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Abstract. This is the last 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.

Keywords. Electric power distribution, emergency response, service restoration, operations research.

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Introduction

This is the last 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 preparedness for distribution networks. Reliability planning in the context of emergency distribution response includes determining distribution substation single-fault capacity, reallocating excess load, configuring distribution systems, partitioning a geographical area into service territories or districts, and locating material stores and depots. Most commonly, decisions concerning the design of more reliable and robust distribution networks in which fault cases are taken into account belong to the strategic planning level, while contingency decisions related to the management of the emergency response logistics resources belong to the real-time planning level.

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. (2000). Reliability planning problems with fault considerations for emergency response logistics in electric distribution systems were reviewed in the first part of the survey (Perrier et al., 2010).

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. 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. A more detailed review on distribution systems, their function, components, characteristics, and operations is presented in the books by Brown (2002) and Willis et al. (2001).

1.1. Emergency distribution operations

After a fault occurring on a distribution system, a sequence of *emergency distribution operations* to be taken follows: fault diagnosis, fault location, fault isolation, restoration, and repair. For each fault, this sequence generates a set of system operating states characterized by sectionalizing and protection devices placed at strategic locations so that the connection between two line segments within the distribution feeder can be opened or closed, with corresponding customers being energized or interrupted. Certain devices are locally controlled on feeders and can remotely be operated. Crews are used to operate other devices. Each fault may impact many different customers in different ways. In general, depending on how the system is configured by sectionalizing and protection devices and how long the fault takes to repair, the same fault can result in momentary interruptions for some customers and varying lengths of sustained interruptions for other customers.

Real-time control and operation of distribution systems are performed by system operators located in dispatch centers. Each operator or dispatcher is assigned a region to monitor and coordinate. 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.

After the fault has been cleared, the system can be reconfigured to isolate the fault and restore power to some customers. 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. Radial distribution systems are characterized by having only one path between each consumer and a substation. Consequently, in radial systems the protection devices generally take out of service not only the faulted network element, but a much larger number of non-faulted service sections. 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. However, since the switch is manual, restoration may not occur for an hour or more. In general, choosing automated switching restores fewer customers in a very short time, within minutes or less, after a fault occurs, and choosing manual switching restores more customers, but within a longer period of time. Most distribution feeder systems either have no automated switches or are partially automated with a combination of manual and automated switches. After switching is accomplished, the crew repairs the fault in the *repair step* and, when finished, returns the system to its normal state.

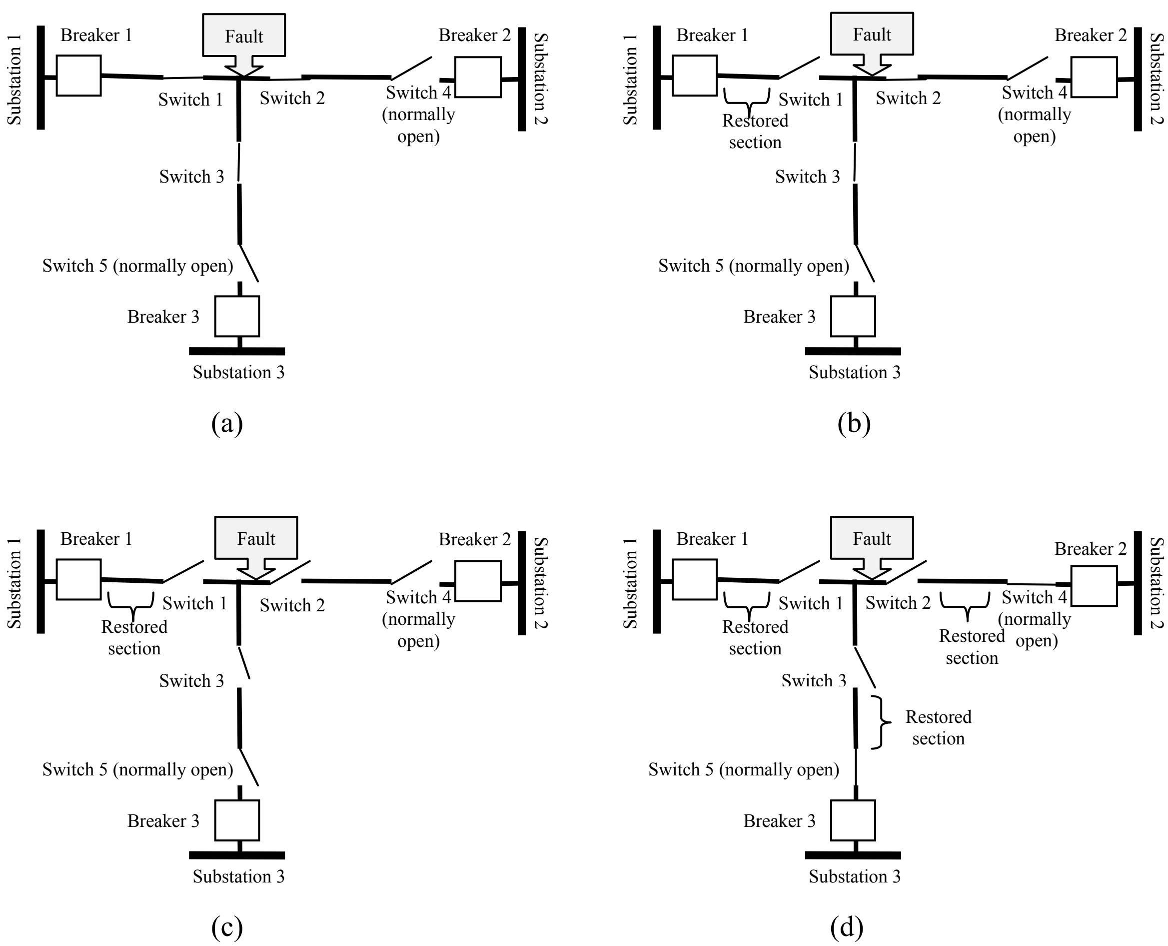


Figure 1. Sequence of emergency distribution operations after a fault: (a) Fault location. (b) Upstream restoration. (c) Fault isolation. (d) Downstream restoration.

To illustrate the sequence of switching operations, consider a fault occurring on the system represented on Figure 1a, taken from Brown (2002). 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 (Figure 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 (Figure 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 (Figure 1d). The entire switching sequence is called *system reconfiguration*. After the fault is repaired, the crew returns the system to its normal state.

The following sections describe contingency planning problems of emergency distribution response that have been addressed by operations research techniques. Contingency planning problems concern 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 resource depots.

1.2. Emergency service restoration problems

The *restoration problem* consists of reconfiguring temporarily a distribution system by transferring the loads in the out-of-service area to neighbouring 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. Furthermore, remotely controlled switching devices should be prioritized over manually operated switching devices in order to reduce the implementation time. 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. Such customers include hospitals, traffic signal plants, communication centres, nurseries and schools, public centres, embassies and industrial plants. 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. In the normal state, the network can be reconfigured for two purposes: to minimize electrical losses due to the electric resistance of any device and to keep load balance of all elements of the network as equal as possible to prevent a fault occurrence. However, loss minimization and load balancing requiring additional switching operations are usually neglected during the restoration period.

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. 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 in distribution systems are a matter of observing the quality of the electrical energy supply. These constraints are usually expressed in terms of permitted voltage drop since lowering voltage can significantly reduce system demand. However, excessive low voltages can cause motors to overheat and lead to customer complaints. 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. In case of emergency, overload protection is ensured by the settings of the protection devices. 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. Relaxing loading constraints during emergencies typically permits to exceed the limitations set on expected loading during normal regime. For example, Kim et al. (1992) consider overloading the transformers up to 133% of their rated capacity. Some utilities set the overloading protection to even higher than 133%, but such a level of overloading can only be allowed for a very short time, well below the usual length of the restoration period, to avoid damaging consequences. Also, although restoration with relaxed voltage constraints leads to electricity supply of poor quality, several authors believe that this is acceptable during emergencies (Ćurčić et al., 1996). 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 in order to make such operations 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. Also, the switching order should give priority to the switching operations that restore more customers or highest priority customers, if any.

1.3. 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 for repair 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 can be repaired, which is possibly dependant on the hierarchy of the network. 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, 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. Furthermore, depending on the requirements of the tasks, some crews having specific technical licenses may be prioritized. The number of continuous working hours and the experience of the crews can also be concerned. 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

The emergency service restoration problem consists in minimizing the number of customers faced with an interruption of power delivery by transferring them to supporting feeders via network reconfiguration and in accordance with their importance, while satisfying topological and electrical constraints such as radial design, equipment emergency ratings and low voltage constraints.

Emergency service restoration models can be classified into two categories according to the type of network element fault considered: substation fault and feeder fault. The type of faulted network element determines the number of customer service interruptions, a faulted distribution substation transformer resulting in a larger number of customers experiencing service interruptions than a faulted distribution feeder. More importantly, the type of faulted network element also determines the number and type of supporting network elements, and thus, the problem size and the solution method. 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.

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

Composite methods construct a starting reconfiguration and then attempt to find a better reconfiguration by performing a sequence of switch exchanges. A switch exchange consists of selecting a pair of switches, one for opening and the other for closing, in order to improve the reconfiguration.

One of the first contributions dealing with the emergency restoration problem is due to Aoki et al. (1987). Given a single fault occurrence at a substation transformer resulting in service interruptions, 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 Figure 2, adapted from Aoki et al. (1987). 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.

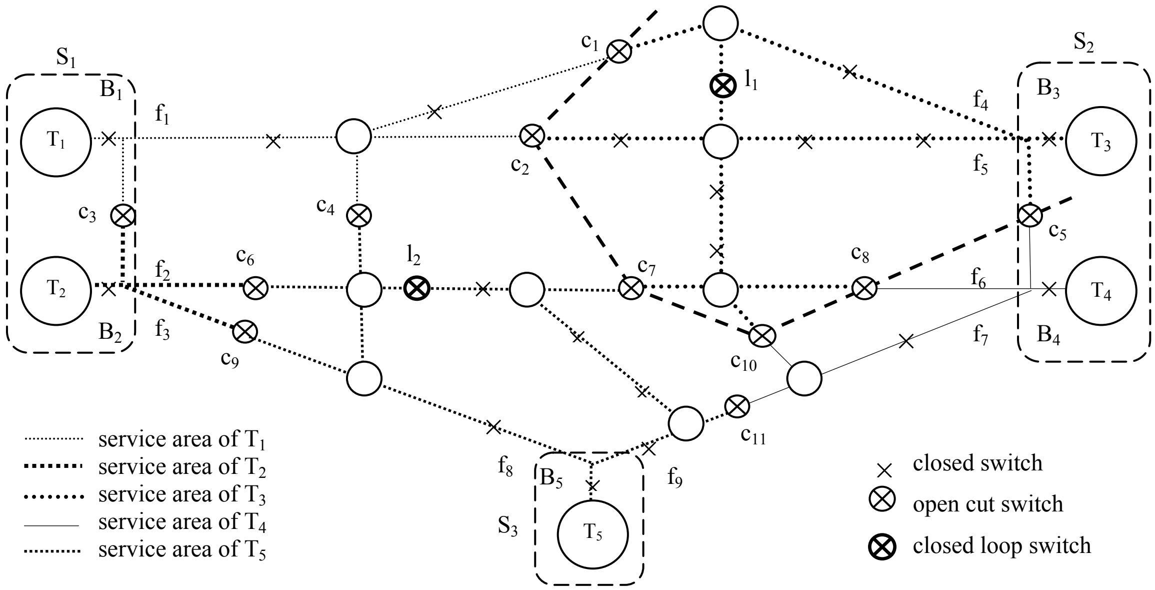


Figure 2. Example of radial distribution system

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 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

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

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

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

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

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 this model 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 model (2.1)-(2.5). Although the authors assume that a fault occurs on a transformer, the load transfer algorithm can also be applied to the case where a fault occurs on a distribution feeder. The algorithm includes a switch exchange procedure to increase the transferable loads. Also, the minimum capacity allowance can be increased by moving the opened position of loop switches. 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 can not 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. Each transformer for load transfer is selected considering capacity allowance of transformers and feeders, geographical distance between substations, characteristics of the system and flexibility of the switching operation. For example, in Figure 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. Then, the transformer T_1 or T_2 follows. 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 reallocated loads in a few seconds. Aoki et al. (1988a) 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. (1988b) 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,

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

assure that the voltage drop limits are respected at only the end switches of the feeders, where $s_{iq} = a_{iq}$ if $q \neq l$ 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 at only the end switches of the feeders. For example, for the system in Figure 1, voltage drop checks are needed at both sides of the switches c_1, c_2,..., c_{11}, l_1 and l_2. To solve the extended model (2.1)-(2.6), the authors developed an effective gradient method similar to the primal methods for the solution of knapsack problems. Successive load transfer is applied between pairs of transformers until the outage is restored. The criterion for selecting a transformer, to which the load of out-of-service is transferred, is maximum capacity allowance. Again, the method, which was tested on transformer fault cases in the large-scale real system from the city of Hiroshima in Japan, can also deal with feeder faults.

Aoki et al. (1989) 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. However, by using radiality of the feeders, the feeder/transformer capacity constraints are simplified. In fact, these constraints are assumed to be observed only at the roots of the branches where the diameters of the wires change. 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 tried to be 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. (1988b) 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 (1989) 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. Certain rules are introduced to significantly reduce the number of paths leading to each load point after a substation fault. For example, since it is realistic to assume a maximum of five switching operations for restoring the supply to each deenergized load point, paths containing more than five opened switches can be ignored. Then, the set of possible restoration procedures is determined by combining the available paths leading to each load point. Again, the combinations of paths may be reduced by exploiting the topology of the system. Finally, 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. Chen et al. (1989) 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 an implicit enumeration, a special branch-and-bound procedure for integer programs with only binary variables.

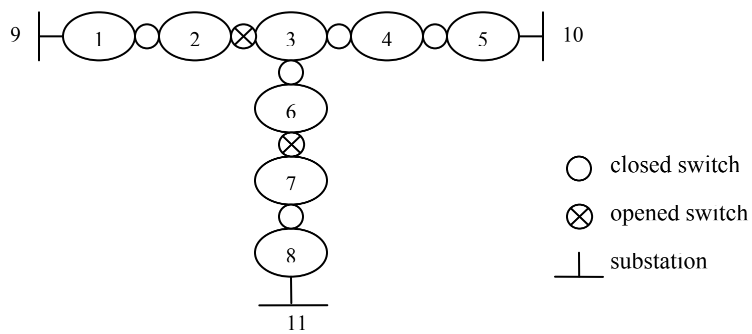
The search ends when the iteration count exceeds the maximum iteration limit. The heuristic was tested on real data from the Taiwan Power Company. The authors also suggested an algorithm to determine the switching operations required to isolate the faulted sections.

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. (1988) 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. (1992) 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 both distribution dispatch center 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. (1992) proposed an expert system to help planners at a Japanese electric power company determine the optimal switching operation sequence for load rerouting during substation or feeder fault restoration, emergency operation overload relieving and network maintenance planning. Knowledge base rules, classified in the order of priority of their application to satisfy some topological and electrical constraints, are used to select the load rerouting pattern that minimizes the number of switch operations. More recently, Van Harte and Atkinson-Hope (2002) 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. Tests showed that the model was useful in analyzing a variety of scenarios related to the modification of monthly feeder loading profiles.

2.1.2 Metaheuristics

In a major departure from composite methods which terminate at a local optimum, three types of metaheuristics that we are aware of have been applied to the restoration of service after a substation fault: genetic algorithms, tabu search and simulated annealing. These solution methods allow intermediary deteriorating and even infeasible reconfigurations in the course of the search process, so as to identify better local optima than with composite methods.

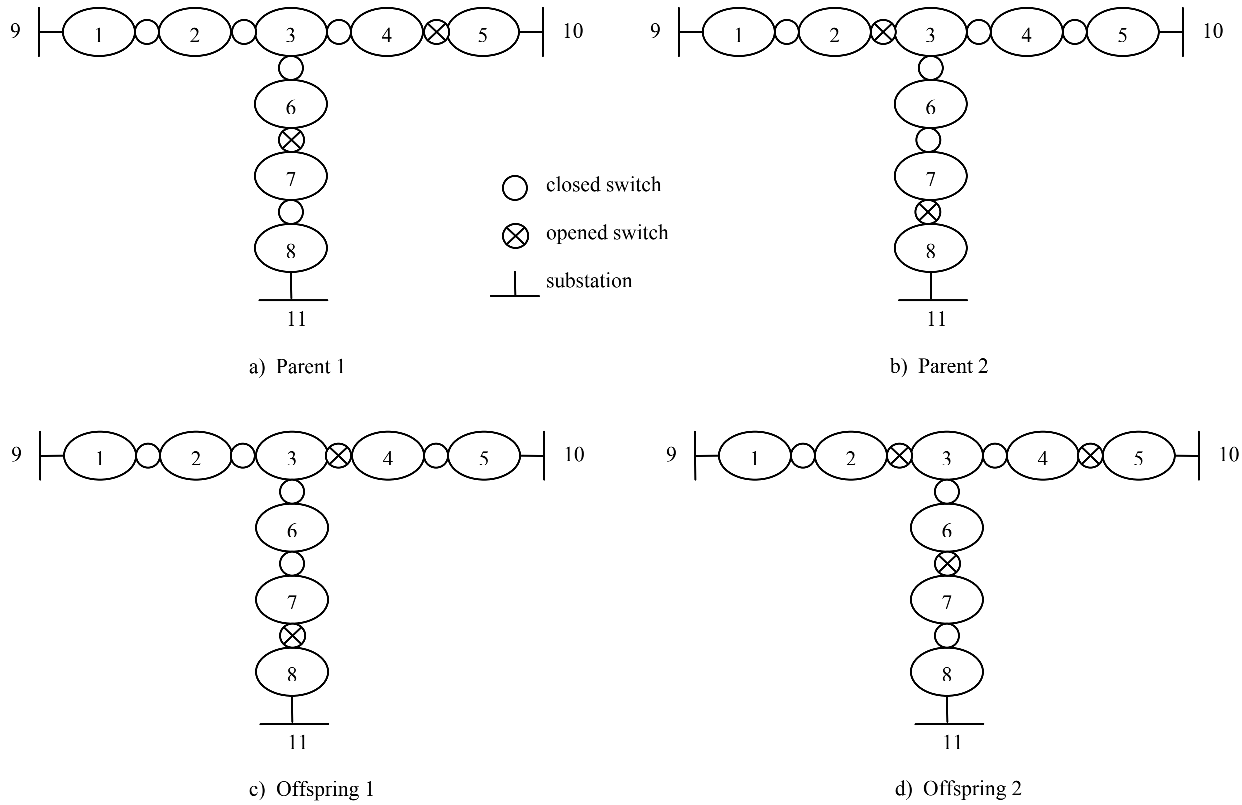
Fukuyama et al. (1996a) developed a parallel genetic algorithm for solving a service restoration problem in electric power distribution systems. The objective is to restore as much load as possible after a substation fault occurrence by transferring deenergized loads via network reconfigurations to other supporting distribution feeders without violating the radiality constraint, equipment loading limits and voltage limits. The parallel genetic algorithm performs several genetic algorithms in parallel in order to search various solution spaces of the problem. 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 neighbouring load point closer to the substation supplying that particular point. The length of a string equals the number of load points. For example, Figure 3 illustrates the representation of a service restoration solution in a radial distribution system (Fukuyama et al., 1996a).



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

Figure 3. Example of a service restoration solution in a radial distribution system

Specialized crossover and mutation operators must be developed to produce new offspring sequences. For example, Figure 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 string operation. Moreover, a penalty function is introduced to avoid generating strings violating the loading and voltage limits. 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 Figure 1 a), only load points 4, 5, 6 and 7 can mutate. Computational tests performed on instances with up to 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, were imbedded in a hybrid system (Fukuyama et al., 1996b).



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

Figure 4. One-point crossover

Ferreira et al. (2001) proposed specific evolutionary-based algorithms to search for optimal reconfigurations, following a main substation fault in radial networks, so as to maintain 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 minutes.

Finally, a few researchers have addressed the inherently multiobjective nature of the restoration problem with substation fault. Toune et al. (1998) 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. In each iteration of the four metaheuristic methods proposed, neighbouring solutions are generated by changing the power source direction of one load point in the current network configuration. The opened position of at least two switches has to be moved for changing the direction of power source of one load point. Again, the radiality constraint limits the selection of the load points at which the direction of power source can be changed to the load points next to an opened switch. For example, power source direction of load points 4, 5, 6 and 7 can be changed in the network configuration of Figure 4a. (For details, see Fudo et al., 2000 and Toune et al., 2002). 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. (1998) 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, to maximize the amount of total load restored and to minimize the number of switching operations. A discrete variable is associated with each network switch status. A second set of continuous variables is used to represent the network voltages and current flows. The four-step heuristic prioritizes the objectives as follows : first, the restoration of as much priority load as possible; second, the restoration of as much total load as possible; and third, the use of a minimal number of switches. During the search process, if overload and voltage violations occur, the overload violations are addressed first. The first step 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. If multiple out-of-service areas exist, the heuristic is applied sequentially to each area starting with the areas containing the most priority load, followed by areas with the largest amount of total load. The local search heuristic appears as robust as an exhaustive search method, but significantly faster. Finally, Augugliaro et al. (2001) suggested a method that combines fuzzy sets with genetic algorithms in the consideration of two criteria: minimization of load supplied and minimization of power losses.

Articles	**Problem type**	**Problem characteristics**	**Objective function**	**Model structure**	**Solution method**
Aoki et al. (1987)	Single-objective	Radiality and load limits	Max total load restored	Knapsack problems	Composite heuristic
Aoki et al. (1988a)	Single-objective	Radiality, load limits and voltage drop limits	Max total load restored	Knapsack problems	Gradient method
Aoki et al. (1988b)	Single-objective	Radiality, load limits and load balance	Max total load allocated	Knapsack problems	Composite heuristic
Aoki et al. (1989)		Radiality, load limits, voltage drop limits and load balance	Max total load allocated	Knapsack problems	Four-stage heuristic
Dialynas et al. (1989)	Single-objective	Radiality, load and voltage drop limits	Min number of switch operations	—	Heuristic search
Chen et al. (1989)	Single-objective	Radiality, equipment overloads and load balance	Min feeder overloading and unbalance	Linear 0-1 IP	Implicit enumeration
Okuda et al. (1988)	Single-objective	Radiality, service hierarchy, load limits	Min power failure duration	—	Composite heuristic
Kim et al. (1992)	Single-objective	Radiality, voltage violations, load limits, load balance, service hierarchy	Min number of switch operations	Binary decision tree	Best-first search
Fujii et al. (1992)	Single-objective	Equipment overloads and voltage drop limits	Min number of switch operations	—	Composite heuristic
Van Harte and Atkinson-Hope (2002)	Single-objective	Voltage drop limits and equipment overloads	Min customer interruptions	Simulation model	Scenario analysis
Fukuyama et al. (1996a,b)	Single-objective	Radiality, load limits and voltage limits	Min out-of-service load and load unbalance	—	Genetic algorithm
Ferreira et al. (2001)	Single-objective	Radiality, equipment overloads and voltage violations	Min out-of-service load	—	Evolutionary-based algorithm
Toune et al. (1998)	Multi-objective	Radiality, load and voltage limits	Max load balance and lowest voltage level	Nonlinear P	Metaheuristics
Miu et al. (1998)	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
Augugliaro et al. (2001)	Multi-objective	Radiality, service hierarchy, equipment overloads and voltage limits	Max load supplied Min power losses	—	Fuzzy sets and genetic algorithm

Table 1. Characteristics of substation fault models

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 binary variable equal to 1 if and only if switch k is closed. The decision process can be illustrated by a binary tree as shown in Figure 5. 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 more than one feasible solution exists, then the one that offers the largest loading margin is chosen unless other compelling factors need to be considered. If there is no feasible solution, than infeasible solutions form partial solutions and other routes are found to relieve the overload.

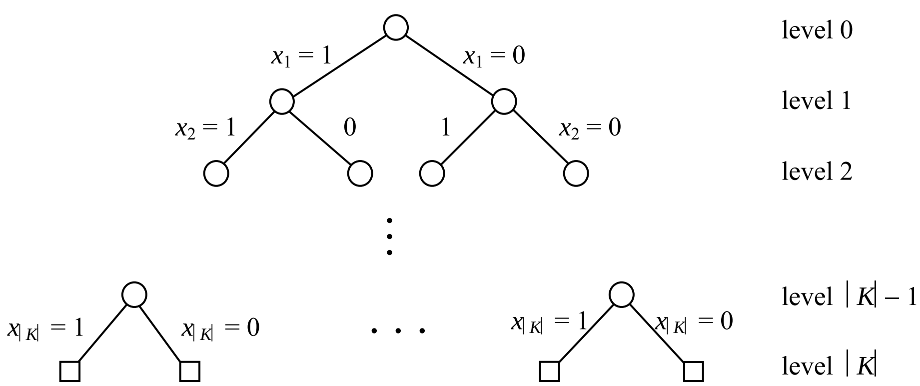


Figure 5. Binary decision tree

Any decision variable that corresponds to a closed switch in the initial configuration (after fault isolation) can be used to generate a subdivision. Depending on the order of traversal of the tree, strategies such as best-first search (Devi et al., 1990, 1991), depth-first search (Morelato and Monticelli, 1989; Sarma et al., 1990; Sudhakar et al., 2004) and breadth-first search (Sudhakar et al., 2004) are used to guide the search. Wu et al. (1991) 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. (1992) 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 (1992) 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. A limit on the number of switching operations can also be specified by the operator. However, if the size of load to be restored is too large or the specified limit on the number of switching operations is too small, loading and voltage limits can be violated, but such violations are restricted to the shortest branches in the network. 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. (1997) 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 neighbouring 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 real UK network with 534 nodes, 987 switching devices and up to 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. The authors proposed to use the heuristic as an effective tool in training and in establishing network reconfigurations for maintenance work and in assisting system security analyses.

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. (1988) and Srinivasan (1994).

2.2.2. Metaheuristics

We are aware of three types of metaheuristics that have been applied to the restoration of service after a feeder fault: genetic algorithms, neural network and simulated annealing. These three classes of metaheuristics are reviewed in this section and the following section.

A classical genetic search algorithm was used by Siqing et al. (1998) 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). If the state of the branch has not changed, then 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. Classical crossover and mutation operators are used to produce new offsprings from parents. The genetic algorithm was embedded in an expert system. Tests showed that the computation time increases rapidly with the number of operating branches. The authors thus conclude that parallel genetic algorithm should be adopted to reduce the computation time.

Neural networks were used by Ruiz-Paredes (1998) 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 backpropagation neural network model, trained using network topologies and related load patterns, is 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

Recent papers have addressed the inherently multiobjective nature of the emergency service restoration problem after a feeder fault occurrence. Lee et al. (1998) applied the fuzzy logic technique to evaluate the preference degree of a given restoration plan. A restoration plan is considered preferred if it involves less switching operations, less number and smaller amount of the load transfer, and its resultant configuration has a higher contingency preparedness, better load balance and higher level of protection coordination. Matos and Melo (1999) proposed a simulated annealing method for the reconfiguration of radial distribution networks and service restoration. Overloads, voltage drops and deviations out of the maximum number of switching operations are penalized in a cost function that maximizes the load supplied. The neighbourhood 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.

Many 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 (1999) 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 defined local network, a selection of high quality variants of alternate supply is made using a reconfiguration algorithm based on a decision tree. Each variant is then ranked according to the following criteria: power amount of the un-serviced load, switching operation costs, critical power reserve of the supply transformer, critical current reserve of the feeder, critical voltage drop and reliability. In a subsequent paper, Ćirić and Popović (2000) 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 in a scenario which considers 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 Ćirić and Popović (2000), but a more compact version of the model, proposed by Garcia and França (2008), 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 to 1000 nodes led to conclude that the approach is an efficient and robust tool for distribution network management. Also, Huang (2003) 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. These criteria are converted into a single objective function by giving relative weighting values for each criterion. The analytical hierarchy process technique is employed to help the operators assess the associated weighting factor of each objective.

Finally, Garcia and França (2008) proposed a multiobjective, linear mixed integer programming model, based on Cirić and Popović (2000), which considers the minimization of the load not supplied and of the number of switching operations, while respecting radial network configuration, equipment and voltage drop limits. The model is based on a graph representation of a radial distribution system. 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. Figure 6, taken from Garcia and França (2008), illustrates the light and black areas, the source node and the linking arc for a hypothetical radial distribution system obtained after fault isolation.

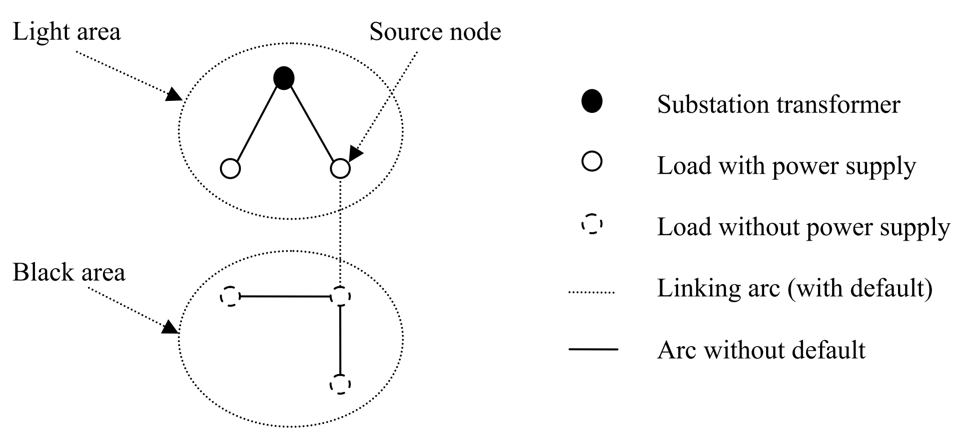


Figure 6. Graph representation for a hypothetical radial distribution system

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 $I_{\max}^{Fk}$ as the flow capacity at branch k. In order to avoid negative branch currents, 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 $S \subset B$ 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

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

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

$$y_k^{'} - I_{\max}^{F_k} x_k^{'} \le 0 \qquad (k \in F) \tag{2.11}$$

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

$$\sum_{k \in F_i} \left(y_k + y_k^{'} \right) + \sum_{k \in T_i} \left(y_k + y_k^{'} \right) \le L_i z_i \qquad (i \in B) \tag{2.13}$$

$$\sum_{k \in T_i} \left(x_k + x_k^{'} \right) \le 1 \qquad (i \in B) \tag{2.14}$$

$$x_k + x_k^{'} \le 1 \qquad (k \in F) \tag{2.15}$$

$$x_k, x_k^{'} \in \{0,1\}, y_k, y_k^{'} \ge 0 \qquad (k \in F) \tag{2.16}$$

$$z_k \in \{0,1\} \qquad (k \in B) \tag{2.17}$$

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), (2.11) and (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 (2.15) only permit the use of the real or of the fictitious branch. 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 (Ahuja et al. 1993). The local search phase tries to improve on the initial solutions by using a multiobjective search procedure, which generates neighbour solutions by changing the source node for each node in the black area. Numerical experiments performed on instances with up to 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 have also been proposed to address the multiobjective nature of the service restoration problem. Such algorithms were described, for example, by Mun et al. (2001) and Manjunath and Mohan (2007). However, these authors consider a weighted additive multicriteria function. In an attempt to emphasize the convenience of considering the service restoration problem as a truly multiobjective problem, not requiring weighting factors to convert the multiobjective function into an equivalent single objective function, Kumar et al. (2006, 2008) proposed a non-dominated sorting genetic algorithm to solve the multiobjective service restoration problem for minimizing power losses, the load not supplied, and the number of switching operations. Results based on the simulation studies carried out in four different systems showed that the genetic algorithm proposed by Kumar et al. (2006, 2008) was superior to a genetic algorithm requiring weighting factors.

Articles	**Problem type**	**Problem characteristics**	**Objective function**	**Model structure**	**Solution method**
Liu et al. (1988)	Single-objective	Radiality, load and voltage limits	Max number of customers with a restored service	—	Composite heuristic
Morelato and Monticelli (1989)	Single-objective	Radiality, load and voltage limits	Min load unbalance	Binary decision tree	Depth-first search
Sarma et al. (1990)	Single-objective	Radiality, load and voltage limits	Min number of switch operations	Decision tree	Depth-first search
Devi et al. (1990, 1991)	Single-objective	Equipment overloads and load balance	Min number of switch operations	Binary decision tree	Best-first search
Wu et al. (1991)	Single-objective	Radiality, equipment overloads and load balance	Min number of switch operations	Decision tree	Breadth-first search

Articles	Problem type	Problem characteristics	Objective function	Model structure	Solution method
Hsu et al. (1992)	Single-objective	Radiality and load limits	Min number of switch operations	—	Composite heuristic
Shirmohammadi (1992)	Single-objective	Radiality, voltage limits violations, maximum number of switch operations and equipment overloads	Min number of switch operations	—	Composite heuristic
Srinivasan (1994)	Single-objective	Load and voltage drop limits	Min number of switch operations	—	Composite heuristic
Ćurčić et al. (1997)	Single-objective	Radiality, service hierarchy, loading and voltage limits	Max out-of-service load demand restored	—	Composite heuristic
Sudhakar et al. (2004)	Single-objective	Radiality and load limits	Min number of switch operations and power losses	Binary decision tree	Breadth and depth-first search
Siqing et al. (1998)	Single-objective	Radiality and load limits	Min number of switch operations	—	Genetic algorithm
Ruiz-Paredes (1998)	Single-objective	Radiality, service hierarchy, load and voltage limits, loss reduction	Max load supplied	—	Neural network
Lee et al. (1998)	Multi-objective	Load limits, voltage drop limits, load balance, similarity to the existing configuration	Multi-objective	Multiple criteria	Fuzzy logic
Matos and Melo (1999)	Multi-objective	Radiality, load limits and voltage drop limits	Min number of switch operations Min load not supplied	Nonlinear MIP	Simulated annealing
Popović and Ćirić (1999)	Multi-objective	Radiality, load and voltage limits, similarity to the existing configuration	Multi-objective	Multiple criteria	Composite heuristic
Ćirić and Popović (2000)	Multi-objective	Radiality, load and voltage limits	Min weighted additive multicriteria function	Linear MIP	Composite heuristic
Mun et al. (2001)	Multi-objective	Radiality, load balance, load limits and voltage drop limits	Min weighted additive multicriteria function	Nonlinear MIP	Genetic algorithm
Huang (2003)	Multi-objective	Load limits	Min weighted additive multicriteria function	Multiple criteria	Fuzzy cause-effect algortihm
Kumar et al. (2006, 2008)	Multi-objective	Radiality, load and voltage limits	Min load not supplied Min number of switch operations Min power losses	Nonlinear MIP	Genetic algorithm
Manjunath and Mohan (2007)	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
Garcia and França (2008)	Multi-objective	Radiality, load limits, voltage drop limits, load balance	Min load not supplied Min number of switch operations	Linear MIP	Composite heuristic

Table 2. Characteristics of feeder fault models

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 (Uçak and Pahwa, 1994; Lee and Park, 1996) or adaptation of metaheuristics, such as genetic algorithms (Oyama, 1996) and ant systems (Watanabe, 2005), 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. (2007) proposed the following mathematical formulation for the switching sequencing problem:

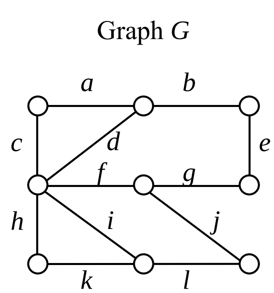
$$\text{Maximize} \quad f\left(S,\bar{o}\right) \tag{2.18}$$

subject to

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

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

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.



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)

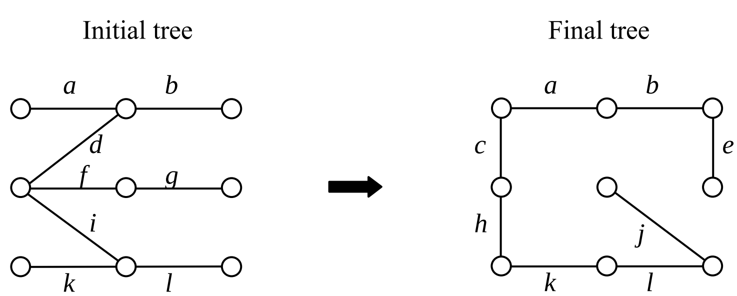


Figure 7. Example of two spanning trees, their graph and a few sets from the possible sets of Σ

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*, ō) is called a sequence of switching operations if *S* is a set of switching operations and ō 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*, ō) is said to be a feasible sequence if all networks generated by (*S*, ō) are spanning trees of graph *G*. The pair (*S*, ō) is said to be an admissible sequence if all networks generated by (*S*, ō) are electrically admissible. Figure 7 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.

The model is solved with a dynamic programming approach to sequence the switching operations in order to maximize customer satisfaction without intermediate network operational violations. Table 3 provides a summary of the switching sequence models.

Articles	**Problem characteristics**	**Objective function**	**Model structure**	**Solution method**
Uçak and Pahwa (1994)	Equipment overloads, service hierarchy	Min total restoration time and customer interruption duration	Single- machine scheduling	Composite heuristic
Lee and Park (1996)	Radiality, load limits, load balance, service hierarchy	Min load not supplied	—	Composite heuristic
Oyama (1996)	Radiality, load limits	Min equipment overloads, load not supplied and number of switch operations	—	Genetic algorithm
Watanabe (2005)	Radiality, load limits	Min power not supplied	Scheduling problem	Ant colony algorithm
Carvalho et al. (2007)	Load and voltage limits, service hierarchy	Max customer satisfaction	Spanning tree	Dynamic programming

Table 3. Characteristics of switching sequence models

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

Very little work has been accomplished concerning the routing of repair vehicles, the scheduling of repair crews and the assignment of crews to repair sites in the context of emergency response logistics in electric distribution systems.

Vehicle routing problems related to emergency distribution operations are generally formulated as node routing problems. A book on the vehicle routing problem was edited by Toth and Vigo (2001). Due to the difficulty of these problems, heuristic procedures have been developed. For example, Johns (1995) 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. (1999) 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. (1992) for the traveling salesman problem. Improvements in the solution are then sought through the balancing of workloads between vehicles. The heuristic also incorporates knowledge of future possible random demands and service priorities according to the urgency of breakdowns. 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. (2007) 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. 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_{li}^{I} and d_{li}^{D} 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_{lmi}^{R} be a nonnegative real, random variable representing the repair duration at substation i under earthquake l and damage state m and let e_{lmi}^{R} 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 neighbouring substations under earthquake l and damage state m. Let T be the set of periods. For every for every earthquake $l \in L$, for every substation $i \in J$ and for every period $t \in T$, let S_{lit}^{I} and S_{lit}^{D} 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_{lmit}^{R} and S_{lmit}^{F} 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.

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

subject to

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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

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 (3.2)-(3.4) require, respectively, that for substation i, damage assessment can only begin after inspection is completed, repair can only begin after damage assessment is completed, and the substation can only be marked as finished after repair is completed. These precedence constraints are all stochastic because each is a function of random variables. 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. (2007) 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 Cagnan et al. (2006) and Cagnan and Davidson (2007).

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 (1998) 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. (1999) 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. The two cases are considered for general networks as well as for trees and bipartite networks. Guikema et al. (2006) 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 so as to minimize the average time each customer is without power, while respecting the available crew training budget and the minimum allowable crew levels at each location. 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_J^{I}, β_J^{D}, β_J^{R} as the minimum number of inspectors, damage assessment crews, and repair crews at location j, respectively; and let α_J^{I}, α_J^{D}, α_J^{R} 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:

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

subject to

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

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

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

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

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

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 in 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 (Cagnan et al., 2006; Cagnan and Davidson, 2007).

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. (2004), Carstens and Bruffy (2005), Lubkeman and Julian (2004) and Wu et al. (2004). Finally, Khan Mohammadi et al. (2000), Banan et al. (2005) and Khan Mohammadi et al. (2006) developed fuzzy decision-making procedures to assist planners in scheduling power distribution between different regions during emergency conditions. Table 4 summarizes the characteristics of vehicle routing, crew scheduling and crew assignment models.

Articles	**Problem type**	**Problem characteristics**	**Objective function**	**Model structure**	**Solution method**
Johns (1995)	Vehicle routing	Repair time windows, stochastic repair requests	Min total distance	Traveling salesman problem	Constructive heuristics
Weintraub et al. (1999)	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. (2007)	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 (1998)	Crew assignment	Crew demands	Min delays and costs	Goal programming	Software package Lindo
Guha et al. (1999)	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. (2006)	Crew assignment	Minimum number of crews, crew training budget	Min average time each customer is without power	Nonlinear MIP	Genetic algorithm
Wu et al. (2004)	Combined crew and vehicle scheduling	Repair hierarchy, repair resources limits, crew and vehicle priorities	Min time of power interruptions	—	Fuzzy-rule based algorithm

Table 4. Characteristics of routing, scheduling and assignment models

4. Conclusions

This paper is the last 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. The service restoration step requires to decide the opened or closed status of all system switches. Over the years, many algorithms have been developed in an attempt to restore as many customers as possible with as few switching actions as possible. 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 emergency 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. As mentioned by Brown (2002), metaheuristics, however, can be problematic to apply to radial structure reconfiguration problems, since most of the generated switch position combinations can not represent feasible solutions. Furthermore, generating a new radial tree structure for each combination of switch positions can become computationally intensive. These problems can, however, be avoided by using an improvement method making small changes in the radial structure, one at a time, by closing a normally opened switch and opening a nearby upstream switch.

However, the use of operations research methodologies for emergency distribution response problems is still in its infancy. As highlighted by Lindenmeyer (2000), 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 system, using expert system and genetic algorithm, proposed by Fukuyama et al. (1996b) is a good example of a hybrid optimization method. 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, several extensions based on these models are possible. For example, by relaxing some of the simplifying assumptions (e.g., repair units are no longer identical), more realistic models can be formulated. 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. (2006) with the crew scheduling model developed by Xu et al. (2007) can 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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