POWER SYSTEM ANALYSIS

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POWER SYSTEM ANALYSIS

To David, Dodie, Gramp, Larry,
Michael, Mom, Nanny, and Robert

PREFACE

This book is intended to serve as a textbook for an introductory course in power system analysis. It is estimated that the material presented can be easily covered in six semester credit hours. Prerequisite topics are sinusoidal steady state circuit theory, basic matrix notations and operations, and basic computer programming; a course in machines is desirable but not essential. The student should have at least a junior standing.

It is assumed that the book will be used at some schools in courses required of all electrical engineering students and so the topics included were selected because of their "double-valued quality"—their importance not only to power specialty students, but their possession of general academic merit. This is particularly true of the first half of the book. Thus, the study of symmetrical components is important not only because of its application to power systems, but also because of its contribution to an understanding of degrees of freedom and linear transformations. This does not mean the material is "watered down", but that topics of central importance are developed with an attempt to avoid being sidetracked with necessary, but minor, details.

The introductory chapter was written to demonstrate the basic importance of electrical energy conversion and delivery systems in a technological society. A short history of the electrical power industry is provided. The SI unit system is presented and electrical power transmission is discussed. Consideration is given to available sources of energy.

The remainder of the book is divided into five basic parts. Chapter 2 presents circuit theory as applied to power systems. This material is expected to be part review, and part new material for most students, and features an early emphasis on symmetrical components. The student is encouraged to think of the balanced case as a special case of the general unbalanced situation. Matrix methods are used to keep the equations organized, but are developed in such a way that physical understanding is not compromised. Chapter 3 explains the basics of power system representation and the per unit system. Chapters 4, 5, and 6 develop traditional mathematical models for the transmission line, the transformer, and the synchronous machine. The approach used compromises completeness with the need to develop simplified system models. The book is not a machines text, but harmonizes with rigorous and thorough work in machines.

Chapter 7 presents a discussion of the power flow problem. The objective is to give students a clear understanding of the problem, its solution, its application, and the use of the computer. Students should finish with the confidence that they could write their own working power flow programs.

Chapters 8 through 11 deal with fault analysis and system protection. The four basic fault types are discussed, with symmetrical components used as the analytical approach. The fault analysis problem is formulated for computer solution. Considerable emphasis and detail is given to the system protection problem. Breakers, relays, and instrument transformers are covered. Distance relaying is explained.

Chapter 12 of the book deals with the general problem of power system stability. Transient, and steady state stability concepts are explained. The single machine problem is discussed in some detail, with governor and exciter effects included. The equal area method is applied to the problem. The discussion is extended to the multimachine siutation and the problem solved by Runge–Kutta methods adapted to computer formulation.

The extent to which computer methods are used to solve power system problems is of necessity a compromise; there was not available the time, the space, or the inclination to provide much detail on how to optimally program power system problems. More advanced courses in the area would be taken by power specialists, and other textbooks would be more appropriate.

The units used throughout the book are those of the SI system because of its simplicity and its increasing acceptance. Also it was decided to work mainly in the per unit system because the use of per unit in some situations simplifies the system circuit models, and all indications are that the power industry will continue to operate in this system. The advantage of numerical simplicity produced by per unit is offset somewhat by some differences between the system equations before and after scaling. Experience has indicated that per unit can cause students some difficulties and appropriate coverage has been given to this topic.

Finally, this book was written for the student, not the instructor. The role of the instructor is to clarify difficult points, to "color" the material by adding anecdotes from his or her own experience, and to generally inspire the student in this area. This book is intended to help both partners in the learning experience. Also, it should satisfy the dual needs of the nonpower student studying the material as a required subject, and the future power specialist who needs instruction in the fundamentals of power system analysis.

Charles A. Gross

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C. A. G.

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INTRODUCTION

"Go placidly amid the noise and the haste, and remember what peace there may be in silence."

Max Ehrmann, DESIDERATA

Introduction

Human civilized progress has historically been in proportion to the human ability to control energy. Humanity can feed itself through the efforts of a small minority of the population only because we know how to channel sufficient energy into these activities. In the past we could use energy in essentially unlimited quantities (per person) with little regard for its impact on the environment—there were relatively few of us and nature by comparison was of "infinite" extent. Today the inexorable geometric progression of population growth has caught up with us, making us acutely aware that our planet resources are indeed finite and the simple ways of producing controllable energy are no longer reasonable.

The forms energy assumes in nature are manifold, including:

- Radiant—the most obvious example is sunlight.
- Thermal—an example is the thermal energy stored in the earth's interior.
- Chemical—the energy content of fuels such as wood, coal, and oil is stored in chemical form.
- Kinetic—moving bodies, such as planets revolving in their orbits, represent energy.
- Potential—any system with forces varying with position has potential energy.
- Nuclear—forces that bind atom parts together relate to energy.
- Electrical—an example of "natural" electricity is lightning.

Like all living things, we use natural energy directly (e.g., sunlight for light) or make use of natural conversion processes for our purposes (e.g., sunlight for growing crops). Human intelligence allows us to go beyond these primitive methods and contrive ways of storing, controlling, and converting energy into forms suitable for use when and where we decide. The problem is not that of having insufficient energy; it is incredibly abundant. What is needed are technologies that can channel energy into beneficial applications.

What are these beneficial applications? We require light sources, cooling and heating capability, transportation systems, communication systems, industrial and manufacturing processes, construction applications, and agricultural production. All are broad areas of energy use; a detailed list would be voluminous. In each area, energy converted into the electrical form can be used extensively. Some of the inherent advantages of electrical energy include the following.

- It is amenable to sophisticated control. Consider the incredibly complicated control exerted on an electron beam to produce a TV picture.
- It can be transmitted at the speed of light.
- It can be transmitted and converted to other forms at typically high efficiencies.
- It is inherently pollution free. Conversion into the electrical form does, of course, involve many important environmental problems.
- Conversion to other forms is direct.

Electrical energy generation and delivery systems are and will continue to be of fundamental importance to a technological society, and therefore to engineering. We shall discuss the basic structure of such systems, focusing our study on electrical considerations. Bear in mind that electrical power systems are extremely large by virtually any measure: capital invested, physical size, amount of energy delivered, and so on. It is not practical to design a totally new system "from the ground up"; we must always take into account the existing system. The system will be, is being, and has been continually modified to take advantage of technological advances. To appreciate the existing system it is useful to review its evolution from a historical perspective.

1-1 A Brief History of the Power Industry

Prior to 1800 the study of electrical and magnetic phenomena was of interest to only a few scientists. William Gilbert, C. A. de Coulomb, Luigi Galvani, Otto von Guericke, Benjamin Franklin, Alessandro Volta, and a few others had made significant contributions to a meager store of piecemeal knowledge about electricity, but at that time no applications were known, and studies were motivated only by intellectual curiosity. People illuminated their homes with candles, whale oil lamps, and kerosene lamps, and motive power was supplied mostly by people and draft animals.

From about 1800 to 1810 commercial illuminating gas companies were formed, first in Europe and shortly thereafter in the United States. The tallow candle and kerosene interests, sensing vigorous competition from this young industry, actively opposed gas lighting, describing it as a health menace and emphasizing its explosive potential. However, the basic advantage of more light at cheaper cost could not be suppressed indefinitely, and steady growth in the industry occurred throughout the nineteenth century, with the industry at its zenith in about 1885.

Exciting advances in understanding electrical and magnetic phenomena occurred during this same period. Humphrey Davy, Andre Ampere, Georg Ohm and Karl Gauss had made significant discoveries, but the discovery that was to become basic to elevating electricity from its status as an interesting scientific phenomena to a major technology with far reaching social implications was made by two independent workers, Michael Faraday and Joseph Henry. Ampere, and others, had already observed that magnetic fields were created by electric currents; yet no one had discovered how electrical currents could be produced from magnetic fields. Faraday worked on such problems from 1821 to 1831, finally succeeding in formulating the great law that bears his name. He subsequently built a machine that generated a voltage based on magnetic induction principles. Workers now had an electrical source that rivalled—and ultimately far exceeded—the capacities of voltaic piles and Leyden jars. Independently, Joseph Henry also discovered electromagnetic induction at about the same time, and went on to apply his discoveries to many areas, including electromagnets and the telegraph.

Several workers, including Charles Wheatstone, Alfred Varley, Werner and Carl Siemens, and Z. T. Gramme applied the induction principle to the construction of primitive electrical generators in the period from about 1840 into the 1870s. About the same time a phenomenon discovered some years earlier began to receive serious attention as a practical light source. It was observed that when two current-carrying carbon electrodes were drawn apart an electric arc of intense brilliance was formed.

Commercialization of arc lighting was achieved in the 1870s, with the first uses in lighthouse illumination; additional applications were street lighting and other outdoor installations. Predictably, arc lighting provided the stimulus to develop better and more efficient generators. An American engineer, C. F. Brush, made notable contributions in this area with his series arc lighting system and associated generator. The system was practical and grew into a successful business with little opposition from gas illuminating companies, since they did not directly compete for the same applications. The principle objection to arc lighting was its high intensity, making it unsuitable for most indoor applications. For those uses, gas lighting was still the best choice.

Observers had noted as early as 1809 that current-carrying materials could heat to the point of incandescence. The idea of use as a light source was obvious, and a great many workers tried to produce such a device. The main problem was that the incandescent material quickly consumed itself. In an effort to retard or prevent this destruction, the material was encased in a globe filled with inert gas or a vacuum. The problem of placing a material with a high melting point, proper conductance, and good illuminating properties into a globe with a proper atmosphere proved too much for the technology of the time. Some small improvement was noted from time to time, but until the 1870s the electric lamp was far from a practical reality. The struggle never quite ended, however, chiefly because of continued improvements in electrical generators. It became clear that if and when an incandescent electric light was developed, an electrical source would be available.

A 29-year-old inventor named Thomas Edison came to Menlo Park, New Jersey, in 1875 to establish an electrical laboratory to work on a number of projects, including the development of an incandescent electric lamp. In October 1879, after innumerable unsuccessful trials and experiments, an enclosed evacuated bulb containing a carbonized cotton thread filament was energized. The lamp glowed for about 44 hours until it finally burned out. There now was no doubt that a practical incandescent lamp could be developed. Edison subsequently improved the lamp, and also proposed a new generator design that proved to have an unbelievable efficiency of almost 90%. Some three years later, in 1882, the first system installed to sell electrical energy for incandescent lighting in the United States began operation from Pearl Street Station in New York City. The system was dc, three wire, 220/110 volts, and supplied a load of Edison lamps with a total power requirement of 30 kilowatts. This, and other early systems, were the beginnings of what would develop into one of the world's largest industries.

The early electrical companies referred to themselves as "illuminating companies" since lighting was their only service. However, very soon a technical problem was encountered that persists today: a company's load would build, starting at dark, hold roughly constant throughout the early evening and drop precipitously at about 11 P.M. to about half or less. It was obvious that here was an elaborate system that lay idle, or at least underutilized, for most of the time. Could other applications be found that could take up the slack? The electric motor was already known, and the existence of an electrical supply was a ready-made incentive to its refinement and commercial acceptance. Use of electrical motive power quickly became popular, and was employed for many applications. In recognition of their broader role, electric companies began to name themselves "power and light companies."

Another technical problem was encountered. Increasing loads meant increasing currents, which caused unacceptable voltage drops if generating stations were located any appreciable distance from the loads. The requirement of keeping generation in close proximity to loads became increasingly difficult because acceptable generation sites were frequently unavailable. It was known that electrical power was proportional to the