POWER SYSTEM ANALYSIS

SECOND EDITION

CHARLES A. GROSS

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ABOUT THE AUTHOR

Dr. Gross holds a B.S. in Physics and a B.S. in electrical engineering from the University of Alabama. He also received his M.S. and Ph.D. degrees in electrical engineering from the University of Missouri at Rolla. He has twenty-three years teaching experience, and his industrial experience includes work with the firm of Howard, Needles, Tammen, and Bergendoff (consulting engineering); the Naval Ordinance Test Station, China Lake, California; the Tennessee Valley Authority; the Los Angeles Department of Water and Power; Southern Services; the Alabama Electric Cooperative; the General Electric Company; and the Electric Power Research Institute. Dr. Gross has won several teaching awards at UMR and Auburn, and was selected as the recipient of the Square D Chair of Electrical Power Engineering in 1982.

Dr. Gross is a member of Tau Beta Pi, Eta Kappa Nu, Pi Mu Epsilon, and Sigma Xi. He is a senior member of IEEE and is a Registered Professional Engineer. The first edition of his book. *Power System Analysis*, was published by John Wiley & Sons, Inc., in the spring of 1979.

PREFACE

This second edition of *Power System Analysis* is a text for introductory courses in power system analysis. The material presented here can be covered in a two-semester course (6 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. Students should have at least a junior standing.

A new feature of the second edition is the discussion of balanced three-phase circuit concepts as a special case of a balanced N-phase operation. This approach will enhance students' understanding of the three-phase case. Over the years, there have been many conventions, jargons, and practices adopted in electric power engineering that are difficult to defend as rational to a beginning student of the subject. A concerted effort is made here to render such concepts as clear as possible, preserving those traditional conventions that are reasonable and avoiding those that are basically illogical. Thus, *Power System Analysis* should be equally readable by new students and experienced power engineers alike.

The introductory chapter presents the case for the basic importance of electrical energy conversion and delivery systems for a technological society. The structure of an electric power system is discussed as well as the basic concepts of electric load modeling. Some consideration is given to available sources of electrical energy. Appendix A contains some information on SI units.

Chapter 2 presents circuit theory as applied to power systems, with additional material on N-phase. Matrix methods are used to organize the equations; these methods are developed in such a way that physical understanding is not compromised. Background material on matrix methods is provided in Appendix C. Chapter 3 explains the basics of power system representation. The author continues to believe that per-unit scaling causes most people considerable difficulty. Thus, the topic is treated in some depth in Chapters 3 and 5. Chapters 4-6 develop traditional mathematical models for the transmission line, the transformer, and the synchronous machine. The approach used is a compromise between completeness and the need to develop simplified system models; for example, the development of line models, simplified in Chapter 4, is expanded in Appendix D.

Chapter 7 has been extensively revised to provide a thorough fundamental treatment of the power flow problem. The objective is to give students a clear understanding of the problem, its solution, application, and the role of the computer. Chapter 8 provides a basic treatment of power system operation and control. The interrelationships between $P - f$ and $Q - V$ are presented. The economic dispatch problem is defined, formulated, and solved.

Chapters 9-11 deal with fault analysis and system protection. The second edition covers new material on linear couplers and [Z] methods. The fault analysis problem is formulated for a computer solution. Considerable emphasis and detail are given to the system protection problem. Breakers, relays, and instrument transformers are covered, and distance relaying is explained.

Chapter 12 deals with the general problem of power system stability. Transient, dynamic, and steady-state stability are explained. The single-machine/infinite-bus problem is treated in detail. The discussion is extended to the multimachine situation and the problem solved by Runge-Kutta's methods adapted to computer formulation. Governor and exciter effects are discussed.

A major feature of the second edition is the presentation of examples which is used to illustrate technical points of interest throughout the book. These provide examples of continuity between the various major power system analyses. A majority of the end-of-chapter problems are either revised or completely new.

The second edition is designed to achieve the same educational objectives as the first and is an aid to understanding the fundamentals of power system analysis.

Charles A. Gross

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INTRODUCTION

Socrates said that the unconsidered life is not worth living. If the statement is valid, as I believe it is, then those of us who are engineers in the final quarter of the twentieth century are confronted with certain questions of compelling interest. What is the nature of the engineering experience in our time? What is it like to be an engineer at the moment that the profession has achieved unprecedented successes, and simultaneously is being accused of having brought our civilization to the brink of ruin?

Samuel C. Florman
The Existential Pleasures of Engineering

Human civilized progress has historically been in proportion to man's† ability to control energy. When primitive man was limited to his own muscle power, he spent virtually all of his time hunting, gathering, and basically staying alive. Like all living things, man uses natural energy directly (e.g., sunlight for light) or natural conversion processes for his purposes (e.g., sunlight for growing crops). Human intelligence transcends these primitive methods and contrives ways of storing, controlling, and converting energy into forms suitable for our use when and where we decide. The discovery of fire, the wheel, and animal power are all major achievements in the ascent of man, and all are important advancements in controlling energy. As man learned to control larger amounts of energy in a variety of forms, a smaller percentage of the population was required to provide the necessities of life, releasing more of us to work in the arts, medicine, literature, mathematics, science, and engineering.

Why the need to control and use energy? We need energy for light sources, cooling and heating capability, transportation systems, communication systems, industrial and manufacturing processes, construction applications, and agricultural production. These are just broad areas of energy use; a detailed list would be quite extensive.

In 1973, the world experienced what many described as an "energy shortage." Actually, we live in a veritable sea of energy, bathed in radiation from the sun; cooled by huge masses of moving air; moved by powerful ocean currents; and occasionally destroyed by the gargantuan forces of hurricanes, tornadoes, earthquakes, volcanoes, and the like. What really happened was that a shift in international politics had made major changes in the economics of energy conversion from fossil fuel sources. It is true that the world's fossil fuel reserves are limited and we must eventually turn to other energy sources, including nuclear and solar. However, in the future, as well as in the past, man's control of energy must account for political, economic, sociological, and religious factors as well as those that are technological.

From the time when man uprooted a few bushes to fashion a bed for himself, he has attempted to alter his environment for his benefit and comfort. As the human population grew, it became evident that altering the natural environment for some immediate advantage was not necessarily in man's long-term best interests. Also, solutions that benefit one segment of society may do so at the expense of another: Dumping sewage in a free-flowing stream may solve my waste disposal problem; however, my downstream neighbor's lack of enthusiasm for the solution is understandable. And so it shall always be: Man will continue to alter his environment as long as he exists. What is needed are technological and political systems designed with wisdom, rationality, and justice.

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† *Man*, and the pronouns *he* and *his*, and so forth, are defined here to mean human being. No sexist meaning should be inferred.

Energy comes in many forms, such as

Radiant energy the most obvious example is sunlight.

Thermal energy an example is the thermal energy stored in the earth's interior.

Chemical energy the energy content of such fuels as wood, coal, and oil is stored in the chemical form.

Kinetic energy moving bodies, such as planets revolving in their orbits, represent energy.

Potential energy any system that has forces that vary with position has potential energy.

Nuclear energy forces that bind together atom parts are related to energy.

Electrical energy an example of "natural" electricity is lightning.

Energy in the electrical form has many inherent advantages.

- It is amenable to sophisticated control. Consider the incredibly complicated control exerted on an electron beam to produce a television picture.
- It can be transmittted at the speed of light.
- It can be transmitted and converted into 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 into other forms is direct and usually simple.

Electrical energy's major disadvantage is that it is expensive to produce.

This book provides a technical introductory discussion to the electrical aspects of electrical generation and delivery systems. We shall discuss the basic structure of such systems, focusing our study on electrical engineering 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 forth. 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 interested only a few scientists. William Gilbert, C. A. de Coulomb, Luigi Galvani, Otto von Guericke, Benjamin Franklin, Alessandro Volta, and a few others had all 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 lighted their homes with candles and whale oil 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 a lower 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, André Ampère, George Ohm, and Karl Gauss had made significant discoveries, but the discovery that was to elevate 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. Ampère 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 rivaled, and ultimately far exceeded, the capacities of voltaic piles and Leyden jars. Independently, the American 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 to the 1870s. About the same time a phenomenon discovered some years earlier began to receive serious attention once more 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 1870's, 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 founded 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 these uses, gas lighting was still the best choice.

Observers had noted as early as 1809 that current-carrying materials could be heated to the point of incandescence. The idea of using such materials 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 in 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 due to 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 was now 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 operating from Pearl Street Station in New York City. The system was direct current three wire, 220/110 V and supplied a load of Edison lamps with a total power requirement of 30 kW. 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 electric load would build up starting at dark, hold roughly constant throughout the early evening, then drop precipitously about 11 P.M. to about half or less. It was obvious that here was an elaborate system that lay idle, or at least under-used, for most of the time. Could other applications be found to 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. Electrical motive power quickly became popular and was used for many applications. In recognition of their broader role, electric companies began to call 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 unacceptable, because acceptable generation sites were frequently unavailable. It was known that electrical power was proportional to the product of voltage and current, clearly, less current would be needed at a higher voltage. Unfortunately, higher voltage was not desirable from either the viewpoint of present technology or customer safety.