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Massachusetts Institute of Technology, USA

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ELECTRIC POWER PRINCIPLES

Preface

At the time of this writing (autumn of 2009), there appears to be a heightened awareness of the importance of energy to our social welfare. There are, in my opinion, two reasons for this. First, there is an awareness of the finite supply of fossil fuels stored beneath the surface of our planet, and that one day we will have to make do with sustainable sources of energy. The other is the fact that use of these fossil fuels releases carbon back into the atmosphere, leading to possible changes in heat transfer from the surface of the earth to space with attendant climate change. For both of these reasons the traditional methods for producing electric power may have to change, and this will mean the need for well educated, innovative engineers to build the power systems of the future.

In addition to the need for engineering of the electric power system itself is the plain fact that electric power, in the broad sense, is being used for a wider range of applications as time goes on. Virtually all rail transportation employs electric propulsion; hybrid electric automobiles have become important items of commerce and promise to become part of our energy future. Reduction of the need for energy (that is conservation) requires enhanced efficiency and effectiveness of the use of energy, and very often that involves the use of electricity.

The implications for education are clear: we in the academic world must educate engineers to be the leaders in designing, building and operating new types of electric power systems. Perhaps even more important, we must also educate a broader class of students who will become leaders in the industrial and political realms to understand at least the rudiments and implications of energy, including electric power.

This book is the descendant of sets of lecture notes that I have used in two subjects at the Massachusetts Institute of Technology: *6.061, Introduction to Electric Power Systems* and *6.685, Electric Machines*. These notes have existed in various forms for about three decades, and they have benefited from the experience of being used by multiple generations of MIT undergraduate and graduate students.

It is my hope that this book be used by students who want to gain a broad understanding of how electric power is generated, transmitted, distributed and used. Thus there is material here beyond the traditional electric power system and electric machinery disciplines. That said, this book does have chapters that discuss some of the traditional material of electric power systems: per-unit normalizations, symmetrical components and iterative load flow calculations. In keeping with my feeling that fundamental understanding is important, I have included chapters on the principles of electromechanical energy conversion and on magnetic circuits. To round out the power systems story is a fairly extensive chapter on synchronous machines, which are still the most important generators of electric power. There are also

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short discussions of the different types of power plants, including both traditional plants and those used for extracting sustainable energy from wind and sun, and topics important to the power system: protection and DC transmission. On the usage side there is a chapter on power electronics and chapters on the major classes of electric motors: induction and direct current. MATLAB is included, and each of the chapters is accompanied by some problems with a fairly wide range of difficulty, from quite easy to fairly challenging.

The material in this book should be accessible to an undergraduate electrical engineering student at the third year level. I have assumed the reader of this book will have a basic but solid background in the fundamentals of electrical engineering, including an understanding of multivariable calculus and basic differential equations, a basic understanding of electric circuit theory and an understanding of Maxwell's equations.

This book could be used for subjects with a number of different areas of emphasis. A 'first course' in electric power systems might use Chapters 1 through 4, 6, 7, 10 and 11. Chapter 7 has an appendix on transmission line inductance parameters that can probably be safely skipped in an introductory subject.

Chapter 9 is about synchronous machines and instructors of many power systems subjects would want to address this subject. Chapter 12 is an introduction to power electronics and this, too, might be considered for a course in power systems.

A 'first course' that deals primarily with electric machines could be taught from Chapters 4, 5, 8, 9 and 12 to 15. Tutors can find solutions for end-of-chapter problems at www.wiley.com/go/kirtley_electric.

The number of students who have influenced, hopefully for the better, the subject material in this book is so large that there would be no hope in calling them all out. However, I must acknowledge a few of the people who have taught me this material and influenced my professional career. These include Herb Woodson, Jim Melcher, Gerald Wilson, Alex Kusko, Joe Smith, Charles Kingsley, Steve Umans and Steve Leeb.

I would also like to thank Steve Sprague of the Electric Motor Education and Research Foundation for the electrical sheet steel data graphics.

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1

Electric Power Systems

There are many different types of power systems, such as the propulsion systems in automobiles and trucks and the hydraulic systems used in some industrial robots and for actuating scoops and blades in digging equipment. All power systems have certain fundamental elements. There is some sort of prime mover (such as a gasoline engine), a means of transport of the power produced (such as the drive shaft, transmission, differential and axles), and a means of using that power (wheels on the road). The focus of this book is on *electric* power systems, in which the means of transporting energy is the flow of electrical current against an electric potential (voltage). There are many different types of electric power systems as well, including the electrical systems in cars and trucks, propulsion systems in electric trains and cruise ships. The primary focus in this book will be the kinds of electric power systems incorporated in public utilities, but it must be kept in mind that all electric power systems have many features in common. Thus the lessons learned here will have applicability well beyond the utility system.

It has become all too easy to take for granted the electric utility service that is ubiquitous in the developed countries. Electric utilities are wired to nearly every business and residence, and standardized levels of voltage and frequency permit a wide range of appliances to be simply 'plugged in' and operated. Consumers don't have to give any thought to whether or not an appliance such as a television set, a computer or an egg beater will work. Not only will these appliances work when plugged in, but the electric power to make them work is quite reliable and cheap. In fact, the absence of useful electric power is quite rare in the developed countries in the world. Widespread failure to deliver electric power has become known as a 'blackout', and such events are rare enough to make the nightly news across the country. Even substantial distribution system failures due to weather are newsworthy events and very often cause substantial hardship, because we have all come to depend on electric power to not only keep the lights on, but also to control heating, cooling, cooking and refrigeration systems in our homes and businesses.

At the time of this writing, electric power systems in the United States and most of the developing world use as their primary sources of energy fossil fuels (coal and natural gas), falling water (hydroelectric power), and heat from nuclear fission. There are small but rapidly growing amounts of electric power generated from wind and solar sources and some

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electric power is generated from volcanic heat (geothermal energy). These 'renewables' are expected to grow in importance in the future, as the environmental impacts of the use of fossil fuels become more noticeable and as the fossil fuels themselves are exhausted. There are some differences between technologies involved in the older, existing power generation sources and the newer, sustainable technologies, and so in this book we will discuss not only how existing utility systems work but also how the emerging technologies are expected to function.

1.1 Electric Utility Systems

A very 'cartoon-ish' drawing of a simple power system is shown in Figure 1.1.

Electric power originates in 'power plants'. It is transmitted by 'transmission lines' from the power plants to the loads. Along the way the voltage is first stepped up by transformers, generally within the power plants, from a level that is practical for the generators to a level that provides adequate efficiency for long-distance transmission. Then, near the loads the electric power is stepped down, also by transformers, to a voltage useable by the customer. This picture is actually quite simplified. In modern utility systems there are thousands of power plants connected together through networks, and many more connections to loads than are indicated in Figure 1.1. The connections to actual loads is usually a bit more like what is shown in Figure 1.2. At the distribution level the connection is 'radial', in that there is one connection from the source of electric power (the 'grid'), and that is broken down into many load connections. Usually the distribution primary line is at a voltage level intermediate between the transmission level and the voltage that is actually used by customers.

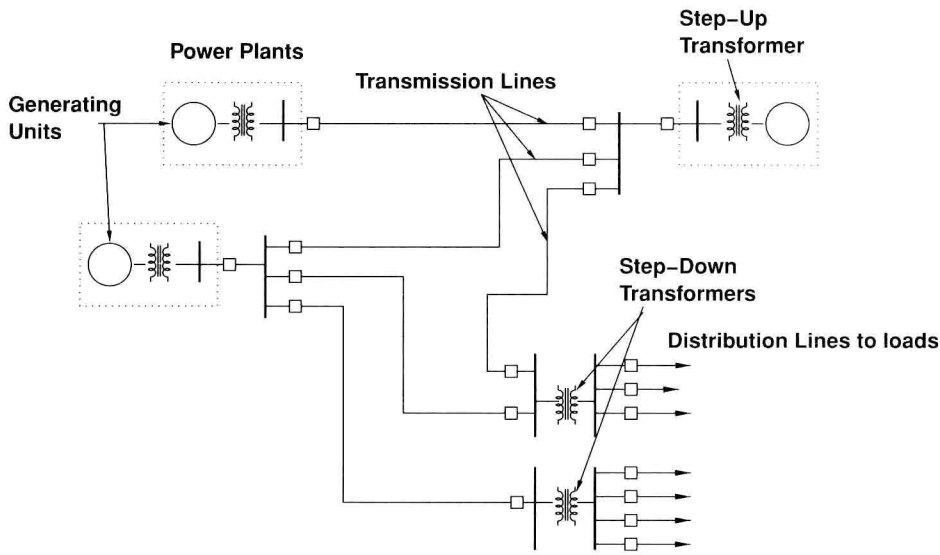

Figure 1.1 Cartoon of a simple power system

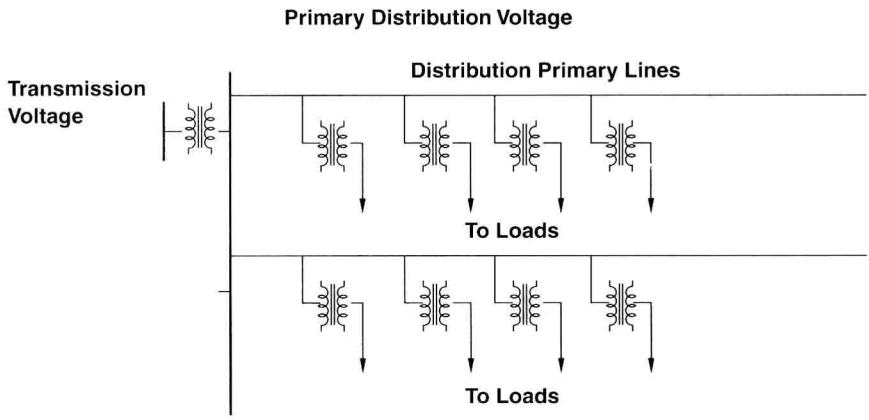

Figure 1.2 Distribution circuits

1.2 Energy and Power

1.2.1 Basics and Units

Before starting to talk about electric power systems it is important to understand some of the basics of energy and power. In the international system of units (SI), there are two basic units of energy. One is the joule (J), which is the energy expended by pushing a newton (N), a unit of force, over one meter. So a joule is a newton-meter. (A kilogram 'weighs' about 9.8 newtons at the surface of the earth). The other unit of energy is related to heat, and it is the Calorie. This story is complicated by the fact that there are actually two definitions of the Calorie. One is the heat (amount of energy) required to heat 1 gram of water 1 degree Celsius. This amounts to about 4.184 joules. The second definition is often called the 'kilogram Calorie', the amount of energy required to heat 1 kilogram of water 1 degree Celsius. This is obviously just 1,000 of the 'gram Calories', or 4,184 joules.

The basic unit of power is the watt, which is one joule/second. As it our predecessors crafted it, 1 watt is also 1 volt $\times$ 1 ampere. The volt is a unit of electrical potential and the ampere is a unit of current flow. Power is expressed in watts, kilowatts, etc., and a basic unit of energy is the kilowatt-hour (kWh), (3.6×10^6 J). Electricity is sold at retail by the kilowatt-hour and, usually, at wholesale by the megawatt-hour.

Another unit of heat that is commonly used in discussing power plants is the British Thermal Unit (BTU), which is the amount of heat required to raise 1 pound of water 1 degree Fahrenheit. This is about 0.252 kilogram calories or 1054 joules. In the United States, fuels are often sold based on their energy content as measured in BTUs, or more commonly in millions of BTU's (MBTU). See Tables 1.1 and 1.2.

1.3 Sources of Electric Power

There are two basic ways in which electric power is produced: by generators turned by some sort of 'prime mover' or by direct conversion from a primary source such as sunlight, or conversion of chemical energy in fuel cells. The prime movers that turn generators can be heat

Table 1.1 Some of the unit symbols used in this book

Unit	Unit of	Symbol
Ampere	current	A
British Thermal Unit	heat energy	BTU
Coulomb	charge	C
Calorie	heat energy	Cal
degree Celsius	temperature	°C
Farad	capacitance	F
Gauss	flux density	G
Hertz (cycles/second)	frequency	Hz
Henry	inductance	H
hour	time	h
Joule	energy	J
Kelvin	temperature	K
kilogram	mass	kg
meter	length	m
Newton	force	N
volt	electric potential	V
volt-ampere	apparent power	VA
watt	power	W
Weber	flux	Wb

engines such as steam turbines, gas turbines, internal combustion engines burning diesel fuel, natural gas or (rarely) gasoline, or turbines that convert power directly from falling water or wind. Geothermal heat is sometimes used to power heat engines in places where that heat is accessible (this is the major source of electric power in Iceland). Even sunlight has been used as the power input to heat engines.

1.3.1 Heat Engines

Most power plant 'prime movers' are heat engines that burn a primary fuel such as coal or natural gas and that use the energy released by combustion to produce mechanical power (generally turning a shaft) that is used to drive a generator to produce electrical power. We

Table 1.2 Multiplying prefixes used in this book

Prefix	Symbol	Multiple
tera	T	10^{12}
giga	G	10^{9}
mega	M	10^{6}
kilo	k	10^{3}
centi	c	10^{-2}
milli	m	10^{-3}
micro	μ	10^{-6}
nano	n	10^{-9}

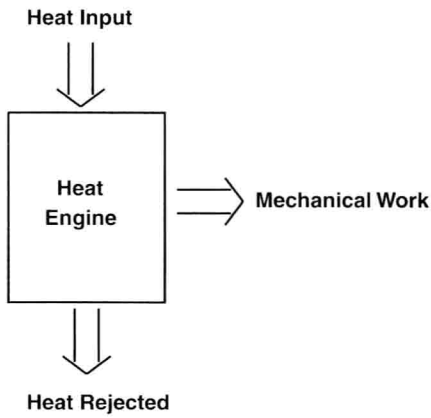

Figure 1.3 Energy balance

will, in later chapters of this book describe how generators work. Heat engines can convert only some of the heat energy that is input to the engines into mechanical work. The details of this are beyond our scope here, but as is shown in Figure 1.3, there will always be waste heat associated with a heat engine. Heat engines take energy at a high temperature and reject heat energy at a lower temperature. The difference between the heat input and rejected heat energy is what is converted to mechanical power, and efficiency is the ratio of mechanical power output to heat power input.

There is a well known bound on efficiency of a heat engine, called the 'Carnot efficiency', and that is associated with the temperature of the input heat and the temperature of the rejected heat. This is:

$$W_{\mathrm{m}} < Q_{\mathrm{h}} \frac{T_{\mathrm{h}} - T_{\ell}}{T_{\mathrm{h}}}$$

where Q_{h} is the input energy. Mechanical work is the difference between heat input and heat rejected, and the efficiency depends on the heat input temperature T_{h} and heat rejection temperature T_{ℓ}. Practical heat engines do not approach this Carnot limit very closely, but this expression is a guide to heat engine efficiency: generally higher heat input temperatures and lower heat rejection temperatures lead to more efficient heat engines.

In discussing power plant efficiency, we often note that one kilowatt-hour is 3.6 MJ or 3,414 BTU. The fuel energy input to a power plant to produce one kilowatt hour is referred to as its 'heat rate', and this is inversely related to its thermal efficiency. A power plant that has a heat rate of, say, 10,000 BTU/kWh would have a net thermal efficiency of $\eta = \frac{3414}{10000} \approx 0.3414$.

1.3.2 Power Plants

Figure 1.4 shows a cartoon of a power plant that burns fossil fuels. The heat engine in this case is a steam turbine. Water is first compressed and pumped into a 'boiler', where a fire heats it into steam. The steam is expanded through a turbine which turns a generator. The turbine exhaust is then fed to a 'condenser' where the waste heat is rejected. There are several

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