INFRASTRUCTURE

A FIELD GUIDE TO THE INDUSTRIAL LANDSCAPE

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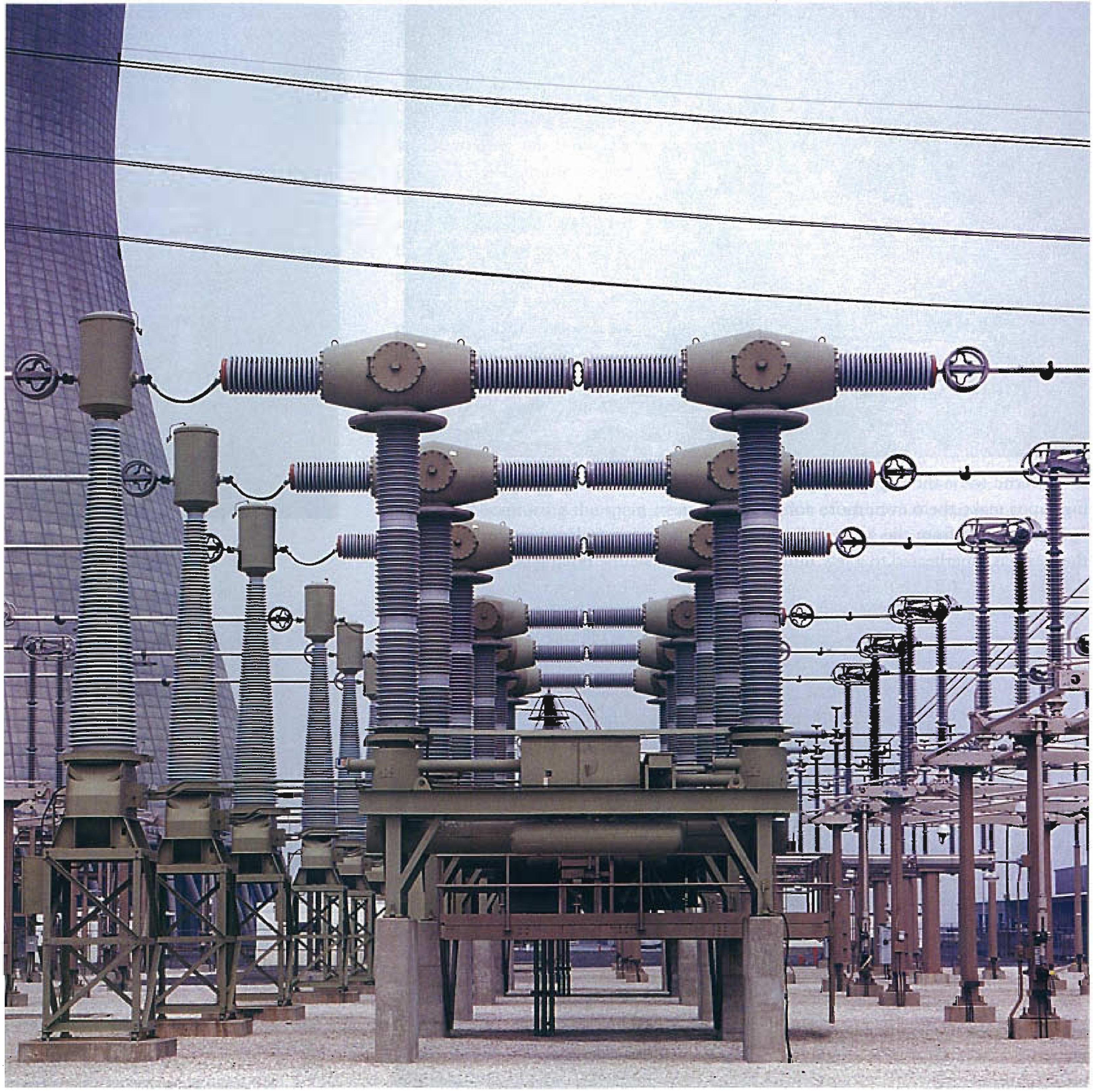


CHAPTER 6

THE POWER GRID

ELECTRICITY IS INVISIBLE STUFF, and yet it makes quite a mark on the modern landscape. The power plants that generate it, the transmission lines that carry it across the countryside, and the substations that dispatch it are all giant structures, hard to hide from view. The smaller-scale wires, utility poles, transformers, and other hardware that distribute electricity to homes and businesses are less impressive individually, but they are seen everywhere on city streets and rural roadways. In built-up areas, it's hard to make a landscape photograph that doesn't take in a power line. The whole country hums with the 60-cycle-per-second note of the electric power grid.

Generating plants are described in the preceding chapter. This chapter covers everything else electrical: power lines, substations, and the local-distribution network.

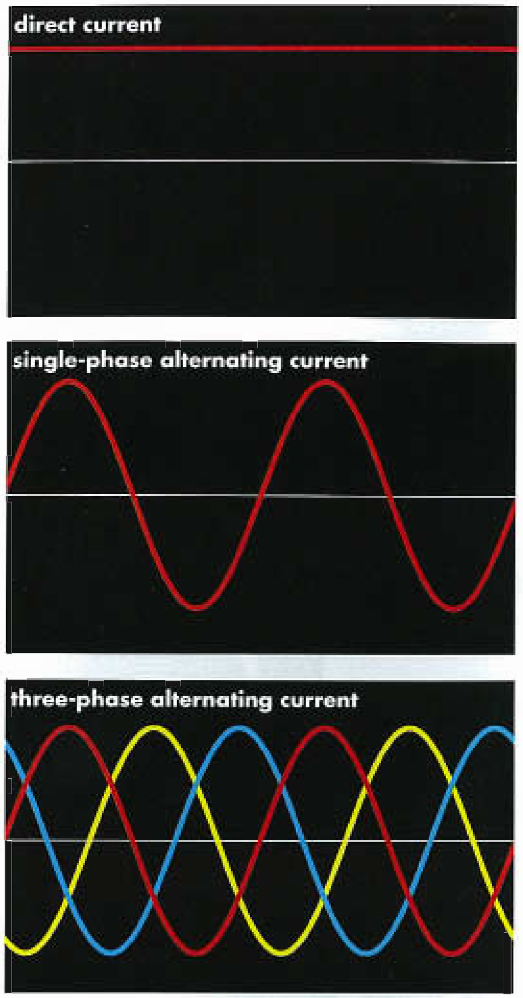
SOME ELECTRIFYING CONCEPTS

The network that brings power to a nation is not fundamentally different from the electrical system in your home. Wires carry electricity from city to city, just as they distribute it to lamps and outlets. The national network has switches, circuit breakers, and fuses that work much the same as those in your basement fuse box. They're just bigger.

The basic unit of all electrical technology is the circuit. Current flows out from a source (such as a generator), along a conductor to a load (such as a motor or a light bulb), and then along another conductor back to the source. Without the complete round-trip path, nothing happens; breaking the circuit open at any point stops the current. (The opposite of an open circuit is a short circuit, when the outbound and inbound conductors touch, bypassing the load: Pffft!)

The simplest electrical circuits operate on direct current, or DC, in which electricity flows steadily in one direction around a loop. Direct current is what comes

Fluted porcelain insulators, shiny aluminum conductors, posts and frames that lift all the machinery high overhead—high-voltage electrical gear has a characteristic look to it that could never be mistaken for anything else. The equipment on the opposite page is in the switchyard of the Salem Creek nuclear power plant in southern New Jersey. The large devices in the middle of the image are air-blast circuit-breaker switches, designed to interrupt a 500,000-volt circuit in emergencies. The large curved structure in the background is a cooling tower.



Direct current provides a steady flow of electricity, but in an alternating-current circuit the voltage and current rise and fall rhythmically. Household electricity is single phase, with just one sinuous wave, but power is generated and transmitted with three overlapping waves in a three-phase system.

out of a flashlight battery. The world's power systems are based on alternating current, or AC; the current flows first clockwise around the loop and then counterclockwise, reversing direction many times each second. Nothing ever moves very far in an AC circuit; the current just sloshes back and forth. In the United States and Canada the current completes 60 cycles per second; the power frequency is said to be 60 hertz. In Europe and most of the rest of the world the standard frequency is 50 hertz. (Japan is split down the middle, with both 50-hertz and 60-hertz areas.)

A graph of the voltage in an AC circuit looks something like an ocean wave, with peaks and troughs. From a positive peak, the voltage falls off smoothly, passes through zero, reaches a negative peak, then climbs through zero again to return to the positive peak. The intermittent nature of alternating current has a remarkable consequence: twice in every cycle, there is no current—everything stops. In other words, 120 times a second, the electricity you pay for is slacking off—just sitting there and doing nothing. And the power company is no happier about this situation than you are. Because of all the time spent idling, a simple AC system uses only about 70 percent of the capacity of the wires and other equipment.

The remedy for this waste is three-phase power. Think of three ocean waves following one another so closely they overlap. One wave reaches its crest, and then before its trough arrives, the second wave crests, and then the third. In a three-phase circuit, whenever one phase is at zero voltage, the other two phases are still carrying power, and the system is never idle. Today virtually all commercial electric power is three-phase. Industrial equipment (such as the big motors that drive elevators and large water pumps) is built to run directly on a three-phase circuit. For other uses (including household consumption), a single-phase loop is split off from the three-phase signal simply by forming a circuit between conductors carrying any two of the three phases.

The widespread use of three-phase circuits gives the electric-power infrastructure one of its most distinctive features: just about everything is done in triplicate. A power transmission line is made up of three conductors. At a substation, switches or circuit breakers stand in banks of three. On utility poles, trios of transformers are ganged together. When you start looking around at electrical gear, you begin noticing that almost everything comes in threes.

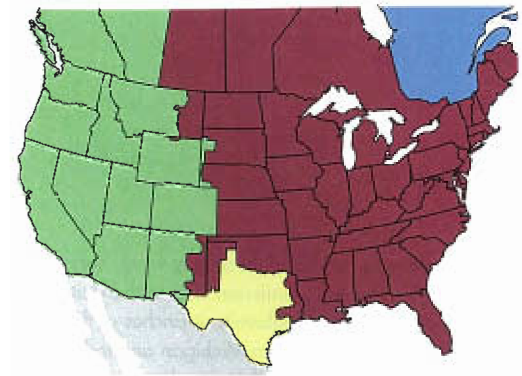
TRANSMISSION LINES

Steel towers march single file across the countryside, with heavy cables draped from their shoulders. If you follow the line of towers, at one end you are likely to find a generating plant; in the other direction the line will probably lead you to a substation, or switchyard, on the outskirts of a city. Power-company engineers call the transmission lines "feeders," and the energy they supply is indeed a form of nourishment for the way we live today.

The Grid. Hundreds of transmission lines lace together to form a network spanning all but the remotest territories of the North American continent. It's known as the grid. Power flows freely throughout most of this network, finding its own best path from source to consumer. Thus, you can never say for certain where the electricity comes from when you flip a light switch or plug in the hair drier. In Los Angeles a major share of your power comes from the river gorges of Washington State and the coal beds of Wyoming; New York City draws on the hydroelectric resources of Niagara and northern Quebec.

Having many sources of power and many pathways for it to follow improves reliability. If one generating station has to shut down, another can pick up the load. If a transmission line fails, the power it was carrying is instantly diverted onto other feeders. The far-flung grid can also have economic benefits. Utility companies can buy power from the cheapest source, even if it is thousands of miles away, and generating plants in remote areas can sell surplus power to distant cities.

The North American grid is divided into two large zones, the eastern and the western interconnections, which meet at a boundary line that runs along the eastern flank of the Rocky Mountains. Two smaller regions are relatively isolated from the eastern and western networks: Quebec and most of Texas. Inside any one of the four zones, the power system can be looked on as a single gigantic machine. Every generator connected to the grid turns in perfect lockstep with all the other generators, as if they were all attached to the same rotating shaft. Once upon a time, the motors in electric clocks also turned in lockstep with the power system, so that you could



The geography of power: the electrical network in the United States and Canada is broken up into four main regions, called interconnections. The eastern and western interconnections cover most of the territory, but parts of Texas and Quebec are off on their own. Inside each region, electricity flows freely from whoever has it to whoever needs it. Transfers of power across boundaries between regions are actively controlled.

VOLTS, AMPS, AND WATT-NOT

One way to understand electricity is to think about plumbing. Electrons flowing through a wire are like water flowing through a pipe, but the water is something you can see and hear and feel, so its behavior is a little less mysterious.

In the plumbing analogy, voltage is the electrical equivalent of water pressure; it is the force that drives electrons through a wire, measured in volts. Current in an electrical circuit corresponds to the rate of flow in a pipe. In a plumbing system, flow might be measured in gallons per minute; the electrical unit is the ampere, or amp.

Resistance is what opposes the current and dissipates the voltage. When water flows through a pipe, friction slows it and reduces its pressure; the same thing happens to electrons flowing through a wire. In general, the thicker the wire or pipe, the lower the resistance. The unit of electrical resistance is the ohm.

The power passing through an electrical circuit depends on both the voltage and the current. Think about water turning a turbine. A small volume of water under high pressure produces the same amount of power as lots of water at low pressure. Likewise, in the electrical world, high voltage and low current produce the same amount of power as low voltage and high current. The unit of power is the watt.

The volts, amps, ohms, and watts in a circuit are all related; you can't change one without affecting the others. The most important relation is called Ohm's law. It says that current increases with voltage and decreases with resistance. Mathematically, the law is $I = E/R$, where I is the current, E is the voltage, and R is the resistance. In other words, 100 volts across a resistance of 50 ohms produces a current of 2 amperes. The formula for power is $W = E \times I$: the power is equal to the voltage multiplied by the current. Thus, 100 volts and 2 amperes yields 200 watts.

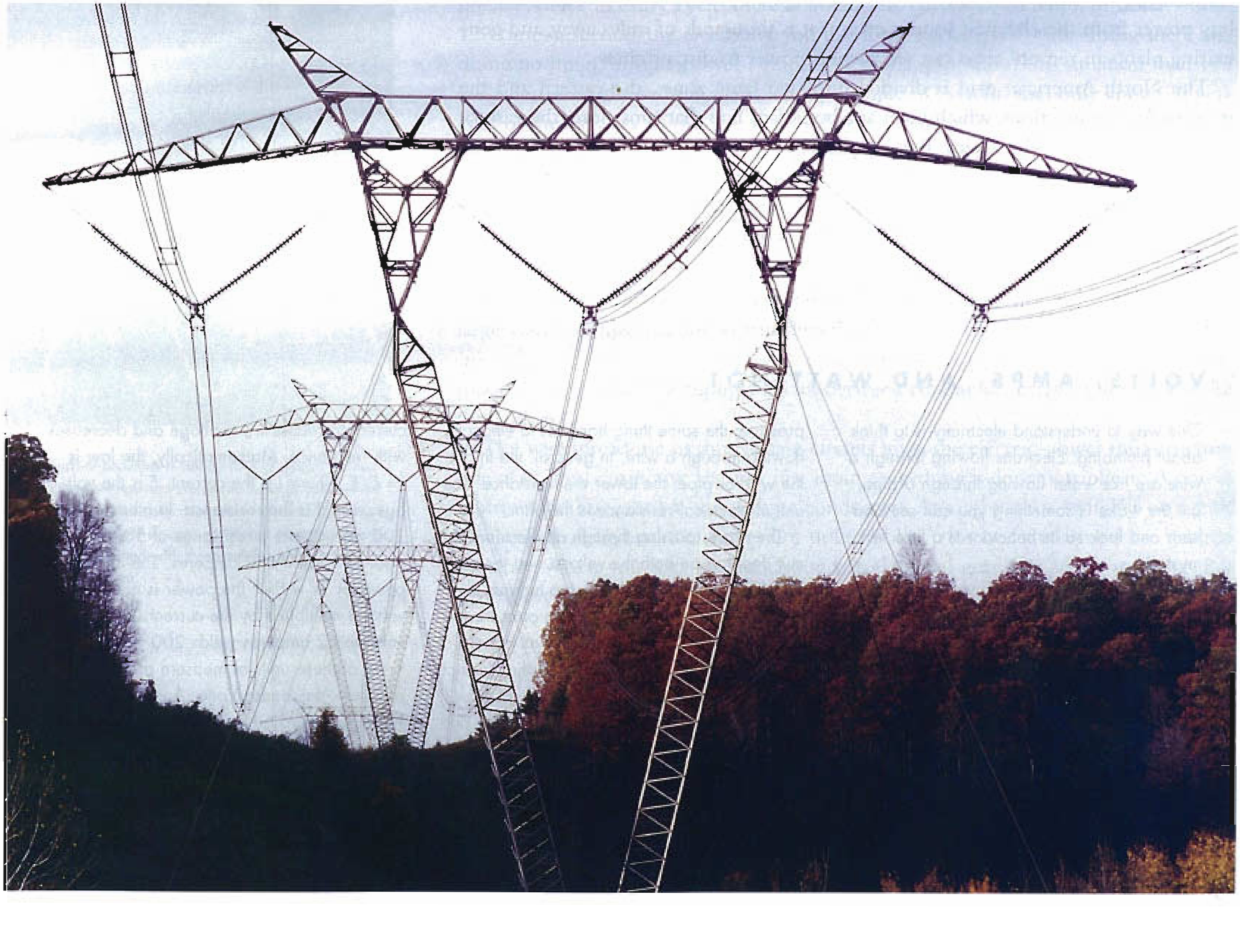
All of these units of measure are named for people—Alessandro Volta, André-Marie Ampère, Georg Ohm, and James Watt. There are a few more electrical eponyms as well. The unit of capacitance is the farad, after Michael Faraday; inductance is measured in henries, for Joseph Henry; and frequency is expressed in hertz, named for Heinrich Hertz.

have on your kitchen wall a tiny rotating device with a direct, second-by-second link to the massive turbines at Niagara or Hoover Dam. (Today, motor-driven electric clocks are antiques. Modern clocks have a digital mechanism, and their timekeeping doesn't depend on the power-line frequency.)

Ties between the four North American zones are looser than the dense network of connections within any one zone. Power is transferred across the boundaries by direct-current links. This allows closer control of the transfers and eliminates the need to keep generators synchronized all the way from coast to coast.

V-shaped towers, held upright by guy wires, carry one of the largest power transmission lines in the United States, operating at 765 kilovolts. Branches of the transmission line extend from Michigan and Indiana into southern Virginia; this photograph was made near Ashland, Kentucky.

High Voltage. The most important thing about a transmission line is the voltage it carries. It is the voltage that determines the height of the towers, the size of the insu-



lators, the width of the right-of-way, and much else. Short-haul transmission lines—up to 40 or 50 miles—often operate at 115,000 or 138,000 volts (more conveniently expressed as 115 or 138 kilovolts). For longer lines the favored voltages vary from region to region. Along the West Coast, in the Mid-Atlantic states, and in the Southeast, the common voltages are 230 and 500 kilovolts. In New England, New York, and the Midwest, most long feeders run at 345 kilovolts, with a few high-capacity lines operated at 735 or 765 kilovolts.

You might think of 115- and 138-kilovolt feeders as the two-lane rural roads of the electric-power system. The 230- and 345-kilovolt lines are like major U.S. highways, and the 500- and 765-kilovolt lines are Interstate routes.

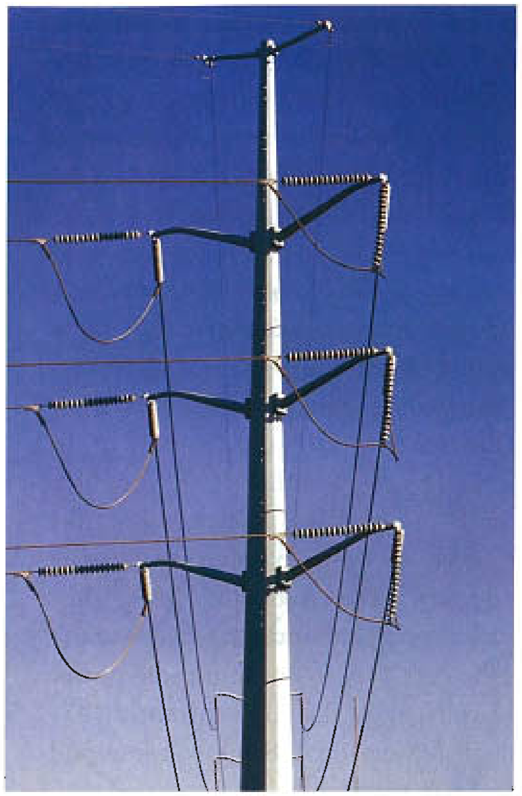
Why are the voltages so high? Electricity comes out of the generator at 10,000 or 20,000 volts, and it reaches your household light socket at 120 volts. So why go to the trouble of boosting the voltage to such a high level, if you then have to reduce it again at the end of the line? The answer lies in the way voltage, current, and power are related. To push more electricity through a power line, you can either increase the current or increase the voltage. But higher currents heat the conductors, just as they heat the filament in a light bulb or a toaster. For any given conductor, there is a maximum safe current. Once you reach that point, the only way to transmit more power is to keep the current constant and go to higher voltages. At the same current, a 345-kilovolt feeder carries more than 6 times as much power as a 138-kilovolt line, and a 765-kilovolt transmission line carries 30 times as much.

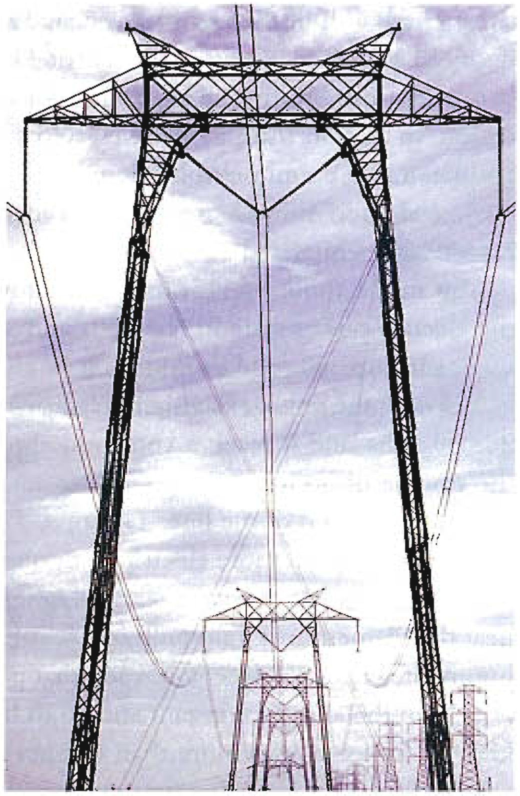
Using higher voltages instead of higher currents reduces the waste of energy that goes into heating the transmission-line conductors. A 345-kilovolt line that carries 1,000 megawatts of power might lose 20 megawatts, or 2 percent, in overcoming the electrical resistance of the conductors. In other words, the efficiency is 98 percent, which is pretty good compared with other parts of the power system. Still, the wasted 20 megawatts is enough to run about 40,000 toasters.

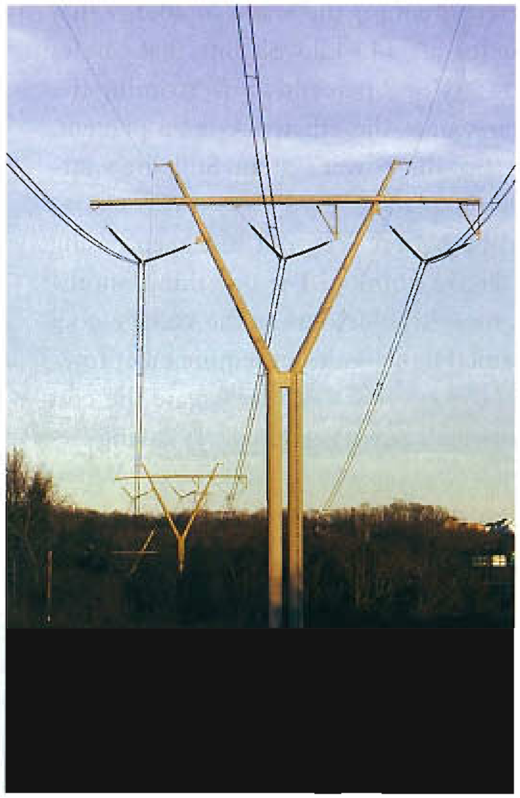
If kilovolts is good, maybe megavolts would be better? Why not just keep raising the voltage until you cut the resistive losses to almost nothing? For one thing, another kind of energy loss, called corona, becomes more troublesome as the voltage goes up. But there is an even more important constraint. Higher voltages require taller towers, bigger insulators, and a wider swath of land. All of these factors increase the cost of building the line, and at some point they outweigh any possible energy savings.

How can you judge the voltage of a transmission line from its appearance? When I was a kid, the neighborhood lore was that you just had to count the segments of the insulators, and then multiply by a certain number; the result would be the voltage. But no one could tell me the multiplier. And no wonder. There is no simple and foolproof method to determine the voltage of a transmission line just by looking at it. In particular, lines with the same voltage can have insulators with very different numbers of segments, depending on the design of the insulators.

Still, there are a few things you can look for to make a rough guess about a line's voltage. The best indicator is the distance between the conductors. If the conductors







are less than 15 or 20 feet apart, the feeder probably operates at 200 kilovolts or less. Most 345-kilovolt transmission lines have conductor-to-conductor separation of about 25 feet. The giant 765-kilovolt lines are easy to spot because the distance between conductors is more than 50 feet. (To make a rough measurement of the separation, pace off the distance between the shadows of the wires. You may need to correct for the angle of the sun.)

Another clue to a feeder's voltage is the use of "bundled" conductors. At voltages below 230 kilovolts, each phase of the circuit is almost always carried by a single conductor, but above 345 kilovolts each phase has a bundle of two, three, or even four wires held together by spacers. Circuits at 230 and 345 kilovolts can use either single or bundled conductors.

Transmission Towers. The transmission-line tower everybody knows is an Erector Set latticework of steel girders and diagonal braces. The techniques for designing and building these towers are the same ones used in constructing steel bridge trusses or crane booms. The individual pieces can be made cheaply from rolled steel and then bolted together on the site. This last point is more important than it might seem: transporting a fully assembled tower 100 feet tall is an awkward and expensive business.

Although the steel-lattice tower has long been favored by utility companies in most parts of the country, it is also one of the least-loved objects on the industrial landscape. (Telling people it is built on the same principles as the Eiffel Tower doesn't seem to change their opinion.) And there are lots of other designs. On a Sunday drive you might spot a dozen species.

Many of the alternative towers are single-pylon designs, much like modern street-lighting poles but larger. The pylon is typically four or five feet in diameter at the base and tapers to half that thickness at the pinnacle. The conductors are hung from "boughs" that branch from the mast near the top. Newer single-pylon towers are constructed from hollow steel sections 15 or 20 feet long that fit together like the sections of a fishing pole.

A pylon generally has a smaller footprint than a steel-lattice tower, and so the monopole designs are favored in built-up areas, where the cost of land is high. Out in the countryside, on the other hand, the compactness of the monopole can be a disadvantage. A pylon design requires a deeper and more massive foundation, which means more concrete has to be trucked to the site. This not only raises costs but also does more damage to farmland.

Another drawback of the single-pylon tower is that the conductors generally must be arranged one above the other. Because safety considerations (and government standards) specify the minimum height of the *lowest* conductor, a tower that carries three conductors in a vertical row has to be taller than one with the same three conductors arrayed horizontally. One way of achieving the horizontal layout is with a double-pylon tower, made up of two poles (usually wood) set a few yards apart. The conductors are suspended from a crossbeam near the top.

A gallery of transmission-line towers suggests the variety of forms that can be adapted to the task of holding high-voltage conductors aloft. From left to right and from top to bottom: The red, white, and green steel-lattice tower is in Redipuglia, Italy; the single pylon is in Raleigh, North Carolina; the two-legged colossus carries a 500-kilovolt feeder near Dixon, California; both the X-shaped and the Y-shaped towers are at New Hope, Pennsylvania; and the wood goalpost is in the southern California desert east of Glamis.

Since the basic function of a transmission-line tower is really no more complex than that of a pole used for stringing clothesline—it just has to keep the conductors from touching the ground or one another—many shapes and materials can be adapted to the purpose. There are giant bobby pins and tripods, wishbones and hangman's derricks. Much of the alphabet has been exploited: there are towers in the form of the letters *A, H, I, T, X* and *Y*, as well as in the shape of the Greek letter π.

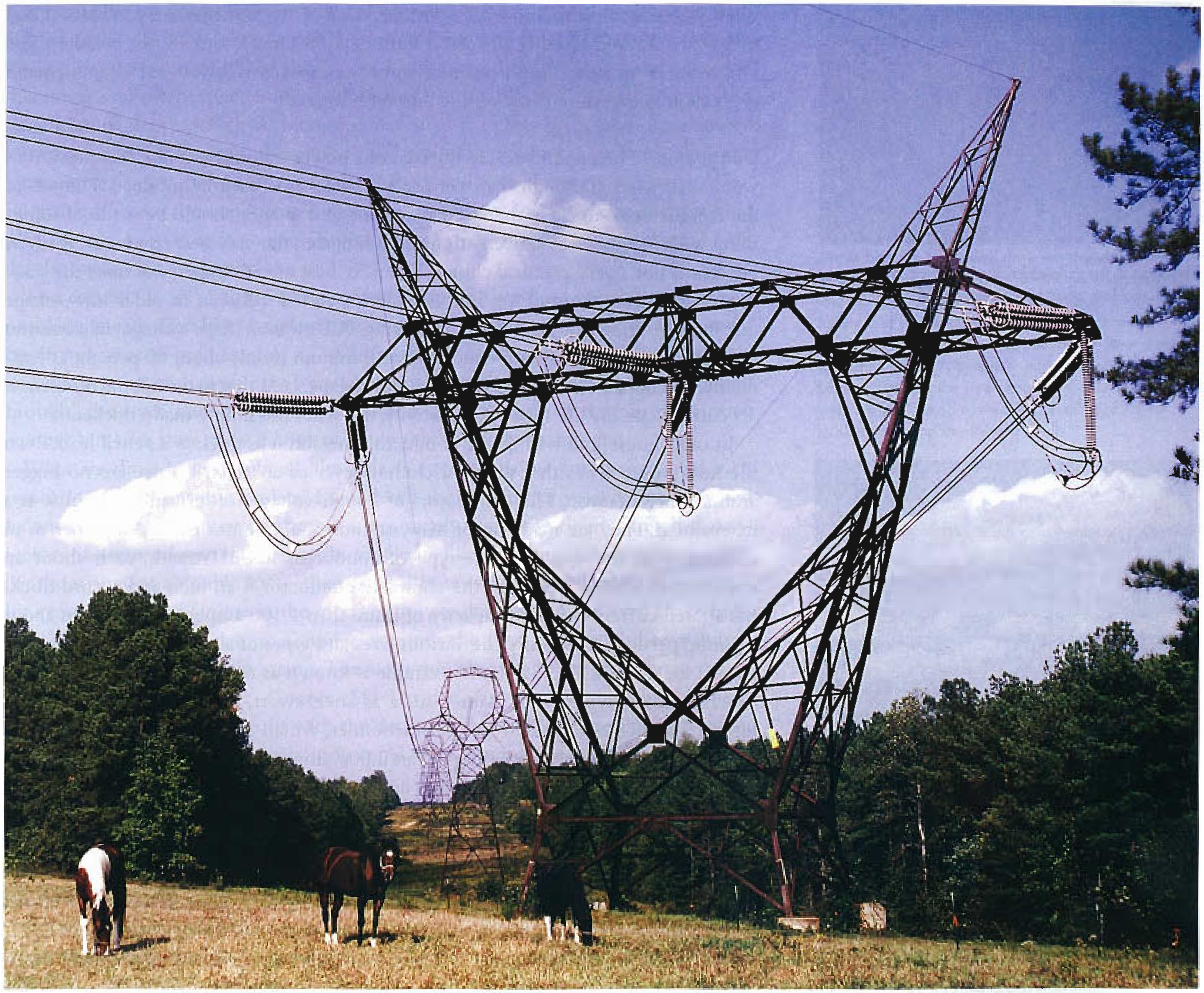
Often two feeders—a total of six conductors—will be strung on the same line of towers. Doubling up in this way has obvious money-saving potential—towers that carry two feeders cost little more than those that carry one—but it also means that a single lightning strike could knock out both feeders. Sometimes multiple lines of towers run side by side along the same swath of land, presumably because it's easier to assemble one wide power-line corridor than several narrow ones. North of Buffalo, New York, where several power lines from Canada join those coming from the American side of Niagara Falls, nine separate lines of towers run in parallel for a few miles, carrying a total of 16 feeders. It's quite a forest of steel and aluminum.

Not all the towers along a transmission line are identical. Look closely at a tower where the line makes a sharp turn and you will likely find it is wider and beefier than other towers along the route. The added strength and weight are needed to resist the unbalanced pull of the conductors, which might overturn an ordinary tower. These special towers are called deviation or angle towers. Also, at each end of a transmission line there is a heavy-duty termination tower, which serves as an anchor against the tremendous tension in the conductors. And sometimes unusually tall towers are installed where the line crosses a river.

From the air, the pathway of a transmission line stands out as a series of straight lines and abrupt turns, very different from the sweeping bends of roads and railroads. Electricity has no trouble turning sharp corners or climbing steep hills.

If you're driving along a highway parallel to a power line, here's something to watch for: the transposition of conductors, where two of the three conductors exchange places. When three conductors are arranged in a row, the one in the middle has a somewhat different electrical environment; it "feels" the presence of the two flanking conductors, whereas those on the outside each have only one neighbor. On a long feeder, this imbalance can distort the flow of power. The cure is to braid the conductors so that each one is in the middle for about a third of the route. The transpositions usually require a tower with a design different from the rest.

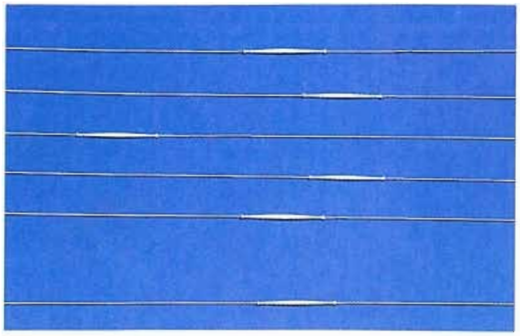
When an engineer lays out a transmission line, one of the basic starting points for the design is the minimum height of the conductors. For a 345-kilovolt feeder, the lowest conductor has to be kept at least 20 feet above the ground; for a 765-kilovolt line the minimum height is 33 feet. The lowest point is usually in the middle of the span between towers. To increase the height of the conductors, the engineer might choose taller towers, or else the towers could be placed closer together, so the conductors don't sag as much at midspan. Another way to reduce sag is to stretch the conductors tighter, but then the conductors, the insulators, and the towers have to be



made stronger to withstand the force. All of these options entail some expense, and in practice the designer seeks the lowest-cost compromise. There are also aesthetic compromises: which looks better—fewer tall towers or more short ones?

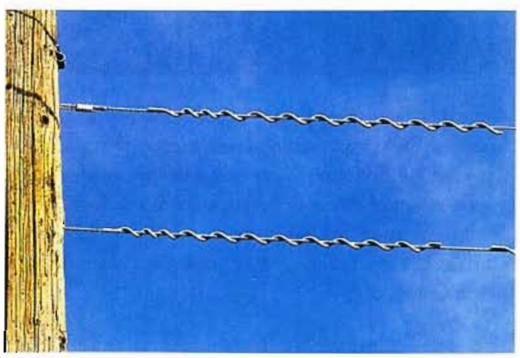
And the engineer faces yet another complication: the midspan sag is not a constant. As the conductors heat up (both from hot weather and from the current flowing through them), they expand and droop; as they cool, they contract and stretch tighter. To compensate for these changes, the power rating of a feeder depends on the

A brawny "deviation tower" absorbs the unbalanced forces where a transmission line makes a sharp turn. In this case the deviation tower has a design totally different from that of the rest of the towers along the route. The transmission line, which operates at 500 kilovolts, carries the output of the Mayo generating plant in North Carolina.



Fat cigars in the middle of a conductor are splicing sleeves, holding together two pieces of wire.

Dumbbells hanging from the underside of power conductors *(below)* are installed to absorb wind-induced vibrations that might weaken and fray the wires. This design is known as the Stockbridge damper. Another device with the same function *(bottom)* looks like a snake crawling out onto the wire.



weather. A transmission line with a normal rating of 1,800 megawatts can carry 2,200 megawatts in cold weather but has a limit of 1,580 megawatts in hot weather. The hot-weather "derating" is unfortunate, since the capacity is lowest just when demand is greatest, as everyone turns on the air conditioner.

Conductors. The conductors are the part of a power transmission line that most of us would call wires (although that word seems to be little used by insiders). The job of the conductors is to carry the electric current, and so they should be made of something with very low resistance. Among all substances, the very best conductor is silver, but that is not a very practical choice. The next-best metal, copper, was once the standard material for transmission-line conductors and is still seen in older low-voltage distribution lines and in household wiring. All modern high-voltage transmission lines, however, use aluminum conductors. Aluminum is only about 60 percent as conductive as copper, but it is much lighter and cheaper, and that makes all the difference. To compensate for the lower conductivity, the wires are simply made thicker.

In most household wiring, the conductors are about as thick as a pencil lead. Even the heavy-duty wires that supply a clothes dryer or an electric stove are no bigger around than a crayon. The conductors of a high-voltage feeder can be as thick as a baseball bat. They are made up of many strands of aluminum twisted together, as in a hemp rope. For example, one type of conductor has 61 strands, each about an eighth of an inch in diameter; the complete conductor is an inch and a third thick, has a rated current-carrying capacity of more than 1,100 amperes, and weighs about a pound per foot. Curiously, the various sizes and types of aluminum conductors are named for flowers. The 61-strand example is known as narcissus; there are about 50 other standard types, with names such as sneezewort, valerian, snapdragon, and lupine. The biggest standard size is bluebonnet, which is more than two inches in diameter and can safely carry more than 2,000 amperes of current.

Some transmission-line conductors consist of aluminum strands wrapped around a steel core. Steel is only a mediocre conductor, but it adds mechanical strength. The steel-core conductors are named for birds rather than flowers. The type designated starling, for example, has 26 aluminum strands surrounding seven finer steel strands.

The strength of modern transmission-line conductors was demonstrated dramatically in an ice storm that hit New England and Quebec in the last few days of 1997. In several places the ice-loaded conductors didn't break; instead, they pulled down the steel towers that supported them. This was not the intended mode of failure: rebuilding the towers takes much longer than resplicing a conductor.

On the highest-voltage transmission lines, each phase is carried not by a single conductor but by a bundle of two or three or four subconductors. The reasons for this arrangement are explained later in the discussion of corona discharge. Many 345-kilovolt feeders have two subconductors per phase, separated by spacers about a foot long, so the bundle looks like a spindly ladder with widely spaced rungs. At 500 kilovolts and above, most transmission lines have three or four subconductors per phase.

Conductors for power lines are shipped on giant wooden spools that hold as much as a few miles of wire—but not nearly enough for a long feeder. Where two lengths of wire have to be joined, the splice is not made by twisting the conductors together, the way you might splice household wiring. Instead, the two ends are slipped into an aluminum sleeve, which is then compressed so it tightly grips both conductors. Sometimes the sleeve is compressed with a powerful hydraulic ram; in other cases the compressive force comes from a specially shaped explosive charge, which is set off on the ground before the conductor is raised into position. In either case the resulting splice is easy to spot: it is a cigar-shaped enlargement, making the conductor look like the snake that swallowed the pig.

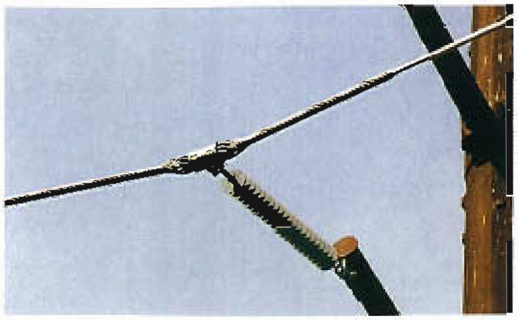
The conductors of a high-voltage transmission line are bare metal; they have no insulating sheath of rubber or plastic. Adding such a layer would accomplish nothing. If you were to grab hold of a live 345-kilovolt conductor, the thin coating that insulates a lamp cord would not protect you; the voltage would instantly "punch through" the layer. Bare aluminum conductors glint brightly in the sun when they are new, but later they grow a layer of oxide that turns them dull gray.

What are those little dumbbell-like objects attached to the conductors near each supporting tower on some feeders? I wondered about them for years before I learned the answer. They are vibration dampers. In a steady wind, the tightly stretched conductors of a transmission line can begin to vibrate like violin strings (or perhaps more like the strings of a double bass—their natural note is a very deep one). The oscillations cause stress and fatigue in the metal of the conductors and can even shake bolts loose in the supporting towers. Dampers suppress the vibrations much like a thumb held lightly against a violin string. The common dumbbell design is known as a Stockbridge damper, after George Stockbridge, an engineer with Southern California Edison who came up with the device in the 1920s. There are many other styles, including one that wraps a long spiral tube around the conductor—it looks just like a snake winding around the line.

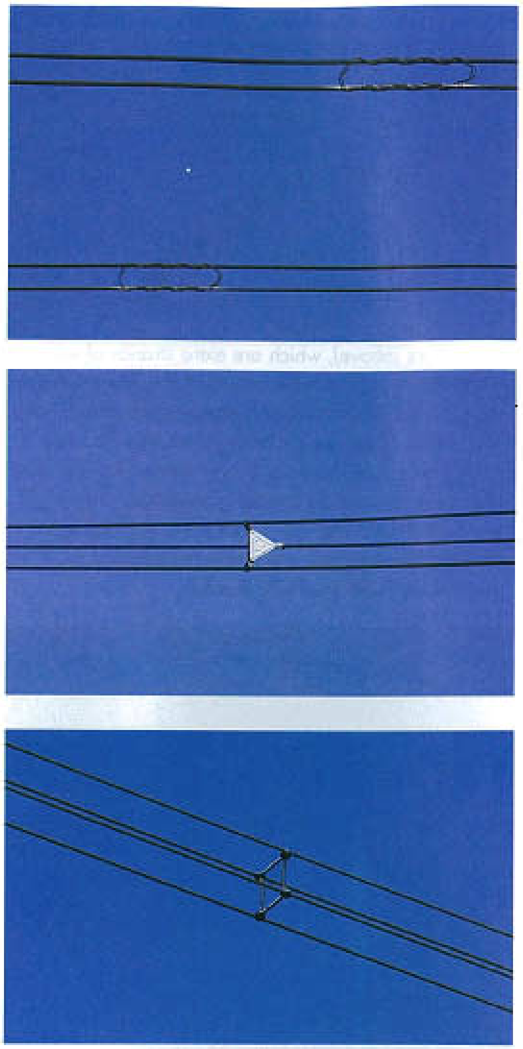
Armor bars are another defensive measure against damage from wind-induced vibrations. Actually they are not bars but reinforcing wires wrapped around the conductor at the point where it is clamped to an insulator. From the ground what you will notice is a bulge in the conductor at each tower.

Still another curiosity you might spot is a series of brightly colored spheres, the size of beach balls, attached to a power line. They are often seen near airports, where they make the conductors more visible to the pilots of low-flying aircraft. At river crossings, similar devices alert the skippers of tall-masted sailboats. In Europe neon tubes and fluorescent bulbs have been hung from power lines to warn off swans and other migratory birds that fly at night. The lights draw their energy from the electric field surrounding the conductor. (I'm surprised no one has thought of exploiting this effect for advertising.)

In the American West, bird problems take another form: eagles like to survey their territory from atop transmission towers, and with their tremendous wingspan can



Armor bars *(above)*, which are extra strands of wire wrapped around a conductor where it is clamped to an insulator, are another mechanism for dealing with fatigue and vibrations. Colorful globes attached to a power line where it crosses a river *(below)* have a quite different function. A bystander guessed that they might be meant to keep the wire afloat if it should fall in the water. In fact, they are a warning to pilots of tall-masted boats and low-flying aircraft.



Double, triple, and quadruple bundles of conductors help to control the sizzling of corona discharge, which becomes more of a problem as the voltage gets higher. From the point of view of an overexcited electron trying to escape, the bundle acts almost like one big conductor.

sometimes bridge the gap between two conductors. Rather than try to drive the raptors away, some utilities have built platforms well above the conductors, where the birds can perch in safety.

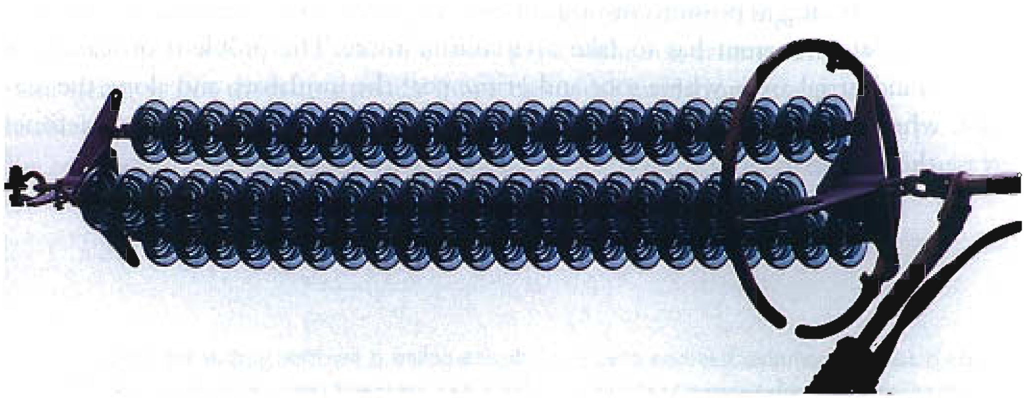
Corona. Near the surface of a high-voltage conductor, the electric field can be so intense that molecules of the air are torn apart. Electrons, which have a negative electric charge, are stripped from molecules of nitrogen and oxygen in the air, leaving behind positively charged fragments called ions. When the electrons and the ions recombine, they emit light and radio waves. The light gives the corona its name: *corona* is Greek for "crown" or "wreath," and the discharge takes the form of a faint blue or lavender halo around the conductor. St. Elmo's fire on the mast of a ship is the same phenomenon induced by natural electrical activity in the atmosphere.

To see a corona discharge, find a spot along a high-voltage line well away from streetlights. The ideal conditions are a moonless night with a soft rain or mist. Let your eyes adapt to the dark, then look along the underside of the conductors. The glow is usually fuzzy or diffuse and may be mottled. Sometimes the discharge is noticeably stronger at the clamps where the conductors are held fast to the insulators. Even in daylight, when you can't see the corona, you may be able to hear it. The characteristic note is a hissing or sizzling, like bacon frying, and it may be intermittent. You can also hear the radio-frequency emissions associated with corona: just tune your car radio to the AM band and drive under a high-voltage line. That harsh buzz is the mating cry of atmospheric electrons and ions.

Corona becomes a problem only at very high voltages. At less than 100 kilovolts or so, the discharge is undetectable, but at 345 kilovolts and above, it can waste megawatts of power. Furthermore, the radio emissions—and sometimes even the audible noise—are subject to regulations. And corona generates small quantities of ozone and nitrogen oxides, which are smog-causing pollutants that also attract the attention of regulators. Thus, power companies work hard to minimize corona effects.

The intensity of a corona discharge depends on the shape of the emitting object. Sharp points or edges are strong corona radiators because the electric field has to bend and stretch around them. Accordingly, high-voltage hardware tends to be designed with gentle curves, rounded corners, and smooth surfaces. But nature can spoil the designer's efforts. When a water droplet clings to the underside of a conductor, the electric field distorts the droplet into a sharp spike, shaped like a rose thorn, which becomes an excellent corona source. This is why corona is so much worse in wet weather.

One way to reduce corona emissions is to make the conductor as thick as possible, so that the surface is more gently curved. Expanded conductors have a mat of light, nonmetallic fibers between a steel core and the current-carrying aluminum strands; the mat makes the conductor thicker without greatly increasing its weight or cost. Bundled conductors, as described earlier, have the same purpose. When two, three, or four subconductors run parallel to one another a foot or two apart, the elec-



Three strings of insulators *(left)* are rigged in parallel to sustain the weight and the tension of a transmission line near Three Mile Island in Pennsylvania. Each string consists of 22 disks of translucent green glass the size of salad bowls. The ring at the "hot" or high-voltage end of the insulator helps to suppress corona discharge.

tric fields of the subconductors combine and overlap so that the bundle acts much like a single fat conductor, almost as big as the entire bundle. Corona emissions are greatly reduced.

The troublesome corona hot spots where conductors are clamped to insulators are sometimes protected by corona rings, or shields. These smooth metal rings look just like great handles attached to the end of the insulator, as if they might be used for maneuvering it into place. That is definitely not their function. They work much like a bundled conductor to spread out the electric field and minimize corona losses.

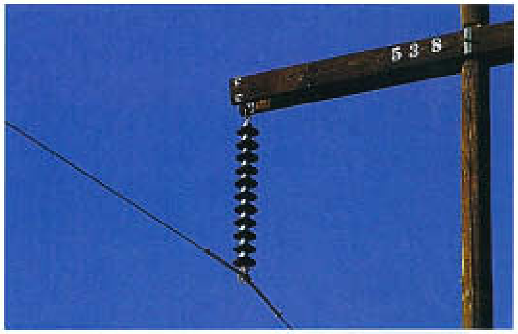
Incidentally, because of corona you will not see birds perching on the energized conductors of a high-voltage transmission line. A bird would not receive a shock from the wire, as long as it didn't touch something grounded at the same time, but evidently the sizzling discharge makes the wire an uncomfortable or unpleasant place to sit. Birds do perch on the aerial ground wires strung above the active conductors.

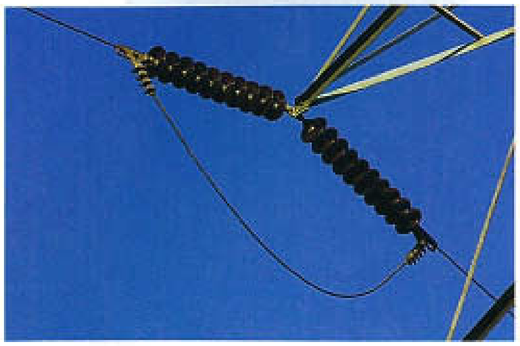
Insulators. Whereas conductors are meant to carry electricity as efficiently as possible, insulators have the opposite job: blocking the flow of current. They are made of porcelain, glass, or plastic—materials that present an impenetrable barrier to electricity.

The most common insulator on high-voltage lines is an assembly of porcelain segments, called disks, linked together into an insulator string, which looks like some gigantic marine worm, something that might have washed up on a prehistoric beach. One end of the insulator string is hung from the transmission-line tower; the other end supports the conductor. The segments in the string are held together by metal balls and sockets that interlock like the links of a keychain, allowing the assembly to flex as the conductors move in the wind.

A good insulator is one that doesn't leak—one that lets no electricity escape from the high-voltage conductors to the supporting tower and the earth. As a rule, leakage through the body of a glass or porcelain insulator is not a problem; it seldom happens. But sometimes there is troublesome leakage along the surface of an insulator, especially when it is wet or dirty. Designers combat this problem by making the surface smooth and slick so contaminants won't stick to it, and by careful attention to the shape of the insulator. To make the leakage path over the surface—known as the

Conductors can be suspended from a single string of insulators, from a V-string, or anchored to the tower in a "dead-end" arrangement.





creep path—as long as possible, most insulator disks have rings, ridges, or crenelations so that any stray current has to take a circuitous route. The problem of leakage is worst in industrial areas, where soot and grime coat the insulators, and along the seacoast, where deposits of salt build up. Power companies in these places sometimes grease the insulators or else wash them regularly with high-pressure hoses.

AC/DC

One of the great pitched battles in American industrial history was the fight over alternating and direct current. It was bigger than Coke vs. Pepsi, or Ford vs. Chevy. The DC forces were generaled by Thomas Edison, with the AC insurgents commanded by George Westinghouse. Each side argued that its own system was better for everything—with one exception: they both conceded that the other kind of current was more deadly and thus would be better for electrocuting prisoners.

In the end AC won total victory—even for the electric chair. But in recent decades DC has made a surprise comeback in one area. Some of the longest, highest-capacity power transmission lines carry direct current.

It's easy to recognize a high-voltage DC transmission line. There are just two conductors, whereas all AC lines have three conductors. A DC line operating at 500 kilovolts runs 846 miles from The Dalles in northern Oregon to Sylmar, California, in the suburbs north of Los Angeles. During summer peaks in electricity consumption it carries more than 3,000 megawatts. Another major DC link extends from the hydroelectric plants of northern Quebec to Waltham, Massachusetts. Still more DC ties have been built in Manitoba, North Dakota, and Minnesota, and along a route from Utah to Los Angeles.

The reason DC lost favor a century ago is that you can't build DC transformers to change the voltage level. So how do DC transmission lines work? The power is generated as AC and raised to high voltage by conventional transformers, then it is converted to DC for long-distance transport. At the far end of the line, another station converts the current back to AC again.

The first AC/DC converter stations, built in the 1960s, were based on a device called a mercury-arc valve. It looks and works much like a vacuum tube in an old radio, except that it stands three feet tall, handles 1,000 amperes or more and 100,000 volts, and needs a constant flow of water to keep from burning up. In more recent stations, mercury-arc valves have been replaced by a solid-state device called a thyristor (just as transistors long ago replaced vacuum tubes in radios). The thyristors are smaller than mercury valves, but they're still enormous as semiconductors go—the same silicon "wafer" that might hold a few hundred microprocessor chips, each with a million transistors, makes a single thyristor for power-grid duty.

Unlike most substation equipment, AC/DC converters have to be kept out of the weather, which means you can't see them from outdoors. The Celilo Converter Station, at the northern end of the Pacific DC Intertie, has a visitor center where you can look into one of the enclosed galleries filled with mercury-arc valves. At Celilo you can also stroll around outside the fenced yards of conventional transformers and switchgear. Some of this equipment even has helpful labels, just like the plaques that identify trees and shrubs in a formal garden or arboretum. (The Celilo station, operated by the Bonneville Power Administration, is on a hill above the dam at The Dalles on the Columbia River.)

Why all this bother to convert from AC to DC and back to AC again? DC transmission has a number of advantages. For a given conductor size, resistive losses are lower. And only two conductors are needed; on a long intertie, this is not a small cost savings. The number of insulators is reduced as well, and since the towers have less weight to support, they can be built lighter. Perhaps even more important, two conductors take less space than three, allowing the use of a narrower right-of-

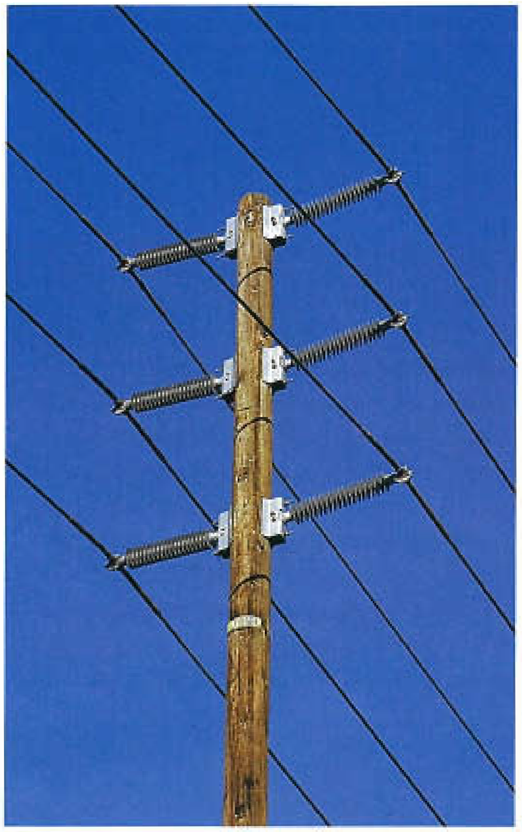
Often, each conductor is hung from a single insulator string at each tower. In other cases you will notice two insulators per conductor, arranged in a V shape. The extra string is not there to provide more electrical insulation; as a matter of fact, it doubles the leakage current. The purpose of the V-string is mechanical: it prevents the conductor from swinging from side to side. At some towers the line must be

way. And DC transmission lines are sometimes easier to control. With an AC line, the only way to regulate the flow of power is to change the throttle setting at a generating station. With DC, it's just a matter of turning a dial that controls the mercury valves or thyristors.

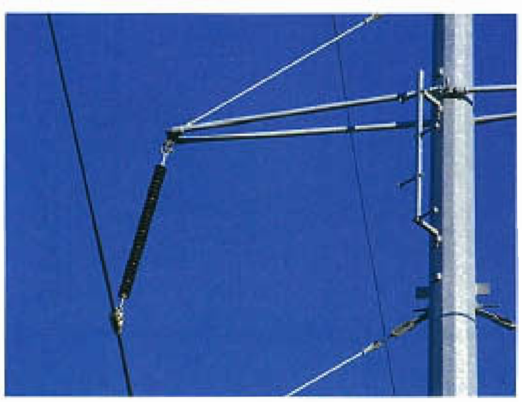
Still another advantage of DC is that there's no need to synchronize the distant power systems. (With AC, all the interconnected generators must turn in lockstep.) For this reason alone, several utilities have built back-to-back converter stations, where an AC-DC-AC link transfers energy between two nearby power systems that do not run synchronously. All the links along the east-west divide in the United States work this way, and so do many stations along a similar boundary in Europe.

Along a high-voltage DC transmission line you may be able to figure out which conductor carries a positive charge and which is negative. Corona loss is much greater from the positive-polarity conductor. On a dark night, if the corona discharge is visible, the negative conductor will have just a uniform glow, but the positive conductor will give out plumes and streamers. An AM radio may also be able to detect the difference; the positive side produces a stronger rasp of interference. You may even be able to hear the difference in ordinary audible noise. DC transmission lines sound quite different from AC ones. They click and crackle rather than buzz; the DC line sounds just like a Geiger counter. And when you walk under the conductors, the pace of the clicking accelerates, as if you were radioactive. Your own body is disturbing the electric field around the wires overhead.

The electric fields on the ground near DC conductors are also different from those associated with AC transmission. With DC there is a sustained current of ions flowing from the conductors to the ground—a slow rain of slowly moving charged particles. Standing under the line, you intercept some of this charge. If you are well insulated—wearing sneakers—and you wait to accumulate a charge, you'll draw a spark when you touch something grounded. Those who regularly work near high-voltage DC equipment report that they can feel the charge: it repels the fine hairs on the nape of the neck and the tips of the ears, producing a "crawling" sensation. It is the same feeling you get when you place the back of your hand near the television screen.



The Iron Cross of insulators: rigid struts *(above)* are increasingly popular with power-line builders. The core of the strut insulator is fiberglass, which gives it the strength to hold up the conductors with arms outstretched. The same fiberglass is also turning up in the newest, slimmest suspension insulators *(below)*.



dead-ended: two separate insulator strings take up the full tension of the conductors on each side of the tower, and often a third string is needed to guide the slack loop of conductor around the tower structure. With very heavy lines or long spans, even more elaborate arrangements may be needed.

For a long time most transmission-line insulators were brown or black. Many of the porcelain ones had a handsome red-tinged glaze that would have looked good on a fine china teapot. But fashions have changed. The color of choice for newer insulators (and for much other electrical equipment) is neutral gray, a shade that one manufacturer calls Skytone. The makeover has no functional significance; it's just somebody's idea of what looks best, or what looks least—as the name suggests, Skytone insulators are supposed to blend into the background when seen from below.

The latest thing in high-voltage insulators is the single-piece rigid post or strut. Instead of a string of jointed disks suspended from overhead, a strong insulating rod juts out directly from the tower. The mechanical strength comes from a fiberglass beam at the core of the insulator, but there is often a glazed ceramic covering to create a smooth surface and cut down on leakage.

Lightning and Other Hazards. A steel tower poking 100 feet out of the landscape is an obvious target for lightning. Transmission towers are struck thousands of times a year, in most cases without damage and without even interrupting the flow of power.

The main defense against lightning is to ground the tower—to connect it electrically with the earth. At the base of a steel-lattice tower you will generally find a heavy copper wire bolted or clamped to each leg. (You can tell the wire is copper because of the green copper-oxide patina.) Each ground wire is attached to a copper rod driven deep into the soil. Metal towers of other designs have similar provisions for grounding, and wood poles have ground wires that run from top to bottom.

The ground wire cannot prevent lightning from striking; all it can do is offer the lightning current a direct and harmless route to the ground—and a route that's supposed to be more inviting than the power-line conductors. The ground wire is analogous to a drain pipe that carries excess water away before it can flood your basement.

Grounding the tower protects the tower itself, but what if lightning strikes the transmission line between towers? The power-line conductors themselves cannot be grounded; after all, the entire edifice of towers and insulators is intended to prevent the conductors from coming in contact with the earth. The answer is to provide a kind of electrical umbrella, a metallic shield at ground potential that extends over the power-carrying conductors. The umbrella consists of aerial ground wires that are strung from the pinnacle of one tower to the next, parallel to the main conductors but above them. The aerial grounds are easy to distinguish from current-carrying conductors because they have no strings of insulators. They are also the highest wires on a tower, and they are thinner than the main conductors.

The role of the aerial ground wires is to intercept a lightning stroke before it reaches the power-line conductors. Aerial grounds work best when they are directly above the conductors. Where the main conductors are in a vertical arrangement, a single aerial ground can be mounted directly over them. With a horizontal configuration the usual practice is to install two aerial ground wires spaced to provide coverage for all three conductors.

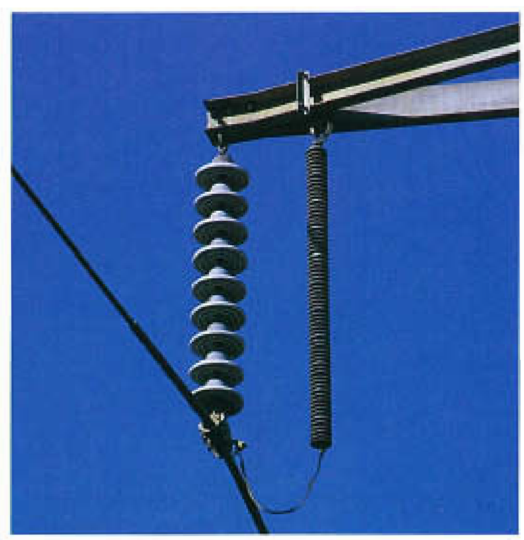
The grounding strategy sometimes fails. A powerful lightning bolt can deliver several million volts, which is far beyond the rating of the power-line insulators. The usual result is a flashover, an arc from the tower to one (or more) of the phase conductors. The arc itself can damage insulators and conductors; a more serious worry is that the voltage surge traveling along the conductors can damage generators, transformers, and other equipment at the end of the power line—including, perhaps, the television set you've plugged into the wall outlet. To deal with these perils there are further lines of defense—circuit breakers, lightning arresters, and surge suppressors at substations and throughout the power-distribution system.

At operating voltages up to about 500 kilovolts, lightning is the only likely cause of flashovers. At still higher voltages the power system can become a hazard to itself. The source of this self-destructive behavior is the energy stored in the magnetic field that surrounds a current-carrying conductor. If the current in the line stops suddenly (for example, when a circuit breaker opens), the magnetic field collapses, and the stored energy is transformed into a high voltage. (The principle is the same one that fires an automobile's spark plugs when the breaker points interrupt the current to the ignition coil.) The transient voltages induced in this way can be three times the normal operating voltage of the line. Protecting against them would be expensive: a 765-kilovolt feeder would have to be insulated as if it were operating at two million volts. A better solution is to design the circuit breakers so that they cannot interrupt the current so suddenly.

In recent years there has been much controversy about possible dangers of exposure to the electric and magnetic fields surrounding high-voltage power lines. Certain rare diseases are alleged to be slightly less rare among people who live near transmission lines and among power-company maintenance workers. Personally, these alarms leave me unconvinced, but I'm not a medical expert. In any case, the casual explorer of the industrial landscape—someone who occasionally spends a few minutes near a power line—should have nothing to worry about: the supposed effects of electric and magnetic fields are attributed only to long-term exposure.

The fields in question certainly do exist. If a conductor 35 feet overhead is at 350,000 volts, the voltage gradient—the rate of change—between the conductor and the ground is 10,000 volts per foot. In other words, if you're six feet tall, then when you stand under a transmission line, your head is 60,000 volts above your feet. How can people walk through such an intense field without being electrocuted? Because air is such an effective insulator, the field remains a static one; no electric current flows through the body in spite of the enormous voltage difference. Anyway, power lines are not the only source of such fields. On a dry winter day you can create a field just as intense by rubbing your feet on a wool carpet.

Aerial ground wire *(above)*, at the very top of the tower, provides a perch for pigeons, which avoid the high-voltage conductors lower down. But the aerial ground is not put there for the convenience of birdlife; it protects the power conductors from lightning strikes. Another form of lightning protection *(below)* relies on an arrester—the slender rod to the right of the insulator string—to divert voltage surges through the tower and safely into the ground. Arresters are common in substations but rare on power lines; this specimen was photographed in Spartanburg, South Carolina.



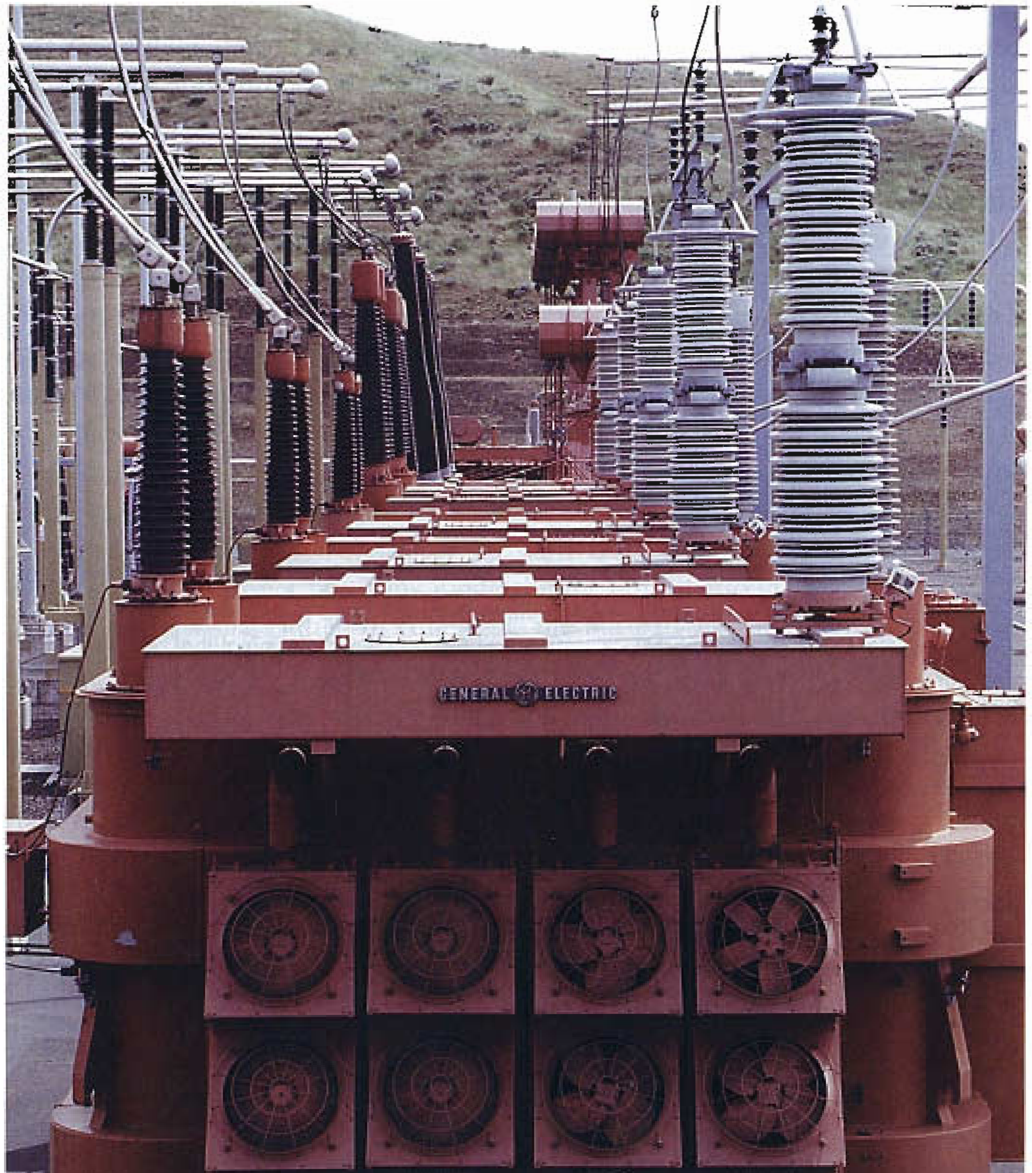
An electric personality lights up the night: the electric field emanating from a high-voltage transmission line can be made visible with apparatus no more complicated than a fluorescent tube. Electrons are set in motion by the field beneath the conductors and stimulate the phosphors inside the tube to emit light. The power line used for this experiment operates at 500 kilovolts.

You can detect the electric field under a power line with a simple instrument: a fluorescent light bulb. When I first read about this, I was skeptical, but an experiment on a dark night, at a spot where a 500-kilovolt feeder hangs low over a country road, soon made a believer of me. As I approached the conductors, the 18-inch fluorescent tube suddenly came to life, emitting a mottled blue glow, dimmer than the bulb's full normal output but quite easy to see. Running my hand over the glass, I could chase the glow from one end of the tube to the other. Holding the tube near the ground extinguished the light; it reignited at a height of about four feet. When I stood directly under the middle conductor, the light became feeble and irregular, presumably because the fields from the three phases nearly cancel out there. (*Warning*: If you try this experiment, use a short fluorescent tube—no more than two or three feet long. Holding an eight-footer up over your head could too easily cause *you* to light up. And no baton-twirling!)

SUBSTATIONS

A power-system substation functions like the fuse box in your basement. Power enters the substation on large, high-capacity feeders, and it leaves via smaller distribution lines, much as electricity enters your home through a heavy-duty cable (with a capacity of 100 amperes or more) and is distributed in the fuse box to several 15- and 20-ampere circuits. Large circuit breakers at the substation protect the power system from overloads and surges, just as fuses or smaller circuit breakers at home disconnect circuits if something goes wrong. One point where the analogy breaks down is that the home fuse box has no equivalent of the substation's transformers, which reduce voltages from transmission levels to more manageable distribution levels.

A good place to look for a large substation is on the outskirts of a city. Often two or three major feeders will converge on the station, with multiple lines at lower voltage carrying the power on to smaller substations closer to town. There the voltage is reduced still further, for the many distribution lines that fan out through the city.



Nine massive transformers are lined up at the Celilo substation in northern Oregon.

A substation "bus" is a set of parallel conductors that carry electric current from one component to the next. Here two buses (with a total of six conductors) are formed out of aluminum tubing held aloft on insulated pedestals. The columnar devices at the left are instrument transformers that monitor voltage on the two buses. The substation is in Redipuglia, Italy.

At first glance, a substation is a bewildering array of hulking steel machines whose function is far from obvious. Ponderous tanklike or boxlike objects are lined up in rows. Some of them have cooling fins or fans; many have fluted porcelain insulators poking out in all directions. Overhead is a clutter of metal scaffolding, studded with still more insulators. There are no moving parts to offer a clue to how it all works; and most of the time, there is no one to be seen tending the equipment; the only sign of life is a steady, droning hum.

If you look closer, you will find there is a logic to this melange of equipment. You can make sense of it. The substation has inputs and outputs, and with a little study you can trace the pathways between them.

Catching the Bus. The organizing principle in almost all substations is the idea of a bus, which is a set of three conductors that run parallel to one another, carrying the three phases of the electric current. Incoming and outgoing transmission lines, transformers, breakers, and other equipment are all connected to the bus conductors. Why is it called a bus? Someone tried to tell me once that it was because city buses, like trains, used to have conductors. It was a bad joke, but there *is* a connection: in both of its meanings, bus is an abbreviation of the Latin word *omnibus*, which means "for

SONG OF THE SUBSTATION

America hums at a slightly higher pitch than Europe and most of the rest of the world. The power grid in the United States runs at 60 hertz—or 60 cycles of alternating current every second—whereas Europe is on a slower 50-hertz beat. If you have a good musical ear, you will be able to tell the difference. (The tones you hear are actually double those of the power frequency—120 hertz and 100 hertz. That's because each half-cycle of the power wave causes the transformer core to vibrate.)

Technically, there is no strong reason to prefer either 50 or 60 hertz; it's just one of those annoying nonstandards that makes life a little more difficult for everybody. In the early years of the twentieth century, 50 hertz was proposed as an international standard, and U.S. utilities adopted it along with everybody else. A few years later, though, American manufacturers of electrical equipment persuaded Congress to mandate a switch to 60 hertz, as a way of protecting the home market against European competitors. But a few islands of 50-hertz service survived until after World War II, the largest of them being the city of Los Angeles. Nearly two million electric clocks, record players, washing machines, refrigerators, and other motor-driven appliances in Los Angeles had to be rewired or replaced before the great switchover on October 26, 1948.

Several other frequencies have had their vogue. The first big hydroelectric plants at Niagara Falls produced AC power at 25 hertz, and a few of them on the Canadian side continue supplying customers who have ancient equipment operating at this frequency. Some electrified routes of the New Haven and Pennsylvania railroads also ran on 25 hertz for nearly a century. The trains themselves have converted to 60 hertz, but at last report there were still sump pumps deep in the bowels of Grand Central Terminal that required a 25-hertz feed. Many European railroads use power at a frequency of 16⅔ hertz. Lower frequencies have advantages for running large motors, but they won't do for electric lighting because people can detect the flickering. Low-frequency power also requires heavier and bulkier transformers; aircraft use 400-hertz power to save weight.

In one respect, the frequencies chosen for the world's power grids couldn't be worse. If you accidentally touch a live wire, your muscles may seize, so that you can't let go. This involuntary contraction is more severe with alternating current because the pulses of current mimic the firing of nerve cells. It so happens that the most dangerous frequencies are near 50 and 60 hertz. These hertz hurt! (Of course this wasn't known at the time the frequencies were chosen.)

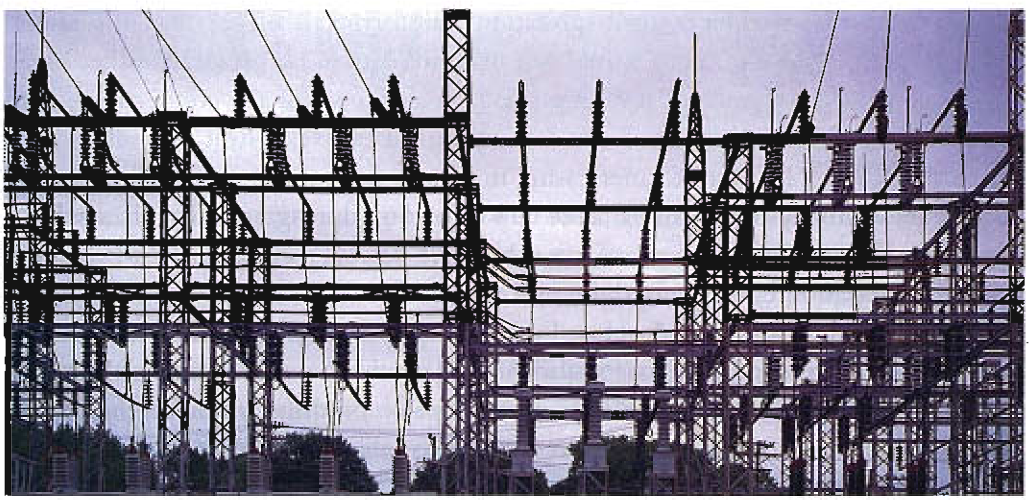
all." Just as the vehicle called a bus carries any and all passengers, the electric-power bus carries currents from all sources to all destinations. (Lately, the word has also become familiar to those who tinker with computers; the parallel conductors that carry signals throughout a computer are also called a bus.)

The conductors of a substation bus are usually rigid aluminum tubes, called bus bars, rather than flexible wires. The tubes are hollow and look much like the ones used in cheap lawn-and-beach furniture, although they are larger in diameter. You might mistake them for the kind of metal conduit that encloses electrical wiring in some buildings, but the bus bars do not have wires (or anything else) inside; it is the tubing itself that carries the current. Some utility companies favor square rather than round tubes, or channels with an L-shaped or U-shaped cross section. Occasionally the bus bars are painted bright colors to make them more conspicuous to workers. In older substations you might still find a few solid copper bus bars, recognizable by their distinctive green patina.

A long run of bus bar is usually interrupted every 50 feet or so by a length of flexible copper braid. This allows for thermal expansion and contraction. In earthquake country it also improves the chance that the substation will survive a shaking without major damage.

Holding the bus bars aloft is the purpose of the metal scaffolding, or superstructure, that towers over the rest of the substation equipment. The classic design relies on beams and girders assembled from the same lacy, Erector-Set framework seen in transmission-line towers, but many modern substations use solid stanchions or poles that create less visual clutter. In either case the bus bars are supported by porcelain insulators similar to the ones that carry transmission-line conductors.

The simplest substation design would have a single set of bus bars running the length of the station. High-voltage feeders might be attached to each end of the bus, and several transformers would draw off current from intermediate taps, reducing the voltage for distribution. Unfortunately, this simple design is not workable in practice.



Multiple buses crisscross to form a confusing gridwork over many substations. At a substation in Durham, North Carolina, the steel members extending from left to right merely support the structure; the conductors—set off on insulated struts—mainly go from front to rear.

The reason is that a single transformer failure, or a lightning strike on either of the incoming feeders, would probably shut down the entire system. So would routine maintenance anywhere in the substation. At home this situation may be acceptable: when the toaster blows a fuse, no great harm is done if the refrigerator and the microwave shut down as well. But in a municipal power system, no one fault should knock out an entire substation.

The solution is redundancy. Most substations have two buses, which can be ganged together or isolated from each other as circumstances require. The incoming power can be directed onto either of the buses, much as trains are switched onto various tracks in a rail yard. Similarly, the transformers supplying the low-voltage distribution system can draw their power from either bus. In the event of a mishap, power can be rerouted around a failed device. And if necessary an entire bus can be shut down for maintenance without cutting off power to customers.

Where space is extremely tight, the buses may run directly over the transformers, breakers, and other equipment, but that plan makes access awkward when something has to be moved or replaced. More commonly, the heavy equipment is off to one side of the buses or in a gallery between them, connected by conductors running at right angles to the main bus bars.

Adding to the visual complexity of a substation, sometimes there is a low-voltage bus, where the outputs of several transformers are gathered for connection to the distribution system. The low-voltage bus bars are generally at a lower height and are supported by smaller insulators. Sometimes the low-voltage circuits are carried by underground cables, to keep them out of the way. Often they emerge from the ground onto pole lines at the perimeter of the substation.

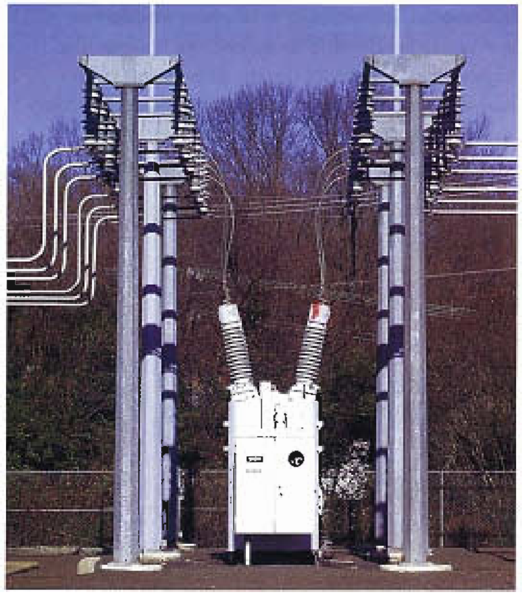
Transformers. The jumbo items at a substation—the biggest boxes on the lot, and also the most expensive—are the transformers. Much of the other equipment is there to protect the transformers in case something goes wrong.

Size is the first clue when you try to pick out the transformers amid all the other gear in a substation. Even a small substation transformer is bigger than the family refrigerator, and some of them would not fit inside a two-car garage. Another identifying sign is the presence of both high-voltage and low-voltage connections, with differently sized insulators. Provisions for getting rid of excess heat are still another distinctive feature. The transformer casing may have fins or tubes, or it could have a complete radiator system, with banks of fans turned on during periods of heavy load. Finally, if you can't identify a transformer by sight, you might recognize it by sound: of all the substation equipment, the transformers hum the loudest.

What's inside the big box? As a boy I cracked open a doorbell transformer and was disappointed to find nothing but a wad of varnished wire and a stack of E-shaped metal plates that I never got back together properly. Nothing inside seemed to do anything. That's because there are no moving parts in a transformer. The mechanism relies entirely on the ethereal throbbing and pulsing of invisible magnetic fields.

The main components of a power transformer are two coils of insulated copper wire, like spools of twine, wound on an iron core called a yoke. The coils are usually concentric, with the lower-voltage one slipped inside the higher-voltage coil. The iron core is made of many thin laminations instead of one thick lump of steel. This method of construction reduces the little whirlpools of electric current in the iron—called eddy currents—that would otherwise waste large amounts of power. The flexing of the laminations as they are magnetized and demagnetized 120 times per second is what produces most of the transformer's hum.

Large transformers at Marysville, Ohio, take in power from long-distance 765-kilovolt feeders and deliver it to a 345-kilovolt network. The bank of transformers seems to violate the fundamental rule that elements of the electrical infrastructure come in groups of three. But of the four transformers here, only three are active at any given time; the fourth is a spare. Also note the walls separating the transformers, meant to contain oil fires.



Oil-filled switches, or circuit breakers, are a common sight at American substations. The switches can be used to open a circuit under manual control, but they also operate automatically in the event of an overload or a lightning strike or an equipment failure. The hundreds of gallons of oil in the tanklike enclosures help to snuff out the arc that forms when a large current is interrupted.

The big cylindrical tank on top of many substation transformers is called a conservator, and it holds oil overflows. The oil expands when it heats up, and the conservator gives it a place to go without spilling; when the oil cools again, it is automatically sucked back into the main transformer tank. Sensors continually monitor the state of the oil. Hydrogen bubbles are a sign of arcing within the transformer windings. If a sensor detects a few small bubbles, it will alert maintenance crews to have a look at the transformer. A sudden surge in oil pressure indicates more serious trouble, and immediately triggers a circuit breaker that disconnects the transformer. Transformer hum is another diagnostic sign. Old hands in the switchyard say they can hear the difference when a transformer is about to go bad.

One last thing to look for on a big transformer is a mechanism, called a tap-changer, for adjusting the output voltage. A tap is a connection to one of the transformer windings not at the end of the coil but to one of the interior turns. Changing from one tap to another changes the turns ratio and thus the output voltage. Adjustments of this kind are needed to make sure the voltage reaching customers stays reasonably close to what is promised. Once upon a time, changing a tap meant sending somebody out in the yard to shove a big lever on the side of the transformer casing. Nowadays it's done by remote control, and all you see is a metal box hanging on the side of the transformer; it houses a motor-driven switch. Often the tap can be changed only when the transformer is off-line.

Circuit Breakers and Switches. A switch seems like such a simple piece of hardware. Take two conductors and join them together: The switch is closed, and current flows. Pull the conductors apart and the current stops. This is how a light switch works. But the switches in substations have to handle thousands of amperes and hundreds of thousands of volts, and they are not so simple.

The basic problem in building a switch for high voltages and high currents is that merely pulling two conductors apart does not necessarily stop the current from flowing. Electricity will cheerfully jump across the gap, forming a white-hot arc, which then proceeds to melt the whole mess. If you want your switch to work more than once, you need a way to extinguish the arc. Fortunately for the power engineer, the use of alternating current makes this task easier. Because the current and voltage fall to zero 120 times a second, you don't actually have to stop the current; you just have to wait for the arc to die out at such a "zero crossing" and then cool it quickly enough that it can't reignite.

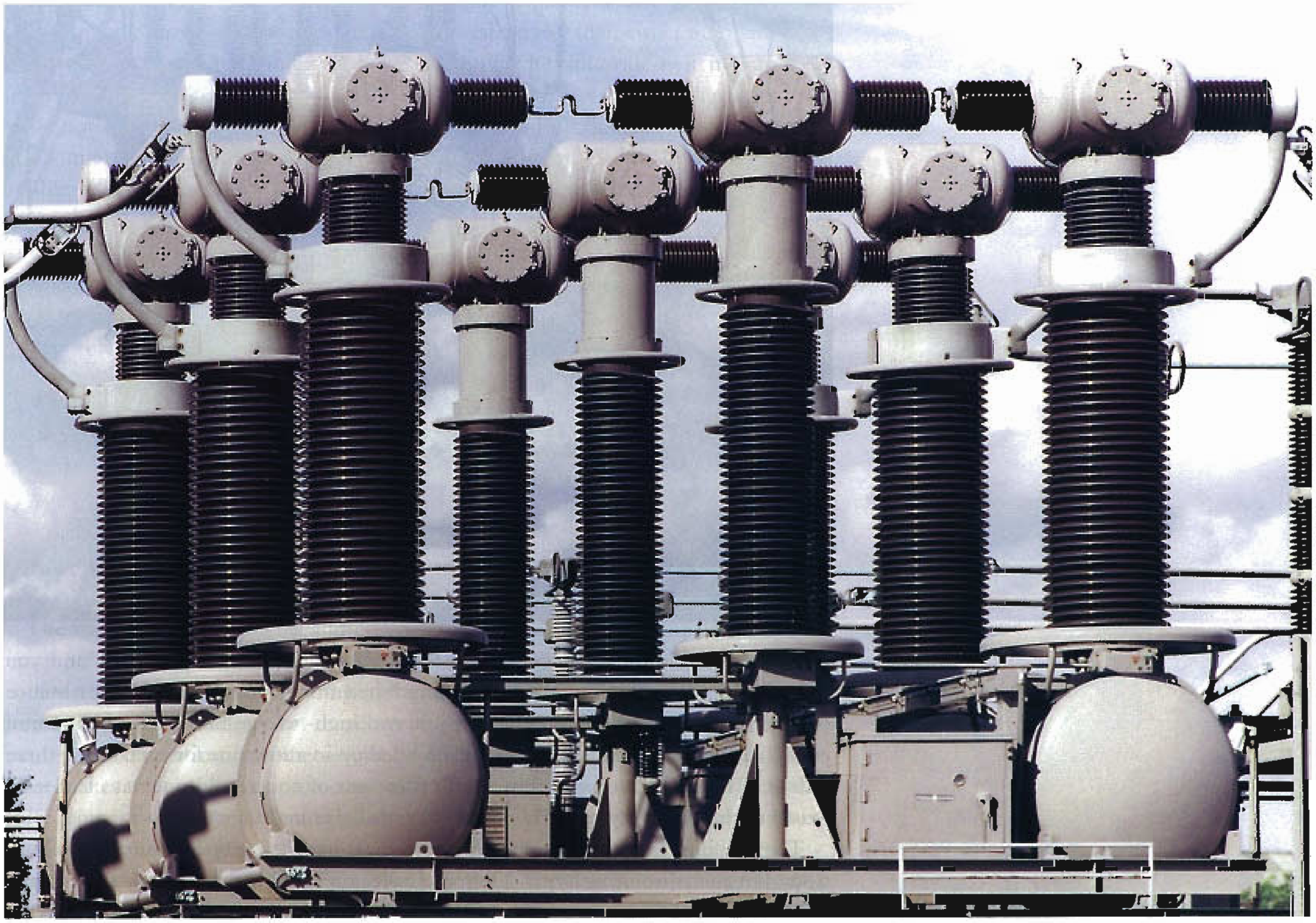
Most substation switches in the United States use oil to quench the arc—the same kind of oil that cools transformers. The switch contacts are immersed in a deep tank of oil, and when the contacts pull apart, the oil fills the space between them and smothers the arc. Actually, it's not the oil itself that puts out the arc. The extreme heat of the arc breaks down a little of the oil into its chemical components and creates a bubble of hydrogen gas. The hydrogen bubble carries away heat so efficiently that—if all goes according to plan—the arc fails to reignite after the voltage crosses zero.

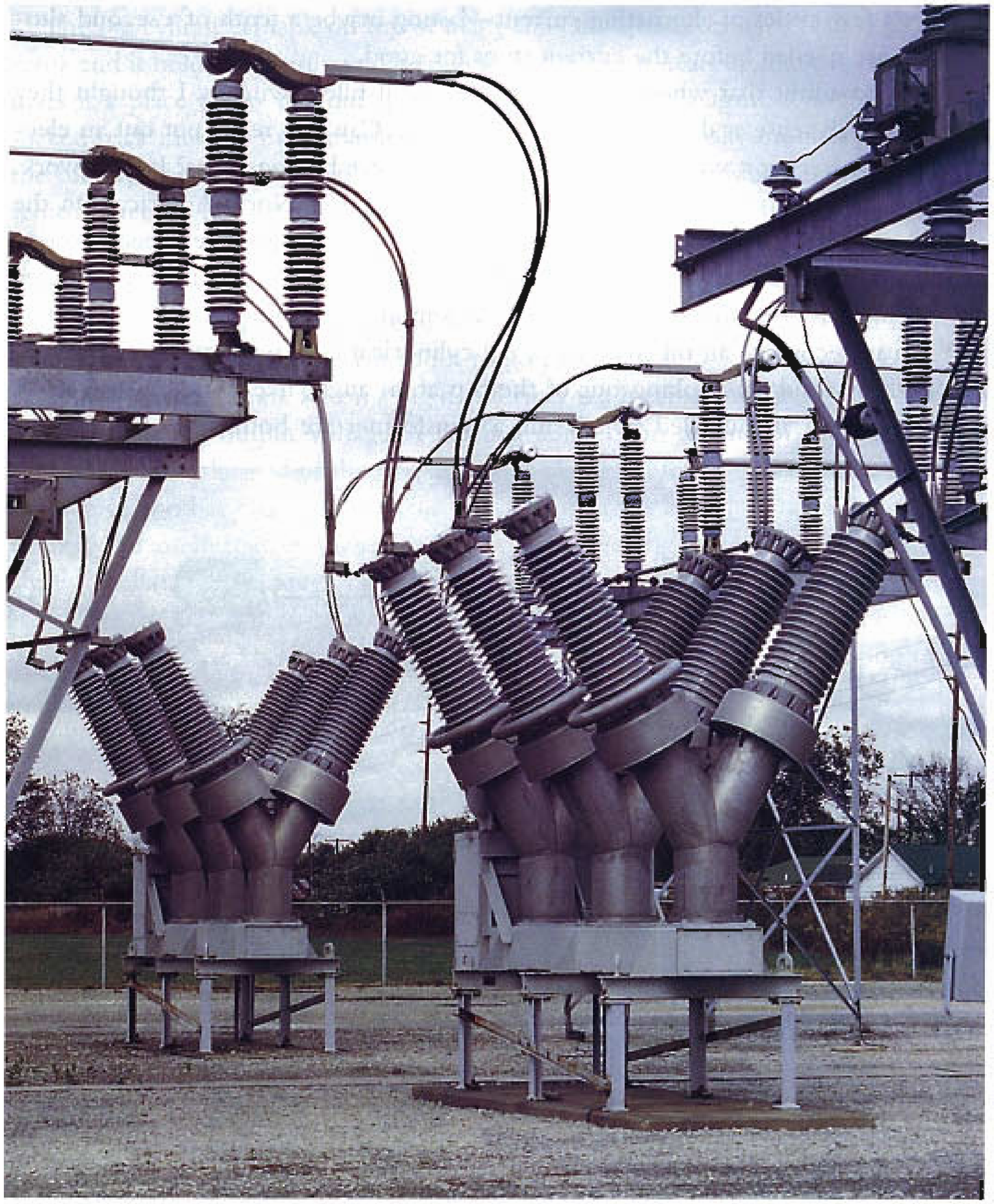
Usually a few cycles of alternating current—lasting maybe a tenth of a second altogether—are needed before the current stops for good.

I have to admit that when I first heard about oil-filled switches, I thought they made as much sense as dousing a fire with gasoline. Can you really put out an electric arc by covering it with flammable oil and explosive hydrogen gas? It does work: there are thousands of the switches in substations all over North America. On the other hand, they are the most troublesome equipment on the lot. They need frequent maintenance, including an oil change at regular intervals. And when they fail, they fail spectacularly—with a ball of flame and a column of smoke.

You can recognize an oil switch as a tall cylindrical tank with two fluted porcelain bushing insulators poking out of the top at an angle, like horns or an insect's antennae. Since an oil-filled switch and a transformer are both, from the outside,

Air-blast switches rely on a supersonic wind to blow the arc out, rather than a bath of oil. The switches are the nine tall, T-shaped structures. Porcelain insulators form both the vertical stalk and the lateral arms of each T; the switching elements themselves lie in the football-like pod where the vertical and horizontal members intersect. The air blasts come from the tanks mounted directly below each switch. Three switches are rigged in series on each phase of a 345-kilovolt circuit. The installation is outside the Ravenswood power plant in Queens, New York.





"Metalclad" switches use a heavy, inert fluid, sulfur hexafluoride, to smother the arc. Metalclad switchgear is more popular in Europe than in the United States, but these units are in a substation at New Madrid, Missouri.

nothing but a big oil tank, it's possible to confuse them—but look closely and you can tell the difference. Switches are distinguished from transformers by the absence of cooling fins and by the presence of just two high-voltage bushings, which are of equal size. Three identical switches will be lined up in a row, one for each of the three phases. (Three-phase oil switches—with three sets of contacts in one vat of oil—do exist but they're pretty rare. They have six equal-size bushings.)

The oil-filled switch is the kind you are most likely to spot in American substations, but there are other types. They use other mechanisms to quench the arc, and they are quite different in appearance.

Air-blast breakers blow out the electric arc the way you blow out a candle—except it takes supersonic breath to do it. The switch is a Y- or T-shaped structure, most of it made up of fluted porcelain insulators. The actual switch contacts are inside a small housing at the intersection where the three arms of the Y or T meet. When the contacts open, air under high pressure blows the heated gases away with such force and speed that the arc can't reignite. Air-blast switches eliminate all the problems of oil-filled equipment—not only the explosion hazard but also the danger of leaks and spills and the cost of oil changes. The most serious drawback of air-blast switches is noise. No large switches could be described as quiet, but air-blast switches produce a noise like the report of a cannon. They are not a popular choice for suburban substations with litigious neighbors. You're more likely to find them in the switchyard outside a generating plant.

In another kind of high-voltage switch, the arc is quenched by sulfur hexafluoride, an exotic heavy gas that does the job more effectively than either oil or air, with the result that the switch can be made smaller. Sulfur hexafluoride switches are usually Y-shaped, but they differ from air-blast switches in that most of the housing is made not of insulating porcelain but of conducting metal. (Indeed, sulfur hexafluoride equipment is sometimes called metalclad switchgear.) Sulfur hexafluoride has the big advantage of being nonflammable; on the other hand, it breaks down into sulfur and fluorine, which are nasty and corrosive. In recent years, sulfur hexafluoride has also become fabulously expensive. You're most likely to see metalclad equipment in downtown substations where space is at a premium. It is more common in Europe than in North America.

The circuit breakers in your home can be used in two ways. On an overload or a short circuit, the breaker "trips" automatically, but you can also throw the lever manually if you need to shut down a circuit to make a repair. Substation breakers have the same dual role. Instruments throughout the system continually monitor voltages, currents, and frequencies; when anything goes wrong, the sensors transmit signals that trigger the appropriate breakers. A breaker can also be tripped manually—although "manually" almost never means sending someone out into the yard to pull a lever. The switches are operated from inside a control room, which might be on the grounds of the substation or miles away at a power-company central facility.

The network of instruments and controls for what the power companies call system protection is more complicated than the power network itself. The sensors have to detect faults—such as a lightning strike, or an insulator that has flashed over—in thousandths of a second, so that transformers, generators, and other expensive equipment—not to mention customers—can be disconnected before any damage is done. What makes the problem of protection difficult is that you want to shut off only the faulty segment of the system, not pull the plug on an entire city. Rigging up a set of controls that will trip just the right breakers is a highly respected art in power engineering. For decades it had to be done with nothing but electromechanical relays—switches operated by magnetic coils. Now computers allow faster responses and more

The special insulators called bushings are an essential (and often troublesome) component of many substation devices. Like the rubber grommet that guides a power cord through the casing of a toaster or a vacuum cleaner, a bushing carries electricity along an insulated passage through the metal housing of a switch or transformer. These are spares, photographed in the switchyard at the Fontana Dam hydroelectric plant in western North Carolina. The glass globes at the top allow inspection of the insulating oil that fills the interior.

elaborate fault analysis; on the other hand, the power grid itself has gotten more complex and harder to control. A number of major power outages have been traced to malfunctions of the equipment that was supposed to protect against power outages.

Many power-system faults are momentary: a tree limb touches a conductor and then falls to the ground. Accordingly, most breakers are set to automatically reclose after a second or two. If the fault has cleared itself, all you notice at home is a brief dimming of the lights (unless, of course, you are staring at a suddenly blank computer screen). If the fault persists, the breaker immediately reopens and waits a little longer before trying to close yet again. After two or three unsuccessful attempts, the breaker locks out and has to be reset manually. If you happen to be near a substation when all this opening and reclosing is going on, you'll know it: the noise is like a very large machine gun.

The switches in a power network have to be carefully planned and placed so that every piece of equipment can be isolated from the live circuit for maintenance and repair. That includes the switches themselves: you need to be able to switch off power to the switches so that you can work on the switches! But then don't you need switches for the switches for the switches, and so on? It's not quite that hopeless. If you trace along the overhead bus bar feeding a major breaker or transformer, you will probably notice a hinged link, called an isolator or cutout or disconnect, which serves as the simplest kind of switch. You can see at a glance how it works: when the metal gate swings open, current cannot cross the gap; when the gate is closed, the circuit conducts. But the simplicity of the isolator raises another question: if it's so easy to build a switch, why bother with all those huge oil-filled or air-blast breakers? The answer is that an isolator cannot be opened or closed when the circuit is under power; trying to do so would produce a fireworks show and a demonstration of the principle of the arc welder. Before opening an isolator, you first have to shut down the circuit by opening the breaker; once the isolator is open, the breaker can be reclosed to restore service to other areas. A substation has scores of isolators, arranged so that every item of equipment can be taken off line independently.

More Substation Sights. Transformers and circuit breakers are the big-ticket items at a substation, but there are also other kinds of equipment.

Bushings. The bushing-type insulators that poke out of the top of every transformer and breaker are worth a closer look. Superficially they are much like other insulators: a ridged column of glazed ceramic. But the bushing has a harder job to do. Other insulators merely block the flow of all current; a bushing must conduct current through its core while preventing leakage from the inside to the outside.

A high-voltage bushing is not just a hollowed-out ceramic insulator with a copper conductor through the middle. It has a complex internal structure, with alternating layers of conductor and insulator that help to distribute electrical stresses equally. Most bushings are oil-filled. Older ones have a glass globe at the top for monitoring the quantity and quality of the oil. Just like the oil in your car's engine, the oil in a bushing insulator turns from tawny to black as it ages. But the cause of these changes is slightly different: it is not dirt and mechanical wear that does the damage, but chemical breakdown caused by microscopic electrical discharges.

Bushings are a common trouble spot in substation operations. Because replacements might be needed on short notice, you are likely to see spares kept in open racks somewhere on the substation grounds. The spares may allow you to get a look at the lower half of the bushing, which is normally concealed inside the transformer or breaker housing.

Lightning arresters. You might think of a lightning arrester as a kind of antifuse. An ordinary fuse is a weak link that stops conducting when the current gets too large. A lightning arrester works the opposite way: it starts conducting when the voltage gets too high, thereby closing a circuit and shunting the excess voltage into the ground. Under normal operating conditions a lightning arrester is an insulator; when exposed to a lightning surge, it briefly becomes a good conductor.

The typical arrester is yet another tall and slender column of ribbed porcelain insulators, stacked up in alternation with smaller, disklike objects. Passing through the middle of each insulating segment is a high-resistance conductor that limits the maximum current passing through the arrester. In older arresters the disks are spark gaps, which arc over when the voltage gets too high. In newer arresters the disks are blocks of the semiconductor material zinc oxide, which switches abruptly from being a good insulator to a fair conductor at a certain threshold voltage. (The same zinc-oxide device, by the way, is the working mechanism of the "surge suppressor" that protects your home computer or television from bad juju coming down the power line.)

Look for lightning arresters where each feeder enters the substation. Additional arresters are often installed close to each piece of expensive equipment. With large transformers, the arrester may even be mounted directly on the case.

Choke coils. What is that washing machine–size, concrete-and-metal basket-like thing at one end of the high-voltage bus? It is another line of defense in the war against faults. When a short circuit develops far out on a transmission line, the fault current is limited by the resistance of the miles of conductors between the substation and the trouble spot. But when the short circuit is nearby, or even inside the substation, the current can climb to dangerous levels so fast that a breaker does not have time to open the circuit before damage is done. A choke coil—known more formally as a current-limiting reactor—chokes off the highest peak currents.

The coil is usually open to the weather, so you can see just how it is built. A few dozen turns of very heavy copper wire or bar stock are wound in a helix two or three feet in diameter. At ordinary current levels, this coil has little effect on the electrical system; from an electron's point of view, it's not much different from a straight wire. But the very sudden surge of current through a nearby short circuit generates a tremendous magnetic field in the coil, which saps energy from the current and thereby limits it. It's the suddenness that makes the difference. The faster the current tries to grow, the more the choke acts to limit it.

Lightning arresters are installed near every transformer and other items of expensive hardware in a substation. The arrester is the tall strut in the foreground, with the skirt at the top. Ordinarily, the arrester acts as a simple insulator, but when voltage on the system rises to extreme levels, the arrester becomes a conductor, shunting the excess current into the earth. The strange lampshade at the top is an arc ring, meant to limit the damage if a lightning bolt "flashes over" from the arrester to the ground.

Choke coils provide another form of protection from lightning and current surges. The choke coils are the six brown cylinders suspended from the steel framework at this Ohio substation. Under normal operating conditions the coils have little effect on the current flowing into the substation. But when lightning or a malfunction causes an abrupt surge, the coil chokes it off, like a constriction in a garden hose.

You'll note that the coil is built very sturdily, with the conductors threaded through notches or holes in a heavy concrete frame. The structure needs to be strong because the magnetic field that chokes off the fault current also exerts tons of force, tending to collapse the coil. Failures are rare but spectacular.

Some reactor coils give off a distinctive, pure-pitch tone, more musical than transformer hum.

Capacitors. One of the trickier aspects of an AC power system is that the voltage and the current can get out of step with each other. Since voltage is the force that pushes current, you might think the two things would always stay synchronized, but that's true only in the simplest circuits. Voltage and current would remain well matched if no one ever plugged in anything but toasters and incandescent light bulbs. These devices offer an almost purely resistive load—all the electrical energy goes into overcoming the friction-like forces that oppose the motion of electrons. But the power supply must also run motors, transformers, and fluorescent lamps, and these devices have not only resistance but also properties called inductance and capacitance. An inductor stores and eventually dissipates energy in a magnetic field; a capacitor does the same in an electric field. When an AC signal hits a large inductance, the current comes out lagging behind the voltage; high capacitance has the opposite effect, making the current peaks lead the voltage peaks.

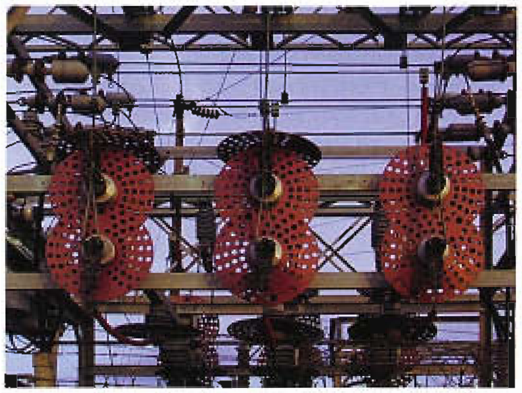
In practice, inductive loads are more common than capacitive ones, mostly because so much electricity goes to run motors. Every refrigerator, air conditioner, washing machine, and garage-door opener adds a bit of inductance to the power company's load, and the much bigger motors that drive industrial pumps and machinery add a great deal more. As a result, current tends to lag behind voltage at most places in the national power grid. This is not a good situation. The amount of work you can get out of electricity is measured as voltage multiplied by current, but in AC systems that simple formula holds true only if the voltage and the current are present simultaneously. When they are out of sync, the work is reduced by a percentage called the power factor.

One way to fix a lagging power factor is to attach capacitors to the system, to balance out the inductive load. Conceptually, a capacitor is two metal plates separated by an insulating layer; the bigger the plates and the thinner the insulator, the greater the capacitance. For the capacitors used in the power system, the plates are metal foils and the insulator is a plastic film. These are rolled up together jelly-roll style and stuffed into a rectangular box the size of a briefcase. Substation capacitor banks are usually easy to recognize because there are dozens or hundreds of these boxes lined up side by side on steel racks, like some big luggage checkroom.

When you look closely at how the capacitors are wired, you'll see "jumpers" going from one capacitor to the next all down the row. Only one box at the end of the row is connected to one of the overhead bus bars; the capacitor at the opposite end of the row is connected to a grounding strap. In other words, the capacitors are wired in series. This arrangement is necessary because a single capacitor could not withstand the full voltage of the power line; it has to be divided up among the 10 or 20 capacitors in series.

Instrument transformers. Voltages and currents have to be measured in a substation, but it would be inconvenient (not to mention dangerous) to bring wires carrying

Banks of capacitors at a substation help to keep voltage and current in synchrony. Evidently no one has figured out how to make capacitors on the same gargantuan scale as substation transformers and switches, so hundreds of smaller ones are stacked like books on a shelf.



Mystery item: What are the bright red perforated pie plates? I noticed them and puzzled over them at a number of substations, until a worker at this Louisiana installation explained: squirrel shields.

500,000 volts or 10,000 amperes into the control room. The solution is to use much smaller signals that are proportional to the actual voltages and currents. For example, a power-line current that can range from 0 to 1,000 amperes might be represented by a current between 0 and 1 ampere; an instrument that monitors the small current can be calibrated to read out in units of the larger current. Voltages are handled in the same way: the North American custom is to reduce all voltages to a range of 0 to 110 volts.

The reduced-magnitude signals needed by measuring instruments come from current transformers and voltage transformers. These devices work on the same physical principles as the hefty power transformers at the heart of a substation, but there's no chance of confusing them.

A current transformer is often built directly into the bushing insulator that enters a circuit breaker or a power transformer. The primary "winding" of the current transformer is not a winding at all but simply the high-voltage conductor that bores straight through the core of the bushing; it counts as a winding of one turn. The secondary winding consists of many turns of fine copper wire spun around the core of the bushing. Reducing the current by a factor of 1,000 calls for a secondary winding with 1,000 turns. From the outside you can't see much of a bushing transformer. The telltale sign is small-gauge wiring coming out of a bushing near its base. The wire will be housed in a small metal conduit, which typically either disappears underground or leads to a steel cabinet.

Some recent current transformers are easier to spot. They are doughnut-like collars that surround a bus bar in free air. The collar is in fact a coil of fine wire, which monitors the current passing through its interior.

A voltage or potential transformer is designed the opposite way. Its primary winding, which gets connected to the transmission-line voltage, has thousands of turns of fine wire, and the secondary has just a few turns. The two windings are usually housed inside what looks like an unusually fat porcelain insulator, mounted on a pedestal and connected at the top to a bus bar.

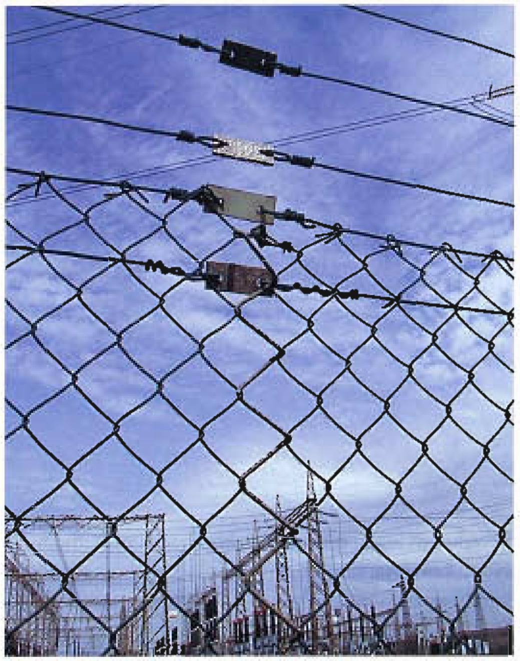
Batteries. An electric-company substation is the last place in the world you might expect to find equipment running on battery power. But it makes sense. Think of all of those relays and computers that protect the system against malfunctions: the moment when they are most needed is the very moment when the regular power supply is most flaky. As a consequence, much of the substation is powered by a roomful of lead-acid batteries. These are the same kind of batteries that start your car, although they don't look it. Each cell of the battery is a heavy glass vessel the size of a large dictionary, and 50 or 60 of these cells are lined up on wood racks like books on a bookshelf. A "trickle charger" keeps them topped up.

Grounding. Near the foundation line of any substation equipment, you'll likely find a heavy strap of braided copper or a thick copper wire entering the earth. With so much high voltage around, good grounding is a major preoccupation of substation designers and operators. If the outer casing of a transformer were not grounded, then a fault in one of the windings could charge the casing with thousands of volts; this would be a very unpleasant discovery for the next person to touch the case. Grounding provides two kinds of protection. First, as long as the ground strap is intact, the casing simply cannot have a voltage very different from that of the ground. Second, if a high-voltage conductor should come in contact with the casing, the fault current flowing into the ground would trip a breaker. (These are the same arguments that favor grounding kitchen appliances and home power tools—this is why you're not supposed to defeat that annoying three-pronged plug.)

Even the chain-link fence that surrounds the substation may have special grounding provisions in case a conductor should fall on it. The fence may also have insulating links at certain points around the periphery of the station, which have the effect of dividing the fence into electrically isolated segments. In this case the aim isn't protection against the high voltage of a fallen conductor. Instead, the segmenting insulators limit the voltage induced into the fence by the electric and magnetic fields surrounding the conductors.

The grounding straps attached to equipment and fences connect to an array of long rods driven into the ground on a grid pattern, or to a network of rods or pipes that were buried before the station was built over them. In dry and rocky soil, where getting a good ground can be difficult, the ground electrodes may be bonded to the steel casing of wells drilled down into a deep aquifer. The reason for all this trouble becomes apparent when a substation absorbs a really heavy fault, such as a direct lightning strike. Currents through the ground near the point of entry can be intense enough to light grass fires.

Hot sticks. Somewhere on the grounds of a substation there should be some long fiberglass poles with metal fittings at one end. They are not for pole-vaulting over the bus bars! These hot sticks are used for opening or closing isolators, and in emergencies for clearing fallen debris from equipment. A common place to stash them is in a length of plastic pipe attached to a building wall or the perimeter fence.



Even the chain-link fence that surrounds a substation has its points of interest. The fence above has a twine thread running through it to block currents induced by power lines crossing overhead. The fencepost below has multiple grounding straps to drain away any stray voltages.

DISTRIBUTION: POWER TO THE PEOPLE

The final segment of the electric-power system carries current from the substation to your home. The distribution network has two main parts. Primary distribution lines cover distances of several miles, and in rural areas may stretch to 50 miles or more. They commonly operate at voltages of 2,400 to about 25,000 volts, or occasionally as high as 46,000 volts. Secondary distribution circuits bridge the last few hundred yards from the utility pole or the underground cable to the electric meter on the wall of your house. The secondary voltages are the familiar ones you find at household outlets: 120 volts and 240 volts in North America.

Sometimes there is no need for a distribution network. A large customer, such as an aluminum smelter or a municipal pumping plant will buy the entire output of a substation. But most substations serve a town or a neighborhood of several hundred or a few thousand homes and businesses. Distribution lines radiate from the substation to all parts of this territory.

Poles. Most distribution lines are carried on wood poles, which have thus become one of the most common sights of the modern roadside and streetscape. We live in a forest of these leafless trees. In North America there are 100 million of them—almost as many as there are houses or cars. Yet we seldom notice them.

When I was growing up, we called them telephone poles. The term has historical merit—telephone service came before electricity in most areas, and so the first pole lines were put up to carry telephone wires. Today, though, the majority of poles are owned by power companies, which lease space to telephone companies and other utilities such as cable-TV operators.

The poles are most commonly cedar, yellow pine, or Douglas fir—trees that grow tall and straight. They are treated with creosote or other preservatives to stave off decay and insects. (Nevertheless, rot is the eventual fate of most poles; they tend to

Power lines fanning out to neighborhoods of Durham, North Carolina, are draped over the crossbars of more than a dozen utility poles.

go soft at the ground line.) On high-voltage transmission lines, you might see wood poles as much as 90 feet long, but the poles set along the curb of a suburban street are more likely to be 30 or 40 feet, with 5 or 6 feet of this length below the ground. That doesn't seem like much of an anchorage, but I have never seen a pole uprooted; when they come down in a storm, they are more likely to break than to overturn. Poles carrying an unusually heavy load are braced with guy wires anchored in the soil or to another pole.

Many utilities tag their poles with inventory numbers. The identifying tag is an aluminum or plastic plate at about eye level—if you can find it among all the lost-dog notices and yard-sale posters. When you report a power outage, you might gain a bit of credibility with the dispatcher if you can give the pole number of the trouble spot. Another tag on many poles gives the date of installation or last inspection.

Primary Distribution Circuits. Primary distribution lines are invariably the topmost wires on a utility pole, following the general rule that higher voltages call for higher elevations. In the arrangement seen most often, the three primary conductors are arrayed horizontally on a crossbar near the top of the pole, but there are many variations. Instead of a single horizontal crossbar, there might be an X- or K-shaped arrangement of beams, or the conductors may be hung in a vertical row from insulating struts bolted directly to the pole. Sometimes metal brackets hold the three conductors in an equilateral triangle—one conductor above the top of the pole and the others on either side. If a line of poles carries two or three primary circuits, there will be six or nine conductors near the top of the pole, usually on multiple crossbars.

In recent construction, the conductors themselves are bare stranded aluminum, perhaps half an inch in diameter. But there are still many distribution circuits in service with solid copper conductors.

The conductors are usually supported by porcelain insulators that perch on top of the crossbar (unlike the underslung suspension insulators of high-voltage transmission lines). Pin-type insulators are threaded onto a wood or metal pin set into the top of the crossbar. They have a distinctive shape: a broad skirt flares outward from the waist; underneath it are circular ridges that naturally enough are called petticoats. Post-type insulators bolt directly to the crossbar; the insulator is a tall cylinder with corrugations around its circumference. As with transmission-line insulators, the purpose of all these skirts and petticoats and ridges is to increase the creep length of the insulator—the distance that a leakage current would have to travel over the surface.

Both pin-type and post-type insulators have a groove along the upper surface to receive the conductor. With binoculars you may be able to see how the conductor is fastened into this groove. Various kinds of clips and clamps are made for the purpose, but there are also still plenty of distribution lines where the conductors are lashed on with twisted lengths of wire. Creating neat and secure lashings has traditionally been an important element of the lineman's craft and training. It's particularly impressive to see it done with eight-foot hotsticks when the worker is repairing a live line.

Not all poles are wood: This one, in western Virginia, is made of cast concrete. The thin copper wire running down the surface is a grounding strap.

There is no easy way to judge the voltage of a primary distribution line, although larger and more elaborate insulators usually signify higher voltages. Distribution voltages have been climbing steadily over the years as the system has been stretched to supply greater loads over longer distances. The most widespread voltage was once 2,400 volts; then many systems migrated to 4,160 volts, 7,620 volts, and 13,200 volts. Utilities give careful thought before going beyond this level because it is near the limit for doing live-line maintenance with rubber gloves; procedures for maintaining higher-voltage lines are more awkward and expensive. Nevertheless, more and more distribution systems operate at 23,000 or 34,500 or even 46,000 volts.

THE INDUSTRIAL ECOLOGY OF A UTILITY POLE

In the tropical rain forest, ecologists study the communities of plants and animals that live in vertical zones, from the leafy canopy of the tallest trees down through the understory to the rotting litter on the forest floor. Utility poles also have a series of vertically stratified habitats, each with its own characteristic inhabitants. From top to bottom, here are some of the species you might observe in the utility-pole ecosystem:

• Primary distribution lines for electric power. These are the topmost wires. They are usually hung on a crossarm, and they come in groups of three, mounted on big insulators.

• Switches, fuses, and surge arresters. These connect to the primary distribution lines.

• Transformers. They are mounted below the primary distribution lines but above the secondary ones, with connections to both.

• Secondary distribution lines. Just below the transformer level, they are rubber-sheathed conductors carried on spool-type insulators or twisted around a steel messenger cable.

• Street-lighting fixtures. They draw their power from the secondary circuits.

• Traffic signals. These too are powered by the secondaries. The signal lights are often hung from a steel cable stretched between utility poles.

Everything from the top of the pole down to this level is the domain of the power company. Below is the realm of communications lines, which operate on lower voltages and therefore don't need to be kept quite as far out of reach.

• The municipal zone. Cities and counties that allow poles to be set on public land sometimes demand a bit of utility-pole real estate in compensation. This zone was once used for the wiring of fire alarms and police call boxes; today those signals are more likely to go over leased telephone lines.

• Cable television feeders. These may be finger-thick coaxial cables, in either a black plastic sheath or a bare metal jacket. In newer systems the trunk lines that carry signals over longer distances are fiber-optic cables.

• Telephone cables. Often the thickest of all the wires strung on a pole, they are actually bundles of dozens or hundreds of pairs of fine copper wires. Fiber-optic cables also show up at this level.

Still lower—indeed, reaching the ground—are some wires that ought to have no voltage at all on them.

• Guy wires. Their function is strictly mechanical; they help to hold the pole up. There may be an insulator inserted into the guy wire for safety, in case a power conductor should touch the upper part.

• Grounding lead. A pole with a transformer generally has a copper grounding wire that runs down the side of the pole and into the ground.

Finally, at eye level, comes the bottommost ecological stratum of the urban or suburban utility pole:

• The yard-sale zone, where the wood bristles with a thousand rusty staples.

On a crossbar carrying a primary distribution line, you might notice small placards labeling the three conductors *A*, *B*, and *C*. Or there may be three colored tags, usually red, yellow, and blue. These markers are meant to identify the three phases of the electric current. Why would anyone care which is which? In a household with single-phase service, it makes little difference which of the three phases you tap into. But a factory that draws on three-phase power cannot be so indifferent. If a lineman were to accidentally transpose two of the phase conductors, every three-phase motor on that circuit would suddenly begin running backward.

So far, a primary distribution circuit looks just like a miniature transmission line, but there is a fundamental difference, apart from the lower voltage levels. In the United States most distribution lines are actually four-wire systems, in contrast to the three-wire standard that prevails throughout the transmission network. The fourth wire is lower down on the pole, less conspicuous, set off on smaller insulators, and usually shared with the secondary distribution system. The presence of this fourth conductor calls for a bit of explanation.

It is in the nature of an electrical circuit that all the power that flows out has to flow back in; indeed, that's why it's called a circuit. In a three-wire, three-phase system, there is no problem balancing inflow and outflow as long as the loads on the three conductors are equal. But in distribution circuits, individual customers draw power from different phases. If you happen to be burning the midnight juice while your neighbor is sleeping, the loads will be imbalanced. The fourth conductor, called the neutral, carries any leftover currents created by the imbalance. Because the power company tries to equalize loads on the three phases as best it can, the currents in the neutral conductor are generally small.

There are distinctive national and regional customs in the engineering of power-distribution systems. In North America, each branch circuit that supplies electricity to houses and small businesses is wired between one of the phase conductors and the neutral conductor. In Europe single-phase service is usually wired between two of the phase conductors. You can tell the difference by looking at the connections to the pole transformers (see section below). Also, three-phase service is much more common in Europe. In the United States only industrial or large commercial buildings are likely to have a three-phase connection, but in several European countries many homes have three-phase service for running the motors in refrigerators, air conditioners, and other large appliances. The three-phase motors are more efficient, although also more expensive.

Along rural or suburban roads in some areas you may see a primary distribution line that violates the sacred rule-of-three: instead of three primary conductors at the top of the pole, there is just one, along with a neutral somewhat lower down. Even in these areas the basic power system is still three-phase. It's just that the power company has saved some wiring cost by running only one of the phases along a given road, and feeding all the houses there from it. Other streets draw their power from the other phases, so that the overall load remains balanced.

Post-type insulators *(top)* are heavy porcelain castings bolted to the crossbar. Glass pin-type insulators *(bottom)* are now collector's items, but a few are still in service. Here the conductors are also vintage equipment: The green patina shows they are copper, whereas all new power lines are strung with aluminum.

Pole-Mounted Transformers. The big steel can bolted high overhead on a utility pole—I've heard workers call the thing a "pole pig"—is the last stage in the long series of up-and-down transformations that finally delivers electricity at household voltages. This is where the voltage drops from the primary distribution level (typically a few thousand volts) to the tamer and more familiar 120 or 240 volts. (Some big customers take their jolts at 480 volts.)

Like the larger transformers at substations, the pole-mounted transformer has windings of copper wire wrapped around a steel core. The windings are immersed in oil for insulation and cooling. Larger units are festooned with tubes or fins to radiate away excess heat. Filled with oil, a transformer can weigh 500 pounds or more.

LIVE-WIRE GUYS

Electricity has become such a 24-hour-a-day necessity that the power company has a hard time shutting down transmission lines for repairs. As a result, a great deal of maintenance is done on live wires.

For distribution circuits up to about 12,000 volts, the work can be done with rubber gloves. These are nothing like the supple latex gloves of the surgeon, or even the gloves you might use to wash dishes. They are as heavy and thick as galoshes, and they come with sleeves that go all the way up your arms and link together behind your back. You test them by blowing them up like a balloon; no leaks are allowed, since electrons will wiggle through even the tiniest hole.

You say you wouldn't touch a live wire with a 10-foot pole? That's exactly how it's done at higher voltages. The poles are called hot sticks, and they are made of fiberglass or plastic, materials that provide excellent insulation as long as they stay clean and dry. Hot sticks have various kinds of tools and hooks on the business end so a work crew can do jobs such as replacing insulators while staying a safe distance from the energized conductors. But doing any kind of close manipulation with a long pole is pretty awkward; it takes practice, skill, and strength. And the higher the voltage, the longer the pole needs to be.

The most impressive kind of live-wire work is also the simplest. It is called bare-hand maintenance. It's possible because electricity flows only when there is a difference in voltage. If you touch a transmission-line conductor and a grounded steel tower at the same time, you're toast. But you can safely hold onto either one if you keep your distance from the other. The bare-hand worker leaves the grounded world behind and lives at high voltage.

The challenge is getting there. Sometimes a bucket truck with an insulated boom will reach high enough. Or workers can climb a transmission-line tower and then make their way to the live conductors using insulated fiberglass ladders. Still another choice is to lower a worker from a helicopter.

Strictly speaking, bare-hand work isn't done with bare hands. You wear a conductive suit, with booties, gloves, and a hood covering everything but your face. The suit is made of a fabric woven with silver or carbon threads, and it has a "tail" that you clamp onto the live wire, to ensure that your body is always at the same voltage as the circuit. Those who have done such work tell me there is a strong tingling sensation at the moment you bond onto the conductor, but it fades in a second or two.

Who could fail to admire the mettle of these workers? Even when you understand the physics of the situation—even when you believe beyond question—it is surely a test of faith to grab onto a sizzling 500,000-volt power line.

Hoisting it up the pole with block and tackle was once heavy labor for the lineman; now the lifting is done by the hydraulic boom of the bucket truck.

When you are standing on the sidewalk looking up at a pole transformer, the first things to check out are the "high-side" connections—the wires running from the top of the transformer to the primary distribution conductors overhead. If you're in a residential neighborhood in North America, you'll probably see just one high-side wire, connected to one of the three primary phase conductors. This is the signature of a single-phase transformer connected between a "hot" primary conductor and the neutral, or ground, conductor. Another kind of single-phase transformer has two high-side leads, connected to two of the overhead conductors. These are rare in North America but common in Europe. Finally there are three-phase transformers, which have wires going to all three of the primary conductors. Three-phase transformers tend to be larger, and they mostly serve commercial or industrial customers—a supermarket with a lot of refrigerators to run, or an office building with a heavy-duty air conditioner. Sometimes a three-phase load is served by three single-phase transformers, all hung on the same pole. If you look closely, you'll see that each transformer is wired to a different primary conductor.

Pole-mounted transformers—also known as "pole pigs"—are such commonplace elements of urban street furniture that we tend not to notice them at all. In residential neighborhoods, there is a transformer for every few houses. The six above supply power to a small shopping district. They are single-phase transformers ganged up in threes to handle three-phase power.

Each of the high-voltage connections enters the transformer through a porcelain insulating bushing on the lid of the can. But often there is other miscellaneous hardware up there as well, such as fuses and lightning arresters (see below), so that it can be a little confusing to count the bushings.

The "low-side" wiring generally connects to lugs on the side of the casing, without any need for big porcelain insulators. In the standard American configuration for single-phase power there are two hot wires and a neutral. Usually the hot leads are heavily sheathed in black rubber insulation, whereas the neutral is bare metal. These wires are the ones that loop from the utility pole to your home.

American practice in most residential neighborhoods is to use lots of fairly small pole transformers, each feeding just three or four houses. Thus, when you drive down a suburban street, you may see a transformer hung on nearly every pole. European utilities use fewer but bigger transformers, each of which might supply 50 or 100 homes.

How can you tell the power rating of a transformer? More often than not, the rating is stenciled on the side of the case: it's a number such as 25 or 37.5 or 75. This is the transformer's power-handling limit in kilovolt-amperes, which is the number you get by multiplying the maximum current in amperes by the operating voltage in thousands of volts. Kilovolt-amperes are roughly equivalent to kilowatts, and so a 25-kilovolt-ampere transformer could run 25 toasters that consume a thousand watts apiece. The transformers you see on poles can be as small as 10 or 15 kilovolt-amperes and occasionally as large as 300.

Fuses, Arresters, Switchgear. Like their big siblings back at the substation, pole-mounted transformers need to be protected from overloads, short circuits, voltage surges, and lightning. Moreover, the rest of the power system (including the part that

Distribution transformers are now highly standardized items, but there is still room for occasional variation. The ice-cream cone atop the street lamp above, in Livermore, California, is a disguised pole transformer. European distribution grids often have fewer but larger transformers. The Slovenian one below is a mini-substation, built into a concrete tower.

runs through the walls of your home) has to be protected from malfunctions inside the transformer. Both kinds of protection are provided by fuses and surge arresters.

The kind of fuse you'll most likely see near the top of a power pole is a cardboard tube the size of a large cigar. The tube has a thin metal rod running through it, and the circuit is arranged so that current has to pass through the rod on its way from the primary conductors into the transformer. In the event of an overload or a short circuit, the rod melts, interrupting the current. But that's not the end of the story. The melted fuse element is replaced by an electric arc, which won't necessarily die out anytime soon; it has to be extinguished somehow. That's where the cardboard tube comes in. It's a low-tech solution to the arc problem, but a surprisingly effective one. What happens is that the heat of the arc vaporizes some of the organic material on the inner surface of the tube. The hot gases produced in this way are expelled from the ends of the tube with enough force to blow the arc out. The force is also enough to create quite a loud bang. People often report that a transformer has blown up when the noise they heard was actually an expulsion-tube fuse blowing.

Expulsion-tube fuses occasionally fail, allowing current to continue flowing even after the fuse has blown. To deal with this problem some utilities install backup fuses in series with the regular fuses. The current has to get through both fuses in order to reach the transformer. One style of backup fuse looks something like a large tube of caulk, or perhaps an automobile shock absorber. Inside, a silver filament is encased in pure quartz sand; when the silver melts, the surrounding sand is baked into a form of glass that quenches the arc. Silver-sand fuses are bigger, heavier, and more expensive than expulsion-tube fuses, which is why they are used mainly for backup. They are designed not to blow during an ordinary brief fault; their protection kicks in only when the primary fuse fails.

Switches placed at intervals along a primary distribution line are mainly an aid to maintenance and repair. If a tree gets fouled in the wires near the end of a long line, shutting it down from the substation will leave everyone along the way in the dark. If a repair crew can open up an intermediate switch, power can be restored to at least some customers.

The simplest switches are knife-blade switches, similar to the isolators seen in substations. Unlike so much other electrical equipment, you can see at a glance exactly how they work: when the switch is closed, current flows through the blade to complete the circuit; when the switch is open, the break in the conducting path is obvious. This property is important to the lineman who wants to make sure that the equipment he's about to fix is shut down.

Knife-blade switches generally can't be used to open an energized circuit. The idea is to shut the circuit down with the breaker at the substation, then open the appropriate switches to isolate a section of the line, then close the breaker again so that power is restored to the rest of the system. Opening most knife-blade switches requires climbing the pole or going up in a bucket truck. A few of the switches have a lever or crank at ground level.

The more elaborate and more automated switches in the distribution system are called reclosers. They are similar to the high-voltage circuit breakers at substations, but small enough to hang on a pole. Like a substation breaker, a recloser can be operated by remote control or triggered automatically when it senses an overload or short circuit. And like a breaker it has an arc-quenching medium—oil or vacuum or sulfur hexafluoride—so it can interrupt both normal load currents and fault currents.

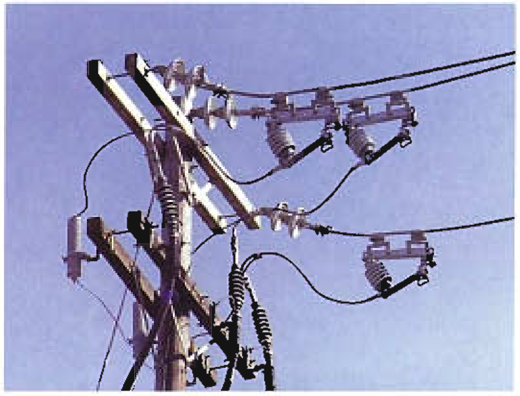
In external appearance a recloser is a nondescript box or cylindrical can, painted the usual gray. You might mistake it for a transformer. Even utility workers get confused, which is presumably why at least one power company stencils the word *RECLOSER* on the case of every one. If your local utility is not so helpful, the best way to identify a recloser is to look carefully at the connections and think like an electron. A recloser will be wired so that current can get past it only by going through it. (A transformer, in contrast, offers an optional path to the current, like an exit ramp from a highway, which you can either take or pass by.) A single-phase recloser has two equal-size bushings on top; a three-phase recloser has six equal-size bushings.

It's called a recloser because it not only interrupts a circuit when something goes wrong but also automatically tries to restore service. Because many faults are only momentary, this strategy can save a lot of service calls. Typically the recloser is set to try three times. When it first detects a fault, it opens the circuit and then immediately tries to close it again. If the fault is gone, then fine. If the fault is still there, the recloser opens again, and this time it waits a few seconds before closing the switch again. If the fault persists, the recloser waits a little longer before trying a third time. At this point if the fault has not cleared itself, the recloser "locks out," and a lineman has to come out and reset it manually. When the lights rapidly flicker on and off during a thunderstorm, that's a recloser in action.

The last items of miscellaneous hardware to look for near the top of a utility pole are capacitors. Like those in substations, their role is to correct power factor—to bring the alternating waves of voltage and current into sync when big motors or other such loads get them out of balance. The individual capacitors are oblong boxes, the shape of a telephone book and just a little larger. They are usually mounted in racks that hold three, six, or a dozen lined up side by side. Short circuits inside capacitors are not rare, and so there is likely to be a fuse in the lead that connects the capacitor to the primary distribution conductor. Or there may be a tiny recloser, which not only protects against faults but also allows the capacitor bank to be switched in and out of service as the power factor on the line changes.

Secondary Distribution Circuits. Secondary circuits carry power across the last few feet to your home. It's easy to tell them from the primary circuits. They are strung lower down on the utility pole, below where transformers are mounted (although above telephone and other communications wiring). The secondary circuits may also be sheathed in insulating rubber, unlike the bare conductors seen almost everywhere else in the electric-power system.

Fuses protect power-line equipment just as they do home appliances. On the pole above, three expulsion-tube fuses are bolted directly to the crossbar; they are wired in series with three silver-sand fuses farther to the left, which serve as a backup. On the pole below, a helpful placard reveals that each phase has two 80-ampere fuses wired in parallel, for a capacity of 160 amps.



Cut-out switches *(above)* have such a simple and open mechanism, it's easy to see how they work: put a hook in the loop at one end of the blade, and pull to break the circuit. A recloser *(below)* is a pole-top version of the switches and circuit breakers found in substations. Reclosers can be hard to recognize. The three cylindrical objects below might be mistaken for transformers—but note the two equal-size bushings on the top of each can. (The smaller devices behind the bushings are lightning arresters.)

In the United States, homes are wired for dual voltages: 240 and 120 volts. The two voltage levels are supplied by three wires—two hots and a neutral. The water heater and electric stove and perhaps a few other big appliances are connected to both hot leads, which supply 240 volts. All the other household circuits are fed by one or the other of the hot conductors and the neutral, a combination that yields just half the voltage, or 120 volts.

The secondary conductors are strung from pole to pole (or sometimes along the back walls of buildings) on spool-type insulators. The spool is just like the one that holds sewing thread but larger (the size of a coffee mug), and is made of porcelain. It is mounted on a steel skewer that passes through the hole down the middle of the spool. In one common arrangement, three spools are mounted one above the other to carry the two hot conductors and the neutral. In another style of wiring, the two rubber-coated hot lines are twisted around the bare neutral, and they are all lashed to a single spool. (The bundled conductors are called triplex.)

Why are the secondary conductors, which carry only a couple hundred volts, thicker and heavier than the primary conductors at several thousand volts? Because the size of a wire depends on the amount of current it carries, not the voltage. And for a given amount of power, the lower the voltage, the higher the current.

Secondary wiring practices vary widely. In a downtown commercial district, there may be a secondary bus or grid: Lots of transformers all pump power into the same set of secondary conductors, which in turn serve many buildings. This way no building goes dark if a single transformer fails. On the other hand, a severe fault might knock out the entire secondary grid.

In the suburbs, each transformer generally feeds its own set of secondary conductors. Often, the wires run straight from the transformer to each of the houses being served. If there's a problem with a transformer, only those few homes will lose power.

Electric Meters. A glass bubble filled with brightly polished, spinning gears is fastened like a suction cup to the side of nearly every house in America. Would a visitor from Mars ever guess what that glass pod is there for? Maybe, indeed, the transparent globe is some kind of Martian surveillance device?

The purpose of the pod is indeed surveillance—though the information gathered goes not to Mars but to the local utility company. Technically speaking, the mechanism inside the glass is a watt-hour meter; power-company insiders know it as a revenue meter; to the rest of us, it's just the electric meter. It is the device that reports your energy consumption to the electric company so they can send you a bill at the end of the month.

The meter mechanism is a special kind of electric motor, calibrated so its speed is directly proportional to the amount of power flowing through the meter. The spinning disk whose edge is visible through the glass is the core part of this motor. The clock dials that record energy consumption just count the revolutions of the disk. The reading on the dials continually increases, rather than being reset each month.

Your bill is calculated by subtracting this month's reading from last month's. That way, even if the meter reader makes a mistake and you are overcharged one month, you automatically get it back the next.

The latest electronic watt-hour meters have no moving parts and display their reading in odometer-style numbers instead of on a series of clocklike dials. And some

LIGHT UP THE NIGHT

These days, street lighting is nobody's idea of a high-tech, high-growth industry, but a century ago it was a driver of technological development. The impetus for building the first municipal electric systems was not the urge to make better toast and coffee; the systems were built exclusively for street lighting. Only years later did electricity find its way indoors.

Street lighting was a tough problem for a long time. In eighteenth-century New York, every seventh house was required to hang out a lantern on moonless nights. Later, whale-oil lamps were installed along the streets, and then came the gaslight era. (The gas industry, too, got its start as a street-lighting utility.)

The first electric street lights were carbon arc lamps, working on the same principle as the World War II searchlights that still see duty when a used-car dealer decides to advertise a sale with a roving beacon in the sky. In an arc lamp, two carbon electrodes are briefly brought together and then held at just the right distance to maintain a brilliant, blue-white arc. In Los Angeles in the 1880s arc lamps were mounted atop 150-foot-high towers, remarkably similar to the towers that now illuminate major interstate highway interchanges. Fifty thousand fascinated Angelenos clogged the streets when the lights were first turned on. (It's been a while, I think, since new street lights drew a crowd in southern California.)

Arc lamps were a high-maintenance item. Someone had to come around every night to get the arc started. The tungsten-filament incandescent bulb finally put the lamplighter out of work; an engineer at the central station could throw a switch and light up an entire town.

Incandescent street lights have been supplanted by more efficient designs. Fluorescent tubes had a vogue in the 1950s and 1960s, but now most street lights use either mercury-vapor bulbs or sodium-vapor bulbs. Both types work by passing a current through a heated gas of metal atoms (either mercury or sodium).

Compared with a tungsten-filament lamp, the metal-vapor lamps convert more energy into light and less into heat.

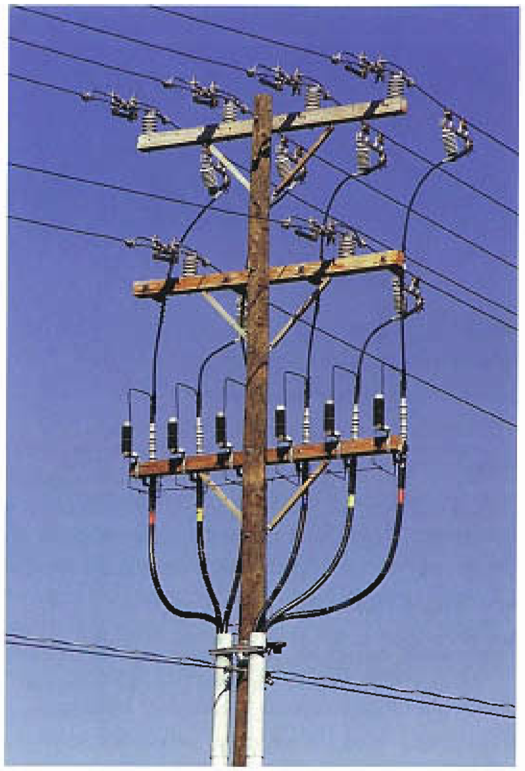
Mercury and sodium lights are easy to tell apart. The mercury ones put out an icy blue-white light that turns your lips purple. Light from sodium-vapor lamps is pink or orange. Actually, there are two kinds of sodium-vapor lamps. The low-pressure ones are more efficient (and also favored by astronomers worried about "light pollution") but the color is a deep orange. The high-pressure lamps emit a broader range of colors but use more electricity.

The colors of mercury and sodium lamps are exaggerated when you see them from a great distance, because the light is filtered by the atmosphere. If you look down on a cityscape from an aircraft at 10,000 feet or so, sodium-vapor lamps look almost buttery yellow. Mercury-vapor lamps remain white or blue.

Recent street-lighting fixtures have a color-coded label that indicates the kind of bulb to be installed—blue for mercury, yellow for sodium, and red for a less common type called the metal-halide lamp. A number on the label encodes the wattage: 10 for 100 watts, 25 for 250 watts, 40 for 400 watts, and 1K for 1,000 watts.

When a metal-vapor bulb is nearing the end of its life, it may begin to cycle off and on every minute or two. What happens is that the vapor grows too cool to maintain the light-producing electric discharge, but once the lamp goes out, a starter filament automatically comes on to heat the vapor again. The whole process then repeats, usually with a fairly stable period. If your timing is good, you may be able to persuade your more gullible companions that by mental effort alone you have the power to turn street lights off and on.

Electric street lighting has eliminated not only the lamplighter's evening rounds but even the central-station engineer throwing the switch at dusk. Almost all street lights are now controlled by a photocell that detects the fall of night. The detector is the little cap or turret mounted atop each light fixture.



Two three-phase power lines duck underground in bundles of inch-thick insulated cables. The cables can be isolated by cut-out switches where they join the primary lines overhead; they are also protected by lightning arresters—the six dark-brown cylinders mounted on the lower crossarm. Also note the red, blue, and yellow bands wrapped around the six cables; the colors identify the phases.

new meters can be read remotely, without sending out a worker to walk from house to house. Some of them communicate with their home base directly over the power lines; some have a connection to the telephone system; some transmit radio signals.

Underground Distribution. Wander around an upscale new housing development and you will see no power lines strung from pole to pole. Electrical wiring and other utilities run underground, either because the developer believed that would help to sell houses or because a zoning board required it.

You might get the impression that underground electric service is a rather new idea. That's not the case at all. In the downtown core of the largest American and European cities, power and communications lines have been buried under the street almost from the beginning of the wired age. In New York, for example, overhead lines were outlawed following the blizzard of 1888 (when a great many of the lines came down in the streets). Los Angeles enacted a similar law in 1896.

In another sense, the suburban underground systems of recent years are indeed a new technology. They differ in several ways from the older city designs.

Urban underground power systems are all about manholes and buried conduits. Transformers and oil-filled circuit breakers are installed in the manholes, or in larger underground chambers called vaults. Some of the equipment is housed in special sealed casings so it can continue operating even if the manhole floods. Insulated cables for both primary and secondary distribution are pulled through the conduits from one manhole to the next.

The newer suburban systems are built in a different style and by different methods. There are no manholes; transformers and switchgear are housed in metal cabinets (usually painted a grassy green, and perhaps hidden among the azaleas) that sit on concrete pads at ground level. There are also no conduits underground. Instead, the power cable is buried directly in a narrow slit trench.

The big issue in underground distribution is insulation. With overhead wiring, insulation is a lot easier because the conductors can be kept several feet away from anything grounded. That's obviously not possible underground, and so the conductors have to be swaddled in elaborate layers of high-performance insulation.

In older underground circuits, each phase of the three-phase service is carried by a separate cable, which is insulated by wrapping the conductor with oil-soaked paper and sealing it in a lead sheath. Splicing these cables requires the electrician to master some of the plumber's skills, since the lead jacket has to be closed with molten solder.

New installations use a more flexible cable with polyethylene insulation; no lead sheath is needed to keep water out, although sometimes the cable is armored with steel rods for protection against the rogue backhoe (principal foe of all underground utilities). Instead of three separate cables, all the conductors are bundled into a single fat cable. In the latest designs, the three phase conductors are given a pie slice–shaped cross section so that they fit together neatly, and a fourth, neutral, conductor is wrapped around the assembly as a concentric sheath.

When a distribution system is entirely underground, there is not much to see. But in many cases the primary distribution lines run underground only for part of their route. On the boundaries of a downtown district or along a main road near subdivisions with underground service, you might see a number of risers, where a line makes a transition between overhead and underground. The actual transition between insulated cable and bare conductor takes place inside a device called a pothead. (Honest. That's what they call it. I wouldn't kid you.) The pothead seals the end of the cable to keep moisture out. There may be three separate potheads (one for each phase) or a three-phase unit with three bushing-type insulators poking out of the top like the legs of an inverted stool. The potheads are mounted near the top of a pole; the cable descends into the earth along the side of the pole, often through a plastic conduit. There will usually be fuses and surge arresters on the lines feeding the potheads, and tags or tapes to label the phases (*A, B, C* or red, yellow, blue) since it's all too easy to get them mixed up in an underground cable.

Why aren't all distribution lines underground? The power companies say it's a matter of money. Burying a line can cost five times as much as stringing it up on overhead poles, largely because the insulated cable is much more expensive than bare wire for overhead use. The cost penalty has been coming down in recent years, but it may never be reduced to zero. Proponents of underground service argue that the premium is worth paying because it not only eliminates an eyesore but also improves reliability, since lines are not brought down by ice, tree limbs, or auto accidents. Power companies counter that when an underground conductor does fail, finding and fixing the fault takes much longer.

Underground utility service is not totally invisible; equipment that might otherwise hang on poles squats on concrete pads at curbside. Here an electrician has opened up the green box that houses a power transformer.