THE

ELECTRIC POWER INDUSTRY

A NONTECHNICAL GUIDE

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Foreword

Clean energy – the phrase rolls pleasantly and hopefully off the tongue. Only "clean energy" does not really exist. No matter the energy type, all energy production and consumption has consequences, some readily apparent, others more subtle. The most apparent consequence of using energy – releasing heat into the surrounding environment – is so common it sinks into the background and is not much discussed or debated. The more energy we use, the hotter our world becomes, even if we achieve "carbon neutral" status. Cleaner (not clean) energy is a complex topic with known and unknown consequences.

Conserving and limiting our use of energy and improving energy efficiency in the quest to reduce energy use *per capita* must be part of the energy dialogue. Those goals serve as important cornerstones of the energy policy debate and are, arguably, as important, if not more important, than other parts of achieving "cleaner energy."

We hope this book provides insight into the electrical power industry and aids in the energy dialogue moving the world along its journey to cleaner energy.

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Electrical Energy Basics

There is no greater satisfaction for a just and well-meaning person than the knowledge that he has devoted his best energies to the service of the good cause.

—Albert Einstein (1879–1955)

"Grandpa Tom, it was exciting! The teacher told us about electricity and how electricity does not cause pollution or climate change," Luke exclaimed. But then he turned quizzical and asked, "If electricity does not cause pollution, why don't we just switch to using only electricity?"

Luke's grandfather explained that electricity does not occur naturally, or at least not in sustainable amounts. Rather, electricity is generated from other forms of energy. "The world is trying to switch from carbon-based fuels like crude oil, coal, and natural gas to renewable fuels – primarily wind and solar," Grandpa Tom said. "But wind and solar are not as dependable as those carbon-based fuels and require lots of storage for when they aren't generating," Grandpa Tom elaborated.

The grandfather went on to explain that one of the primary advantages of electricity produced from "fossil fuels" is fossil fuels contain chemical energy derived many years ago from the sun, and the chemical energy stored in fossil fuels is convertible to electrical energy nearly instantaneously and on demand, whereas wind and solar can only generate significant amounts of electricity when atmospheric conditions allow.

A pensive frown came onto Luke's face, and, after a brief pause, he said, "It sounds like maybe electricity is not as simple as I thought."

"And life in general," Grandpa Tom added.

Electricity and Magnetism

Magnetic fields generate most of the electricity consumed in the world. Conversely, electricity can generate magnetic fields. So, magnetic fields and electricity are causally, and directly, related – a recurrent theme throughout this text. Most people use the terms magnetic field and magnetic force interchangeably, but physicists consider that incorrect. They say magnetic fields acting on an object produce a positive is positive, and negative multiplied by negative is also positive, power is always positive – at least as long as voltage and current are synchronized.

Figure 1-12 combines the voltage and current from Figure 1-11 to graph the power they produce.

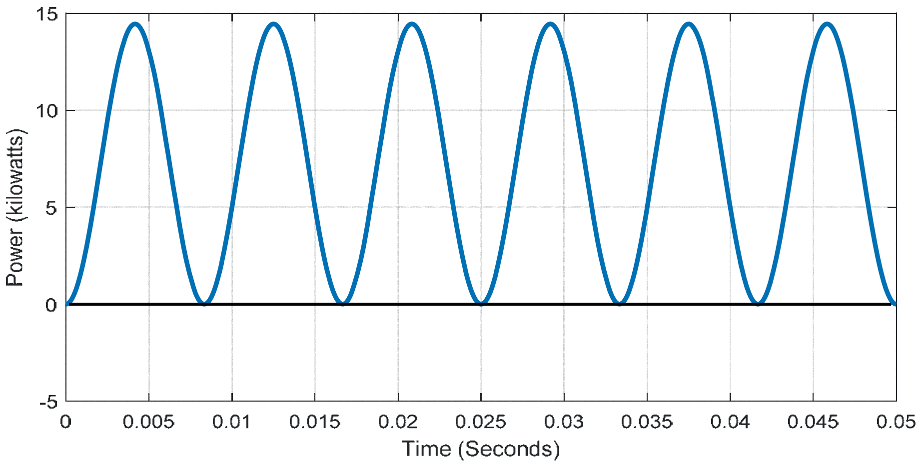

Figure 1-12. Graph of Power Resulting from 60 Hz, 120 Volt AC Applied to a 2-Ohm Resistor. Voltage and current are in phase, so power is always positive, indicating energy transfer from the generator is to a load resistor.

AC can be thought of as electrical energy waves alternating quickly and traveling fast.

Figure 1-12 shows power driving a resistive load. This text will discuss in a later section the concept of reactive loads and how those loads impact volts, current, and power.

Converting AC to DC

Many electronic devices operate on DC current, meaning AC must be converted to DC for them to work properly. Devices called *rectifiers*, which allow current transmission in only one direction, commonly accomplish that conversion. Figure 1-13 shows what happens if the alternating current from Figure 1-11 passes through a *half-wave* rectifier.

Figure 1-14 shows what happens if the alternating current from Figure 1-11 passes through a *full-wave* rectifier.

From these two figures, it is easy to guess where each got its name.

outskirts of the city (at that time). From there, the utility distributed electricity to eight transformer stations in the city.

Electric supply to the city of Mumbai, India (formerly known as Bombay) and its southern suburbs comes from Bombay Electric Supply and Transport. Originally, Brihanmumbai Electricity Supply and Transport was set up in 1873 as a tramway company called "Bombay Tramway Company Limited." In 1905, the company set up a thermal power station to generate electricity for its trams and to supply electricity to the city. It then rebranded itself to Bombay Electric Supply & Tramways (BEST) Company. In 1947, the Municipal Corporation took over BEST and rebranded it Bombay Electric Supply & Transport. In 1995, it was renamed Brihanmumbai Electric Supply & Transport.

Electrical Cooperatives

The Rural Electrification Act, passed by the U.S. Congress in 1936, provided federal loans for the installation of electrical distribution systems to serve isolated rural areas of the United States. The funding was channeled through cooperative electric power companies, hundreds of which still exist in the U.S today. By 1942, almost one-half of the farms in the U.S. had electricity due to the Rural Electrification Administration. By 1950, virtually all farms in the U.S. had electricity.

Two examples of a rural cooperative are Pedernales Electric Cooperative, headquartered in Johnson City, Texas, which was organized in 1938, and the San Bernard Electric (Co-op), which built eighty-nine miles of power lines in 1940. It initially served 141 members in the rural areas of Colorado and Austin Counties.

U. S. Federal Involvement

The U.S. Federal Government also became involved in electricity generation and transmission through various entities including the Boulder (later Hoover) Dam, beginning in 1931 (completed in 1936); the Tennessee Valley Authority (1933); Bonneville Power Administration (1937); the Grand Coulee Dam (between 1933 and 1942); Southwestern Power Administration (1943); and Southeastern Power Administration (1950).

1950–2000: Nuclear, Geothermal, Solar, Wind, Storage, and DC

The post-war years saw global economic growth driven by mounting consumer expectations for reliable and inexpensive energy and fueled by cheap energy of all kinds, including electricity produced from traditional fossil fuels. The world entered the last half of the twentieth century hungry for energy and

Ocean Thermal Energy Conversion (OTEC)

This technology uses the temperature difference between the ocean's surface and deeper water. Deep water, typically defined as 1,000 meters, has a temperature around 5°C. At the surface, temperatures average 25°C. This 20°C temperature difference drives a turbine and generator. OTEC uses two approaches: open and closed.

The open system resembles a geothermal flash system. Injecting seawater from the surface into a vessel at low pressure causes it to vaporize. This vapor (low-temperature steam) goes to a turbine to power a generator. Cool seawater extracted from the deep condenses the steam before it gets returned to the ocean. Because vaporization leaves behind the salt, the condensation can also produce desalinated water.

The closed system looks like a geothermal binary system because it flashes a working fluid with a lower boiling point than water, such as ammonia, to drive the turbine. The working fluid condenses and goes through the cycle again. The 20°C temperature difference between surface water and deep water means the efficiency of this process hovers around 7%.

Tidal Energy

The gravitational force of the moon causes tides to cycle about every twelve hours. As tides change, water flows towards the shore and then away from the shore. This moving water turns a turbine attached to a generator. Tidal turbines work best in shallow water where tidal flow occurs. Because water is much denser than air, tidal water turbines capture more energy than wind turbines.

Another tidal system called a *tidal barrage* can capture tidal energy by using a dam-like structure to capture water during high tide. During low tide, it releases water through the penstock to turn the turbine to generate electricity.

Wave Energy

Wave motion also provides energy from the ocean. This text covers several ways to capture wave energy.

Floating Buoy: A floating buoy anchored to the bottom of the sea rises and falls with the waves. That up-and-down motion turns a shaft and moves a generator to make electricity.

Surface Floats: A device with multiple arms anchored to the ocean floor floats on the ocean surface. The arms flex with the wave motion and a hydraulic pump powers a generator to produce electricity.

Oscillating Water Columns (OWC): A partially submerged structure in the ocean allows incoming waves to enter at the bottom, and the rising water column pressurizes air in the structure's top. As the water recedes, the top part depressurizes and the pressure change pushes and pulls air through a turbine connected to a generator. A 500kW OWC has operated in Islay, Scotland, since 2000.

as they lay out the route and choose the support structures, conductors, and other components. In the words of one veteran designer, laying out the route and selecting the components has its challenges, but the two largest challenges and the ones taking the longest are permitting and acquiring ROWs. Transmission engineers seek safe, reliable, resilient, secure, and cost-effective designs, and work with a myriad of stakeholders towards achieving that goal.

Acquiring Rights-of-Way

Transmission lines can extend hundreds of miles and involve thousands of landowners with individual needs and wants. Some work diligently with the transmission companies for an acceptable arrangement. Some just do not want a transmission line built on their property (often referred to as the "Not in My Backyard" philosophy or NIMBY). They see that many others benefit while they bear the lion's share of the burden.

This text acknowledges the challenge of acquiring ROWs but offers no elegant solutions other than starting early, conducting thorough analysis and justification, meeting with regulators well in advance, and communicating with transparency. The authors acknowledge and admit they like clean and abundant power but would prefer not having a transmission line or substation in their backyards.

Permitting

Line construction requires many permits. In the United States, permitting can stretch from the Federal Energy Regulatory Commission (FERC) for an overall permit to the county commissioners who approve road crossings.

The National Environmental Protection Act (NEPA) may require an Environmental Impact Statement (EIS) or Environmental Assessment (EA). Transmission planners wade through a labyrinth of federal, state, and local laws, rules, regulations, procedures, and public comment periods, attempting to balance the viewpoints and needs of numerous stakeholders, all with their own point of view.

Substation Design

Substation designers start with the substation's function and location. They consider many other factors and select the components and best control scheme for the needed functions at the specified voltage and current. Designers consider how to arrange components on the substation property and create detailed drawings reflecting that arrangement. They also consider how the components connect and provide those details on plan drawings. Like transmission engineers, substation engineers work to provide safe, reliable, resilient, secure and cost-effective designs to satisfy stakeholder needs.

Distribution Components

Various components connect to distribution systems along their routes. This section discusses grid protection devices, including circuit breakers, automatic distribution circuit reclosers, sectionalizers, and disconnects, as well as voltage regulating transformers, capacitors, and meters.

Circuit Breakers

As distribution lines exit the substation, circuit breakers protect the substation and feeders by separating the substation from the line in the event of a fault (abnormal current). Circuit breakers have fixed and moving contacts (electrodes) in a closed chamber containing a fluid (either liquid or gas) to smother any arc between the contacts. In normal conditions, the contacts stay closed. When a fault occurs, the contacts open manually or by remote control (when needed). When the grid experiences a fault, the breaker trip coils energize and pull apart the contacts to open (break) the circuit.

Because circuit breakers are designed to operate under load, grid operators and field technicians use them to de-energize substations prior to opening substation incoming and outgoing disconnects.

Automatic Distribution Circuit Reclosers

Normally just called *reclosers*, this device, like a circuit breaker, detects faults and opens to interrupt the fault current. Unlike circuit breakers, reclosers automatically reclose (hence the name recloser) if the fault clears quickly – for example, when a tree limb momentarily touches a power line and then falls to the ground.

Sectionalizer

Sectionalizers work in concert with reclosers and keep track of how many times reclosers open and close. When the number of cycles reaches a preset value, the sectionalizer opens and remains open until reset (manually or remotely). Sectionalizers cannot operate under load and need an upstream circuit breaker or recloser that can operate under load. Because the sectionalizer opens before the recloser closes, it does not have to operate under load. Preset cycle values vary by application and are often only one cycle for underground lines because repetitive faults might damage the underground conductor's protective coating.

Reclosing and sectionalizing are functions that, in the past, were performed by two separate devices. Technology improved, and reclosers can now be programmed to also act as sectionalizers and remain open after a preset number of cycles. Figure 5-16 shows a protective device on a single-phase line.