [9] have developed Guided Local Search for combinatorial optimization problems. It is a memory-based intelligent search scheme. During the iterative use of local search, the information of the solutions is collected and exploited to guide local search to promising search space. It has also properties of other metaheuristic algorithms, such as Genetic Algorithm, Tabu Search and Simulated Annealing algorithms.

Local Search is an iterative method for finding better solution. It is the basis for almost all heuristic methods. The idea is to explore the neighborhood of the current solution and through some moves to achieve other feasible solutions that could be better. The most commonly used operators of Local Search are 2-opt and Or-exchange in Figure 2 and Relocate, Exchange and Crossover in Figure 3. Burkhardt [8] has applied 2-opt successfully to the distribution network planning. 2-opt means to replace lines that connect substation *a*, *a'*, *b* and *b'*, $L_{aa'}$ and $L_{bb'}$ with L_{ab} and $L_{a'b'}$. If the move reduces the total costs and all constraints are still fulfilled, we can get a better solution. The Or-exchange operator is to move one MV/LV-substation to another position in the same feeder. Relocate operator means removing one MV/LV-substation from one feeder to another feeder. Exchange operator is to exchange two MV/LV-substations in two feeders. The Crossover operator is to replace two old lines with two new lines between two feeders. There are two types of operator selection strategy: *best improvement* and *first improvement*. *Best improvement* means that the operator, which reduces the total cost maximally, will be chosen to get a new solution. *First improvement* applies the first operator, which reduces the total cost. By applying the *best improvement*, we can achieve the local minimum solution after each search. In this paper, we use the *best improvement*.

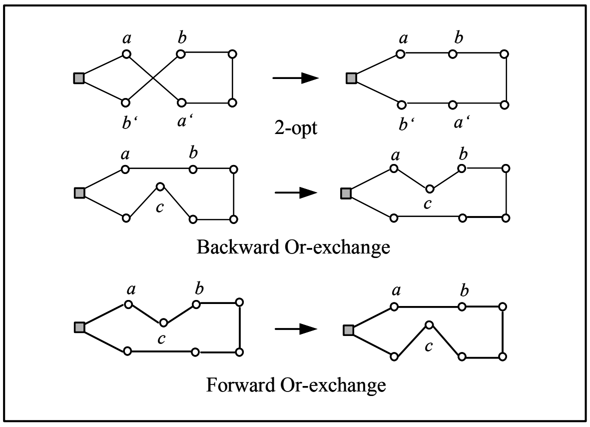

Figure 2: 2-opt and or-exchange heuristic in one feeder

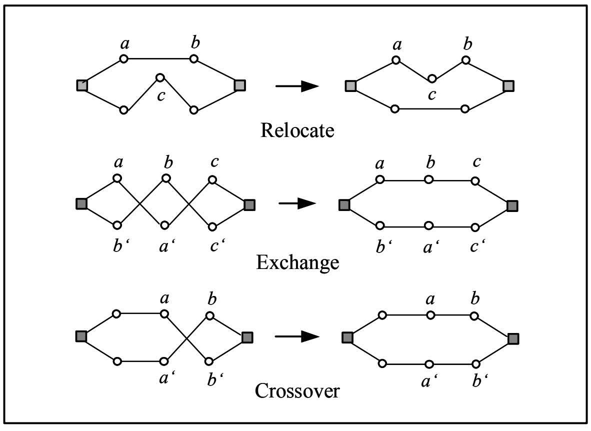

Figure 3: Relocate, exchange and crossover heuristic between feeders

GLS employs solution features as the means to characterize solutions. Each solution (network configuration) has some features. A *feature* can be any solution property that satisfies the important constraints, such as line distance or trench distance between substations. The cost of features affects directly the corresponding solution properties on the solution cost. A solution feature is formulated as an indicator function,

$I_i(S)=1$ If feature *i* is in solution *S*, and 0 otherwise

In GLS solution features are considered by augmenting the cost function *g(S)* with a set of penalty terms to penalize the search if it is too close to the previous visited local minima. The new cost function *g'(S)* is called the *augmented cost function* and defined in the following way,

$$g'(S) = g(S) + \lambda \sum_{i=1}^{M} (c_i \cdot p_i \cdot I_i(S)) \qquad (2)$$

Where,

λ: penalty factor,

c_i: cost of the feature *i*

p_i: penalty number of feature *i*

The local search is carried out with the new defined objective function. We define a utility function as follows,

$$util_i(S) = \frac{I_i(S) \cdot c_i}{(1 + p_i)} \qquad (3)$$

After some searches the local search reaches a local optimum. We will penalize a set of features with the maximal utility value. The idea of utility function is to concentrate on penalizing the most costly features. After each penalty of feature *i*, p_i is modified as $p_i = p_i + 1$. After some penalties on the "bad" feature *i* the utility value decreases, therefore other features have also the chance to be penalized. In this paper, we select the lines between substations as the features.

3.2 Large Neighborhood Search

Large Neighborhood Search (LNS) is also a heuristic search technique [10]. It improves the solution via relaxation and re-optimization of current solution. The relaxation and re-optimization strategies are very important for the solution quality and optimization time. In this paper we will follow the method by Shaw [10] to relax the solutions. To re-optimize the relaxed solution quickly we will apply Mester's simple method [11] by using a controlling parameter instead of the exploration tree by Shaw [10]. With LNS we can explore more promising search space to escape from the local minima.

3.3 Efficient treatment of the constraints

To deal with the constraints efficiently, we will save the voltage drop of each substation, length and total demand of each feeder during the search. As for the objective function, we modify the method by Díaz-Dorado [3] to considerate the trench cost during the search process.

3.4 Parameters of the proposed method

Penalty parameter λ is 2.5. The maximal iteration number depends on the problem size, for the test case 1000 is selected. The size of neighborhood is set as 20% of the problem size.

4 CASE STUDY AND COMPARISON WITH THE EXACT METHOD

4.1 Test case

A real distribution network is modified as the test case in Figure 4. The test case has 143 MV/LV-Substations with 31 MW peak load and one HV/MV-transformer substation. The proposed feeder types are 3xAl150mm^2 and 3xAl185mm^2. The maximal voltage drop in normal operation is 6% and the maximal fault frequency of each feeder is 0.15 1/year. The maximal number of MV/LV-substations in one loop is 30 and the maximal loop length is 20 km. Fault frequency parameters of the equipments are: MV/LV-substation 1/670year, power line 1/100km*year. Figure 4 presents the possible Lines.

The result is presented in Figure 4 with 7 loops, 100.5 km 3xAl150mm^2 power cable. The optimization CPU time is ca. 10 minutes on a 1.8GHz PC with 256MB RAM. The implementation language is C++.

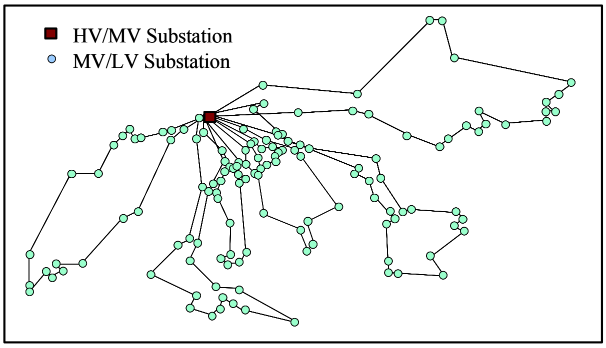

Figure 4: Result using the proposed metaheuristic method

Figure 5 shows the total cost rated on the cost of initial solution during the search process. We have applied savings heuristic to get a relatively high-quality initial solution, so the total costs do not decrease very quickly as with other heuristic algorithms [3, 4]. The curve of actual total costs shows the hill-climbing characteristic, so that it is more possible to escape from one local minimum to another minimum. Comparing with Genetic Algorithms and newly developed Ant Colony, the proposed algorithm has the chance to explore more feasible search space and to achieve a better solution.

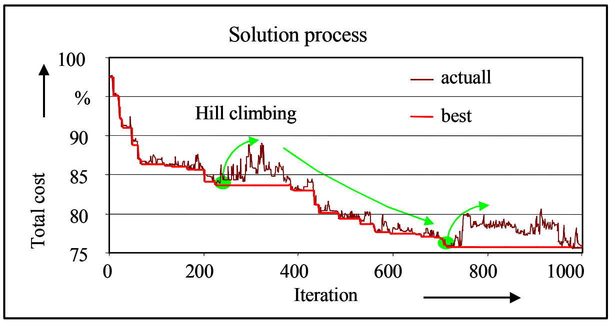

Figure 5: Solution process of the test case

To show the strength of this algorithm, we relax some constraints and solve the test case again using the Branch-and-Cut method, an exact mathematical method, to get the global optimal solution and compare the results.

4.2 Comparison with the exact method

Using heuristic methods we carry out generally the optimization for a very long period of time, for example, some hours, to get the best solution as optimal solution. But the heuristic methods cannot prove the global optimality or the quality of the solution. It is very likely that the optimal solution via heuristic algorithms is only a local minimum and still some percent far away from the global optimal solution, so that it is very difficult to define the stop criteria for the heuristic search.

Distribution system planning is a nonlinear mixed integer problem. The traditional exact method to solve this problem is Branch-and-Bound [1]. Branch-and-Bound uses a searching tree to enumerate all possible solutions. The problem is known as NP-hard problem, thus it is impossible to get an optimal solution of a problem with many binary variables via Branch-and-Bound in acceptable time. To solve the combinatorial problems efficiently, some authors propose the Branch-and-Cut for the problems in the logistics research area. Branch-and-Cut is an extension of Branch-and-Bound applying the decomposition strategy. In Branch-and-Cut constraints are dynamically added to the problem in each Branch-and-Bound tree node to reduce the computation time of each linear problem at the search nodes. Ralphs [12] has applied successfully the Branch-and-Cut method to solve some Capacitated Vehicle Routing Problems, which are not solved via Branch-and-Bound. In Branch-and-Cut the solutions during the optimization process are not integral, therefore it is impossible to consider some technical constraints, such as voltage drop. But the analysis of the solution of the test case via our proposed algorithm shows that the maximal voltage drop is only 2.5% and the maximal fault frequency is 0.1 1/year, thus we can simplify the problem by neglecting such constraints. The objective is simplified to minimize only the investment costs of feeders and switchgears. We use Ralphs's CVRP solver to solve the simplified problem. The solution is presented in Figure 6. Optimization CPU time is about 5 hours, 30 times longer than via our proposed algorithm.

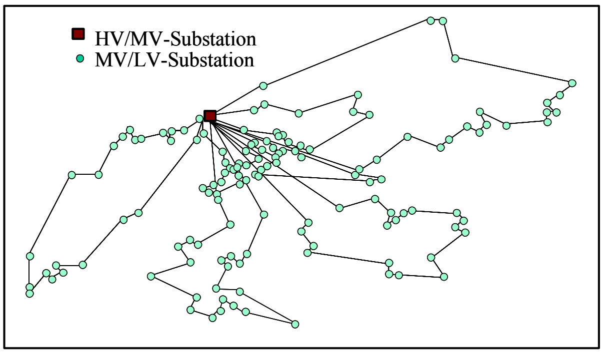

Figure 6: Solution using Branch-and-Cut method

The total cost of solution in Figure 4 is about 0.1% higher than the cost of solution in Figure 6. This proves that we can achieve a high-quality solution of the planning problem of the medium-size distribution system using our proposed algorithm only within a few minutes.

5 CONCLUSION

This paper proposes a hybrid heuristic method, combining the guided local search and large neighborhood search, for the electric distribution system planning. The planning problem is to minimize the sum of investment costs, operational cost and cost of power losses under the consideration of supply security, supply quality and other special constraints. The results of a test case using the proposed method are reported and compared with the optimal solution via exact method. It is proved that the proposed method can provide a high-quality solution of a planning problem of the medium-size distribution system within a few minutes. It is especially suitable for the network efficiency analysis and study on the relationship between network costs and supply quality that needs commonly many simulations. The method can also be applied to the expansion planning by considering the existing trenches and feeders.

6 ACKNOWLEGEMENT

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