Chapter 1

Electric Power

Relative to the digital age, the electric utility industry may seem old hat. But power electronics and the power industry have a growing symbiotic relationship. Nearly all power electronics systems draw power from the grid, and utility companies benefit from the application of power electronics to motor drives and to converters used for high-voltage DC transmission lines. The two fields are very much in a state of constant development of new systems and applications. For that reason, a short review of the history and the present state of the electric utility industry is appropriate for consideration by the power electronics engineer.

1.1. AC versus DC

> *Take warning! Alternating currents are dangerous. They are fit only for powering the electric chair. The only similarity between an a-c and a d-c lighting system is that they both start from the same coal pile.*

And thus did Thomas Edison try to discourage the growing use of alternating-current electric power that was competing with his DC systems. Edison had pioneered the first true central generating station at Pearl Street, in New York City, with DC. It had the ability to take generators on and off line and had a battery supply for periods of low demand. Distribution was at a few hundred volts, and the area served was confined because of the voltage drop in conductors of a reasonable size. The use of DC at relatively low voltages became a factor that limited the geographic growth of the electric utilities, but DC was well suited to local generation, and the use of electric power grew rapidly. Direct current motors gradually replaced steam engines for power in many industries. An individual machine could be driven by its own motor instead of having to rely on belting to a line shaft.

Low-speed reciprocating steam engines were the typical prime movers for the early generators, many being double-expansion designs in which a high-pressure cylinder exhausted steam to a low-pressure cylinder to improve efficiency. The double-expansion Corliss engines installed in 1903 for the IRT subway in New York developed 7500 hp at 75 rpm. Generators were driven at a speed higher than the engine by means of pulleys with rope or leather belts. Storage batteries usually provided excitation for the generators and were themselves charged from a small generator. DC machines could be paralleled simply by matching the voltage of the incoming machine to the bus voltage and then switching it in. Load sharing was adjusted by field control.

Alternating-current generators had been built for some years, but further use of AC power had been limited by the lack of a suitable AC motor. Low-frequency AC could be used on commutator motors that were basically DC machines, but attempts to operate them on the higher AC frequencies required to minimize lamp flicker were not successful. Furthermore, early AC generators could be paralleled only with difficulty, so each generator had to be connected to an assigned load and be on line at all times. Battery backup or battery supply at light load could not be used. Figure 1.1 shows the difference. Finally, generation and utilization voltages were similar to those with DC, so AC offered no advantage in this regard.

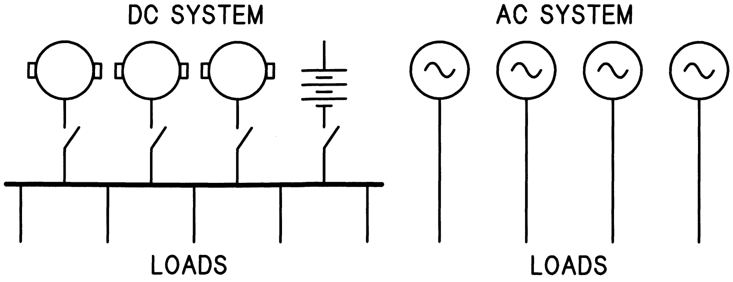

FIGURE 1.1 Generation systems.

1.2. Pivotal Inventions

Two key inventions then tipped the scales toward AC and initiated Edison's famous statement that opens this chapter. The first of these was the transformer. George Westinghouse acquired the patent rights from Gaulard and Gibbs for practical transformers. They allowed AC power to be transmitted at high voltages, then transformed to serve low-voltage loads. Power could now be transmitted with low losses yet be utilized at safe voltages, and this meant power could be generated at locations remote from the load. Hydroelectric generation could supply industries and households far from the dam. An early installation of AC generation and distribution was made by William Stanley, a Westinghouse expert, in Great Barrington, MA, in 1886. Distribution was at 500 V, and the Siemens generator, imported from London, supplied two transformers connected to some 200 lamps throughout the town.

The second invention was that of the induction motor, the result of research by a brilliant young engineer, Nikola Tesla, employed by Westinghouse. The first designs were for two-phase power, although three-phase designs soon followed. Three-phase transmission was preferred, because it minimized the amount of copper required to transmit a given amount of power. The simple, rugged induction motor was quickly put into production and was the key to utilizing AC power by industry. The induction motor required no elaborate starting means, it was low in cost, and it offered important advantages in unfavorable environments. Together, the transformer and induction motor were responsible for the rapid growth of AC power.

The superiority of AC power was proven when Westinghouse lighted the Columbian Exposition at Chicago in 1893 with a two-phase system and literally turned night into day. Edison held the patents on the glass sealed incandescent lamp, so Westinghouse devised a stopper lamp design utilizing sealing wax. It was not a commercially successful design, but it did the job. The dazzling display was a source of awe for the visitors, many of whom had never seen an electric light.

A second major advance in AC generation and transmission was an installation at Niagara Falls. The power potential of the falls had been recognized for many years, and various schemes had been proposed for using compressed air and mechanical methods to harness the power. A final study resulted in the installation by Westinghouse in 1895 of AC generators using a 25-Hz, two-phase system that incorporated transformers and transmission lines to serve a number of factories. The 25-Hz frequency was chosen despite the growing popularity of 60 Hz, because it was recognized that a number of the process industries would require large amounts of DC power, and the rotary converters then used could not function on 60 Hz. Frequencies of 30, 40, 50, and 133 Hz were also in use in the 1890s, and 50 Hz persisted until mid century on the Southern California Edison System. A number of utilities also provided 25-Hz power late into the last century.

1.3. Generation

Slow-speed reciprocating steam engines kept growing in size to keep up with the demand for power until they topped out at around the cited 7500 hp. Some high-speed steam engines were used in England, but there was usually an order of magnitude difference between the preferred speeds for the engine and for the generator. The huge steam engines in use around the beginning of the twentieth century would shake the ground and were disturbing to the local inhabitants. A steam turbine, directly connected to the generator, was the solution to this problem. A number of small turbines had been built on an experimental basis, but the 1901 installation of a 2000-kW, 1200-rpm, 60-Hz turbine generator set in Hartford, CT, set the stage for a rapid switch to turbines for future generation from steam. Ultimately, steam turbine generators were built at power levels over 1500 MW.

Hydroelectric generation also continued to grow in size. The Hoover Dam generators were installed with an 87 MVA rating each, but some were later rewound for 114 MVA. The huge generators for the Grand Coulee Third Powerhouse are rated 700 MW each, and the total Coulee generation is 6480 MW. These large concentrations of generation have made economies of scale possible, which have reduced generation costs and brought large-scale aluminum reduction plants and other power intensive industries to many remote locations.

1.4. Electric Traction

Siemens, in Germany, developed a DC motor suitable for use in powering trams. Electric power not only replaced the horses then in use on surface lines but made possible the development of vast subway systems. Because these systems served a large metropolitan area, the usual problem of DC distribution developed. The problem was not as acute as with residential use, because traction systems could use the relatively higher voltage of 600 V, and the earliest traction systems utilized DC generation and distribution. Around the turn of the century, however, the trend was to AC generation and high-voltage distribution with conversion to DC using rotary converters at local substations. These fed the trolley wires on surface lines or the third rails on subways and elevateds at 600 Vdc. In 1903, the Interborough Rapid Transit Company, in New York, adopted a system that used 11,000-V, 25-Hz, three-phase power for distribution and a 600-Vdc third rail pickup for the cars of the new subway. Interestingly, the directors had decided in favor of reciprocating steam engines over turbines for generation, although they used several small turbine sets for lighting and excitation.

The use of electric power for transit also made possible interurban trolley lines, and by the early years of the last century, vast networks of trolley systems were extended to serve many small communities at lower cost than the steam trains could achieve. Again, higher-voltage AC generation and distribution were coupled with rotary converters to supply DC to the trolley wires. Interurban transit lines lasted until the development of good roads and reliable automobiles. Most were gone by mid century.

There were also a number of installations of electric motors to provide power for main-line traction. The New York New Haven and Hartford Railroad used 11,000-V, 25-Hz, three-phase power for transmission and single-phase power to supply the catenary. Transformers on the locomotives powered the traction motors in a parallel connection at 250 Vac. The motors were then switched in series to operate on a 600 Vdc third-rail so the trains could continue into Manhattan underground. The same distribution is in use today by Amtrak on the Northeast Corridor with the catenary supplied at 25 Hz by solid-state cycloconverters powered from the 60-Hz utility system. Several pioneering electric railroads in the USA used 3000 Vdc on the catenary, and three-phase 25-Hz AC systems were also used. Nearly every imaginable configuration of AC and DC power, including 16-2/3 Hz, was used for traction somewhere in the world. Except for commuter lines and special installations, most of the electric locomotives have been replaced by diesel electrics that offer lower operating costs and less overhead.

1.5. Electric Utilities

Utility operations are usually considered in the three classes of generation, transmission, and distribution, although recent deregulation has separated generation from the latter two. Figure 1.2 shows a typical hierarchy of voltages and loads. Transmission lines carry the power over the longer distances to substations that step the transmission voltage down to a sub-transmission level. Some high-voltage transmission lines are also the interconnect points between utilities in a regional grid. High-power loads, such as electric arc furnaces and electrochemical plants, may be fed directly from the transmission system. Others are fed from the subtransmission system or from distribution feeders that supply small industries as well as commercial and residential loads. The electric utility systems in this country have grown to a generation capacity of more than 1000 GW at this date. Steam turbines, coal or nuclear powered, and hydraulic turbines supply the vast majority of the motive power for generators, but natural gas fired combustion turbines are growing rapidly as environmental concerns limit additional coal and nuclear power. Much lower levels of power are produced by wind farms, although this area is expanding as the art progresses. Still lesser amounts of power are produced by reciprocating diesel engines in small municipal utilities.

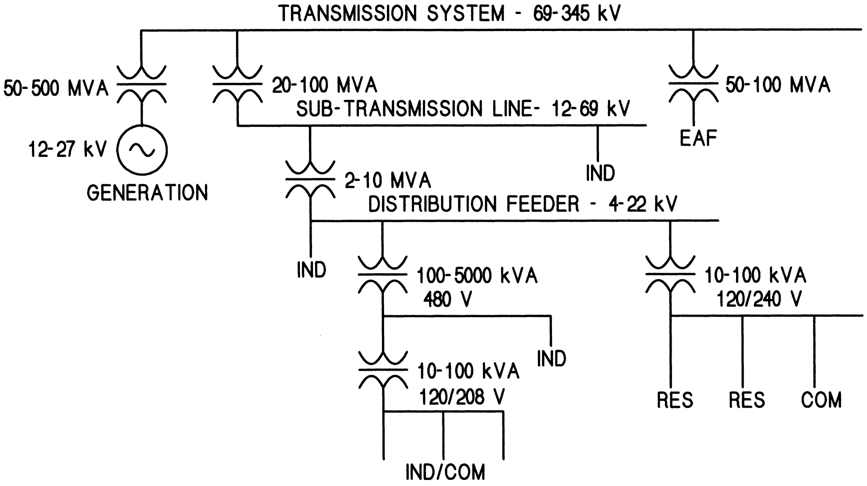

FIGURE 1.2 Typical section of a utility.

The national transmission system is operated cooperatively by regional power pools of interconnected utilities, whereas generation, because of government regulation, is now in the hands of many independent operators. Transmission voltages increased over the years and topped at around 230 kV for some time. The construction of the Hoover Dam, however, made it possible to augment the Los Angeles energy supply with hydroelectric power. When installed in the late 1930s, this line was the longest and, at 287 kV, the highest voltage line in this country. A considerable amount of research went into the insulation system and the conductor design to minimize corona losses. Progressively higher transmission voltages have been introduced until switchgear standards have now been developed for 800 kV service. Transmission lines at or above 500 kV are termed EHV for *extra high voltage*. A major EHV project in the U.S. is the 905-mile Pacific Intertie from the Bonneville Power Administration in Washington to the Los Angeles area. Two 500-kV transmission lines supply some 2500 MW, bringing hydroelectric power from installations on the Columbia River to the major load centers in Southern California. Hydro-Québec operates a large system of 765-kV transmission lines to bring hydroelectric power from northern Québec to load centers in Canada and the U.S.

Although most transmission lines are referred to by their nominal transmission voltage, they are designed for a given *basic insulation level (BIL)* in consideration of lightning strokes and switching transients. Lightning strokes have been measured at voltages of 5 MV, currents of 220 kA, and a maximum dv/dt of 50 kA/μs, so they have the potential for doing serious damage. Lightning arresters are discussed in Chapter 2.

High-voltage DC (HVDC) transmission lines have come into service through the advent of power electronics. These have an advantage over AC lines in that they are free from capacitive effects and phase shifts that can cause regulation problems and impair system stability on faults. An early HVDC transmission line ran from BPA sites in Washington to Sylmar, CA, a few miles north of Los Angeles, to supplement the AC Pacific Intertie. It is rated 1200 MW at ±400 kVdc. The converter station at Sylmar was originally built with mercury vapor controlled rectifiers but was destroyed by an earthquake. It was rebuilt as one of the early silicon controlled rectifier (SCR) converters used in HVDC service. Some other large HVDC installations are in Japan from Honshu to Hokkaido; in Italy from the mainland to Sardinia; and between North Island and South Island in New Zealand. Hydro-Québec operates an HVDC system, ±450 kV, 2250 MW, from Radisson station near James Bay 640 miles to a 1200-MVA converter station at Nicolet, then 66 miles to a 400-MVA converter station at Des Cantons, an interchange point to the New England Power Pool in Vermont. From there, it continues through Comerford, NH, and finally terminates in the last converter station at Ayer (Sandy Pond), MA, northwest of Boston. In a sense, we have come full circle on DC power.

Residential customers of electric utilities are generally billed on the basis of kilowatt hours, independent of the power factor of their loads. Many industrial customers, however, are billed in two parts. First, they are billed for energy consumed on the basis of kilowatt hours for the billing period. Such charges are in the vicinity of 3 to 5 cents per kilowatt-hour at this time. They basically pay for the utility fuel cost of coal, gas, or oil and some of the generation infrastructure. Even hydroelectric power is not free!

The other portion of most bills is a demand charge based, typically, on the maximum half-hour average kilowatt load for the billing period. This is recorded by a demand register on the kWhr meter that retains the maximum value. Then, this kilowatt demand is adjusted upward, roughly by the reciprocal of the average power factor over the month. A typical metropolitan demand charge is $5 to $15 per month per power factor adjusted peak kilowatt demand. This charge supports the transformers, transmission lines, and distribution system necessary to deliver the power. The power factor adjustment recognizes the fact that it is amperes that really matter to the delivery system. Demand charges often provide a powerful incentive for industrial customers to improve their power factor, since the installation of capacitors may result in a rapid payoff. This example is merely illustrative, however, and there are many variations in billing practices among the electric utilities in this country. Utility representatives are generally helpful in providing advice to minimize a power bill. This matter is further discussed in Chapter 14.

A growing problem in the U.S. is the increasing demands being placed on the transmission system. Prior to deregulation by the government, most utilities generated and transmitted their own power with interconnections to other utilities for system stability and emergency sources. The freewheeling market now present for generation has often resulted in the remote generation of power to loads that would have been supplied by local generation. The result is overloaded transmission lines and degraded system stability. Building additional transmission lines has been made increasingly difficult by *not in my back yard (NIMBY)* reactions by the public. Also, there is little incentive for utilities to install transmission lines to carry power that they cannot bill to their customers. Despite these problems, additional transmission capacity is vital to maintaining a high level of reliability in the interconnected systems.

The entire northeast portion of the U.S. was darkened by a major power outage on 14 August 2003 that cost billions of dollars in lost production and revenue. The problem turned out to be simply poor maintenance of the right of way under some major transmission lines by an Ohio utility. A large hue and cry was raised about the "antiquated" transmission system, but the fact of the matter is that the electric utility industry has achieved a remarkable record of reliability in view of the changed conditions resulting from deregulation. However, the challenge for the future is to do even better.

A significant advance in system stability has come from the development of FACTS converter systems. This acronym for *flexible AC transmission systems* describes power electronics control systems that are able to effect very rapid changes in system voltages and phase angles. Voltages can be maintained through fault swings, and power oscillations can be damped. System stability can be maintained even with increased transmission line loadings. FACTS installations can defer or eliminate the need for additional transmission lines that are difficult to install because of environmental concerns, permitting processes and right-of-way costs.

1.6. In-Plant Distribution

Power distribution systems in industrial plants vary widely. Some of the more popular systems follow. At the bottom of the power ratings, distribution will be at 120/240-V single-phase, lighting loads being connected at 120 V and small motors at 240 V. Three-phase 120/208-V distribution, widely used for lighting at 120 V, can also supply three-phase motors at 208 V, since many induction motors are dual rated for 208/240 V. The 120/208-V neutral is usually solidly grounded for safety of lighting circuits. A 277/480-V distribution system is probably the most popular one for medium-sized industrial plants. The wye secondary neutral is usually solidly grounded, although a resistance or reactance ground is sometimes used. The most common distribution voltage in Canada is 600 V.

Older plants often have a 2300-V, three-phase system, delta connected with no ground. Some, however, may ground one corner of the delta. Distribution at 2400/4160 V is the most popular system at the next higher power level. At still higher powers, older plants often have 6900 V or 7200 V distribution, although the trend is toward 13.8 kV in newer plants. The supplying utility usually installs a fused distribution transformer for lower powers, but the higher-power installations will utilize padmount transformers with circuit breakers and protective relays.

The typical distribution arrangement of a medium-size plant is to bring the incoming power to a number of distribution centers known as *load centers* or *motor control centers*. These consist of a series of circuit breakers or load break switches in metal cabinet sections, some containing the control for a motor circuit. The center may also provide protective relays and instrumentation. It may have one or more breakers to serve lighting circuit transformers scattered throughout the building. Lighting circuits at 120/208 V are collected in panel boards, with a master breaker serving a multiplicity of molded case circuit breakers. A lighting panelboard may be rated at 100 to 400 A with individual lighting circuits of 20 to 30 A and air conditioning or similar loads at higher currents.

Internal wiring practices use either plastic or metal conduit or cable trays. Conduit is used for the lower power levels with conductors pulled through the rigid tubing. An advantage of conduit is that it protects the conductors from dripping water and mechanical injury. More common at the higher power levels are cable trays. Here, the sizes of conductors are almost unlimited, since they are simply tied down in the trays to prevent movement on faults. The trays themselves are simple angles and cross braces with open construction to aid ventilation. If high- and low-voltage circuits are run together in either conduit or cable trays, all conductors must be rated for the maximum voltage.

1.7. Emergency Power

There are three levels of reliability to consider for emergency power. First, there is the power required for mandatory emergency exit signs and interior lighting in the event of a power outage. This is often supplied from an engine generator set powered by natural gas with automatic starting in the event of an external power failure. Battery backup may be used. Larger installations may have diesel engine-generator sets. A short loss of power is acceptable for these purposes. It is important to test these systems periodically to ensure their availability when needed.

The second reliability level of emergency power is the maintenance of operations in an industrial plant where loss of production is expensive. The usual procedure is to provide two separate power feeders to the plant from separate utility lines. Transfer breakers are used to switch from an ailing circuit to a live one. A momentary power interruption may be acceptable with only a minor inconvenience to production. Diesel engines or combustion turbines and generators may also be used for plant generation where warranted. If a momentary outage cannot be tolerated, solid-state transfer switches can be used for subcycle switching.

The highest level of reliability is required for critical operations that cannot stand any interruption of power whatsoever. These may be computers in a data processing center or wafer fabrication in a semiconductor plant where even a momentary outage can cost millions of dollars. It is necessary to provide absolutely uninterrupted power to these facilities. One system that is gaining acceptance is to utilize fuel cells operating on natural gas to generate DC power. This power can then be converted to AC with power electronics and used to supply the plant. Critical loads can be powered from two directions as with a utility supply and controlled with solid-state transfer switches. In some cases, excess generation is available from the fuel cells, and the power can be sold to the utility. Many variations on this scheme are being used at this time.