Electric Power Systems Research 163 (2018) 301–309

Contents lists available at ScienceDirect

Electric Power Systems Research

journal homepage: www.elsevier.com/locate/epsr

Scheduling maneuvers for the restoration of electric power distribution networks: Formulation and heuristics

André L. Maravilha[a,c,*], Fillipe Goulart[a,c], Eduardo G. Carrano[a,b], Felipe Campelo[a,b]

[a] Operations Research and Complex Systems Laboratory, Universidade Federal de Minas Gerais, Brazil
[b] Department of Electrical Engineering, Universidade Federal de Minas Gerais, Brazil
[c] Graduate Program in Electrical Engineering, Universidade Federal de Minas Gerais, Av. Antônio Carlos 6627, Belo Horizonte 31270-010, MG, Brazil

ARTICLE INFO

Keywords:
Load restoration
Scheduling
Heuristics

ABSTRACT

When a fault occurs in a power distribution network, energy utilities have limited time to define and run a restoration plan. While this problem is widely studied in the literature, existing works consider neither the work in parallel of multiple maintenance teams, nor the time taken by the teams to move between locations. In this paper, we address the problem of assigning and sequencing maneuver operations of a restoration plan. We propose modeling this situation as a scheduling problem, and then present specific heuristics for its solution. Computational experiments show that ignoring multiple teams and time requirements leads to solutions that seem to be efficient, but are in fact not. The proposed heuristics are able to quickly return good solutions, even for large instances, allowing their use within the constrained time frames required for the resolution of power outages.

1. Introduction

Power outages can cause severe impacts on customers as well as on distribution utilities, which may be fined by regulatory agencies. The quality of service provided by power distribution companies is usually measured by at least two reliability indices [1]: one relative to the duration (System Average Interruption Duration Index, SAIDI) and the other to the frequency (System Average Interruption Frequency Index, SAIFI) of outages. In terms of SAIDI, the longer a load is disconnected, the worse this index value can get, so there is a strong motivation for recovering healthy but *out of service* (*oos*) loads as fast as possible. The process of reconfiguring a power distribution network for recovering healthy *oos* loads after a fault is called *load restoration* [2]. The expected result is a sequence of switching maneuvers that changes the network topology, with the goal of restoring as much service as possible in the shortest time, without violating operational constraints.

Despite the importance of the time taken to execute the restoration maneuvers, this dimension of the problem tends to be poorly modeled in the literature. Several studies [3–7] use the number of maneuvers as a proxy for the time taken to execute a restoration plan. However, a sequence of fewer maneuver is not necessarily faster than one with more operations, since the actual time taken to perform all maneuvers depends on the initial location of the dispatch teams, traffic, weather, etc. Besides, if multiple teams are available, it is possible to coordinate their actions such that several maneuvers can be performed in parallel or with very small delays. Neglecting these features may lead to restoration plans that appear to be good, when in fact they are not. This impacts the whole process, reducing efficiency and resulting in financial loss [8–10].

To overcome this issue and obtain a more reliable estimation of the time taken to execute a restoration plan, we model the assignment and sequencing of maneuvers as an *identical parallel machines scheduling problem with sequence-dependent setup times and precedence constraints* [11] and propose specific heuristics to solve it. This scheduling problem is known to be NP-hard [11], and solving it to proven optimality is prohibitive in practice, since the computation of a restoration plan normally begins when the knowledge of an outage becomes available. Moreover, there are other intensive tasks that need to be executed during this process, such as load flow algorithms [12]. As a consequence, the method used to solve the respective scheduling problems has to provide a response quickly, which motivates the use of heuristics.

The main contributions of this paper are: (i) the proposition of an approach to get a reliable estimation of the time taken to execute a restoration plan that considers displacement times and multiple maintenance teams working in parallel; (ii) the assignment of switching maneuvers to teams and the sequence in which they should be performed; and (iii) the proposition of specific heuristics that return the estimation of time and the schedule of the switching maneuvers, which

* Corresponding author at: Operations Research and Complex Systems Laboratory, Universidade Federal de Minas Gerais, Brazil.
E-mail addresses: andrelms@ufmg.br (A.L. Maravilha), fgsm-c@ufmg.br (F. Goulart), egcarrano@ufmg.br (E.G. Carrano), fcampelo@ufmg.br (F. Campelo).

https://doi.org/10.1016/j.epsr.2018.06.020
Received 27 October 2017; Received in revised form 28 March 2018; Accepted 30 June 2018
0378-7796/

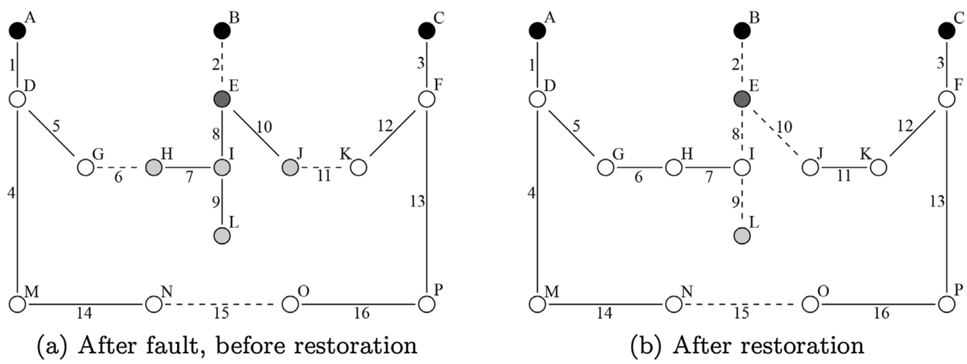

Fig. 1. Example of the effect of a fault in a radial distribution network. Black circles (A, B, C) indicate feeder nodes, while all other nodes represent load sectors. Solid lines indicate the current configuration of the network, while dashed ones represent currently open switches. (a) A fault on sector E disconnects all loads downstream from it. (b) A possible restoration plan. In this example node L was not restored due to overload constraints.

are fast enough to be embedded into algorithms of network restoration without compromising efficiency.

The remainder of this work is organized as follows. Section 2.1 provides a brief definition of the problem under investigation. A mixed integer programming (MIP) formulation for the problem is presented in Section 3, and heuristics to solve it are proposed in Section 4. Computational experiments to evaluate the proposed heuristics are presented in Section 5, and a case study in a real-world network is provided in Section 6, in which the proposed approach is compared with the conventional approach in the literature. Conclusions and final remarks are presented in Section 7.

2. The load restoration problem

Electrical distribution systems are often operated in a radial configuration, which provides several advantages [1] but also leads to drawbacks, as the consequences of a fault in any part of the system propagate to all downstream loads, as illustrated in Fig. 1a. Here, the system is represented by an undirected graph $\mathcal{G}_{\mathrm{DS}} = (\mathbb{V}, \mathbb{E})$, with edges indicating maneuverable switches and solid/dashed lines depicting currently closed (CC)/currently open (CO) switches, respectively. Nodes indicate load sectors. In the figure, a hypothetical fault in node E causes protection switch 2 to activate,[1] leaving (healthy) nodes H, I, J and L out of service. A possible restoration strategy is shown in Fig. 1b, and consists of changing the network topology (opening and closing switches) to reconnect the healthy *oos* load sectors to one of the feeders, subject to operational constraints. In this particular example, the restoration plan consists of two stages: (i) open switches 8 and 9 and close switch 6, to recover nodes H and I; (ii) open switch 10 and close switch 11 to restore node J. Notice that node L remains disconnected, which may be needed to prevent constraint violations.

The usual goal of load restoration is to recover as much service as possible in the shortest time, without violating operational constraints. The literature on this particular problem includes rule-based and constructive heuristic strategies [3,5,6], local search-based techniques and other high-level heuristics [14,4,7,15], and mathematical programming approaches [16,17].

The quality of a restoration plan is usually measured by several indices, with the three most relevant to this work being the total power not restored ($\mathcal{I}_{\mathrm{SNR}}$), the number of maneuvers ($\mathcal{I}_N$), and the time of maneuvers ($\mathcal{I}_T$). Most studies [3–7] use the number of maneuvers as a proxy for the time taken to execute a restoration plan, despite the disadvantages discussed in the Introduction, and the fact that remotely controlled switches allow some maneuvers to be performed very quickly, while others require a team to physically reach the switch for manually operating it.

Some works [14,15] recognize that $\mathcal{I}_T$ is more realistic than $\mathcal{I}_N$, and try to estimate it by defining constant times required for operating each switch. Watanabe [15] arbitrarily sets this value to 1 for all switches, while Carrano et al. [14] assume it to be provided by the engineer. In both cases the total time would be sum of the individual times for each operated switch, which has two fundamental problems: (i) assuming sequentially operated switches means ignoring the existence of multiple maintenance teams whose coordinated actions can considerably reduce the time; and (ii) the time to execute a maneuver depends mostly on the relative position between the team and the switch, and thus modeling it with a constant value is not realistic. In effect, this index becomes a weighted $\mathcal{I}_N$, with the weights bearing no physical interpretation of time, and thus provides little advance with respect to what is customary in the literature. As far as the authors are aware, there is currently no work in the literature which considers the existence of displacement times when attempting to generate restoration plans. Addressing this shortcoming is one of the main objectives of this work, as will be detailed in Sections 3 and 4.

2.1. Scheduling maneuvers

The expected output of a restoration plan is a sequence of maneuver stages, each consisting of zero or more openings followed by a single closing. As discussed earlier, the quality of these plans are commonly measured by three indices. While $\mathcal{I}_{\mathrm{SNR}}$ and $\mathcal{I}_N$ can be readily computed given a new network configuration, estimating the total time of maneuvers $\mathcal{I}_T$ requires assigning the operation of manually controlled switches to maintenance teams, as well as determining the sequence in which the maneuvers of both manual and remotely-controlled switches are to be performed. Only then it is possible to reliably estimate the time required for the restoration plan.

For assigning and sequencing operations, only switches that have to be operated need to be considered. The remaining switches, and the nodes they connect, are irrelevant to this process. Thus, let $\mathbb{E}' \subseteq \mathbb{E}$ be the set of relevant switches in a restoration plan. A switch $e \in \mathbb{E}'$ can be opened or closed, depending on its current state. Thus, the notation (e, θ) is used to describe a maneuver operation, in which $\theta \in \{O, C\}$ is the operation (O for opening and C for closing) to perform on switch $e \in \mathbb{E}'$. Fig. 2 illustrates an example of a restoration plan with this notation.

For performing these operations, some precedence rules must be satisfied to avoid violating constraints (e.g., overloading a feeder) or reconnecting faulted sectors. A problem formulation must therefore be able to determine the assignment of (manual) maneuvers to maintenance teams, and the sequence and specific moments to perform each maneuver, to minimize the completion time of the restoration plan; while considering the displacement times and respecting the precedence rules.

2.2. Modeling as a parallel machine scheduling problem

The problem of assigning and sequencing maneuvers in the restoration of a power distribution network can be modeled over a directed graph $\mathcal{G} = (\mathbb{N}, \mathbb{A})$. Nodes $\mathbb{N} = \{0, 1, 2, \ldots, n\}$ represent the

[1] Throughout this work we assume the protection system is properly coordinated [13].