ELECTRIC POWER DISTRIBUTION SYSTEM ENGINEERING

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McGraw-Hill Book Company
New York St. Louis San Francisco Auckland Bogotá Hamburg
Johannesburg London Madrid Mexico Montreal New Delhi
Panama Paris São Paulo Singapore Sydney Tokyo Toronto

This book was set in Times Roman.
The editors were Sanjeev Rao and J. W. Maisel;
the cover was designed by Rafael Hernandez;
the production supervisor was Marietta Breitwieser.
The drawings were done by Accurate Art, Inc.
Halliday Lithograph Corporation was printer and binder

ELECTRIC POWER DISTRIBUTION SYSTEM ENGINEERING

1234567890 HALHAL 898765

ISBN 0-07-023707-7

Library of Congress Cataloging in Publication Data

Gönen, Turan.
Electric power distribution system engineering.

(McGraw-Hill series in electrical engineering.
Power and energy)
Includes bibliographies and index.
1. Electric power distribution. I. Title.
II. Series.
TK3001.G58 1986 621.319 85-79
ISBN 0-07-023707-7

PREFACE

Today, there are many excellent textbooks dealing with topics in power systems. Some of them are considered to be classics. However, they do not particularly address, nor concentrate on, topics dealing with electric power distribution engineering. Presently, to the author's knowledge, the only book available in the electric power systems literature that is totally devoted to power distribution engineering is the one by the Westinghouse Electric Corporation entitled *Electric Utility Engineering Reference Book—Distribution Systems*. However, as the title suggests, it is an excellent reference book but unfortunately not a textbook. Therefore the intention here is to fill the vacuum, at least partially, that has existed so long in power system engineering literature.

This book has evolved from the content of courses given by the author at the University of Missouri at Columbia, the University of Oklahoma, and Florida International University. It has been written for senior-level undergraduate and beginning-level graduate students, as well as practicing engineers in the electric power utility industry. It can serve as a text for a two-semester course, or by a judicious selection the material in the text can also be condensed to suit a single-semester course.

The book includes topics on distribution system planning, load characteristics, application of distribution transformers, design of subtransmission lines, distribution substations, primary systems, and secondary systems; voltage-drop and power-loss calculations; application of capacitors; harmonics on distribution systems; voltage regulation; and distribution system protection and reliability.

This book has been particularly written for students or practicing engineers who may want to teach themselves. Each new term is clearly defined when it is first introduced; also a glossary has been provided. Basic material has been explained carefully and in detail with numerous examples. Special features of the book include ample numerical examples and problems designed to use the information presented in each chapter. A special effort has been made to familiarize the reader with the vocabulary and symbols used by the industry. The addition of the appendixes and other back matter makes the text self-sufficient.

ACKNOWLEDGMENTS

This book could not have been written without the unique contribution of Dr. David D. Robb, of D. D. Robb and Associates, in terms of numerous problems and his kind encouragement and friendship over the years. The author also wishes to express his sincere appreciation to Dr. Paul M. Anderson of Power Math Associates and Arizona State University for his continuous encouragement and suggestions.

The author is most grateful to numerous colleagues, particularly Dr. John Thompson who provided moral support for this project, and Dr. James Hilliard of Iowa State University; Dr. James R. Tudor, Dr. Cyrus O. Harbourt, and Dr. Richard G. Hoft of the University of Missouri at Columbia; Dr. Earl M. Council of Louisiana Tech University; Dr. David K. Pantalone of the New England Power Service Company; Dr. Don O. Koval of the University of Alberta; Dr. John J. Grainger of North Carolina State University; Dr. Olle I. Elgerd of the University of Florida; Dr. Abdel-Aziz A. Fouad and Dr. Aly A. Mahmoud of Iowa State University; Enver Masud of the U.S. Department of Energy; Dr. James Story of Florida International University; and Dr. Kenan Bakin of Teledyne Electronics, Inc., for their interest, encouragement, and invaluable suggestions.

The author also wishes to thank Dr. William R. Kimel, Dean of the College of Engineering, and Dr. Charles Slivinsky, Chairman of the Electrical and Computer Engineering Department, at the University of Missouri at Columbia for creating the right environment for the author that enabled him to complete his project.

A special thank-you is extended to John Freed, Chief Distribution Engineer of the Oklahoma Gas & Electric Company; C. J. Baldwin, Advanced Systems Technology; Westinghouse Electric Corporation; W. O. Carlson, S & C Electric Company; L. D. Simpson, Siemens-Allis, Inc.; E. J. Moreau, Balteau Standard, Inc.; and T. Lopp, General Electric Company, for their kind help and encouragement.

The author is indebted to Prof. Bernard R. Sarchet, Dr. Derald J. Morgan, and Dr. Max Anderson of the University of Missouri at Rolla for their support and encouragement given to write this book. The author is also indebted to numerous students, particularly to F. Djavashi, M. Tahani, and D. C. Yu, who studied portions of the book in a graduate course and made countless contributions and valuable suggestions for improvements.

The author would also like to express his thanks for the many useful comments and suggestions provided by colleagues who reviewed this text during the course of its development, especially to J. J. Grainger, North Carolina State University; James P. Hilliard, Iowa State University; Syed Nasar, University of Kentucky; John Pavlat, Iowa State University; Lee Rosenthal, Fairleigh Dickinson University; Peter Sauer, University of Illinois; and R. L. Sullivan, University of Florida.

Finally, the author's deepest appreciation goes to his wife, Nilüfer Neel, and to his daughter, Sevil, for their limitless patience and understanding.

Turan Gönen

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CHAPTER

ONE

DISTRIBUTION SYSTEM PLANNING AND AUTOMATION

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 after the year 2000. It is estimated that the installed generation capacity will be about 1200 GW in the United States by the year 2000.

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 percent of the total system investment [1]. In recent years, however, these figures have somewhat changed. For example, Fig. 1-1 shows electric utility plants in service for the years 1960 to 1978. The data represent the privately owned class A and class B utilities, which include 80 percent 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 Fig. 1-2. The major investment has been in the production sector, with distribution a close

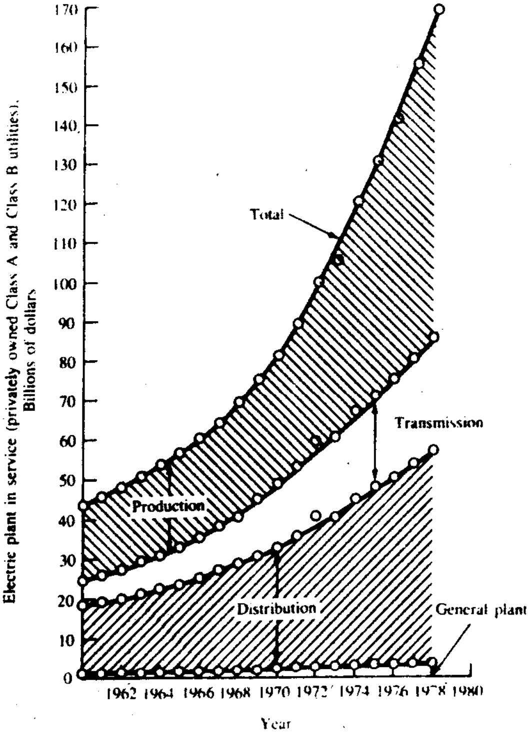

Figure 1-1 Electric utility plant in service (1960–1978). (*From* [2].)

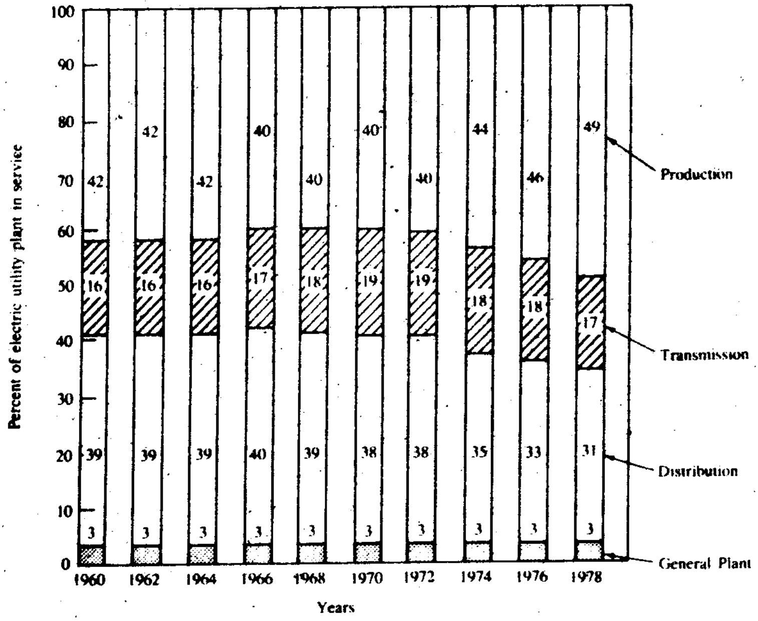

Figure 1-2 Electric utility plant in service by percent of sector (1960–1978). (*From* [2, 3].)

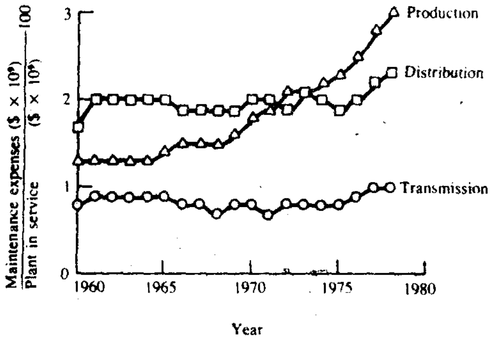

Figure 1-3 Ratio of maintenance expenses to plant in service for each utility sector (1968–1980). The data is for privately owned class A and class B electrical utilities. (*From* [*2*].)

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.

Furthermore, total operation and maintenance costs for the privately owned utilities have increased from $8.3 billion in 1969 to $40.2 billion in 1978 [4]. Production expense is the major factor in the total electrical operation and maintenance (O&M) expenses, representing 64 percent of total O&M expenses in 1978. The main reason for the increase has been rapidly escalating fuel costs. Figure 1-3 shows 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 which are both technically adequate and reasonably economical. Even though considerable work has been done in the past on the application of some type of systematic 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, e.g., 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 the other portions of the electric power supply system and distribution system frequently has been authorized at the company division level without 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. 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 which 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 systems planning, e.g., 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 appears 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 which 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 geographical 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 which influence the load forecast. As one would expect, load growth is very much dependent on the community

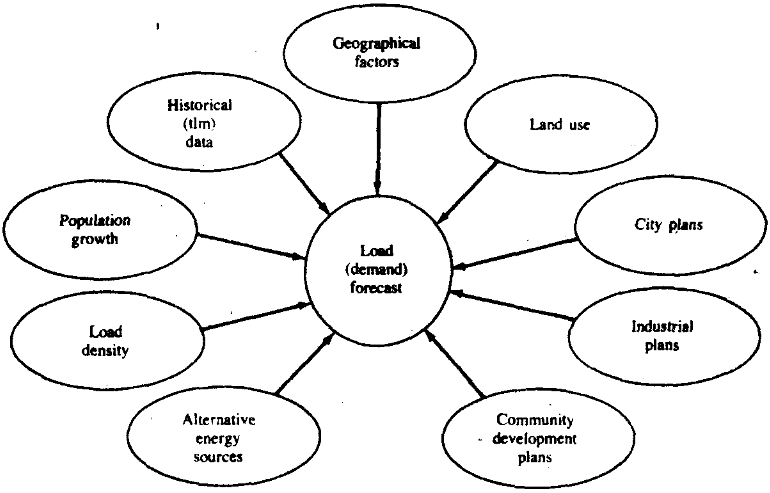

Figure 1-4 Factors affecting load forecast.

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. 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 geographical 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.

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, are important.

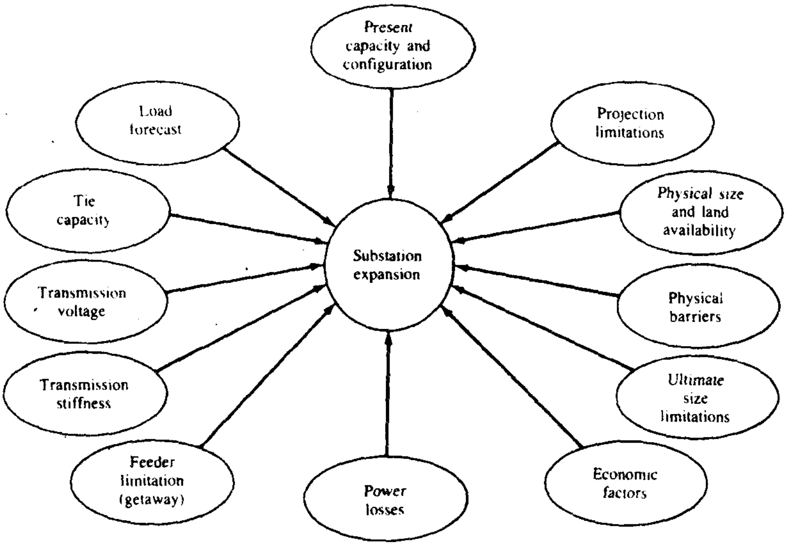

Figure 1-5 Factors affecting substation expansion.

The substation siting process can be described as a screening procedure through which all possible locations for a site are passed, as indicated in Fig. 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 by using a set of considerations, e.g., safety, engineering, system planning, institutional, economics, 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

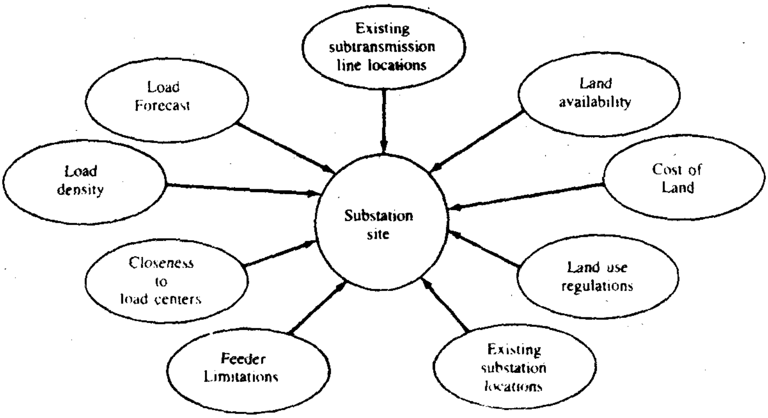

Figure 1-6 Factors affecting substation siting.

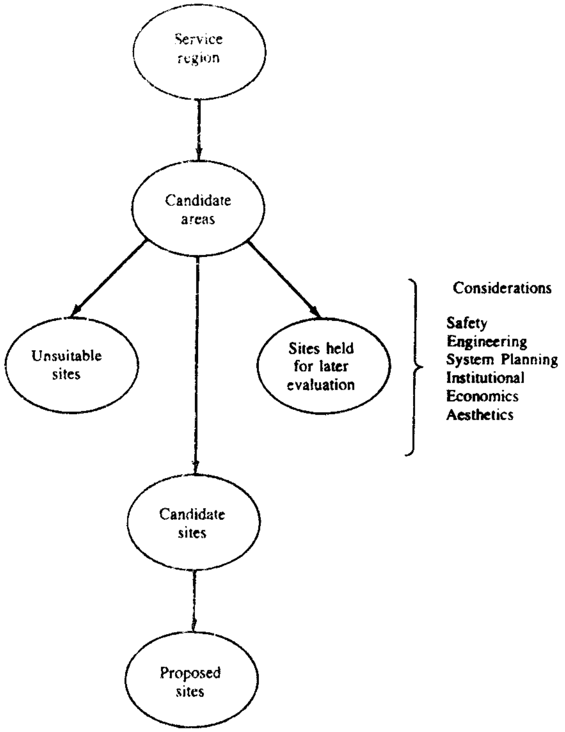

Figure 1-7 Substation site selection procedure.

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 Fig. 1-8, need to be considered.

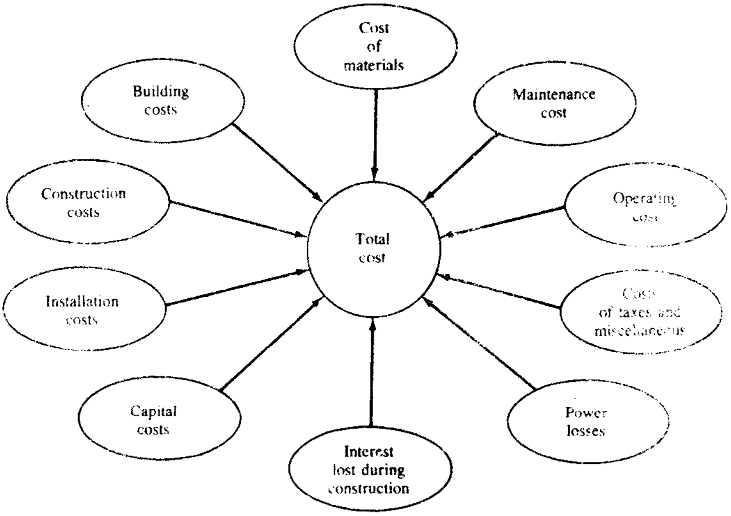

Figure 1-8 Factors affecting total cost of the distribution system expansion.

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 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.

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 two 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

As illustrated in Fig. 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,

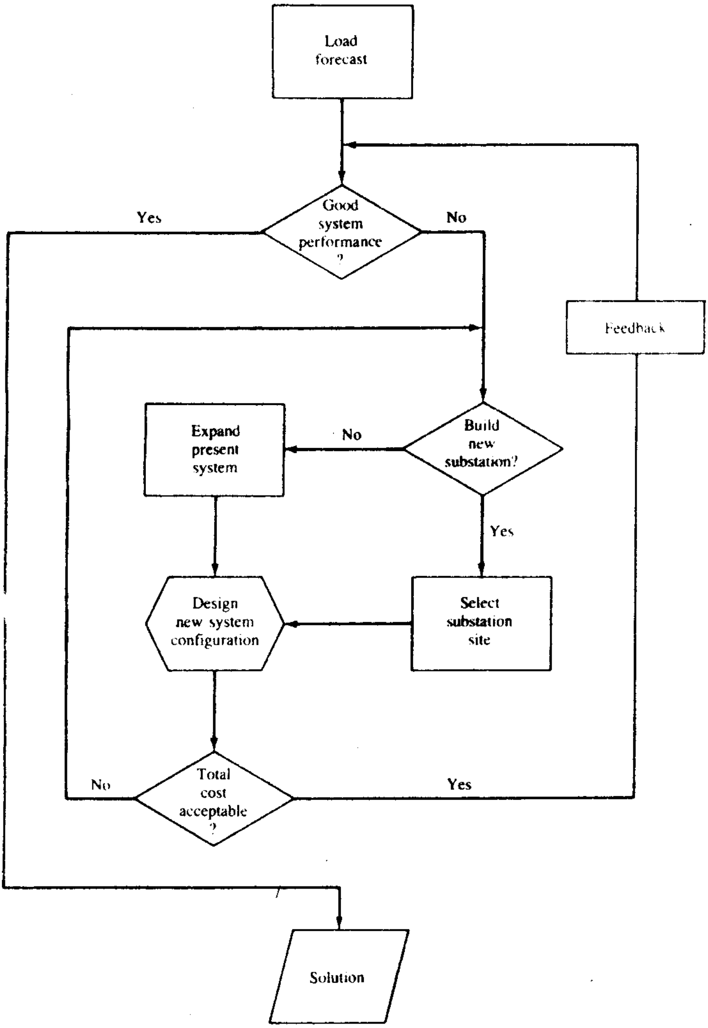

Figure 1-9 A block diagram of a typical distribution system planning process.