Electric Energy

An Introduction

Third Edition

Mohamed A. El-Sharkawi

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Electric Energy

An Introduction

Third Edition

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This textbook is dedicated to my wife, Fatma, and my sons, Adam and Tamer.

The book is also dedicated to all engineers, without
whom we would still be living in caves.

A special dedication goes to the founders of our electric
power systems: Nikola Tesla and Thomas Edison.

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Preface

The first course on electric energy in engineering schools is traditionally taught as an energy conversion course. This was justified during most of the last century, as power was the main topic of electrical engineering. Nowadays, the field includes a number of new specializations such as digital systems, computer engineering, communications, imaging, and networks. With the field being so widespread, energy conversion turned into a topic for students specializing only in power. Consequently, a large number of schools have decided to move their energy conversion courses from the core curricula to the elective curricula. Other schools with limited resources have dropped the energy conversion courses altogether.

In recent years, renewed interest in electric energy has emerged due to several important reasons. Among them are the ongoing search for renewable energy and smart grid, the societal impact of blackouts, the environmental impact of generating electricity, and the lack of knowledge by most electrical engineers in fundamental subjects such as electric safety and power plants. In addition, the new ABET criteria in the United States encourages the development of curricula that underline broad education in engineering, contemporary engineering, and the impact of engineering solutions in a global and societal context. All these requirements can be met by restructuring the introductory electric energy course and making it relevant to all electrical engineering and most mechanical engineering students. This is the main objective of this textbook.

The book is authored to assist schools that wish to establish a course with a wider view of electric energy while maintaining high levels of depth. Most of the topics in this book are related to issues encountered daily and, therefore, should be of great interest to all engineering students. The majority of the chapters in the book are structured to be stand-alone topics; instructors can thus pick and choose the chapters they want to teach. They can also select the sequence in which they prefer to teach the chapters. Most of the examples in the book are from real systems and with real data to make the course relevant to all students.

Among the topics covered in this third edition are energy resources, renewable energy, power plants and their environmental impacts, electric safety, power quality, power market, blackouts, and future power systems. In addition, the topics of electromechanical conversion, transformers, power electronics, and three-phase systems are included in the book to address the needs of some schools for teaching these important topics. However, these traditional topics have been made more relevant to students. For example, the section on electric motors includes linear and levitated motors as well as stepper motors.

Chapter 1 is dedicated to the history of developing the electric energy system. The innovations started with the Greek philosopher Thales of Miletus around 600 BC, passing through William Gilbert (1544–1603), Alessandro Guiseppe Antonio Anastasio Volta (1745–1827), André-Marie Ampère (1775–1836), Georg Simon Ohm (1789–1854), Michael Faraday (1791–1867), Hippolyte Pixii (1808–1835), Antonio Pacinotti (1841–1912), Thomas Alva Edison (1847–1931), and Nikola Tesla (1856–1943). In addition, the chapter includes key inventors in power electronics such as John Ambrose Fleming (1849–1945) and Julius Edgar Lilienfeld (1881–1963). The chapter analyzes the merits and demerits between the direct current (dc) and alternate current (ac) systems that were promoted by Thomas Edison and Nikola Tesla, respectively.

In Chapter 2, the modern power system is described and its main components are discussed. The system is divided into three distinct parts: generation, transmission, and distribution. In the generation part, the main types of turbines are summarized. In the transmission systems, key components are presented, including transformers, transmission lines, insulators, conductors, bundled conductors, static wires, and substations. In this third edition, substation and distribution equipment are added including current and voltage transformers, circuit breakers, disconnecting switches, reclosers, sectionalizers, and surge arresters. The chapter includes a brief description of control centers. At the consumer voltage level, the chapter addresses the frequency and voltage standards worldwide and gives reasons for the differences among the various standards.

Chapter 3 deals with energy resources, which are often divided into three categories: fossil fuel, nuclear fuel, and renewable resources. Fossil fuels include oil, coal, and natural gas. Renewable energy resources include hydrokinetic, wind, solar, hydrogen, biomass, and geothermal energy. All these resources are also classified as primary and secondary resources. Primary resources include fossil fuel, nuclear fuel, and hydroelectric energy. Secondary resources include all renewable energy apart from hydroelectricity. The chapter discusses the known reserves as well as the world consumptions of the primary resources. In this third edition, all data are updated with 2009 or 2010 statistics.

Chapter 4 covers primary resource power plants. It describes various designs, the main components of power plants, the theory of operation, and their modeling and analyses. It provides several examples of key calculations for hydroelectric, fossil fuel, and nuclear plants. For the hydropower plant, impulse and reaction turbines have been added, explained, and modeled in the third edition. For the nuclear power plant, the enrichment process of uranium and the CANDU reactors have been added.

Chapter 5 deals with the environmental impact of generating electricity. Each of the primary resources is associated with some type of air, water, or land pollution. Although there is no pollution-free method for generating electricity, the primary resources are often thought to be responsible for most of the negative environmental impacts. In this chapter, the various pollution problems associated with the generation of electricity are presented, discussed, and put into perspective.

Chapter 6 describes renewable energy methods. “Renewable energy” is a loosely used term to describe energy generated in any manner from resources other than fossil or nuclear fuels. They include hydrokinetic systems; wind, solar, and geothermal energy; and fuel cell. The chapter describes these technologies, their main components, the merits and demerits of each technology, the mathematical modeling, and the energy calculations of key systems. In this third edition, several enhancements have been made. In the section on wind energy, aerodynamic principles, coefficient of performance dependency on pitch angles, classification of wind turbines, and the various types of existing systems have been added. The hydrokinetic systems have been expanded to include modeling and analysis for wave, tidal, and stream systems. In the section on geothermal energy, the dry rock system has been added. The chapter also discusses the intermittency of renewable resources and the impact of its integration into power grids. As a solution, energy storage systems such as pumped hydro, compressed air, battery, and flywheel systems have been added.

Chapter 7 is a review of the ac circuit analysis that is required for subsequent chapters. Usually, the topics in this chapter are covered in earlier courses. However, for convenience, they are also included in this book.

Chapter 8 discusses three-phase systems. In addition to mathematical analysis, it discusses the reasons for using three-phase systems and the various connections in power systems.

Chapter 9 deals with electric safety, a topic often overlooked by most engineering schools. Students will learn what constitutes harmful levels of currents and their biological effects. They will also learn about primary and secondary shocks and how they are affected by various variables such as currents, voltages, frequencies, and pathways. Body and ground resistance calculations are studied as well as their effects on step and touch potentials. The impact of ground resistance on the level of electric shock is explained by various common safety scenarios. In this edition, electric safety at homes has been expanded to include discussions on the need for neutral and ground conductors. Various world safety standards for neutral and ground are discussed and justifications for three-prong plugs and outlets are made. Furthermore, safety equipment for household applications such as the ground fault interrupter are presented. The practices in most parts of the world with regard to neutral and ground wires are explained and their safety is analyzed. Magnetic field and its biological effects are also discussed.

Chapter 10 deals with various power electronic devices and circuits. Because of the power electronic revolution, the boundary between dc and ac is becoming invisible. Besides the main solid state devices such as the silicon-controlled rectifier, insulated gate bipolar transistor, and metal oxide semiconductor field effect transistor, the chapter analyzes four types of converters: ac/dc, dc/dc, dc/ac, and ac/ac. For each of these converters, at least one circuit is discussed and analyzed in detail using waveforms and mathematical models. In this edition, the dc/ac converter has been expanded to include three-phase systems and the pulse width modulation technique.

Chapter 11 provides an introduction to transformers and includes single- and three-phase transformers as well as autotransformers and transformer banks. Detailed analyses for ideal and actual transformers are also given.

Chapter 12 discusses essential electric machines such as induction machines, synchronous machines, single-phase motors, dc motors, and stepper motors. All these machines are addressed in the context of their applications to make the theory more relevant to all students. For example, linear and magnetically levitated trains are used as applications to induction machine, while hard disk drives and printers are associated with stepper motors. Besides basic machine modeling, students can also analyze application scenarios such as a train powered by a linear induction motor traveling under certain road and wind conditions. In this edition, a section on induction generator, which is widely used in wind energy systems, has been added.

Chapter 13 deals with the imperfection of the ac waveform. It includes analyses of voltage problems such as flicker and sag as well as frequency problems. Besides the analyses, the chapter identifies the impact of imperfect waveforms on other system components as well as methods to alleviate the problems associated with power quality.

Chapter 14 covers the operation of the power system. It describes secure and insecure operations as well as stable and unstable conditions of the power system. The difference between radial and network structures as related to power system reliability is addressed. The effect of a power imbalance on the power system stability is studied. The concepts of power angle, system capacity, and transmission limits are introduced. Energy demand and energy trade between utilities are addressed as an economic necessity as well as a reliability obligation. The concept of spinning reserve and its impact on system reliability is explained. The various conditions that could lead to outages and blackouts are addressed; major blackout scenarios are also described.

Chapter 15 deals with future directions in power system research. It includes smart grids, smart houses, self-diagnosis and healing, phasor measurement units, electric and hybrid vehicles, alternative resources, distributed generation, and many more.

Author

Mohamed A. El-Sharkawi is a fellow of the IEEE. He received his PhD in electrical engineering from the University of British Columbia in 1980 and joined the University of Washington as a faculty member the same year. He is presently a professor of electrical engineering in the energy area. He has also served as the associate chair and the chairman of graduate studies and research.

Professor El-Sharkawi served as the vice president for technical activities of the IEEE Computational Intelligence Society. He founded and chaired the IEEE Power and Energy Society's subcommittee on renewable energy machines and systems. He is the founder and cofounder of several international conferences and the founding chairman of numerous IEEE task forces, working groups, and subcommittees. He has organized and chaired numerous panels and special sessions in IEEE and other professional organizations. He has also organized and taught several international tutorials on power systems, renewable energy, electric safety, induction voltage, and intelligent systems.

Professor El-Sharkawi is an associate editor and a member of the editorial boards of several engineering journals. He has published over 250 papers and book chapters in his research areas. He has authored two textbooks—*Fundamentals of Electric Drives* and *Electric Energy: An Introduction*. He also authored and coauthored five research books in the area of intelligent systems and power systems. He holds five licensed patents in the area of renewable energy VAR management and minimum arc sequential circuit breaker switching.

For more information, please visit El-Sharkawi's website at http://cialab.ee.washington.edu

List of Acronyms

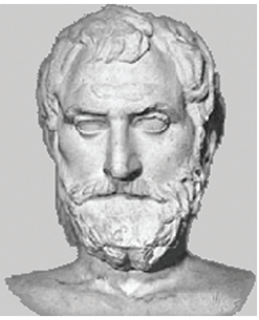
AAAC	All aluminum alloy conductors
AAC	All aluminum conductors
AC	Alternating current
ACSR	Aluminum conductors steel reinforced
BJT	Bipolar junction transistor
BM	Buoyant moored
BTU	British thermal unit
BWR	Boiling water reactor
CAES	Compressed air energy storage
CANDU	Canada Deuterium Uranium
CB	Circuit breaker
CGS	Centimeter-gram-second
COx	Carbone oxide
Cp	Coefficient of performance
CT	Current transformer
DC	Direct current
DFIG	Doubly-fed induction generator
Diac	Bilateral diode
DMFC	Direct methanol fuel cell
DS	Disconnecting switch
DT	Darlington transistor
EF	Electric field
EGC	Equipment grounding conductor
EMF	Electromagnetic field
EPA	Environmental Protection Agency
EV	Electric vehicle
FACTS	Flexible alternating current transmission system
FC	Fuel cell
FET	Field effect transistor
GFCI	Ground fault circuit interrupter
GPR	Ground potential rise
GSU xfm	Generation step-up transformer
GTO	Gate turn-off SCR
HAWT	Horizontal axis wind turbine
HC	Hinged contour
HEV	Hybrid electric vehicle
HSM	Hybrid stepper motor
HV	High voltage
ICEV	Internal combustion engine vehicle
IEEE	Institute of Electrical and Electronics Engineers
IGBT	Insulated gate bipolar transistor
IHD	Individual harmonic distortion
IM	Induction motor

ISCCS	Integrated solar combined cycle system
KE	Kinetic energy
LEO	Low Earth orbit
LIM	Linear induction motor
MagLev	Magnetically levitated
MCFC	Molten carbonate fuel cell
MF	Magnetic field
MOSFET	Metal oxide semiconductor field effect transistor
MOV	Metal oxide varistors
MPE	Maximum permissible exposure
NAAQS	National Ambient Air Quality Standards
NASA	National Aeronautics and Space Administration
NERC	North American Electric Reliability Corporation
NOx	Nitrogen oxide
NRC	Nuclear Regulatory Commission
OHGW	Overhead ground wire
OSHA	Occupational Safety and Health
OWC	Oscillating water column
P	Real power
PE	Potential energy
PEM	Proton exchange membrane
pH	Potential of hydrogen
PHS	Pumped hydro storage
PMSM	Permanent magnet stepper motor
PMU	Phasor measurement unit
PT	Potential transformer
Pu	Plutonium
PV	Photovoltaic
PWM	Pulse width modulation
PWR	Pressurized water reactor
Q	Reactive power (in ac circuits)
REM	Radiation equivalent man
rms	Root mean square
rpm	Revolutions per minute
S	Complex power, apparent power
SCR	Silicon-controlled rectifier
SCRAM	Safety control rod axe man
SF_6	Sulfur hexafluoride
SIDAC	Silicon diode for alternating current
SOx	Sulfur oxide
SOFC	Solid oxide fuel cell
TEC	Thermal energy constant
THD	Total harmonic distortion
TL	Transmission line
TSR	Tip speed ratio
U	Uranium
UCTE	Union for the Co-ordination of Transmission of Electricity
UPS	Uninterruptible power supply
VAWT	Vertical axis wind turbine
VF	Voltage fluctuation

VRSM	Variable reluctance stepper motor
WHO	World Health Organization
WLIM	Wheeled linear induction motor
WS	Water stream
WT	Wind turbine
xfm	Transformer

1 History of Power Systems

A large number of great scientists created wonderful innovations that led to the electric power systems as we know them today. Although electricity was discovered around 600 BC, it was not until the end of the nineteenth century that we could have electric energy on demand by flipping a switch at every home, school, office, or factory. Today, dependence on electric power is so entrenched in our societies that we cannot imagine our life without electricity. We indeed take electricity for granted, so when we experience an outage, we realize how our life is dependent on electricity. This dependency creates a formidable challenge to engineers to make the power system the most reliable and efficient complex system ever built by man.



The road to creating an electric power system began when the Greek philosopher Thales of Miletus discussed electric charge around 600 BC. The Greeks observed that when rubbing fur on amber, an electric charge would build up on the amber. The charge would allow the amber to attract light objects such as hair. However, the first scientific study of the electric and magnetic phenomena was done by the English physician William Gilbert (1544–1603). He was the first to use the term *electric*, which is derived from the Greek word for amber (ηλεκτρον). The word amber itself was derived from the Arabic word *Anbar*. Indeed, several volumes are needed to justifiably credit the geniuses behind the creation of our marvelous power system. Unfortunately, because of the lack of space, we shall only highlight the milestone developments.

A good beginning point in history would be the middle of the eighteenth century when the Italian scientist, Alessandro Guiseppe Antonio Anastasio Volta (1745–1827), showed that galvanism occurred whenever a moist substance was placed between two different metals. This discovery eventually led to the first battery in 1800. Figure 1.1 shows a model of Volta's battery that is displayed in the U.S. Smithsonian Museum in Washington, DC. The battery was the source of energy used in subsequent developments to create magnetic fields and electric currents. Today we use the unit *volt* for electric potential in honor of this great Italian inventor.

When the Danish Professor Hans Christian Oersted (1777–1851) was working on an experiment that involved the use of battery, he noticed that a compass needle had deflected from its normal heading of the magnetic north. This was the first reported discovery of electromagnetic force created by electric current. This discovery is the basis for the design of electromechanical devices such as motors and actuators. This important relationship between electricity and magnetism was not interpreted by Oersted, but was later explained by André-Marie Ampère. In honor of Oersted, his name is used as a unit for the magnetic field intensity in the centimeter–gram–second (CGS) system.

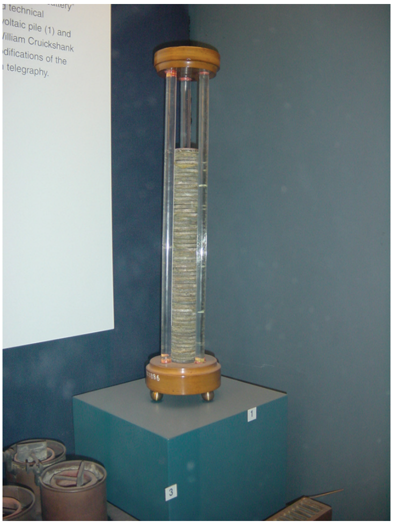


FIGURE 1.1 Model of Volta's battery. (Courtesy of the Smithsonian Museum, Washington, DC.)

The next scientist is the French mathematician and physicist André-Marie Ampère (1775–1836). He was the first to explain the ambiguous link between magnetism and electric currents that Oersted could not rationalize. His work is known as *Ampere's law*, which relates the magnetic field to electric current. Ampere's law eventually led to the development of electromagnetic devices such as motors, generators, and transformers. Today we use *ampere* as the unit of electric current in honor of this French scientist.

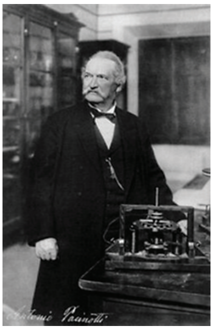
The German scientist Georg Simon Ohm (1789–1854) was the first to discover electrical resistance. He noticed that the current passing through a wire increased when the cross section of the wire increased and was reduced when the length of the wire increased. By this discovery, Ohm explained the fundamental relationship between the electric current, the electromotive force, and the resistance. His theory is known as *Ohm's law*. Although simple, the theory opened the door for all electrical circuit analysis and designs. We use *ohm* as the unit for resistance (or impedance) in his honor.

The English chemist and physicist Michael Faraday (1791–1867) was a superb matriculate experimentalist who laid the foundations for the electromechanical theories that we use today. Faraday, through experimentation, demonstrated the relationships between the electric current, magnetic field, and mechanical force. In 1821, Faraday built a device that produced a continuous circular motion, which was the basis for the first alternating current (ac) motor. He published his electromagnetic work in three volumes entitled *Experimental Researches in Electricity* from 1839 to 1855. These classical books have been reprinted several times and are still available in specialized bookstores. Faraday's work inspired the Scottish physicist James Clerk Maxwell (1831–1879) to develop the vector relationships of the electric current, magnetic field, and mechanical force, which

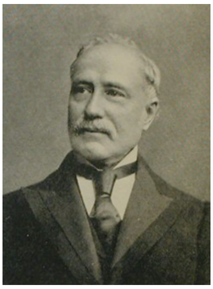
FIGURE 1.2 Pixii's generator. (Courtesy of the Smithsonian Museum, Washington, DC.)

are known today as *Maxwell's equations*. The unit of capacitance, farad, is named in memory of Michael Faraday.

The next inventor is probably the least known, but had enormous impact on power systems. Hippolyte Pixii (1808–1835) was a French instrument maker who built the first generator (or dynamo). His machine consisted of a magnet rotated by a hand crank and surrounded by a coil. Pixii found that the rotation of the magnet induced voltage across the coil. Pixii's machine, which was named magnetoelectric by him, was later developed into the electrical generator we use today. Figure 1.2 shows one of the early models of Pixii's generators.



The Italian inventor Antonio Pacinotti (1841–1912) invented a device that had two sets of windings wrapped around a common core. The windings were electrically isolated from the core and from one another. When an alternating voltage was applied across one winding, an induced voltage was observed across the second winding. The induced voltage had similar shape to the applied voltage but with different magnitude. This was the invention of the transformer we use today. Westinghouse further developed the transformer and had several early models, among them are the Gaulard and Gibbs transformer developed in 1883, shown in Figure 1.3, and the Stanley transformer developed in 1886.



John Ambrose Fleming (1849–1945) was an English electrical engineer and physicist. In 1904, he invented the first electronic device that consisted of two electrodes inside a vacuum tube. One electrode was a heated filament (cathode) that emitted electrons and the other (anode) collected them. This way, the vacuum tube allowed the electrons to pass only in one direction, thus creating the first diode. His invention inspired others to create different types of vacuum tubes. One of them is the American scientist Lee DeForest, who wrapped a thin grid of wires around the cathode. By applying a small

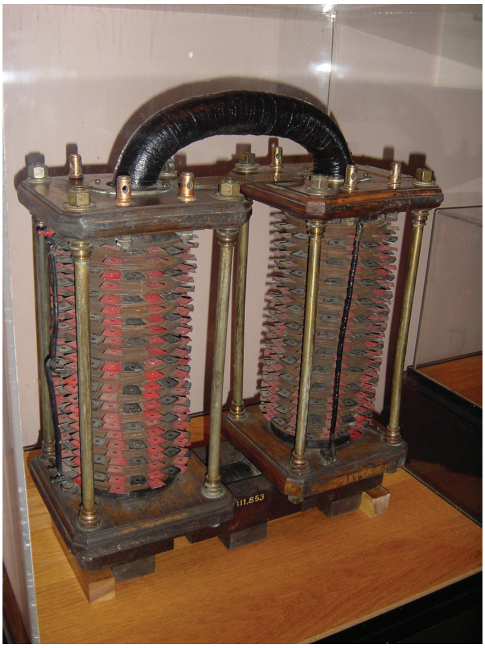


FIGURE 1.3 Gaulard and Gibbs transformer. (Courtesy of the Smithsonian Museum, Washington, DC.)

negative voltage to the grid, he managed to control the amount of electrons reaching the anode, thus controlling the electrical current. The vacuum tubes were then called *valves* as they act as a water valve where the flow of current can be reduced to zero by applying high enough negative voltage to the grid. This is the basic principle behind amplifiers. So it is not surprising that the vacuum tubes, Figure 1.4, led to the invention of the radio, television, and phone communications. The current ratings of these vacuum tubes were made high enough to allow their use in power applications. For example, the first generations of direct current (dc) lines were based on the vacuum tube technology. The vacuum tubes were used in all electronic equipment for decades until solid-state technology materialized in the 1950s.

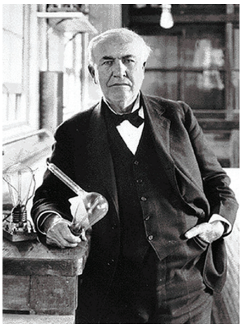
Julius Edgar Lilienfeld (1881–1963) was born in Lemberg in Ukraine. He did his graduate studies in Germany and obtained his habilitation in 1910. He became a professor of physics at the University of Leipzig in Germany. Lilienfeld immigrated to the United States in 1927. In 1926, he discovered the field effect principle of the transistor, which was first disclosed in a U.S. patent in 1930. Later, he filed several other patents that describe the construction and operation of layered semiconductor materials. Although, there is no evidence that Lilienfeld built a working transistor based on his discoveries, his patents describe many key theories for the bipolar transistors. The first practical bipolar-junction transistor was later developed in 1947 by Bell Laboratories' physicists Walter Houser Brattain (1902–1987), John Bardeen (1908–1991), and William Bradford Shockley (1910–1989). These scientists shared the Nobel Prize in physics in 1956 for their transistor. The invention of the transistor opened the door wide to a range of semiconductor inventions such as the field effect transistor (FET) in 1952 and the metal–oxide–semiconductor field-effect transistor (MOSFET) in 1963. In 1957, General Electric developed the silicon-controlled rectifier (SCR), which is one of the most

FIGURE 1.4 Vacuum tube.

important power electronic devices. The semiconductor inventions led to what is known as the *power electronics revolution*. Because of these devices, we can now build electric equipment with new capabilities and better performance while drastically reducing their sizes, costs, and losses. The power capabilities of these devices range from the milliwatt to the gigawatt, making them usable in low-power applications such as household chargers to high-power applications such as transmission line converters. Today, it is almost impossible to find electric equipment without a power electronic device.

Most of these marvelous innovations inspired two great scientists who are considered by many to be the fathers of electric power systems: Thomas Alva Edison and Nikola Tesla. Before we discuss their work, let us first summarize their biographies.

1.1 THOMAS A. EDISON (1847–1931)



Thomas Alva Edison was born on February 11, 1847, in Milan, Ohio, and died in 1931 at the age of 84. Early in his life, Edison showed brilliance in mathematics and science and was a very resourceful inventor with a wealth of ideas and knowledge. In addition to his engineering brilliance, Edison was also a businessman, although not highly successful by today's standards. During his career, he had a large number of patents (total of 1093 patents) issued under his name. His first patent was granted at the age of 21 in 1868, and his last one was at the age of 83. This makes him one of the most productive inventors ever with an average of about 1.5 patents per month. Of course, most of his patents were due to the teamwork with his research assistants.

His first patent was on an electric voting machine that tallied voting results fairly quickly. He tried to convince the Massachusetts Legislatures to adapt his machine instead of the tedious manual process used at that time, but did not succeed. The politicians did not like his invention because the slow process at that time gave them a chance to influence, and perhaps change, the voting results.

From 1862 to 1868, Edison worked as a telegrapher in several places, including New England which was the Silicon Valley of that time; all the new and interesting innovations were made in New England. During this period, he invented a telegraphic repeater, duplex telegraph, and message printer. However, Edison could not financially gain from these inventions, so he decided to move to New York City in 1869. While there, the Wall Street stock trade was disrupted by a failure in the stock ticker machine. Coincidentally, Edison was in the area and managed to fix the machine. This landed him a high-paying job that allowed him to continue with his innovations during his off-working hours.

In 1874, at the age of 27, Edison opened his first research and development laboratory in Newark, New Jersey. In 1876, he moved the facility to a bigger laboratory at Menlo Park, New Jersey. These facilities were among the finest research and development laboratories in the world. Great scientists worked in his laboratories such as Tesla, Lewis Howard Latimer (an African-American who worked on carbon filaments), Jonas Aylsworth (who pioneered plastics), Reginald Fessenden (a radio pioneer), William K.L. Dickson (movie developments), Walter Miller (sound recording), John Kruesi (phonograph), and Francis R. Upton (dynamo). At that time, the innovations and productivities of Edison's laboratories were unmatched by any other research facility in the world. By today's jargons, these laboratories were the core of the Silicon Valley of the nineteenth century. Because of his success with various innovations, Edison expanded his research and development laboratory in 1887 and moved it to West Orange, New Jersey. There, he created the Edison General Electric Company, which in 1892 became the famous General Electric Corporation.

The large number of inventions that Edison made includes the silent movie, alkaline storage battery, electrical generator, ore separator, printer for stock ticker, printer for telegraph, electric locomotive, motion picture camera, loudspeakers telephone, microphone, mimeograph, and the telegraph repeater.

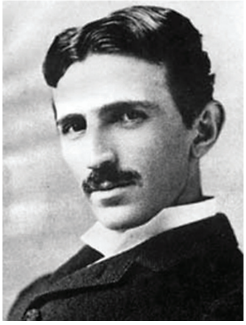
Edison was a highly competitive scientist who was willing and able to compete with great scientists in several areas at the same time. Among his innovations is the carbon transmitter, which ultimately was developed into the telephone. However, Alexander Graham Bell was also working on the same invention, and he managed to beat Edison to the telephone patent in 1876. This specific event upset Edison tremendously, but did not slow him down. He worked on the phonograph, which was one of Bell's projects, but this time Edison patented the phonograph in 1878 before Bell could apply for his own patent. One of Edison's most important inventions was the electric lightbulb. This simple device is probably one of his everlasting inventions. The first incandescent lightbulb was tested in Edison's laboratories in 1878 (see the photo in Figure 1.5). Although the filament of the bulb burned up quickly, Edison was very aesthetic about the commercial prospects of his invention. Several developments were later made to produce filaments with longer lifetimes.

Before the invention of the electric lightbulb, New York streets were illuminated by oil lamps. So when Edison invented his bulb, the technology was resisted by Rockefeller, who was an oil tycoon. But soon after realizing that oil would be used to generate electricity, Rockefeller accepted this new technology and was among its promoters.

Edison received the U.S. Congressional Gold Medal for Career Achievements in 1928. When he died in 1931, people worldwide dimmed their lights in honor of his achievements. Initially it was suggested that the proper action would be to turn off the electricity completely for a few minutes, but the suggestion was quickly ruled out because of its impracticality; the power systems worldwide would have to shut down and restart, which was considered to be an inconceivable task. Today, a number of museums around the world have sections dedicated to Edison and his inventions. Among the best in the United States are the Edison National Historic Sites in West Orange, New Jersey, and Menlo Park in Edison, New Jersey. Also, the National Museum of American History has a section dedicated to Thomas Edison.

FIGURE 1.5 Edison's lightbulbs. (Courtesy of the Smithsonian Museum, Washington, DC.)

1.2 NIKOLA TESLA (1856–1943)



Nikola Tesla was born in Smiljan, Croatia, on July 9, 1856. Tesla was a gifted person with an extraordinary memory and highly analytical mind. He had his formal education at the Polytechnic School of Gratz, Austria, and the University of Prague in the areas of mathematics, physics, and mechanics. In addition to his strength in science and mathematics, Tesla spoke six languages. During his career, Tesla had more than 800 patents. Although lesser in number than Edison's record, his patents were mostly the direct result of his own work. Furthermore, unlike Edison, Tesla was broke most of his life and could not afford the cost of patent applications. Actually, his most resourceful era was his last 30 years, but because of his poor financial condition, he managed to apply for very few patents.

Tesla moved from Europe to the United States in 1884 and worked for Edison in his laboratory as a research assistant. This was during the time Edison patented the lightbulb and was looking for a way to bring electricity to homes, offices, and factories. He needed a reliable system to distribute electricity and Tesla was hired to help in this area.

Among Tesla's inventions are the ac motor shown in Figure 1.6, the hydroelectric generator, the radio, x-rays, vacuum tubes, fluorescent lights, microwaves, radar, the Tesla coil, the automobile ignition system, the speedometer, and the electronic microscope.

In the opinion of many scientists, historians, and engineers, Tesla invented the modern world. This is because he developed the concept of the power system we use today. By today's business standards, Tesla should have been among the richest in the world. But because of his unfortunate business failures, Tesla was broke when he died at the age of 86 on July 7, 1943. Among the honors given to Tesla was the IEEE Edison Medal in 1917, the most coveted prize in electrical engineering in the United States. Tesla was inducted into the Inventor's Hall of Fame in 1975. He received honorary degrees from institutions of higher learning, including Columbia University, Yale University, University of Belgrade, and the University of Zagreb. He also received the Elliott Cresson Medal of the Franklin Institute. In 1956, *tesla* was adopted as the unit of magnetic flux density in the meter-kilo-second-amp (MKSA) system in his honor. In 1975, the IEEE Power Engineering Society

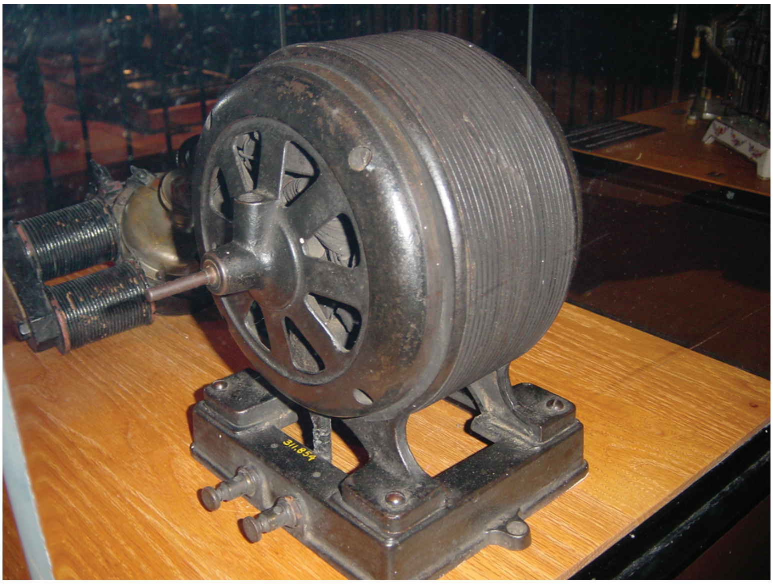


FIGURE 1.6 Tesla's ac motor. (Courtesy of the Smithsonian Museum, Washington, DC.)

established the Nikola Tesla Award for outstanding contributions in the field of electric power in his honor. Among the best museums for Tesla are the Nikola Tesla Museum in Belgrade and the Nikola Tesla Museum of Science and Industry in Colorado Springs, Colorado.

1.3 BATTLE OF AC VERSUS DC

Edison continued to develop the lightbulb and made it reliable enough for commercial use by the end of the nineteenth century. He powered his bulbs by dc sources that were commonly used at that time. The voltage and current of a dc source are unchanging with time; an example is shown in Figure 1.7. The battery is an excellent example of a dc source.

The people in the northeast of the United States were very eager to use this marvelous electrical bulb in their homes because, unlike oil lamps, electrical bulbs did not emit horrible fumes. Edison, who was also a businessman, decided to build a dc power system and sell electricity to these eager customers. He erected poles and extended wires (conductors) above the city streets. In September 1882, his Pearl Street plant in lower Manhattan started operation as the world's first commercial electric lighting power station. One of the most significant events in technological history took place in 1883 when Edison electrified the city of Brockton, Massachusetts. The center of the city was the first place on earth to be fully electrified by a central power station.

Edison's dc generators were low voltage (100 V) machines. As a result of the increasing demand for electricity, the wires carried larger currents causing larger voltage drops across the wires, thus reducing the voltage at the customers' sites. To understand these relationships, consider the simple representation of Edison's system shown in Figure 1.8. The voltage across the load V_{load} can be expressed by Equation 1.1

$$V_{load} = V_S - IR_{wire}$$

$$V_{load} = IR = \frac{V_S}{R + R_{wire}} R = \frac{V_S}{1 + \left(\frac{R_{wire}}{R}\right)} \tag{1.1}$$

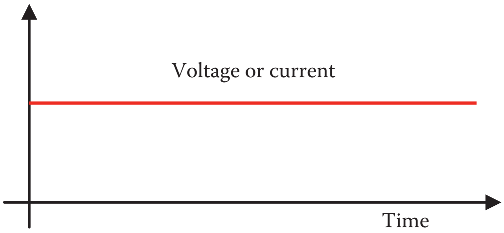


FIGURE 1.7 Direct current waveforms.

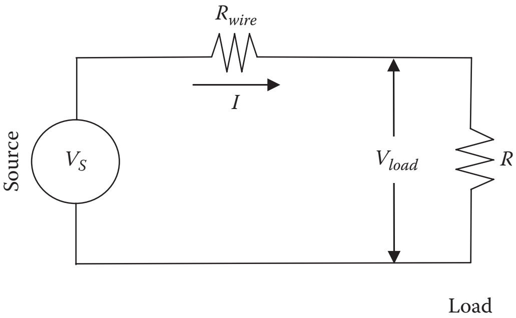


FIGURE 1.8 Simple representation of Edison's dc system.

where

V_S is the voltage of the dc source (100 V)
R is the load resistance (large number of bulbs for large number of homes)
R_{wire} is the resistance of the wire (conductor) connecting the source to the load

Because more customers mean more load resistances are added in parallel, the total load resistance R decreases when more customers are added to the system. As you can see from Equation 1.1, higher loads (i.e., more customers and smaller R) lead to lower voltage at the customers' end of the line V_{load}.

Example 1.1

Assume $V_S = 100$ V, $R = 1\ \Omega$, and $R_{wire} = 0.5\ \Omega$. Compute the following:

a. Voltage at the load side
b. Percentage of the load voltage with respect to the source voltage
c. Energy consumed by the load during a 10 h period
d. Maximum load (minimum resistance) if the load voltage cannot be reduced by more than 10% of the source voltage
e. Energy consumed by the new load during a 10 h period

Solution

a. By direct substitution in Equation 1.1, we can compute the voltage at the load side:

$$V_{load} = \frac{V_S}{1 + \left(\frac{R_{wire}}{R}\right)} = \frac{100}{1 + \left(\frac{0.5}{1}\right)} = 66.67\ \text{V}$$

This low voltage at the load side may not be high enough to shine the lightbulbs:

b.

$$\frac{V_{load}}{V_s} = 66.67\%$$

c. The energy is the power multiplied by time. Hence, the energy consumed by the load is

$$E = Pt = \frac{V_{load}^2}{R}t = \frac{66.67^2}{1}10 = 44.444\text{ kWh}$$

d. If the minimum load voltage is 90% of the source voltage, the load resistance can be computed from Equation 1.1 as

$$\frac{V_{load}}{V_s} = \frac{1}{1+\left(\frac{R_{wire}}{R}\right)}$$

$$0.9 = \frac{1}{1+\left(\frac{0.5}{R}\right)}$$

$$R = 4.5\,\Omega$$

Notice that the new load resistance is 4.5 times the original load resistance. This means that fewer customers are connected, and less energy is consumed by the load:

$$E = Pt = \frac{V_{load}^2}{R}t = \frac{(0.9\times 100)^2}{4.5}10 = 18.0\text{ kWh}$$

This is less energy than the one computed in step c.

As seen in Example 1.1, the load voltage V_{load} is reduced when more customers are added. The main reason is because the conductor resistance R_{wire} and the load current I cause a voltage drop across the conductor, thus reducing the voltage across the load resistance as given in Equation 1.1. The wire resistance increases when the length of the wire increases or the cross section of the wire decreases, as given in the following equation:

$$R_{wire} = \rho\frac{l}{A} \tag{1.2}$$

where

ρ is the resistivity of the conductor in Ω-m which is a function of the conductor's material
A is the cross section of the wire
l is the length of the wire

Example 1.2

Assume $V_S = 100$ V and the load resistance $R = 1\ \Omega$. Compute the length of the wire that would not result in load voltage reduction by more than 10%. Assume the wire is made of copper and the diameter of its cross section is 3 cm.

Solution

From Equation 1.1, we can compute the wire resistance:

$$\frac{V_{load}}{V_S} = \frac{1}{1+\left(\frac{R_{wire}}{R}\right)}$$

$$0.9 = \frac{1}{1+\left(\frac{R_{wire}}{1}\right)}$$

$$R_{wire} = 0.111\ \Omega$$

From the table of units in Appendix C, the resistivity of copper is 1.673×10^{-8} Ω-m. Hence, the length of the wire can be computed by using Equation 1.2.

$$l = \frac{AR_{wire}}{\rho} = \frac{\left(\pi r^2\right)R_{wire}}{\rho} = \frac{\left(\pi \times (0.015)^2\right)0.111}{1.673 \times 10^{-8}} = 4.69\,\text{km}$$

A wire with length longer than 4.69 km will result in lower voltage across the load than needed.

As seen in Equation 1.2 and Example 1.2, long wires cause low voltage across the load. Because of this reason, the limit of Edison's system was about 3 miles, beyond which the wire resistance would be high enough to render the lightbulbs useless. To address this problem, Edison considered the following three solutions:

1. Reduce the wire resistance by increasing its cross section. This solution was expensive because
    a. Conductors with bigger cross sections are more expensive
    b. Bigger conductors are heavier and would require higher poles to be placed at shorter spans
2. Have several wires feeding areas with high demands. This was also an expensive solution as it would require adding more wires for long miles.
3. Place electrical generators at every neighborhood. This was also an impractical and expensive solution.

Edison was faced with the first real technical challenge in power system planning and operation. He looked at all possible solutions from anyone who could help. That was probably why he hired Tesla in his laboratory and promised him lucrative bonuses if he could solve this problem. Tesla knew

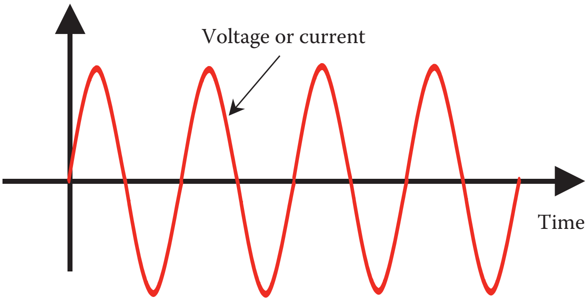


FIGURE 1.9 Alternating current waveform.

the problem was related to the low voltage (100 V) Edison was using in his dc system. The viable alternative was to increase the supply voltage so the current could be reduced and, consequently, the voltage drop across the wire could be reduced as well. Since the power consumed by the load is the multiplication of voltage by current (as given in Equation 1.3), an increase in the source voltage results in a decrease in current. If the current decreases, the voltage drop across the wire IR_{wire} is reduced, and the load voltage $V_{load} = V_S - IR_{wire}$ becomes a higher percentage of the source voltage. Although logical, adjusting the voltage of the dc systems was an unknown technology at that time.

$$P = VI \tag{1.3}$$

Instead of the dc system, Tesla promoted a totally different concept. Earlier in his life, Tesla conceived the idea of the *alternating current* (ac) whose waveform is shown in Figure 1.9. The ac is a sinusoidal waveform changing from positive to negative and back to positive in one cycle. Tesla wanted to use the ac to produce a rotating magnetic field that can spin motors (see Chapter 12). While working at the Continental Edison Company in Paris, Tesla actually built the first motor running on ac. The machine was later named the *induction motor* (see Chapter 12).

Tesla was also aware of the device invented by Pacinotti in 1860 that could adjust the ac voltages. This device was further developed by Tesla and became the transformer we use today (see Chapter 11). The transformer requires alternating magnetic field to couple its two separate windings. Therefore, it is designed for ac waveforms and is ineffective in dc systems.

Tesla molded these various technologies into a new design for the power system based on the ac as shown in Figure 1.10. The voltage source of the proposed system was ac at generally low voltage. *Transformer 1* was used to step-up (increase) the voltage at the wire side of the transformer to a high level. The high voltage of the wire resulted in lower current inside the wire. Thus, the voltage drop across the wire IR_{wire} was reduced. At the customers' sites, the high voltage of the wire was stepped down (reduced) by *transformer 2* to a safe level for home use.

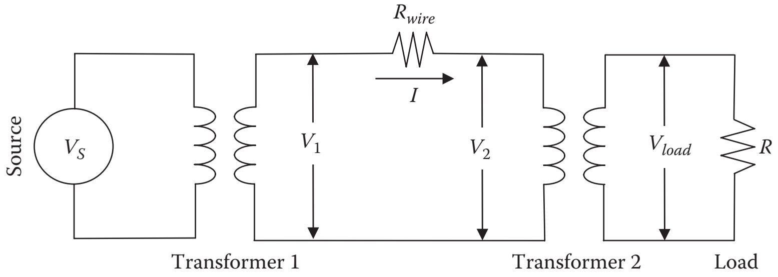


FIGURE 1.10 Tesla's proposed system.

Tesla stated three main advantages for his ac system:

1. Power can be transmitted over long distances with little voltage drop across its wires.
2. Generating plants need not be installed at residential areas as suggested by Edison for his dc system.
3. Rotating magnetic fields can be created for electric motors.

Edison was not impressed by Tesla's ac system because of its unsafe high-voltage wires that would pass through residential areas. However, most historians believe that Edison's rejection to the ac system was because he had too much money invested in the dc infrastructure. This disagreement created an irreparable rift between these two great scientists. Tesla and Edison continued to disagree on various other issues, and Tesla left Edison's laboratory and eventually worked for Westinghouse.

The dc versus ac battle started between Edison and General Electric, on one side, and Tesla and Westinghouse, on the other. Edison used unconventional methods to convince the public that Tesla's high-voltage ac system was too dangerous. He made live demonstrations where he used high voltage to deliberately electrocute animals such as puppies, cats, horses, and even elephants. Edison went so far as to convince the state of New York to use an electric chair powered by high voltage ac system to execute condemned inmates on death row. Most historians believe that his real motive was to further tarnish the safety of the ac system. Sure enough, New York City executed its condemned inmates by the proposed electric chair, and Edison captured the occasion by referring to the execution process as "Westinghoused," a clear reference to the ac system promoted by Tesla and Westinghouse. When Tesla signed a contract with Westinghouse to erect ac wires, posters were put on the power poles to warn residents from the danger of being "Westinghoused." In addition to the negative publicity, Westinghouse ran into financial trouble, and Tesla's contract with Westinghouse was terminated before the ac system was fully implemented. Instead of becoming the world's richest man, Tesla died broke. Despite all the negative publicity created by Edison, the advantages of the ac systems were overwhelming. In fact, Edison later admitted that ac is superior to dc for power distribution and was quick to exploit the economical advantages of the ac system through several inventions. Once when Edison met with George Stanley, the son of the William Stanley who developed the transformer for Westinghouse, he told him "tell your father I was wrong." Tesla was considered by many historians to be the inventor of the new world. This is probably true since social scientists use energy consumption as a measure of the advancement of modern societies.

1.4 TODAY'S POWER SYSTEMS

The great scientists mentioned in this chapter, and many more, have provided us with the power systems we know today. The power engineers made use of the various innovations to deliver electricity safely and reliably to each home, commercial building, and factory. Indeed, it is hard to imagine our life without electricity.

In 2009, the world produced over 20 PWh (20×10^{15} Wh) of electric energy as shown in Figure 1.11. In about 10 years, the world generated 40% more electric energy. This awesome amount of energy is the main reason for the highly developed societies we enjoy today. To deliver this amount of power to the consumers, power engineers constructed several millions of transmission lines, power plants, and transformers. It is overwhelming to fathom how such a massive system is controlled and operated on a continuous basis.

National Aeronautics and Space Administration (NASA) often publishes a fascinating panoramic photo of the earth at night; one of them is shown in Figure 1.12. The photo shows the earth's man-made lights and comprises of hundreds of pictures generated by the orbiting Defense Meteorological Satellites Program (DMSP). As you see in the photo, man-made lights make it quite

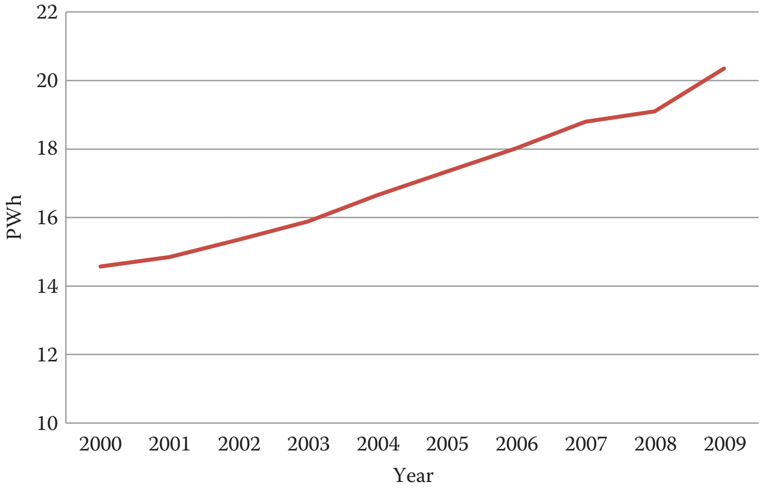


FIGURE 1.11 World's electric energy capacity. (From British Petroleum statistical review of world energy, 2007.)

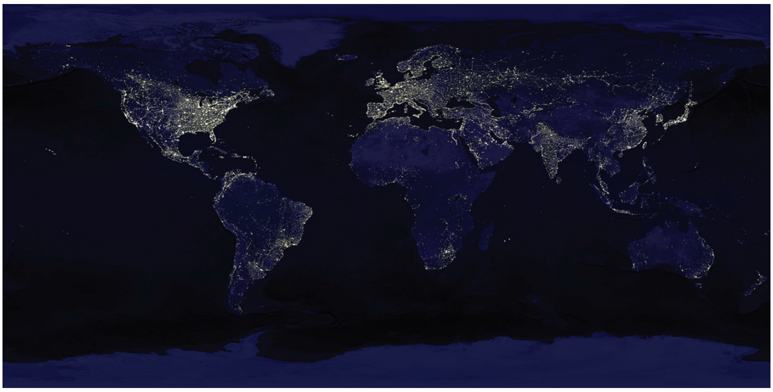


FIGURE 1.12 Earth at night. (Courtesy of NASA, Washington, DC.)

possible to identify the borders of cities and countries. Note that the developed or populated areas of the earth, such as Europe, eastern United States, and Japan, are quite bright, reflecting their high consumption of electric energy. Also, for countries with high populations around rivers, such as Egypt, the path of the rivers can be traced by following the light trails. The dark areas, such as in Africa, Australia, Asia, and South America, reflect low consumption of electricity or unpopulated regions. In North Africa, you can identify the great Sahara desert by the dark and expanded region. Similarly, you can identify the unpopulated outback region in Australia.

EXERCISES

1.1 In your opinion, identify 10 of the most important innovations in electrical engineering and name the inventors of these innovations.

1.2 Thomas Alva Edison has several innovative inventions. Select one of them and write an essay on the history of its development and the impact of the invention on society.

1.3 Nikola Tesla has several innovative inventions. Select one of them and write an essay on the history of its development and the impact of the invention on society.

1.4 The transformer is one of the major inventions in power systems. Why cannot we use it in dc systems?

1.5 State the advantages and disadvantages of using low-voltage transmission lines.

1.6 State the advantages and disadvantages of using high-voltage transmission lines.

1.7 In your opinion, what are the major developments in future power systems?

1.8 A simple power system consists of a dc generator connected to a load center via a transmission line. The load resistance is 10 Ω. The transmission line is 50 km copper wire of 3 cm in diameter. If the voltage at the generator terminals is 400 V, compute the following:

a. Voltage across the load
b. Voltage drop across the line
c. Line losses
d. System efficiency

1.9 A simple power system consists of a dc generator connected to a load center via a transmission line. The load power is 100 kW. The transmission line is 100 km copper wire of 3 cm diameter. If the voltage at the load side is 400 V, compute the following:

a. Voltage drop across the line V_{line}
b. Voltage at the source side V_{source}
c. Percentage of the voltage drop V_{line}/V_{source}
d. Line losses
e. Power delivered by the source
f. System efficiency

1.10 Repeat the previous problem assuming that the transmission line voltage at the load side is 10 kV.

1.11 Identify 10 household appliances that use power electronic devices and circuits. Discuss the advantages of using power electronics in two of these appliances.

2 Basic Components of Power Systems

Modern power networks are made up of three distinct systems: generation, transmission, and distribution. Figure 2.1 shows a sketch of a typical power system. The generation system includes the main parts of the power plants such as turbines and generators. The energy resources used to generate electricity in most power plants are combustible, nuclear, or hydropower. The burning of fossil fuels or a nuclear reaction generates heat that is converted into mechanical motion by the thermal turbines. In hydroelectric systems, the flow of water through the turbine converts the potential or kinetic energy of the water into rotating mechanical energy. These turbines rotate the electromechanical generators that convert the mechanical energy into electric energy.

The generated electricity is transmitted to all customers by a complex network of transmission systems composed mainly of transmission lines, transformers, and protective equipments. The transmission lines are the links between power plants and load centers. Transformers are used to increase (step up) or decrease (step down) the voltage. At the power plant, a transmission substation with step-up transformers increases the voltage of the transmission lines to very high values (220–1200 kV). This is done to reduce the current through the transmission lines, thus reducing the cross section of the transmission wires and consequently reducing the overall cost of the transmission system. At the load centers, the voltage of the transmission lines is reduced by step-down transformers to lower values (15–25 kV) for the distribution of power within city limits. At the consumer sites, the voltage is further reduced to values from 100 to 240 V for household use depending on the standards of the country.

Transmission lines are classified by their voltage levels. There are generally four classes: low, medium, high, and extra high. Figure 2.2 shows the general classification used by utilities. Since there is no clear border between classes, they may overlap. For example, 500 kV is considered by some utilities to be high voltage and by others to be extra high voltage.

The power system is extensively monitored and controlled. It has several levels of protections to minimize the effect of any damaged component on the system's ability to provide safe and reliable electricity to all customers. A number of key devices and equipment used in power systems are covered in this chapter.

2.1 POWER PLANTS

At the power plant, energy resources such as coal, oil, gas, hydropower, or nuclear power are converted into electricity as shown in Figure 2.3. The main parts of the power plant are the burner (in fossil plants), the reactor (in nuclear power plants), the dam (in a hydroelectric plant), the turbine, and the generator. The power plants can be huge in size and capacity. For example, the Itaipu hydroelectric power plant located at the Brazilian–Paraguayan border produces 75 TWh annually (Figure 2.3b). China is building the largest nuclear power plant in the southern province of Guangdong with a capacity of 6 GW.

Although power plants are enormous in mass, they are delicately controlled. A slight imbalance between the input power of the turbine and the output electric power of the generator may cause a blackout unless rapidly corrected. To avoid blackouts, the massive amount of water or steam inside

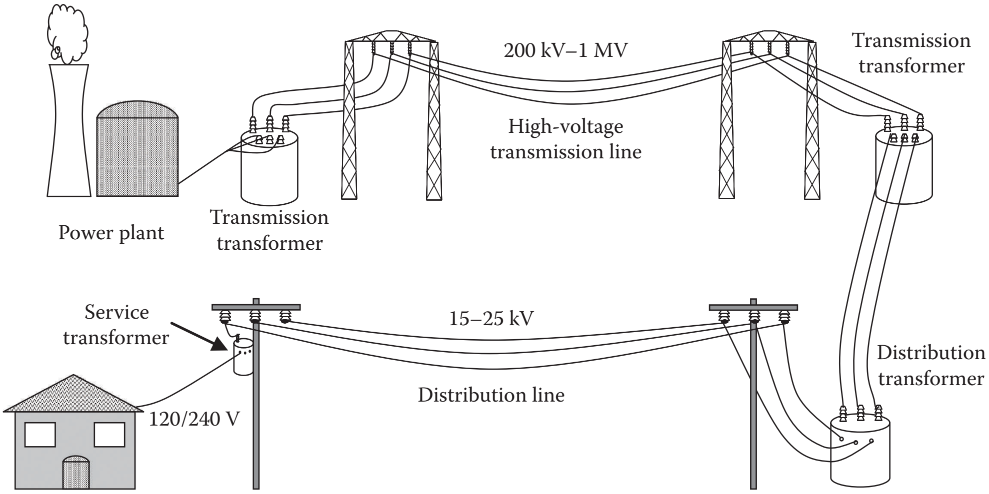


FIGURE 2.1 Main components of power systems.

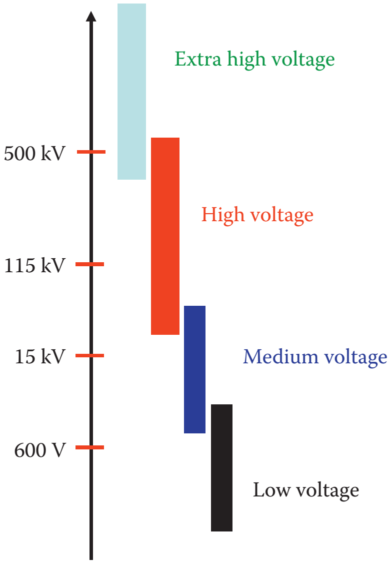


FIGURE 2.2 Categorization of transmission lines.

the plant must be tightly controlled at all times, which is an enormous challenge to mechanical, electrical, and structural engineers.

2.1.1 TURBINES

The function of the turbine is to rotate the electrical generator by converting the thermal energy of the steam or water into rotating mechanical energy. There are two types of turbines in conventional power plants: thermal and hydroelectric. Figure 2.4 shows a model of a hydroelectric turbine. It consists of blades mounted on a rotating shaft and curved to capture the maximum energy from water. The angle of the blade can be adjusted in some types of turbines for better control on its output mechanical power.


(a) (b)
(c)

FIGURE 2.3 Power plants (a) nuclear, (b) hydro, (c) thermal.

FIGURE 2.4 Model of hydroelectric turbine.

In thermal power plants, fossil fuels or nuclear reactions are used to produce steam at high temperatures and pressures. The steam is passed through the blades of the thermal turbine and causes the turbine to rotate. The steam flow is controlled by several valves at critical locations to ensure that the turbine rotates at a precise speed.

A typical hydroelectric power plant consists of a dam that holds the water upstream at high elevations with respect to the turbine. The difference in height between the water surface behind the dam and the turbine blades is called *head*. The larger the head, the more potential energy is stored in the water behind the dam. When electricity is needed, the water is allowed to pass to the turbine blades through pipes called *penstocks*. The turbine then rotates, and the valve of the penstock regulates the flow of water, thus controlling the speed of the turbine.

Since the generator is mounted on the shaft of the turbine, the generator rotates with the turbine and electricity is generated. To ensure that the voltage of the generator is at a constant frequency, the turbine must run at a precise and constant speed. This is not a simple task as we shall see later in Chapter 14.

2.1.2 GENERATORS

The generator used in all power plants is the *synchronous* machine (see Chapter 12). The invention of the synchronous generator goes back to Hippolyte Pixii (1808–1835), who was the first to build a dynamo. The synchronous machine has a magnetic field circuit mounted on its *rotor* and is firmly connected to the turbine. The stationary part of the generator, called a *stator*, has windings wrapped around the core of the stator. When the turbine rotates, the magnetic field moves inside the machine in a circular motion. As explained by Faraday, the relative speed between the stator windings and the magnetic field induces voltage across the stator windings. When an electrical load is connected across the stator windings, the load is energized as explained by Ohm's law. The output voltage of the generator (5–22 kV) is not high enough for the efficient transmission of power. Higher voltage generators are not practical to build as they require more insulation, making the generator unrealistically large in size. Instead, the output voltage of the generators is increased by using step-up transformers.

2.2 TRANSFORMERS

The main function of the transformer is to increase (step up) or decrease (step down) the voltage (see Chapter 11). As explained in Chapter 1, the voltage of the transmission line must be high enough to reduce the current in the transmission line. When electric power is delivered to the load centers, the voltage is stepped down for safer distribution over city streets as seen in Figure 2.1. When the power reaches customers' homes, the voltage is further stepped down to the household level of 100–240 V, depending on the various standards worldwide.

2.3 TRANSMISSION LINES

Power lines (conductors) deliver electrical energy from the generating plant to customers as shown in Figure 2.1. The bulk power of the generating plant is transmitted to load centers over long distance lines called *transmission lines*. The lines that distribute the power within city limits are called *distribution lines*. There are several other categories such as *subtransmission lines*, but these are fine distinctions that we should not worry about at this stage. In the United States alone, there is about 300,000 km of transmission lines rated 110 kV or above. This is equivalent to at least 7.5 times the circumference of the earth. The construction of such an immense grid, and maintaining the flow of power through it is one of the hardest tasks for power system engineers.

The transmission lines are high-voltage wires (220–1200 kV) mounted on tall towers to prevent them from touching the ground, humans, animals, buildings, or equipment. High-voltage towers are normally 25–45 m in height; one of these towers is shown in Figure 2.5. The higher the voltage of the wire, the taller is the tower.

High-voltage towers are normally made of galvanized steel to achieve the strength and durability needed in harsh environments. Since steel is electrically conductive, high-voltage wires cannot be attached directly to the steel tower. Instead, insulators made of nonconductive material mounted on the tower are used to hold the conductors away from the tower structure. The insulators withstand

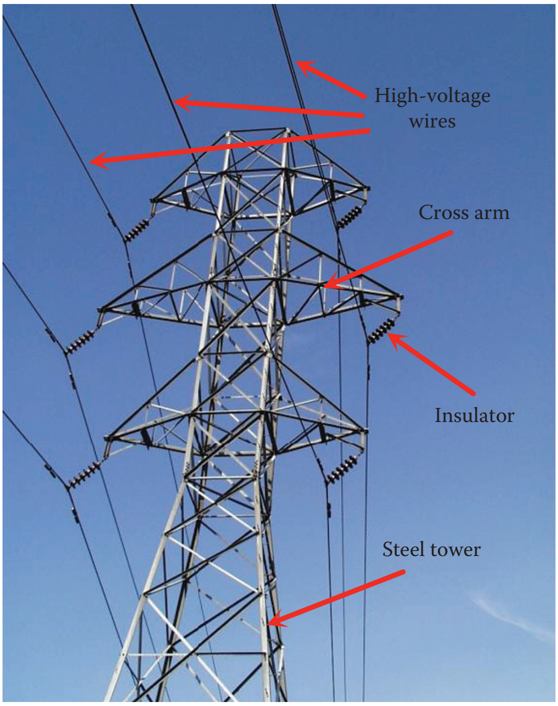
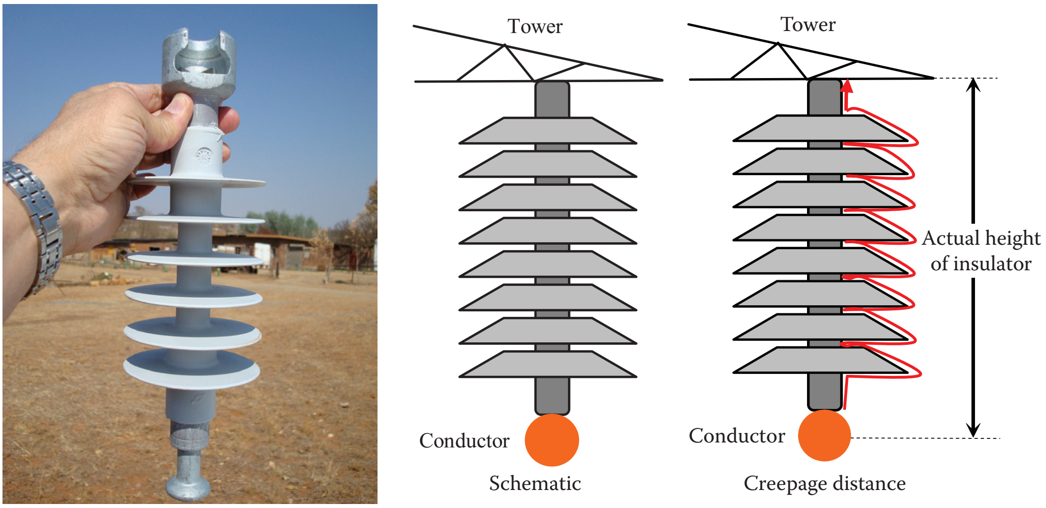


FIGURE 2.5 Transmission line tower.

the static and dynamic forces exerted on the conductor during windstorms, freezing rain, or earth movements. Insulators come in various shapes and designs; one of them is shown in Figure 2.6a. It consists of mounting ends and insulated central rod with several disk-shaped insulating materials. In some types of insulators, the disk has a slightly conical shape, where the top diameter is slightly smaller than the bottom diameter as shown in Figure 2.6b. The top end of the central rod is attached to the tower, and the lower end is attached to the conductor. The disks have two main functions:

1. They increase the flashover distance between the tower and the conductor (called *creepage* distance).
2. When it rains, the insulators are automatically cleaned since the disks are conical shaped or are slightly bent toward the earth.

An electrical discharge between any two metals having different potentials depends on the potential difference and the separation between the two metals. If an insulator is placed between two metals, a flashover may occur along the surface of the insulator if the potential difference between the two metals is high enough or the length of the insulator is small enough. To protect against the flashover in high-voltage transmission lines, the insulators must be unrealistically long. However, if a disk-shaped insulator is used, the distance between the tower and the conductor over the surface of the insulator is more than the actual length of the insulator. This is explained in Figure 2.6c, where the jagged arrow shows the flashover path which is longer than the actual height of the insulator. The flashover path is called the *creepage* distance and is defined as the shortest distance along the surface of the insulation material. But why are the disks slightly bent toward the ground or have their upper radii smaller than their lower radii? The simple answer is to make it easy to clean the insulators. When it rains, the salt and dust deposited on the insulator are washed away. If it were to be mounted upside down, there would still be pockets where dust would be trapped, thus reducing the insulation capability of the insulators.



(a) (b) (c)

FIGURE 2.6 (a) Insulator, (b) schematic, and (c) flashover path.

2.4 DISTRIBUTION LINES

The conductors of the distribution lines are lower in voltage and are either buried underground or mounted on poles or towers. In most cities, the distribution network is mainly underground for esthetic and safety reasons. However, it is also common to have overhead distribution lines; one of these is shown in Figure 2.7.

Since the voltage of the distribution lines is much lower than that for the transmission lines, the distribution towers are shorter and their insulators are smaller. The distribution towers are often made of steel, wood, concrete, or composite materials. Most of the commercial and industrial plants have direct access to the distribution network, and they use their own transformers to step down the voltage to the levels needed by their various equipment. In residential areas, utilities install transformers in vaults or on towers to reduce the distribution line voltage to any value between 100 and 240 V, depending on the standard of the country.

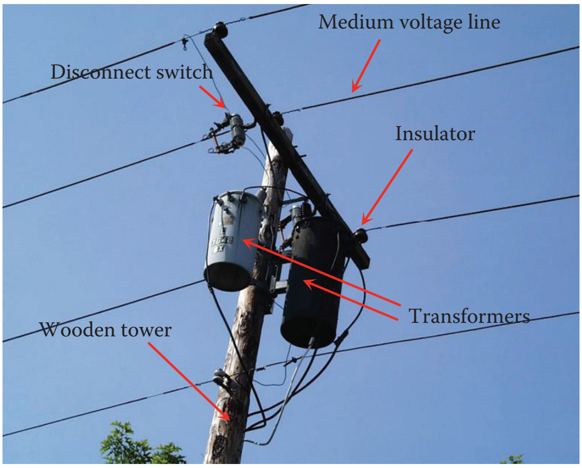


FIGURE 2.7 Distribution line tower.

2.5 CONDUCTORS

In the early days, transmission line conductors were made of copper. With the expansion of the transmission grid, copper was replaced by aluminum because of two main reasons: (1) aluminum conductors are much cheaper than copper and (2) aluminum is lighter than copper, which allows the use of longer spans between towers. The conductors used in transmission lines are not solid wires. This is because solid conductors are not flexible enough to curve and bend during transportation, storage, and the stringing of the conductors. Instead, conductors are made of a group of smaller conductors called strands that are spiraled as shown in Figure 2.8. If more than two layers of aluminum strands are used, the layers are spiraled in opposite directions to prevent unwinding. Since aluminum is a relatively soft metal and can easily break under tension (its tensile strength is relatively low), reinforcement steel alloy strands can be placed at the core of the conductor. The cross-section area of most conductors ranges from 12 to 800 mm^2. For cables, the conductors are also made of strands, but the conductor is encapsulated by insulation material to provide the needed isolation from the surrounding ground.

The power industry uses several types of conductors; the most common ones are the following three:

1. *All aluminum conductors* (AAC): This conductor has one or more strands of aluminum alloy without reinforcement strands. AAC is used when the span between towers is short (urban areas). In coastal areas, where corrosion is a problem, AAC conductors are used.
2. *Aluminum conductors steel reinforced* (ACSR): To increase the strength of the aluminum conductors, the ACSR has steel strands at its core surrounded by one or more layers of aluminum strands. The steel of the core is often galvanized steel (zinc coated). The ACSR are used when the span between towers is long. Even though the steel is galvanized, it can still be corroded over a period of time, especially in coastal areas.
3. *All aluminum alloy conductors* (AAAC): This is an alloy conductor made of aluminum, magnesium, and silicon. The AAAC has excellent tension characteristics and superior corrosion resistance.

The industry gives bird names to the type and size of conductors. Among the names are hen, eagle, squab, etc. The conductor is also represented by an alphanumeric code such as ACSR 24/7, which means aluminum conductors steel reinforced with 24 aluminum strands and 7 reinforcement strands.

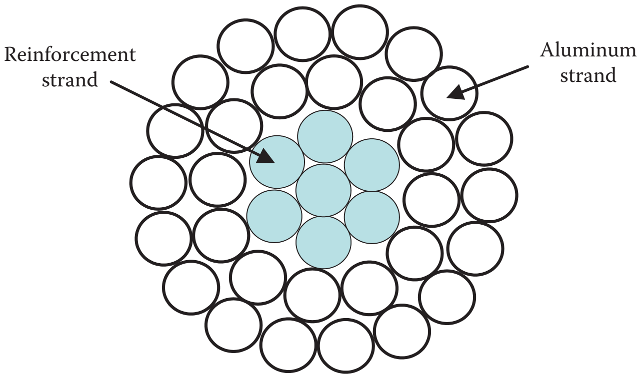


FIGURE 2.8 Transmission line conductor.

2.5.1 BUNDLED CONDUCTOR

Very-high-voltage transmission lines have their conductors split into subconductors bonded together electrically, but are separated from each other. This type of conductors is called *bundled conductor*, and is shown in Figure 2.9. But why do we bundle the conductors? After all bundling conductors is more expensive. The reason is related to the corona effect as explained next.

An object with high electric field ionizes the air surrounding it. This ionization is a form of leakage current and is called *corona*. The presence of the corona is highly undesirable for several reasons:

- Over time, corona damages the conductor; the leakage current creates spotted burns on the surface of the conductor.
- Corona produces electromagnetic fields with wide frequency spectrum that interferes with wired and wireless communications.
- Corona is a form of leakage current that causes energy losses.

The corona is intensified with the increase in the electric field strength (E) at the surface of the conductor. This electric field is

$$E = \frac{V}{d} \tag{2.1}$$

where

V is the voltage of the conductor
d is the diameter of the conductor

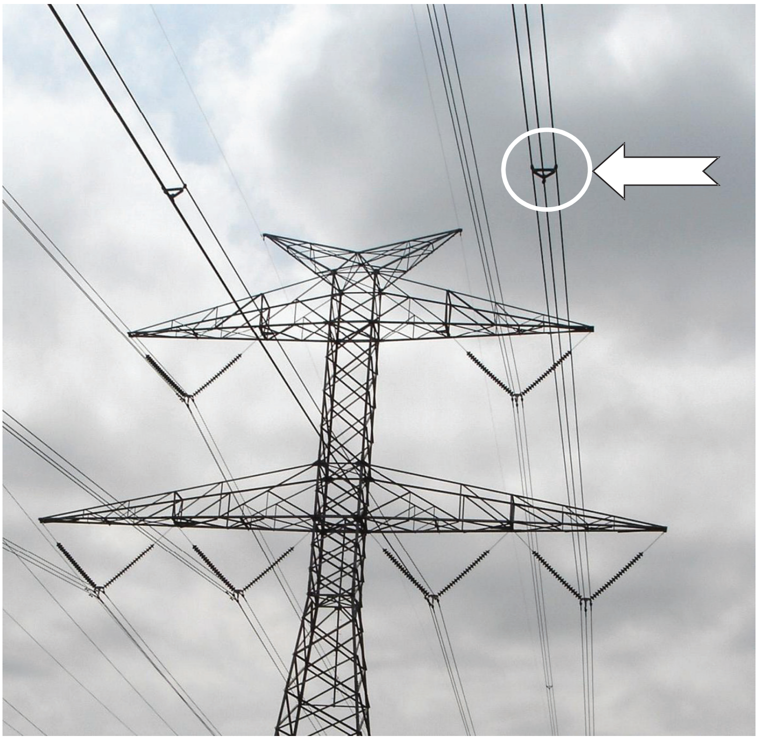


FIGURE 2.9 Bundled conductors.

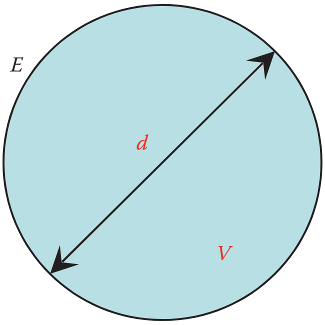
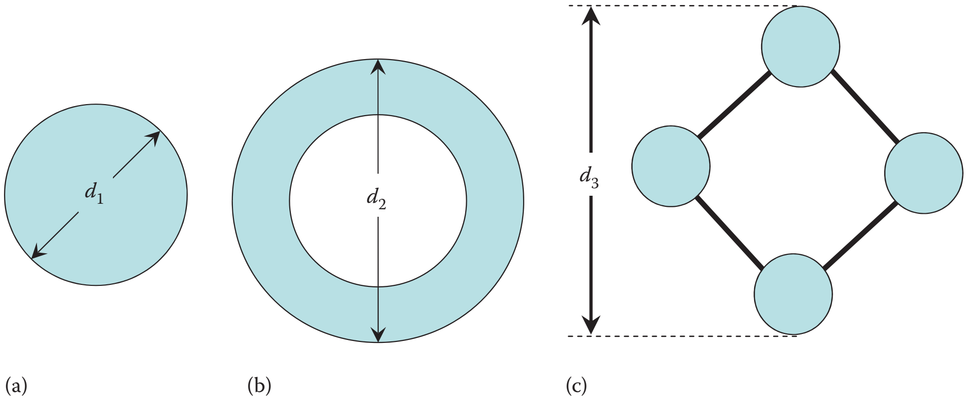


FIGURE 2.10 Electric field at surface of conductor.

Figure 2.10 shows a conductor with a voltage *V* and a diameter *d*. If the electric field at the surface of the conductor is high enough to cause corona, then we have basically two choices: reduce the voltage or increase the diameter of the conductor. The first choice is not desirable because high voltage allows us to transmit more power. The second choice has a few challenges:

- We must use more material to transmit the needed current; hence, the current density of the conductor is unnecessarily reduced.
- Conductors become more expensive.
- Conductors become heavy and difficult to string.
- Towers will have to be placed at shorter spans making the construction of the transmission line expensive.

To increase the diameter of the conductor without adding more material (i.e., maintain the same cross-section area), engineers have two options: (1) to use hollow conductors or (2) to bundle the conductors. Figure 2.11 shows these two options. In Figure 2.11a, the solid conductor with the needed cross section is shown. Assume that the voltage of this conductor is high enough to cause corona. In Figure 2.11b, a hollow conductor that has a large diameter, but with the same cross-section area, is shown. This option is not practical as the conductor becomes weak and can collapse under the pressure exerted on it during the stringing process, or due to the dynamic forces of winds. The option in Figure 2.11c is known as bundled conductor. It is composed of several subconductors with total area equal to that in Figure 2.11a. All subconductors are spaced from each other and their voltages are equalized. To maintain their space and to equalize the voltage of all subconductors,



(a) (b) (c)

FIGURE 2.11 Options to reduce electric field strength: (a) solid conductor, (b) hollow, and (c) bundled.

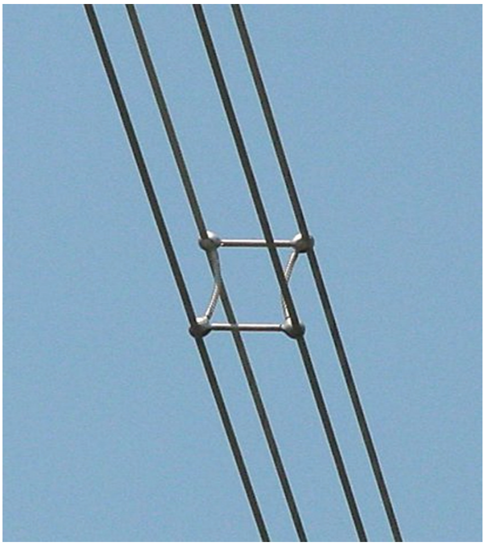


FIGURE 2.12 Bundled line with four sub-conductors.

conductive spacers are used at short distances along the transmission line. In this case, the electric field at the surface of the bundled conductor is reduced without the need to reduce the line voltage. This is because $d_3 > d_1$. Bundled conductors are typically used for transmission lines rated at or higher than 340 kV. Figure 2.12 shows a four-subconductor bundle. The spacer in the figure is repeated every few meters.

2.5.2 STATIC (SHIELD) WIRE

In some transmission lines, you can see one or two thin wires installed at the top of the tower. These wires are known as static, shield wire, or overhead ground wire (OHGW). The term *static* is used because the conductor does not carry current under normal conditions and is grounded along the transmission line and at the substations. The term *shield* is used because it protects the transmission line against lightning strikes. Figure 2.13 shows a tower with two static wires. In areas with little or no lightning storms, you may not find the static wire.

Because lightning often hits the highest point with the lowest potential, the static wire that is the highest wire at ground potential will attract the lightning strike. But why do we want to attract the lightning strike? The answer is simple; if we do not, the lightning may hit the conductors or the towers and the damage could be severe. If the line is hit, the strike could damage the insulators, rendering the transmission line unusable until the insulator is replaced. Because the buildup energy in the cloud often be dissipated through lightning strikes, engineers have decided to dissipate the energy through the static wire and protect the towers. The static wire is therefore bonded to all metal tower structures and at substations. In this way, the static wire dissipates the lightning energy throughout all ground paths along the transmission line.

The photo in Figure 2.13 shows two static wires. This is because the tower is windy and one wire may not be enough to protect all conductors.

2.6 SUBSTATIONS

The substation is where the voltage is adjusted, circuits are switched, system is monitored, and equipment is protected. A typical substation includes

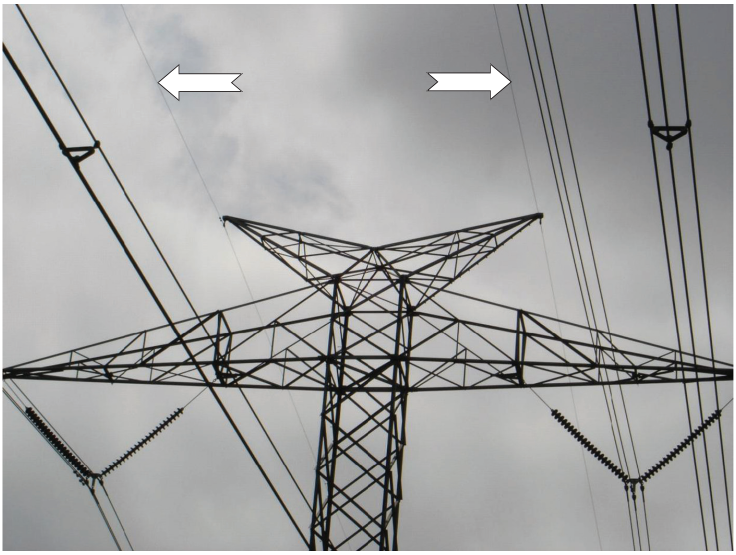


FIGURE 2.13 Static wires.

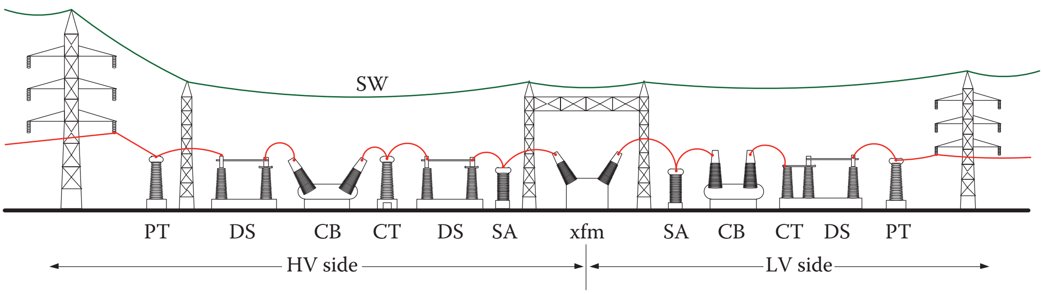


FIGURE 2.14 Main parts of a substation.

- Transformers
- Switching equipment
- Protection equipment
- Measuring devices
- Control systems

A schematic of a substation is shown in Figure 2.14. The substation steps up or steps down the voltage of the incoming power. In the figure, we assumed the high-voltage side is on the left of the graph. The incoming line reaches the substation, and its voltage is measured by a potential transformer (PT). Next, a disconnecting switch (DS) is placed to isolate a section of the substation when needed. A circuit breaker (CB) is connected to the DS to open the circuit when faults occur. A current transformer (CT) then measures the line current of the high-voltage side. Another DS is placed after the CB. When the CB is being serviced, the two adjacent DSs are opened to isolate the CB from any energized part. Before going to the transformer (xfm), a surge arrester (SA) is installed. This device is designed to dissipate any lightning or surge transients from reaching and damaging the transformer. The transformer steps down the voltage to lower levels. The low-voltage side of the transformer has another surge arrester to protect the xfm from the surges or lightning strikes that may come from the low-voltage side. Next are lower-voltage CBs, CTs, DSs, and PTs.

2.6.1 POTENTIAL TRANSFORMER

A photo of a PT is shown in Figure 2.15. To measure the voltage of the line V_1, we can use the capacitor divider in Figure 2.16. If we make $C_2 \gg C_1$, the voltage across C_2 will be much smaller than transmission line voltage, allowing us to use low-voltage voltmeter. In this case, the current through the capacitors is

$$I = V_1\left[2\pi f\left(\frac{C_1 C_2}{C_1 + C_2}\right)\right] = V_2\left(2\pi f\, C_2\right) \tag{2.2}$$

FIGURE 2.15 Potential transformer.

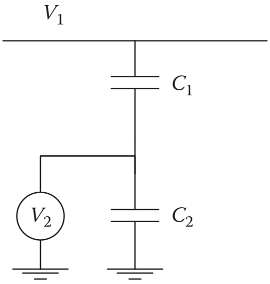


FIGURE 2.16 Capacitor divider.

where f is the frequency of the system. Equation 2.2 can be written as

$$V_1 = V_2\left(1 + \frac{C_2}{C_1}\right) \tag{2.3}$$

By measuring the low-voltage V_2, we can compute the high-voltage V_1 of the line.

Example 2.1

Design a capacitor divider to measure the voltage of 289 kV line.

Solution

The first step is to select the capacitors that limit the current through them to say 1 A. Also, select the voltage V_2 to be 200 V. This is low enough voltage to measure. Hence,

$$x_{c2} = \frac{V_2}{I} = \frac{200}{1} = 200\ \Omega$$

$$C_2 = \frac{1}{\omega x_{c2}} = \frac{1}{2\pi \times 60 \times 200} = 13.26\ \mu\text{f}$$

C_1 can be obtained by Equation 2.3.

$$V_1 = V_2\left(1 + \frac{C_2}{C_1}\right)$$

$$289 \times 10^3 = 200\left(1 + \frac{13.26 \times 10^{-6}}{C_1}\right)$$

$$C_1 = 9.18\ \text{nF}$$

2.6.2 CURRENT TRANSFORMER

A CT in a distribution network is shown in Figure 2.17; its main parts are shown in Figure 2.18 and the circuit diagram is shown in Figure 2.19. The CT is a special type of transformer where the primary winding is replaced by the conductor whose current is to be measured. The secondary winding is wrapped around an iron core and has hundreds or thousands of turns. The secondary windings are shorted by an ammeter. If we ignore the leakage flux, we can use the ampere-turn theory to estimate the secondary current I_2

$$I_1 N_1 = I_2 N_2 \tag{2.4}$$

where

I_1 is the current in the transmission line conductor
I_2 is the current in the secondary winding of the CT
N_1 is the number of turns of the transmission line conductor, which is equal to 1
N_2 is the number of turns of the secondary windings

FIGURE 2.17 Current transformer.

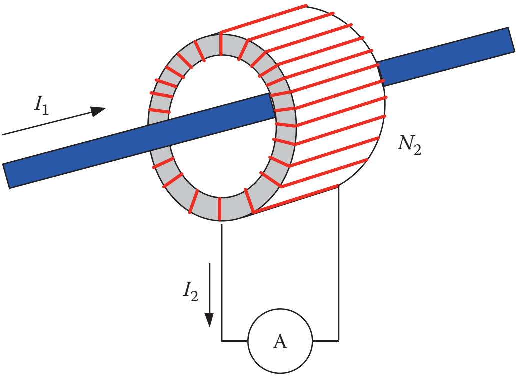


FIGURE 2.18 Main parts of CT.

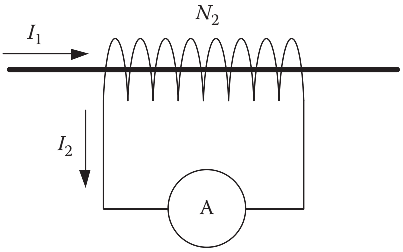


FIGURE 2.19 Circuit diagram of CT.

Hence, if we measure the current I_2, we can compute the line current I_1:

$$I_1 = I_2 N_2 \tag{2.5}$$

The rated secondary current I_2 is standardized at 1–5 A.

The CT must have its secondary windings shorted. This is done by the ammeter connected between its terminals. If the secondary winding is accidentally opened, the CT will be damaged. This is because the voltage per turn ratio is almost constant in the primary and secondary windings

$$\frac{V_1}{N_1} = \frac{V_2}{N_2} \tag{2.6}$$

or

$$V_2 = N_2 V_1 \tag{2.7}$$

Because N_2 and V_1 are high values, V_2 is extremely high and will cause insulation failures and arcing to force the current to pass through the secondary windings.

Example 2.2

A CT is designed to measure 10 kA in a 13.8 kV conductor; compute the turn ratio of its secondary windings.

Estimate the voltage across the secondary winding if its terminals are opened.

Solution

CTs are designed to have 1–5 A in its secondary windings. Let us select 2 A. Using Equation 2.5,

$$N_2 = \frac{I_1}{I_2} = \frac{10^4}{2} = 5000 \text{ turns}$$

When the secondary winding is open circuited, the voltage across it is

$$V_2 = 5000 \times 13.8 = 69\,\text{MV}$$

This level of voltage will certainly damage the CT.

2.6.3 CIRCUIT BREAKER

The CB is a high-voltage switching device designed to interrupt the flow of current even during faults. To operate the CB, supporting components such as the ones shown in Figure 2.20 are needed. The switching of the CBs is often by solenoids that are activated by a controller. For intentional switching, the controller receives the activation command from the control center operator. For fault clearing, the CB is automatically opened when the current exceeds predetermined values. This could be done as fast as a fraction of an alternating current (ac) cycle.

Because the energy of any inductors in the system cannot be permanently stored, all inductors must return the energy to the source when the breaker initiates the opening action. When the blades of the breaker starts to separate, an arc is developed to allow the inductors energy to return to the source. If the arc is not quickly quenched, the current keeps flowing even after the inductors' energy is fully returned to the source. Arc is a form of fire with high temperature that can easily damage the CB itself. Therefore, the arc must be quenched very quickly. To do that, the CB is immersed in

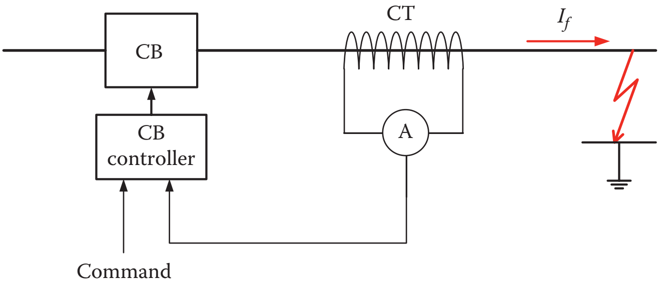


FIGURE 2.20 CB operation.

FIGURE 2.21 SF_6 CB.

a medium without oxygen and with good cooling property. Among these medium are oil and sulfur hexafluoride (SF_6). SF_6 is a colorless, odorless, nontoxic, non-flammable gas. It is not soluble in water and is higher in density than air. This is the most popular medium used today. A photo of an SF_6 breaker is shown in Figure 2.21. Other CBs, especially the ones used in distribution networks, are placed in vacuum containers to starve the arc from oxygen. Older models of CBs use air blast to blow high speed air through the arc. This prolongs the path of the arc, causing the arc to break.

The CB has two main settings: *tap setting* and *time dial setting*. The tap setting determines the level of current above which the CB is to open. Since most faults are temporary and can be cleared by themselves, the breakers are designed to wait a while before they initiate the opening. This delay time is the time dial setting. Because of all its complex features and the level of energy it can handle, the CB is among the most expensive equipment in the power grid. The power grid uses tens of thousands of CBs in the United States.

Another type of CB commonly used in distribution networks is the *recloser*. Reclosers are less expensive types of CBs with lower current ratings and slower action than substation CBs. They can interrupt fault currents and can automatically reclose after a momentary outage. However, if the fault is permanent, the recloser locks itself in the open positive after a preset number of reclosing operations occur.

Since most faults in the distribution networks are temporary, reclosers serve a very important role by automatically closing the circuit after a preset period of time. You probably have noticed its operation after an outage and have seen the power coming back and then go away again. This is a recloser closing the circuit then interrupting it again because the fault is still there.

2.6.4 DISCONNECTING SWITCHES

DSs are automatic or manually operating devices. In either case, they are not designed to interrupt a fault current and are less precise than CBs. They are normally used to isolate sections of the network. Take, for example, the case in Figure 2.22. The CB has one DS on each side. This is to allow workers to perform maintenance on the CB. The CB is first opened to interrupt the current. Then, the two DS are opened to isolate the CB from the grid. A photo of a disconnect switch is shown in Figure 2.23.

Another type of DS is the sectionalizer. This device is more sophisticated than the DS described earlier. Sectionalizers do not interrupt fault currents and are often used in conjunction with reclosers. They have counters that keep track of the number of times a recloser operates and can isolate sections of the network when the power is off. An example of operation is shown in Figure 2.24. The figure shows a recloser after the distribution transformer. Loads 1–3 are served by the recloser. A sectionalizer is installed between Loads 2 and 3. Assume that the recloser is designed to operate twice (two counts) and the sectionalizer is designed to operate once (one count). Assume a fault occurs in the line between Loads 2 and 3. The fault causes the recloser to open. The sectionalizer notices that the recloser is open. Assume that the fault is not cleared and the recloser is closed into the fault. The recloser will quickly open again as the fault is still there. The sectionalizer will know that the recloser is opened the second time. This is when the sectionalizer opens its contacts.

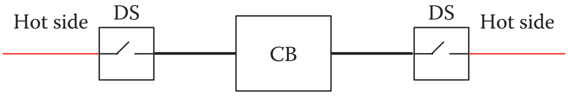


FIGURE 2.22 An application of DS.

FIGURE 2.23 Disconnect switch.