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Models and Methods for Emergency Response Logistics in Electric Distribution Systems

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Abstract

Emergency response operations in electric distribution systems involve a host of decision-making problems at the reliability, performance monitoring and evaluation, and contingency planning levels. Those operations include fault diagnosis, fault location, fault isolation, restoration, and repair. The aim of this paper is to provide a comprehensive survey of optimization models and solution methodologies for reliability and contingency planning problems related to electric distribution operations. Reliability planning models address the determination of distribution substation capacity, the configuration of distribution systems, the partitioning of a geographical area into service territories or districts, and the location of material stores and depots. Contingency planning models 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.

Keywords: Electric distribution systems; Emergency planning; Service restoration; Operations research.

1 Introduction

Emergency response logistics in electric distribution systems presents a variety of decision-making problems that can be grouped into a number of categories according to the planning horizon which is concerned. The *reliability planning level* involves strategic planning decisions related to the design of more reliable and robust distribution networks which fault cases are taken into account. The planning horizon for reliability issues is usually around five years [1]. Decisions related to distribution substation capacity planning, distribution system configuration and the establishment of service centers and service territories or districts may be viewed as strategic. The *performance monitoring and evaluation planning level* is related to short term planning decisions, and generally involves the seasonal adjustment of emergency response logistics resources and the performance monitoring of the emergency actions based on statistical information on the demand, supply and performance of the emergency response mechanism. Finally, decisions related to real-time management of the emergency response logistics resources belong to the *contingency planning level*. For example, the assignment of service calls to emergency response units and the routing of emergency response units could be termed real-time.

The aim of this paper is to provide a comprehensive survey of optimization models and solution methodologies for reliability and contingency planning for emergency distribution operations. The field of fault diagnosis, fault location and fault isolation will not be treated here but we instead refer the interested reader to recent review by Lazzari et al. [2]. The paper is organized as follows: Section 2 describes the operations of emergency distribution response and the decision problems related to those operations. Section 3 describes models for the configuration of reliable distribution networks with fault considerations. Next, Section 4 reviews models dealing with the restoration of service and the sequencing of switching operations in distribution systems. Section 5 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 paths in distribution emergency response planning are presented in the last section.

2 Electric Distribution Systems

Distribution systems deliver power from bulk power systems to retail customers. To do this, distribution substations receive power from the transmission grid and step down voltages with power transformers. These transformers supply *primary distribution systems* made up of many distribution *feeders*, typically overhead distribution lines mounted on wooden poles or underground buried or ducted cable sets that deliver power from distribution substations to *distribution transformers*. Passing through these transformers, power is lowered in voltage once again, to the final utilization voltage and routed to the *secondary system* within very close proximity to the consumer or directly to the consumers. Usually, each transformer serves a small radial network of secondary and service lines of utilization voltage. These lead directly to the meters of consumers in the immediate vicinity. The following section contains a brief description of electric distribution operations. A more detailed review on distribution systems, their function, components, characteristics, and operations is presented in the book by Brown [3].

2.1 Emergency Distribution Operations. After a fault occurring on a distribution system, a generalized sequence of *emergency distribution operations* to be taken 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. 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. After the fault has been cleared, the system can be reconfigured to isolate the fault and restore power to certain customers. In the *fault isolation* step, the faulted network element is isolated so that neighbouring elements can perhaps be taken back into service and the faulted element repaired in subsequent steps. 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 system is referred to as the normal state when all customers are adequately supplied within acceptable voltage tolerances, all components are operating properly, the system is configured in its usual manner, and equipment loading levels are within design limits. 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 were made. This reconfiguration is performed by sectionalizing devices, such as switches, dividing each feeder. After switching is accomplished, the crew repairs the fault in the *repair step* and, when finished, returns the system to its normal state.

2.2 Decision Problems in Distribution Emergency Response. This section describes reliability planning problems and contingency planning problems of emergency distribution response that have been addressed by operations research techniques. Reliability planning problems include determining distribution substation capacity, configuring distribution systems, partitioning a geographical area into service territories or districts, and locating material stores and depots. 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.

The planning of electric distribution reliability with fault considerations involves decisions related to the configuration of more reliable and robust distribution networks so as to maintain power supply in fault situations (see Section 3). At the most basic level, reliability strategies dealing with faults address the determination of distribution substation single-fault capacity and the reallocation of excess load demand to substations. In many large electric utilities, a substation's capacity is determined based on the maximum load it can handle during emergencies. One emergency policy widely used among large electric utilities, called the *single-fault policy*, allows a single transformer fault among the substations of a service area at any given time. More involved reliability strategies, in which fault cases are considered, concern the reconfiguration of the system by addition of new feeders, substation transformers, or substations. Reliability plans with fault considerations can also help to partition a geographical area into emergency repair districts. The *district design problem* consists of partitioning a large service area into non-overlapping small subareas, called *districts*, according to several criteria such as contiguity, size and workload. The contiguity criterion requires that districts do not include distinct parts separated by other districts. Also, to balance the level of service offered to the customers across districts, they are often approximately the same size and are balanced in workload, i.e. districts are assigned equivalent emergency repair resources. Finally, reliability plans with fault considerations can help to locate resource depots. A resource depot is a place where resources for restoring the electric power in a locality are stored. These resources include poles, transformers, repair crews and vehicles. The depots may be different, i.e. the types of the resources and the amount of each type of resources in each depot may be different. The *resource depot location problem* consists of simultaneously selecting the proper sites to allocate different depots with resource capacities, and determining the amounts of the resources shipped from the depots to various geographically scattered locations or customers in order to satisfy the demands of the customers, while minimizing the total transportation cost for the power restoration.

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 (see Section 4). 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 resistance to the flow of electricity of any electrical device and to keep load balance of network elements 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. A radial structure is characterized by having only one path between each consumer and a substation. 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. During the restoration step, the capacity of the supporting network elements is normally used to the limit. To ensure that the restoration will not cause further outages, the supporting network elements must not be overloaded. 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. [4] 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.

In order to change the initial faulted configuration into the reconfiguration given by the restoration plan, a set of switching operations has to be sequenced. 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 (see Section 4). Also, the switching order process should give priority to the switching operations that restore more customers or highest priority customers, if any.

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 5). 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 cable 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. To *balance the workload* across vehicles, they have often approximately the same number of repair requests, travel and repair times. 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 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.

3 Reliability Planning Models

A summary of reliability planning models is presented in Table 1. Most works on reliability planning problems with fault considerations usually proposed models of special structure: linear programming (P), mixed integer programming (MIP) or binary integer programming (0-1 IP). Also, largely due to the nature of the single-fault policy, there are strong interactions between the determination of substation load capacity, the permanent reallocation of excess load, the installation of new feeders, and the addition of substation transformers. In an effort to integrate these closely interrelated decisions into a single decision scheme, Khator and Leung [5] proposed a heuristic approach for the combined problem of substation capacity planning, load reallocation, feeder configuration and transformer configuration. The approach, which is based on the four models proposed by Leung et al. [6], Sarada et al. [7] and Leung et al. [8], also integrates a substation transformer configuration model with no fault consideration developed by Leung and Khator [9].

Papers	Problem type	Problem characteristics	Objective function	Model structure	Solution method
[1,10, 11]	District design	Contiguity, balanced districts, maximum district sizes, and fixed number of districts	Min total demand-weighted distance	Linear P	Heuristic
[12]	System configuration	Radiality, voltage drops and loading limits	Min equipment installation costs	Linear MIP	Heuristic
[6]	Substation single-fault capacity	Equipment overloads and voltage drops	Max substation load and total demand supplied	Linear P	MPS mathematical programming
[6]	Substation load reallocation	Loading and voltage limits	Min total load reallocated	Linear P	MPS mathematical programming
[7]	Feeder configuration	Voltage ratings and loading limits	Min feeder costs and load transfer costs	Linear MIP	Branch-and-bound
[8]	Substation transformer configuration	Equipment overloads and voltage drops	Min transformer opportunity costs, purchase costs, transport costs, disassembly costs and installation costs	Linear 0-1 IP	MPS mathematical programming
[13]	Material depot location	Resource supplies, restoration time, maximum material levels and material demands	Min store costs, outage costs, material costs, personnel costs and equipment costs	Probabilistic P	No solution method
[14]	Resource depot location	Different depots, multiple resources, depot capacities and customer demands	Min transport costs	Nonlinear MIP	Heuristic

TABLE 1. Characteristics of reliability planning models

4 Emergency Service Restoration 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 three categories: composite methods, adaptation of metaheuristics and multi-objective analysis. The characteristics of the contributions are summarized in Table 2. 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. Also, we are aware of three types of metaheuristics that have been applied to the restoration of service after a substation fault: genetic algorithms (GA), tabu search (TS) and simulated annealing (SA). These solution methods allow deteriorating and even infeasible intermediary reconfigurations in the course of the search process, so as to identify better local optima than composite methods. Finally, a few researchers have addressed the inherent multiobjective nature of the restoration problem with substation fault.

Papers	**Problem type**	**Problem characteristics**	**Objective function**	**Model structure**	**Solution method**
[15]	Single-objective	Radiality and load limits	Max total load allocated	Knapsack problems	Composite heuristics
[16,17]	Single-objective	Radiality, load limits and voltage drop limits	Max total load allocated	Linear 0-1 IP	Dual effective gradient
[18]	Single-objective	Radiality, load limits, voltage limits and load balance	Max total load allocated	Linear 0-1 IP	Composite heuristics
[19]	Single-objective	Radiality, service hierarchy, load limits	Min power failure duration	No model	Composite heuristics
[20]	Single-objective	Radiality, load and voltage drop limits	Min duration of switch operations	Shortest paths	Composite heuristic
[21]	Single-objective	Radiality, equipment overloads, load balance, voltage limits	Min number of switch operations	Linear 0-1 IP	Branch-and-bound
[1]	Single-objective	Radiality, voltage violations, load limits, load balance, service hierarchy	Min number of switch operations	Binary decision tree	Best-first search
[22]	Single-objective	Equipment overloads and voltage drop limits	Min number of switch operations	No model	Composite heuristics
[23]	Single-objective	Radiality, load limits, voltage limits and load balance	Min out-of-service load	No model	GA
[24]	Multi-objective	Radiality, service hierarchy, load and voltage limits	Max priority load restored Max total load restored Min number of switch operations	Nonlinear MIP	Composite heuristics
[25]	Multi-objective	Radiality, load and voltage limits, similarity to the existing configuration	Multi-objective	Multiple criteria	Composite heuristics
[26]	Multi-objective	Radiality, load and voltage limits	Min weighted additive multicriteria function	No model	TS
[27]	Single-objective	Radiality, equipment overloads and voltage violations	Min out-of-service load	No model	Evolutionary-based algorithms
[28]	Multi-objective	Radiality, equipment overloads and voltage limits	Max load supplied Min power losses	Nonlinear P	Fuzzy sets and GA
[29]	Single-objective	Voltage drop limits and equipment overloads	Min customer interruptions	No model	Simulation
[30]	Single-objective	Radiality, load and voltage limits	Max load balance and lowest voltage level	Nonlinear IP	GA, SA, TS

TABLE 2. Characteristics of substation fault models

Heuristic procedures for the restoration of service after a fault on an overhead feeder component can be divided into four classes: composite methods, adaptation of metaheuristics (GA, TS, neural networks (NN), and SA) and multi-objective analysis. Table 3 provides a summary of the contributions. Most composite methods that have been proposed involve a heuristic search on a binary decision tree where the status of each switching device is set to 0 or 1 (closed or open). Depending on the order of traversal of the tree, strategies such as best-first search, depth-first search and breadth-first search are used to guide the search. 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.

Papers	**Problem type**	**Problem characteristics**	**Objective function**	**Model structure**	**Solution method**
[31]	Single-objective	Radiality, load and voltage limits	Max number of customers with a restored service	No model	Composite heuristics
[32]	Single-objective	Radiality, load and voltage limits	Min load unbalance	Binary decision tree	Depth-first search
[33]	Single-objective	Radiality, load and voltage limits	Min number of switch operations	Shortest paths	Depth-first search
[34,35]	Single-objective	Equipment overloads and load balance	Min number of switch operations	Binary decision tree	Best-first search
[36]	Single-objective	Radiality, equipment overloads and load balance	Min number of switch operations	Decision tree	Breadth-first search
[37]	Single-objective	Radiality and load limits	Min number of switch operations	No model	Composite heuristics
[38]	Single-objective	Radiality, voltage limits violations, maximum number of switch operations and equipment overloads	Min number of switch operations	No model	Composite heuristics
[39]	Single-objective	Load and voltage drop limits	Min number of switch operations	No model	Composite heuristics
[40]	Single-objective	Radiality, load limits and voltage drop limits	Min out-of- service loads and load unbalance	No model	Genetic algorithm
[41]	Single-objective	Radiality and load limits	Min number of switch operations	No model	GA
[42]	Multi-objective	Load limits, voltage drop limits, load balance, similarity to the existing configuration	Multi-objective	Multiple criteria	Fuzzy logic
[43]	Single-objective	Radiality, load and voltage limits	Max load balance and lowest voltage level	Nonlinear IP	TS
[44]	Single-objective	Radiality, service hierarchy, load and voltage limits, loss reduction	Max load supplied	No model	NN
[45]	Multi-objective	Radiality, load limits and voltage drop limits	Min number of switch operations Min load not supplied	Nonlinear MIP	SA
[46]	Multi-objective	Radiality, load and voltage limits	Multi-objective	Linear MIP	Composite heuristics
[47]	Multi-objective	Radiality, load limits and voltage drop limits	Min weighted additive multicriteria	Nonlinear MIP	GA

Papers	Problem type	Problem characteristics	Objective function	Model structure	Solution method
			function		
[48]	Multi-objective	Load limits	Min weighted additive multicriteria function	Multiple criteria	Fuzzy cause-effect algortihm
[49]	Single-objective	Radiality and load limits	Min number of switch operations and power losses	Binary decision tree	Breadth and depth-first search
[50,51]	Multi-objective	Radiality, load and voltage limits	Min load not supplied Min number of switch operations Min power losses	Nonlinear MIP	GA
[52]	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	GA
[53]	Multi-objective	Radiality, load limits, voltage drop limits, load balance	Min load not supplied Min number of switch operations	Linear MIP	Composite heuristics

TABLE 3. Characteristics of feeder fault 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 or adaptation of metaheuristics (GA and ant systems) that embed the adjacent pairwise interchange improvement heuristics. 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. Table 4 provides a summary of the switching sequence models.

Papers	Problem characteristics	Objective function	Model structure	Solution method
[54]	Equipment overloads, service hierarchy	Min total restoration time and customer interruption duration	Single-machine scheduling	Composite heuristics
[55]	Radiality, load limits, load balance, service hierarchy	Min load not supplied	No model	Composite heuristics
[56]	Radiality, load limits	Min equipment overloads, load not supplied and number of switch operations	No model	GA
[57]	Radiality, load limits	Min power not supplied	Scheduling problem	Ant colony algorithm
[58]	Load and voltage limits, service hierarchy	Max customer satisfaction	Spanning tree	Dynamic programming

TABLE 4. Characteristics of switching sequence models

5 Routing, Scheduling and Assignment Models

Vehicle routing problems related to emergency distribution operations are generally formulated as node routing problems. A book on the subject was edited by Toth and Vigo [59]. Due to the difficulty of these problems, heuristic procedures have been developed. In addition to their goal programming model for crew assignment, Yao and Min [60] proposed two reliability planning models for simultaneously acquiring and locating resource depots and assigning repair crews to resource depots. The quality of the crew schedules and assignments produced with the genetic algorithms developed by Xu et al. [61] and Guikema et al. [62] was evaluated by running a discrete event simulation model described by Cagnan et al. [63] and Cagnan and Davidson [64]. Table 5 summarizes the characteristics of vehicle routing, crew scheduling and crew assignment models.

Papers	**Problem type**	**Problem characteristics**	**Objective function**	**Model structure**	**Solution method**
[65]	Vehicle routing	Multiple vehicles, repair hierarchy, workload balance, stochastic repair requests	Min weighted total time of the routes	Traveling salesman problem	Composite heuristics
[66]	Vehicle routing	Repair time windows, stochastic repair requests	Min total distance	Traveling salesman problem	Constructive heuristics
[61]	Crew scheduling	Maximum number of crews, precedence relationship	Min average time each customer is without power	Stochastic 0-1 IP	Genetic algorithm
[67]	Combined crew and vehicle scheduling	Repair hierarchy, repair resources limits, crew and vehicle priorities	Min time of power interruptions	No model	Fuzzy-rule based algorithm
[60]	Crew assignment	Crew demands	Min delays and costs	Goal programming	Software package Lindo
[62]	Crew assignment	Minimum number of crews, crew training budget	Min average time each customer is without power	Nonlinear MIP	Genetic algorithm
[68]	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

TABLE 5. Characteristics of routing, scheduling and assignment models

6 Conclusions

This paper has presented a review of optimization models proposed for solving reliability and contingency planning problems in electric distribution systems. 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 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. However, the use of operations research methodologies for emergency distribution response problems is still in its infancy. 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. Another interesting line of research would be the further development of compound models that address the integration of various decisions in emergency distribution response. 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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