Electric Power Transmission Systems

Second Edition

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Preface

This book is intended to give a first-level presentation of the technical aspects exhibited by electric systems which transmit power from the generators to the loads. It should be of value to the technologist who builds, maintains, and operates electric power equipment; to the student engineer who later goes on to more advanced study in preparation for design and analysis of power systems; and to those persons whose technical problems are closely associated with the electric power industry.

This second edition of the book is an expanded version of the first one, laying greater emphasis on those aspects of power systems which concern a broader spectrum of engineers and technologists in the performance of their tasks. In particular, the calculation of short-circuit currents due to symmetrical faults and its impact on the ratings of circuit-interrupting devices have been expounded. Besides, a new chapter on distribution has been added, the analytical determination of transmission-line voltages has been stressed, and the load-flow problem has been introduced.

Problems have been added in this edition requesting the student to use a computer for their solution. Some are simple enough to be solved with a hand-held programmable calculator; others are more involved requiring the formation of a data base; a few require an iterative algorithm. It is hoped that these problems will spur the student to a greater use of the computational facilities at his disposal.

It is assumed that the reader has had a basic course in electric circuit theory. His or her knowledge of mathematics should include elementary algebra and calculus, and complex numbers. Chapter 2 summarizes most of the relations used in the remainder of the book.

The first edition of the book was produced by the first author under the sponsorship of the American Electric Power System. The second edition was prepared by the second author while on sabbatical leave from his institute.

The authors acknowledge the assistance of many organizations that made available data presented in this book.

The Indiana and Michigan Electric Company provided many photographs and circuit diagrams.

Public Service Indiana provided photographs of an ac generator and a damaged circuit breaker.

Westinghouse Electric Corporation provided tables of overhead line constants, data on transformer impedances, and a photograph of programmable controller.

Anaconda Wire and Cable Company supplied pictures of typical overhead and underground cables.

The Institute of Electrical and Electronics Engineers granted permission for publication of a table of machine reactances from ANSI/IEEE Standards.

Some of the diagrams of circuit breakers are adaptations of more detailed diagrams published in bulletins of Allis Chalmers Manufacturing Company and General Electric Company.

Edwin Cohen

Contents

chapter 1

The Electric Power System

1-1. REQUIREMENTS OF AN ELECTRIC SUPPLY SYSTEM

A great amount of effort is necessary to maintain an electric power supply within the requirements of the various types of customers served. Large investments are necessary, and continuing advancements in methods must be made as loads steadily increase from year to year. Some of the requirements for electric power supply are recognized by most consumers, such as proper voltage, availability of power on demand, reliability, and reasonable cost. Other characteristics, such as frequency, wave shape, and phase balance, are seldom recognized by the customer but are given constant attention by the utility power engineers.

The voltage of the power supply at the customer's service entrance must be held substantially constant. Variations in supply voltage are, from the consumer's view, detrimental in various respects. For example, below-normal voltage substantially reduces the light output from incandescent lamps. Above-normal voltage increases the light output but substantially reduces the life of the lamp. Motors operated at below-normal voltage draw abnormally high currents and may overheat, even when carrying no more than the rated horsepower load. Overvoltage on a motor may cause excessive heat loss in the iron of the motor, wasting energy and perhaps damaging the machine. Service voltages are usually specified by a nominal value and the voltage then maintained close to this value, deviating perhaps less then 5 percent above or below the nominal value. For example, in a 120-volt residential supply circuit, the voltage might normally vary betweer the limits of 115 and 125 volts as customer load and system conditions change throughout the day.

Power must be available to the consumer in any amount that he may require from minute to minute. For example, motors may be started or shut down, lights may be turned on or off, without advance warning to the electric power company. As electrical energy cannot be stored (except to a limited extent in storage batteries), the changing loads impose severe demands on the control equipment of any electrical power system. The operating staff must continually study load patterns to predict in advance those major load changes that follow known schedules, such as the starting and shutting down of factories at prescribed hours each day.

The demands for reliability of service increase daily as our industrial and social environment becomes more complex. Modern industry is almost totally dependent on electric power for its operation. Homes and office buildings are lighted, heated, and ventilated by electric power. In some instances loss of electric power may even pose a threat to life itself. Electric power, like everything else that is man-made, can never be absolutely reliable. Occasional interruptions to service in limited areas will continue. Interruptions to large areas remain a possibility, although such occurrences may be very infrequent. Further interconnection of electric supply systems over wide areas; continuing development of reliable automated control systems and apparatus; provision of additional reserve facilities; and further effort in developing personnel to engineer, design, construct, maintain, and operate these facilities will continue to improve the reliability of the electric power supply.

The cost of electric power is a prime consideration in the design and operation of electric power systems. Although the cost of almost all commodities has risen steadily over the past many years, the cost per kilowatt-hour of electrical energy has actually declined. This decrease in cost has been possible because of improved efficiencies of the generating stations and distribution systems. Although franchises often grant the electric power company exclusive rights for the supply of electric power to an area, there is keen competition between electric power and other forms of energy, particularly for heating and for certain heavy-load industrial processes.

The power-supply requirements just discussed are all well known to most electric power users. There are, however, other specifications to the electric power supply which are so effectively handled by the power companies that consumers are seldom aware that such requirements are of importance.

The frequency of electric power supply in the United States is almost entirely 60 hertz (formerly cycles per second). The frequency of a system is dependent entirely upon the speed at which the supply generator is rotated by its prime mover. Hence frequency control is basically a matter of speed control of the machines in the generating stations. Modern speed-control systems are very effective and hold frequency almost constant; deviations are seldom greater than 0.02 hertz.

In an ac system the voltage continually varies with time, at one instant being positive and a short time later being negative, going through 60 complete cycles of change in each second. Ideally a plot of the time change should be a sine wave, as shown in Fig. 1-1a. In poorly designed generating

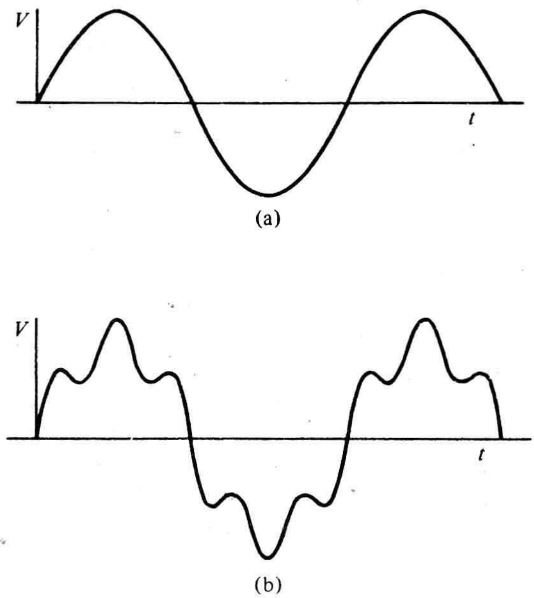

FIG. 1-1. (a) A voltage which varies sinusoidally with time. (b) A voltage wave shape which contains a fifth harmonic.

equipment, harmonics may be present and the wave shape may be somewhat as shown in Fig. 1-1b. The presence of harmonics produces unnecessary losses in the customer's equipment and sometimes produces hum in nearby telephone lines. The voltage wave shape is basically determined by the construction of the generation equipment. The power companies put specification limitations on the harmonic content of generator voltages and so require equipment manufacturers to design and build their machines to minimize trouble from this effect.

Practically all major power equipment is supplied by three-phase circuits. Three-phase circuits are essentially three single-phase circuits each of which has its own sine wave of voltage. If phase balance is perfect, each of the three voltages is of the same magnitude but displaced in time from the other two by one third of a cycle. Modern three-phase generators are designed to have almost perfect phase balance, as shown in Fig. 1-2.

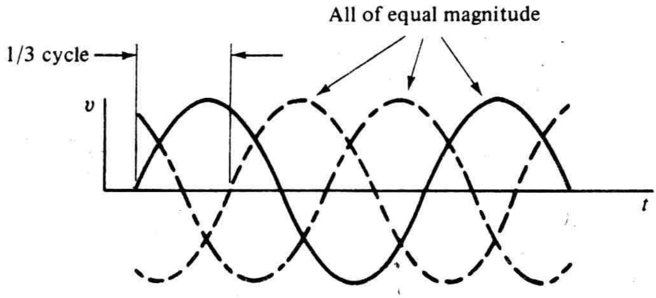

FIG. 1-2. The three voltage waves produced by a balanced three-phase generator.

Voltage unbalances produce unnecessary losses in three-phase motors and reduce the maximum starting torque. Few customers are aware of the problem of phase balance except in those rare instances where abnormal conditions are encountered.

Practically all consumers use the electric power supply to operate motors, transformers, and other devices in which iron is magnetized by currents from the electric power system. The currents that magnetize the iron do not influence the electric power bill (except where power-factor clauses apply) and so are seldom recognized by the customer. Nevertheless, provision must be made in the power system for supplying these magnetizing currents, and so their supply must be considered in specifying the characteristics of the generating, transmission, and distribution facilities that deliver power to the customer.

1-2. MINIMUM POWER SYSTEM

Electric power systems may be of great complexity and spread over large geographical areas. There is, however, a minimum system that can function as an electric power supply as shown in Fig. 1-3. The system consists of an energy source, a prime mover, a generator, and a load. Supervising it is some sort of a control system.

The *energy source* may be coal, gas, or oil burned in a furnace to heat water and generate steam in a boiler; it may be fissionable material which, in a nuclear reactor, will heat water to produce steam; it may be water in a pond at an elevation above the generating station; or it may be oil or gas burned in an internal combustion engine.

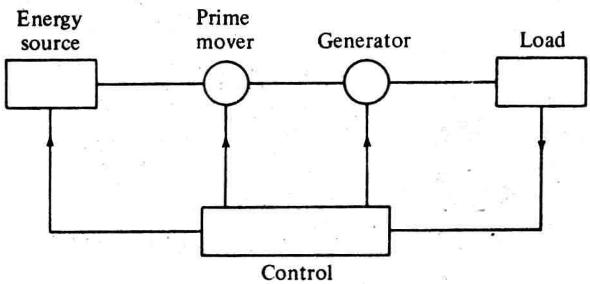

FIG. 1-3. The minimum electric power system.

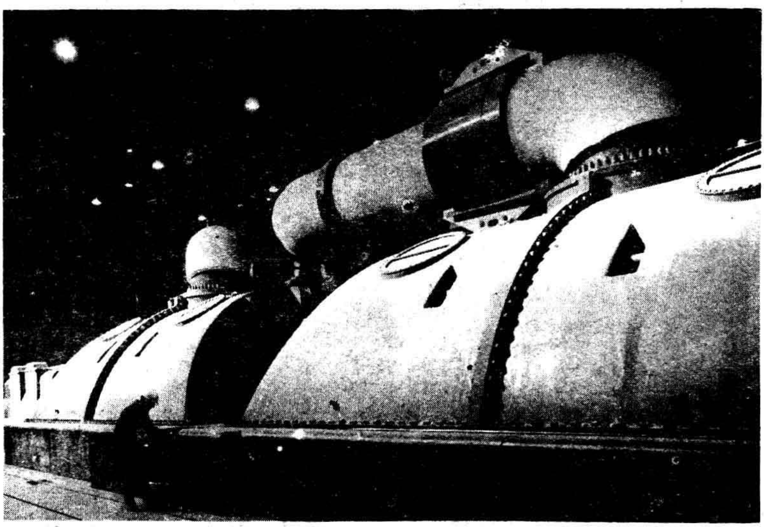

FIG. 1-4. A large steam turbine which drives a generator.

The *prime mover* may be a steam-driven turbine (Fig. 1-4), a hydraulic turbine or water wheel (Fig. 1-5), or an internal combustion engine (Fig. 1-6). Each one of these prime movers has the ability to convert energy in the form of heat, falling water, or fuel into rotation of a shaft, which in turn will drive the generator.

The *generator* may be an ac machine (or alternator) (Fig. 1-7), the type of machine that supplies most of the electric power used today. In special cases the generator may be a dc machine (Fig. 1-8).

The electrical *load* on the generator in Fig. 1-3 may be lights, motors, heaters, or other devices, alone or in combination. Probably the load will vary from minute to minute as different demands occur.

The *control system* functions to keep the speed of the machines sub-

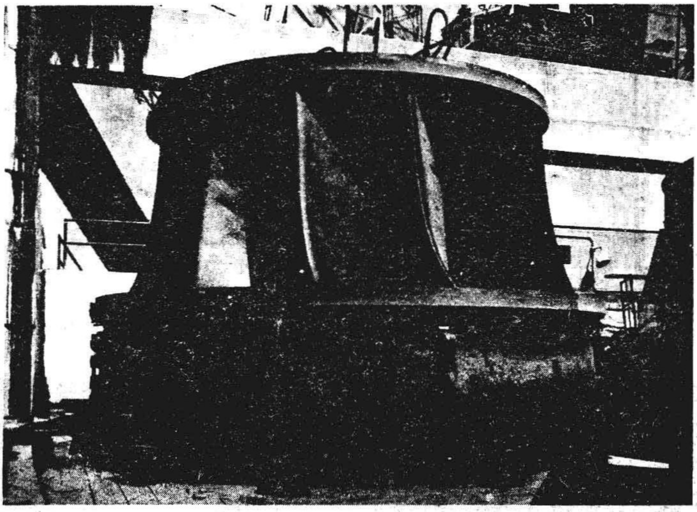

FIG. 1-5. The rotor of a 204,000 H.P. water wheel.

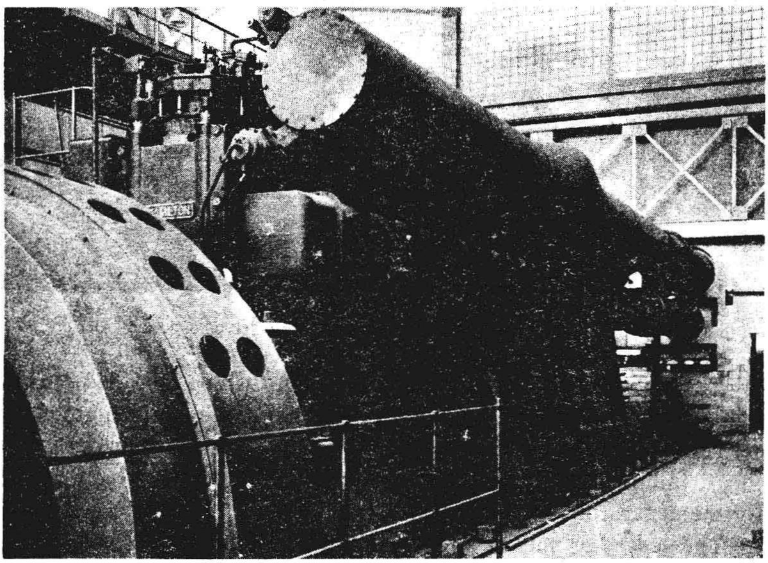

FIG. 1-6. A diesel engine.

stantially constant and the voltage within prescribed limits, even though the load may change. To meet these changing load conditions, it is necessary for fuel input to change, for the prime-mover input to vary, and for the torque on the shaft from the prime mover to the generator to change

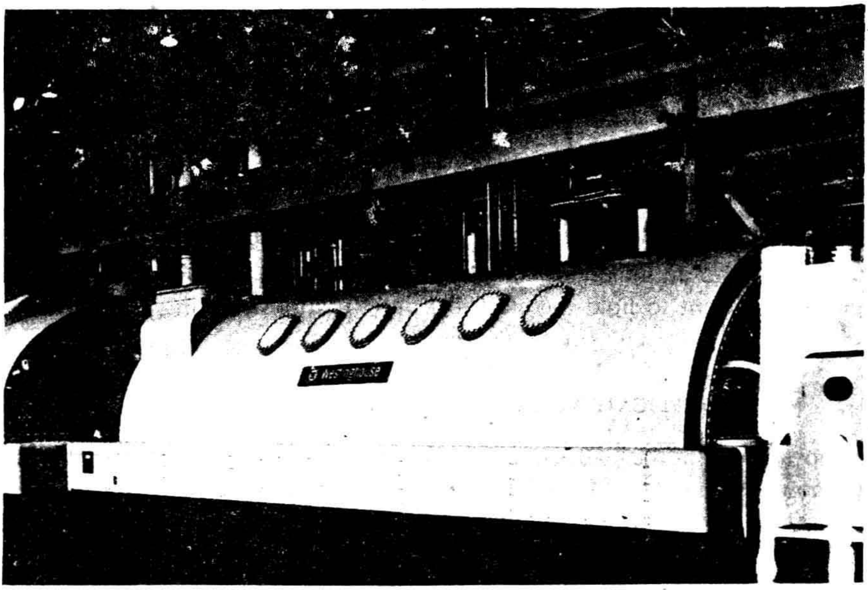

FIG. 1-7. An ac-generator rated 430,000 kVA, 24 kV, 3600 RPM.

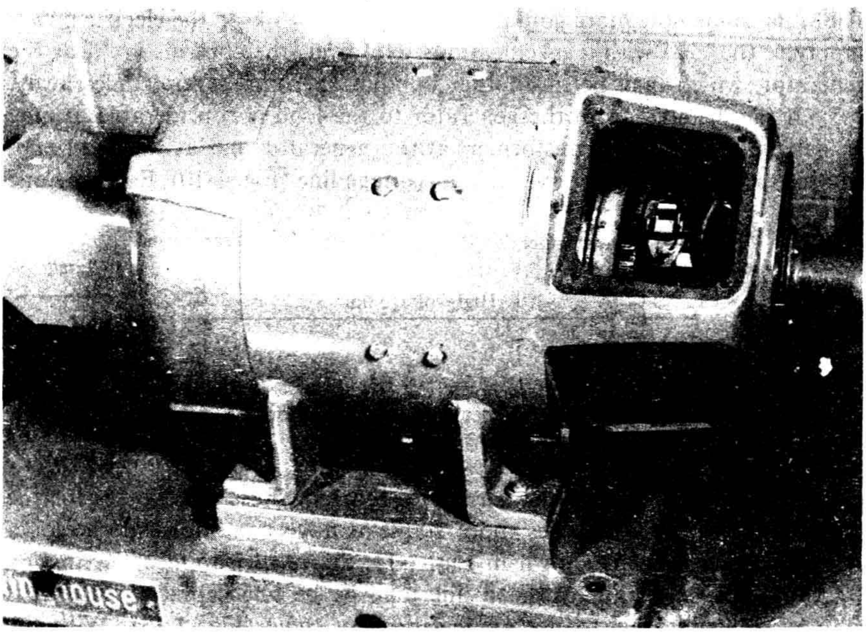

FIG. 1-8. A dc-generator rated 6 kW, 240 V, 1800 RPM.