High-Power Electronics

A new generation of silicon switches enables power grids to meet the needs of utility customers with high efficiency and reliability

by Narain G. Hingorani and Karl E. Stahlkopf

Consumers of electricity are demanding customers. The silicon chips that now pervade daily life, bringing sophisticated behavior to everything from toasters to machine tools, are highly vulnerable to irregularities in their electrical diet. A loss of power for a single cycle of alternating current, one sixtieth of a second, can make computer screens go blank or interrupt other sensitive electronic equipment. At the same time that users of electric power demand quality, they also want more power. As a result, transmission networks are being pressed closer to their operating limits. Yet a range of problems hobbles expansion, and power transfers from one part of the country to another challenge the network's adequacy. All these factors increase the risk of instability and even blackout.

To avoid such problems, the engineers who manage the transmission of electric power must act with extreme caution. They operate the power grid well below its theoretical maximum capacity. The strategy reduces the possibility that a sudden, unforeseen increase in demand or loss of capacity might cause overloads that would ripple outward until they engulfed a significant portion of the nation's transmission network. On the infamous night of November 9, 1965, for example, a blackout struck most of the northeastern U.S. and parts of Canada. Utilities must also maintain large reserves of generating capacity as a safety margin against such contingencies.

The traditional equipment does not make the job any easier. When engineers switch in additional generating equipment or otherwise cope with failures or changing demand, they rely on massive electromechanical switches—essentially enormous cousins of the household circuit breaker—that take several AC cycles to turn on or off. These switches introduce their own electrical noise and potential instabilities into the system. They cannot be used to make the continuous, fine adjustments that full utilization of power transmission capacity would require.

The development of high-voltage silicon switches may provide utilities with a technology that enables them to cope effectively with economic constraints as they meet the needs of their customers. These switches are the basis of control systems that can guide the flow of megawatts as rapidly and efficiently as integrated circuits handle microwatts. They can fend off cascading power interruptions and significantly increase the usable capacity of many transmission lines. Indeed, they open up avenues for controlling the distribution of power that could not be exploited by their electromechanical predecessors. Utilities using them will be able to deliver more power of better quality while reducing transmission losses and thus the amount of energy they must generate.

The troubles that power transmission systems experience today go back to the roots of the industry and the conflict that raged a century ago between Thomas Edison and George Westinghouse: direct versus alternating current. In DC systems, electrical charge

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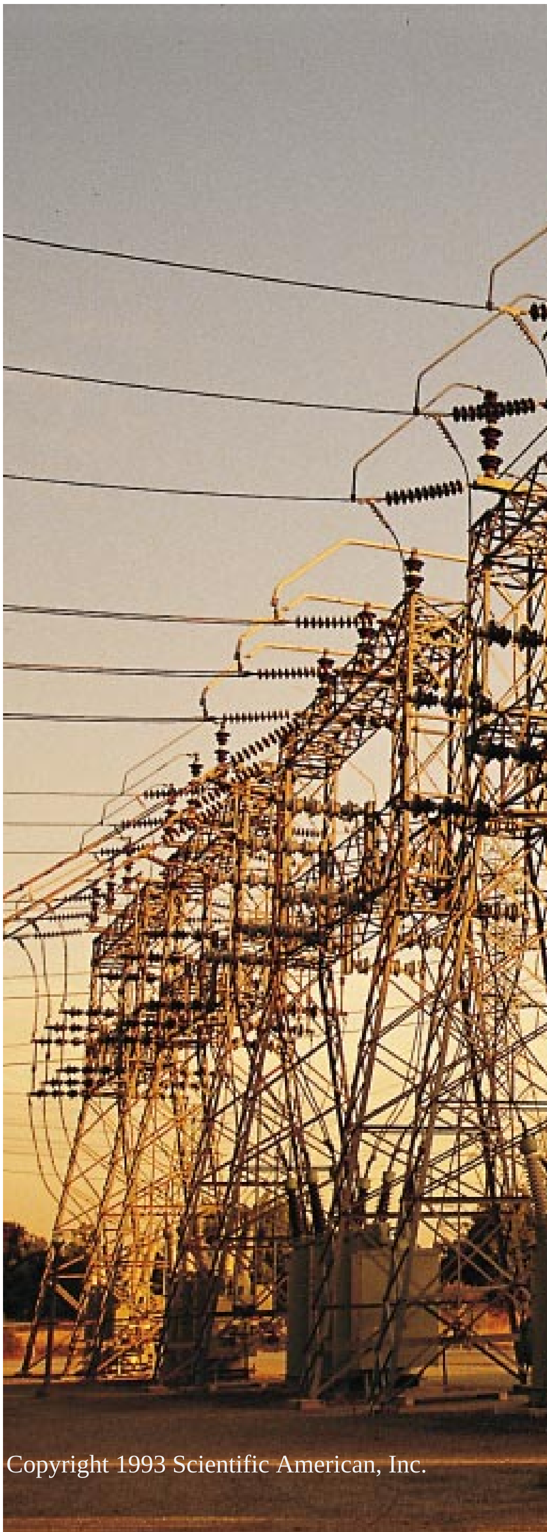
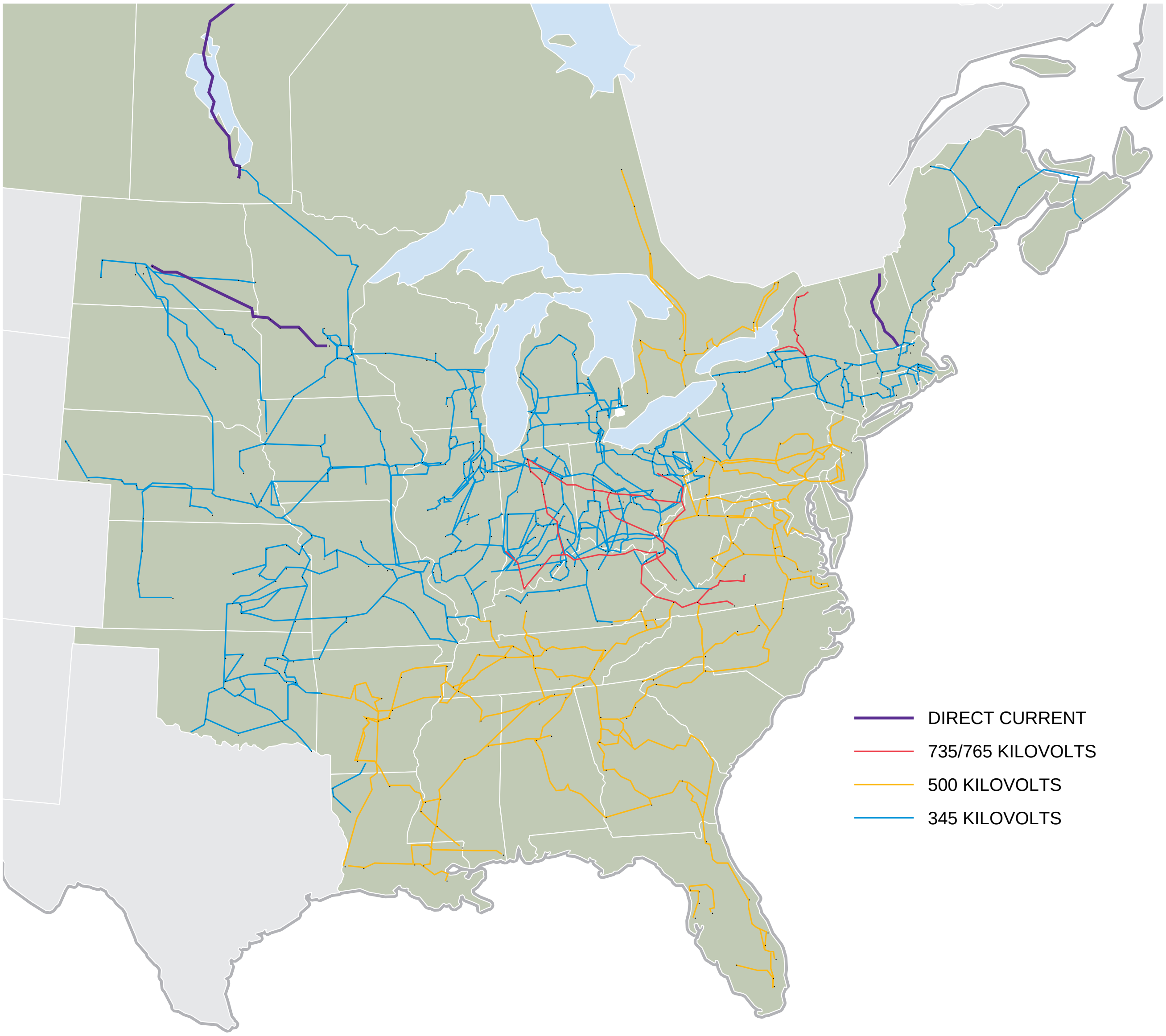


flows in only one direction: from producer to consumer. In AC systems, the flow of charge reverses itself many times each second; a terminal that had a positive potential a fraction of a second ago may now have a negative potential (and will have a positive one in another fraction of a second). A simple generator, consisting of a coil rotating in a magnetic field, will produce alternating current because the relative orientation of the coil and the magnetic field reverses with every half rotation.

Edison chose direct current for his first power plant, built to light lower Manhattan in 1882. DC at low voltage was safe, reliable and easy to control. It was also very inefficient: low voltage meant high current, and resistive losses increase as the square of the current transmitted. As a result, power plants could not serve customers who lived or worked more than a few miles away.

These limitations prompted Westinghouse to push for alternating current, which could be converted by transformers to high voltages for efficient transmission and then back to lower levels for safe use. (A transformer consists of two interwound coils; an alternating

ELECTRICAL SUBSTATION in San Jose, Calif., transforms power from a 500-kilovolt long-distance transmission line to 230 and 115 kilovolts for more local distribution. Utility managers operate such facilities and their associated transmission lines at a fraction of their potential capacity because conventional switching equipment cannot react quickly to unanticipated disturbances. Solid-state power devices, which are able to respond much faster to outages or to sudden changes in voltage, could increase the capacity of many transmission lines and distribution systems by as much as 50 percent.



POWER GRID ties together most of the U.S. and parts of Canada east of the Mississippi River (*left*). Other networks link the rest of the U.S. and Canada. By adjusting the voltage and phase of alternating current flowing through high-voltage transmission lines, utility companies are able to move power from one region to another.

current of one voltage passing through the primary coil generates an alternating current of another voltage in the secondary coil; the ratio between the two voltages depends on the number of turns in each coil.)

Edison warned against the dangers of alternating current, which can be more hazardous than equivalent levels of direct current. The advantages of alternating current became clear in 1896, however, when a high-voltage transmission line began to carry current to Buffalo, N.Y., from the first hydroelectric power plant at Niagara Falls. Other high-voltage links between widely separated load centers and power plants followed. Today most of the U.S. and Canada has been tied to one of several highly interconnected AC power systems.

Opponents of alternating current did have a point. AC power is more difficult to control than is DC. Line voltages tend to rise or fall in complicated ways as loads change. Voltage instabilities are more likely to get out of hand. These problems arise because AC generates changing electric and magnetic fields around the lines that carry it; these fields in turn affect the flow of current. Ideally, the power flowing through an AC line consists of a series of waves of rising and falling voltage and current that reverse polarity 120 times a second, in perfect sinusoidal rhythm.

When the sine waves representing voltage and current at any given point in the transmission line rise and fall in synchrony, they are said to be "in phase"—that is, the phase angle between them is zero. When a load is imposed at one end of a line, current flows through the load (doing work and creating heat in the process); this flow of electrical charge causes a slight drop in the line voltage, and so power flows from the higher-voltage end of the line to the lower-voltage one.

The relation between current and voltage in a DC line depends only on the resistance of the cables. In a line carrying AC, however, the relation is governed by a complex quantity known as impedance. Impedance is akin to resistance but varies with frequency. It can alter not only the strength of an AC flow but also its phase. Coils, for example, have a form of impedance called inductive impedance that passes direct current untouched but acts as a barrier to rapidly changing current flows. If a sudden voltage is applied to a simple inductor, such as a coil of wire, initially no current will pass; only after a characteristic time will the current flow build up to its full value. Consequently, voltage and current can get out of phase: voltage reaches its proper value on schedule, but the increase in current is delayed. When the sinusoids of commercial AC pass through an inductor, the rise and fall of current lags the peaks and troughs of voltage. In addition, overall voltage drops.

Capacitors, devices that store electrical charge, display a form of impedance that operates in opposing fashion. They present little hindrance to the passage of rapidly changing voltages but block the passage of direct current completely. Because capacitors act as reservoirs of electrical charge, they can allow large amounts of current to flow for a short time without an appreciable change in voltage. Hence, in AC systems, capacitance makes the sinusoids of current tend to run ahead of those of voltage.

The amount of power transmitted through an AC line is simply the product of current and voltage. As a result, either kind of phase mismatch between voltage and current impairs capacity; it does not matter whether the sinusoids of voltage run ahead of the sinusoids of current, or vice versa.

In a real power transmission system, these factors grow even more complicated. The impedance along any given path depends on the interaction between the cables and other equipment and the changing electric and magnetic fields engendered by the power flow. Transformers and motors create inductive impedance, whereas capacitors and long, lightly loaded transmission lines create capacitive impedance. As power flows change in response to these distortions, however, the magnitude of capacitive and inductive effects can change with them, thus altering the milliseconds-earlier balance and causing power flows to change yet again.

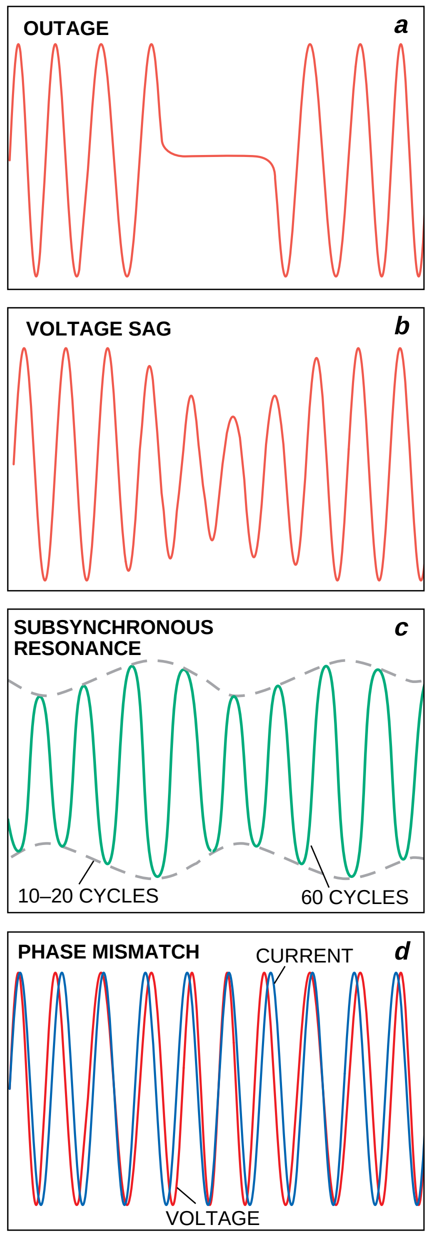
Controlling impedance is crucial to the proper distribution of power, but it is also very difficult. Once a transmission line, transformer or motor has been built, its impedance is fixed and cannot easily be changed. The impedance of transmission lines can be changed in large steps by inserting either series capacitors or inductors in the line, but this process is time-consuming and does not lend itself to the rapid control of electrical flows.

Interaction between impedance and current subjects AC networks to several different kinds of degradation. Among them are loop flow (the flow of current along unintended paths), large-scale instability (violent, uncontrollable fluctuations in power flow), poor control of line voltage and small-scale instability in the face of rapid load changes.

Loop flow occurs when many lines connect a power source and a load—hydroelectric plants in Ontario and air conditioners in New York City, say. Rather than taking the shortest physical path, power will flow along the lines that offer the least impedance. Ontario power destined for Manhattan may flow through transmission lines as far west as Ohio and Kentucky. Even though this distance may be physically longer than the "direct" path, impedance makes it appear much shorter in an electrical sense. The detour can be costly for the utilities whose lines carry the unwanted power, because the current passing through on its way elsewhere consumes transmission capacity that they could use to serve their own customers.

Large-scale instability is a result of the way that power flows from point to point in high-voltage transmission networks. Power always flows from areas with surplus capacity to areas with a deficit, but the number of megawatts transferred through specific lines depends on the impedance of the intervening lines and on the difference in phase between the sinusoids at the sending and receiving ends. The larger the phase difference, the more power is transferred. If the phase angle becomes too large, however, small phase shifts can lead to large changes in the magnitude of the flow. The system becomes unstable, producing a disturbance that can result in a widespread blackout. Utilities limit the amount of power transferred over their high-voltage lines so that instabilities occur only rarely. If there were some way of damping sudden fluctuations, however, power flows could be increased.

In addition to their problems in regulating phase angle, utilities can have difficulties in maintaining a constant line voltage. A factory with many large motors, for example, places a substantial inductive load on the line. Inductive impedance tends to pull voltage down, which can create problems for other customers connected to the same circuit. Long lines that are only lightly loaded, in contrast, may see voltage rise above acceptable levels. Finally, such events as lightning strikes, short circuits on power lines or sudden shifts in loads cause voltage instabilities. Uncontrolled, some of these disturbances can damage equipment or even cause full-scale blackouts. Usually, impedances inherent in transmission systems quickly



ALTERNATING-CURRENT transmission and distribution systems are subject to a variety of ills. Outages (*a*), which can be either momentary or lengthy, can disrupt complex manufacturing processes. Voltage sags (*b*) can also cause damage to devices that consume electricity. Subsynchronous resonance (*c*) can set up vibrations that destroy transmission and generation equipment. Phase mismatches between voltage and current (*d*) are generally not destructive, but they reduce the amount of power that can be transmitted from one location to another. Under extreme conditions, such reductions could cause blackouts.

bring the voltage back to normal, but sometimes the combination of capacitance and inductance can amplify surges or ebbs. Indeed, if subjected to certain kinds of periodic disturbance, a power system may exhibit subcycle resonance, in which it sustains alternating-current waves at frequencies in addition to the standard 60 cycles per second. Interactions between the normal power frequency and these spurious frequencies can set generators vibrating with enough energy to tear apart steel shafts three feet in diameter.

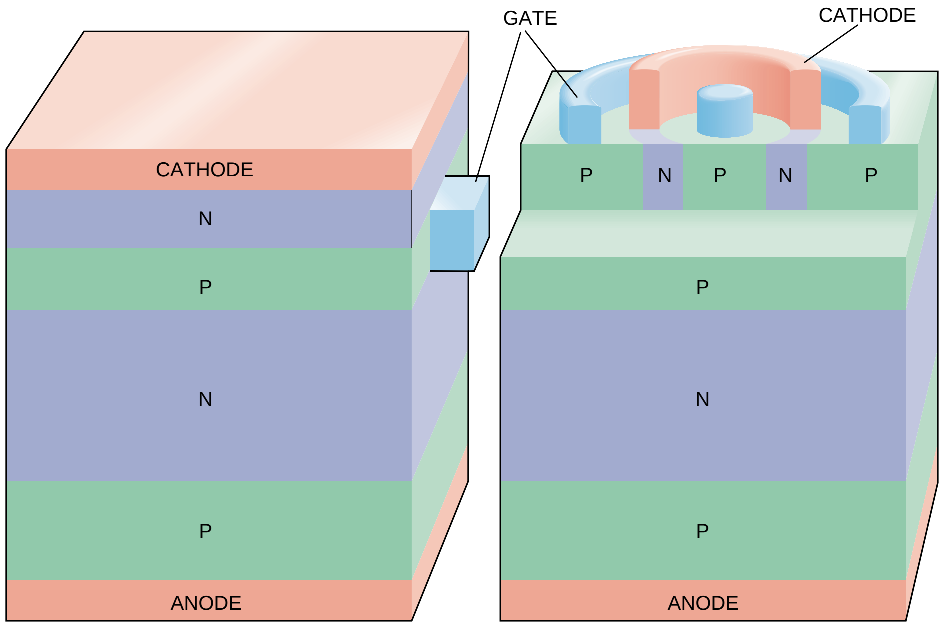
Disturbances in transmission systems are complex in cause and symptomology, but the effect on utility customers is invariable: lost work, disrupted manufacturing processes and damage to valuable equipment. Even the shortest of glitches can be exceedingly costly. In a recent survey of several industries, workers at Westinghouse found that an outage of just five cycles—83 milliseconds—cost a glass plant $200,000; an outage of little more than five minutes cost a semiconductor manufacturer $500,000. They estimate that such losses total between $3 billion and $5 billion annually in the U.S.

To avoid such outages, many companies are investing in their own power-conditioning equipment. Such equipment ranges from uninterruptible power supplies (UPS), which can provide enough energy to ride through short outages, to full-scale generation facilities that offer complete backup power for a plant. Unfortunately, current UPS technology is inefficient: between 10 and 20 percent of the energy that flows through such a device is lost. An estimated three billion kilowatt-hours go to waste every year, at a direct cost of more than $100 million (not to mention the indirect costs of burning additional fossil fuels and building new power plants and transmission lines).

In search of a way out of the choice between costly outages and wasted energy, engineers turned to semiconductor technology. For the past two decades, they have been developing high-voltage, high-power electronic devices known as thyristors. These components, disks of silicon a few inches in diameter and a fraction of an inch thick, can carry many hundreds and even thousands of amperes of current at potentials of thousands of volts. Furthermore, by acting in a small fraction of an AC cycle, they can prevent instabilities from damaging equipment or causing outages. A thyristor switch, for example, can cut off a failing power line and bring in a backup source without interrupting the alternating-current waveform.

How Thyristors Work

Solid-state power control starts with the silicon-controlled rectifier, the simplest kind of thyristor (*left*). A positive voltage applied to the gate of an SCR at the beginning of an AC cycle will cause it to conduct as long as the voltage at the anode is higher than the voltage at the cathode. (In general, current



SILICON-CONTROLLED RECTIFIER　　**GATE TURN-OFF THYRISTOR**

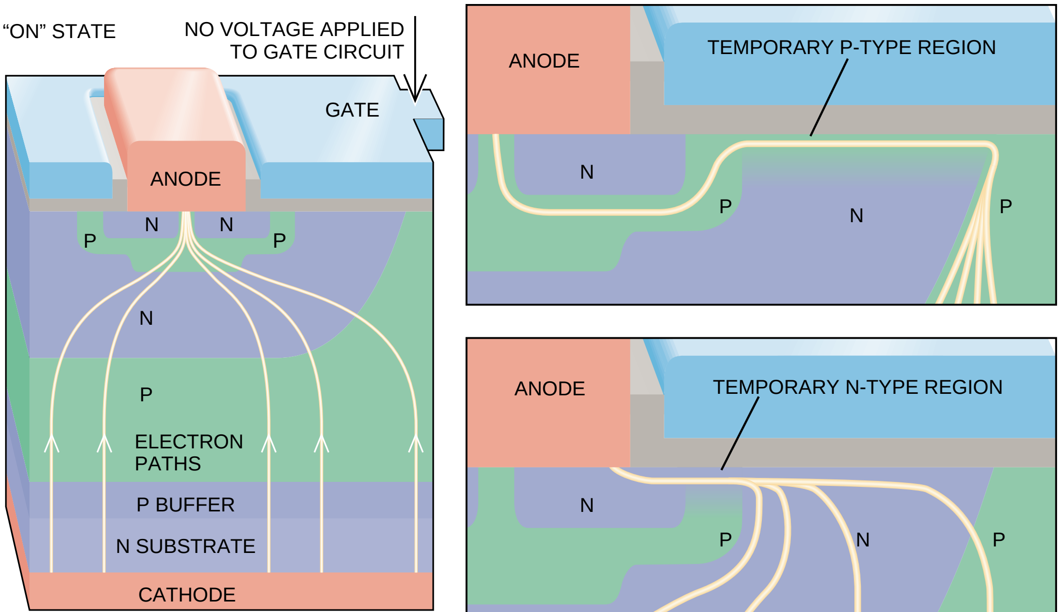
Thyristor-based systems can control impedance, voltage, current and phase angle in ways that would be impossible with mechanical switches.

These devices can improve the flexibility of transmission networks by enabling utilities to increase the loading of lines that are now limited by concerns over loop flow, stability or other problems. Indeed, in some cases, such controllers may be able to double the capacity of crucial transmission corridors; utilities can thus defer the construction of new lines and power plants. The Electric Power Research Institute, a collaborative research and development arm of U.S. utilities and several international affiliates, has coined the term "FACTS" (flexible AC transmission system) to cover the wide range of applications for thyristor-based circuits.

As do conventional transistors and integrated circuits, the new high-power devices depend on the conducting properties of crystalline silicon doped with impurities. A typical transistor might consist of two layers of silicon doped with phosphorus or other elements that donate free electrons (negative, or *n* regions) separated by a layer doped with boron or other elements that accept free electrons (positive, or *p* regions). A small voltage applied to the *p* layer can change its conductivity and thus switch on or off the flow of current from one *n* layer to the other.

In general, electricity flows across a junction between the *n*- and *p*-type material when a positive voltage is imposed on the *p* side and a negative one on the *n* side. (Current in *n* regions is carried by electrons, which are negatively charged, and in *p* regions by positively charged "holes" that represent the absence of an electron where one would normally be.) A single *p-n* junction, a diode, permits current to pass in only one direction, from the *p* to the *n* region. Such devices are also called rectifiers because they can convert alternating current to direct current.

Thyristors, the workhorses of power electronics, have four layers, arranged in a *p-n-p-n* configuration. The first *p-n* junction acts as a diode rectifier that controls the direction of current. The second is controlled by a gate and so acts as a switch: the voltage applied to the gate (hence to the *p* layer) determines whether the second junction—and thus the device as a whole—will conduct. The simplest form of thyriswill flow across a junction between *p*- and *n*-type semiconductors whenever the potential on the *p* side is higher than the potential on the *n* side.) The gate turn-off (GTO) thyristor (*center*) can be turned on or off at any point in the AC cycle; applying a voltage to the gate diverts current from the junction between the *p* and *n* regions and so prevents the device from conducting. The MOS-controlled thyristor (MCT) is more efficient than are other kinds of thyristors but is significantly more complex (*right*). When the device is conducting, current flows through the thin *p* region immediately below the anode. To turn the device off, one applies a voltage to the gate; the resulting electric field makes a small part of the *p*-type material act like *n*-type material; the current thus flows around the *p* region, disrupting the thyristor's conductivity (*far right, top*). To turn the MCT back on, a voltage of opposite polarity is applied to the gate; this causes a thin *n* layer to act like *p*-type material. Current flows through this layer to the *p* region under the anode and establishes the conditions for normal conduction (*far right, bottom*).



MOS-CONTROLLED THYRISTOR

tor, the silicon-controlled rectifier (SCR), can be turned on by applying a positive voltage to its gate (and so to the buried *p* layer) when the voltage on the surface *p* layer is also positive. Current then flows through the entire device. Once a rectifier has been turned on, it will continue to conduct, regardless of the gate voltage, until the voltage on the surface *p* layer returns to zero.

One step up in sophistication is the gate turn-off (GTO) thyristor, which can interrupt current at any point in the AC cycle. The second *n* layer in this device consists of multiple channels, all embedded in the adjacent *p* layer. This *p* layer is controlled by a gate electrode, also divided into multiple channels: when there is no voltage on the gate, current flows from *p* to *n*. A negative voltage on the gate sidetracks current from the *n* channels and thereby prevents current from flowing through the device. GTO thyristors are not yet in use; the Tennessee Valley Authority expects to install units capable of controlling 100 megawatts on a transmission line in 1995.

Because they require that current pass through many narrow channels, GTO devices are inefficient. They are also relatively expensive to build. Engineers have been working on other switch designs that will require much less control current and be able to turn current on or off more quickly. One such device is the MOS-controlled thyristor (MCT). It consists of conventional integrated circuits ("metal oxide semiconductor" devices) etched into the top surface of the silicon that forms the main part of the thyristor. When a voltage is applied to the gate of the MOS circuit, the resulting electric field enhances the conductivity of the buried *p* layer so that current can flow. MCTs are at a fairly early stage of development. Devices now reaching the market can control only 120 kilowatts and are being sold for industrial applications. Utility-scale MCTs are expected to become available around 1997.

Although FACTS devices have clear theoretical advantages over the slow electromechanical switches now used to operate high-current, high-voltage lines, many utilities are waiting for solid-state technology to become available and cost-effective before adopting it on a wider scale. EPRI is now working to demonstrate FACTS controllers in several key applications. First comes the solid-state subsynchronous damping scheme. Next is the thyristor-controlled variable capacitor system, which can reduce impedance on transmission lines and thus control and increase power flow. Fast-acting voltage regulators will be able to prevent voltage fluctuations on heavily loaded lines. Finally, EPRI is promoting the use of phase angle regulators to reduce power on transmission lines overloaded by loop flow. These devices can also increase flow on underutilized lines.

Although power companies in western states have employed fixed series of capacitors for years to reduce impedance on long transmission lines, utilities in the rest of the country have avoided them because a line with too much capacitance is vulnerable to subsynchronous resonance. Such low-frequency vibrations, once triggered, can damage generators and other equipment. Thyristor-controlled series capacitors (TCSCs) avoid this danger. If power fluctuates, the thyristor can change the period for which the capacitor is in the circuit. In this way, the device controls the impedance and damps the unwanted resonance.

EPRI first demonstrated thyristor-based systems for voltage control and damping of power system oscillations in 1978. In 1985 the institute installed another system for damping subsynchronous oscillations on a 500-kilovolt transmission line belonging to Southern California Edison. Each of these in turn allowed some increase in transmission capacity of these lines.

In 1991, as part of the FACTS program, the American Electric Power Service Corporation tested a thyristor-based switch in part of a series capacitor bank installed on a 345-kilovolt line near Charleston, W.Va. Since then, the Western Area Power Administration has installed a similar capacitor system for testing at the midpoint of a 200-mile-long 230-kilovolt line in Arizona. The system increases power transfer on the line from 300 to 400 megawatts. The Bonneville Power Administration, with EPRI sponsorship, has now completed a much larger TCSC system, on a 500-kilovolt, 2,500-megawatt transmission line in north-central Oregon. This installation, built by General Electric, consists of multiple small capacitor sections; each section contains its own thyristor-based controller so that engineers can tune capacitance to the precise level desired. The Bonneville Power Administration expects that the system will increase transmission capacity during springtime peaks. Indeed, preliminary studies indicate that an installation of this type could pay for itself in less than a year. Furthermore, the controller is designed in a highly modular fashion that will allow it to be adapted readily to other transmission lines.

When the thyristor-controlled capacitor system begins operation late in 1993, the Bonneville Power Administration will conduct tests to determine whether precise control over capacitance current and power can in fact damp subsynchronous resonance. The Portland General Electric Company, which owns a power plant near the TCSC installation, will join in these tests. Other utilities are studying the benefits of installing TCSCs. Southern Company Services of Georgia, for example, has concluded that it could save $120 million by installing a thyristor-controlled series inductor system rather than building a new transmission line where its facilities join those of the Tennessee Valley Authority.

EPRI's next transmission project is an outgrowth of technology that has been used to regulate voltage since the 1970s. Adding a capacitor or inductor to a line can keep voltage within acceptable limits when sags or surges threaten stability. The devices now used, called SVCs, consist, in effect, of a conductor running from a transmission line to ground through a capacitor or an inductor; thyristor switches determine whether current can flow through the capacitor or inductor. When voltages on transmission lines go below about 80 percent of normal, these simple shunts can no longer compensate enough to bring it up to proper levels.

A new type of shunt, based on GTO thyristors, can do a better job of compensating for voltage variations than can the current SCR-based devices. Instead of simply changing the amount of capacitance and inductance in the shunt, this so-called static condenser employs a direct-current capacitor that feeds precisely timed pulses of voltage into the transmission line to raise its potential to the proper level. The GTO device connects the capacitor to the transmission line and then disconnects it—producing a pulse—as many as 48 times in a single alternating-current cycle. The new device can also lower the voltage on a line by injecting pulses that oppose the normal cycle of alternating-current sinusoids.

With EPRI's support, Westinghouse and the Tennessee Valley Authority are building a GTO-based static condenser near Johnson City, Tenn. The system will regulate voltage on a 500-kilovolt transmission line and two 161-kilovolt lines, which are connected by large transformers. The device is scheduled to go into operation in 1995. It will hold down voltage on the 500-kilovolt line, which tends to rise when loads are light. It will also prevent voltage on the 161-kilovolt lines from sagging under peak loads. In addition, it will help damp voltage oscillations that have begun to appear on the lines of a neighboring utility. The Tennessee Valley Authority might otherwise have to construct another 161-kilovolt line to provide adequate operating margin for this area of its power system, at considerably greater cost.

The static condenser technology is also expected to find use in distribution systems, where it will provide reliable, high-quality power for commercial and industrial customers. Today a utility cannot effectively supply a customer with two independent, redundant distribution lines. A mechanical circuit breaker would take too long to switch to the second line if the first failed. A solid-state circuit breaker, however, can make the transfer in a single AC cycle. A GTO-based regulator can hold the voltage constant during this transition so that equipment will not be affected. Such regulators are already working in the laboratory; they could be on the market as soon as 1995.

Even more complex than the static condensers are thyristor-controlled phase angle regulators, which may also be available in the future. These devices consist of a large transformer equipped with an extra coil that can, in effect, bleed off voltage and then reinject it at a different phase angle with respect to the current. Depending on the precise angle at which the voltage is reinjected, the overall voltage waveform will lead or lag current by varying amounts. By varying the phase angle of the voltage, engineers can control the amount of power that flows from one end of a transmission line to the other. Thyristors control the flow of electricity through this extra coil and so determine the phase relation between voltage and current for power passing through the device.

One demonstration project is now under study: a thyristor-controlled phase angle regulator (TCPR) at International Falls, Minn., would help control power flow on a 115-kilovolt line that connects Ontario Hydro and Minnesota Power and Light. The direction of this flow typically shifts with the seasons—energy flows north during winter and south during summer. The two systems are only weakly connected, however, and voltages on one power system may become widely out of phase with those on the other. Increasing the 100-megawatt carrying capacity of the line requires direct control of the phase angle; otherwise, phase mismatch caused by a voltage disturbance on either system could rapidly lead to an overload.

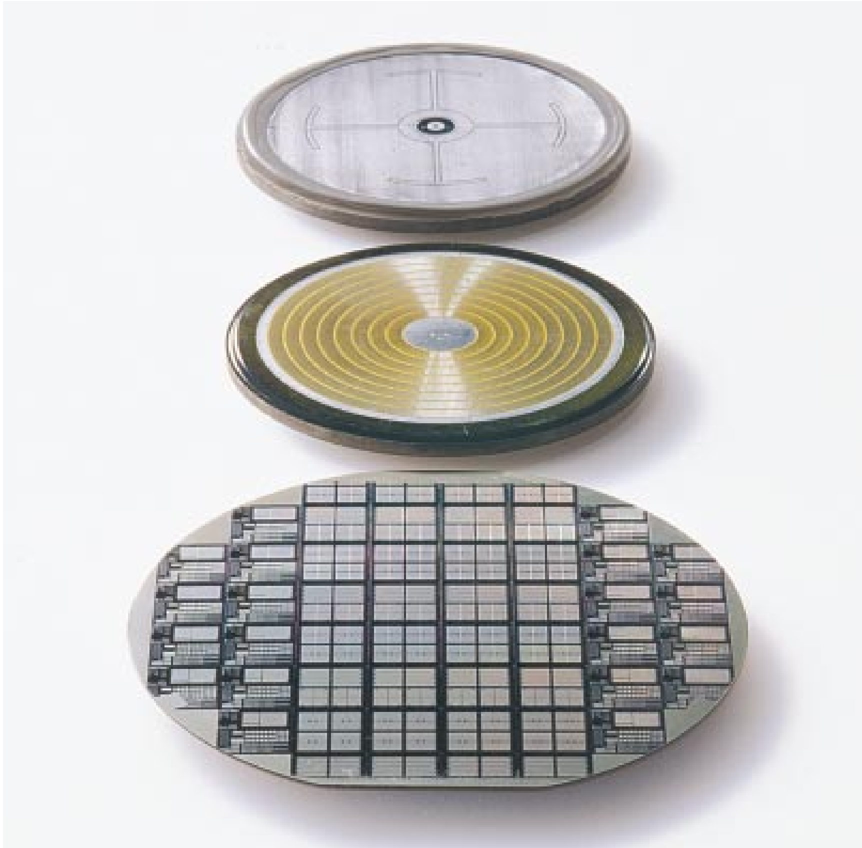
Specifically, the TCPR at International Falls would shield the interconnection from a power surge that could be caused by the inadvertent shutdown of a nearby 500-kilovolt line in Canada. This protection will enable utility managers to up the safe transfer limit to 150 megawatts. The phase angle regulator may also help damp low-frequency oscillations in the area. EPRI is directing detailed design studies, but implementation is at least two years away.

Whereas EPRI is sponsoring work primarily on a few key controllers, manufacturers inspired by potential market opportunities are developing various other thyristor-based controllers. Perhaps the most prosaic of these is the solid-state circuit breaker. Because these devices are not yet suited for high-voltage transmission, they will appear (in contrast to the other controllers) first in local power distribution systems, where they need only carry hundreds of kilowatts rather than the hundreds of megawatts of power flowing in transmission systems. These solid-state devices are much faster than their mechanical counterparts and last far longer because they do not have contacts that are damaged by arcs when they turn off.

An example of the more sophisticated controllers is the thyristor-controlled series reactor (TCSR), the inductive counterpart of the thyristor-controlled series capacitor. It adds impedance to reduce the load on a line or to limit current in the case of a sudden fault. Like its sibling, the TCSR can be placed into operation on a few microseconds' notice. Together the TCSR and TCSC may provide a lower-cost alternative to phase angle regulators. TCSR technology should be ready for demonstration by the late 1990s.

A thyristor-controlled braking resistor, meanwhile, could protect generators supplying power to long transmission lines from a sudden loss of load. Without such protection, a generator feeding an unloaded line would start gaining speed until it was damaged or had to be disconnected. Although mechanically controlled resistors can also brake generators, these devices have never gained acceptance among utility engineers because they can only be slammed on or turned off. They are useful in major emergencies but could cause more trouble than they avert. Thyristor-controlled units, in contrast, can be applied gently when only small braking actions are needed or sharply in an emergency. Manufacturers are expected to demonstrate a prototype before the end of the decade.

Another kind of device that shows promise is the thyristor-controlled active filter. Such filters address problems of power quality rather than reliability. Heavy electrical equipment often produces higher harmonics—voltage fluctuations at multiples of 60 cycles per second—that feed back into the power grid and cause disruptions. Utilities now use passive filters, which permit only specific frequencies to pass, on some lines subject to harmonics. Unfortunately, passive filters add impedance and so waste energy. Active filters, in contrast, would detect harmonics and apply a precisely timed counter voltage to neutralize them. Such devices have yet to leave the laboratory.



THREE GENERATIONS of thyristors show how these devices have increased in complexity and capability. The first-generation silicon-controlled rectifier (*top*) can switch power off only at the beginning of an AC cycle. Gate turn-off devices (*middle*) can switch at any point in the cycle, and MOS-controlled thyristors (*bottom*) switch more quickly while consuming significantly less power.

Taken together, the various kinds of high-power silicon devices offer utilities unprecedented control over power transmission and distribution. The economic benefits of the technology should be substantial for both utilities and their customers. Reduction of sags, momentary outages and subharmonic resonances will save some of the billions that those problems cost every year, as well as the billions now spent on uninterruptible power supplies. Moreover, "smart" power devices in utility lines consume only about 1 percent of the power they deliver, instead of the 10 to 20 percent that existing devices take.

In addition, solid-state controllers could increase the overall capacity of today's transmission network by 20 percent or more. Engineers have estimated, for example, that adding thyristor-controlled series capacitors to two 500-kilovolt lines serving Florida could increase the power transfer capacity from 2,000 megawatts to 3,000 megawatts. Such an investment could pay for itself in less than a year. Nationwide, utilities could save $6 billion compared with the cost of adding the same capacity with new lines.

Even more important, increased flexibility in distribution will make it easier to transfer power from one region to another on demand, thus permitting individual utilities to reduce their generating reserve margins. Smaller reserve margins, in turn, will enable utilities to defer construction of new power plants. If thyristor-based devices make it possible to reduce margins from the current 20 percent to 15 percent, $50-billion worth of power plants could be left unbuilt over the next 25 years.

FURTHER READING

ADVANCED STATIC VAR COMPENSATOR EMPLOYING GATE TURN-OFF THYRISTORS FOR UTILITY APPLICATIONS. L. Gyugyi, N. G. Hingorani, P. R. Nannery and N. Tai in *International Conference on Large High Voltage Electric Systems: Proceedings of the 33rd Session.* CIGRE, Paris, 1990.

UNIFIED POWER-FLOW CONTROL CONCEPT FOR FLEXIBLE AC TRANSMISSION SYSTEMS. L. Gyugyi in *IEE Proceedings–C*, Vol. 139, No. 4, pages 323–331; July 1992.

FACTS: THE DELIVERY SYSTEM OF THE FUTURE. J. Douglas in *EPRI Journal,* Vol. 17, No. 7, pages 4–11; October 1992.

FLEXIBLE AC TRANSMISSION. N. Hingorani in *IEEE Spectrum,* Vol. 30, No. 4, pages 40–45; April 1993.