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Online prognosis for priority power supply restoration

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ABSTRACT

Automatic monitoring of the vulnerability of the power supply to a high-priority facility has important practical considerations. As opposed to the well studied optimization task for power supply restoration which is carried out *after* a fault has happened, the task of analyzing the restorability of a high-priority line under possible fault conditions is a decision problem that has to be solved periodically as the load conditions in the network change. The outcome of this decision problem may be used to alert the high-priority facility about the vulnerability of the state of the network, in the sense that some faults may cause a non-restorable outage to the line supplying that facility. This paper studies the prognosis of a high-priority line in a network in terms of power supply restorability and proposes the first method for this problem.

1. Introduction

The power supply restoration (PSR) problem deals with the problem of restoring power to the areas in a power distribution network that are affected due to a fault in some line on the same feeder. When a fault occurs in a line in the distribution network, the protection circuitry in the network automatically isolates a part of the affected feeder containing the faulty line, thereby causing power outage in the lines that were served through the faulty line. The restoration of power on the lines that are not faulty but affected by this isolation, is effected by reconfiguring the switches in the distribution network such that these lines receive power through other feeders. In distribution networks with large loads, the excess capacities in the other feeders may not be adequate to cover all the affected lines, thereby lending a combinatorial aspect to the underlying problem of restoration.

Power supply restoration has been studied in many different settings and under many different optimization goals. Section 2 presents a survey of these problems and the algorithmic approaches that have been studied in the past. In this paper we consider a closely related problem, namely the decision problem of restorability of a given line in the network. Let us suppose some line in the network supplies power to a high-priority facility, such as a defense establishment, a hospital, or the load dispatch center of a power grid. Our intention is to ensure at all times that the high-priority line is restorable even if any fault occurs in the network. Therefore, as opposed to the available literature on finding the best restoration *after a fault has occurred*, our objective is to *periodically monitor* the restorability of the given high-priority line *before a fault has actually occurred*.

It is important to note that our objective is not to provide a restoration strategy, but to alert the high-priority facility when the system is in a vulnerable state where one or more specific faults can cause a non-restorable outage to the high-priority facility. Therefore, we are not concerned with the many different objectives that an optimal restoration strategy must consider. Rather, the prognosis studied in this paper is useful for the following reasons:

1. Our analysis determines the percentage of lines where faults can lead to non-restorable outage in the high-priority line. This may be used as a vulnerability metric for the power supply to the high-priority facility.
2. Depending on the vulnerability assessment, the high-priority facility may decide to deploy its in-house back-up power generators.
3. The grid operator may take appropriate measures to restore the load-flow state of the network to a less vulnerable state before any fault takes place.
4. The grid operator may put more emphasis on the maintenance and protection of lines where faults can lead to non-restorable outage of the high-priority line.

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It may be noted that the decision problem studied in this paper retains some of the combinatorial nature of the well studied PSR optimization problem. For example, a restorability check will need to examine load balancing between the feeders, which is a combinatorial task.

In the first part of the paper we present the *priority power supply restorability* problem in terms of the formal representation of the circuit elements. We present a theoretical analysis of the problem, which establishes that the problem is NP-complete in general. This result imposes a computational challenge for performing our task online, and the rest of the paper is devoted towards finding an effective solution.

At the heart of our approach is a greedy algorithm that finds the load sharing combinations between the feeders in the network. In the second part of the paper we use this algorithm to determine the set of faults that can cause non-restorable outage to the high-priority line. Both these algorithms have to be executed periodically for effective prognosis of power supply restoration on the high-priority line.

Our algorithm for finding load sharing combinations is a greedy algorithm designed to solve the underlying intractable problem quickly at the cost of preciseness, so that alerts can be generated in real time. Consequently in some cases, our method may report the state of the network as vulnerable even though the high-priority line is restorable under all faults. We observe that such cases are rare, thereby lending credibility to our approach from a practical point of view. *A more important aspect of our algorithm is that it guarantees safety, that is, a truly vulnerable state is always reported.*

The approach presented in this paper relies on the availability of load information on the lines of the network in real time. This is not an unrealistic assumption today given the use of SCADA systems in power system monitoring and the use of synchrophasors in modern grids.

The main contributions of this paper are as follows:

1. We prove that the power supply restorability problem for a high-priority line is NP-complete in general.
2. We propose an online algorithm for capturing a succinct summary of the available load sharing capabilities among various feeders.
3. We propose an algorithm for finding the set of faults that may cause non-restorable outage on the high-priority line. If this set is empty, the supply to the high-priority line is guaranteed to be safe (not vulnerable).
4. We present experimental results on PSR benchmarks with discussions on the factors impacting the problem complexity from a practical point of view.

The paper is organized as follows: Section 2 presents related work on supply restoration of distribution networks. Section 3 presents the problem formulation and the complexity analysis of the problem. Section 4 presents the graphical abstraction of the distribution network. Section 5 presents the proposed algorithm with working examples. Experimental results on PSR benchmarks are presented in Section 6 followed by concluding remarks in Section 7.

2. Related work

A significant volume of recent literature addresses the *power supply restoration* (PSR) problem in a power distribution network. Several methods have been used to solve the PSR problem, like AI planning [1,2], search techniques [3,4], mixed integer programming [5,6], etc. The survey presented in [7] covers some of the early works on the PSR problem. A more recent survey in [8] outlines existing work on PSR using knowledge based methods.

The work in [9,10] presents a power supply restoration problem in the distribution network and illustrates the constraints that the operator should meet while restoring power. The supply restoration problem becomes more challenging due to the non-ideal nature of the sensors and actuators (that is, one has to deal with measurement uncertainties), where the fault location and the network configuration becomes partially observable. In [10] the authors have proposed this restoration problem as a planning problem under uncertainty. In [2] PSR has been solved as a planning problem, but the formulation ignores the capacity constraints of the basic PSR problem. In [1], a model based planner (MBP) is used to solve the restoration problem as a planning problem via symbolic model checking. The PSR problem was modeled in MBP's input language and is fed to MBP which generates plans to achieve the goal of the PSR problem, namely to find a restoration strategy.

In [3] the PSR problem has been solved using breadth-first and best-first search techniques, with the objective being to minimize the switching operations under the constraints of capacity and load balancing. In [11] a power restoration methodology has been presented, which yields a list of solutions for restoring power to the affected area for the consideration of an experienced operator. A brute-force algorithm for finding a solution for the reconfiguration problem has been presented in [12], which is suitable for networks of moderate size. In [4], informed A* search algorithm has been used to find the optimal reconfiguration for supply restoration. In this work, the authors have used level-1 plans, where load transferring among healthy feeders is not considered. In general, approaches that consider only level-1 plans may not find a solution even if one exists. Other optimization techniques which are used to solve the PSR problem are genetic algorithm [13], mixed integer programming [6], Ant colony optimization along with artificial immune systems [14], evolutionary approach [15], etc. But none of the above literature considers the concept of priority customers.

However, there also exists literature which considers priority during restoration. In [16] PSR has been formulated as a multi-objective optimization problem, where the objective functions to be optimized are the number of switching operations, minimizing the outage area and power loss under the constraints like restoration of power to priority customers. [17] uses a variant of genetic algorithm to solve the restoration problem with priority customers and distributed generations. A ranking-based search methodology is used in [18] to restore power to as many priority customers as possible while maximizing the amount of total load restored and minimizing the switching operations.

3. The power supply restorability problem

Fig. 1 shows a distribution network which consists of switches S_i, distribution lines l_i, and circuit breakers CB_i. There are two states for each switch, namely: open (represented as white box) or closed (represented as colored box). The circuit breakers CB_i are located at the distribution substations where the transmission lines bring in the power which is to be distributed to the customers. The PSR problem is relevant only when the distribution network has a meshed topology, such that there exists more than one way to feed a given line. During operation a radial structure is maintained, that is, a given line is connected to only one CB at a time and the paths to the other CBs are disconnected through switches which are kept open.

The region of the network which is fed by a particular circuit breaker CB_i is called a feeder F_i. The circuit breakers at the distribution substations have a capacity to supply a definite amount of power to the distribution side and hence the load of the feeder should not exceed the capacity of its corresponding circuit breaker. A feeder is partitioned into a number of subsidiary feeders/lines l_i. Two lines are connected with each other through switches S_i when