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An iterated sample construction with path relinking method: Application to switch allocation in electrical distribution networks

Alexander J. Benavides [a], Marcus Ritt [a,*], Luciana S. Buriol [a], Paulo M. França [b]

[a] Instituto de Informática, Universidade Federal do Rio Grande do Sul – UFRGS, Brazil
[b] Faculdade de Ciências e Tecnologia, Universidade Estadual Paulista – UNESP, Brazil

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ABSTRACT

We present a metaheuristic approach which combines constructive heuristics and local searches based on sampling with path relinking. Its effectiveness is demonstrated by an application to the problem of allocating switches in electrical distribution networks to improve their reliability. Our approach also treats the service restoration problem, which has to be solved as a subproblem, to evaluate the reliability benefit of a given switch allocation proposal. Comparisons with other metaheuristics and with a branch-and-bound procedure evaluate its performance.

1. Introduction

Most of the faults of an electrical power system take place in the distribution network [1,2]. The installation of redundant lines and switches is a common method to improve the reliability of a distribution network. In this way, in case of failures, service providers can modify the network topology and reduce the areas without energy. The installation of switches in every line is impracticable due to high costs. For this reason, companies must carefully choose the lines to install switches. This combinatorial optimization problem is called the switch allocation problem. To assess the reliability of an allocation proposal for a set of switches, we have to determine the expected non-supplied energy for a given distribution of failures. Since the actual non-supplied energy depends on how much of the service area can be restored by reconfiguring the network, the service restoration with electrical constraints occurs as a subproblem of the switch allocation problem.

In this paper, we propose a sample construction and a sample local search for the switch allocation problem, and, based on these algorithms, a new iterated sample construction with path relinking (ISCPR) to solve the switch allocation problem. Another contribution is that our treatment of the service restoration problem makes no assumption on the topology of the network and includes electrical restrictions.

In Section 2 we give a formal description of the problem. In Section 3 we describe the construction and local search algorithms based on sampling. In Section 4 we introduce the ISCPR algorithm which uses the sample construction to modify the current solution and the path relinking to perform a guided local search. Section 5 first compares the performance of sample based construction and local search methods to other such methods, and then compares several heuristics for the switch allocation problem. When compared to a heuristic based on Greedy Randomized Adaptive Search Procedure (GRASP) [3], ISCPR shows the best performance. Another comparison with a branch-and-bound procedure attests the quality of the solutions yielded by our approach.

2. Description of the problems

Fig. 1a shows an example of an electric power distribution network in normal operation. The basic circuit of an operational distribution network has no cycles. It is composed of substations (square nodes), consumers (round nodes), and feeder lines (solid lines). Additionally, redundant lines (dotted lines) can restore the energy in areas affected by failures. Switches control the power flow. In normal operation, switches of redundant lines are open, and switches in the basic circuit are closed.

2.1. Graph model of distribution networks

We use an undirected graph $G=(N,E)$ to model a distribution network. The set of nodes N represents substations and consumer load points, and the set of edges E represents the feeder lines. A Boolean value B_e indicates the presence of a switch on a line

* Corresponding author. Tel.: +55 5133086818.
E-mail addresses: ajbenavides@inf.ufrgs.br (A.J. Benavides), marcus.ritt@inf.ufrgs.br (M. Ritt), buriol@inf.ufrgs.br (L.S. Buriol), paulo.morelato@fct.unesp.br (P.M. França).

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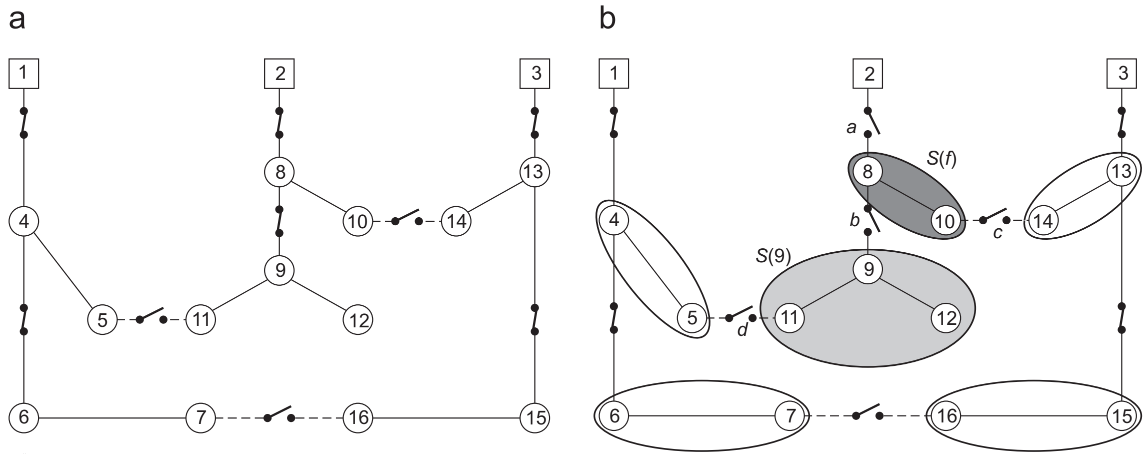

Fig. 1. Three-feeder example of a distribution network by Civanlar et al. [4]. (a) Normal operating conditions and (b) sectors affected by a failure.

$e \in E$. We represent a solution for the switch allocation problem by a set $E_B = \{e \in E | B_e = 1\}$ of lines that are selected to install new switches. The *sector* $\mathcal{S}(n)$ of a node $n \in N$ is the largest connected subgraph which contains n and is connected only with basic circuit feeder lines (normally closed) that have no switch installed ($B_e = 0$). Ellipses in Fig. 1b represent sectors. The sector of a line $e \in E$ is defined as the union of e with the sectors corresponding to the two incident nodes. The *frontier* $\mathcal{F}(G')$ of a subgraph (or sector) G' is the set of edges $e \in E$ which are incident to exactly one node in G'.

2.2. Network reliability estimation

In this paper, we use the expected energy non-supplied (EENS) [5] to measure the network reliability. It is defined as

$$\text{EENS} = \sum_{f \in E_{nc}} \lambda_f r_f \sum_{n \in N_f} P_n \quad (\text{MW h/year}),$$

where E_{nc} is the set of lines that can fail (normally closed), N_f is the set of nodes affected by a failure f, λ_f is the average failure rate, r_f is the average outage time, and P_n is the average energy consumption of node n.

Our reliability estimation algorithm simulates a failure f in each sector $\mathcal{S}$ of the network, and opens the switches of the corresponding frontier $\mathcal{F}(\mathcal{S}(f))$ to isolate the failure. Then, it determines the set N_f of consumers affected by the failure with a service restoration algorithm, and calculates their partial EENS. Evaluating sector by sector, the partial reliability of every feeder line of a sector is evaluated at once, reducing the number of service restoration problems that have to be solved. The same process is applied to the remaining lines that are not part of any sector.

2.3. The service restoration problem

Network reconfiguration is the process of opening and closing some switches to change the network topology. When a power failure is detected, the network is reconfigured to isolate the failure and to restore energy by alternate lines.

Consider a failure in line f of Fig. 1b. Without switches, the whole tree under substation 2 would be unattended. When the frontier switches $\mathcal{F}(\mathcal{S}(f)) = \{a,b,c\}$ are opened, the failure is isolated in sector $\mathcal{S}(f)$. Consequently, sector $\mathcal{S}(9)$ has neither failure nor power supply. The service on sector $\mathcal{S}(9)$ is restored when the switch on line d is closed.

The *service restoration problem* consists in choosing which switches must be opened or closed to minimize the unattended area after the isolation of a failure. A solution has to satisfy electrical constraints. The electrical constraints considered in this paper are the radiality of the reconfigured network, the capacities of the lines and substations, and the maximum allowed voltage drop.

Since we are interested in solving the service restoration problem as a subproblem of the switch allocation problem, we do not consider secondary objective functions, such as minimizing the number of switching operations. For the same reason, we do not consider additional constraints such as the priority of customers, switching times, or restoration cost.

For a single substation, the service restoration problem can be modeled as finding a spanning tree minimizing the non-supplied energy subject to electrical constraints [6]. Different from the minimum weight spanning tree, this version is NP-hard [7,8].

Our service restoration algorithm calculates the affected consumers after a failure isolation. It expands the attended area starting from the substations sector by sector, when this is possible without violating the electrical constraints. The electrical simulation is computationally expensive, but important to obtain a realistic approximation of the attended area.

A detailed description of the reliability estimation and the service restoration algorithm can be found in [9]. For a survey of approaches to service restoration we refer the reader to Ćurčić et al. [10] and Sudhakar and Srinivas [11].

2.4. The switch allocation problem

The number and position of the switches in the network influences the amount of non-supplied energy in case of contingencies. The *switch allocation problem* consists in selecting a set of feeder lines to install a given number of new switches in a distribution network. The objective is to maximize the reliability, and is subject to electrical and topological constraints.

The switch allocation problem is NP-hard, since its solution requires to solve the NP-hard service restoration problem. For this reason the literature concentrates on heuristic solution methods.

Exact methods for the switch allocation problem based on integer programming have been proposed by Zambon et al. [12], Bupasiri et al. [13], Soudi and Tomsovic [14,15], Sohn et al. [16]. These methods apply only to small-sized distribution networks.

Among the heuristics proposed are simulated annealing [17], immune algorithms [18,19], genetic algorithms [20–22], divide-and-conquer [23], reactive tabu search [24], evolutionary algorithms [25], particle swarm optimization [26], and ant colony optimization [5]. Some of these methods address the more general problem of network reinforcement planning, allowing to