What's Wrong with the Electric Grid?

The warnings were certainly there. In 1998, former utility executive John Casazza predicted that "blackout risks will be increased" if plans for deregulating electric power went ahead. And the warnings continued to be heard from other energy experts and planners.

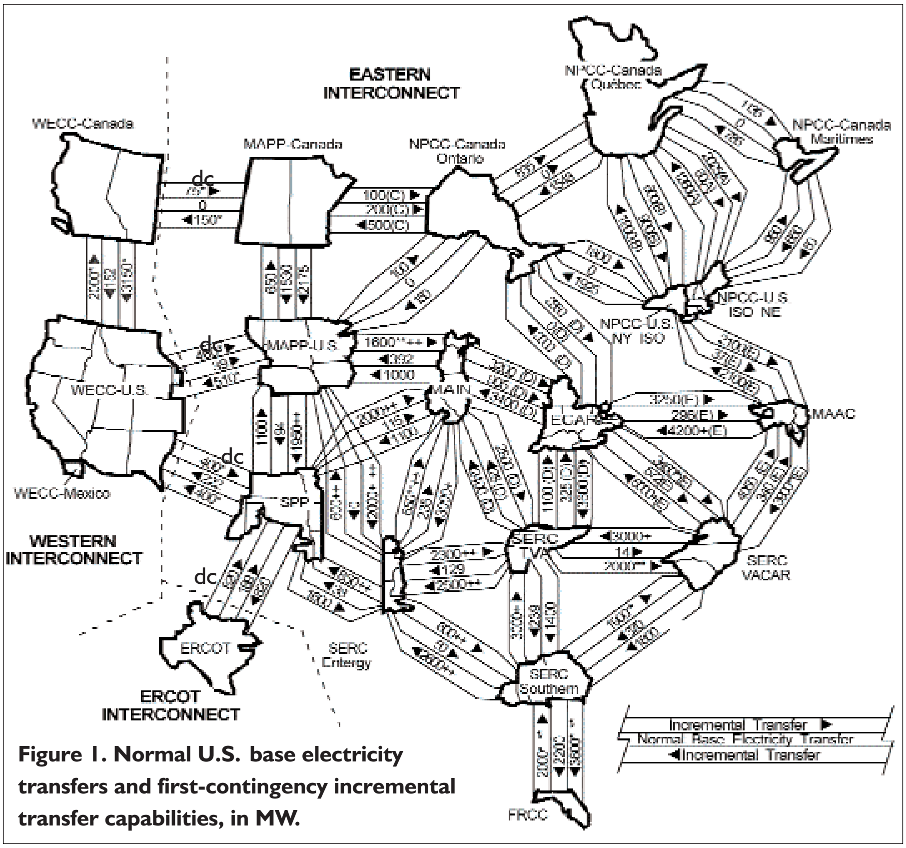


Figure 1. Normal U.S. base electricity transfers and first-contingency incremental transfer capabilities, in MW.

North American Electric Reliability Council

So it could not have been a great surprise to the electric-power industry when, on August 14, a blackout that covered much of the Northeast United States dramatically confirmed these warnings. Experts widely agree that such failures of the power-transmission system are a nearly unavoidable product of a collision between the physics of the system and the economic rules that now regulate it. To avoid future incidents, the nation must either physically transform the system to accommodate the new rules, or change the rules to better mesh with the power grid's physical behavior.

Understanding the grid's problems starts with its physical behavior. The vast system of electricity generation, transmission, and distribution that covers the United States and Canada is essentially a single machine—by many measures, the world's biggest machine. This single network is physically and administratively subdivided into three "interconnects"— the Eastern, covering the eastern two-thirds of the United States and Canada; the Western, encompassing most of the rest of the two countries; and the Electric Reliability Council of Texas (ERCOT), covering most of Texas (Figure 1). Within each interconnect, power flows through ac lines, so all generators are tightly synchronized to the same 60-Hz cycle. The interconnects are joined to each other by dc links, so the coupling is much looser among the interconnects than within them. (The capacity of the transmission lines between the interconnects is also far less than the capacity of the links within them.)

Prior to deregulation, which began in the 1990s, regional and local electric utilities were regulated, vertical monopolies. A single company controlled electricity generation, transmission, and distribution in a given geographical area. Each utility generally maintained sufficient generation capacity to meet its customers' needs, and long-distance energy shipments were usually reserved for emergencies, such as unexpected generation outages. In essence, the long-range connections served as insurance against sudden loss of power. The main exception was the net flows of power out of the large hydropower generators in Quebec and Ontario.

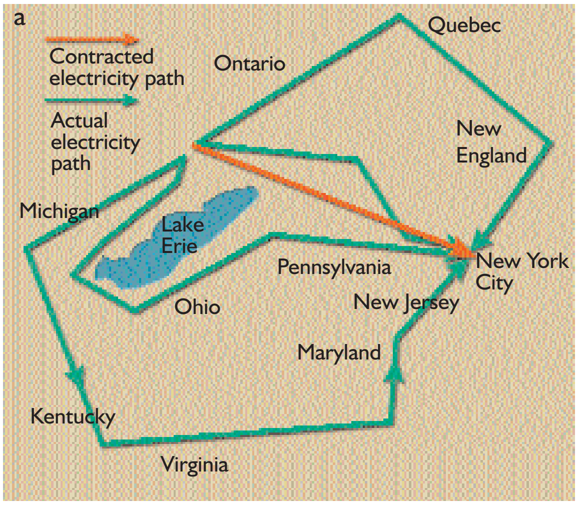
This limited use of long-distance connections aided system reliability, because the physical complexities of power transmission rise rapidly as distance and the complexity of interconnections grow. Power in an electric network does not travel along a set path, as coal does, for example. When utility A agrees to send electricity to utility B, utility A increases the amount of power generated while utility B decreases production or has an increased demand. The power then flows from the "source" (A) to the "sink" (B) along all the paths that can connect them. This means that changes in generation and transmission at any point in the system will change loads on generators and transmission lines at every other point—often in ways not anticipated or easily controlled (Figure 2).

To avoid system failures, the amount of power flowing over each transmission line must remain below the line's capacity.

TABLE 1. CAPACITY LIMITS FOR ELECTRICAL TRANSMISSION LINES

Voltage (kV)	Length (miles)	Maximum capacity (GW)
765	100	3.8
	400	2.0
500	100	1.3
	400	0.6
230	100	0.2
	400	0.1

Data from *Transmission Planning for a Restructuring U.S. Electricity Industry*, by Eric Hirst and Brendan Kirby, June 2001, prepared for Edison Electric Institute, Washington, DC.



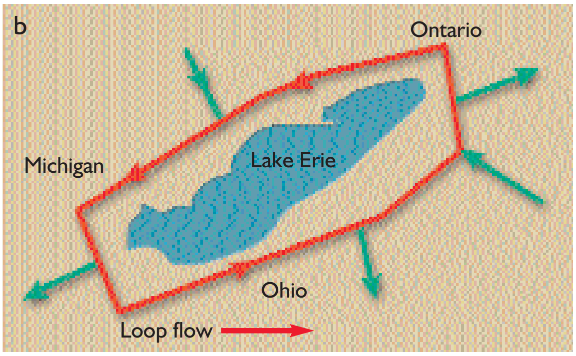


Figure 2. Electric power does not travel just by the shortest route from source to sink, but also by parallel flow paths through other parts of the system (a). Where the network jogs around large geographical obstacles, such as the Rocky Mountains in the West or the Great Lakes in the East, loop flows around the obstacle are set up that can drive as much as 1 GW of power in a circle, taking up transmission line capacity without delivering power to consumers (b).

Exceeding capacity generates too much heat in a line, which can cause the line to sag or break or can create power-supply instability such as phase and voltage fluctuations. Capacity limits vary, depending on the length of the line and the transmission voltage (Table 1). Longer lines have less capacity than shorter ones.

In addition, for an ac power grid to remain stable, the frequency and phase of all power generation units must remain synchronous within narrow limits. A generator that drops 2 Hz below 60 Hz will rapidly build up enough heat in its bearings to destroy itself. So circuit breakers trip a generator out of the system when the frequency varies too much. But much smaller frequency changes can indicate instability in the grid. In the Eastern Interconnect, a 30-mHz drop in frequency reduces power delivered by 1 GW.

If certain parts of the grid are carrying electricity at near capacity, a small shift of power flows can trip circuit breakers, which sends larger flows onto neighboring lines to start a chain-reaction failure. This happened on Nov. 10, 1965, when an incorrectly set circuit breaker tripped and set off a blackout that blanketed nearly the same area as the one in August.

After the 1965 blackout, the industry set up regional reliability councils, coordinated by the North American Electric Reliability Council, to set standards to improve planning and cooperation among the utilities. A single-contingency-loss standard was set up to keep the system functioning if a single unit, such as a generator or transition line, went out. Utilities built up spare generation and transmission capacity to maintain a safety margin.

In 1992, the economic rules governing the grid began to change with passage of the Energy Policy Act. This law empowered the Federal Energy Regulatory Commission (FERC) to separate electric power generation from transmission and distribution. Power deregulation—in reality, a change in regulations—went slowly at first. Not until 1998 were utilities, beginning in California, compelled to sell off their generating capacity to independent power producers, such as Enron and Dynergy.

The new regulations envisioned trading electricity like a commodity. Generating companies would sell their power for the best price they could get, and utilities would buy at the lowest price possible. For this concept to work, it was imperative to compel utilities that owned transmission lines to carry power from other companies' generators in the same way as they carried their own, even if the power went to a third party. FERC's Order 888 mandated the wheeling of electric power across utility lines in 1996. But that order remained in litigation until March 4, 2000, when the U.S. Supreme Court validated it and it went into force.

In the four years between the issuance of Order 888 and its full implementation, engineers began to warn that the new rules ignored the physics of the grid. The new policies "do not recognize the single-machine characteristics of the electric-power network," Casazza wrote in 1998. "The new rule balkanized control over the single machine," he explains. "It is like having every player in an orchestra use their own tunes."

In the view of Casazza and many other experts, the key error in the new rules was to view electricity as a commodity rather than as an essential service. Commodities can be shipped from point A through line B to point C, but power shifts affect the entire single-machine system. As a result, increased long-distance trading of electric power would create dangerous levels of congestion on transmission lines where controllers did not expect them and could not deal with them.

The problems would be compounded, engineers warned, as independent power producers added new generating units at essentially random locations determined by low labor costs, lax local regulations, or tax incentives. If generators were added far from the main consuming areas, the total quantity of power flows would rapidly increase, overloading transmission lines. "The system was never designed to handle

TABLE 2. AVERAGE PRICE OF ELECTRIC POWER IN THE U.S., 1994–2002 (cents/kWh)

Year	Cost of power	Cost of fuel	Cost of power minus cost of fuel
1994	6.91	1.23	5.68
1999	6.64	1.24	5.40
2000	6.81	1.61	5.20
2001	7.32	1.58	5.74
2002	6.97	1.28	5.69

Energy Information Administration

Table 2. Prior to the implementation of Federal Energy Regulatory Commission Order 888, which greatly expanded electricity trading, the cost of electricity, excluding fuel costs, was gradually falling. However, after Order 888, and some retail deregulation, prices increased by about 10%, costing consumers $20 billion a year.

long-distance wheeling," notes Loren Toole, a transmission-system analyst at Los Alamos National Laboratory.

At the same time, data needed to predict and react to system stress—such as basic information on the quantity of energy flows—began disappearing, treated by utilities as competitive information and kept secret. "Starting in 1998, the utilities stopped reporting on blackout statistics as well," says Ben Carreras of Oak Ridge National Laboratory, so system reliability could no longer be accurately assessed.

Finally, the separation into generation and transmission companies resulted in an inadequate amount of reactive power, which is current 90 deg out of phase with the voltage. Reactive power is needed to maintain voltage, and longer-distance transmission increases the need for it. However, only generating companies can produce reactive power, and with the new rules, they do not benefit from it. In fact, reactive-power production reduces the amount of deliverable power produced. So transmission companies, under the new rules, cannot require generating companies to produce enough reactive power to stabilize voltages and increase system stability.

The net result of the new rules was to more tightly couple the system physically and stress it closer to capacity, and at the same time, make control more diffuse and less coordinated—a prescription, engineers warned, for blackouts.

In March 2000, the warnings began to come true. Within a month of the Supreme Court decision implementing Order 888, electricity trading skyrocketed, as did stresses on the grid (Figure 3). One measure of stress is the number of transmission loading relief procedures (TLRs)—events that include relieving line loads by shifting power to other lines. In May 2000, TLRs on the Eastern Interconnect jumped to 6 times the level of May 1999. Equally important, the frequency stability of the grid rapidly deteriorated, with average hourly frequency deviations from 60 Hz leaping from 1.3 mHz in May 1999, to 4.9 mHz in May 2000, to 7.6 mHz by January 2001. As predicted, the new trading had the effect of

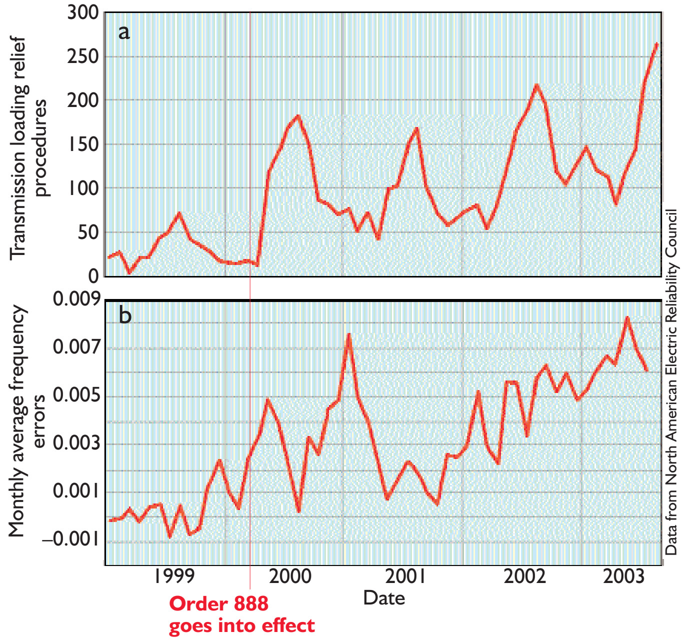


Figure 3. After wholesale electricity trading began in earnest following Federal Energy Regulatory Commission's Order 888, stress on the transmission grid jumped and continued to climb, as shown by the transmission loading relief procedures (a) and the monthly average frequency errors (b).

overstressing and destabilizing the grid.

"Under the new system, the financial incentive was to run things up to the limit of capacity," explains Carreras. In fact, energy companies did more: they gamed the system. Federal investigations later showed that employees of Enron and other energy traders "knowingly and intentionally" filed transmission schedules designed to block competitors' access to the grid and to drive up prices by creating artificial shortages. In California, this behavior resulted in widespread blackouts, the doubling and tripling of retail rates, and eventual costs to ratepayers and taxpayers of more than $30 billion. In the more tightly regulated Eastern Interconnect, retail prices rose less dramatically.

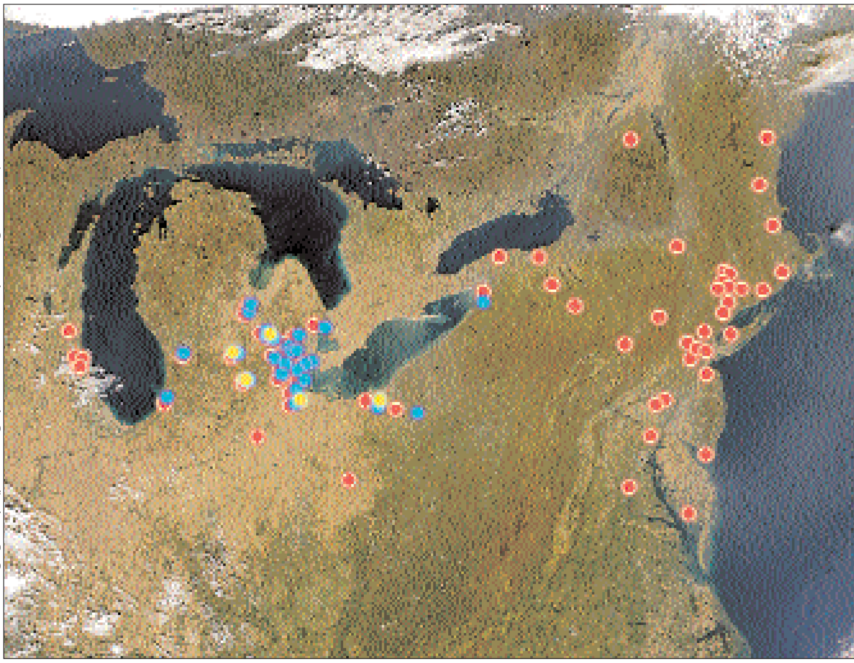
After a pause following Enron's collapse in 2001 and a fall in electricity demand (partly due to recession and partly to weather), energy trading resumed its frenzy in 2002 and 2003. Although power generation in 2003 has increased only 3% above that in 2000, generation by independent power producers, a rough measure of wholesale trading, has doubled. System stress, as measured by TLRs and frequency instability, has soared, and with it, warnings by FERC and other groups.

Major bank and investment institutions such as Morgan Stanley and Citigroup stepped into the place of fallen traders such as Enron and began buying up power plants. But as more players have entered and trading margins have narrowed, more trades are needed to pay off the huge debts incurred in buying and building generators. Revenues also have shrunk, because after the California debacle, states have refused to substantially increase the rates consumers pay. As their credit ratings and stock prices fell, utility companies began to cut personnel, training, maintenance, and research. Nationwide, 150,000 utility jobs evaporated. "We have a lot of utilities in deep financial trouble," says Richard Bush, editor of *Transmission and Distribution*, a trade magazine.

The August 14 blackout, although set off by specific chance events, became the logical outcome of these trends (Figure 4). Controllers in Ohio, where the blackout started, were overextended, lacked vital data, and failed to act appropriately on outages that occurred more than an hour before the blackout. When energy shifted from one transmission line to another, overheating caused lines to sag into a tree. The snowballing cascade of shunted power that rippled across the Northeast in seconds would not have happened had the grid not been operating so near to its transmission capacity.

How to fix it

The conditions that caused the August 14th blackout remain in place. In fact, the number of TLRs and the extent of frequency instability remained high after August 14 until September's cool weather reduced stress on the grid. What can be done to prevent a repetition next summer?



Orbital Imaging Corp. (processing by NASA Goddard Space Flight Center)

FIGURE 4. BLACKOUT SEQUENCE OF EVENTS, AUGUST 14, 2003

1:58 p.m. The Eastlake, Ohio, generating plant shuts down. The plant is owned by First Energy, a company that had experienced extensive recent maintenance problems, including a major nuclear-plant incident.

3:06 p.m. A First Energy 345-kV transmission line fails south of Cleveland, Ohio.

3:17 p.m. Voltage dips temporarily on the Ohio portion of the grid. Controllers take no action, but power shifted by the first failure onto another power line causes it to sag into a tree at 3:32 p.m., bringing it offline as well. While Mid West ISO and First Energy controllers try to understand the failures, they fail to inform system controllers in nearby states.

3:41 and 3:46 p.m. Two breakers connecting First Energy's grid with American Electric Power are tripped.

4:05 p.m. A sustained power surge on some Ohio lines signals more trouble building.

4:09:02 p.m. Voltage sags deeply as Ohio draws 2 GW of power from Michigan.

4:10:34 p.m. Many transmission lines trip out, first in Michigan and then in Ohio, blocking the eastward flow of power. Generators go down, creating a huge power deficit. In seconds, power surges out of the East, tripping East coast generators to protect them, and the blackout is on.

One widely supported answer is to change the grid physically to accommodate the new trading patterns, mainly by expanding transmission capacity. The DOE and FERC, as well as organizations supported by the utilities, such as the Electric Power Research Institute and the Edison Electric Institute, advocate this approach. In reports before and after the blackout, they urged expanding transmission lines and easing environmental rules that limit their construction. The logic is simple: if increased energy trading causes congestion and, thus, unreliability, expand capacity so controllers can switch energy from line to line without overloading.

To pay the extensive costs, the utilities and the DOE advocate increases in utility rates. "The people who benefit from the system have to be part of the solution here," Energy Secretary Spencer Abrams said during a television interview. "That means the ratepayers are going to have to contribute." The costs involved would certainly be in the tens of billions of dollars. Thus, deregulation would result in large cost increases to consumers, not the savings once promised (Table 2).

But experts outside the utility industry point to serious drawbacks in the build-more solution other than increasing the cost of power. For one, it is almost impossible to say what level of capacity will accommodate the long-distance wholesale trading. The data needed to judge that is now proprietary and unavailable in detail. Even if made available to planners, this data refers only to the present. Transmission lines take years to build, but energy flows can expand rapidly to fill new capacity, as demonstrated by the jump in trading in the spring of 2000. New lines could be filled by new trades as fast as they go up.

The solution advocated by deregulation critics would revise the rules to put them back into accord with the grid physics. "The system is not outdated, it is just misused," says Casazza. "We should look hard at the new rules, see what is good for the system as a whole, and throw out the rest." Some changes could be made before next summer, and at no cost to ratepayers. For one thing, FERC or Congress could rescind Order 888 and reduce the long-distance energy flows that stress the system. Second, the data on energy flows and blackouts could again be made public so that planners would know what power flows are occurring and the reliability records of the utilities. Other changes, such as rehiring thousands of workers to upgrade maintenance, would take longer and might require rewriting regulations and undoing more of the 1992 Energy Act.

These changes also would have costs, but they would be borne by the shareholders and creditors of the banks and energy companies who bet so heavily on energy trading. With cash flows dwindling and debt levels high, many of these companies or their subsidiaries might face bankruptcy if energy trading is curtailed. The decision will ultimately fall to Congress, where hearings are scheduled for the fall. However the decision turns out, what is nearly certain is that until fixed, the disconnect between the grid's economics and physics will cause more blackouts in the future.

Further reading

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