CHAPTER 1

INTRODUCTION

The mathematics related to optimization is not new. Even its application to solve practical problems has already spanned well over half a century. During the World War II, the use of Operation Research techniques to optimize the use and movement of men and material was not uncommon. The application to the power industry is also over 40 years old. With the advent of digital computers, system dispatch to minimize cost came into vogue. Electrical engineering science also borrowed mathematical models that were popular in management sciences. Such models are now used in planning system expansion, system operation, and ratemaking.

The emphasis of this book is on the electrical industry. Despite this, it is not at all surprising that the mathematical formulation of the problems for solution in this industry bears a remarkable resemblance to those in other industries. Consequently, notwithstanding the emphasis on the electric power industry, we digress occasionally into problems in other fields. Such an excursion not only illustrates the common themes in the problems of industries, but also will demonstrate the beauty of this branch of applied mathematics.

The electric power industry has undergone colossal changes in the last decade. It appears that such changes in the future are also inevitable. Because of such changes, the incorporation of optimization into decision-making has also become inevitable. By and large, the engineering curriculum has not permitted teaching undergraduate students optimization theory. It is not uncommon to see graduates not having been exposed even to linear optimization such as linear programs. In the evolving deregulated electric power industry, models used for system dispatch, auctions of rights and hedging instruments, and models for settlement of markets, all

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use optimization of one type or another. In particular, Optimal Power Flow (OPF), which has been around for some 30 plus years, has come into prominence for system dispatch, security-constrained unit commitment, declaration of locational marginal prices in a transmission network, and a myriad of other tasks. The primary intent of this book is to familiarize those in the electric power industry with the principles and the development of such models. The emphasis is more toward the practical applications of optimization principles. However, since a mere practical use of an algorithm without a theoretical understanding would not develop an engineer in his or her profession, some theoretical background is also included. However, a student might prefer to glean only the practical applications by studying the solved problems of chapters.

The primary intent of this book is to provide a practical insight into optimization technique via demonstration programs in Microsoft Excel. The book is organized essentially into three parts and appendices. The first part addresses mathematical preliminaries and shows examples of some mathematical techniques via solved problems. The second part deals with linear optimization techniques. This part is in consists of chapters, Chapter 3 addresses theoretical material followed by solved problems in Chapter 4 demonstrating practical applications. The third part addresses some mathematical theory of nonlinear optimization in Chapter 5, unconstrained nonlinear optimization in Chapter 6, and constrained optimization in Chapter 7. Solved problems of practical interest are in Chapter 8. The first appendix deals with basic principles of electricity directed toward those who are not engineers. Additional appendices deal with background material addressing network theory and other matters related to optimization.

This book has a secondary purpose as well. Because of the changes in the industry, there are an increasing number of professionals with some or no engineering background at all. Such professionals usually are engaged in markets, trading, and the settlement activities of this evolving deregulated industry. There is a need for them to understand the inner workings of the mathematical models that they use in their day-to-day tasks. Such an understanding will make their tasks more interesting, and, possibly, more pleasant. To such readers, Appendix A.2 provides some basic principles of electricity, particularly as applied to networks. Clearly, in one book of this nature a reader cannot be made into an electrical engineer. The reason for outlining the basic principles is to impart to such readers an appreciation of network equations, in particular the concept of reactive power. Clearly, the outline in Appendix A.2 is too simplistic and redundant for engineers who are familiar with network equations.

1.1 DEREGULATED ELECTRICITY MARKETS — TERMINOLOGY AND ACRONYMS

There are several acronyms and terminologies associated with the deregulated electricity industry. It is impossible to list them all. However, the following is a brief discussion of a few of them as they pertain to the subject matter of the remaining chapters of this book.

In the past, an electric utility had the responsibility to install generation and transmission to serve load. In this structure, called the vertically integrated structure, utilities were permitted by their respective regulatory agencies to set rates that recovered prudent costs plus some return on investment. The cost of energy, by and large, was based on the average cost of providing it.

In the deregulated scenario, the entities that generate energy, build and own transmission, and serve load may all be different. The entity generating energy is called the Generator (note the capitalization), and the entity serving load is called the Load Serving Entity (LSE) or Load. Similarly, Transmission providers have different labels. Depending on the organizational structure and tariff, some associated names are: Independent Transmission Company (ITC), Independent Transmission Provider (ITP), Transmission Company (TRANSCO), Grid Company (GRIDCO), Regional Transmission Organization (RTO), and Transmission Provider (TP). The Independent System Operator (ISO) operates the generation and transmission network, and does not earn profits.

There are different rules and the structure of markets at different locations. Consequently, it is not possible to discuss the nuances and rules of different markets. However, the essential feature of all markets is that the Generators submit offer bids (called offers) to supply energy (prices and quantities) and also submit other commodities such as reserve capacity and regulating capacity. The System Operator dispatches generation to minimize cost, making sure that the reliability of the system is not jeopardized. Some markets accept demand side bids in which loads or LSE submit price quantity bids for energy withdrawals from the grid. The System Operator reconciles offers and bids, which essentially resembles an auction. Examples in this book indicate this process.

In 1979, Bohn and co-workers (Caramanis et al., 1982) introduced the concept of Spot Prices. This is now called Locational Marginal Price (LMP) or Location-Based Marginal Price (LBMP). In this method, the cost of supplying the next unit of energy is calculated at each major node (bus bar) of the electrical network. This, therefore, represents the marginal cost of supplying the energy at those locations. The basis of computing LMP is by using a procedure called Optimal Power Flow (OPF). The OPF program optimizes the system dispatch to minimize cost.

In markets that adopt LMP pricing, withdrawal of energy from the network is charged at the marginal rate at that node (LMP times consumption), and injection of energy by Generators is paid at this rate at the node of injection.

Examples in subsequent chapters outline the OPF procedure and show how to compute LMP from the results of OPF.

1.2 STUDY PLAN

There are other books that discuss the application of optimization techniques to power systems (Mamoh, 2000; Song, 2002). The emphasis of this book is on using Excel spreadsheets to educate the reader about practical aspects of optimization. Of course, some theoretical background material on optimization cannot be avoided. The expectation is that by setting up Excel spreadsheets, the reader becomes somewhat of a programmer gaining an understanding of the theoretical basis of algorithms. Readers who are well-versed in the theoretical underpinnings of algorithms and want to pursue solution techniques further may consult Mamoh (2000), which uses MATLAB to obtain solutions.

It is obvious that the reader is expected to have access to a personal computer and be familiar with the use of Microsoft Excel. The examples of this book, in the interest of clear exposition, are of limited size, generally restricted to less than five or six design variables. That is not to say that larger problems cannot be solved by using such spreadsheets, limited only by the capability of Excel program (help menu of Excel outlines that there cannot be more than a certain number of variables and other such limits on its use). The question then is—How can one write larger spreadsheets? The answer to this is that as the reader gains confidence in setting-up small spreadsheets, their extension to larger problems becomes readily obvious. Writing larger programs is a process of increasing the number of choice variables and the number of constraints—but the fundamental requirement is that one should be able to conceive and formulate optimization problems.

For the reader familiar with the mathematics of matrices and wishing to learn practical applications of linear optimization first, it is suggested that he or she proceed directly to Chapters 4 and 8. In a similar vein, readers familiar with the mathematics of nonlinear optimization may skip Chapter 5 and proceed directly to Chapters 6, 7, and 8 to study the applications of nonlinear optimization. Of course, those who want a refresher of matrix operations and solution of linear inequalities will do well to read Chapters 2 and 3. The philosophy of linear optimization, in particular the simplex method, is the topic of discussion in Chapter 3. Chapters 6 and 7 describe the mathematics behind the algorithms for unconstrained and constrained nonlinear optimization methods.

Appendix A.1 is directed to readers without training in electrical engineering. Consequently, electrical engineers can well avoid this rudimentary section of the book. Appendix B is devoted to the development of ac network flow equations. The equations derived there are used in the chapters of this book to solve optimal load flow problems. Appendix C develops the mathematics behind least-square error techniques leading to state estimation.

While it is expedient to gain a practical understanding of optimization techniques, it is rewarding to understand some theoretical underpinnings to demystify the process of obtaining a solution. Hence, for those that take the practical route first, it is suggested that during the course of time, they revisit the chapters that explain the theory behind the methods of optimization. Understandably, in view of many excellent books on the mathematical theory of these methods, this book's intent is to give a quick sketch of popular procedures rather than that of mathematical rigor. Of course, the punctilious reader will do well to read all chapters in their serial order, as well as the reference materials listed in the bibliography.

1.3 ORGANIZATION AND CONVENTIONS

The marginal notes in the text indicate the appropriate Excel file to be opened by the reader that corresponds to the text. These files can be downloaded from Wiley's ftp site at ftp://ftp.wiley.com/public/sci_tech_med/electric_power/. It is expected of the student to study the spreadsheet carefully, checking the formulas associated with the cells. After some exercises of that nature, it may become either faster or unnecessary for the student to examine details of formulas associated with the cells. Additionally, it is clear that spreadsheets can be set in different fashions depending on the preference of the user. In the spreadsheets associated with this book, no attempt has been made to set up an efficient procedure because their intent is only to illustrate the solution procedure. Consequently, a reader wishing to extend the solution to a larger system is cautioned against a mere reproduction and expansion of the spreadsheets. Although such a procedure may be acceptable in some cases, it is better to examine an efficient way of setting up spreadsheets for larger problems.

The conventions used in this book are as follows. Lowercase letters signify scalars. For example, x_1 and x_2 are scalars. However, lowercase bold letters represent vectors. For example, $\mathbf{y}$ is a vector of dimension 3 (a three-vector) whose elements are y_1, y_2, y_3. The elements of a vector are normally written vertically as

$$\mathbf{y} = \begin{pmatrix} y_1 \\ y_2 \\ y_3 \end{pmatrix},$$

or as $\mathbf{y} = [y_1, y_2, y_3]^T$.

Uppercase bold letters represent matrices. For example, $[\mathbf{A}]$ or $(\mathbf{A})$ represents a matrix. Sometimes, when there is no confusion with network parameters (see below), a matrix is simply represented by uppercase bold letters as $\mathbf{A}$. If $\mathbf{A}$ is a 4×3 matrix, $\mathbf{A}$ can be written as $[\mathbf{A}] = [\mathbf{a}_1, \mathbf{a}_2, \mathbf{a}_3]$, where $\mathbf{a}_1$, $\mathbf{a}_2$, and $\mathbf{a}_3$ are "four-vectors." A four-vector implies that the vector contains four scalar components. Each vector, for example $\mathbf{a}_1$, can be expressed in terms of its scalar components as $\mathbf{a}_1 = [a_{11}, a_{21}, a_{31}, a_{41}]^T$. The "row-column" notation is used for the subscripts of matrix elements. Thus, a_{13} implies the element in the first row and the third column of matrix $\mathbf{A}$.

The exceptions to this convention are symbols related to network equations. The general convention used by power engineers is that voltage, current, power, and reactive power are expressed in uppercase letters. Thus V, I, S, P, and Q represent the voltage, current, complex power, real, and reactive powers at a single node while bold uppercase letters $\mathbf{V}$, $\mathbf{I}$, $\mathbf{S}$, $\mathbf{P}$, and $\mathbf{Q}$ represent a vectors of the same variables at several nodes. The power angle at a node δ is always represented in lowercase, while $\boldsymbol{\delta}$ represents a vector of angles at several nodes. The admittance of branches is also written in uppercase such as Y_{34} to represent the admittance of branch 3–4. However, an uppercase bold $\mathbf{Y}$ with associated braces represents the $\mathbf{Y}$ matrix.

To represent matrices in the network equations, bold letters with the associated braces is used. For example, $[\mathbf{A}]$ or $(\mathbf{Y})$ represents an A matrix or Y matrix. These conventions will be obvious from their context.