A New Method for Planning Secondary Distribution Networks

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Alysson M. Costa
University of São Paulo

Vinicius Jacques Garcia
Universidade Federal de Santa Maria

Paulo M. França
São Paulo State University

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Alysson M. Costa, Vinícius J. Garcia, Paulo M. França and Christiano L. Filho
Faculty of Electrical and Computer Engineering
State University of Campinas
C.P. 6101 13083-270 Campinas - SP - Brazil
email: {alysson,jacques,franca,christi}@densis.fee.unicamp.br

ABSTRACT
The electrical distribution system is the part of the power systems that connect the primary substations to the street transformers (primary system) and these to the consumers (secondary system). Due to the low voltage levels, it is in the distribution systems, particulary in the secondary system, where occur most of the system losses. The greenfield secondary network planning problem always appears when a new area needs to be supplied. Therefore, well planned networks, even when small gains are obtained, may yield a large final savings due to the great number of times the procedure is repeated. In this work we present a new 2-phase planning methodology that has shown to present cost reductions of up to 3.9%, when compared to a strategy found in the literature.

KEY WORDS
Power System Distribution Planning, Secondary Networks, Heuristics

1 Introduction

The electrical energy distribution network is the part of the power systems that connects the substations to the street transformers (primary network) and these to the consumers (secondary network). Due to the low voltages, the distribution system concentrates a major part of the system losses. As an example, in the studied case (Brazilian distribution systems), the common values for the technical losses in the distribution networks are in the range 7% – 15% [1].

The distribution network expansion problem takes place every time a new area needs to be supplied (greenfield planning) or when an existing area presents an important demand growth. Basically, the problem is to find the most economical way to supply the new system demand.

As stated in [2], this problem can be decomposed in three phases: (a) load forecasting, (b) facility location/sizing and (c) feeder routing/design. For the primary network planning, the facilities are substations while the feeders are the transmission lines arriving at the substations and the primary feeders connecting them to the demand areas. In the secondary network planning, we have an analogous problem where the facilities are the street transformers, which must be supplied by the primary feeders and who must supply the demand points via secondary feeders.

Most of the literature concerning the power system distribution planning is devoted to the primary network problem [3–5]. Though the primary and secondary problems are similar, particular characteristics of the secondary networks justify the development of specific methodologies. Amongst the most important of these characteristics, we can cite: the secondary networks operate with very low voltage levels, what makes the losses issue even more important; the secondary networks connect the system to the final user, making critical some issues as voltage drops, reliability and load balance. Moreover, these issues must be treated during the planning, as the secondary networks are rarely reconfigured (in contrary to what happens in the primary networks).

In spite of these particularities, very few works have dealt specifically with this problem. Davies [6] presents an analytical study about the low-voltages network greenfield design problem. Snelson and Carson [7] extend Davies work to consider the installed network. In these former works, only the feeder routing is optimized.

The first article to deal with the transformers allocation was the work of Backlund and Bubenko [8].

Aoki *et al.* [9] consider the primary/secondary integrated problem.

In 1996, Carneiro *et al.* [10] dealt with the problem without such reduction assumptions. Their work divides the secondary network planning into three subproblems, which they solve via heuristic methodologies. First, they allocate the transformers and, then, they route the primary and secondary feeders. The major drawback in their methodology is that they disregard the connection between these three problems. In spite of this, the method achieves very good results and will be used in this article as a benchmark for comparisons.

In this work we present a new methodology for the distribution network planning, focusing on the secondary networks greenfield case. The paper is organized as follows: in section 2, we define the studied problem. In section 3 we present a new heuristic solution methodology. The computational results are in section 4, followed by brief conclusions in section 5.

2 Problem Definition

The voltage level is usually used to subdivide the distribution system network. In an upper level we have the the primary distribution network at 13.8kV, for instance, and in a lower level the secondary distribution network at 220V. These levels are connected via the street transformers. Figure 1 shows the two levels schematically.

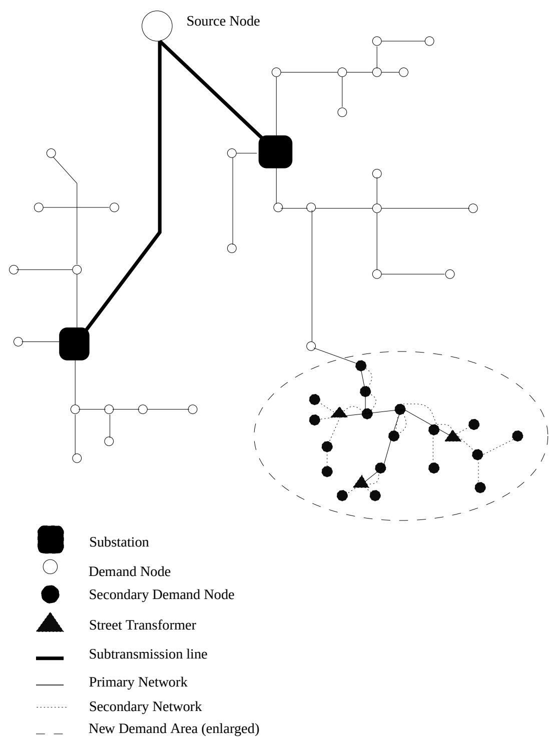

Figure 1. Distribution Network

The secondary network design problem can be viewed in the enlarged new demand area in Fig. 1. Basically, the problem consists in defining (a) the transformers position and their nominal capacity, (b) the primary network arcs connecting the substations to the transformers and (c) the secondary network arcs connecting the transformers to the demand points.

We can define the problem as a two-level routing problem, where the two levels are connected by the transformers. Therefore, the transformers positions play a key role in the problem: they define the demand nodes for the upper level (primary network) and the source nodes for the lower level (secondary network).

The optimal solution for this problem consists in the minimum total cost network that supplies the load. Total cost includes the equipment costs (e.g.: transformer and feeder costs) and the quadratic operation costs due to the electrical losses in the network.

In order these costs to be comparable, all values must be annualized, i.e., the equipment costs are amortized during the equipment life time and the electrical costs are considered for a whole operation year. Table 1 shows the transformer costs for different transformers, while Fig. 2 shows the cost for different feeder sizes. Note that for each feeder size there is a fixed acquisition cost and a energy loss which is a function of the power flow.

Capacity (kVA)	Cost (US$)	Cost/Capacity (US$/kVA)
15	178.8	11.92
30	240.6	8.02
45	276.7	6.15
75	348.9	4.65
112.5	468.3	4.16

Table 1. Transformers costs according to their nominal capacity

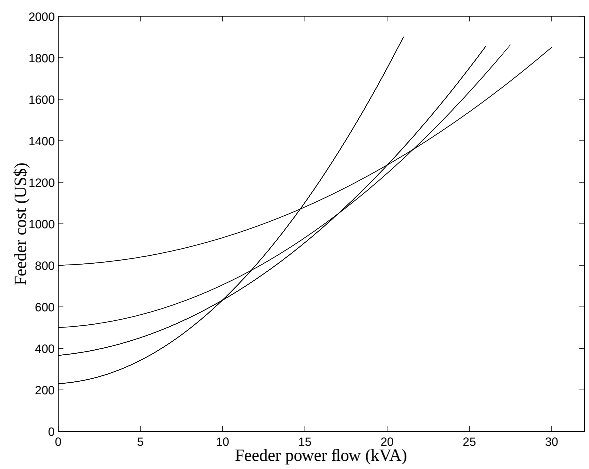

Figure 2. Feeders costs according to power flow

It is interesting to note that the cost/kVA experiences a huge drop when one goes from small nominal capacity transformers to larger ones. Therefore, considering only the transformer cost, it would be interesting to have a few large transformers in the network. However, a small number of transformers presupposes long secondary feeders (with higher cost). The optimal solution is, therefore, a trade off dictated by the number of transformers/lenght of the secondary network.

Another remark is related to the feeder costs. In Fig. 2, we can see the costs for four types of feeders. Each feeder is the most economical one in a range of flow. The important fact is that this economical analysis is enough to choose the feeder since the capacities are much bigger than the flows in the economical range. For example, the capacity of the feeder A01 is 68kVA, while its economical applicability is in the range 0–5kVA. For that reason, during the optimization process, we can assume that the secondary feeder costs can be represented by the inferior curve that supports all the four cost curves as shown in Fig. 3.

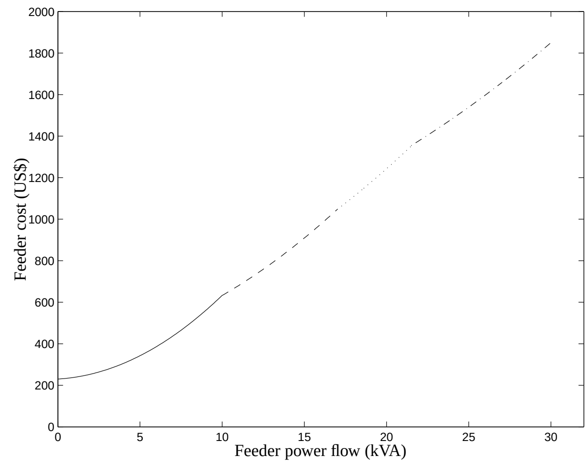

Figure 3. Feeders costs considering economical analysis

3 Proposed Methodology

In this section a heuristic methodology to solve the problem defined in section 2 is proposed. The use of heuristic methods is motivated by the high complexity of the problem, expressed by its NP-hardness.

The problem is clearly composed by three subproblems: a) the transformer allocation/sizing; b) the primary feeders routing and c) the secondary feeders routing. The heuristic methodology proposed here considers these costs to find the best solution approach to each one of the subproblems.

The methodology is divided into two phases: the first one seeks to find an initial solution, which quality is improved in the second phase.

In the first phase, each subproblem is solved independently, i.e., the solution approach for each subproblem only considers the costs associated to itself, ignoring the global aspects of the integrated problem. For this reason, this phase is named greedy approach. Section 3.1 presents more details.

The obtained greedy solution goes through an improvement phase in which the global cost of the problem is taken into account, with the objective of correcting possible mistakes caused by the myopic aspect of the the greedy approach. Section 3.2 shows the improvement phase in more details.

3.1 Phase 1: Greedy Approach

The greedy phase considers the three mentioned subproblems in a hierarchical manner, as proposed in [10] and explained in section 2. The main subproblem is the transformer location/sizing. This problem is in a upper level in the hierarchical solution approach. The routing problems (primary and secondary networks) can only be solved after the transformer positions are defined.

3.1.1 Transformer Allocation/Sizing Problem

Determining the number of transformers: One necessary condition for feasibility is that total transformer capacity must be greater than the total demand. It can be achieved either by a few large transformers, by many small transformers or by an intermediate solution. For example, considering the costs and nominal capacities for the transformers in Table 4, a total 90 kVA demand can be supplied either by three 30 kVA transformers (with cost $3 \times 240.6 = \$721.8$), two 45kVA transformers (with cost $2 \times 276.7 = \$553.4$) or by a single 112.5 kVA transformer (with cost $468.3).

A possible approach to determine the number of transformers in the network is the myopic approach that considers only the transformer costs: considering only the transformer cost term, the solution with less transformers is always the one chosen. This is due to cost/kVA drop showed in Table 1.

However, we know that the optimal number of transformers is highly dependent on the secondary costs and lay somewhere in between the extreme solutions, as sketched in Fig. 4.

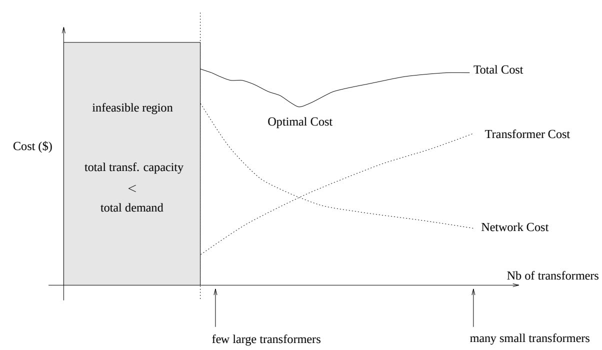

Figure 4. Cost Trade-offs

To overcome the limitation of the greedy approach, the solution given by this method is used only as an indication of the number of transformers in the network. For instance, if the methodology indicates an optimum number of p transformers, the networks with p, $p+1$, $\ldots$, $p+n$ transformers are tested, where n is a number large enough to include the optimum region of Fig. 4. Note that n can be obtained interactively: the whole network configuration is obtained for p transformers, $p+1$, and so on. When the cost of the network increases for two interactions $p+m$ and $p+m+1$, for example, we can stop the simulation, since the total cost curve in Fig. 4 is relatively well conditioned and resembles an unimodal function.

Determining the location of the transformers: Once the possible numbers of transformers have been determined, the next step is to obtain the transformer sites. This is done by the classical *p-median* problem, which consists in finding the p best positions for the facilities (in our case, transformers) to serve the demand points.

The solutions are evaluated in the following manner: each demand point is allocated to the closer median. The *p-median* cost is done by the sum of all "distances" from the demand nodes to the corresponding medians. As "distance", we do not use the distance from the node to the median but the electric momentum (distance to the median[1] $\times$ node demand). This is a very natural choice since the real cost, considers not only the distance (implicit in the term c_{ijn}) but also the power flow.

The transformer allocation problem is the core of the whole problem. Therefore, a good solution to the *p-median* problem is crucial to produce good global solutions. However, *p-median* is also a NP-hard problem, what suggests the use of a heuristic methodology based on Lagrangian relaxation, as proposed in [11]. Even if we can not assure that the method will always converge to the optimal solution, we can always obtain good quality solutions with a optimality gap information.

3.1.2 Primary Routing

Once the transformer locations are known, all entry data for the primary routing is available. The primary cost is only associated to the length of the primary network (since the costs of losses are negligible due to the relatively short length of the primary network in the considered area).

The problem of determining the primary network is then expressed by the problem of connecting the transformer nodes to the primary points. This is the classical Steiner problem: given a graph where N is the set of nodes and P is a subset of these nodes, construct a tree connecting the nodes in P, using the nodes in N when convenient.

We have chosen to solve the Steiner problem by the following manner: first a complete graph with nodes P is considered. The distance between two nodes of this graph is done by the shortest path between the two nodes in the original graph. In this complete graph, a Minimum Spanning Tree problem is solved via a greedy approach, giving an initial solution.

This initial solution is improved by inserting Steiner points, i.e., points in N that are not in P, but that can reduce the total length of the network.

3.1.3 Secondary Routing

The secondary routing problem has been considered implicitly in the solution of the *p-median* problem. Indeed, the solution to that problem yields not only the transformer locations and sizes but also the secondary feeder routing.

[1] given by the shortest-path from the demand node to the median.

3.2 Phase 2: Improvement Approach

The major drawback of the greedy approach described in the last subsection is the resolution of the three subproblems in a totally independent manner, given that the subproblems are highly interrelated. Therefore, the optimal solution for the subproblems can result in a suboptimal configuration, when we consider the transformers/network real costs.

The idea of the *improvement approach* is to carry out a local search considering the global cost of the problem. Consequently, an improvement in this phase means an improvement in the real cost of the problem.

The consideration of the global cost forbids the trapping of the solution in a local optimum composed by optimal solution of the subproblems (which combination is not globally optimum).

The local search acts changing the position of the transformers and recalculating the global cost. If an improvement is verified the solution is updated, otherwise the changes are discarded, as shown in Fig. 5.

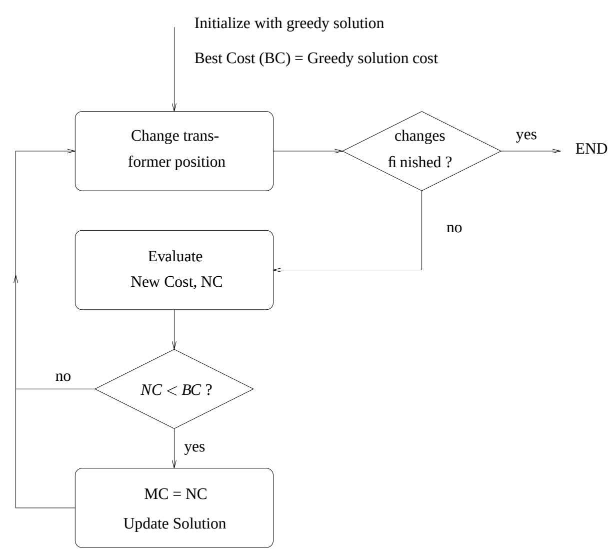

Figure 5. Improvement Phase

4 Computational Tests

In this section we present the results to the computational tests that were carried out to evaluate the performance of the proposed heuristic. In subsection 4.1 the test instances are presented, while in subsection 4.2 the results themselves are presented. All simulations were carried out in a Sun workstation running Solaris. We used the commercial mixed-integer linear programming solver Cplex version 6.6 and the JAVA platform 1.3.1.

4.1 Instance Generation

We worked with two groups of instances. The first group is composed by small test instances randomly generated with a methodology based on the one proposed by Aneja in 1980 [12]. The used procedure is described below:

* Procedure for generating a test instance with *N* nodes and *A* arcs:

1) Select *N* nodes in the plane.

2) Connect the nodes to form a tree.

3) Add complementary arcs to the tree, until one attains the desired number of arcs: *A*.

4) Allocate a demand to each node.

5) Choose some nodes to receive the primary network.

Some useful observations: 1) the node coordinates are limited to integer values in the interval [0,100]; 2) the tree is obtained in the following manner: node 1 is connected to node 2, which in turn is connected to node 3 and so on until node *n* is reached; 3) node demand is randomly chosen in the interval [0,5]; 4) we assume that the primary network is always present on nodes 1 and 2.

With this methodology, 15 instance have been created and named cbaxx (where xx is the number of the instance). Using a mathematical model, optimal solutions have been found using the Cplex code. These values are then used as benchmarks to evaluate the proposed heuristic.

The second group of instances is composed by two real cases, obtained from [13]. The first case, named car1, is an instance with 156 nodes. The second case, car2, is a 173 node instance. For these instances, the Cplex code has failed to find optimal solutions. The comparisons are therefore limited to the best values found in the literature.

4.2 Results

Table 2 presents the results obtained by the proposed method in opposition to the values described in the literature. The values are shown in absolute values and also in percent deviation from the optimum.

The proposed heuristic equalizes or improves the results in the literature for all the instances, excepted for the instance cba10.

Table 3 presents the results for the real network examples. Here, the optimal solution can not be obtained via the exact algorithm, due to the NP-Hardness characteristics of the problem. The results obtained by the proposed heuristic is, therefore, compared to the results in the literature. Again, a slight gain in terms of the network total cost is obtained with the new heuristic, as shown by the values in parenthesis. Table 3 also presents the optimal number of transformers and some adjacent solutions. In all cases, the proposed heuristic presents more economical solutions.

Inst.	(N,A)	Optimum	Carneiro *et al.*	Proposed heuristic
cba01	(4,4)	225.65	**225.65 (0.0%)**	**225.65 (0.0%)**
cba02	(4,6)	198.68	236.77 (19.2%)	**222.17 (12.1%)**
cba03	(8,8)	510.42	527.08 (3.3%)	**517.50 (1.4%)**
cba04	(8,12)	323.19	**324.98 (0.0%)**	**324.98 (0.0%)**
cba05	(8,16)	357.73	378.60 (5.8%)	**369.72 (3.3%)**
cba06	(12,12)	738.21	771.02 (4.4%)	**753.85 (2.1%)**
cba07	(12,18)	708.14	718.45 (1.5%)	**714.11 (0.0%)**
cba08	(12,24)	489.97	**500.12 (2.0%)**	**500.12 (2.0%)**
cba09	(16,16)	1103.83	**1105.42 (0.0%)**	**1105.42 (0.0%)**
cba10	(16,24)	636.71	**654.19 (2.7%)**	684.97 (7.6%)
cba11	(16,32)	743.37	796.49 (7.1%)	**791.00 (6.4%)**
cba12	(20,20)	1641.83	1680.12 (2.3%)	**1659.21 (1.2%)**
cba13	(20,30)	969.91	1048.97 (8.1%)	**1023.33 (5.6%)**
cba14	(20,40)	986.66	1025.47 (3.9%)	**1025.46 (3.9%)**
cba15	(24,24)	2073.45	2419.02 (16.6%)	**2086.97 (0.0%)**

Table 2. Results for the instances in group 1, in terms of total cost (US$)

Instance	(N,A)	P	Carneiro *et al.*	Proposed Heuristic
car1	(156,155)	9	8310.40	8263.51 (-0.5%)
car1	(156,155)	10	8385.46	8218.78 (-2.0%)
car1	(156,155)	11	8416.66	8241.14 (-2.1%)
car1	(156,155)	12	8478.74	8378.15 (-1.2%)
car2	(173,192)	9	8187.95	8101.98 (-1.0%)
car2	(173,192)	10	8263.65	7938.62 (-3.9%)
car2	(173,192)	11	8056.14	7912.96 (-1.8%)
car2	(173,192)	12	8065.36	7942.53 (-1.5%)

Table 3. Results obtained by the proposed heuristic compared to the literature, in terms of total cost (US$).

The execution times of the proposed heuristic is about one minute for the real cases.

5 Conclusions

In this work we studied the greenfield Power Systems Secondary Network Planning Problem (PSSNPP), a very difficult problem which consists in determining the optimal cost network to supply the forecast demand in new electrical energy demand areas.

The investment costs involved in the secondary network planning may lead to a false impression that they are not relevant when compared with the high costs of the primary network planning. Indeed, a substation is much more expensive than a transformer. However, it is enough to remember that the greenfield PSSNPP is present in every new area of the system. Therefore, even low gains obtained in each new planned area may result in a large final economy.

In this work a new methodology, based on Lagrangian relaxation is proposed. For real networks, the costs obtained presented gains of up to 3.9% when compared to the best methodology known in the literature [10].

It is worth noting that part of this gain is due to the reduced network losses. Therefore, besides of the direct monetary advantage, there is the fact that less losses also means less necessity of investments in generation (bringing indirect monetary gains) and/or greater stability of the power system.

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