# 1 Distribution System Planning and Automation

To fail to plan is to plan to fail.

**A.E. Gasgoigne, 1985**

Those who know how can always get a job, but those who know why, may be your boss!

**Author Unknown**

To make an end is to make a beginning. The end is where we start from.

**T.S. Eliot**

## 1.1 INTRODUCTION

The electric utility industry was born in 1882 when the first electric power station, Pearl Street Electric Station in New York City, went into operation. The electric utility industry grew very rapidly, and generation stations and transmission and distribution networks have spread across the entire country. Considering the energy needs and available fuels that are forecasted for the next century, energy is expected to be increasingly converted to electricity.

In general, the definition of an electric power system includes a generating, a transmission, and a distribution system. In the past, the distribution system, on a national average, was estimated to be roughly equal in capital investment to the generation facilities, and together they represented over 80% of the total system investment [1]. In recent years, however, these figures have somewhat changed. For example, Figure 1.1 shows the investment trends in electric utility plants in service. The data represent the privately owned class A and class B utilities, which include 80% of all the electric utility in the United States. The percentage of electric plants represented by the production (i.e., generation), transmission, distribution, and general plant sector is shown in Figure 1.2. The major investment has been in the production sector, with distribution a close second. Where expenditures for individual generation facilities are visible and receive attention due to their magnitude, the data indicate the significant investment in the distribution sector.

Production expense is the major factor in the total electrical operation and maintenance (O&M) expenses, which typically represents two-thirds of total O&M expenses. The main reason for the increase has been rapidly escalating fuel costs. Figure 1.3 shows trends in the ratio of maintenance expenses to the value of plant in service for each utility sector, namely, generation, transmission, and distribution. Again, the major O&M expense has been in the production sector, followed by the one for the distribution sector.

Succinctly put, the economic importance of the distribution system is very high, and the amount of investment involved dictates careful planning, design, construction, and operation.

## 1.2 DISTRIBUTION SYSTEM PLANNING

*System planning* is essential to assure that the growing demand for electricity can be satisfied by distribution system additions that are both technically adequate and reasonably economical. Even though considerable work has been done in the past on the application of some types of systematic

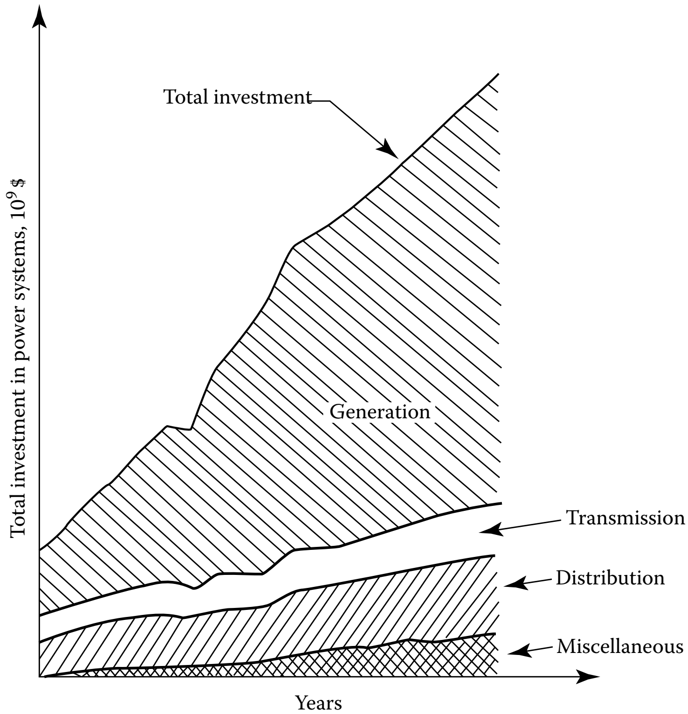


**FIGURE 1.1** Typical investment trends in electric utility plants in service.

approach to generation and transmission system planning, its application to distribution system planning has unfortunately been somewhat neglected. In the future, more than in the past, electric utilities will need a fast and economical planning tool to evaluate the consequences of different proposed alternatives and their impact on the rest of the system to provide the necessary economical, reliable, and safe electric energy to consumers.

The objective of *distribution system planning* is to assure that the growing demand for electricity, in terms of increasing growth rates and high load densities, can be satisfied in an optimum way by additional distribution systems, from the secondary conductors through the bulk power substations, which are both technically adequate and reasonably economical. All these factors and others, for example, the scarcity of available land in urban areas and ecological considerations, can put the problem of optimal distribution system planning beyond the resolving power of the unaided human mind.

*Distribution system planners* must determine the load magnitude and its geographic location. Then the distribution substations must be placed and sized in such a way as to serve the load at maximum cost effectiveness by minimizing feeder losses and construction costs, while considering the constraints of service reliability.

In the past, the planning for other portions of the electric power supply system and distribution system frequently has been authorized at the company division level without the review of or coordination with long-range plans. As a result of the increasing cost of energy, equipment, and labor, improved system planning through use of efficient planning methods and techniques is inevitable and necessary.

The distribution system is particularly important to an electrical utility for two reasons: (1) its close proximity to the ultimate customer and (2) its high investment cost. Since the distribution system of a power supply system is the closest one to the customer, its failures affect customer service more directly than, for example, failures on the transmission and generating systems, which usually do not cause customer service interruptions.

Therefore, distribution system planning starts at the customer level. The demand, type, load factor, and other customer load characteristics dictate the type of distribution system required.

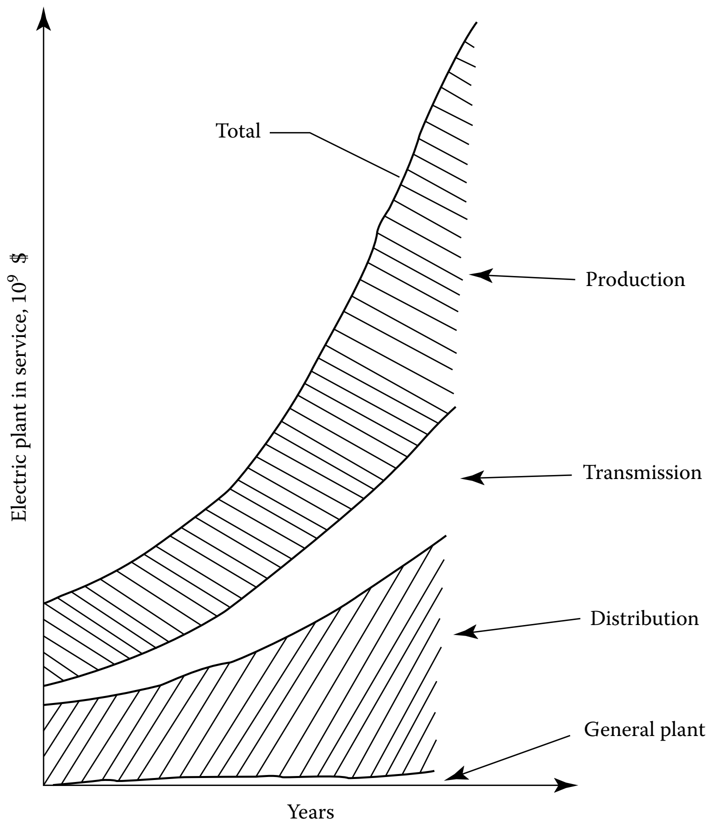


**FIGURE 1.2** Typical trends in electric utility plants in service by percent of sector.

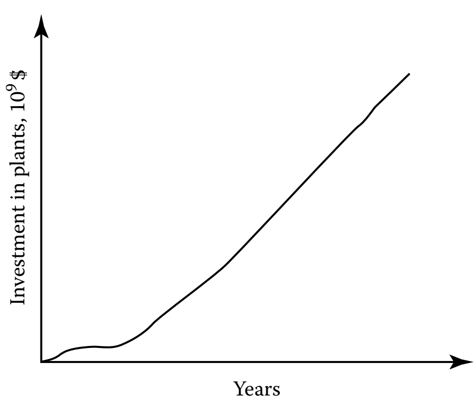


**FIGURE 1.3** Typical ratio of maintenance expenses to plant in service for each utility sector. The data are for privately owned class A and class B electric utilities.

Once the customer loads are determined, they are grouped for service from secondary lines connected to distribution transformers that step down from primary voltage.

The distribution transformer loads are then combined to determine the demands on the primary distribution system. The primary distribution system loads are then assigned to substations that step down from transmission voltage. The distribution system loads, in turn, determine the size and location, or siting, of the substations as well as the routing and capacity of the associated transmission lines. In other words, each step in the process provides input for the step that follows.

The distribution system planner partitions the total distribution system planning problem into a set of subproblems that can be handled by using available, usually ad hoc, methods and techniques. The planner, in the absence of accepted planning techniques, may restate the problem as an attempt to minimize the cost of subtransmission, substations, feeders, laterals, etc., and the cost of losses. In this process, however, the planner is usually restricted by permissible voltage values, voltage dips, flicker, etc., as well as service continuity and reliability. In pursuing these objectives, the planner ultimately has a significant influence on additions to and/or modifications of the subtransmission network, locations and sizes of substations, service areas of substations, location of breakers and switches, sizes of feeders and laterals, voltage levels and voltage drops in the system, the location of capacitors and voltage regulators, and the loading of transformers and feeders.

There are, of course, some other factors that need to be considered such as transformer impedance, insulation levels, availability of spare transformers and mobile substations, dispatch of generation, and the rates that are charged to the customers.

Furthermore, there are factors over which the distribution system planner has no influence but which, nevertheless, have to be considered in good long-range distribution system planning, for example, the timing and location of energy demands; the duration and frequency of outages; the cost of equipment, labor, and money; increasing fuel costs; increasing or decreasing prices of alternative energy sources; changing socioeconomic conditions and trends such as the growing demand for goods and services; unexpected local population growth or decline; changing public behavior as a result of technological changes; energy conservation; changing environmental concerns of the public; changing economic conditions such as a decrease or increase in gross national product (GNP) projections, inflation, and/or recession; and regulations of federal, state, and local governments.

## 1.3 FACTORS AFFECTING SYSTEM PLANNING

The number and complexity of the considerations affecting system planning appear initially to be staggering. Demands for ever-increasing power capacity, higher distribution voltages, more automation, and greater control sophistication constitute only the beginning of a list of such factors. The constraints that circumscribe the designer have also become more onerous. These include a scarcity of available land in urban areas, ecological considerations, limitations on fuel choices, the undesirability of rate increases, and the necessity to minimize investments, carrying charges, and production charges.

Succinctly put, the planning problem is an attempt to minimize the cost of subtransmission, substations, feeders, laterals, etc., as well as the cost of losses. Indeed, this collection of requirements and constraints has put the problem of optimal distribution system planning beyond the resolving power of the unaided human mind.

### 1.3.1 Load Forecasting

The load growth of the geographic area served by a utility company is the most important factor influencing the expansion of the distribution system. Therefore, forecasting of load increases and system reaction to these increases is essential to the planning process. There are two common time scales of importance to load forecasting: long range, with time horizons on the order of 15 or 20 years away, and short range, with time horizons of up to 5 years distant. Ideally, these forecasts would predict future loads in detail, extending even to the individual customer level, but in practice, much less resolution is sought or required.

Figure 1.4 indicates some of the factors that influence the load forecast. As one would expect, load growth is very much dependent on the community and its development. Economic indicators, demographic data, and official land use plans all serve as raw input to the forecast procedure. Output from the forecast is in the form of load densities (kilovoltamperes per unit area) for long-range forecasts. Short-range forecasts may require greater detail.

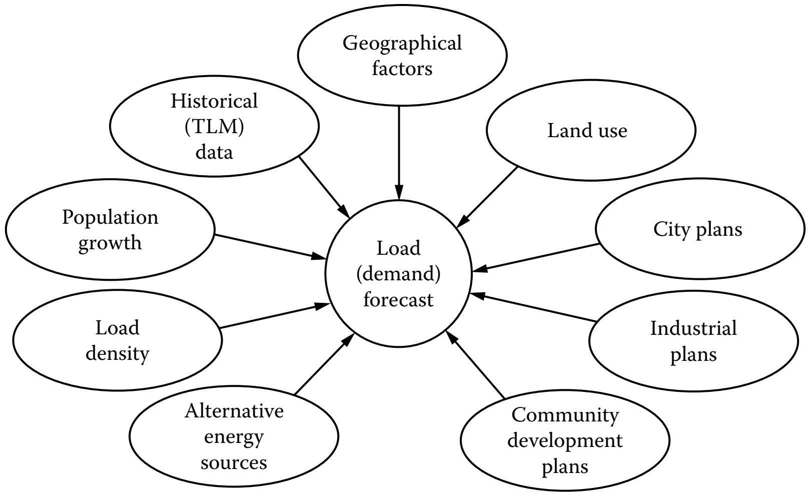


**FIGURE 1.4** Factors affecting load forecast.

Densities are associated with a coordinate grid for the area of interest. The grid data are then available to aid configuration design. The master grid presents the load forecasting data, and it provides a useful planning tool for checking all geographic locations and taking the necessary actions to accommodate the system expansion patterns.

### 1.3.2 Substation Expansion

Figure 1.5 presents some of the factors affecting the substation expansion. The planner makes a decision based on tangible or intangible information. For example, the forecasted load, load density, and load growth may require a substation expansion or a new substation construction. In the system expansion plan, the present system configuration, capacity, and the forecasted loads can play major roles.

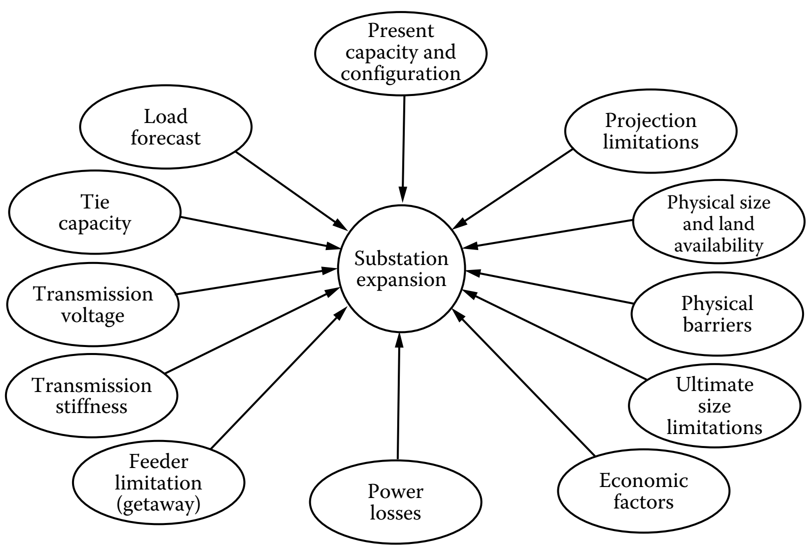


**FIGURE 1.5** Factors affecting substation expansion.

### 1.3.3 Substation Site Selection

Figure 1.6 shows the factors that affect substation site selection. The distance from the load centers and from the existing subtransmission lines as well as other limitations, such as availability of land, its cost, and land use regulations, is important.

The substation siting process can be described as a screening procedure through which all possible locations for a site are passed, as indicated in Figure 1.7. The service region is the area under evaluation. It may be defined as the service territory of the utility. An initial screening is applied

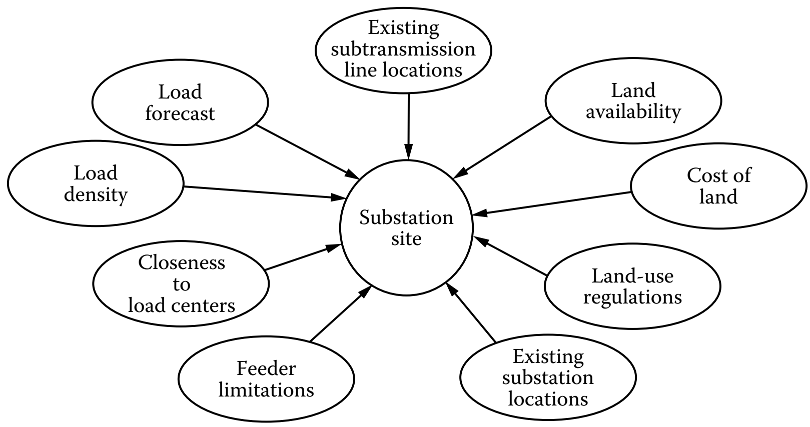


**FIGURE 1.6** Factors affecting substation siting.

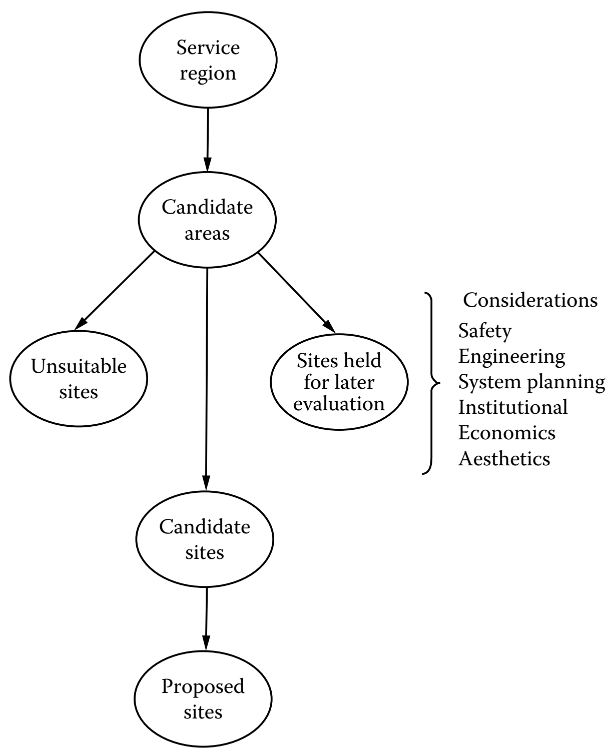


**FIGURE 1.7** Substation site selection procedure.

by using a set of considerations, for example, safety, engineering, system planning, institutional, economics, and aesthetics. This stage of the site selection mainly indicates the areas that are unsuitable for site development.

Thus the service region is screened down to a set of candidate sites for substation construction. Further, the candidate sites are categorized into three basic groups: (1) sites that are unsuitable for development in the foreseeable future, (2) sites that have some promise but are not selected for detailed evaluation during the planning cycle, and (3) candidate sites that are to be studied in more detail.

The emphasis put on each consideration changes from level to level and from utility to utility. Three basic alternative uses of the considerations are (1) quantitative vs. qualitative evaluation, (2) adverse vs. beneficial effects evaluation, and (3) absolute vs. relative scaling of effects. A complete site assessment should use a mix of all alternatives and attempt to treat the evaluation from a variety of perspectives.

### 1.3.4 Other Factors

Once the load assignments to the substations are determined, then the remaining factors affecting primary voltage selection, feeder route selection, number of feeders, conductor size selection, and total cost, as shown in Figure 1.8, need to be considered.

In general, the subtransmission and distribution system voltage levels are determined by company policies, and they are unlikely to be subject to change at the whim of the planning engineer unless the planner's argument can be supported by running test cases to show substantial benefits that can be achieved by selecting different voltage levels.

Further, because of the standardization and economy that are involved, the designer may not have much freedom in choosing the necessary sizes and types of capacity equipment. For example, the designer may have to choose a distribution transformer out of a fixed list of transformers that are presently stocked by the company for the voltage levels that are already established by the company. Any decision regarding the addition of a feeder or adding on to an existing feeder will, within limits, depend on the adequacy of the existing system and the size, location, and timing of the additional loads that need to be served.

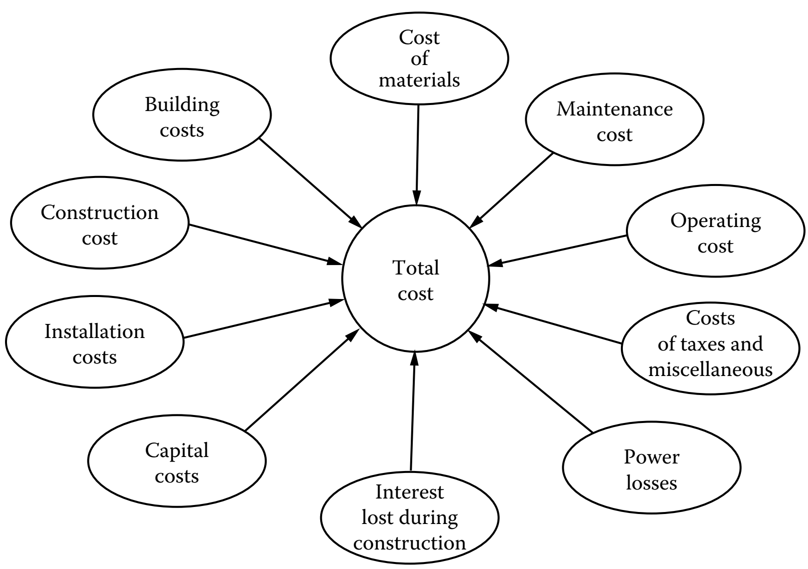


**FIGURE 1.8** Factors affecting total cost of the distribution system expansion.

## 1.4 PRESENT DISTRIBUTION SYSTEM PLANNING TECHNIQUES

Today, many electric distribution system planners in the industry utilize computer programs, usually based on ad hoc techniques, such as load flow programs, radial or loop load flow programs, short-circuit and fault-current calculation programs, voltage drop calculation programs, and total system impedance calculation programs, as well as other tools such as load forecasting, voltage regulation, regulator setting, capacitor planning, reliability, and optimal siting and sizing algorithms.

However, in general, the overall concept of using the output of each program as input for the next program is not in use. Of course, the computers do perform calculations more expeditiously than other methods and free the distribution engineer from detailed work. The engineer can then spend time reviewing results of the calculations, rather than actually making them.

Nevertheless, there is no substitute for engineering judgment based on adequate planning at every stage of the development of power systems, regardless of how calculations are made. In general, the use of the aforementioned tools and their bearing on the system design is based purely on the discretion of the planner and overall company operating policy.

Figure 1.9 shows a functional block diagram of the distribution system planning process currently followed by most of the utilities. This process is repeated for each year of a long-range (15–20 years) planning period. In the development of this diagram, no attempt was made to represent the planning procedure of any specific company but rather to provide an outline of a typical planning process. As the diagram shows, the planning procedure consists of four major activities: load forecasting, distribution system configuration design, substation expansion, and substation site selection.

Configuration design starts at the customer level. The demand type, load factor, and other customer load characteristics dictate the type of distribution system required. Once customer loads are determined, secondary lines are defined, which connect to distribution transformers. The latter provides the reduction from primary voltage to customer-level voltage.

The distribution transformer loads are then combined to determine the demands on the primary distribution system. The primary distribution system loads are then assigned to substations that step down from subtransmission voltage. The distribution system loads, in turn, determine the size and location (siting) of the substations as well as the route and capacity of the associated subtransmission lines. It is clear that each step in this planning process provides input for the steps that follow.

Perhaps what is not clear is that in practice, such a straightforward procedure may be impossible to follow. A much more common procedure is the following. Upon receiving the relevant load projection data, a system performance analysis is done to determine whether the present system is capable of handling the new load increase with respect to the company's criteria. This analysis, constituting the second stage of the process, requires the use of tools such as a distribution load flow program, a voltage profile, and a regulation program. The acceptability criteria, representing the company's policies, obligations to the consumers, and additional constraints, can include

1. Service continuity
2. The maximum allowable peak-load voltage drop to the most remote customer on the secondary
3. The maximum allowable voltage dip occasioned by the starting of a motor of specified starting current characteristics at the most remote point on the secondary
4. The maximum allowable peak load
5. Service reliability
6. Power losses

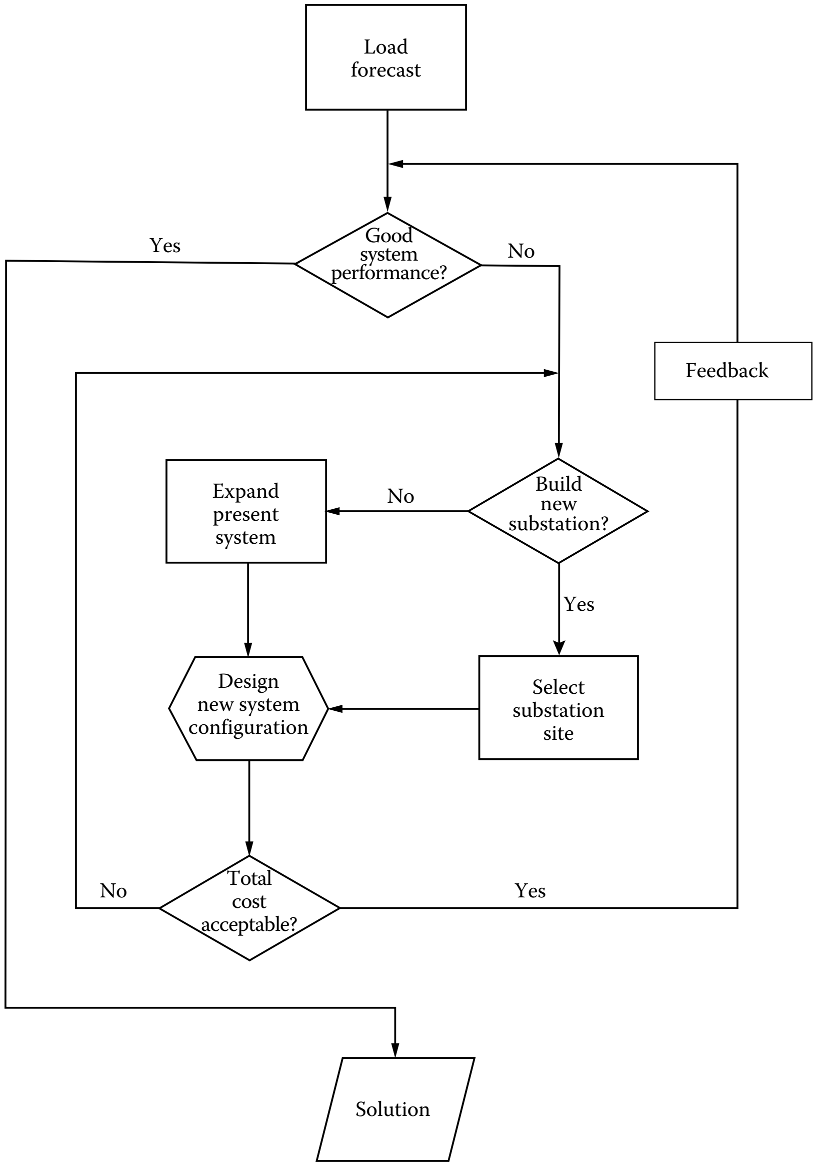


**FIGURE 1.9** A block diagram of a typical distribution system planning process.

As illustrated in Figure 1.9, if the results of the performance analysis indicate that the present system is not adequate to meet future demand, then either the present system needs to be expanded by new, relatively minor, system additions, or a new substation may need to be built to meet the future demand. If the decision is to expand the present system with minor additions, then a new additional network configuration is designed and analyzed for adequacy.

If the new configuration is found to be inadequate, another is tried, and so on, until a satisfactory one is found. The cost of each configuration is calculated. If the cost is found to be too high, or adequate performance cannot be achieved, then the original expand-or-build decision is reevaluated.

If the resulting decision is to build a new substation, a new placement site must be selected. Further, if the purchase price of the selected site is too high, the expand-or-build decision may need further reevaluation. This process terminates when a satisfactory configuration is attained, which provides a solution to existing or future problems at a reasonable cost. Many of the steps in the earlier procedures can feasibly be done only with the aid of computer programs.

## 1.5 DISTRIBUTION SYSTEM PLANNING MODELS

In general, distribution system planning dictates a complex procedure due to a large number of variables involved and the difficult task of the mathematical presentation of numerous requirements and limitations specified by system configuration.

Therefore, mathematical models are developed to represent the system and can be employed by distribution system planners to investigate and determine optimum expansion patterns or alternatives, for example, by selecting

1. Optimum substation locations
2. Optimum substation expansions
3. Optimum substation transformer sizes
4. Optimum load transfers between substations and demand centers
5. Optimum feeder routes and sizes to supply the given loads subject to numerous constraints to minimize the present worth of the total costs involved

Some of the operations research techniques used in performing this task include

1. The alternative-policy method, by which a few alternative policies are compared and the best one is selected
2. The decomposition method, in which a large problem is subdivided into several small problems and each one is solved separately
3. The linear-programming, integer-programming, and mixed-integer programming methods that linearize constraint conditions
4. The quadratic programming method
5. The dynamic-programming method
6. Genetic algorithms method

Each of these techniques has its own advantages and disadvantages. Especially in long-range planning, a great number of variables are involved, and thus there can be a number of feasible alternative plans that make the selection of the optimum alternative a very difficult one [7].

The distribution system costs of an electric utility company can account for up to 60% of investment budget and 20% of operating costs, making it a significant expense [10]. Minimizing the cost of distribution system can be a considerable challenge, as the feeder system associated with only a single substation may present a distribution engineer with thousands of feasible design options from which to choose. For example, the actual number of possible plans for a 40-node distribution system is over 15 million, with the number of feasible designs being in about 20,000 variations.

Finding the overall least cost plan for the distribution system associated with several neighboring substations can be a truly intimidating task. The use of computer-aided tools that help identify the lowest cost distribution configuration has been a focus of much R&D work in the last three decades. As a result, today a number of computerized optimization programs can be used as tools to find the best design from among those many possibilities. Such programs never consider all aspects of the problem, and most include approximations that slightly limit accuracy. However, they can help to deduce distribution costs even with the most conservative estimate by 5%–10%, which is more than enough reason to use them [10].

Expansion studies of a distribution system have been done in practice by planning engineers. The studies were based on the existing system, forecasts of power demands, extensive economic and electrical calculations, and planner's past experience and engineering judgment. However, the development of more involved studies with a large number of alternating projects using mathematical models and computational optimization techniques can improve the traditional solutions that were achieved by the planners. As expansion costs are usually very large, such improvements of solutions represent valuable savings.

For a given distribution system, the present level of electric power demand is known and the future levels can be forecasted by one stage, for example, 1 year, or several stages. Therefore, the problem is to plan the expansion of the distribution system (in one or several stages, depending on data availability and company policy) to meet the demand at minimum expansion cost. In the early applications, the overall distribution system planning problem has been dealt with by dividing it into the following two subproblems that are solved successfully:

1. The subproblem of the optimal sizing and/or location of distribution substations. In some approaches, the corresponding mathematical formulation has taken into account the present feeder network either in terms of load transfer capability between service areas or in terms of load times distance. What is needed is the full representation of individual feeder segments, that is, the network itself.
2. The subproblem of the optimal sizing and/or locating feeders. Such models take into account the full representation of the feeder network but without taking into account the former subproblem.

However, there are more complex mathematical models that take into account the distribution planning problem as a global problem and solving it by considering minimization of feeder and substation costs simultaneously. Such models may provide the optimal solutions for a single planning stage. The complexity of the mathematical problems and the process of resolution become more difficult because the decisions for building substations and feeders in one of the planning stages have an influence on such decisions in the remaining stages.

### 1.5.1 Computer Applications

Today, there are various innovative algorithms based on optimization programs that have been developed based on the earlier fundamental operations research techniques. For example, one such distribution design optimization program now in use at over 25 utilities in the United States. It works within an integrated Unix or Windows NT graphical user interface (GUI) environment with a single open SQL circuit database that supports circuit analysis, various equipment selection optimization routes such as capacitor-regulator sizing and locating, and a constrained linear optimization algorithm for the determination of multifeeder configurations.

The key features include a database, editor, display, and GUI structure specifically designed to support optimization applications in augmentation planning and switching studies. This program uses a linear trans-shipment algorithm in addition to a postoptimization radialization. For the program, a linear algorithm methodology was selected over nonlinear methods even though it is not the best in applications involving augmentation planning and switching studies.

The reasons for this section include its stability in use in terms of consistently converging performance, its large problem capacity, and reasonable computational requirements. Using this package, a system of 10,000 segments/potential segments, which at a typical 200 segments per feeder means roughly 8 substation service areas, can be optimized in one analysis on a DEC 3000/600 with 64 Mbyte RAM in about 1 min [10]. From the application point of view, distribution system planning can be categorized as (1) new system expansion, (2) augmentation of existing system, and (3) operational planning.

### 1.5.2 New Expansion Planning

It is the easiest of the earlier-provided three categories to optimize. It has received the most attention in the technical literature partially due to its large capital and land requirements. It can be envisioned as the distribution expansion planning for the growing periphery of a thriving city. Willis et al. [10] names such planning *greenfield planning* due to the fact that the planner starts with essentially nothing, or greenfield, and plans a completely new system based on the development of a region. In such planning problem, obviously there are a vast range of possibilities for the new design.

Luckily, optimization algorithms can apply a clever linearization that shortens computational times and allows large problem size, at the same time introducing only a slight approximation error. In such linearization, each segment in the potential system is represented with only two values, namely, a linear cost vs. kVA slope based on segment length, and a capacity limit that constrains its maximum loading. This approach has provided very satisfactory results since 1070s. According to Willis et al. [10], more than 60 utilities in this country alone use this method routinely in the layout of major new distribution additions today. Economic savings as large as 19% in comparison to good manual design practices have been reported in IEEE and Electric Power Research Institute (EPRI) publications.

### 1.5.3 Augmentation and Upgrades

Much more often than a greenfield planning, a distribution planner faces the problem of economical upgrade of a distribution system that is already in existence. For example, in a well-established neighborhood where a slowly growing load indicates that the existing system will be overloaded pretty soon.

Even though such planning may be seen as much easier than the greenfield planning, in reality, this perception is not true for two reasons. First of all, new routes, equipment sites, and permitted upgrades of existing equipment are very limited due to practical, operational, aesthetic, environmental, or community reasons. Here, the challenge is the balancing of the numerous unique constraints and local variations in options. Second, when an existing system is in place, the options for upgrading existing lines generally cannot be linearized. Nevertheless, optimization programs have long been applied to augmentation planning partially due to the absence of better tools. Such applications may reduce costs in augmentation planning approximately by 5% [10].

As discussed in Section 7.5, fixed and variable costs of each circuit element should be included in such studies. For example, the cost for each feeder size should include (1) investment cost of each of the installed feeder and (2) cost of energy lost due to $I^2R$ losses in the feeder conductors. It is also possible to include the cost of demand lost, that is, the cost of useful system capacity lost (i.e., the demand cost incurred to maintain adequate and additional system capacity to supply $I^2R$ losses in feeder conductors) into such calculations.

### 1.5.4 Operational Planning

It determines the actual switching pattern for operation of an already-built system, usually for the purpose of meeting the voltage drop criterion and loading while having minimum losses. Here, contrary to the other two planning approaches, the only choice is switching. The optimization involved is the minimization of $I^2R$ losses while meeting properly the loading and operational restrictions.

In the last two decades, a piecewise linearization-type approximation has been effectively used in a number of optimization applications, providing good results.

However, operational planning in terms of determining switching patterns has very little effect if any on the initial investment decisions on ether feeder routes and/or substation locations. Once the investment decisions are made, then the costs involved become fixed investment costs. Any switching activities that take place later on in the operational phase only affect the minimization of losses.

### 1.5.5 Benefits of Optimization Applications

Furthermore, according to Ramirez-Rosado and Gönen [11], the optimal solution is the same when the problem is resolved considering only the costs of investment and energy loses, as expected having a lower total costs. In addition, they have shown that the problem can successfully be resolved considering only investment costs. For example, one of their studies involving multi-stage planning has shown that the optimal network structure is almost the same as before, with the exception of building a particular feeder until the fourth year. Only a slight influence of not including the cost of energy losses is observed in the optimal network structure evolved in terms of delay in building a feeder.

It can easily be said that cost reduction is the primary justification for application of optimization. According to Willis et al. [10], a nonlinear optimization algorithm would improve average savings in augmentation planning to about the same level as those of greenfield results. However, this is definitely not the case with switching. For example, tests using a nonlinear optimization have shown that potential savings in augmentation planning are generally only a fourth to a third as much as in greenfield studies.

Also, a linear optimization delivers on the order of 85% of savings achievable using nonlinear analysis. An additional benefit of optimization efforts is that it greatly enhances the understanding of the system in terms of the interdependence between costs, performance, and tradeoffs. Willis et al. [10] report that in a single analysis that lasted less than a minute, the optimization program results have identified the key problems to savings and quantified how it interacts with other aspects of the problems and indicated further cost reduction possibilities.

## 1.6 DISTRIBUTION SYSTEM PLANNING IN THE FUTURE

In the previous sections, some of the past and present techniques used by the planning engineers of the utility industry in performing the distribution system planning have been discussed. Also, the factors affecting the distribution system planning decisions have been reviewed. Furthermore, the need for a systematic approach to distribution planning has been emphasized.

The following sections examine what today's trends are likely to portend for the future of the planning process.

### 1.6.1 Economic Factors

There are several economic factors that will have significant effects on distribution planning in the 1980s. The first of these is inflation. Fueled by energy shortages, energy source conversion cost, environmental concerns, and government deficits, inflation will continue to be a major factor.

The second important economic factor will be the increasing expense of acquiring capital. As long as inflation continues to decrease the real value of the dollar, attempts will be made by government to reduce the money supply. This in turn will increase the competition for attracting the capital necessary for expansions in distribution systems.

The third factor that must be considered is increasing difficulty in raising customer rates. This rate increase "inertia" also stems in part from inflation as well as from the results of customers being made more sensitive to rate increases by consumer activist groups.