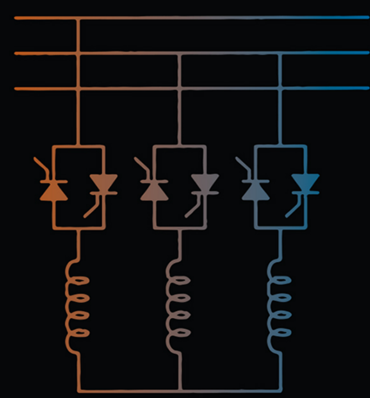
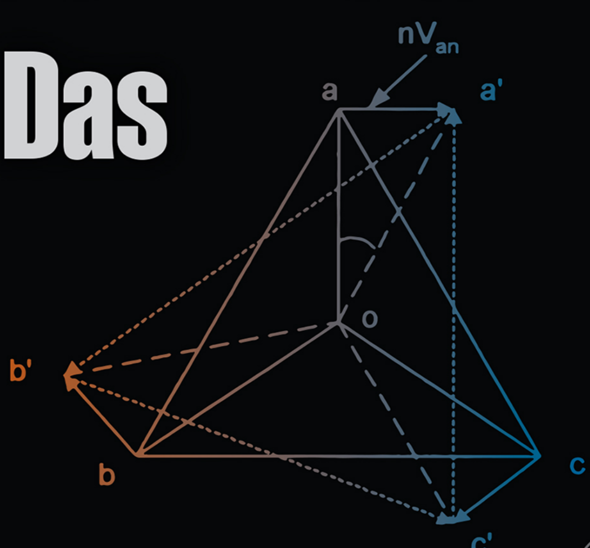
Power Systems Handbook - Volume 2

Load Flow Optimization and Optimal Power Flow



J.C. Das



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Power Systems Handbook

Load Flow Optimization and Optimal Power Flow

Volume 2

Power Systems Handbook

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Volume 1: Short-Circuits in AC and DC Systems:
ANSI, IEEE, and IEC Standards

Volume 2: Load Flow Optimization and Optimal Power Flow

Volume 3: Harmonic Generation Effects Propagation and Control

Volume 4: Power System Protective Relaying

Load Flow Optimization and Optimal Power Flow

Volume 2

J.C. Das

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Series Preface

This handbook on power systems consists of a set of four volumes. These are carefully planned and designed to provide the state-of-the-art material on major aspects of electrical power systems, short-circuit currents, load flow, harmonics, and protective relaying.

An effort has been made to provide a comprehensive coverage, with practical applications, case studies, examples, problems, extensive references, and bibliography.

The material is organized with sound theoretical base and its practical applications. The objective of creating this series is to provide the reader with a comprehensive treatise, which could serve as a reference and day-to-day application guide for solving the real-world problem. It is written for plasticizing engineers and academia, level of education upper undergraduate and graduate degrees.

Though there are published texts on similar subjects, this series provides a unique approach to the practical problems that an application engineer or consultant may face in conducting the system studies and applying it to varied system problems.

Some parts of the work are fairly advanced on a postgraduate level and get into higher mathematics. Yet, the continuity of the thought process and basic conceptual base are maintained. A beginner and advanced reader will equally benefit from the material covered. An undergraduate level of education is assumed, with fundamental knowledge of electrical circuit theory, rotating machines, and matrices.

Currently, power systems, large or small, are analyzed on digital computers with appropriate software packages. However, it is necessary to understand the theory and basis of these calculations to debug and decipher the results.

A reader may be interested only in one aspect of power systems and may like to purchase only one of the volumes of the series. Many aspects of power systems are transparent between different types of studies and analyses—for example, knowledge of short-circuit currents and symmetrical component is required for protective relaying, and knowledge of fundamental frequency load flow is required for harmonic analysis. Though appropriate references are provided, the material is not repeated from one volume to another.

The series is a culmination of the vast experience of the author in solving real-world problems in the industrial and utility power systems for the last more than 40 years.

Another key point is that the solutions to the problems are provided in Appendix D. A reader should be able to independently solve these problems after perusing the contents of a chapter, and then look back to the solutions provided, as a secondary help. The problems are organized, so that these can be solved with manual manipulations, without the help of any digital computer power system software.

It is hoped that the series will be a welcome addition to the current technical literature.

The author thanks Ms. Nora Konopka of CRC Press for her help and cooperation throughout the publication effort.

—J.C. Das

Preface to Volume 2: Load Flow Optimization and Optimal Power Flow

This volume discusses the major aspects of load flow, optimization, optimal load flow, and culminating in modern heuristic optimization techniques and evolutionary programming.

In the deregulated environment, the economic provision of electrical power to consumers requires knowledge of so many related aspects—maintaining a certain power quality and load flow being the important aspects. Chapter 1 provides basic structures: security assessments, load estimation, forecasting, and nonlinear nature of load flow, requiring iterative techniques for optimum solutions. This is followed by Chapter 2 which goes into AGC and AFC concept, controls, and underfrequency load shedding.

Load flow over AC and HVDC transmission lines is somewhat unique in the sense that it much depends upon line length and in HVDC system the system configurations.

Nodal analysis techniques that have developed over the past many years for solution of the load flow problem are covered in Chapters 5 and 6. These discuss and compare almost all available load flow algorithms in practical use on commercial software packages.

Maintaining an acceptable voltage profile on sudden load impacts and contingency load flow problems, large induction and synchronous motor starting, their models and characteristics, and stability considerations are discussed in Chapter 7.

The related topic of reactive power control and voltage instability and impact on the acceptable voltages in the electrical power system is the subject of Chapter 8, followed by FACTS and SVC applications for transmission and distribution systems in Chapter 9.

The distribution systems can have phase unbalances that cannot be ignored. The symmetrical component analysis cannot be applied with prior phase unbalance. The techniques of phase coordinate methods for three-phase modeling and advanced models of three-phase transformers, with optimum locations of capacitor banks using dynamic modeling concepts, are provided in Chapter 10.

Chapters 11 and 12 cover the classical methods of optimization. Gradient methods, linear programming, dynamic programming, barrier methods, security- and environmental-constrained OPF, generation scheduling considering transmission losses, and unit commitment are discussed.

Finally, Chapter 13 provides an introduction to evolutionary programming, genetic algorithms, particle swarm optimization, and the like.

Thus, the subject of load flow, optimization, and optimal load flow is completely covered.

Many case studies and practical examples are included. The problems at the end of a chapter can be solved by hand calculations without resort to any computer software. Appendix A is devoted to calculations of line and cable constants and Appendix B provides solutions to the problems.

—J.C. Das

Author

J.C. Das is an independent consultant, Power System Studies, Inc., Snellville, Georgia, USA. Earlier, he headed the Power System Analysis Department at AMEC Foster Wheeler for the last 30 years. He has varied experience in the utility industry, industrial establishments, hydroelectric generation, and atomic energy. He is responsible for power system studies, including short circuit, load flow, harmonics, stability, arc flash hazard, grounding, switching transients, and protective relaying. He conducts courses for continuing education in power systems and has authored or coauthored about 70 technical publications nationally and internationally. He is the author of the following books:

- *Arc Flash Hazard Analysis and Mitigation*, IEEE Press, 2012.
- *Power System Harmonics and Passive Filter Designs*, IEEE Press, 2015.
- *Transients in Electrical Systems: Analysis Recognition and Mitigation*, McGraw-Hill, 2010.
- *Power System Analysis: Short-Circuit Load Flow and Harmonics,* Second Edition, CRC Press, 2011.
- *Understanding Symmetrical Components for Power System Modeling,* IEEE Press, 2017.

These books provide extensive converge, running into more than 3000 pages and are well received in the technical circles. His interests include power system transients, EMTP simulations, harmonics, passive filter designs, power quality, protection, and relaying. He has published more than 200 electrical power system study reports for his clients.

He has published more than 200 study reports of the power systems analysis addressing one problem or the other.

Mr. Das is a Life Fellow of the Institute of Electrical and Electronics Engineers, IEEE (USA), a Member of the IEEE Industry Applications and IEEE Power Engineering societies, a Fellow of the Institution of Engineering Technology (UK), a Life Fellow of the Institution of Engineers (India), a Member of the Federation of European Engineers (France), a Member of CIGRE (France), etc. He is a registered Professional Engineer in the States of Georgia and Oklahoma, a Chartered Engineer (C.Eng.) in the UK and a European Engineer (Eur. Ing.) in Europe. He received a meritorious award in engineering, IEEE Pulp and Paper Industry in 2005.

He earned a PhD in electrical engineering at Atlantic International University, Honolulu, an MSEE at Tulsa University, Tulsa, Oklahoma, and a BA in advanced mathematics and a BEE at Panjab University, India.

1

Load Flow—Fundamental Concepts

Historically, the development of technology for predictive and control analysis of load flow problems was rather slow—the analogue computing techniques: network analyzers taking much time to model and were slow for a specific load flow problem. Another limitation is that large systems could not be modeled. With the advent of digital computers, much advancement has taken place. This is discussed in the chapters to follow.

The load flow problem arises from the fact that consumers must be provided with reliable source of electrical power for their varying needs, which involves much planning, like generation, renewables, transmission, and distribution and in the deregulated environment, this has become a very competitive field. The economic provisions of electrical power to the consumers require knowledge of so many interrelated functions; for example, adequately sizing the electrical equipment in the long chain of generation, transmission, and distribution: see Volume 1 for the nature of modern electrical power systems. Even in the isolated systems, same fundamental considerations arise, the renewables, microgrids, solar and wind generation, government subsidies for green power adding to the complexity. The load flow and optimization techniques are the tools to provide guidance through this maze.

1.1 Security Assessments

The 1965 blackout led to the various efforts for improving reliability. Several emergency guidelines and criteria were introduced by the Federal Power Commission and North American Power System Interconnection subcommittee. In this respect, "load flow" is not a stand-alone problem. The stability, protection, and transient behavior of a system plus the system management are important links. The power system security means the ability to withstand sudden disturbances such as short circuits and unexpected loss of system components. In terms of planning and operation, a power system should

- Ride through the transients and return to a steady-state operation without much impact on the consumers
- In the new steady state, no system component should be overloaded and should operate within their design parameters

These ideal conditions may not always be met in practice.

We can define three states as follows:

1. Normal
2. Emergency
3. Restorative

Under normal operation, all consumer demands are met and all equipment operates slightly below its rated capability. Mathematically, under normal state

$$\begin{aligned} &x_1(a_1, a_2, \ldots, a_n; b_1, b_2, \ldots, b_n) = 0 \\ &x_2(a_1, a_2, \ldots, a_n; b_1, b_2, \ldots, b_n) = 0 \\ &\ldots \\ &x_n(a_1, a_2, \ldots, a_n; b_1, b_2, \ldots, b_n) = 0 \end{aligned} \tag{1.1}$$

where a_1, a_2,… are a set of dependent state variables and b_1, b_2,… are a set of independent variables, representing demand, inputs, and control. These correspond to load flow equations.

Relative to equipment the constraints are as follows:

$$\begin{aligned} &y_1(a_1, a_2, \ldots, a_n; b_1, b_2, \ldots, b_n) \leq 0 \\ &y_2(a_1, a_2, \ldots, a_n; b_1, b_2, \ldots, b_n) \leq 0 \\ &\ldots \\ &y_n(a_1, a_2, \ldots, a_n; b_1, b_2, \ldots, b_n) \leq 0 \end{aligned} \tag{1.2}$$

The equipment constraints can be described, for example, as upper and lower limits of a generator reactive power limits, system plus minus voltage limits, and the like.

In the emergency state, for example, brought out by a short circuit, some of the inequality constraints may be violated—the frequency may deviate, the lines and machines may be overloaded, etc. Mathematically, we write

$$\begin{aligned} &x_1(a_1, a_2, \ldots, a_n; b_1, b_2, \ldots, b_n) = 0 \\ &x_2(a_1, a_2, \ldots, a_n; b_1, b_2, \ldots, b_n) = 0 \\ &\ldots \\ &x_n(a_1, a_2, \ldots, a_n; b_1, b_2, \ldots, b_n) = 0 \end{aligned} \tag{1.3}$$

and

$$\begin{aligned} &y_1(a_1, a_2, \ldots, a_n; b_1, b_2, \ldots, b_n) \neq\leq 0 \\ &y_2(a_1, a_2, \ldots, a_n; b_1, b_2, \ldots, b_n) \neq\leq 0 \\ &\ldots \\ &y_n(a_1, a_2, \ldots, a_n; b_1, b_2, \ldots, b_n) \neq\leq 0 \end{aligned} \tag{1.4}$$

In the restorative state, only some customers may be satisfied without overloading any equipment—thus, all equality constraints are not satisfied. We write

$$
\begin{aligned}
&x_1(a_1, a_2, \ldots, a_n; b_1, b_2, \ldots, b_n) \neq 0 \\
&x_2(a_1, a_2, \ldots, a_n; b_1, b_2, \ldots, b_n) \neq 0 \\
&\ldots \\
&x_n(a_1, a_2, \ldots, a_n; b_1, b_2, \ldots, b_n) \neq 0
\end{aligned} \tag{1.5}
$$

and

$$
\begin{aligned}
&y_1(a_1, a_2, \ldots, a_n; b_1, b_2, \ldots, b_n) = 0 \\
&y_2(a_1, a_2, \ldots, a_n; b_1, b_2, \ldots, b_n) = 0 \\
&\ldots \\
&y_n(a_1, a_2, \ldots, a_n; b_1, b_2, \ldots, b_n) = 0
\end{aligned} \tag{1.6}
$$

1.2 Control Actions

A normal state is *secure* if following any one of the postulated disturbances, the system remains in the normal state; otherwise, it is *insecure*. An operator may intervene and manipulate the system variables so that the system is secure—this is called preventive control. When the system is in the emergency mode, a *corrective* control action is possible which will send the system to normal state. If corrective control fails, emergency control can be applied. Finally, a restorative control should put the system in normal state.

1.3 Consumer Loads

Before we discuss load types, it is useful to define certain established parameters with respect to consumer loads.

1.3.1 Maximum Demand

The load demand of a consumer is not constant. It varies with the time of the day, the season (i.e., summer or winter months). For industrial processes, the load demand may not be constant and vary with the process or production rate. For residential consumers, the utilities do not, generally, levy a demand charge, but for industrial consumers, the maximum demand registered over a period of 30 min or 1 h is built into the tariff rates.

The instantaneous peak is always the highest. A peaky load imposes constraints on the electrical supply system. Imagine if the peaks of all consumers were to occur simultaneously at a certain time of the day, then the complete supply system should be capable of supplying this peak, while at other times its installed capacity lies idle. When considering peaky loads, we must remember that

- The electrical equipment has limited short-duration overload capability, i.e., power transformers can take a certain amount of overload for certain duration without derating the life expectancy and these limits have been established in the standards. However, the circuit breakers may have only limited overload capability. The overload capability of a system will be established by the weakest link in the system.
- A peaky load may give rise to excessive voltage saga and power quality may become a problem.
- Protective devices may operate on sudden inrush currents. Starting of a large motor in an industrial system is an example of such peaky loads. Another example can be cited of a process plant, which generates most of its power, and has utility's system as a standby. Normally, the plant generators supply most of the power requirements, but on loss of a machine, the utility tie must be capable of supporting the load without voltage dips for continuity of the processes.
- All these scenarios are interrelated and are carefully analyzed before a tie with the utility's system is established.

1.3.2 Load Factor

Load factor can be defined as the ratio of the average power to the maximum demand *over a certain period*. The definition will be meaningless unless the time period is associated with it, i.e., 30 min, monthly, or yearly:

$$\text{Load factor} = \frac{\text{Kwh consumed}}{\text{Maximum demand} \times \text{Hours}} \tag{1.7}$$

1.3.3 Diversity Factor

Diversity factor is the ratio of the sums of the maximum demands of various consumers or subdivisions of a system or the part of a system to the maximum demand of the whole or part of the system under consideration:

$$DF = \frac{\sum d}{D} \tag{1.8}$$

where d is the sum of the maximum demands of the subdivisions or consumers and D is the maximum demand of the whole system. This is graphically shown in Figure 1.1.

Example 1.1

A power station supplies the following consumers with monthly maximum demands of: Industrial = 100 MW, Residential = 30 MW, and Commercial = 20 MW. The maximum demand of the power station is 120 MW and it generates 40 GWh units in 1 month. Calculate the monthly load factor and diversity factor.

Load factor = 46%
Diversity factor = 1.25

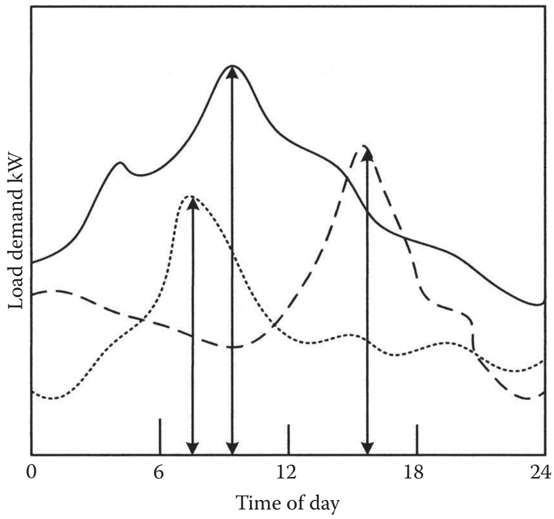

FIGURE 1.1
Illustration of diversity factor.

1.4 Load Types

The load types can be divided into the following categories:

Domestic: These consist of lighting, HVAC, household appliances, television, computers, etc. and have poor load factor. On a cold day, all consumers will switch on their heaters and on a hot day, their air conditioners, practically at the same time.

Commercial: These consist of mainly lighting, computer terminals, HVAC, neon signs, and displays as used in most commercial establishments. The power requirements for hospitals and health care facilities are special requirements.

Industrial: Industrial power systems vary considerably in size, complexity, and nature of loads. A 500 kVA outdoor pad-mounted transformer in a radial feed arrangement connected to a lineup of low voltage motor control center may be classed as an industrial distribution system. Conversely, a large industrial distribution system may consume tens of MW of power.

Transit systems, lighting of public buildings, entertainment parks, and roads are some other examples of specific load types.

Figure 1.2 shows the patterns of residential, commercial, and industrial loads.

1.4.1 Load Characteristics

Load characteristics are important. The voltages in power system swing and the various types of load will behave differently under voltage variations. We can divide the loads into

- Constant MVA type
- Constant impedance type
- Constant current type

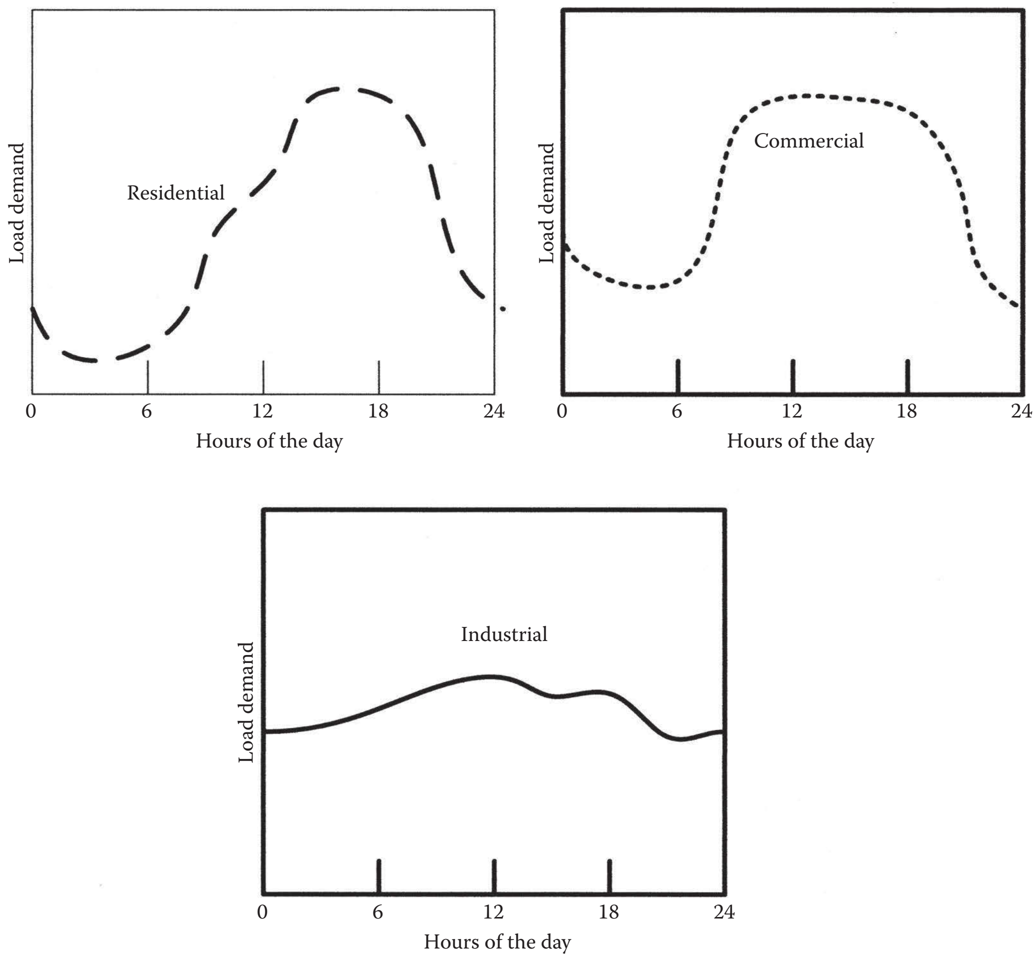

FIGURE 1.2
Daily load profiles of typical customers.

The effect of change of operating voltage on constant current, constant MVA, and constant impedance load types is discussed in Chapter 6. Heavy industrial motor loads are approximately constant MVA loads, while commercial and residential loads are mainly constant impedance loads. Classification into commercial, residential, and industrial is rarely adequate and one approach has been to divide the loads into individual load components. The other approach is based upon measurements. Thus, the two approaches are as follows:

- Component-based models
- Models based upon measurements

See Chapter 6 for further discussions and mathematical equations. Modeling the correct load type in a load flow problem is important to avoid errors and erroneous results. The nonlinar loads are discussed in Volume 3.

1.5 Effect on Equipment Sizing

Load forecasting has a major impact on the equipment sizing and future planning. If the forecast is too optimistic, it may lead to the creation of excess generating capacity, blocking of the capital, and uneconomical utilization of assets. On the other hand, if the forecast errs on the other side, the electrical power demand and growth will not be met. This has to be coupled with the following facts:

- Electrical generation, transmission, and distribution facilities cannot be added overnight and takes many years of planning and design engineering efforts.
- In industrial plant distribution systems, it is far easier and economical to add additional expansion capacity in the initial planning stage rather than to make subsequent modifications to the system, which are expensive and also may result in partial shutdown of the facility and loss of vital production. The experience shows that most industrial facilities grow in the requirements of power demand.
- Energy conservation strategies should be considered and implemented in the planning stage itself.
- Load management systems—an ineffective load management and load dispatch program can offset the higher capital layout and provide better use of plant, equipment, and resources.

Thus, load forecasting is very important in order that a electrical system and apparatus of the most economical size be constructed at the correct place and the right time to achieve the maximum utilization.

For industrial plants, the load forecasting is relatively easy. The data are mostly available from the similar operating plants. The vendors have to guarantee utilities within narrow parameters with respect to the plant capacity.

Something similar can be said about commercial and residential loads. Depending upon the size of the building and occupancy, the loads can be estimated.

Though these very components will form utility system loading, yet the growth is sometimes unpredictable. The political climate and the migration of population are not easy to forecast. The sudden spurs of industrial activity in a particular area may upset the past load trends and forecasts.

Load forecasting is complex, statistical, and econometric models are used [1, 2]. We will briefly discuss regression analysis in the following section.

1.6 Regression Analysis

Regression or trend analysis is the study of time series depicting the behavior pattern of process in the past and its mathematical modeling so that the future behavior can be extrapolated from it. *The fitting of continuous mathematical functions through actual data to achieve the least overall error is known as regression analysis.* The purpose of regression is to estimate one of the variables (dependent variable) from the other (independent variable). If y is estimated from x by some equation, it is referred to as regression. In other words, if the scatter diagram of two variables indicates some relation between these variables, the dots will be concentrated around a curve. This curve is called the curve of regression. When the curve is a straight line, it is called a line of regression.

Typical regression curves used in forecasting are as follows:

$$\text{Linear}: y = A + Bx \tag{1.9}$$

$$\text{Exponential}: y = A(1 + bx)^2 \tag{1.10}$$

$$\text{Power}: y = Ax^B \tag{1.11}$$

$$\text{Polynomial}: A + Bx + Cx^2 \tag{1.12}$$

The limitations are that the past data may not be indicative of the future. They depend upon the standard of living, the GNP, and the geography of the terrain.

For short-term forecasting, a sequence of discontinuous lines or curves may be fitted.

Consider a total process represented by Figure 1.3. It can be broken down into the following subprocesses:

- *Basic trend, Figure 1.4a.*
- *Seasonal variations, Figure 1.4b*: The monthly or yearly variations of the load. The average over the considered period of time is zero. The long-term mean is zero.
- *Random variations, Figure 1.4c* These occur on account of day-to-day changes and are usually dependent upon the time of the week, weather, etc. The long-term mean is zero.

The interest is centered on yearly peaks and not on the whole load curve. A straight regression line can be drawn through the load peaks. The least square regression method is most suitable for long-term forecasts, Figure 1.5a and b.

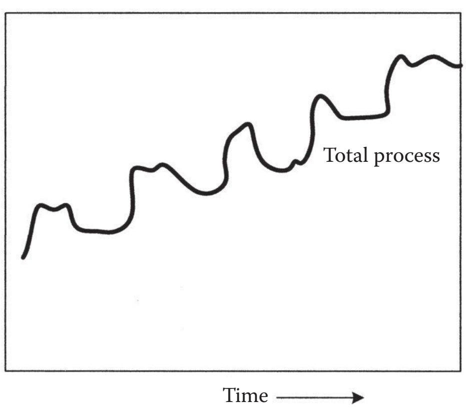

FIGURE 1.3
Total load growth.

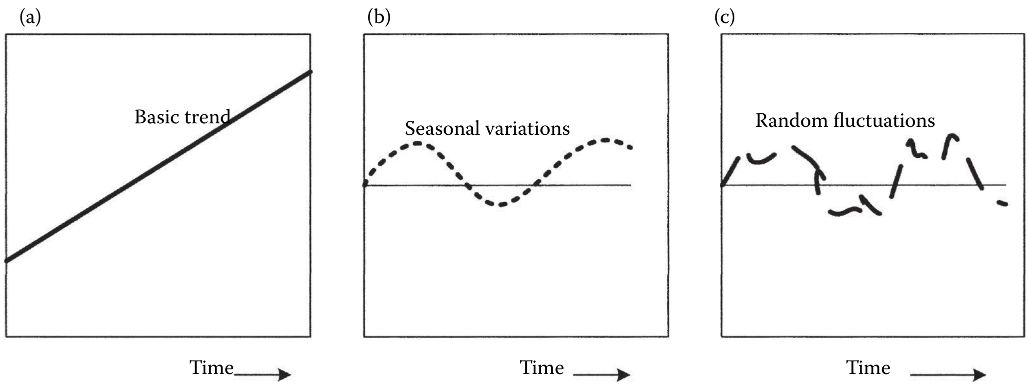

FIGURE 1.4
(a)–(c) Decomposition of total load growth in Figure 1.3.

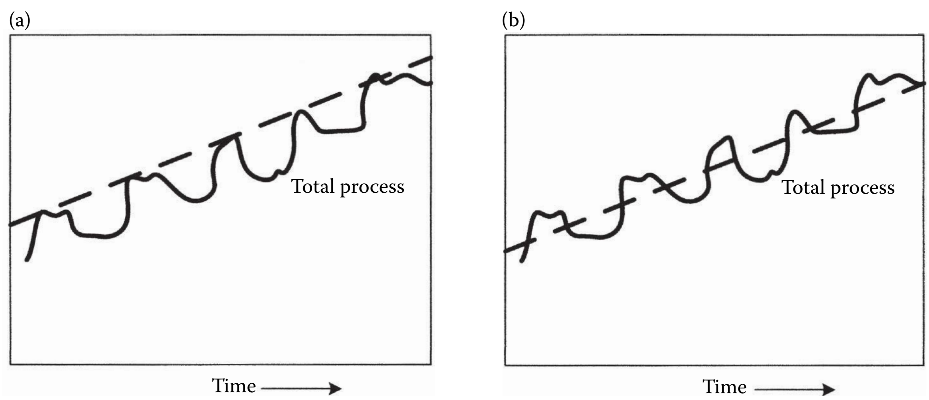

FIGURE 1.5
Regression curves through peak and through mean.

1.6.1 Linear Trend

This denotes a trend where increase in demand from year to year is constant, rarely true. Such a trend can be expressed as follows:

$$C_t = a + bt \tag{1.13}$$

C_t = consumption of electricity in some future year t
a = consumption for base year, $t = 0$
b = annual increase in energy consumption
$t = T - 1 + n$, where T is the number of years for which statistical trend is studied and n is the number of years for which the forecast is required

1.6.2 Exponential Trend

An exponential trend is denoted by

$$C_t = C_0(1 + m)^t \tag{1.14}$$

where m = mean rate of growth observed in T years. By taking logs to base 10, the graph becomes a straight line:

$$\log C_t = a + bt \tag{1.15}$$

1.7 Curve Fitting—Least Square Line

For some given data points, more than one curve may seem to fit. Intuitively, it will be hard to fit an appropriate curve in a scatter diagram and variation will exist.

Referring to Figure 1.6, a measure of goodness for the appropriate fit can be described as follows:

$$d_1^2 + d_2^2 + \cdots + d_n^2 = a = \min \tag{1.16}$$

A curve meeting these criteria is said to fit the data in the *least square sense* and is called a least square regression curve, or simply a least square curve—straight line or parabola. The least square line imitating the points $(x_1, y_1), \ldots, (x_n, y_n)$ has the following equation:

$$y = a + bx \tag{1.17}$$

The constants a and b are determined from solving simultaneous equations, which are called the normal equations for the least square line:

$$\begin{aligned} \sum y &= an + b\sum x \\ \sum xy &= a\sum x + b\sum x^2 \end{aligned} \tag{1.18}$$

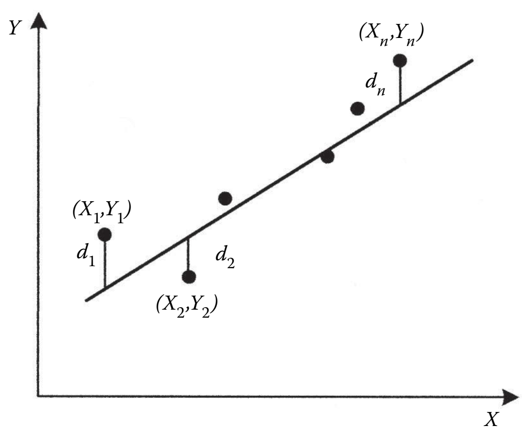

FIGURE 1.6
Fitting a least square line.

This gives

$$a = \frac{\left(\sum y\right)\left(\sum x^2\right) - \left(\sum x\right)\left(\sum xy\right)}{n\sum x^2 - \left(\sum x\right)^2}$$

$$b = \frac{n\sum xy - \left(\sum x\right)\left(\sum y\right)}{n\sum x^2 - \left(\sum x\right)^2} \tag{1.19}$$

The constant *b* can be written as follows:

$$b = \frac{\sum (x - x_{\text{mean}})(y - y_{\text{mean}})}{\sum \left(x - x_{\text{mean}}^2\right)} \tag{1.20}$$

This yields

$$y_{\text{mean}} = a + bx_{\text{mean}} \tag{1.21}$$

From the above equation, we can also write the least square line as follows:

$$y - y_{\text{mean}} = b(x - x_{\text{mean}}) = \frac{\sum (x - x_{\text{mean}})(y - y_{\text{mean}})}{\sum (x - x_{\text{mean}})^2}(x - x_{\text{mean}}) \tag{1.22}$$

Similarly, for *x* on *y*,

$$x - x_{\text{mean}} = \frac{\sum (x - x_{\text{mean}})(y - y_{\text{mean}})}{\sum (y - y_{\text{mean}})^2}(y - y_{\text{mean}}) \tag{1.23}$$

The least square line can be written in terms of variance and covariance. The sample variance and covariance are given by

$$S_x^2 = \frac{\sum (x - x_{\text{mean}})^2}{n}$$

$$S_y^2 = \frac{\sum (y - y_{\text{mean}})^2}{n} \tag{1.24}$$

$$S_{xy} = \frac{\sum (x - x_{\text{mean}})(y - y_{\text{mean}})}{n}$$

In terms of these, the least square lines of y on x and x on y

$$y - y_{\text{mean}} = \frac{S_{xy}}{S_x^2}(x - x_{\text{mean}})$$
$$x - x_{\text{mean}} = \frac{S_{xy}}{S_y^2}(y - y_{\text{mean}}) \tag{1.25}$$

A sample correlation coefficient can be defined as follows:

$$r = \frac{S_{xy}}{S_x S_y} \tag{1.26}$$

For further reading see References [3–5].

Example 1.2

Given the data points (x, y) as (1, 1), (3, 2), (4, 5), (6, 7), (7, 6), (9, 8), (12, 10), (15, 16), fit a least square line with x as independent variable, y as dependent variable.

Table 1.1 shows the various steps of calculations. Then, we have

$$8a + 57b = 55$$
$$57a + 561b = 543$$

where n=number of samples=8. Solving these equations, a=−0.0775 and b=0.975. Therefore, the least square line is

$$y = -0.0775 + 0.975x$$

If x is considered as the dependent variable and y as the independent variable, then

$$8c + 55d = 57$$
$$55c + 535d = 543$$

Solution of which gives, c=0.507 and d=0.963.

TABLE 1.1

Fitting the Least Square Line, Example 1.2

x	y	x^2	xy	y^2
1	1	1	1	1
3	2	9	6	4
4	5	16	20	25
6	7	36	42	49
7	6	49	42	36
9	8	81	72	64
12	10	144	120	100
15	16	225	240	256
$\sum x = 57$	$\sum y = 55$	$\sum x^2 = 561$	$\sum xy = 543$	$\sum y^2 = 535$

1.8 Load Estimation and Projection in Distribution Systems

The load estimation and forecasting is one key element in the distribution system planning. The metered loads at all points in the distribution system are rarely available. Thus, multi-scenario load studies become mandatory. For every MW of load, engineering analysis of roughly 100 nodes is required. The location of substations, routing of feeders, and sizing of equipment depend on it. Furthermore, there is an element of uncertainty—even the best estimates may leave some uncertainty about the future conditions.

Thus, forecasting involves projecting the number and types of customers, providing geographical or spatial information on future load growth required to identify future problem areas in advance and perform studies of substation sizing, locations, and feeder routings.

1.8.1 Small-Area Forecasting

The utility service area is divided into a number of small areas and the load forecasting is done in each area; this gives an idea where and how much the load will grow throughout the system. Two approaches are as follows:

- Equipment-area-oriented forecasting by feeder, substation, or other sets of areas defined by equipment—most utilities define small areas in the range of 10–160 acres (0.04–0.64 km^2)
- A uniform grid based on some mapping coordinate systems

See Figure 1.7a and b.

The planning is performed on an annual basis. The small-area forecasts concentrated on a projection of the annual peak load for each area, over the period of time for which planning is to be done. The concept is to provide a load forecast change over time. The average short-range period used by utilities is 5 years. Long-range planning involves 5–25 years. Figure 1.8 shows the load behavior with respect to area size (number of consumers).

1.8.2 Spatial Forecast Methods

Mainly, there are two categories:

Trending methods that extrapolate past trends in annual peaks—these are applied to equipment on small-area basis.

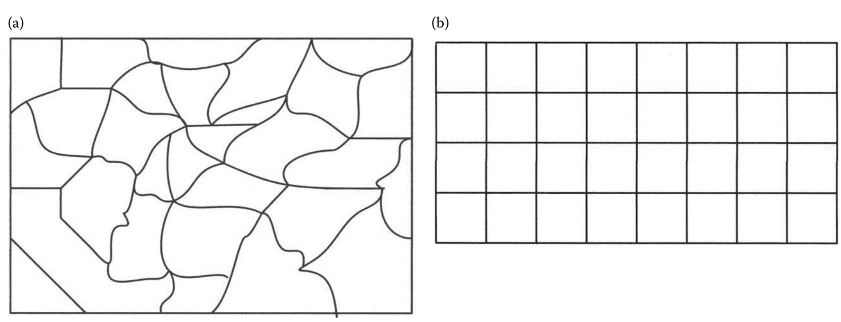

FIGURE 1.7
(a) Diffused small areas for load growth defined by equipment; (b) by an explicit grid.

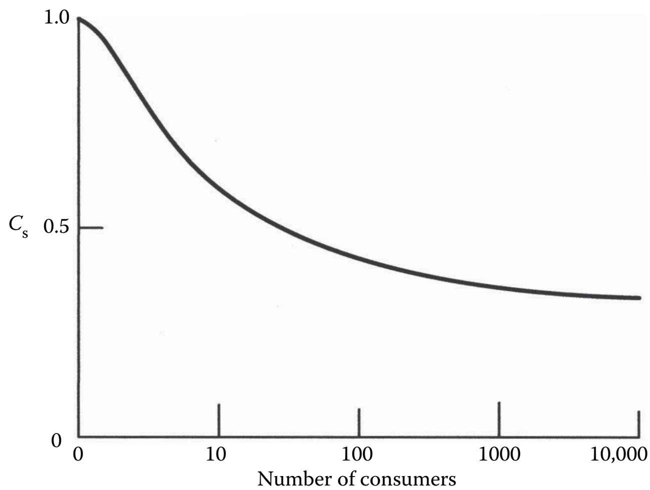

FIGURE 1.8
Coincidence of peak load of a number of consumers.

Land-use-based methods that forecast by analyzing zoning, municipal plans, and other land-use factors—these are applied on a grid basis.

The spatial forecast methods on digital computers were first applied in 1950 and land-use methods in the early 1960s. Development of computer-based forecast methods has accelerated during the last 20 years. EPRI project report RP-570 investigated a wide range of forecast methods, established a uniform terminology, and established many major concepts and priorities [6]. Almost all modern spatial forecast methods are allocation methods, on a small-area basis.

We have already observed that the load demands vary, and these will not occur simultaneously. Define a "coincidence factor":

$$C_s = \frac{(\text{Peak system load})}{(\text{Sum of customers peak loads})}$$

The more the number of customers, the smaller will be the value of C_s. For most power systems, it is 0.3–0.7.

One approach is to use coincidence factors and the equipment may be sized using a coincidence curve similar to Figure 1.8. But few spatial models explicitly address coincidence of the load as shown in Figure 1.8. An approach to include coincidence is given by

$$I_k(t) = \frac{C(e)}{C(a)} \times N_k \times L \tag{1.27}$$

where a is the average number of consumers in an area, e is the average number of consumers in a substation of feeder service area, N is the total consumers in the small area, and L is their average peak load. The load behavior as a function of the area size is shown in Figure 1.9. Figure 1.9a is the total system, Figure 1.9b is several km^2, and Figure 1.9c is small

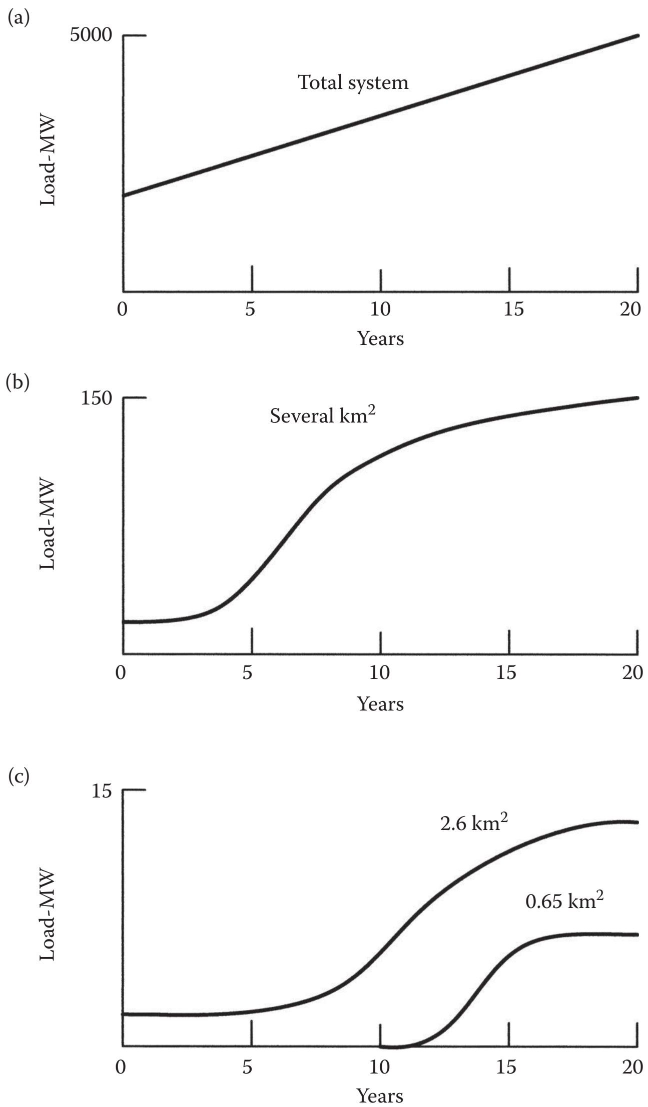

FIGURE 1.9
Average load growth profiles as a function of area: (a) total load growth; (b) area of several km^2; and (c) areas of 2.6 and 0.65 km^2.

areas. Furthermore, Figure 1.10 shows the behavior of load growth in a small area; the first dotted curve is so-called *S* curve. The majority of load growth occurs only in a few years and the curve flattens out. The *S* curve varies with respect to the size of the area.

In spite of all the advancements in computer modeling, the future load projections may have errors, which impact the distribution system planning. The political climate of an area may change, the industries may move in and out, and with that the number of consumers.

This led to the spatial frequency analysis. The errors can be broken into their spatial frequencies. The planning is not sensitive to that portion of the error that is composed of high spatial frequencies—like load forecast errors. The low-frequency spatial errors have a high impact. Forecasting algorithms can be studied in the spatial frequency

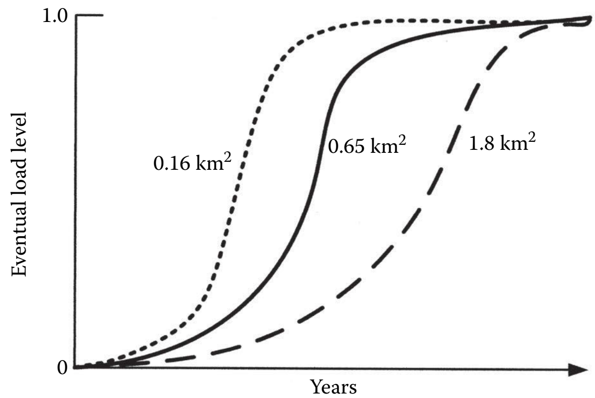

FIGURE 1.10
Typical load behavior in small areas, *S* curves, the sharpness depending on the area.

domain with respect to their impact on distribution system planning. The forecast of individual small-area loads is not as important as the assessment of overall spatial aspects of load distribution.

1.9 Load Forecasting Methods

We can categorize these as follows:

- Analytical methods
- Nonanalytical methods

1.9.1 Analytical Methods: Trending

There are various algorithms that interpolate past small-area load growth and apply regression methods as discussed in Section 1.7 These extrapolate based on past load values—these are simple, require minimum data, and are easy to apply. The best option is the multiple regression curve fitting of a cube polynomial to most recent, about 6 years of small-area peak history. However, this extrapolation can lead to inaccuracy. When a "horizon load estimate" is inputted, the accuracy can be much improved, see Figure 1.11 curves *A* and *B*.

Other sources of error in trending forecast are as follows:

Load transfer coupling (LTC) regression. The load is moved from one service area to another—these load shifts may be temporary or permanent. These create severe accuracy problems. The exact amount of load transfer may not be measured. The accuracy can be improved with a modification to the regression curve fit method, called LTC. The exact amount of load transfer need not be known. LTC is not described, see Reference [7].

The other problem is inability to trend vacant areas. Future growth in a vacant area can often be estimated by assuming that the continuous load growth in an area can continue

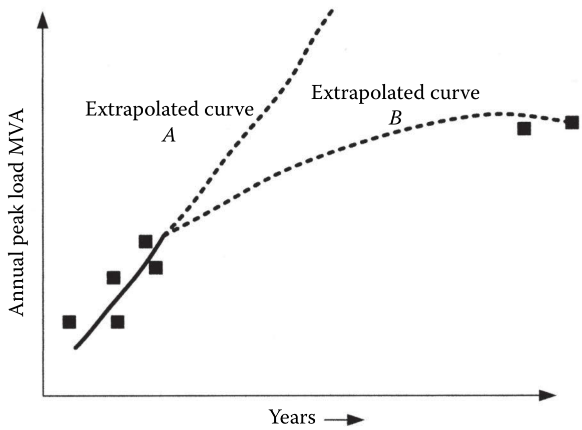

FIGURE 1.11
(a) Trending analysis and extrapolation with no ultimate or horizon year load, curve *A*; (b) with input of horizon year loads, curve *B*.

only if vacant areas within the region start growing. A technique called vacant area interference applies this concept in a repetitive and hierarchical manner [8].

Another variation of the trending methods is clustering template matching method—a set of about six typical *"s"* curves of various shapes called templates are used to forecast the load in a small area.

1.9.2 Spatial Trending

An improvement in trending can be made by including parameters other than load history. For example, the load density will be higher in the central core of the city. Small-area trending used a function that is the sum of one or more monotonically decreasing functions of distance from the central urban pole, see Figure 1.12.

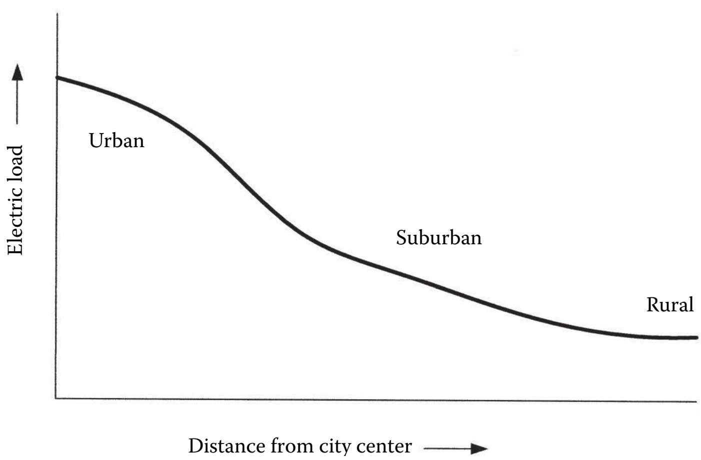

FIGURE 1.12
Spatial load distribution urban, suburban, and rural, as the distance from the city center increases.

1.9.3 Multivariate Trending

Multivariate trending used as many as 30 non-load-related measurements on each small area. These total variables are called "data vector." The computer program was developed under EPRI, known as "multivariate" [6]. This produced better results compared to other trending methods as per a series of test results conducted by EPRI.

1.9.4 Land-Use Simulations

Land-use spatial methods involve an intermediate forecast of growth of land-use type and density as a first step in electrical load forecast. The steps are listed as follows:

- The total growth and the regional nature of its geographical distribution are determined on a class-by-class basis. This means determining growth rated for each land-use class.
- Assign growth to small areas and determine how much of total growth in each class occurs in which small area.
- Determine the load of each small area based on its forecast land-use class composition and a class-based load model which converts class-based use to kW of load.

All land-use-based methods employ analyses in each of three categories, see Figure 1.13.

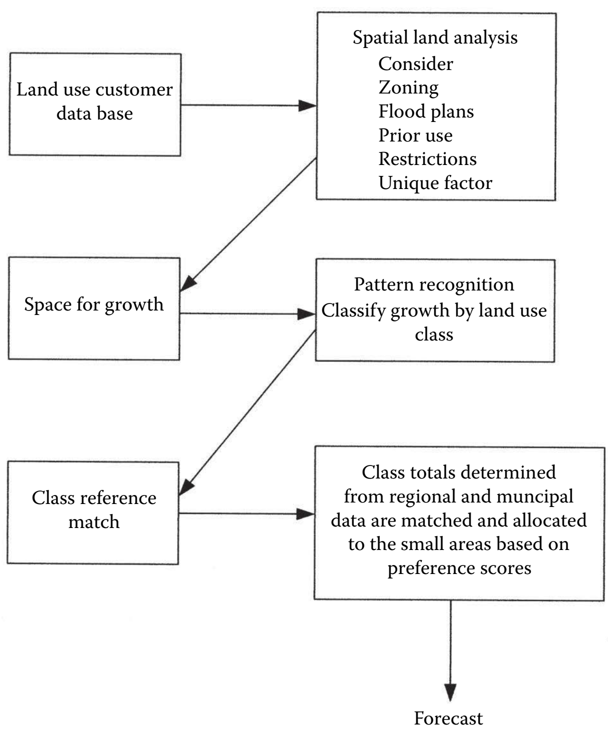

FIGURE 1.13
Land-use-based load estimation simulation steps.

1.9.5 Nonanalytical Methods

These rely on users intuition and do not use computer simulations. A "color-book" approach is described in Reference [9]. A map of utility area is divided into a series of grid lines. The amount of existing land use, for example, industrial, residential, and commercial is colored in on the map. Future land use based on user's intuition is similarly coded in to the map. An average load density for each land use is determined from experience, survey data, and utilities overall system load forecast.

Figure 1.14 shows the accuracy of major types of load forecasts over a period of time, also see Reference [10].

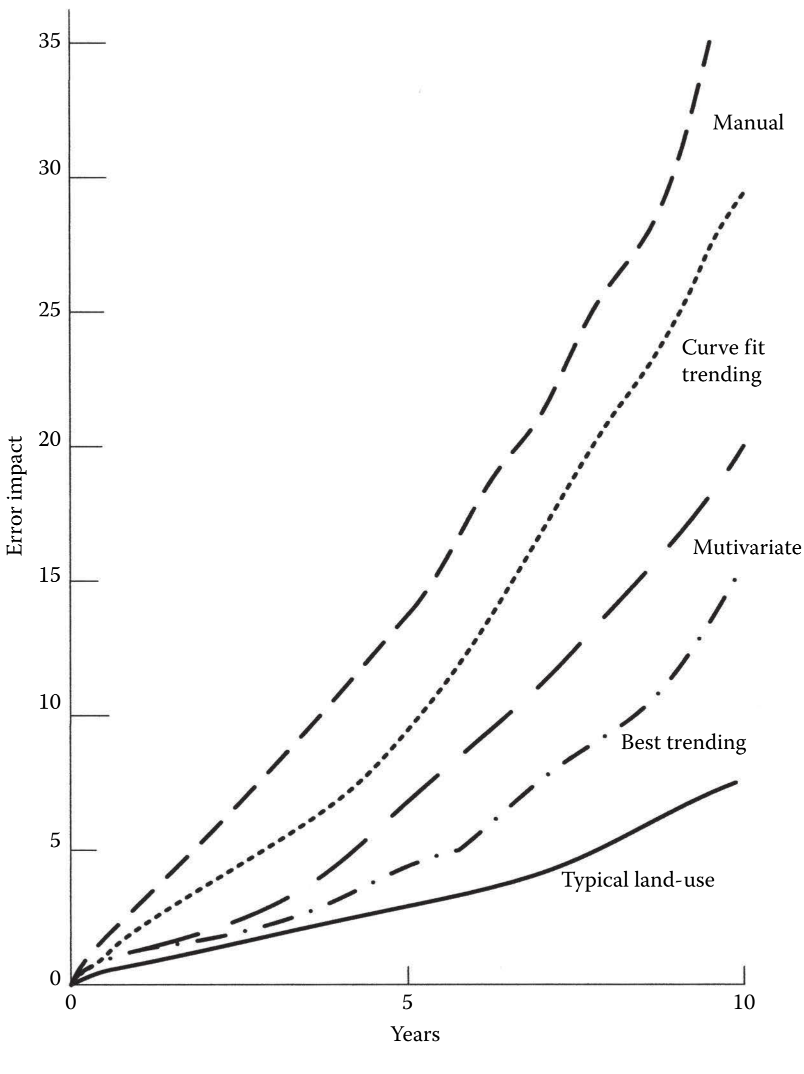

FIGURE 1.14
Estimated load forecasting errors with different methodologies.

1.10 Iterative Nature of Load Flow Problem

Load flow solutions require numerical techniques, discussed in the chapters to follow. To explain the nature of load flow, consider a simple circuit, as shown in Figure 1.15a, which depicts a 2.5 MVA 13.8–0.48 kV transformer, carrying a constant impedance type of 2000 kVA load at a power factor of 0.8 lagging. The transformer impedance and source short-circuit levels are as shown. It is required to calculate the transformer secondary voltage.

The loads on buses are invariably specified in terms of MW/Mvar or KVA and power factor. In this small problem, we need to find the current flowing through the system impedance, to calculate the voltage, assuming that the source voltage is known. However, the load current at the secondary of the transformer, in the above example, cannot be calculated, as the voltage is not known. Thus, there are two unknowns: current and voltage that depend on each other.

We conceive a "swing bus" or an "infinite bus," which is a hypothetical bus, for the load flow problem. It is an ideal Thévenin source as well as an ideal Norton's source. In other words, any amount of current taken from this source does not result in any voltage drop. This means zero Thévenin impedance.

Figure 1.15b shows the equivalent impedance circuit in ohms referred to 480 V side. Load flow programs work on a pu base, generally 100 or 10 MVA. All impedances are converted to this common base.

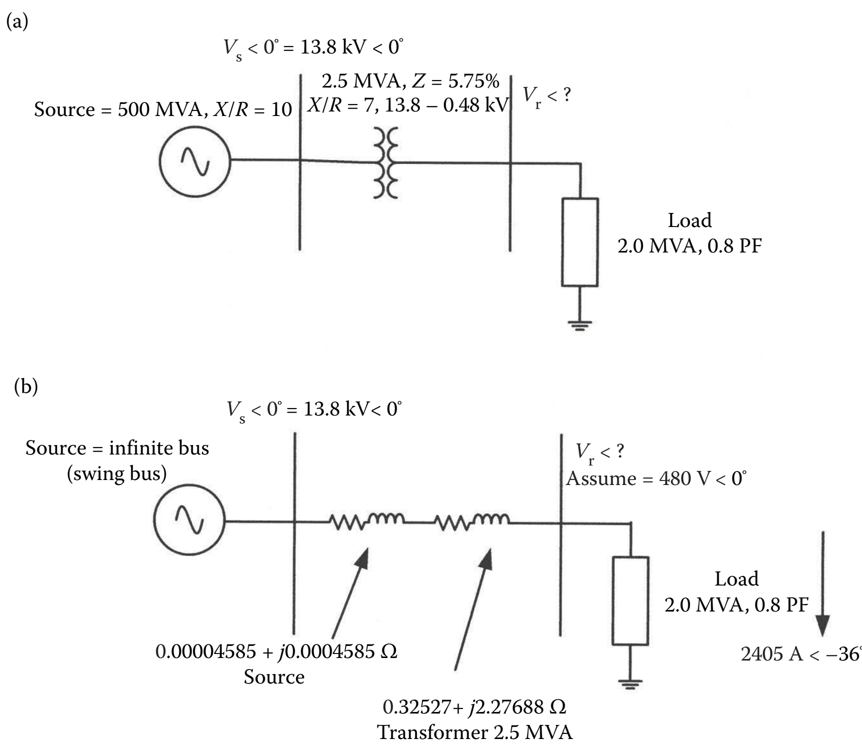

FIGURE 1.15
Hand calculations of secondary voltage on 2.5 MVA transformer carrying 2.0 MVA load at 0.8 PF: (a) system configuration; (b) step one of the calculations.

As a first step assume that

$$V_s < 0° = V_R < 0°$$

This means no voltage drop on load flow. Here, we have only one load bus, and practically, there may be hundreds or thousands of load buses interconnected through cables, transformer, or overhead lines. Initially, a voltage equal to 1.0 pu at an angle of 0° is assumed for all the buses.

As the secondary voltage is assumed as 480<0°, we can calculate the load current: 4520 < –36°.

As it is constant impedance load, the load impedance is 0.199<36°.

Then, the transformer secondary voltage is

$$480 - \left[\sqrt{3}(2405)(0.8 - j0.6)(0.000795 + j0.005704)\right] = 480 - 16.905 - j17.021$$

$$= |463.40| < -2.105°$$

This is the first estimate of the voltage. The final result can be close to it or very much different.

Based on this first estimate of voltage, recalculate the load current. As it is a constant impedance load, the current varies in proportion to the load. The new load current is

$$\frac{463.09 - j17.02}{1.99(0.8 + j0.6)} = 1810 - j1465$$

Then, the second estimate of the voltage is

$$480 - \left[\sqrt{3}(1810 - j1465)(0.000795 + j0.005704)\right] = 480 - 16.965 - j15.864$$

$$= |463.30| < -2.180°$$

This is fairly close to the first result. It is a simple one-bus system that we are studying to illustrate the procedure. The iterations are stopped when the differences between two successive calculations go on decreasing. The final result is printed when the difference goes as little as 0.00001 for the Gauss–Seidel method. (The tolerance limits are user adjustable.) In this case, we say that the load flow has converged.

Sometimes, the results in successive calculations may first narrow down and then increase; the results may swing and a convergence may not be achieved. The characteristics of various load flow algorithms are discussed in the chapters to follow.

Using a computer program with Gauss–Seidel method, the load flow converges in 14 iterations and the final value of the voltage is 46.392 V. The power input to the transformer is 1.5404 MW and 1.211 Mvar (power factor 77.90 lagging); the system losses are 0.013 MW and 0.092 Mvar.

The transformer is provided with off-load taps of +5%, +2.5%, rated tap, –2.5% and –5% on the 13.8 kV windings. By setting the taps to –5% (13,110 V), the turns ratio of the transformer is reduced and the secondary voltage rises by 5% at no-load. Table 1.2 shows the

TABLE 1.2
Effect of Off-Load Tap Settings on Load Flow

		Load on Transformer			Losses	
Tap	**Bus Voltage (%)**	**MW**	**Mvar**	**PF**	**MW**	**Mvar**
–5%	101.59	1.606	1.342	77.88 Lag	0.014	0.105
–2.5%	99.00	1.582	1.274	77.89 Lag	0.014	0.097
Rated	96.54	1.504	1.211	77.90 Lag	0.013	0.092
+2.5%	94.20	1.4323	1.152	77.91 Lag	0.012	0.088
+5%	91.97	1.365	1.098	77.91 Lag	0.012	0.083

effect of various tap settings on load flow. Note that the transformer load varies as we have modeled a constant impedance load. Various load types will behave differently. Transformers may be provided with under load tap changing and the appropriate taps to maintain a voltage close to the rated voltage can be automatically selected in the load flow. These aspects are further discussed in the chapters to follow.

Practically, the load flow can be complex. There may be a number of constraints and certain objectives are required to be met, for example,

- Active power cost minimization
- Active power loss minimization
- Minimize control operations
- Unit commitment

The control variables include the following:

- Real and reactive power generation
- Net interchange control, see Chapter 2
- Load scheduling, see Chapter 2
- Control voltage settings
- Load tap changer and phase-shifter controls

The equality and nonequality constraints are as follows:

- Generation and load balance
- Generator active and reactive power limits
- Branch and tie-line load flow limits
- Bus voltage limits
- Limits on control variables

The optimal power flow is a nonlinear numerical optimization problem, discussed in Chapters 11 and 12.

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2

Automatic Generation and Frequency Control—AGC and AFC

2.1 Fundamental Concepts

We have seen that the load at any instant in a power system is not constant and is continuously varying. For the power system stability and control, it is necessary that the varying load demand is met by loading and unloading the generating sources, taking these out of service and bringing them in service as soon as practical. The contingency load flow adds further complexity to this fundamental problem of meeting the varying load demand. Under contingency conditions, say under a fault when a certain route of power flow is taken out of service, the load demand should be met by alternate routes of power flows. Automatic generation control (AGC) is defined as the automatic regulation of the mechanical power to synchronous generators within a predefined control area.

- Power system frequency is one criterion for such controls. For satisfactory operation, the power system frequency should remain nearly constant.
- The performance of generating units is dependent upon frequency. The frequency deviations can seriously impact the operations of auxiliaries like synchronous and induction motors.
- The steam turbines can be damaged due to operation at a reduced or higher frequency. The safe operating times at frequency other than the normal which are critical for operation are supplied by the manufacturers, and a guideline is provided in ANSI/IEEE standard 122, also see Volume 4.
- The frequency is dependent upon active power balance; a change in load cannot be suddenly met by rotating synchronous generators. On a sudden load on a synchronous generator, driven by a steam turbine, the governing system must act to open the steam valves, which can only occur with a certain time constant. Thus, the frequency of the generator will dip. Conversely, on load rejection, the frequency will rise. The synchronous generators may be tripped out with a short-time delay, if the frequency happens to be beyond a certain range (generally indicative of fault conditions).
- As so many generators are paralleled in a grid system supplying power, some means to allocate changes in demand must be provided.
- The operations of all loads vary with the frequency. See EPRI load models with respect to variations in voltage and frequency in Chapter 6.
- The undervoltage due to sudden reactive power demand can give rise to voltage instability; see Volume 4, and also Chapter 9. The active and reactive power flows

can be decoupled, as further discussed. While reactive power flow mainly impacts voltage stability, a sudden increase or decrease in the active power impacts frequency.

- The under frequency load shedding is resorted to, in extreme cases, limit the area of shutdown and counteract voltage instability.
- A speed governor on each generating unit provides primary speed control function, while a central control allocates generation priorities.
- Each area has to be controlled to maintain a scheduled power interchange. The control of generation and frequency is commonly referred to as load-frequency control (LFC).
- The extensive use of timing clocks and timing devices, based on frequency, requires accurate maintenance of synchronous time, which is proportional to integral of frequency.
- It may take 11–12 h or more to start a cold turbine unit and bring it on line. Thus, there should be some spinning reserves in the system which can be quickly loaded on an increase in the demand. Some units are designated "unit on regulation" or there may be more units to meet the changing load demand which are regulated. The base units operate continuously.
- This indicates the problem of unit commitment. How to allocate units most efficiently and economically to meet the load demand? This is further discussed in Chapter 12 considering fuel costs, operating costs, and transmission line losses.

2.2 Control Centers

There are two levels of controls. One is for bulk power generation and transmission (system control center) and the other for distribution (distribution control center). There may be many distribution centers depending on the area served.

The system control functions are as follows:

Automatic generation control (AGC)

Load-frequency control (LFC)

Economic dispatch control (EDC)

These functions overlap each other to some extent.

2.2.1 Scheduling and Forecasting

Table 2.1 describes these functions that are discussed in the following sections.

2.2.1.1 Hourly Interchange

The projected load for hour of interchange must be determined in advance (generally 1–4 h in advance). The production cost of interchange is the cost of total committed load including previous commitments and the new interchange minus the previous commitments. These are determined by assuming that units are economically utilized.

TABLE 2.1

Scheduling and Forecasting

Time Frame		Required Data
Hourly interchange	Hours	Current unit status
Transmission maintenance scheduling	Days	Projected unit status and typical bus load data
Unit commitment	Days or weeks	Long-term interchange forecast Projected unit availability
Generator maintenance scheduling	Weeks or months	Overall unit and load data

2.2.1.2 Unit Commitment

A unit commitment program simulates the generation system over a period of time from a couple of days to a couple of weeks. Economic dispatch, reserve and reliability evaluation, and operating costs are simulated considering unit priority list and other such criteria. The renewable, solar, and wind generation (Volume 1) add to this complexity of programming. The objective is to optimize the total operating cost including startups, within all the imposed constraints. The basic inputs are the daily projected peak loads and long-term interchange schedules already agreed.

2.2.1.3 Transmission and Generator Maintenance Scheduling

As the transmission and generating systems are becoming more complex, these functions are now taken by complex computer simulations. It is not so simple to take a unit or section of the system under maintenance. A study is required, which simulates the system at the time of desired outage. This involves load forecasting, economic dispatch, investigations of bus voltages, projected units on line and standby, and keeping the load demand uninterrupted without excessive risks.

2.3 Controls in Real Time

Controls in real time signify "now" and in the present. The various aspects interconnections are shown in Figure 2.1. Note the interdependence and interrelations between various components. A block wise description is provided.

2.3.1 AGC and LFC

Fundamental concepts have been outlined in Section 2.1. The LFC system operates to regulate the system generation under various load conditions for proper performance of interconnected systems and optimize the economy of dispatch. Earlier, a constant frequency mode of LFC was used; today tie-line bias mode is most common. It strives to keep net interchange and frequency at prescheduled values.

First total generation required to meet area requirements are ascertained. Then, this generation can be apportioned to various units, including renewable sources (Volume 1) to

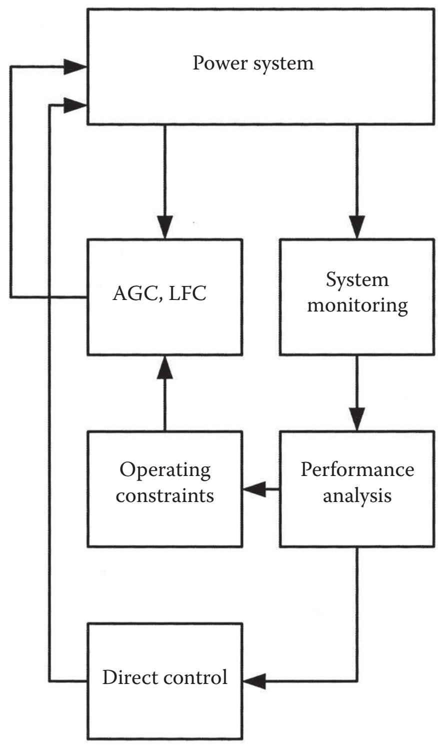

FIGURE 2.1
Forecasting and scheduling functions.

optimize the production costs, transmission losses, relative efficiencies, and environmental constraints like nitrous oxide emissions. The data for tie-line bias regulation are power flow and system frequency. With incremental power loading, the power output for each generator must also be monitored.

The performance should meet the following objectives:

- Minimize fuel costs.
- Avoid sustained operation of generation in undesirable modes, like overloads, out of range set points and avoid unnecessary operation on the generating units, for example, transient overloads.

2.3.2 System Monitoring

The complexity of power systems has grown and the data acquisition is an important link in the control strategies. The data are too voluminous to indicate on meters. Large CRT screens, CRT displays, and color one line diagrams are the modern tools with data updated every 10 s or so. Any switching or fault operation has the priority over the data communication systems.

The supervisory control means monitoring and control of circuit breaker status. The communication facilities for data acquisition and supervisory control are common.

2.3.3 Performance Analysis

A deterministic approach is required to evaluate the security of the system. At a time and periodically, a group of contingencies are selected and the system response monitored for any weaknesses. Undervoltages, overloads, and frequency deviations may be detected, and in some preprogrammed situations, possible corrective actions are displayed to the operating personnel. The manual controls can override the displayed solutions. A very extensive data collection system is required to support this activity (Volume 4). A real-time load flow situation is displayed, and topology of transmission systems and substations, and circuit breaker monitoring can be examined.

2.3.4 Operating Constraints

The constraints are applied say to prevent overloads and other anomalies during operation. Security controlled dispatch systems signify that additional constraints are added to economic dispatch. In real time, the magnitude and phase angle of bus voltages should be known and also MW and Mvar flows. This requires accurate contingency simulations. Allowance has to be made in the measurement and transmission errors of data, and techniques are available for exploiting the redundancy in the measurements. To obtain a better estimate, state estimation (Volume 1) is being accepted as a necessary tool for security monitoring. Human error and judgments are taking a back seat in the modern automation processes.

2.3.5 Direct Control

Much effort is being directed for directly controlling some power system operations, like voltage regulations, exciter controls, control of turbine steam valves, under-load tap changing from a centralized station rather than from a localized location. The objective is to optimize the transient stability performance of the power system. This requires the following:

- Fast data acquisition systems
- Fast actuators' and sensors
- High-speed computers

2.4 Past Data Logging

The future planning and current operation are dependent on the past data logging. The past data that should be available for easy access are as follows:

- Post-disturbance data—any post-disturbance data, say for a fault or overload situation or tripping, are captured and sampled at high speed for analysis and possible future remedial action.
- Dispatcher actions and the specific situations which give rise to these.
- Load survey is helpful for validating computer-based load flow study results. The monthly and yearly peaks and minimums are recorded.

- Energy recording consists of MWh in and out of the tie-line and system net interchange.
- Cost reconstruction provides the means for calculating production costs for a given combination of units operating under given constraints. This is used to determine the cost of interchange and energy billing.
- Intercompany billing data.
- Operating reports are statistical daily reports containing data such as hour of the peak load, total generation, and load interchange.
- Data index reports provide an indicator how well the AGC and LFC systems are operating; and if enough regulating capacity is available. These indexes may be used to improve the system regulation and controls.

2.5 Deregulated Market

Volume 1, Chapter 2, "Modern Electrical Systems" describes the new structure of utility companies GENCO, TRANSCO, DISTCO, and the deregulation of power industry, not repeated here. As discussed above, the interchanges of power can be from any source, from neighboring systems or the power can be *wheeled off* across intermediate systems, depending upon economics of such interchanges. There may be a central pool for dispatch which may economize the interchanges. Wheeling of power could result in transmission losses.

Other types of interchanges between utilities include capacity interchange, diversity interchange, energy banking, and inadvertent power exchange; and these could lead to economic benefits. To maximize these benefits, several utility companies have formed power pools that incorporate a common dispatch center.

2.5.1 Auction-Based Mechanism

In this competitive environment, an auction marker mechanism is one of the ways to price-based operations. It is a method of matching buyers and sellers through bids and offers. Each player generates bids (specified amount of electricity at a given price) and submits to the auctioneer, who matches the buy and sell bids to the approval of contract evaluator. This role of evaluation is played by an independent system operator. The mechanism allows for cash futures and planning markets.

A *forward contract* is an agreement in which the seller agrees to deliver a particular amount of electricity with a specified quality at a specified time to the buyer.

A *future contract* is a financial instrument that allows traders to lock-in a price in some future month—to manage their risks for future losses or gains.

A *future–option contract* is a form of insurance that gives the right (but not the obligation) to an option purchaser to buy or sell future contracts at a given price. Both the options and future contracts are financial instruments to minimize risk.

A reader may draw similarities with a commodity trading stock market.

With the competitive market structure, several technical issues arise, i.e., the capability of network to handle power flows reliably and securely. The Federal Energy Regulatory Commission (FERC) issued orders that specify the role of available transmission capacity (ATC). In using the transmission access for effective competition and established the Open

Access Same Time Information System (OASIS), operational since January 1977. Following it National Reliability Council (NERC) initiated establishment of ATC evaluations. It is a measure of ability of the interconnected electrical systems to transfer power reliability from one location to another considering transmission paths between two areas. Total transfer capability (TTC) determines it and is based on the following:

1. Thermal limits: All facility loadings are within normal ratings and all voltages are within normal limits.
2. Stability: The electrical system is capable of riding through dynamic power swings consequent to loss of any single electrical system element like a transmission line, transformer, or a generating unit.
3. Post-dynamic power swings: After the swings subside and a new operating state is restored, post-item 2, and after operation of any automatic systems, but before any operator initiated system adjustments are made, all transmission loadings are within emergency limits and all voltages within emergency limits, Chapter 9.
4. Post-contingency loadings: With reference to condition (1) when post-contingency loadings reach normal thermal limits, at a transfer level below that at which the first contingency transfer limits are reached, the transfer limits are the ones at which such normal ratings are reached.
5. Multiple contingencies: In some areas, multiple contingencies are required to determine transfer capability limits.

2.5.1.1 Transmission Reliability Margin

Transmission reliability margin is the transfer capability necessary to ensure that the interconnected transmission network is secure under a range of reasonable system conditions. This accounts for uncertainties in the system and operating conditions. Also the system needs to be flexible for secure operations.

2.5.1.2 Capacity Benefit Margin

This is the amount of transfer capability reserved to ensure access to generation from interconnected neighboring systems to meet generation reliability requirements.

Thus, we can write

$$\text{ATC} = \text{TTC} - \text{TRM} - \text{CBM} - \text{existing transmission commitments} \tag{2.1}$$

where,

TTC = min (thermal limits, voltage limits, and transient stability limits).

Transmission reliability margin (TRM): It is the amount of transfer capability necessary to ensure that the interconnected transmission network is secure under various sources of uncertainty under system operating conditions.

Capacity benefit margin (CBM): It is the amount of transfer capability reserved by load-serving entities to ensure access to generation from interconnected neighboring systems.

FERC requires the calculations and posting on OASIS, continuous ATC information for the next hour, month, and for following 12 months. The accuracy of these data depends on many factors, like use of accurate power flow methods and simulations to calculate ATC.

2.6 Load-Frequency Control

Normal governor control relates the load of a unit to the system frequency. Supplementary controls change the load versus frequency characteristics of the governor. Referring to Figure 2.2, a load change, ΔP, changes the electrical torque of the generator which causes a mismatch between the mechanical torque produced by the turbine and this results in speed variations. A rigorous method is solution of the swing equations of the generator using transient stability type of programs. As power is proportional to rotor speed in radians multiplied by the torque, the following relations exist.

2.6.1 Single Generator with Isochronous Governor

Isochronous means constant speed. Referring to Figure 2.2, P_0 is the active MW supplied and ΔP is the incremental load addition. The shaft speed or the frequency of the generator terminal voltage is sensed, and governor operates a valve that controls the flow of steam and therefore mechanical output of the turbine. Define the following:

T_m = mechanical torque (pu)
T_e = electrical torque (pu)
T_a = accelerating torque (pu)
P_m = mechanical power
P_e = electrical power
P_0 = initial active load
ω_r = rotor speed in radians
$\Delta\omega_r$ = rotor speed deviation

Then

$$
\begin{aligned}
P &= P_0 + \Delta P \\
T &= T_0 + \Delta T \\
\omega_r &= \omega_0 + \Delta\omega_r
\end{aligned}
\tag{2.2}
$$

Then, we can write

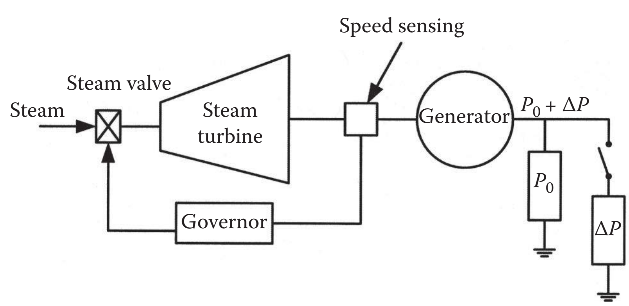

FIGURE 2.2
Step load addition to an isolated generator.

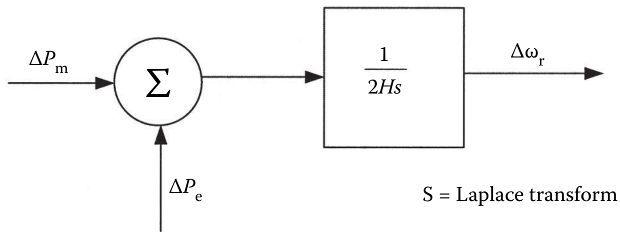

FIGURE 2.3
Transfer function relating speed and power.

$$P_0 + \Delta P = (\omega_0 + \Delta\omega_r)(T_0 + \Delta T) \tag{2.3}$$

from where

$$\Delta P \approx \omega_0 \Delta T + T_0 \Delta\omega_r \tag{2.4}$$

In steady state, electrical and mechanical torques are equal and (ω_0) = 1 pu:

$$\Delta P_m - \Delta P_e = \Delta T_m - \Delta T_e \tag{2.5}$$

Equation 2.5 represents an obvious conclusion. The transfer function relating speed and power can be represented as in Figure 2.3. *H* is the inertia constant, see Chapter 7 for its definition and equation. The turbine mechanical power is a function of valve position: percentage open or closed.

It remains to define the load-frequency characteristics, which vary with the type of load, see Chapter 6. The loads can be divided into two parts; one part is not dependent on frequency and the other part is

$$\Delta P_e = \Delta P_L + D\Delta\omega_r \tag{2.6}$$

where,

ΔP_L = part of the load change that is not frequency sensitive
$D\Delta\omega_r$ = part of the load change that is frequency sensitive
D = damping factor

The response of an isochronous governor is shown in Figure 2.4. As speed drops, the turbine power begins to increase; ultimately, the turbine picks up the additional load and the speed returns to 60 Hz.

2.6.2 Two (or Multiple) Generators with Isochronous Governor

An isochronous governor works well with a single turbine. When more than one turbine and governor are present, they will fight with each other, Figure 2.5. This will be obvious if two governors with slightly different speed controls operate in parallel. Trying to control with two different set points will cause the power to oscillate between the units. This is often referred to as hunting.

The transfer function of a governor with steady-state feedback is illustrated in Figure 2.6. Define *R* as

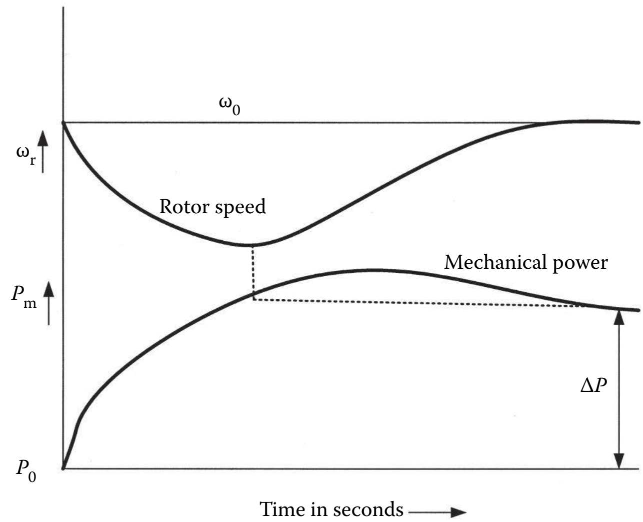

FIGURE 2.4
Response of an isochronous governor.

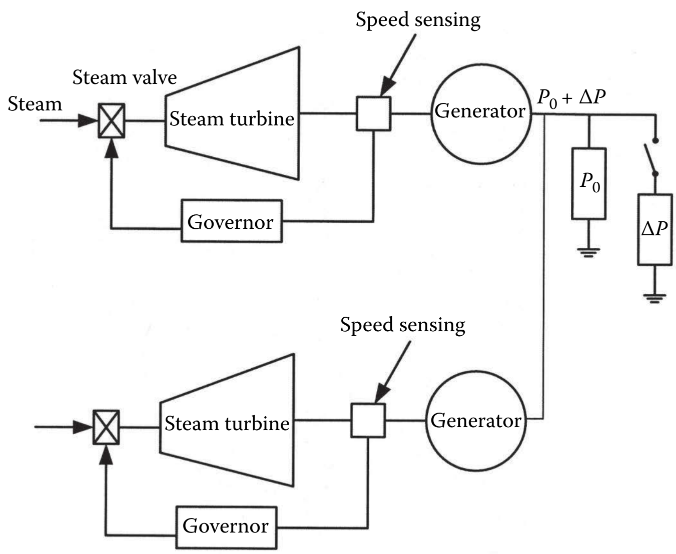

FIGURE 2.5
Multiple generators with step load addition.

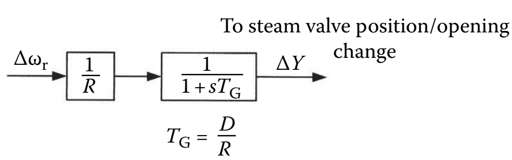

FIGURE 2.6
Block control circuit diagram of an isochronous governor with droop.