# TRANSMISSION AND DISTRIBUTION OF ELECTRICAL ENERGY

Walter L. Weeks

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# Preface

This book evolved from a set of notes I developed for a senior-level course at Purdue University. Before the development of this course, the student could (and usually did) take introductory courses in power systems analysis and introductory machines. It was felt that more education should be available on the general subject of the transmission and distribution of electrical energy. The course and this book are meant to fill this need.

The book is organized to provide answers to a central question: *What problems must be faced in the design and application of some of the hardware that is required to deliver large amounts of power reliably, over considerable distances?* This question will be important for many years to come as requirements for electrical energy steadily increase. However, from among the many topics that might be covered, I have selected those which seem to be most generally applicable to the whole field of electrical engineering for more detailed coverages. With this general education objective in mind, the explanations and methods are not what might be considered the standard approaches of the power specialists, and for this reason, may seem strange and unfamiliar to some. Some practical problems have been greatly idealized and simplified in order to concentrate on broadly applicable fundamentals, rather than details. For example, more time and space than is usual is devoted to the fields and potentials of line charges and the calculation of capacitance for various circular conductor arrangements. The reason for this is the general applicability of this theory, not only to all types of overhead transmission systems but also to the problem of heat transfer from pipes and underground cables. Not only the theory, but the results are directly applicable in the determination of electrical shunt conductance, and thermal resistance, and conductance. Moreover, it is shown that with the capacitance per unit length of a typical transmission structure in hand, no additional detailed calculation is required to find the external inductance per unit length.

Consideration is also given to the *environmental* limitations on the transmission of large amounts of power, such as audio noise, radio frequency interference, and electromagnetic/electrostatic interaction with other systems and organisms. These considerations are in addition to the usual engineering oriented topics (for example, insulation) essential to keep the lines in almost continuous operation.

The number of different topics and details of interest in the general subject of transmission and distribution is vast. In a modern electrical engineering curriculum, let alone in one course, it would be impossible to cover every topic thoroughly and completely. So, for example, Chapters 3, 8, and 9 provide only limited coverage of such topics as transients, system protection, and dc transmission. This light coverage, however, still provides the student with a brief survey of these topics.

Although this text was developed for seniors, many first-year graduate students have taken the course using this text and they have found most of the material both challenging and interesting.

WALTER L. WEEKS

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# Chapter 1

# Transmission and Distribution of Electrical Energy

## 1.1 INTRODUCTION

In the United States, the use of external sources of energy, especially electrical energy, is so ingrained and commonplace that people often fail to appreciate what the electrical energy industries provide. Let us consider briefly the "man power" equivalent of this energy supply.

Note that if an individual lifts 100 pounds (lb) a distance of 2.75 feet (ft) in 1 second (s), he or she is supplying energy at the rate of about 275 ft-lb/s or $\frac{1}{2}$ horsepower (hp) or 373 watts (W) [the MKS person would lift, say, 50 kilograms (kg) through 0.75 meters (m) in 1 s]. Most people cannot do work at this rate for a sustained period; in fact a sustained effort of one tenth of this level would be regarded by most as quite a vigorous and taxing activity. Thus, we conclude that a hardy individual could provide continuously the energy to light a rather feeble incandescent lamp, or the energy for one moderately effective fluorescent light fixture. Further, if every individual in the United States (say 200 million of them) worked an 8-hour (h) shift at the 37.3-W rate, systematically driving electrical generators, we might conceivably generate continuously in this way about $2.5 \times 10^6$ kilowatts (kW) of electric power; this figure is about 1% of the electrical generation capacity that had been installed in the United States up through the year 1965, and is about 0.25% of the capacity planned for the year 1985. It is fortunate for our way of life that we do not presently have to rely on muscle power to generate our electrical energy.

We sometimes joke or perhaps complain about certain aspects of it, but the fact remains that the generation and distribution of electric energy is a big, vital, and serious business. Some general facts about size and growth are important in placing the industry in perspective. Figure 1.1 shows, among other things, the installed generation capacity as a function of year beginning in 1940. Inspection of this graph shows that the capacity has doubled in less than 10 years in each decade since that time. Stated in another way, it shows that between 1962 and 1972, about 200 gigawatts (GW) were installed, which is more than had been installed in history up

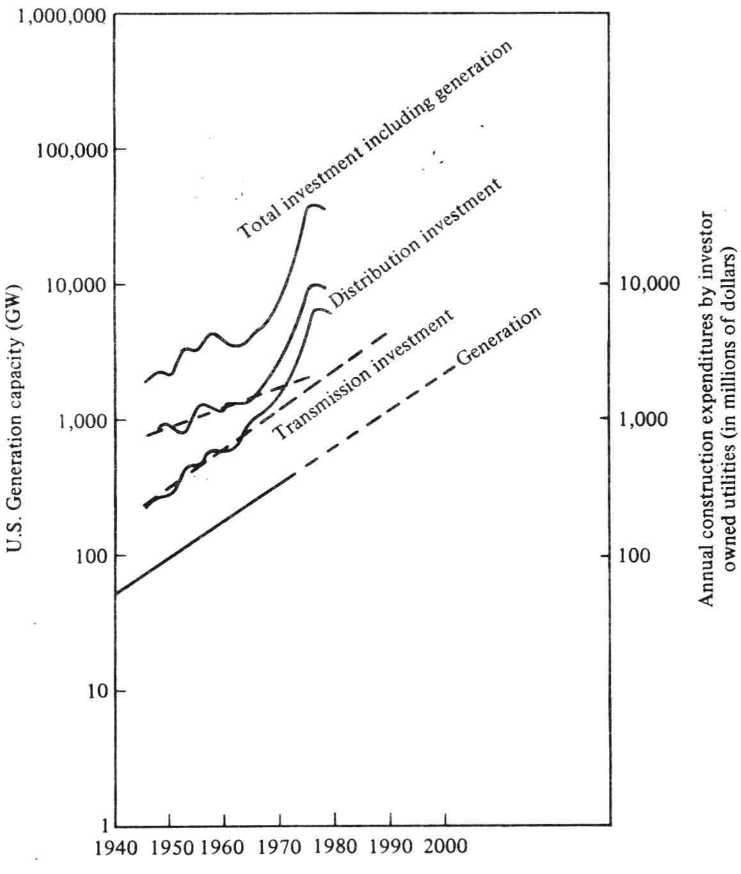


Figure 1.1 Utility company growth.

to 1962. Clearly this exponential growth cannot continue indefinitely, but before it levels off, the plant will be so large that just regular replacement will be a major task. Figure 1.1 also displays the history of annual investment by the investor-owned utilities in their plant construction. These data, especially that displaying the total investment, show that the financing for this expansion is a major problem for the utilities. It is estimated that in a 10-year period starting in 1980, the additional generation capacity will require a capital investment of about 320 billion 1978-dollars.

The electric utility industry is rather unique in that it seeks to supply a product having relatively tight specifications [for example, $117 \pm 10$ volts (V) at $60 \pm 0.1$ cycle] in any quantity, immediately on demand. In view of the difficulty of predicting human behavior and desires, the planning and design of the systems for supplying and delivering the product is very interesting and difficult. Not only must the utility industry as a whole have the generation capacity to meet the peaks in demand, but a system for the delivery of this product to the particular points of demand must be in the required places (and with the required power handling capability) at the time of the demand. To carry out all of this work, the industry must have thousands of well-informed, dedicated, and educated engineers each year. One of the purposes of this book is to provide some of the information necessary for engineers to carry on this business.

## 1.2 THE BASIC POWER SYSTEM

We begin our study with a review of the main features of a "typical" power system in the United States. The minimum power system consists of an energy source, a prime mover, an electrical generator, and a load, each connected to a control system, as shown diagrammatically in Fig. 1.2. The energy source is usually coal, gas, oil or fissionable material operating through a working fluid to run a heat engine; or it may be the potential energy of water stored at an elevation higher than that of the generating station. The prime mover is usually some sort of turbine or internal combustion engine. The generator is usually a three-phase ac alternator

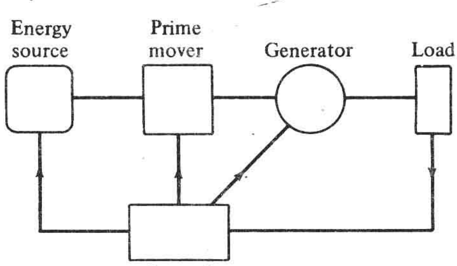


Figure 1.2 The minimum power system.

which is a machine in which conductors are subjected to a varying magnetic field so as to generate a set of three voltages that are equal in magnitude but different in phase by 120°. The control system includes, at least, a speed governor for the prime mover so as to hold the frequency at a nearly constant value, a magnetic field current regulator to hold the voltage constant, and a fuel flow regulator to match the energy input rate to changing load conditions. The load is whatever the consumers connect to the system, and consists of lights, motors, heaters, and electronic equipment; it is important to note that this load may vary widely at different times.

Concentrating on the electrical part of the system, we will now introduce some of the features and problems of power systems by describing an imaginary evolutionary development of a power system. In Fig. 1.3(a), we see only the generator, a disconnect switch for maintenance and protective purposes, and the load, all very close together. In this figure, as in the following diagrams, only one line is shown, although it is understood that there are at least three wires for the three-phase system. Figure 1.3(b) shows an expansion of the system to serve a more distant load. Again the "one-line diagram" is used to indicate the three-phase system. The fact that the resistive losses in the line are proportional to the line current squared (and the resistive losses of the conductors usually dominate by far the losses in the dielectric that increase with voltage) suggests the inclusion of efficient voltage transformers so that the power can be delivered with high voltage and low current in the lines. An extra disconnect switch (really three more for three phases) and a circuit breaker are now necessary for safety and for fault clearing on the now rather extended system. As additional loads develop in other directions, these would be served by additional lines in what is called a *radial* distribution system, in which the lines branch out in tree-like fashion from the generator. Soon thereafter, both to meet the peak load demand and to provide reliable service, a second generator would be added to the system. The site and size for the new generator would be carefully selected, taking into account the magnitude and location of expected load growth, logistics of fuel supply, cooling and environmental problems, and cost and availability of possible sites. An easy solution is often the addition of capacity at the existing site. If this is done, the system might take the form indicated in Fig. 1.3(c), with added connections and circuit breakers for greater reliability and flexibility for maintenance. The loads are now connected in a rudimentary *loop* system, through which all loads may be served even though one line or piece of equipment is out of service. (About this point in time, the planning engineer might wonder if he or she would be better off in the circuit breaker business.)

Still later, increasing loads might demand the addition of still more generation, at different sites, as suggested in Fig. 1.3(d). Here we see the development of a *network* system, in which each load has two or more

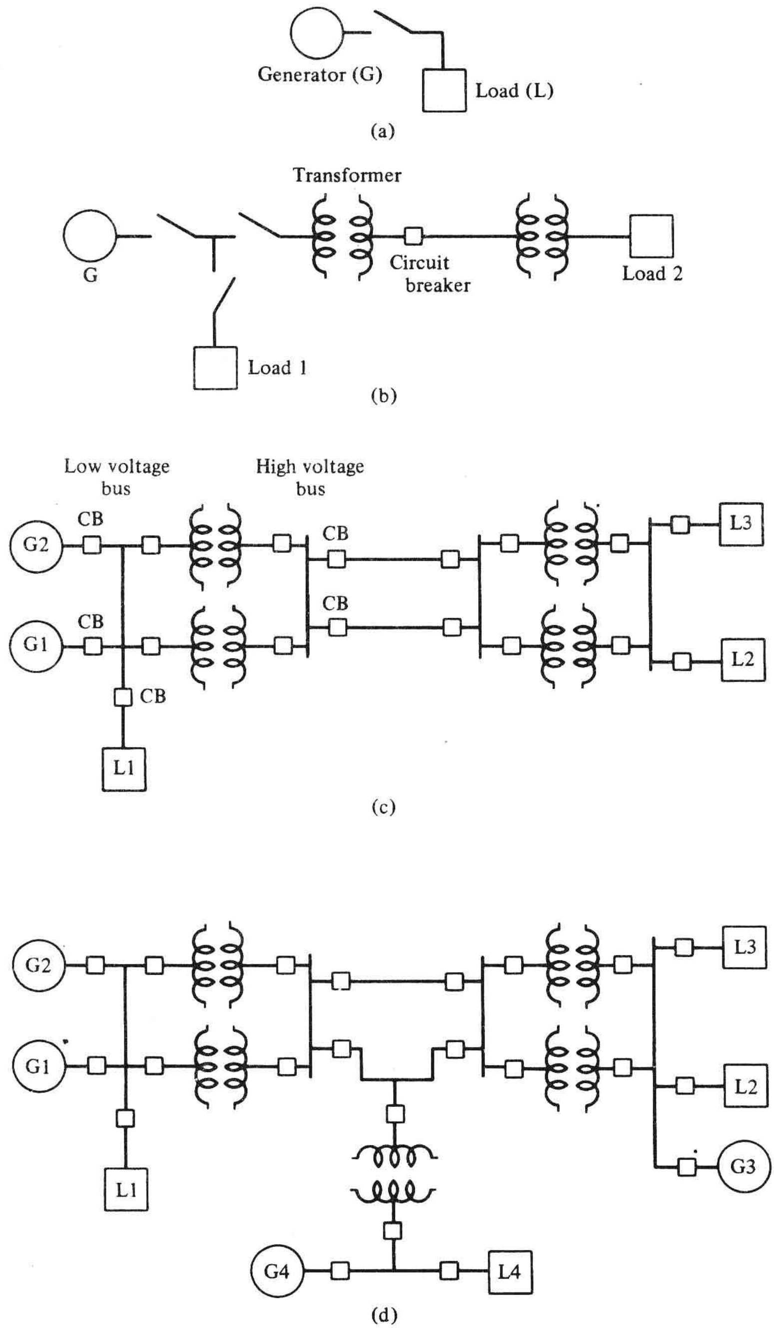


Figure 1.3 Evolution of a power system ("one line" electrical only).

circuits that can supply power to it. With each increase in complexity and size, the control system becomes more complicated. This means that information about the system at one point must be provided at other locations and this implies the need for a communication system associated with the power system. The problem of synchronizing all of the generators on the system becomes more acute.

The hypothetical system shown in Fig. 1.3(d), if extended over hundreds of miles, exhibits most of problems of actual systems but, of course, actual power systems are vastly more complex. As a matter of fact, virtually every system in the continental United States is interconnected to the rest of a network spanning the United States and much of Canada.

## 1.3 DELIVERY OF THE PRODUCT— TRANSMISSION AND DISTRIBUTION SYSTEMS

Of course as the generating plant grows, the delivery system must grow as well. In the language of power system engineering, product delivery is accomplished by two categories of systems: transmission systems and distribution systems. There is no hard and fast, universally applicable, sharp line of demarcation between these, but in general *transmission* systems have large power handling capability, relatively long lines that connect generator sites to load centers or one utility to another, while *distribution* systems branch out from and underlie the transmission systems; they handle lower power levels and have relatively short lines.

The delivery system influences profoundly both the cost and the overall system reliability. This is so for a number of reasons: Since the generators of large sizes usually have lower costs per kilowatt generated, installations of large generating capacity are common; and this implies the need for high power transmission lines to lead this low cost energy far from the point of generation. Line *interconnections* permit the *base loading* of the most efficient generators in a system or area and thus make it possible for the most *economic dispatch* of the energy generated. In case of emergency or scheduled shutdowns of generating plants, transmission systems must make available the energy from other sources and so minimize the amount of reserve generation capacity required on the system to maintain service and satisfy peak demands. Transmission line interconnection between companies helps provide greater overall reliability as well as economic benefits.

Figure 1.1 shows that the expected annual investment in transmission and distribution systems in the 1980s will be about 8 to 9 billion dollars. Since the interest on this capital will probably cost in the vicinity of 900 million dollars a year, it is clear that the systems must not be over-designed. And yet they must be designed with adequate capacity, for under-design leads to poor reliability, high losses, and excessive noise problems.

The power levels that transmission and distribution systems are being called upon to handle are increasing. The reason, as mentioned above, is largely the economies of scale associated with large generating plants. Relatively few new plants have less than 300 megawatt (MW) capacity, while the newer nuclear plants have capacities between 1 and 2.5 GW. The transmission systems must be correspondingly large. The power transmitted depends of course on the voltage and the current and increases as their product increases. The level of voltage possible is limited by dielectric breakdown and corona effects. The level of current possible is limited by the $I^2R$ heating of the components.

## 1.4 TRANSFER OF POWER BETWEEN BUSSES FED BY MACHINES

Transmission line parameters limit the power that can be transferred between distant busses [such as in Fig. 1.3(d)] whose voltages are set by local generators. These generators are called three-phase synchronous machines since they can either provide power or accept power depending on the magnitude and phase of the bus or terminal voltage. The power limitation stems from the fact that the machines must remain locked in synchronism and the phase angle between the voltages must not become too great (as implied in Problem 1.3).

The origin of the limitation can be suggested by the consideration of a very simple model, as in Fig. 1.4. The model consists of ideal voltage generators at the ends of a single phase line, where the line parameters are assumed to be represented adequately by the reactance, $X_L$, alone. With this model it is easy to show that the power transferred from terminal 1 to terminal 2 is

$$P = \frac{|V_1||V_2| \sin \delta}{X_L} \tag{1.1}$$

where $\delta$ is the phase difference between the voltages and $X_L$ is the line

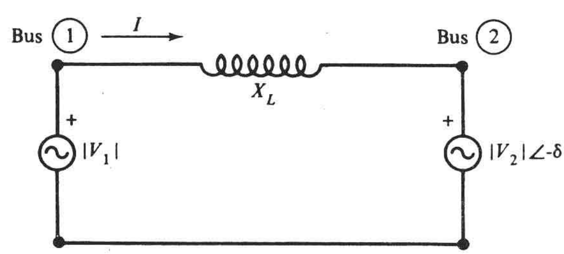


Figure 1.4 Circuit model of two machines connected by a length of transmission line. Power transferred from ① to ② is

$$P = \frac{|V_1||V_2| \sin \delta}{X_L}$$