J. Webster (ed.), *Wiley Encyclopedia of Electrical and Electronics Engineering*

POWER SYSTEM RESTORATION

The continuous supply of electricity is the primary criterion measuring the quality of services offered by an electric utility company. Service unavailability substantially affects the convenience and the economic well-being of consumers. Service unavailability can be reduced by deploying higher-quality equipment, which will demonstrate longer mean time between failures, or by designing the power distribution network in such a way that a service disruption will affect a minimum number of customers (1) and by designing efficient service restoration operations for major and minor events. Such a reduction of service unavailability for a single event leads to the reduction of the mean annual down time (*MADT*), which is commonly used as an annual measure of quality and reliability in power utilities.

Bulk power systems are generally highly reliable, but a combination of unforeseen circumstances can lead to a wide loss of power. This loss is usually caused by transient faults and mainly originates in the transmission systems. Most of these faults are cleared by protective systems (i.e., relays and breakers), but some produce permanent effects that may lead to partial or complete loss of power.

Restoration refers to a series of operations in which the facility that has experienced a fault is repaired and the power system is restored to the status that prevailed before the power failure occurred. In restoration we often include the separation of the facility that has experienced the fault from the system to minimize interruption to power supply. In this article we adopt system operation concepts and describe the procedures undertaken from the time the determination of which facility has experienced the fault is made to the final restoration of power.

Restoration of a power system following a complete or partial blackout is a complex, stressful, and time-consuming task. The cooperation of several people is required. System dispatchers need to coordinate with power plant operators to make sure that the generating units with startup capabilities are started in the right sequence and that the right transmission paths are identified to provide power to other non-black-start units, ensuring in the meantime that the system remains stable. To achieve this it is necessary to follow strict guidelines so that there is minimum or no damage to equipment, no instabilities, and minimum transients. These guidelines need to take into account several system constraints, availability of equipment, synchronization, and strict timing.

Intersystem assistance is also necessary, especially for those utilities that do not have sufficient generation capabilities. After a blackout such a utility will rely on its neighboring utilities for supplying of power to restore customer loads. Even utilities with sufficient generation capability may use tie-line assistance to expedite the restoration process or to guard against any unexpected contingencies in which crucial units fail to start (2).

Other problems associated with power restoration relate to the communications and preparation aspects of the problem (3). A dispatcher receives a large number of alarms, which may be critical or noncritical. Preventing alarm backlog is a difficult task that needs to be done carefully so that correlated alarms can become one single alarm and alarms that are noncritical could at a first pass be ignored. There must also be sufficient capability of communication between the different stakeholders of a service restoration operation. Contingency plans should include a well-designed telecommunication system as well as the necessary means of physical communication between the different locations, vehicles, and personnel.

Automatic computerized techniques to achieve a successful restoration have been widely proposed in the literature of power system restoration. In recent years considerable interest has been shown in applying digital computers for power distribution system planning and control. The development and application of new methods and computational techniques in the field of computer-based distribution automation must satisfy the increasingly demanding requirements of distribution system monitoring and operation. These requirements are dictated by such factors as the growing size and complexity of the distribution networks, the use of a large number of installed apparatus, the supply of a large scope of customers (industrial, commercial, residential, agricultural), and, above all, the need to ensure that the power distribution system as a whole is operated and controlled in the most effective, secure, and economical manner possible. The last factor mentioned is given particular emphasis by the present trend toward the control of distribution systems from digital computer centers. As distribution systems increase in complexity, decisions must be made quickly and safely. It is extremely important to achieve rapid restoration of supply and speedy return to normal operating conditions following a system equipment fault or other system abnormality. Computational design procedures have been proposed for assisting the distribution system engineer in sorting through the alternative designs for the expansion planning for all or a large portion of the system. However, relatively little has been done in the area of automatic restoration and rearrangement of the distribution system following a system abnormality and making maximum utilization of equipment.

A complete optimization model of the restoration procedure from the mathematical point of view usually results in a mixed integer, multiobjective, multistage, nonlinear optimization problem with a large number of constraints. Expert systems techniques have also found wide applicability since they can express the experience of operators and be easily adapted to the particulars of a certain power utility.

In this article we present the service restoration process and its problems as they apply in bulk power restoration and distribution system restoration. We then present the tools used for optimizing these procedures as well as the protective systems that allow for a more efficient restoration exercise. Finally, we look at the organization of restoration operations from the point of view of districting and assigning of service units in the field operations. It needs to be pointed out that bulk power interruptions are relatively infrequent events, while the procedures described in the service unit assignment part of the article mostly refer to more frequent but less severe events.

System Restoration Process

The restoration process can be divided into three distinct phases: *preparation, system restoration,* and *load restoration.* The first stage is a critical phase that lasts 30 to 60 min, and many urgent actions need to be taken. The system operator evaluates the system state and defines a target system based on the equipment and personnel availability. The second stage lasts 3 to 4 h and involves the preparation of larger units for startup, the stabilization of the system, the energization of transmission paths, and the resynchronization of islands. The last stage may last up to 12 h and has as an objective the restoration of load as fully and rapidly as possible (4).

Figure 1 (5) outlines the flow of restoration when a fault occurs in the power system. This is a typical flow created based on the experience of skilled human operators and was produced with the cooperation of operators with substantial experience in power dispatch operations. The major steps in restoration include the following (5):

(1) Recognition of system configuration soon after the fault
(2) Search for the restoration route

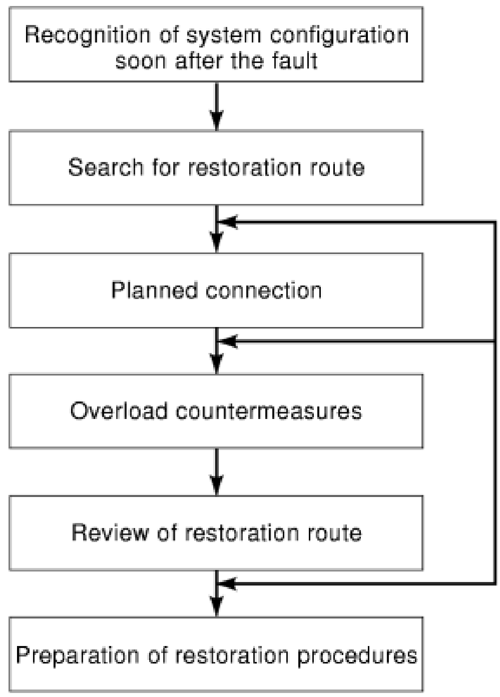


Fig. 1. Processing flow for restoration. The various phases of restoration and their interdependence can be seen. Different units start at different times and have various slopes of increase in their capacities. Reprinted with permission from (5), © IEEE 1996.

(3) Planned connection based on consideration of the supply and demand balance of the system looked for during the search for a restoration route
(4) Overload countermeasures

- Actions against overload by adjusting generator output
- System switchover

(5) Review of the restoration route
(6) Preparation of restoration procedures

- Knowledge of procedure production
- Production of power source restoration procedures
- Production of load restoration procedures

Bulk Power Restoration. Restoration system procedures can be distinguished into bulk, subtransmission, and distribution systems. Bulk power system level requirements include the following (6):

(1) Restart and supply station service to plants, substations, cable pumping plants, compressed air, etc.
(2) Coordinate plant startup timings with load pickups to bring generators to their stable minimum levels and within range of major analog controllers.

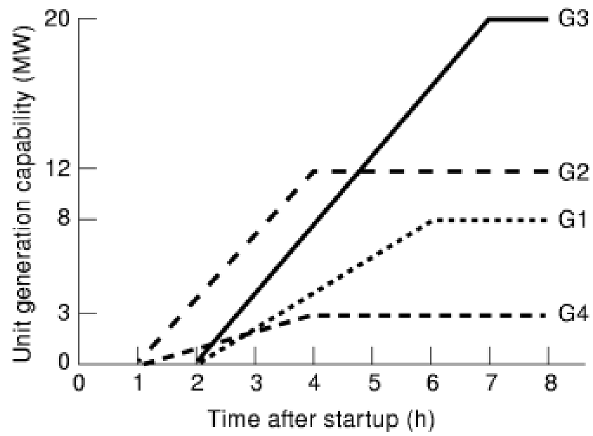


Fig. 2. Generation capability curves of four units. Reprinted with permission from (7), © IEEE 1996.

(3) Energize large sections of transmission lines within the acceptable transient and sustained over voltages.
(4) Pick up load in large increments without the risk of frequency decline.
(5) Reintegrate the skeleton of the bulk power supply with the requisite time-consuming switching operation.
(6) Deactivate automatic load shedding and automatic switched capacitors during initial phase of restoration.
(7) Reduce standing angle when closing loops to firm up transmission paths.
(8) Determine probability of successful startup of thermal units (in particular, combustion turbines).
(9) Ensure stability of black-start and peaking combustion turbines during the time when they constitute a large portion generation.

Distribution systems have their own set of requirements. Load rerouting and overload relief are the main problems encountered. One of the objectives of a successful service restoration strategy is the maximization of the MWh load served over a restoration period. Given the different characteristics of generating units, it is necessary to provide a sequence of unit startups that adheres to all plant constraints. Figure 2 (7), for example, shows the generation capabilities of four units, and Fig. 3 (7) shows the unit startup sequence that will result in the maximum MWh load served. To design such a procedure, several parameters need to be identified. These include the following (7):

(1) Power plant

- Max MW output (normal or emergency)
- Rated power factor (form generator capability curves available for different pressure conditions
- Reactive power over- and underexcitation limits (form generator capability curves)
- Startup and household requirement (MW and MVAR)
- Startup times
- Ramping times (ramping from paralleling to releasing) (ramping from releasing to maximum output)
- Frequency response of prime mover to sudden load pick-up
- Critical minimum and maximum intervals for different types of boilers

(2) System considerations

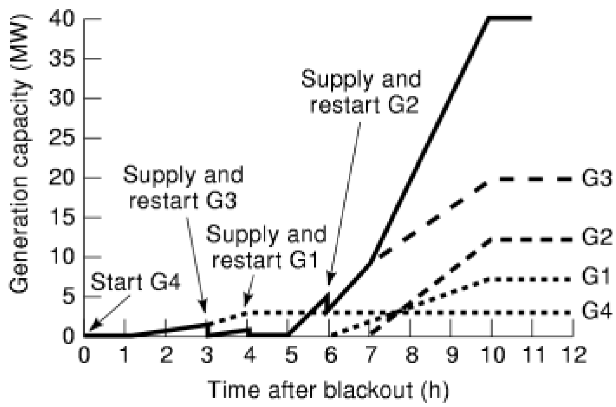


Fig. 3. System generation capability of four-unit example. Break points correspond to times of starts, supply, and restart of various units. In dotted lines one can see the generation capabilities of the four units. Reprinted from (7), © IEEE 1996.

- Reactive power balance
- Load and generation balance
- Underfrequency load shedding (relay modeling)
- Stability limits during restoration
- High and low sustained voltage limits
- MW and MVAR reserve requirement during restoration
- Phase difference in a loop configuration

(3) Lines and substations

- Switching operations
- Line thermal limits (overload of system equipment)
- Line stability limits
- Voltage transients when energizing lines

(4) Load behavior

- Cold load pick-up (load models)
- Recovering load models that store previously evaluated dynamic data for different load types

Distribution System Restoration. The reliability performance of power distribution systems is significantly influenced by their ability to achieve rapid restoration of customer supply and speedy return to normal operating conditions following a system equipment fault or other system abnormality. The development and application of new methods and computational techniques in the field of computer-based distribution automation have, as their objective, the need to satisfy the increasingly demanding requirements of distribution system monitoring and operation. The introduction of automation techniques allows for better investment utilization and improves the service quality. More specifically, automation may reduce the time for fault isolation and service restoration to unfaulted areas.

Computational techniques have been proposed [see (8), for example] for assisting the distribution system engineer in sorting through the alternative designs for the expansion planning for all or a large portion of the system. Additional publications have been devoted to the area of automatic restoration and rearrangement of the distribution system following a system abnormality and making maximum utilization of equipment (9). Recently, some attention has been given to the probabilistic assessment of service restoration (10).

Modeling Concepts of Distribution Systems. A practical distribution system is mainly divided into a primary subsystem and a number of secondary subsystems. The primary subsystem is an interconnected network that consists only of the system supply points. Each secondary subsystem is a radial network that consists of one supply point belonging to the primary subsystem and a number of load points, each of which is supplied by it through exactly one route of supply. After the occurrence of a fault or a system abnormality, one or more load points are taken out of service. The restoration of supply is achieved in three steps:

- Detection of the faulted components and isolation of the appropriate system sections by opening the suitable sectionalizing switches
- Supply of power to the nonfaulted out-of-service sections by closing the appropriate switches
- Restoration of the distribution system to an operating state in which all system load points are supplied through a radial network. The load supply procedure is essentially a combinatorial problem because it is required to decide the open or closed status of all system switches. In real distribution systems it is difficult to find the optimal solution rapidly, while in practical operating conditions it is required to supply power rapidly to all nonfaulted out-of-service load points.

The topology of a distribution system is described by the branches of the system, and each branch is defined as a set of components in series, terminating at two nodes. Two types of branches generally exist. Branches through which the power is permitted to flow in one direction only are defined as unidirectional branches, and those through which power is permitted to flow in either direction are defined as bidirectional branches. The main system components are power transformers, lines, cables, busbars, circuit breakers, instrument transformers, and isolators. The simplest way to join the system circuits is to attach them to a single conductor or busbar. To improve security, facilitate maintenance, and increase the flexibility of power system operation, a number of principal busbar schemes have been used, such as single busbar, three-switch, ring busbar, mesh, transfer single busbar, duplicate busbar, one and a half circuit breaker, transfer duplicate busbar, and triple busbar.

After the occurrence of a failure event on a distribution system component, automatic or manual switching sequences are performed that aim at minimizing the effects of the failure event by returning to service the healthy components as quickly as possible. The effect that the failure event will have on the continuity of supply to each system load point can then be assessed. Load-point supply restoration can be achieved by closing components (breakers and/or isolators) that are in an open condition to provide alternative routes for power supply. A methodology has been developed (10) to deduce the alternative switching operations and evaluate the load that can be supplied. This methodology requires the knowledge of all minimal paths leading to each load point from all system source points under various operating conditions.

In most cases the failure events being considered can be assumed to be of first order, but a more complete assessment of distribution system operation would require the simulation of second-order failure events so that multiple and common mode faults can be also assessed. The failure events that may occur in a distribution system can generally affect the supply of more than one load points. It is reasonable to assume that these load points belong to the same group of coordinated busbars because the faults occurring on the components of the primary subsystem are easily tackled due to the interconnected configuration of the primary subsystem and the increased flexibility of the busbars schemes employed for the supply points (triple or transfer duplicate busbar scheme). Each affected load point can be supplied by energizing one available normally open path and, therefore, each possible supply restoration procedure can be regarded as a combination of open paths consisting of one available open path for each affected load point.

The time duration of the switching procedure on a normally open switch includes the time spent from the instant the failure event occurs until the time the whole procedure is completed. This time depends on the time required for isolating the faulted components, the existing facilities for switching operations, and the importance that is placed on restoring the supply to a particular load point. If the switching procedures of a distribution system are performed using telecontrolled facilities, it is reasonable to assume that all available supply restoration procedures can be performed in almost the same time duration. However, if manual switching operations exist in a distribution system, their duration also depends on the location of the switch and the time taken for the engineers to arrive. In this case, a switching time must be associated to each switch to indicate the time required to operate. Therefore, the supply restoration procedures can be classified according to the reduction in energy not supplied to the load points affected by the failure event under consideration.

Beyond the development of interactive computational techniques for simulating the supply restoration procedures in distribution system operation, there is a need to describe the modeling and evaluating techniques that permit an efficient and practical interactive probabilistic assessment of service restoration in distribution systems and present to the system operator the most appropriate switching procedures to be executed, in a classified order, together with all the associated information. Furthermore, the following set of five probabilistic indices needs to be evaluated for each affected system load point j and time period of analysis t:

- Instantaneous unavailability, $U_j(t)$
- Time-specific frequency of failure, $f_j(t)$
- Interval unavailability, $D_j(0, t)$
- Average interval frequency, $F_j(0, t)$
- Interval energy not supplied, $E_j(0, t)$

These indices quantify the impact of component reliability parameters and system operational practices on the restoration capability of the distribution system. They are calculated from a consideration of the relevant state-space diagram representing the system operating states and the application of an approach, based on the minimal cut set method and Markov processes.

The set of deduced possible restoration procedures for the distribution system after the occurrence of a failure event provides valuable information to the system operator because it identifies the breakers and isolators that must be closed to supply the affected load points. Each deduced restoration procedure is characterized by the order of completion, which indicates the number of switching operations to be performed and the amount of load supplied to each affected load point. These pieces of information are printed out or shown on the computer screen. The task of system operator is to decide which alternative restoration procedure is to be executed. This is a difficult task because each restoration procedure results in a different loading and operating system configuration, while it is desirable to select the most economical actions in terms of switching operations. To help the operator, a classification scheme must be designed to provide an order of execution to each available restoration procedure. For this purpose, various classification criteria can be used, the most important of which are the following (10):

I. The total amount of load supplied to all the affected load points
II. The importance placed on supplying certain load points
III. The need to supply all load points with a minimum amount of load
IV. The number of load points supplied by the same source main feeding line
V. The load distribution of the system supply points
VI. The number of switching actions to be performed (order of completion)

These criteria have been taken into account when developing computational algorithms for classifying the supply restoration procedures that are available after the occurrence of a particular failure event. It must be noted that, when executing each step of this classification approach, the groups of the procedures that equally satisfy the previously executed criteria are only considered, and they are classified according to the criterion under consideration. The basic steps of such an algorithm are the following:

(1) For each procedure, define a code number indicating the maximum number of load points supplied by the source main feeding line(s) in excess of that supplied under normal operating conditions (criterion IV).
(2) For each procedure, define a code number indicating the maximum load supplied by the source point(s) in excess of that supplied under normal operating conditions (i.e., 1 means 10% increase) (criterion V).
(3) Classify the set of all possible restoration procedures according to the total amount of load supplied to all the load points affected by the failure event under consideration (criterion I).
(4) Identify all the groups of the possible restoration procedures supplying the same total amount of load to all the affected load points.
(5) For each such group supplying less load than that demanded and containing more than one possible restoration procedure,
    a. Starting from the load point assigned with the highest priority, classify the procedures according to the amount of supplied load. Repeat this step until all load points have been taken into account. If two or more load points have the same hierarchical order, consider them as a group and classify the procedures according to the total amount of load supplied by them (criterion II).
    b. Classify the procedures according to the number of load points supplied with load greater than the respective minimum required amount. The procedure with the highest number is classified first. If no minimum required load is specified for a particular load point, this load level is assumed to be zero (criterion III).
    c. For each group containing more than one restoration procedure,
        a. If the procedures are supplied by more than one source main feeding lines, classify the procedures according to the code number concerning the loading of the source main feeding lines. The procedure with the lowest code number is classified first (criterion IV).
        b. If the procedures are supplied by more than one source points, classify the procedures according to the code number concerning the loading of the source points. The procedure with the lowest code number is classified first (criterion V).
        c. Classify the procedures according to their order of completion. The procedure with the lowest order is classified first (criterion VI).

Protection

Protective relays and breakers provide information to dispatchers in dispatching centers that could be used to identify faults and help in the fastest emergency power restoration. Detection and removal of the fault section from the rest of the power system is one of the first actions that must be taken during a short-circuit fault or ground fault. Since faults must be cleared fast and selectively, the design of relaying equipment needs to have high reliability and speed, requirements that have resulted in highly sophisticated and complex circuits. Relays are usually idle except for the small period of time that a fault occurs. During the time of the fault, for example, to avoid generator instability and the subsequent possibility of a blackout, a three-phase short circuit near a modern generating station must be isolated from the healthy parts of the system in about 0.15 s. This includes the time to energize the trip coil of the circuit breaker, see if the appropriate breakers open up, and then trip to other breakers if the initial ones do not interrupt the fault current (11).

Protective relays that could affect the duration of the restoration of power include the following (12):

(1) Distance relays/reclosing schemes
(2) Out-of-step relays
(3) Synchrocheck relays
(4) Negative sequence relays
(5) Differential relays lacking harmonic restraint
(6) Volts per hertz relays
(7) Under excitation relays
(8) Generator excitation relays
(9) Low-frequency isolation schemes
(10) Underfrequency and switched-operator relays

There is a growing trend toward microprocessor-based relays that will also be used for control and metering during normal operations.

To sense a fault, and possibly locate it, relays use one or more of the following techniques (11):

(1) Level detection of, for example, abnormally high current, low frequency, or voltage
(2) Magnitude comparison of voltage to line current or of two currents to provide a basis for distance measurements
(3) Angle comparison to indicate the direction of real power flows

To judge the performance and suitability of relay systems, one must look at

(1) Dependability—the degree of certainty that the relay or relay scheme will perform correctly
(2) Security—the degree of assurance against incorrect operation due to all extraneous causes
(3) Speed—the minimum fault clearing time and equipment damage
(4) Selectivity—the minimum removal of equipment from service for isolation of fault or other abnormalities

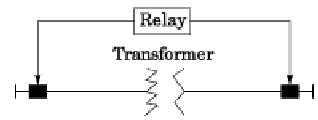
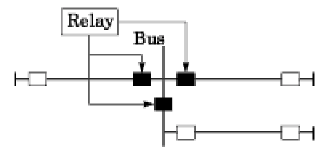
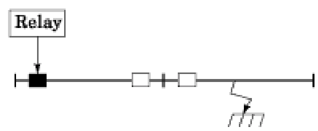
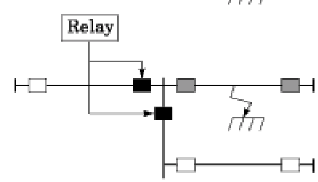
One must also look at the possibility of having failures that go undetected since they do not result immediately at abnormal states and thus can creep into the system for a while, becoming the beginning of major blackouts. Identifying such hidden failures and providing preventive relaying strategies is a difficult task.

Localizing the faults is a difficult operation. Backup operations are supposed to remove false operations of relays or breakers, but this may result in the identification of large areas as faulty and an inability to find the place where the first fault occurred. Traditionally, an operator would have a large wall map of the service area, and faulty devices would be indicated by a light. The increased complexity of the power grid has made the location of the exact fault a difficult task that a human operator cannot accomplish most of the time with success. Several methodologies have been proposed for fault section estimation that use computerized information to process fault and environmental information and help in decision making. Expert systems methodologies as well as computational techniques have been proposed to answer the following questions:

(1) Which is the most likely section where a fault has occurred?
(2) How has this fault resulted in the current system situation (i.e., what was the sequence of relay operations and the tripping of circuit breakers)?

Computational techniques for fault section estimation use optimization techniques like genetic algorithms, Boltzman machines, and simulated evolution methods and have been applied successfully to large-scale

Table 1. Five Types of Reduced Relays

Type	Explanation	Relay Schemes
MR	Relays that use electric values obtained at tow or more substations and make the circuit breakers trip only in one substation. An example is a differential relay for primary line protection.	
TR	Relays for primary transformer protection.	
BR	Relays for primary protection of buses. Usually differential relays are adopted for this kind of purpose.	
RR	Distance relays that use electric values in one station and are often used as remote backup relays.	
LR	Local backup relays that detect the operation failure of circuit breakers and make the alternative circuit breakers trip.	

Notes: ☐ Closed-circuit brakers; ■ Tripped circuit breakers; ▒ Failed-to-trip circuit breakers.
Source: From (13) with permission, © 1996 IEEE.

power systems. Inclusion of uncertainties in the formulation of these problems has been achieved through the use of fuzzy set theory and set covering techniques.

The expert system methodologies store information in databases as facts and the relaying schemes as rules. The inference engine uses the information from relays and breakers to estimate the faulty section and provide the sequence of faults.

Operation of relays can be captured by considering five types of reduced relays, as shown in Table 1 (13).

Problems identified with such a methodology include the following (14):

(1) What data should be collected and what data are available for inferencing?
(2) Limit the number of candidate faults cased to the minimum (or at least to a reasonable) number.
(3) How can multiple faults be processed and diagnosed in a short period of time?
(4) How can the operator receive the results in an easy-to-understand and -handle way, and how well can he or she check the reliability of such data?

It needs to be noted here that protective relays are currently the major components for a plug and play operation in power industries, and research on them brings together service restoration people as well as energy control systems with communications, control, and information processing.

Restoration Time

Power restoration needs to be smooth and deliberate. But restoration time needs to be minimized, taking into account customer needs and equipment limitations. For example,

(1) Minimum and maximum startup times for generators should be observed when designing unit startup sequences. Tripped drum-type steam units should be restarted first as well as generators that are available for quick startup.
(2) Time limits should be observed for backup emergency generators or batteries serving critical equipment.
(3) Restoration actions should be taken after a careful evaluation of the system status.

To design the restoration procedures optimally, researchers have followed two distinct procedures: the use of computational methodologies and the use of expert systems.

Computational Methodologies. Automatic computerized techniques to achieve such a restoration have been widely proposed in the literature of power system restoration. A complete optimization model of the restoration procedure from the mathematical point of view usually results in a mixed integer, multiobjective, multistage, nonlinear optimization problem with a large number of constraints. The objective in such a formulation may be the minimization of the cost of the restoration operations, the maximization of the load served at all times, the minimization of actions to be taken, and the minimization of the residual load capacity. Constraints may include the following:

- Restorative power source capacity restraint
- Supply and demand balance condition
- Line capacity constraint
- Radial capacity constraint

Policy constraints, which are company specific, must also be taken into account as well as scheduling constraints.

Knowledge-Based Methodologies. Knowledge-based systems have gained wide publicity due to their ability to incorporate timing constraints and operator experience in their rules. Disadvantages of such systems include their inability to deal with cases that are not part of their rule base and the need to maintain extremely large knowledge bases.

The first step in the development of such a knowledge-based system is to find out the critical constraints/parameters during restoration, the handling of these parameters, and the sequencing of generator startups and transmission path finding. A knowledge-based system should also be able to provide alternative actions if an unexpected situation occurs, like a fault, a failure, a shortage of personnel. Such knowledge is not always readily available since most power failures are infrequent phenomena and operators are used to working with standard topologies, while nonstandard topologies dominate the after-failure situation.

Training and Organization

The existence of contingency plans is essential in the success of the restoration process. Coordination, planning, training, and organization of resources and procedures always need to be up to date and complete.

Coordination. Contingency plans for power system restoration must be available and must fully describe the necessary coordination procedures and overall organization of the efforts. These plans should be updated periodically and often be drilled for their effectiveness and personnel familiarization. Guidelines must be clear as to how much the aforementioned computer procedures can be trusted, so the procedure moves into a fully automatic gear, or whether there should be considerable human involvement.

Another issue that must also be taken into account is that different utilities have different objectives and priorities, and these must be incorporated in a viable contingency plan. The definition of a target system that the restoration process needs to achieve must be clear and well defined in advance of any actions. This target system can be given in terms of units in service, system load, minimum active network, or some other performance metric.

There should be a clear line of command for the restoration process, a restoration team should be formed from people coming from various departments and locations, a restoration database should be formed, and the available software should be utilized.

Training. Since extensive blackouts are rare events, it is difficult to find experienced personnel to be ready to restore energy efficiently and safely. Thus, the importance of training and improving of skills of personnel cannot be overemphasized.

The design of simulators that will capture these rare phenomena is a difficult technique and involves several company departments and has several phases. These phases include simulation of a variety of faults and restorative procedures.

Analytical tools that may prove necessary include the following (15):

- Power flow program
- Transient stability program
- Long-term dynamic program
- Voltage transient program
- Short-circuit program
- Electromagnetic transient program
- Standing phase angel program
- Cold pick-up program
- Restoration coordination program

It is necessary to stress that customization and adaptation of these programs to the specifics of each utility is absolutely necessary and that it is imperative that user interfaces are user friendly.

Restoration training according to a survey conducted by Wilson (16) is provided in three forms: training for entry-level system operators, refresher training for experienced operators, and advanced training for experienced operators.

Available generic simulators can provide procedural training in the early stages of operation training. However, for exercising and preparing experienced operators to cope with system-specific and time-critical emergency situations such as power service restoration, high-fidelity system referenced simulators are needed. Models and simulators developed for short perturbations cannot describe the large and prolonged perturbations happening during power system restoration (17).

Analysis of the Service Restoration Operations

The duration of the service interruption is the time interval between the service interruption and the service restoration and is expressed by the service restoration time (*SRT*), which power utilities traditionally define as the time that elapses from the time that the customer places the call for service to the utility company until the time that the service is restored. In the previous sections we discussed several organizational and technical requirements and procedures that ensure the safe and fast service restoration, usually concentrating on major outages. In this section we will present the analysis of service operations of an electric utility from the standpoint of the assignment of emergency response units to the areas at fault—a procedure that may be more applicable to minor outages and everyday events that result in disruption of service. Clearly such an approach involves deciding on an optimum methodology governing the deployment of the emergency repair crews to achieve a predetermined threshold value of power restoration time, balance the work load of the units assigned (which we will call *emergency repair trucks, ERT*s), and provide a uniform grade of service to customers (2). SRT can be decomposed to the following four components: ticket creation time (T_0), dispatch time (T_1), travel time (T_2), and repair time (T_3). The duration of the ticket creation time (T_0) is equal to the time interval between the placement of the call and the generation of the ticket. The computerized equipment that the company uses, which will be referred to in this article as trouble call management system (*TCMS*), controls the generation of the ticket. The ticket creation time does not depend on the spatial and temporal distribution of calls. Although TCMS hardware and software modifications can reduce the ticket creation time and consequently the overall service restoration time, these improvements are not treated in this section.

The duration of the dispatch time (T_1) is equal to the elapsed time between the creation of a ticket and the assignment of the ticket to the first available ERT. T_1 depends on the workload assigned to each ERT. In general, for a given emergency repair system the dispatch time depends on the arrival pattern of calls (spatial, temporal, and priority distributions), the dispatching policy, and the number of available ERTs.

The travel time (T_2) is defined as the elapsed time between the ticket assignment and the arrival of the ERT at the scene of the incident. The travel time is a function of the shape and the size of the service area, the underlying transportation network, and the travel speed of the ERT. Mathematical models have been proposed to reduce T_2 and redesign the ERT territories.

The final component of the service restoration time, the repair time (T_3) is defined as the time interval between the arrival of an ERT at the scene of the incident and the event of power restoration. Its duration depends on the type of incident (i.e., severity of the problem), type of failing equipment, day versus night repair, adverse versus favorable weather conditions, and the training and expertise of the repair personnel. It is important to note here that the value of T_3 affects the total service time in two ways. First, it has a direct additive effect on the service restoration time, and second it affects the duration of the dispatch time because of the unavailability of the ERTs that are engaged to ongoing repairs.

The purpose of this utility would be to identify the crucial factors that affect, directly or indirectly, the service restoration time and to investigate the existence of patterns emerging during the service restoration procedure. Such a study provides the foundation for the development of a methodology that aims at reducing the average restoration time and balancing the workload per service area by supplying pointers to the key characteristics that the designer engineer should focus on.

Organization of Emergency Response Operations. Service restoration operations of utility companies are handled by divisions, which are further broken into districts of certain sizes and populations. Service calls are classified into priorities and types. For example, a large utility in the southern United States uses four priorities and seven types as follows. The types are feeder (*FDR*), lateral (*LAT*), meter (*MTR*), no loss of service (*NLS*), oil-circuit recloser (*OCR*), secondary (*SEC*), service (*SV*), and transformer (*TX*). Depending on the extent and the impact of the service disruption, a ticket can have any of the four priorities, with the exception of the no-loss-of-service type, which always has the lowest priority.

Each day is divided into a number of shifts, usually three. According to the shift of the day and the day of the week, weekday or weekend, the districts are further divided into truck areas, each of which is served exclusively by one to three crew members. Repair calls are dispatched to the service crews by dispatchers. It has been observed that the majority of the service calls come during weekdays, when the load on the distribution network is heavier, and during the afternoon shift, when thunderstorms usually break out; the allocation of resources, therefore, should favor these time periods over weekends or the night shift.

Methodology. For the efficient design of the service restoration process, historical data based on the electric utility's experience need to be analyzed. For the analysis of the existing service restoration operations, the following steps need to be taken: *database cleanup, supply analysis, demand analysis,* and *performance analysis.* It is essential to note that in all these steps the interaction between the modelers and the electric utility personnel must be continuous to allow for feedback on general conclusions and direct the study to the items that are critical to the everyday operators of the system. Based on the experience gained, an optimization model can then be developed to analyze alternative districting and dispatching strategies.

The database cleanup step is necessary to guarantee that the data used to estimate the average performance of the system and the demand for services are valid. Three main sources of nonvalid data are identified: tickets that occurred under severe service disruption conditions, data records with unreasonably high values for one or more SRT components, and data records with missing values for one or more of the service restoration components. During severe weather there are always a large number of tickets, but the company needs to operate differently based on reallocation of resources and expected damages. (In this section we present the methodology as applied to normal service disruptions—a similar strategy must be taken for severe service disruptions).

The next step after the database cleanup is to identify the factors that affect the performance of the service restoration operations.

Initially the demand for service restoration is classified by ticket type, shift, district, and truck area. Subsequently the average utilization rate of the service restoration units was calculated by district and shift as well as by truck area and shift. Finally, the performance of the service restoration system in terms of the SRT and its components is calculated on the basis of the service area and shift.

The last step of the analysis involves statistical hypothesis testing. The goal of this part of the analysis was to find out if there is a statistically significant difference in the performance of the service restoration system among the various service areas for the same shift and the shift for the same service area.

Supply Analysis. Simple inspection of service unit assignments usually reveals that within the same district the number of crew members on duty varies among the days of the week and among the shifts of the same day. This type of scheduling is intuitively appealing since the number of arriving calls per shift and the associated workload is definitely not the same always (for example, it is lower for the night shift). Actually it is common for districts not to have anyone assigned during night. In these districts servers are called out, especially if the priority of the ticket is high. The same type of reasoning has also dictated the daily assignment of crews. The weekend days have fewer servers assigned because of the lower anticipated workload.

Demand Analysis. The demand for service restoration can be expressed through the total number of tickets generated by district and shift. A table must then be put together that summarizes the demand for service restoration sorted by district, shift, and day type (weekday or weekend). If from this table it becomes evident that the demand is distributed among the service districts and shifts in a highly skewed manner, then the possibility of redistricting must be evaluated. Since highly skewed demand results in highly skewed—and often high—service restoration times, a careful redistribution of the servers should bring balance to the service restoration operations. The same evaluation must be also made among the working shifts.

The number of service calls arriving per shift at a given district is an easily understandable measure of the work assigned to each crew. It fails, however, to describe thoroughly the workload characteristics of the ERTs. A better indicator for the description of the workload should take into account not only the number of calls assigned to each crew but also the average service time that each one of these calls requires. Thus for a given district (i) and shift (j) the average workload (WL) can be calculated according to

$$WL_{ij} = N_{ij}/(T_2 + T_3)$$

where
N_{ij} = the number of calls that were generated in district (i) during shift (j)
T_2 = the average travel time (min) and
T_3 = the average repair time (min)

If the number of servers in all districts and shifts is equal to one, then the values obtained from the application of the preceding equation can be used to express the workload per server. Given the fact that the number of servers changes between districts and shifts, the preceding equation can be rewritten to express the average utilization rate per server:

$$U_{ij} = WL_{ij}/(480 * n_{ij})$$

where
U_{ij} = the average utilization rate of the servers in district (i) during shift (j) and
n_{ij} = the number of servers in district (i) during shift (j)

The utilization rate U_{ij} is a very good indicator of the degree of utilization of the resources allocated in each district per shift, and it can be used to draw conclusions regarding the distribution of the workload among the districts of the area under study.

Typical evaluations of utilization rates reveal that

- The average utilization rate of the servers differs widely between shifts.
- The utilization rates have seasonal variations.
- There are unequal degrees of utilization among the servers of the various districts.

The utilization rates can be discussed in conjunction with the performance of the service restoration system to identify relationships between the workload of the system and its performance. The following subsection analyzes the performance of the service restoration mechanism.

Performance Analysis. The variables that are used as performance indicators are the average SRT and its four components: ticket creation time (T_0), dispatch time (T_1), travel time (T_2), and repair time (T_3).

In particular, one would like to determine

- if there are differences on the overall service restoration time among the various districts and shifts
- which of the time components have the strongest influence on the overall performance of the system

To achieve these objectives a statistical analysis is performed based on the descriptive statistics of the aforementioned performance measures as well as statistical hypothesis testing to determine if there are statistically significant differences in the means of the SRT and its components among the various districts and shifts.

Optimization. The aforementioned methodology was undertaken for a large utility of southern United States, and the following conclusions were reached. The service restoration operations cannot be studied and evaluated uniformly. The existing partition of the study area has resulted in districts with unbalanced workload and utilization rates. A direct consequence of this partition is the high variation observed in the performance characteristics of the existing districts. The redistricting procedure should consider seriously the balancing of

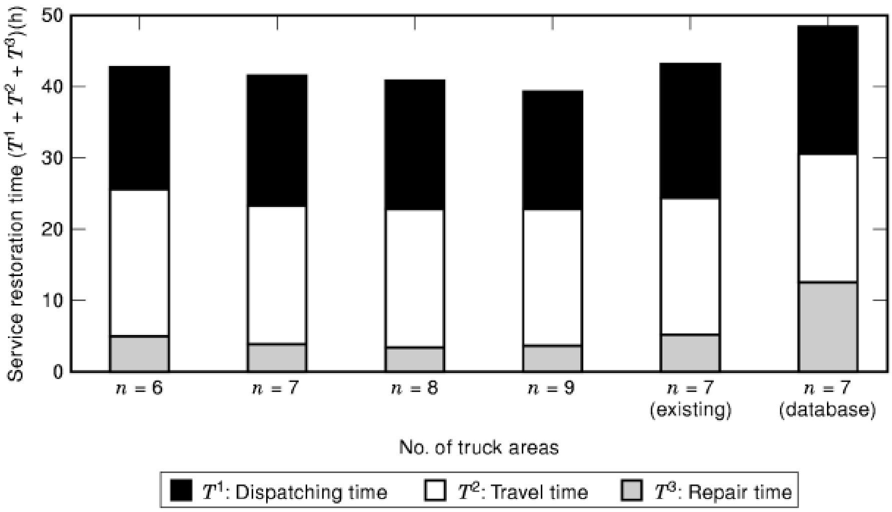


Fig. 4. Relationship between restoration time and number of trucks: Shift 1. *SRT* is reduced as the number of trucks increases. The performance of the existing system is worse than the proposed with fewer trucks.

workload among the various districts and truck areas. Besides the dispatch time, the travel time is the other SRT component that can be reduced. The travel time is affected by the shape, the size, and the properties of the transportation network of the district. The redistricting should take into account all these factors. The design of the service restoration operations should be viewed dynamically. This means that the partitioning of the area into truck areas should change over time. As a result, alternative districting patterns (i.e., number and shape of truck areas) should be designed for the various shifts and days of the week. The ultimate goal should be a districting pattern that will result in utilization rates that can guarantee a target SRT. Based on the aforementioned conclusions, a methodological framework has been developed to address the issues of optimum truck area design and dispatching of ERTs. Although emergency response systems share common characteristics stemming from the random spatial and temporal distribution of calls and the existence of mobile service providers, their operations cannot approached in a generic sense. In emergency repair operations of electric utilities, for instance, there is no patrolling, as in police and freeway incident management operations. There is generally no multiple-vehicle dispatching, as in fire and police management operations, and the service unit does not necessarily return to its home base, as do an ambulance and file protection unit.

For methodological reasons the problem was decomposed into two interrelated nested subproblems: (1) designation of response areas (districting), and (2) determination of the number of emergency repair trucks required to achieve a predetermined level of service. Extensive application of this methodology has suggested that redistricting and reassignment of service units can result in substantial reduction of the number of SRUs necessary (18). Figures 4 and 5 show the improvements in number of required trucks or, equivalently, in service restoration time that can be achieved by careful redistricting and partitioning of the service areas during two shifts.

Incorporation of current technology into dispatching and recording on automated vehicle locator (*AVL*) and geographical information systems (*GIS*) technologies needs also to be evaluated (19).

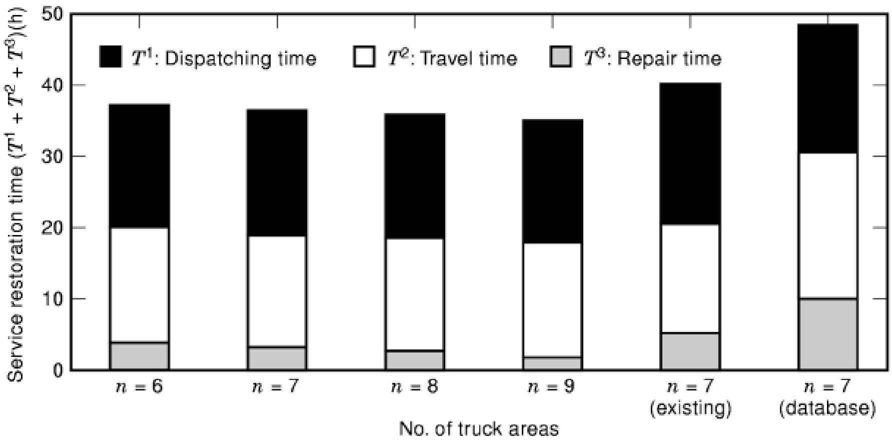


Fig. 5. Relationship between restoration time and number of trucks: Shift 2. SRT is reduced as we increase the number of trucks. By comparing the existing system with the proposed we can see considerable savings in required trucks. Database results and existing performance do not coincide since the former comes from real data, while the latter is from a simulated system.

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