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Review

A survey of models and algorithms for emergency response logistics in electric distribution systems. Part II: Contingency planning level

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ABSTRACT

This is the second part of a two-part survey of optimization models and solution algorithms for emergency response planning in electric distribution systems. The first part of the survey addresses reliability planning problems with fault considerations related to electric distribution operations. The aim of this second part is to provide a comprehensive survey of optimization models and solution methodologies for contingency planning problems related to electric distribution operations. These problems include the restoration of service, the sequencing of switching operations, the routing of repair vehicles, the scheduling of repair crews, and the assignment of crews to repair sites.

Contents

1. Introduction

This is the second part of a two-part survey of optimization models and solution algorithms for emergency response problems related to electric distribution operations. Planning the operations of emergency distribution response involves a variety of decision-making problems relating to the reliability of electric distribution networks with fault considerations and to the contingency

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preparedness for distribution networks. Reliability planning problems with fault considerations for emergency response logistics in electric distribution systems were reviewed in the first part of the survey [55]. The aim of this paper is to provide a comprehensive survey of optimization models and solution methodologies for the contingency planning process related to emergency response in electric distribution systems. These problems include the restoration of service, the sequencing of switching operations, the routing of repair vehicles, the scheduling of repair crews, and the assignment of crews to repair sites. The field of fault diagnosis, fault location, and fault isolation is not treated here but the interested reader is referred to the recent review by Lazzari et al. [38]. The paper is organized as follows. Section 1 describes the sequence of emergency distribution operations after a fault and the contingency decision problems related to those operations. Section 2 reviews models dealing with the restoration of service and the sequencing of switching operations in distribution systems. Section 3 describes models that address the routing of repair vehicles, the scheduling of repair crews, and the assignment of crews to repair sites. Finally, conclusions and future research directions in distribution emergency response planning are presented in the last section.

1.1. *Operations context and contingency planning problems in electric distribution systems*

This section contains a brief description of electric distribution operations. Emergency response problems related to electric distribution operations that have been addressed with operations research methodologies are then discussed.

1.2. *Emergency distribution operations*

Real-time control and operation of distribution systems are performed by system operators located in dispatch centers. After a fault occurs on a distribution system, a sequence of *emergency distribution operations* to be undertaken follows: fault diagnosis, fault location, fault isolation, restoration, and repair. In the *fault diagnosis* step, available data in the dispatch center on network status, device alarms, and service interruptions have to be processed and interpreted with automatic devices and support systems. In some cases, fault diagnosis still has to be confirmed by a crew dispatched by the operator to inspect the circuit associated with the customers experiencing service interruptions. After fault diagnosis, the damaged network element has to be located in the *fault location* step. Typically, an outage management system automatically infers the fault location based on trouble calls. However, this step can also involve some further investigation on the circuit. In the *fault isolation* step, the faulted network element is isolated so that neighboring elements can perhaps be taken back into service and the faulted element repaired in subsequent steps. To isolate the damaged network element, protective equipment can be used or the operator can direct the crew to isolate the fault, even if this means interrupting the power flow to some customers. After the faulted element is isolated, the *restoration step* should restore as many customers as possible without violating system operating limits until the system is returned to normal state. The restoration step restores service to customers that are not located in the faulted section. (To move back to normal state, it will be further necessary to repair and reconnect the faulted section.) Some out-of-service elements can be restored from the same substation. Some others, however, have to be supplied by rerouting power around outaged equipment to restore customers who would otherwise have to remain out of service until repairs are completed. This reconfiguration is performed by sectionalizing devices, such as switches, dividing each feeder. Switching operation may be automatic, or may be performed by a dispatcher through a communications channel. Automated switches are used to quickly isolate damaged sections and restore power to as many customers as possible. Manual switching restores power to additional customers that were not able to be restored by automated switching.

To illustrate the sequence of switching operations, consider a fault occurring on the system represented on Fig. 1a, taken from Brown [9]. When the fault occurs, breaker 1 clears the fault and interrupts all customers on the feeder. Interrupted customers call the utility and crews are dispatched to locate the fault. Once the fault is located, the crew opens the nearest upstream switch (Switch 1). This allows breaker 1 to be closed and all customers upstream of switch 1 to be restored (Fig. 1b). If extended repair time is required, customers downstream of switch 1 can be restored using an alternate electrical path. First, the crew opens switches 2 and 3 to isolate downstream components from the fault location (Fig. 1c). Then, the crew closes normally opened switches 4 and 5 to restore service to customers downstream of switch 1. These customers are now supplied by substations 2 and 3 rather than by substation 1 (Fig. 1d). The entire switching sequence is called *system reconfiguration*. After switching is accomplished, the crew repairs the fault in the *repair step* and, when finished, returns the system to its normal state.

1.3. *Emergency service restoration problems*

Emergency service restoration problems concern the restoration of service and the sequencing of switching operations. The *restoration problem* consists of reconfiguring temporarily a distribution system by transferring the loads in the out-of-service area to neighboring available network elements, referred to as *supporting network elements*, in order to restore as many customers as possible in accordance with their hierarchy with as few switching actions as possible, while satisfying some topological and electrical constraints. Ideally, the restoration step should first attempt to reconnect all out-of-service customers. However, in the event of partial service restoration, the supply must be restored to highest priority customers who will suffer significantly more damage than other customers if not supplied with electric power. These priority customers are categorized based on their sensitivity to power supply cuts which induce a *service hierarchy*, hospitals and similar institutions being given a higher priority than cinemas.

The primary topological constraint is to maintain a *radial structure* for all feeders during the restoration period for ease of fault location and isolation and for the coordination of protective devices. Radial distribution systems are characterized by having only one path between each consumer and a substation. However, the radiality constraint can be compromised momentarily, usually during switching operations, to avoid instantaneous interruptions. This compromise is based on the reasonably small probability that a fault will occur during such a short time. Other constraints concern *voltage drop*, *equipment loading*, and *voltage levels*. Voltage constraints are usually expressed in terms of permitted *voltage drop* since lowering voltage can significantly reduce system demand. Also, during the restoration step, the capacity of the supporting network elements is normally used to its limit. To ensure that the restoration will not cause further outages, the supporting network elements must not be overloaded. Utilities that do not have overload protection devices should determine in advance the *load capacity* of each network element. Nevertheless, in order to maximize the number of customers with a restored supply, there is a strong tendency to relax the loading and voltage constraints to a certain extent during the restoration period. For example, Kim et al. [35]

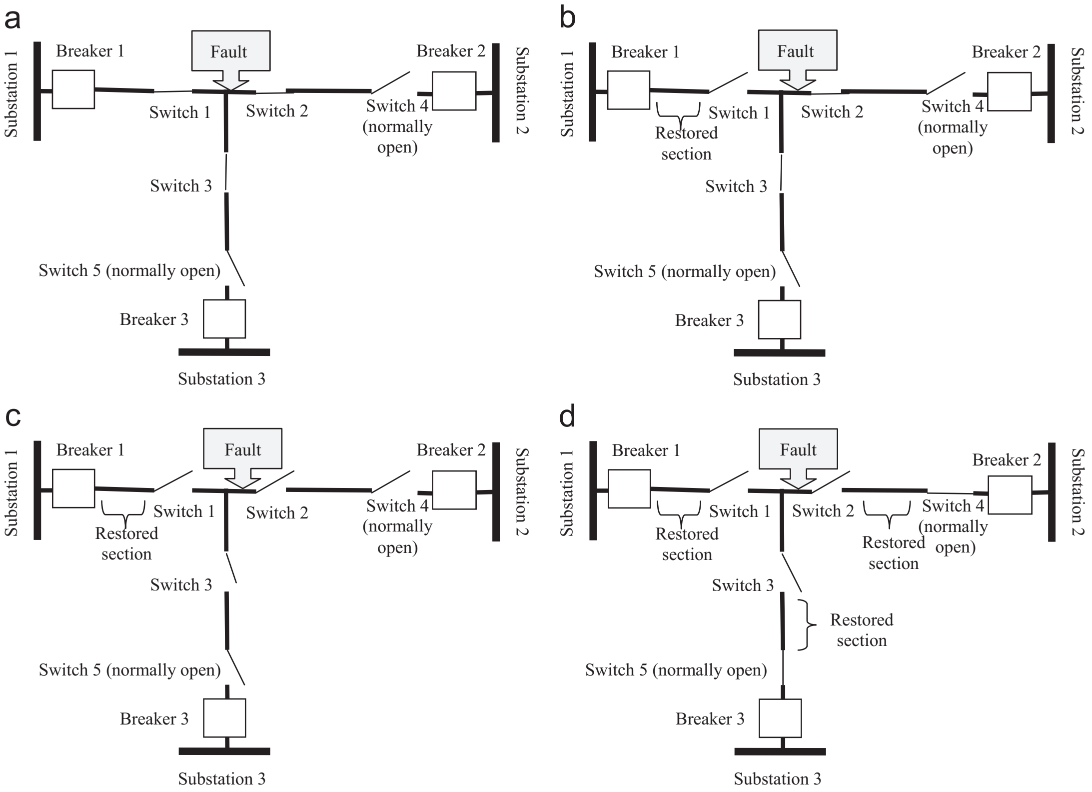


Fig. 1. Sequence of emergency distribution operations after a fault [9]: (a) Fault location. (b) Upstream restoration. (c) Fault isolation. (d) Downstream restoration.

consider overloading the transformers upto 133% of their rated capacity. Also, although restoration with relaxed voltage constraints leads to electricity supply of poor quality, several authors believe that this is acceptable during emergencies [16]. Finally, to provide as much service as possible to the affected customers for faults that take out of service a large portion of neighboring elements, the restoration should, if necessary, *cross voltage levels* by employing a large number of network elements of different voltage levels in the restoration.

The *switching sequencing problem* consists in finding a set of switching operations to recover from the initial faulted configuration and achieve the restoration plan so as to maximize customer satisfaction, while guarantying the electrical constraints to be met for the final network reconfiguration as well as for every intermediate network configuration. The switching order should give priority to the switching operations that restore more customers or highest priority customers, if any.

1.4. Repair vehicle routing, repair crew scheduling, and crew assignment problems

Yet another series of decision problems involves the dispatch and management of repair crews, which can be decomposed into the repair vehicle routing problem, the repair crew scheduling problem, and the crew assignment problem (see Section 3). Given faults at various points in a transportation network over which repair vehicles may travel, the *repair vehicle routing problem* consists of determining a set of routes, each performed by a vehicle that starts and ends at its own depot, such that all faults are repaired, all the operational constraints are satisfied, and the repair completion time is minimized. Typically, the faults are classified into a number of classes according to the degree of danger and urgency which induce a *repair hierarchy*, namely all critical faults such as dangerous fallen cables are given the highest level of priority, while domestic loss of power calls in single homes have the lowest priority. Also, associated with each fault is a time interval, called *repair time window*, during which the fault should be repaired. In addition, knowledge of the probability of faults in the distribution system is necessary for determining the routes. Finally, to *balance the workload* across vehicles, they have often approximately the same number of repair requests and same travel and repair times. This helps ensure that all emergency distribution operations are completed in a timely fashion. Vehicles with special function may also be prioritized.

The *repair crew scheduling problem* deals with the need to find a set of crew schedules that cover all the required inspection, damage assessment, and repair tasks so as to minimize the average time each customer is without power. The schedules must not be allowed to violate operational constraints such as exceeding resource limits or violating precedence relationship constraints. A *precedence relationship* between two tasks states that one of these is to be covered before the other. Finally, given a set of resource depots, the *crew assignment problem* consists of assigning a set of crews to these depots, so as to satisfy the demand for repair tasks while minimizing delays and costs.

2. Emergency service restoration models

Emergency service restoration models can be classified into two categories according to the type of network element fault considered: substation fault and feeder fault. These two categories of models are covered in Sections 2.1 and 2.2, respectively. Models aimed specifically at the sequencing of switching operations are described in Section 2.3.

Table 1
Characteristics of substation fault models, data types and problem sizes.

Articles	Problem type	Problem characteristics	Objective function	Model structure	Solution method	Distribution system	Problem size
Aoki et al. [2]	Single-objective	Radiality and load limits	Max total load restored	Knapsack problems	Composite heuristic	Real (Japan)	5 substations, 11 transformers, 86 feeders, 577 switches
Aoki et al. [3]	Single-objective	Radiality, load limits, and voltage drop limits	Max total load restored	Knapsack problems	Gradient method	Real (Japan)	5 substations, 11 transformers, 86 feeders, 577 switches
Aoki et al. [4]	Single-objective	Radiality, load limits, and load balance	Max total load allocated	Knapsack problems	Composite heuristic	Real (Japan)	5 substations, 11 transformers, 86 feeders, 577 switches
Aoki et al. [5]		Radiality, load limits, voltage drop limits, and load balance	Max total load allocated	Knapsack problems	Four-stage heuristic	Real	5 substations, 11 transformers, 87 feeders, 1188 load sections
Dialynas et al. [20]	Single-objective	Radiality, load and voltage drop limits	Min number of switch operations	—	Heuristic search	Real (Greece)	9 substations, 200 branches, 493 components, 116 nodes
Chen et al.[14]	Single-objective	Radiality, equipment overloads, and load balance	Min feeder overloading and unbalance	Linear 0–1 IP	Implicit enumeration	Real (Taiwan)	4 substations, 9 feeders
Okuda et al. [51]	Single-objective	Radiality, service hierarchy, load limits	Min power failure duration	—	Composite heuristic	Generated	10 substations, 10 load blocks/ substation, 10 loads/block
Kim et al.[35]	Single-objective	Radiality, voltage violations, load limits, load balance, service hierarchy	Min number of switch operations	Binary decision tree	Best-first search	Generated	3 substations, 10 banks, 60 feeders
Fujii et al. [23]	Single-objective	Equipment overloads and voltage drop limits	Min number of switch operations	—	Composite heuristic	Real (Japan)	50 substations, 105 banks, 452 feeders, 5000 switches
Van Harte and Atkinson-Hope [69]	Single-objective	Voltage drop limits and equipment overloads	Min customer interruptions	Simulation model	Scenario analysis	Real (South Africa)	1 substation, 1 transformer, 1 feeder, 27 switching points
Fukuyama et al.[24,25]	Single-objective	Radiality, load limits, and voltage limits	Min out-of-service load and load unbalance	—	Genetic algorithm	Generated	5 substations, 100 loads, 5 feeders, 106 switches
Ferreira et al. [21]	Single-objective	Radiality, equipment overloads, and voltage violations	Min out-of-service load	—	Evolutionary-based algorithm	Generated	54 substations, 8964 nodes, 9080 branches
Toune et al. [65]	Multi-objective	Radiality, load and voltage limits	Max load balance and lowest voltage level	Nonlinear P	Metaheuristics	Generated	2 substations, 60 feeders, 360 load sections (6 sections/feeder)
Miu et al. [48]	Multi-objective	Radiality, service hierarchy, load and voltage limits	Max priority load restored Max total load restored Min number of switch operations	Nonlinear Multi-objective MIP	Local search heuristic	Generated	1 substation, 342 lines without breakers, 14 lines with breakers, 7 transformers, 30 tie switches, 53 sectionalizing switches, 208 loads
Augugliaro et al. [6]	Multi-objective	Radiality, service hierarchy, equipment overloads, and voltage limits	Max load supplied Min power losses	—	Fuzzy sets and genetic algorithm	Generated	6 substations, 109 branches, 81 load nodes, 18 banks

2.1. *Substation fault models*

Several heuristic procedures have been proposed for the restoration of service after a short circuit on a substation component. These can be broadly classified into two categories: composite methods and adaptation of metaheuristics. The characteristics of the contributions are summarized in Table 1 at the end of the section.

2.1.1. *Composite methods*

One of the first contributions dealing with the emergency restoration problem is due to Aoki et al. [2]. Given a single fault occurrence at a substation transformer, the problem considered is to rapidly restore as much load as possible by transferring the loads in the out-of-service area to adjacent supporting feeders by using switching operations, while respecting the radiality of the distribution system topology, the transformer capacity constraints, and the feeder capacity constraints. Adjacent supporting feeders are located nearest to the faulted substation transformer with normally opened cut switches directly connected with the out-of-service area. *Cut switches* "cut off" the service area of one transformer from the other service areas. Similarly, *loop switches* "cut off" a loop in the service area of each transformer. Consider the distribution system with five transformers illustrated in Fig. 2, adapted from Aoki et al. [2].

Since this system is radial, the service area of each transformer defines a spanning tree, rooted at the transformer, whose links, nodes, and leaves represent feeders, branching points, and normally opened switches, respectively. If a fault occurs at the transformer T_3 of substation S_2, then this transformer is separated from the system by opening the bus switch B_3 to isolate the fault. (A *bus* is a rigid conductor used to interconnect primary equipment.) As a result, the service area of transformer T_3, sectionalized by the normally opened cut switches c_1, c_2, c_7, c_{10}, c_8, and c_5 is forced to be out-of-service. By changing the opened positions of these switches, the loads in the out-of-service area can be transferred to the adjacent supporting feeders f_1, f_6, f_7, and f_9, taking into consideration radiality and equipment loading constraints. Let I be the set of feeders in the distribution system. For any feeder $i \in I$, define J_i as the set of all load sections on feeder i and let $S_i \subseteq J_i$ be the set of deenergized load sections on feeder i. A section is a feeder segment sectionalized by two successive sectionalizing switches. For every feeder $i \in I$ and for every load section $j \in S_i$, let x_{ij} be a binary variable equal to 1 if and only if section j on feeder i is re-energized (i.e., the switch connected to

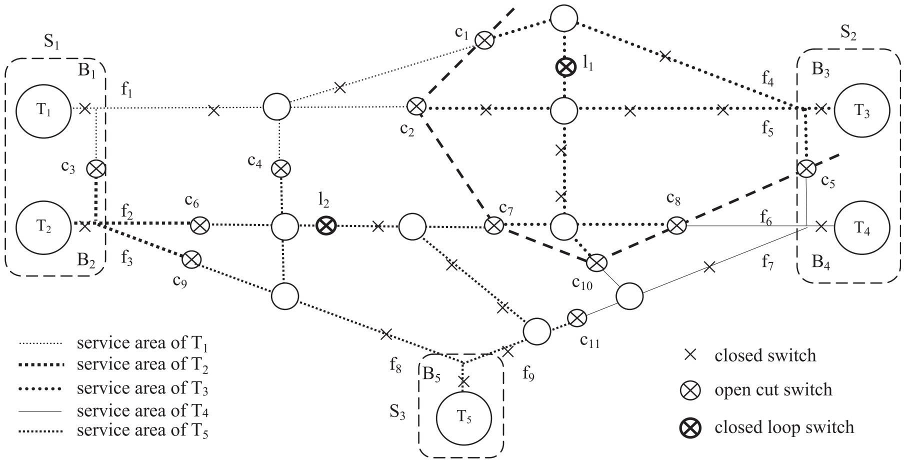


Fig. 2. Example of a radial distribution system (adapted from Ref. [2]).

section j on feeder i is closed to allow load transfer from an adjacent supporting feeder). For every feeder $i \in I$ and for every load section $j \in J_i$, let a_{ij} represent the load of section j on feeder i. For any feeder $i \in I$, let K_i be the set of branching points on feeder i. For every feeder $i \in I$ and for every branching point $k \in K_i$, let S_{ik} be the set of load sections downstream of point k on feeder i and define b_{ik} as the feeder capacity at point k on feeder i. Let T be the set of adjacent supporting transformers in the distribution system. Finally, for every adjacent transformer $t \in T$, let S_{it} and I_t be the set of load sections downstream of the adjacent transformer t on feeder i and the set of feeders emanating from transformer t, respectively, and define b_t as the capacity of transformer t. Then the problem can be modeled as a linear 0–1 integer program as follows:

$$\text{Maximize} \sum_{i \in I} \sum_{j \in S_i} a_{ij} x_{ij} \tag{2.1}$$

subject to

$$\sum_{j \in S_{ik}} a_{ij} x_{ij} \le b_{ik} \quad (i \in I, k \in K_i) \tag{2.2}$$

$$\sum_{j \in S_{it}} a_{ij} x_{ij} \le b_t \quad (t \in T, i \in I_t) \tag{2.3}$$

$$x_{ij} \ge x_{i(j+1)} \quad (i \in I, j \in S_i) \tag{2.4}$$

$$x_{ij} \in \{0,1\} \quad (i \in I, j \in S_i) \tag{2.5}$$

The objective function (2.1) maximizes the total load restored. Constraints (2.2) and (2.3) ensure that the power transfer limits imposed by feeder capacities and transformer capacities, respectively, are respected. Constraints (2.4) states that the power can be supplied to section $j+1$ only if the upstream adjacent section j is energized and the sectionalizing switch connected to it is closed. The authors showed that model (2.1)–(2.5) is equivalent to the multi-dimensional knapsack problem. Thus, a load transfer algorithm, similar to the primal method used for the knapsack problem, is developed to solve it. Generally, the load transfer is carried out between the faulted transformer and the sound transformers. However, when the radial distribution system includes a lot of loop switches, considering all the sound transformers simultaneously can become very complex. Therefore, the authors suggested applying *successive load transfer*, namely the load transfer algorithm is repeatedly applied between pairs of transformers until the out-of-service area is restored. Typically, given the faulted transformer, a single adjacent supporting transformer is selected for load transfer. If the outage cannot be restored without violating equipment capacity and/or voltage drop constraints, then the load of the adjacent transformer is decreased by again transferring loads to a single associate transformer, which has cut switches connected to the adjacent transformer, and so on. For example, in Fig. 2, if a fault occurs at the transformer T_3, the transformer T_4, installed in the same substation, transfers loads firstly. Secondly, the transformer T_5 works since it is located nearest the faulted transformer and has the normal opened cut switch c_7, which is directly connected with the out-of-service area. If the out-of-service area is not restored yet, the transformer T_1 or T_2 transfers loads to T_5. Then, T_5 transfers loads to T_3 and T_4. If the feeders from T_5 to both T_3 and T_4 are saturated with load current, the load transfer from T_1 or T_2 to T_5 is not executed. In that case, the load transfer from T_1 to T_3 is checked considering transformer and feeder capacity constraints. Computational experiments on a real system from the city of Hiroshima in Japan with five substations, 11 transformers, 86 feeders and 577 switches, including 198 normal opened switches, showed that the algorithm was able to reallocate loads in a few seconds. Aoki et al. [3] showed that the algorithm can still be used when load balancing of transformers and feeders is also required.

In a subsequent paper, Aoki et al. [4] extended the original model to take into account voltage drop constraints. For every feeder $i \in I$ and for every load section $j \in J_i$, let S_{ij} be the set of load sections downstream of section j (included) on feeder i, and let z_{ij} represent the impedance of section j on feeder i. For any feeder $i \in I$, let E_i be the set of end switches on feeder i. For any feeder $i \in I$ and for any end switch $e \in E_i$, let S_{ie} be the set of load sections which exist between the substation bus of feeder i and the end switch e, and define V_{ie} as the voltage drop limit at end switch e of feeder i. Then

$$\sum_{l \in S_{ie}} \left\{ \left(\sum_{q \in S_{il}} s_{iq} x_{iq} \right) z_{il} \right\} \le V_{ie} \quad (i \in I, e \in E_i) \tag{2.6}$$

ensure that the voltage drop limits are respected only at the end switches of the feeders, where $s_{iq} = a_{iq}$ if $q \ne l$ and $s_{iq} = a_{iq}/2$ if $q = l$, as uniformly distributed loads are assumed on the feeder sections. As the load point comes near to the end switch, the voltage drop of each load point increases, and it becomes maximal at the end switch. Hence, it is sufficient to consider the voltage drop constraints only at the end switches of the feeders. For example, for the system in Fig. 2, voltage drop checks are needed at both sides of the switches $c_1, c_2, \ldots, c_{11}$, l_1, and l_2.

Aoki et al. [5] proposed a four-stage heuristic for a service restoration problem where load balancing of transformers and feeders is considered, while ensuring that the radiality of the system topology is respected as well as voltage drop limits and feeder/transformer capacity limits. In the first stage, deenergized loads are transferred from the faulted transformer to adjacent supporting transformers one by one. This load transfer problem is solved using the gradient method. Then, if necessary, in the second stage, loads are again transferred to eliminate constraint violations. If some constraints are still violated at the end of the second stage, load curtailment is considered in the third stage. Finally, in the last stage, curtailed loads are restored by considering new load transfer possibilities. The authors compared the performance of the four-stage heuristic and the load transfer algorithm proposed by Aoki et al. [4] on service restoration problems for a real, large scale urban distribution system with five substations, 11 substation transformers, 87 feeders, and 1188 load sections. The four-stage heuristic produced better reconfigurations than the load transfer algorithm, in terms of both the total number of switching operations and the computing time required.

Other composite methods include heuristic search methods and implicit enumeration-based-heuristics. For example, Dialynas and Michos [20] developed a heuristic search method to help system operators in detecting and analyzing the possible switching operations to be performed so as to achieve rapid restoration of customer supply following the occurrence of a substation fault in radial systems. The heuristic starts by identifying the set of electrical paths leading to each load point from all system substations under various operating conditions. Then, the set of possible restoration procedures is determined by combining the available paths leading to each load point. The combination with the lowest number of switching operations, satisfying load and voltage drop constraints, is chosen. The usefulness of the heuristic search method is demonstrated on a hypothetical system based on a real Greek urban distribution system under various fault conditions. Also, Chen and Wu [14] modeled a real-time emergency service restoration problem with load limits, load balancing, and radiality constraints as a linear 0–1 integer programming problem to determine the status of each switching device (closed or opened). The authors assume that loads are uniformly distributed on the feeder sections. The problem is solved using a heuristic search based on a branch-and-bound procedure for integer programs with only binary variables. The search ends when the iteration count exceeds the maximum iteration limit. The heuristic was tested on real data from the Taiwan Power Company.

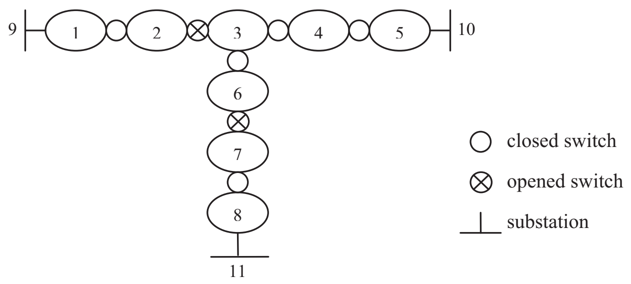
Expert systems have also been developed to assist planners in restoring electricity for out-of-service areas after a substation fault. For example, Okuda et al. [51] described a rule-based decision support system to minimize power failure duration, while taking into account the radial nature of the system, the capacity of the supporting network elements, and the service hierarchy of the priority customers. The system is based on the application of rules and specific expert knowledge dictated by experience, such as successive load transfer, to the process of finding a restoration plan. Kim et al. [35] described a rule-based decision support system for planning of emergency service restoration operations in Korea. The system can deal with radiality, voltage violations of feeders, load limits, load balancing, and service hierarchy. Although the system relies in large part on decision rules obtained from substation operators and distribution dispatch and control center engineers, it also incorporates a heuristic search on a binary decision tree where the status of each switching device is set to 0 or 1 (opened or closed). The best-first search strategy is used to guide the search. Fujii et al. [23] proposed an expert system to help planners at a Japanese electric power company determine the optimal switching operation sequence for load rerouting during substation fault restoration. Knowledge base rules are used to select the load rerouting pattern that minimizes the number of switch operations, while satisfying some topological and electrical constraints. More recently, Van Harte and Atkinson-Hope [69] proposed a simulation model to aid utility distribution planners in making decisions about the optimal position of the normally opened switches on the feeders during emergency conditions after a substation fault occurs. The accuracy of the model was validated using historic data from the Paleisheuwel network in South Africa.

2.1.2. *Metaheuristics*

Fukuyama et al. [24] developed a parallel genetic algorithm for solving a service restoration problem in electric power distribution systems. The objective is to restore as much load as possible after a substation fault occurrence by transferring deenergized loads via network reconfigurations to other supporting distribution feeders without violating the radiality constraint, equipment loading limits, and voltage limits. The string representation of a solution used is a string of integers where each integer represents either the substation supplying a particular load point or the neighboring load point closer to the substation supplying that particular point. The length of a string equals the number of load points. For example, Fig. 3 illustrates the representation of a service restoration solution in a radial distribution system [24].

Specialized crossover and mutation operators are developed to produce new valid offspring sequences. For example, Fig. 4 illustrates the application of the classical one-point crossover on two parent configurations. Substrings coming from parent 2 are shown in bold. Two offsprings are created by exchanging the substring located after the third position. Clearly, offspring 2 is not a valid configuration since load points 3, 4, and 6 lose their power source. When a string violating the radial network constraint is generated, the authors suggest modifying the string after the operation. A straightforward application of the classical mutation operator would also lead to the same kinds of difficulties. Therefore, only load points next to a load point connected to a different substation can experience a mutation operation. For example, in Fig. 4a, only load points 4, 5, 6, and 7 can mutate. Computational tests performed on instances with upto 69 load points showed that the parallel genetic algorithm solved very quickly larger instances than the conventional genetic algorithm. The original genetic algorithm, coupled with an expert system that tries to increase the supply margins of substations by successive load transfer, was imbedded in a hybrid system [25].

Ferreira et al. [21] proposed specific evolutionary-based algorithms to search for optimal reconfigurations, following a main substation fault in radial networks, so as to maintain



load point	1	2	3	4	5	6	7	8
string representation	9	1	4	5	10	3	8	11

Fig. 3. Example of a service restoration solution in a radial distribution system [24].

as much load as possible, while relaxing the loading and voltage constraints. The solution to an instance with 385 nodes, 442 branches, and 3 substations was obtained in a few seconds and had much more load restored than the solution produced with a simplistic method. On an instance with 8964 nodes, 9080 branches, and 54 substations, a solution was found within 30 min.

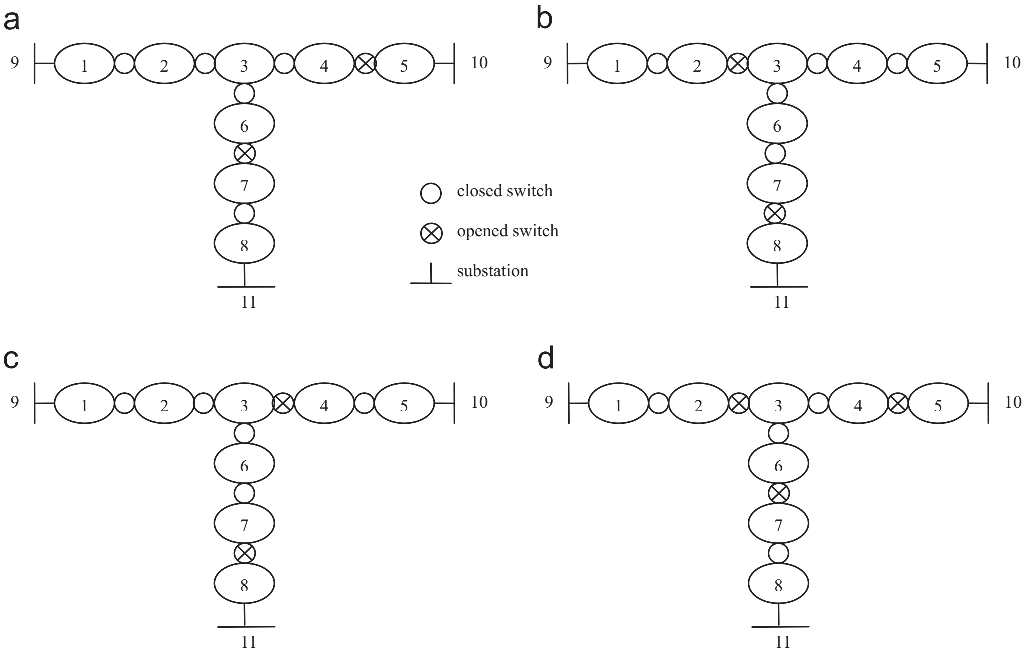
A few researchers have addressed the inherently multiobjective nature of the restoration problem with substation fault. Toune et al. [65] proposed and analyzed the expected performance of metaheuristics (reactive tabu search, tabu search, genetic algorithm, and parallel simulated annealing) for the contingency planning of service restoration configurations. The mathematical formulation considers the counterbalance of the spare capacity of each substation and the maximization of the minimum voltage of the network, while respecting equipment loading and voltage constraints. Radiality constraints are also imposed. At each iteration of the four proposed metaheuristic methods, neighboring solutions are generated by changing the power source direction of one load point in the current network configuration. However, due to the radiality constraint, only the load points next to an opened switch can be selected (for details, see [22,66]). Computational tests on six generated system configurations showed that the reactive tabu search obtained the best solutions in almost all cases and appeared to be faster than genetic algorithm and parallel simulated annealing. The largest instance solved contained two substations, 60 feeders, and 360 load sections (6 sections/feeder). Also, Miu et al. [48] proposed a four-step local search heuristic for a service restoration problem with priority customers, operational, electrical, and radial network constraints. The problem is formulated as a multi-objective, nonlinear mixed integer programming problem to maximize the amount of priority load restored and the amount of total load restored, and to minimize the number of switching operations. The first step of the heuristic finds all candidate switches that can be opened and closed based on analytically determined criteria. The second step then identifies the candidate switch with the largest spare capacity and closes this switch. In the third step, candidate switch pairs are selected to remove constraint violations encountered in the second step. If constraints are still violated, the last step determines which customers not to restore. However, more switch operations are preferable to dropping priority customers or a large amount of load. The search stops when a feasible solution restoring all the out-of-service loads in the area is found. The local search heuristic appears as robust as an exhaustive search method, but significantly faster. Augugliaro et al. [6] suggested a method that combines fuzzy sets with genetic algorithms in the consideration of two criteria: maximization of load supplied and minimization of power losses.

2.2. *Feeder fault models*

Heuristic procedures for the restoration of service after a fault on an overhead feeder component can be divided into three classes: local search methods, adaptation of metaheuristics, and multi-objective analysis. The characteristics of the models in each category are then summarized in Table 2 at the end of the section.

2.2.1. *Local search methods*

Most local search methods that have been proposed to solve the emergency service restoration problem involve a heuristic search on a binary decision tree where the status of each switching device is set to 0 or 1 (opened or closed). The objective considered is usually to minimize the number of switching operations. Let K be the set of switches in the section of the network not affected by the fault. For each switch $k \in K$, let x_k be a



Parent 1	9	1	2	3	10	3	8	11
Parent 2	**9**	**1**	**4**	**5**	**10**	**3**	**6**	**11**
Offspring 1	9	1	2	**5**	**10**	**3**	**6**	**11**
Offspring 2	**9**	**1**	**4**	3	10	3	8	11

Fig. 4. One-point crossover [24].

Table 2
Characteristics of feeder fault models, data types and problem sizes.

Articles	Problem type	Problem characteristics	Objective function	Model structure	Solution method	Distribution system	Problem size
Liu et al. [43]	Single-objective	Radiality, load and voltage limits	Max number of customers with a restored service	—	Composite heuristic	Real (Washington)	3 substations, 6 feeders, 43 zone loads, 43 switches, 6 open tie switches
Morelato and Monticelli [49]	Single-objective	Radiality, load and voltage limits	Min load unbalance	Binary decision tree	Depth-first search	Generated	4 feeders, 20 zone loads, 33 switches
Sarma et al. [58]	Single-objective	Radiality, load and voltage limits	Min number of switch operations	Decision tree	Depth-first search	—	—
Devi et al. [18,19]	Single-objective	Equipment overloads and load balance	Min number of switch operations	Binary decision tree	Best-first search	Real (India)	150 feeders, 2500 load points
Wu et al. [73]	Single-objective	Radiality, equipment overloads, and load balance	Min number of switch operations	Decision tree	Breadth-first search	Real (Kaohsiung, Taiwan)	10 transformers, 31 feeders, 135 normally closed sectionalizing sections, 63 normally open tie switches, 163 zones
Hsu et al. [31]	Single-objective	Radiality and load limits	Min number of switch operations	—	Composite heuristic	Real (Taiwan)	1substation, 9 feeders, 34 branching points
Shirmohammadi [59]	Single-objective	Radiality, voltage limits violations, maximum number of switch operations, and equipment overloads	Min number of switch operations	—	Composite heuristic	Real (San Francisco, CA)	4 feeders, 500 branches, 50 switches
Srinivasan et al. [62]	Single-objective	Load and voltage drop limits	Min number of switch operations	—	Composite heuristic	Generated	180 substations
Ćurčić et al. [17]	Single-objective	Radiality, service hierarchy, loading and voltage limits	Max out-of-service load demand restored	—	Composite heuristic	Real (UK)	534 nodes, 987 switching devices
Sudhakar et al. [64]	Single-objective	Radiality and load limits	Min number of switch operations and power losses	Binary decision tree	Breadth and depth-first search	Real	70 buses, 69 lines, five tie lines
Tsai [67]	Single-objective	Radiality, load balance, and loading and voltage limits	Max number of customers with a restored service	—	Composite heuristic	Real (Taiwan)	6 feeders, 50 load zones, 44 section switches, 9 tie switches, 1 local loop switch
Babu et al. [7]	Single-objective	Radiality, load and voltage limits	Min load unbalance	—	Breadth and depth-first search	Generated	4 feeders, 20 load zones, 33 switches
Lin et al. [41]	Single-objective	Radiality, service hierarchy, load and voltage limits	Max load restored	—	Best-first search	Real (Taiwan)	35 feeders
Siqing et al. [61]	Single-objective	Radiality and load limits	Min number of switch operations	—	Genetic algorithm	Real	5 substations
Ruiz-Paredes, Dávalos [57]	Single-objective	Radiality, service hierarchy, load and voltage limits, loss reduction	Max load supplied	—	Neural network	Generated	8 feeders, 10 line sections
Lee et al. [39]	Multi-objective	Load limits, voltage drop limits, load balance, similarity to the existing configuration	Multi-objective	Multiple criteria	Fuzzy logic	Generated	19 feeders, 152 switches
Matos and Melo [47]	Multi-objective	Radiality, load limits, and voltage drop limits	Min number of switch operations Min load not supplied	Nonlinear MIP	Simulated annealing	Generated	4 substations, 52 buses, 63 switches
Popović and Ćirić [56]	Multi-objective	Radiality, load and voltage limits, similarity to the existing configuration	Multi-objective	Multiple criteria	Composite heuristic	Real (Novi Sad, Yugoslavia)	3 substations, 170 buses, 21 feeders
Ćirić and Popović [15]	Multi-objective	Radiality, load and voltage limits	Min weighted additive multicriteria function	Linear MIP	Composite heuristic	Real (Novi Sad, Yugoslavia)	170 branches, 22 feeders, 100–1000 nodes
Mun et al. [50]	Multi-objective	Radiality, load balance, load limits, and voltage drop limits	Min weighted additive multicriteria function	Nonlinear MIP	Genetic algorithm	Real (Kangdong, Korea)	7 substations, 17 transformers, 100 feeders, 2558 load sections
Huang [32]	Multi-objective	Load limits	Min weighted additive multicriteria function	Multiple criteria	Fuzzy cause-effect algortihm	Real (Taiwan)	3 substations, 10 feeders, 33 lateral loads, 25 line switches, 21 operated switches, 1 tie switch

Table 2 (*continued*)

Articles	Problem type	Problem characteristics	Objective function	Model structure	Solution method	Distribution system	Problem size
Kumar et al. [36,37]	Multi-objective	Radiality, load and voltage limits	Min load not supplied Min number of switch operations Min power losses	Nonlinear MIP	Genetic algorithm	Generated	75 switches, 173 buses, 88 load buses
Manjunath and Mohan [46]	Multi-objective	Radiality, service hierarchy, voltage limits, maximum equipment overload, maximum power loss, maximum number of switch operations	Min weighted additive multicriteria function	Nonlinear MIP	Genetic algorithm	Generated	1 substation, 1 feeder, 133 buses
Garcia and França [26]	Multi-objective	Radiality, load limits, voltage drop limits, load balance	Min load not supplied Min number of switch operations	Linear MIP	Composite heuristic	Real (Brazil)	1 substation, 1057 nodes, 42 sectors, 1078 branches, 63 switches
Singh et al. [60]	Multi-objective	Radiality, load and voltage limits	Min power loss Min number of switch operations	Quadratic program	Sequential switch opening heuristic	Generated	2 feeders, 37 lines, 32 nodes, 5 tie switches
Lu et al. [44]	Multi-objective	Radiality, service hierarchy, load and voltage limits	Min weighted additive multicriteria function	Linear MIP	Ant colony optimization	Real (San Francisco, CA)	69 nodes, 74 lines, 5 loop lines
Huang and Taylor [33]	Multi-objective	Radiality, load and voltage limits	Min priority load unrestored Min total load unrestored Min curtailment of controllable load Min cost of switching operations	Nonlinear MIP	Genetic algorithm	Generated	1 substation, 69 buses, 7 laterals, 3 tie lines, 68 sectionalizing switches, 44 loads
Hossam-Eldin et al. [30]	Multi-objective	Radiality, load and voltage limits	Max total load restored Min number of switch operations	—	Simulated annealing	Generated	1 transformer, 4 feeders, 32 branches, 5 tie lines, 32 buses, 37 switches

binary variable equal to 1 if and only if switch k is closed. The decision process can be illustrated by a binary tree [49]. Each leaf of the tree is associated with a possible solution, not necessarily a feasible one. A solution is feasible if there is no overloading on any part of the system. If there is no feasible solution, than infeasible solutions form partial solutions and other routes are found to relieve the overload. Depending on the order of traversal of the tree, strategies such as best-first search [18,19,41], depth-first search [49,58,64,7] and breadth-first search [64,7] are used to guide the search. Wu et al. [73] proposed a breadth-first search on a decision tree where each node corresponds to a feasible switching option, involving one or more switching pairs, under the radiality constraint. In addition, since exhaustive search is impractical, decision rules based on specific knowledge about the restoration problem are usually introduced to prune the tree to avoid unnecessary search.

Heuristic approaches, based on decision rules employed by experienced operators, were also proposed to solve the service restoration problem. For example, Hsu et al. [31] developed a heuristic rule-based approach to help planners in the service area of Taipei City District Office of Taiwan Power Company in constructing feasible service restoration plans that satisfy radiality constraint and equipment loading limits. The configuration of the restored system should also conform to the original configuration. The objective is to restore as many customers as possible, as soon as possible, with as few switching actions as possible. Also, Shirmohammadi [59] described a heuristic search approach that combines heuristic rules and conventional programming methods for determining the minimum possible number of switching operations needed to restore service to isolated branches of a distribution feeder. The heuristic takes into account the radiality of the network, voltage limits, current rating, and feeder capacity limits. The heuristic was imbedded in a decision support system for use in operations planning of the Pacific Gas and Electric Company's distribution system in San Francisco, CA. Later, Ćurčić et al. [17] proposed a four-module heuristic search guided by expert knowledge to aid control operators in overcoming the outages. The heuristic, which can cope with simultaneous outages, observes radiality, loading and voltage constraints, and gives priority to important customers, such as hospitals, important communication plants, traffic signals, and industrial activities vital for city logistics, while avoiding conflict with the objective to restore as much out-of-service load demand as possible. However, loading and voltage constraints can be relaxed to achieve the stated objective. If necessary, the heuristic also crosses voltage levels in attempt to utilize all available spare loading capacity. In the first module, restoration in a single switching operation attempts to restore an out-of-service area by closing one switching device. If that is not possible, then the second module tries to restore as many nodes as possible. If even that is not possible, the third module attempts to increase available spare loading capacity of the supplying network elements by transferring their load to the neighboring network elements. When these three modules exhaust possibilities, the last module tries to restore supply to important customers, if any, by disconnecting some less important customers. The heuristic was tested on a UK real network with 534 nodes, 987 switching devices, and upto six simultaneous outages due to any fault type. The computation time necessary for reaching a restoration solution was always less than a minute, even for the case of six simultaneous outages.

Expert systems have also been developed to help planners for restoring service after a feeder fault occurrence. Such systems were described, for example, by Liu et al. [43], Srinivasan et al. [62] and Tsai [67].

2.2.2. Metaheuristics

A classical genetic search algorithm was used by Siqing et al. [61] to assist planners in the design of network reconfigurations for emergency distribution operations. The algorithm can deal with radiality and equipment loading constraints. In the binary string corresponding to a solution, each gene represents either an operating branch connecting nodes in the blackout area or a boundary branch, with one end of branch lying in the blackout area and the other end of branch lying in the area under normal conditions. A gene value is equal to 1 if the state of the branch concerned has changed, namely from 1 to 0 or from 0 to 1 (1 and 0 stand for the state of the branch: 1 = branch closed and 0 = branch opened). Otherwise, the gene value is equal to 0. The length of a chromosome equals the total number of operating and boundary branches. Every time a chromosome is generated, its cost is evaluated by calculating the value of a fitness cost function that takes into account the operation cost of operating branches, the load shedding power of the substations service territories, and the number of substations that can be restored. Load shedding refers to the reduction of a substation's peak load by turning off non-critical loads. The genetic algorithm was embedded in an expert system. Tests showed that the computation time increases rapidly with the number of operating branches.

Neural networks were used by Ruiz-Paredes and Dávalos [57] to solve a feeder reconfiguration problem after a fault occurrence. All feeders in the system are assumed to be radial. Operation restrictions such as power loss reduction, loading limits, voltage regulation, and the service hierarchy of the priority customers must be considered, while maximizing the amount of total load restored. A back-propagation neural network model, trained using network topologies and related load patterns, was used to reconfigure a small network. The model was embedded in a decision support system to help operators in reconfiguring distribution networks.

2.2.3. Multi-objective analysis

Some papers have addressed the inherently multiobjective nature of the emergency service restoration problem after a feeder fault occurrence. Lee et al. [39] applied the fuzzy logic technique to evaluate the quality of a given restoration plan. Matos and Melo [47] proposed a simulated annealing method for the reconfiguration of radial distribution networks and service restoration. The neighborhood structure defines a new candidate solution from the current one either by opening any branch or by closing a branch without violating the radiality of the network. To generate a set of compromising points between the number of switching operations and the power not supplied, the simulated annealing process is repeated for different numbers of switching operations, while maximizing the load not supplied. Recently, Singh et al. [60] proposed a sequential switch opening heuristic method for service restoration in distribution networks. The heuristic suggests the best strategy of restoration while satisfying the following requirements: minimum number of switching operations, radial structure of final network, no overloaded feeder and voltage limit violation, and minimum loss.

More algorithms have been developed in an attempt to restore as many customers as possible with as few switching operations as possible. For example, Popović and Ćirić [56] proposed a solution approach based on the concept of a local network to reduce the size of the problem. This network consists of the part of the network affected by the fault and a defined number of adjacent supporting feeders. Within the local network, a selection of high quality variants of alternate supply is made using a reconfiguration algorithm based on a decision tree. In a subsequent paper, Ćiric and Popović [15] extended the original approach to consider the case where no basic variant of the local network enables restoration of power supply without violation of the constraint set. In that case, the problem of determining the target configuration of the local network is formulated as a linear mixed integer programming model to minimize a single objective function involving switching costs and capacity of unserved energy, while considering limits on current and substation power, power balance constraints, and the maintenance of a radial structure. (We do not present the linear mixed integer programming model developed by Ćiric and Popović [15], but a more compact version of the model, proposed by Garcia and França [26], is presented hereunder). The model is solved using a software package for mixed integer programming. Results on real-life urban distribution systems consisting of 100–1000 nodes led to conclude that the approach is an efficient and robust tool for distribution network management. Also, Huang [32] addressed the problem of service restoration with multiple objectives with a fuzzy cause-effect network for minimizing a set of criteria, including the load not supplied and the number of switching operations. Finally, Garcia and França [26] proposed a multi-objective, linear mixed integer programming model, based on Ćiric and Popović [15]. The emergency service restoration problem is characterized by the occurrence of loads without power supply, leading to their disconnection from the energized network. Therefore, the problem can be represented as a forest graph, with one tree for the *light area*, composed of all the loads where the power supply has been maintained, and at least one other tree for the *black area*, including loads without power supply. The ideal case is to re-establish power supply for all loads in the black area. In this representation, arcs and nodes correspond to switches and loads, respectively. Source nodes are used to connect loads to the light area, while respecting the problem constraints. Fig. 5, taken from Garcia and França [26], illustrates the light and black areas, the source node and the linking arc for a hypothetical radial distribution system obtained after fault isolation.

Let B be the set of nodes. For every node $k\in B$, let z_k be a binary variable equal to 1 if and only if load k is energized, and let L_k represent the load of node k. For every node $k\in B$, define also v_k, V_k^{min}, and V_k^{max} as the voltage at node k, the minimum acceptable voltage drop at node k, and the maximum acceptable voltage drop at node k, respectively. Let F be the set of branches. For every branch $k\in F$, let x_k be a binary variable equal to 1 if and only if branch k is used, let y_k be a nonnegative real variable denoting the power flow in branch k, and define $I_{max}^{F_k}$ as the flow capacity at branch k. In order to avoid negative current branches, fictitious branches between each two nodes are introduced. For every branch $k\in F$, let x_k' be a binary variable equal to 1 if and only if fictitious branch k is used, and let y_k' be a nonnegative real variable denoting the power flow in fictitious branch k. Let $S\subset B$

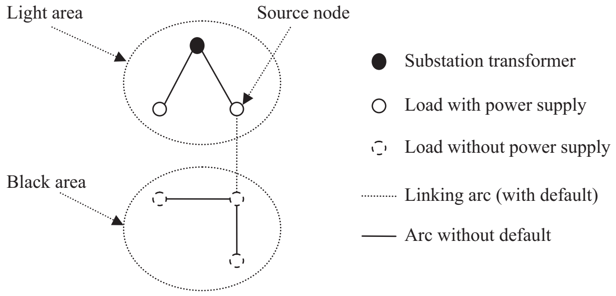


Fig. 5. Graph representation for a hypothetical radial distribution system [26].

be the set of source nodes in the network. For every source node $q \in S$, define G_q as the available power at source node q. Finally, for every node $i \in B$, let $F_i \subset F$ and $T_i \subset F$ be two sets of branches whose initial node and terminal node is node i, respectively. The formulation is given next.

$$\text{Minimize} \sum_{k \in F_{nc}} (1-x_k) + \sum_{k \in F_{nc}} (1-x'_k) + \sum_{k \in F_{no}} x_k + \sum_{k \in F_{no}} x'_k \tag{2.7}$$

$$\text{Minimize} \sum_{k \in B} (1-z_k) L_k \tag{2.8}$$

subject to

$$\sum_{k \in F_q} y_k \le G_q \quad (q \in S) \tag{2.9}$$

$$y_k - I_{max}^{F_k} x_k \le 0 \quad (k \in F) \tag{2.10}$$

$$y'_k - I_{max}^{F_k} x'_k \le 0 \quad (k \in F) \tag{2.11}$$

$$\left| V_k^{min} \right| \le |\upsilon_k| z_k \le \left| V_k^{max} \right| \quad (k \in B) \tag{2.12}$$

$$\sum_{k \in F_i} (y_k + y'_k) + \sum_{k \in T_i} (y_k + y'_k) \le L_i z_i \quad (i \in B) \tag{2.13}$$

$$\sum_{k \in T_i} (x_k + x'_k) \le 1 \quad (i \in B) \tag{2.14}$$

$$x_k, x'_k \in 0,1 \quad y_k, y'_k \ge 0 \quad (k \in F) \tag{2.15}$$

$$z_k \in 0,1 \quad (k \in B) \tag{2.16}$$

The first objective function (2.7) minimizes the number of switching operations involved, while the second objective function (2.8) minimizes the load not supplied. The two sets $F_{nc} \subset F$ and $F_{no} \subset F$ are the sets of switches which are normally closed and normally opened, respectively. Constraints (2.9) include substation limits. Constraints (2.10)–(2.12) refer to the branch and voltage drop limits, respectively. Power balance between supply and demand is addressed by constraints (2.13) and the radial configuration (acyclic graph) is guaranteed by constraints (2.14). Constraints (2.17) only permit the use of the real or of the fictitious branches. We note that constraints (2.17) are implied by the set of constraints (2.14).

$$x_k + x'_k \le 1 \quad (k \in F) \tag{2.17}$$

The problem is solved using a local search based heuristic. The constructive phase is carried out by a random version of the well-known Prim algorithm [1]. The local search phase tries to improve on the initial solutions by using a multiobjective search procedure, which generates neighbor solutions by changing the source node for each node in the black area. Numerical experiments performed on instances with upto 1057 nodes and 1078 branches showed that a variety of possible well distributed solutions throughout the Pareto front are obtained by considering the multiobjective nature of the problem.

Genetic algorithms, simulated annealing, and ant colony optimization have also been proposed to address the multiobjective nature of the service restoration problem. Such algorithms were described, for example, by Mun et al. [50], Manjunath and Mohan [46], Kumar et al. [36,37], Lu et al. [44], Huang and Taylor [33] and Hossam-Eldin et al. [30].

2.3. *Switching sequence models*

Very few solution methods have been proposed for the sequencing of switching operations to reach the reconfiguration given by the restoration plan. Most of them are composite heuristics [68,40] or adaptation of metaheuristics, such as genetic algorithms [52] and ant systems [70], that embed the adjacent pairwise interchange improvement heuristic. This improvement procedure attempts to improve any sequence of switching operations by interchanging two adjacent reconnections in order to reduce the length of the restoration period. Recently, Carvalho et al. [13] proposed the following mathematical formulation for the switching sequencing problem

$$\text{Maximize}\, f(S, \bar{o}) \tag{2.18}$$

subject to

$$(S, \bar{o}) \in F \cap E \tag{2.19}$$

$$S \in \Sigma \tag{2.20}$$

where f stands for the customer satisfaction function and Σ stands for the set of all possible switching operations that may turn the initial faulted configuration into the restored configuration.

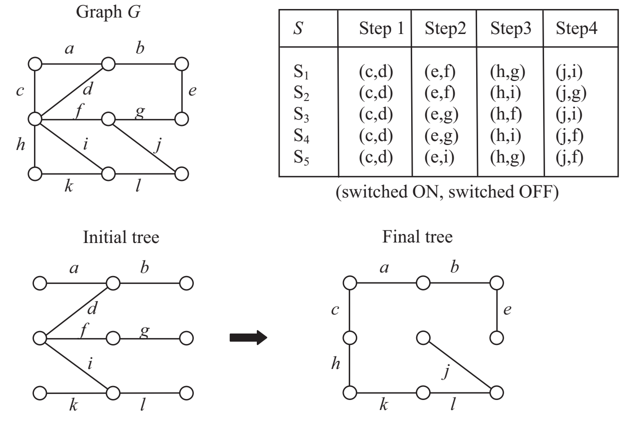
The distribution network topology consists in a graph G over which some opened switches define a radial configuration, i.e., a spanning tree. The pair $(S, \bar{o})$ is called a sequence of switching operations if S is a set of switching operations and $\bar{o}$ is an order to do the switching operations. The set F is the set of feasible sequences and E, the set of admissible sequences. The pair $(S, \bar{o})$ is said to be a feasible sequence if all networks generated by $(S, \bar{o})$ are spanning trees of graph G. The pair $(S, \bar{o})$ is said to be an admissible sequence if all networks generated by $(S, \bar{o})$ are electrically admissible. Fig. 6 illustrates two spanning trees and their graph. The table enumerates a few sets S from the possible sets of Σ that turn the initial tree into the final tree. Each step (a,b) corresponds to an exchange of an arc b by an arc a by one switched ON operation and another switched OFF operation. Recently, Sudhakar and Srinivas [63] described a methodology based on Kruskal's algorithm for the problem of finding an optimal switching sequence by considering the reliability of the entire distribution network even during varying load conditions. Table 3 provides a summary of the switching sequence models.

3. Repair vehicle routing, repair crew scheduling, and crew assignment models

Johns [34] proposed a set of heuristic approaches for scheduling emergency call-outs as and when they occur. The problem is modeled as a traveling salesman problem with time windows subject to uncertain demands. The heuristics produced good tours by sequencing visits on the basis of closeness to existing visits. Also, Weintraub et al. [71] developed a composite heuristic for the problem of assigning and routing repair vehicles for the electricity utility for the city of Santiago, Chile. The constructive step finds the initial routes using a "cluster first, route second" approach. The route of each vehicle is defined with an adaptation of the

GENI method proposed by Gendreau et al. [27] for the traveling salesman problem. Improvements in the solution are then sought through the balancing of workloads between vehicles. Comparisons with the actual operation of the emergency unit showed a 16% improvement in service quality and a 53% improvement under adverse climate conditions.

Xu et al. [76] proposed a stochastic integer program to identify the schedules of inspection, damage assessment, and repair under different earthquakes and damage states. Let J be the set of substations and L be the set of possible earthquakes (that together represent the full extent of the regional seismic hazard). For every possible earthquake $l \in L$, let M_l be the set of possible damage states associated with earthquake l. For every earthquake $l \in L$ and for every damage state $m \in M_l$, define p_{lm} as the probability that earthquake l and damage state m occur. For every earthquake $l \in L$ and for every substation $i \in J$, let d^I_{li} and d^D_{li} be two nonnegative real, random variables, with known probability distributions, representing the inspection and damage assessment durations, respectively, at substation i under earthquake l. Similarly, for every earthquake $l \in L$, for every substation $i \in J$ and for every damage state $m \in M_l$, let d^R_{lmi} be a nonnegative real, random variable representing the repair duration at substation i under earthquake l and damage state m and let e^R_{lmi} be a nonnegative real, random variable denoting the time required to repair substation i, after which time the substation can begin to transfer power to neighboring substations under earthquake l and damage state m. Let T be the set of periods. For every earthquake $l \in L$, for every substation $i \in J$ and for every period $t \in T$, let S^I_{lit} and S^D_{lit} be two binary variables equal to 1 if and only if inspection and damage assessment, respectively, start at substation i at period t under earthquake l. Similarly, for every earthquake $l \in L$, for every damage state $m \in M_l$, for every substation $i \in J$ and for every period $t \in T$, let S^R_{lmit} and S^F_{lmit} be two binary variables equal to 1 if and only repair starts and power is restored, respectively, at substation i at period t under earthquake l and damage state m. For every substation $i \in J$, define A_i as the set of substations adjacent to substation i. For every earthquake $l \in L$, for every damage state $m \in M_l$, for every substation $i \in J$ and for every substation $k \in A_i$, let y_{lmik} be a binary variable equal to 1 if and only if substation k is able to transfer power to substation I for the determined schedules of inspection, damage assessment, and repair. The formulation is given next.



S	Step 1	Step2	Step3	Step4
S_1	(c,d)	(e,f)	(h,g)	(j,i)
S_2	(c,d)	(e,f)	(h,i)	(j,g)
S_3	(c,d)	(e,g)	(h,f)	(j,i)
S_4	(c,d)	(e,g)	(h,i)	(j,f)
S_5	(c,d)	(e,i)	(h,g)	(j,f)

(switched ON, switched OFF)

Fig. 6. Example of two spanning trees, their graph and a few sets from the possible sets of Σ [13].

$$\text{Minimize} \sum_{l \in L, m \in M_l} p_{lm} \left(\sum_{i \in J} w_i \left(\sum_{t \in T} tE\left[S^F_{lmit}\right] \right) \right) \tag{3.1}$$

subject to

$$\sum_{t \in T} tS^I_{lit} + d^I_{li} \le \sum_{t \in T} tS^D_{lit} \quad (i \in J,\ l \in L) \tag{3.2}$$

$$\sum_{t \in T} tS^D_{lit} + d^D_{li} \le \sum_{t \in T} tS^R_{lmit} \quad (i \in J,\ l \in L,\ m \in M_l) \tag{3.3}$$

$$\sum_{t=1}^{\infty} tS^R_{lmit} + d^R_{lmi} \le \sum_{t \in T} tS^F_{lmit} \quad (i \in J,\ l \in L,\ m \in M_l) \tag{3.4}$$

$$\sum_{t \in T} S^I_{lit} = 1 \quad (i \in J,\ l \in L) \tag{3.5}$$

$$\sum_{t \in T} S^D_{lit} = 1 \quad (i \in J,\ l \in L) \tag{3.6}$$

$$\sum_{t \in T} S^R_{lmit} = 1 \quad (i \in J,\ l \in L,\ m \in M_l) \tag{3.7}$$

$$\sum_{t \in T} S^F_{lmit} = 1 \quad (i \in J,\ l \in L,\ m \in M_l) \tag{3.8}$$

$$\sum_{i \in J} \sum_{\tau = t - d^1_{li} + 1}^{t} S^I_{li\tau} \le NI \quad (l \in L,\ t \in T) \tag{3.9}$$

$$\sum_{i \in J} \sum_{\tau = t - d^D_{li} + 1}^{t} S^D_{li\tau} \le ND \quad (l \in L,\ t \in T) \tag{3.10}$$

$$\sum_{i \in J} \sum_{\tau = t - d^R_{lmi} + 1}^{t} S^R_{lmi\tau} \le NR \quad (l \in L,\ m \in M_l,\ t \in T) \tag{3.11}$$

Table 3
Characteristics of switching sequence models.

Articles	Problem characteristics	Objective function	Model structure	Solution method
Uçak and Pahwa [68]	Equipment overloads, service hierarchy	Min total restoration time and customer interruption duration	Single- machine scheduling	Composite heuristic
Lee and Park [40]	Radiality, load limits, load balance, service hierarchy	Min load not supplied	—	Composite heuristic
Oyama [52]	Radiality, load limits	Min equipment overloads, load not supplied, and number of switch operations	—	Genetic algorithm
Watanabe [70]	Radiality, load limits	Min power not supplied	Scheduling problem	Ant colony algorithm
Carvalho et al. [13]	Load and voltage limits, service hierarchy	Max customer satisfaction	Spanning tree	Dynamic programming
Sudhakar and Srinivas [63]	Voltage limits, loading constraints, radiality, line losses, priority of customers	Max power restored	Minimum spanning tree	Kruskal based-algorithm

$$\sum_{t\in T} tS^R_{lmkt} + e^R_{lmk} \le \sum\nolimits_{t\in T} tS^F_{lmit} + C(1-y_{lmik}) \quad (k\in A_i,\ i\notin P,\ l\in L,\ m\in M_l) \tag{3.12}$$

$$\sum_{k\in A_i} y_{lmik} \ge 1 \quad (i\notin P,\ l\in L,\ m\in M_l) \tag{3.13}$$

$$y_{lmik} = 1 \quad (i\in P,\ k\in A_i,\ l\in L,\ m\in M_l) \tag{3.14}$$

$$y_{lmik} + y_{lmki} \le 1 \quad (k\in A_i,\ i\notin P \ \text{ or } \ k\notin P,\ l\in L,\ m\in M_l) \tag{3.15}$$

$$d^I_{li}, d^D_{li}, d^R_{lmi} \ge 0 \quad (i\in J,\ l\in L,\ m\in M_l) \tag{3.16}$$

$$e^R_{lmi} \ge 0 \quad (i\in J,\ l\in L,\ m\in M_l) \tag{3.17}$$

$$S^I_{lit}, S^D_{lit}, S^R_{lmit}, S^F_{lmit} \in 0,1 \quad (i\in J,\ l\in L,\ m\in M_l,\ t\in T) \tag{3.18}$$

$$y_{lmik} \in 0,1 \quad (k\in A_i,\ i\in J,\ l\in L,\ m\in M_l) \tag{3.19}$$

The objective function (3.1) minimizes the average time each customer is without power, where w_i is the number of customers that receive power from substation i. Constraints (3.2)–(3.4) establish precedence among the inspection, damage assessment, and repair tasks for each substation. Constraints (3.5)–(3.8) establish that inspection, damage assessment, and repair must be completed for each substation under each earthquake and damage scenario. The repair also must be marked as finished at each substation. Constraints (3.9)–(3.11) ensure that the number of crews available for inspection (NI), damage assessment (ND), and repair (NR) are not exceeded during any time period. Constraints (3.12)–(3.15) relate to the connectivity and operation of the electric power network. P is the set of substations that are connected to generation stations and C is a large number. Constraints (3.12) indicate that substation i cannot be marked finished until at least one load bank in a substation k has been repaired. Constraints (3.13) require that at least one substation must transfer power to each substation not connected to a generation station. Constraints (3.14) require that all substations connected to a generation station can transfer power to the substations that are connected to them after their repairs are finished. Constraints (3.15) require that if substation i transfers power to substation k, then substation k cannot transfer power to substation i. Xu et al. [76] proposed a solution procedure using genetic algorithms to solve the repair crew scheduling problem. The quality of the crew schedules produced with the genetic algorithms was evaluated by running a discrete event simulation model described by Cağnan et al. [10] and Cağnan and Davidson [11].

Some models were proposed to assist electric utilities to locate and dispatch repair units (e.g., vehicles and crews) so as to restore distribution failures efficiently. For example, in addition to their goal programming model for crew assignment, Yao and Min [77] proposed two reliability planning models for simultaneously acquiring and locating resource depots and assigning repair crews to resource depots, where each repair unit is identical (e.g., a standard vehicle and crew). Also, Guha et al. [28] developed approximation algorithms for two versions of the crew assignment problem. The first version aims at maximizing the number of highest priority customers recovered in a single day. The second version requires a recovery of the whole network, i.e., connecting all disconnected customers, which may be a lengthy process that takes several days. The first case is modeled as a budgeted problem and the second variant as a minimum weighted latency problem. Guikema et al. [29] proposed a nonlinear mixed integer programming model for the assignment of inspectors, damage assessment crews, and repair crews to a set of potential locations in the case of an earthquake. Let S be the set of district locations. For each district location $j\in S$, let I_j, D_j, R_j be three nonnegative integer variables representing the number of inspectors, damage assessment crews, and repair crews trained to respond to location j, respectively; define β^I_J, β^D_J, β^R_J as the minimum number of inspectors, damage assessment crews, and repair crews at location j, respectively; and let α^I_J, α^D_J, α^R_J be the costs of one inspector, damage assessment crew, and repair crew at location j, respectively. The formulation for the crew assignment problem can be stated as follows:

$$\text{Minimize} \sum_{l,m} p_{lm} \left(\sum_i w_i E\left[T^F_{lmn}\right] \right) \tag{3.20}$$

Table 4
Characteristics of routing, scheduling, and assignment models.

Articles	Problem type	Problem characteristics	Objective function	Model structure	Solution method
Johns [34]	Vehicle routing	Repair time windows, stochastic repair requests	Min total distance	Traveling salesman problem	Constructive heuristics
Weintraub et al. [71]	Vehicle routing	Multiple vehicles, repair hierarchy, workload balance, stochastic repair requests	Min weighted total time of the routes	Traveling salesman problem	Composite heuristics
Xu et al. [76]	Crew scheduling	Maximum number of crews, precedence relationship	Min average time each customer is without power	Stochastic 0–1 IP	Genetic algorithm
Yao and Min [77]	Crew assignment	Crew demands	Min delays and costs	Goal programming	Software package Lindo
Guha et al. [28]	Crew assignment	Service hierarchy, maximum number of repairmen, number of repairmen required for each fault	(1) Max highest priority customers restored (2) Min weighted customer latency	(1) Budgeted problem (2) Minimum weighted latency problem	Approximation algorithms
Guikema et al. [29]	Crew assignment	Minimum number of crews, crew training budget	Min average time each customer is without power	Nonlinear MIP	Genetic algorithm
Wu et al. [72]	Combined crew and vehicle scheduling	Repair hierarchy, repair resources limits, crew and vehicle priorities	Min time of power interruptions	—	Fuzzy-rule based algorithm
Wu et al. [75]	Combined crew scheduling and crew assignment	Repair time windows, number of repairmen required for each fault, and workload balance	Min amount of outage loading and repair completion time	—	Genetic algorithm

subject to

$$\sum_{j \in S} \left(\alpha_j^I I_j + \alpha_j^D D_j + \alpha_j^R R_j \right) \le B \tag{3.21}$$

$$I_j \ge \beta_j^I \quad (j \in S) \tag{3.22}$$

$$D_j \ge \beta_j^D \quad (j \in S) \tag{3.23}$$

$$R_j \ge \beta_j^R \quad (j \in S) \tag{3.24}$$

$$I_j, D_j, R_j \ge 0 \text{ and integer} \quad (j \in S) \tag{3.25}$$

The objective function (3.20) minimizes the average time each customer is without power, where p_{lm} is the probability that earthquake l and damage state m occur, w_i the number of customers supplied by substation i, and T_{lmn}^F the time at which power is restored at substation i at iteration n of the simulation model for earthquake l and damage state m. Constraint (3.21) assures that the total amount spent on training crews does not exceed the available budget B. Constraints (3.22)–(3.24) limit the crew allocations to those that meet the minimum allowable crew levels at each location. The model is solved using a genetic algorithm and the crew assignments produced are evaluated by running a discrete event simulation model [10,11].

Computerized systems have also been developed to help utility distribution planners in making vehicle routing, repair crew scheduling, and crew assignment decisions for emergency distribution operations. Such systems were described, for example, by Biletsky et al. [8], Carstens and Bruffy [12], Lubkeman and Julian [45] and Wu et al. [72,75]. Table 4 summarizes the characteristics of vehicle routing, crew scheduling, and crew assignment models.

4. Conclusions

This paper is the second part of a two-part survey of optimization models and solution algorithms for emergency response problems related to electric distribution operations. It addresses emergency service restoration, switching sequencing, repair vehicle routing, repair crew scheduling, and crew assignment models for electric distribution operations. (The first part of the survey discusses reliability planning models with fault considerations related to electric distribution operations.)

Emergency service restoration problems are the most studied of any distribution emergency response problems. Because of the inherent difficulties of these problems, most solution methods that have been proposed are heuristics. Early models were generally solved with simple composite methods that often neglected to incorporate the inherently multiobjective nature of the service restoration problem. Later research generally focused on the design of more sophisticated local search techniques (e.g., composite methods and metaheuristics) to tackle multiobjective problems. Lagrangian relaxation and dynamic programming have also been applied to the restoration of distribution systems after a blackout [53,54]. However, the use of operations research methodologies for emergency distribution response problems is still in its infancy. Even though recently proposed models were tested on realistic data instances, few of them have been applied in practice. As highlighted by Lindenmeyer [42], power system restoration problems are of a combinatorial nature, and their solution is often based on the operator's knowledge and experience. Consequently, it is not surprising that most of the research work that has been done in the area of system restoration has focused on the development of knowledge-based systems, such as expert systems and fuzzy expert systems. Knowledge-based systems cannot optimize the design of network reconfigurations, but the heuristic rules used certainly contain information about good designs. In this situation, where optimal designs are seek and large amounts of expert knowledge exist, it is often beneficial to combine optimization techniques and expert rules into a hybrid optimization method. The hybrid systems proposed by Fukuyama et al. [25] and Wu et al. [74] are good examples of hybrid optimization methods. Knowledge-based systems can also be used to generate initial solutions in an attempt to improve the performance of local search techniques.

In addition to the development of hybrid optimization methods, the development of more mathematical formulations is crucial to reveal problem structures that may be used to develop fast heuristic algorithms producing good approximate solutions. Most proposed models include some of the elementary but essential characteristics of emergency distribution response problems. Therefore, more realistic models can be formulated by relaxing, for example, some of the simplifying assumptions (e.g., repair units are no longer identical). Another interesting line of research would be the further development of compound models that address the integration of various decisions in emergency distribution response. (For example, coupling more closely the crew assignment model proposed by Guikema et al. [29] with the crew scheduling model developed by Xu et al. [76] could provide better results.) Models that integrate multiple interdependent subcomponents of the contingency planning process can significantly help to maintain certain quality limits related to frequency and duration of interruptions and reduce financial losses for electric distribution utilities.

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