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Permutation-based optimization for the load restoration problem with improved time estimation of maneuvers

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ABSTRACT

After the occurrence of faults in a radial distribution system, the load restoration problem consists in implementing a sequence of switch opening and closing operations such that the resulting network configuration restores services to the most loads in the shortest possible time. We formulate this optimization problem in terms of two complementary objectives, minimizing simultaneously the energy not supplied and the power not restored. The search space is encoded as a set of permutation vectors containing all maneuverable switches, and the decoding mechanism always guarantees feasibility and allows for multiple solutions per vector. In order to cope with the possibly large search space, an efficient reduction mechanism is proposed to decrease the number of allowed permutations. The resulting optimization problem is solved using Simulated Annealing followed by a local search refinement. The time taken to perform the maneuvers is estimated using a scheduling approach, which takes into account the existence of multiple dispatch teams and thus provides a more reliable computation than the usual approach of using the number of switch operations. The proposed method is validated using known optimal results in small problem instances, and is able to return significantly better results when compared against a Branch and Bound method with a pruning heuristic in a more complex scenario.

1. Introduction

Electrical distribution systems are usually operated in a radial configuration, which provides several advantages such as easier fault current protection, voltage control, prediction and control of load flows, and lower installation costs [1]. However, in the event of a fault, all loads located downstream from the faulted point become *out of service* (*oos*), and, as a consequence, the interruption can affect a greater portion of the system. Fig. 1 illustrates this concept. The distribution network is represented by an undirected graph $\mathscr{G} = (\mathscr{N}, \mathscr{E}^{CC})$, with edges indicating maneuverable switches.[1] Solid lines indicate currently closed (CC) switches, while dashed/dotted edges indicate the currently open (CO) ones. Nodes in the graph indicate load sectors. As shown in Fig. 1 (left), a fault in node 3 leaves this sector and all downstream ones (4, 5 and 6) disconnected from the source 0 (i.e., out of service).

Power outages can have severe impacts on customers as well as on the distribution utility, which may be financially penalized by regulatory agencies. Service interruptions are usually quantified by (at least) two *reliability indices* [1], one relative to the duration of the outages (SAIDI) and the other referent to their frequency (SAIFI). In terms of SAIDI, the longer a node is out of service, the greater its contribution to this indicator, which provides a strong motivation for utilities to attempt to restore service as fast as possible. In radial systems, this restoration is usually achieved by reconfiguring the network (i.e., opening CC switches and closing CO ones) so that the faulty sector is *isolated* from the network, and the healthy sectors are reconnected to a (possibly distinct) source. This is illustrated in Fig. 1 (right), in which switches $(4,10)$ and $(6,15)$ are closed to restore sectors 4, 5 and 6. Notice that the CC edges $(3,4)$ and $(3,5)$ need to be opened first, to keep the faults isolated as well as to maintain the radiality of the system.

This system reconfiguration process to restore power delivery to customers is called *load restoration*. It represents a very complex problem, and while there is no universally adopted formulation, most authors agree that the fundamental goals are [2] to recover the most *oos* loads in the shortest time possible, without violating constraints of minimum voltage in nodes and maximum current in lines, as well as the feeder capacity and system radiality. These characteristics result in a problem that can be modeled as a multiobjective nonlinear combinatorial optimization task, as will be presented later in this work.

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[1] Throughout this work the terms "edge" and "switch" are used interchangeably.

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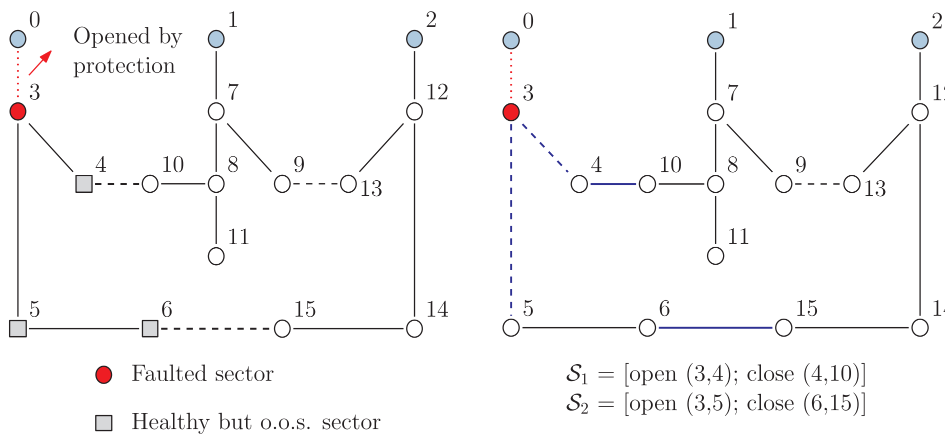

Fig. 1. Graph representation of a distribution network. Nodes 0, 1 and 2 represent sources, and all others are load sectors. **Left**: a fault in sector 3 results in the upstream protection switch operating and disconnecting it from the source. **Right**: a restoration plan for this scenario.

1.1. Literature review

The timely service restoration task possesses a large body of previous studies in the literature. Unfortunately, given the lack of a common formulation, each work approaches this problem using distinct quality indices (see Section 2.3), search space codifications, and optimization techniques, such as heuristics, mathematical programming methods and metaheuristics. This review focuses on studies that solve the load restoration problem using metaheuristics,[2] since these are more closely related to the approach proposed in Section 3.

Metaheuristics have been widely employed for the load restoration problem in the recent literature [3–7], but despite being under the same category these works still approach the load restoration problem very differently. Kumar et al. [3,4] adopt a binary codification for the network, in which radiality is guaranteed by performing a breadth first search from each source and opening any repeated switches. Their first work [3] employs a Genetic Algorithm (GA) to minimize a weighted sum of the power not restored $S_{NR}(\cdot)$, number of maneuvers $N_m(\cdot)$ (split into manual and remote parts), power losses $P_{loss}(\cdot)$ and overload constraints. The main issues of this approach are the lack of concern about the choice of weights and objective scaling in the aggregation function, which can compromise trade-off analysis [8]; and the absence of any guarantees of feasibility in the final configuration. Their follow-up study [4] handles the same quality indices without aggregation, and computes an approximation of the Pareto-optimal front using a multi-objective GA. However, it is not clear how the voltage and current constraints are handled, and the selection of the final solution is lexicographic in $S_{NR}(\cdot)$, which makes the problem treatment using a multi-objective approach unnecessary.

Other works [5,6] adopt a node-depth encoding [9], which guarantees the radiality constraint and the recovery of all *oos* nodes. The authors then minimize the number of maneuvers $N_m(\cdot)$ and the overload constraints as independent objectives with the use of evolutionary algorithms. They report fast results for very large networks, and Marques et al. [6] provide a post-processing step to return a proper sequence of maneuvers from a chosen configuration. Unfortunately, because this technique assumes that all *oos* loads are *always* recovered, some results are unfeasible in terms of voltage and current, even with a large number of maneuvers.

Finally, Carrano et al. [7] use the set of all permutations of maneuverable switches. The evaluation of a permutation vector closes the first CO edge that appears in it, then isolates the fault with the appropriate isolating switch and, if required, performs load shedding by opening other CC switches in the order that they appear in the vector. This is repeated until no CO edge remains available to restore *oos* loads. Their work minimizes the power not restored $S_{NR}(\cdot)$ and the total maneuver time $T_m(\cdot)$ using an evolutionary algorithm to return an approximation of the Pareto-optimal front. This method guarantees feasibility of solutions, and outputs a proper sequence of maneuvers. However, the estimation of $T_m(\cdot)$ is done by simply attributing a scalar T_e to each switch $e \in \mathscr{E}$, representing its time to be operated, which neglects the availability of more than one dispatch team and the dependency of time on their current positions.

Given the use of different models and formulations, it is essentially impossible to provide a fair comparison of these works. Nevertheless, it is possible to highlight some desirable features that the methods should possess [7]. This information is summarized in Table 1, which also includes works dealing with this problem using mathematical programming and heuristics (reviewed in the Supplemental Materials, Part 1). The desirable features considered here are:

F1: Are all constraints guaranteed to be satisfied?
F2: Can the method handle simultaneous failures?
F3: Is the technique able to perform partial restoration, that is, does it work if not all *oos* loads are recoverable?
F4: Is the method guaranteed to output a solution in reasonable time (e.g., up to ten minutes)?
F5: Is there a decoding procedure to output a proper sequence of maneuvers, or is it evident from the algorithm?
F6: Is the formulation multi-objective, i.e., do the authors use more than one quality index to model the problem? (Y) Yes; (P) Yes, but there is no control over the trade-offs of the final solutions (e.g., a weighted sum with no guidelines for choosing the weights); (N) No, only one quality index is essentially adopted.
F7: Is the actual time to perform the load restoration (i.e., the time of maneuvers) considered? (Y) Yes; (P) Partially: the work only differentiates remote from manual switches, but time differences among the latter are not considered; (N) No, only $N_m(\cdot)$ (or a weighted version using a scalar T_e for a switch e) is employed.

It is important to keep in mind that the information provided in the table is not definitive when comparing the methods, but it can be useful for contrasting approaches and developing new strategies. For instance, Table 1 suggests that no study so far presents a proper estimation of the actual time to implement a restoration plan, taking the number of dispatch teams and their displacement times into consideration, which is one of the proposed contributions of this work.

In this paper, we propose formulating the load restoration problem as the simultaneous minimization of the power not restored and energy

[2] An extended literature review, including works approaching this problem using mathematical programming and heuristics, is provided in the Supplemental Materials, Part 1.