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Electrical Blackouts: Repeating Our Mistakes

The causes of blackouts run much deeper than individual errors, and the air traffic control system provides a model for a better way to operate the power grid.

The day after the August 14, 2003 blackout, President Bush and Prime Minister Chrétien directed that a joint U.S.-Canada Power System Outage Task Force be established to investigate the causes of the blackout and how to reduce the possibility of future outages. On November 19th, the task force reported that the blackout was due to human error: mistakes by operators in two control centers. This interim report follows a long tradition of singling out individuals and companies who made the wrong decisions. While firing individuals and suing companies might be satisfying to those who suffered in the blackout, it will do little to prevent future blackouts. The frequency and geographic distribution of blackouts indicate that similar problems are common in generation and transmission companies.

Major advances in system regulation and control often evolve in complex systems only after significant accidents open a policy window. The recent blackouts in this country and abroad have created such an opportunity.

To understand what must be done, we need some basic facts. About every four months, the United States experiences a blackout large enough to darken half a million homes. While the 1965 New York blackout got the nation's attention and started remedial action, we have not succeeded in ending blackouts nor even in reducing their frequency significantly.

Promises to end blackouts have been made for decades, but they ignore the reality that complex systems built and operated by humans will fail. Congress and the Federal Energy Regulatory Commission (FERC) must implement a framework that recognizes that individuals and companies will make errors, and limits their effects. Such a system would also be useful when natural disruptions (such as hurricanes) occur, and is likely to improve reliability in the face of deliberate human attacks as well.

Fortunately, air traffic control provides us a guide to a system designed to minimize the effects of human error. The problems uncovered by the August blackout can be addressed by the kind of change that transformed the air traffic control system from one of chance deadly accidents to a system that has provided a relatively accident-free environment, despite enormous growth in daily flights, and occasional errors by pilots and controllers.

August 14th and earlier blackouts

There were indeed many individual errors on August 14th. A plant operator pushed one generator near Cleveland too hard and it exceeded its limits, resulting in automatic shutdown at 1:31 that afternoon. The utility failed to appreciate the seriousness of the situation because it did not perform a contingency analysis (a computer model which takes only a few minutes to give results) after the loss of the plant to see if another failure would lead to serious trouble (the computer model which performs this analysis was running, but not consulted by operators at any time that afternoon, according to interviews cited in the report). With that generator lost, power flowed over transmission lines to fill the need in Cleveland. At 2:02, one line failed because, carrying less than half its design power, it sagged into a tree which had not been recently trimmed. Accident analysts describe most accidents as caused by a chain of events; one link in the chain was the failure to recognize that tree trimming is an essential part of the design of the transmission system. With both the generator and the line failed, other lines were overstressed and failed between 3:05 and 3:39 PM, leading to more failures and the blackout at 4:08. Data were not shared among competing generating companies or power transmission line operators as the situation worsened. Some data which were shared could not be interpreted because companies did not keep up with changes in the grid made by others. The transmission system operations center had trouble with their computer analysis tool starting at 12:15. They had only a single analyst on duty, and that person fixed the problem by 1:07, but then went to lunch without setting the program to run automatically (it is supposed to report every five minutes), and the analysis tool was not available until 4:04 PM. Meanwhile, back at the utility, the operators did not notice that their own alarms and graphs were disabled when the computers driving them froze at 2:14. They had no training in recognizing and reacting to failures of their computer systems. They believed their rosy, if static, data even when calls came in reporting trouble. The control displays were hard to interpret, even after they began working again at 3:59. When it finally became clear that there was insufficient generation or transmission to supply all customers, there was no attempt to shed load – that is to blackout a few customers in order to prevent blacking out 50 million.

The task force interim report concludes: “training was inadequate for maintaining reliable operation … internal control room procedures and protocols did not prepare them adequately to identify and react to the August 14 emergency.”

It is tempting to decide that these were isolated errors made by one or two organizations. It is always easy to blame individuals. Such complacency is misplaced. Operators at consoles in 140 control centers around the country are charged with controlling the grid by calling for generators to ship power over the proper lines at just the right time to meet demand. These operators work for some of the 3,000 power companies and transmission operators in the U.S. They don’t get the information required for informed decisions: “Most control facilities do not receive direct line voltage and current data on every facility for which they need visibility,” the task force concluded. To make up for the lack of real-time data, computers are sometimes used to estimate the state of the grid. Use of such models is uneven in the 140 control centers: “control areas that have them commonly run a state estimator [a computer tool used to estimate what is working and what is broken, since very little actual data is monitored] on regular intervals or only as the need arises (i.e., upon demand). Not all control areas use state estimators." Investigators, while pointing a finger at the failure to trim vegetation under transmission lines frequently, noted "A 5-year cycle is consistent with industry standards."

The task force listed new causal features of the August 2003 blackout: "inadequate interregional visibility over the power system; dysfunction of a control area's SCADA/EMS [data system]; and lack of adequate backup capability to that system." Each of these is closely related to causes identified for previous blackouts.

The task force made a welcome departure from previous reports by listing causes for earlier blackouts, indicating that the issues may be widespread. A few common themes emerge from investigations of the 2003 and earlier blackouts:

- Monitoring of the power grid is sparse, and even these limited data are not shared among power companies.
- Industry standards are lax: vegetation under transmission lines is routinely trimmed only every five years.
- Operators are not trained routinely using realistic simulations to practice dealing with the precursors to cascading failures and the management of large scale emergencies.
- Power companies have very different levels of equipment, data, and training. Some companies can quickly interrupt power to customers during an emergency, while others are nearly helpless.
- Decades-old recommendations to display data in a form that makes it easy to see the extent of a problem have been ignored. For example, the data system was cited as a contributing cause of the 1982 west coast blackout: "…the volume and format in which data were displayed to operators made it difficult to assess the extent of the disturbance and what corrective action should be taken."
- There is inadequate regional and interregional monitoring of the power system.

How the grid is operated

The United States has attempted voluntary measures to prevent electrical blackouts for much of the past century. Originally, vertically integrated utilities planned for their own system reliability, with a few tie lines to neighboring utilities which might be helpful in some emergencies. It became clear in the 1965 Northeast blackout that growing electric demand had made regional issues important: a failure in Ontario blacked out New York City eleven minutes later. In the next two years, ten voluntary regional reliability councils were established to coordinate the planning and operation of their members' generation and transmission facilities. In 1968, the North American Electric Reliability Council (NERC) was formed to coordinate the regional councils. One of NERC's primary functions is development of reliability standards for the regional generation and transmission of power. According to its website, "NERC has operated successfully as a voluntary organization, relying on reciprocity, peer pressure and the mutual self-interest of all those involved."

Consumers of electricity may have a different definition of success. Despite the voluntary standards, large blackouts unrelated to storms occurred in Pennsylvania, New Jersey and Maryland on June 5, 1967 (affecting 4 million people); Miami on May 17, 1977 (1 million); New York on July 17, 1977 (9 million); Idaho, Utah and Wyoming on January 1, 1981 (1½ million); four western states on March 27, 1982 (1 million); California and five other western states on December 14, 1994 (2 million); the Pacific Northwest on July 2, 1996 (2 million); eleven western states on August 10, 1996 (7½ million); and San Francisco on December 8, 1998 (½ million).

After the passage of the Public Utilities Regulatory Policies Act in 1978 and the Energy Policy Act of 1992, the electricity industry became a hybrid of vertically-integrated utilities and new structures of multiple forms. "Merchant generators" independent of utility companies installed their own plants and sought customers anywhere in the country. Aggregators bargained for better rates on behalf of large numbers of customers. Energy brokers used the open market and long-term contracts to buy and sell power. Restructuring has transformed the operation of the electricity system. Utilities formerly transmitted power from a nearby generation plant to customers. Now, industrial customers can buy power from plants hundreds of miles away, putting major burdens on the transmission system and increasing the likelihood of a blackout. That has made a huge difference: the number of times the transmission grid was unable to transmit power for which a transaction had been contracted jumped from 50 in 1997 to 1,494 in 2002. The metamorphosis of the electricity system has done little to improve the physical system of transmission, its control systems, or the human factors aspects of its operation. The burden of making the new system operate reliably has instead fallen on people.

No organization involved with the generation, transmission, or distribution of electric power wants low reliability. In a deregulated electricity market, companies have to pay for investments out of the revenues that they earn in competitive markets. Unless companies can find a way to bill customers for reliability or unless regulators mandate reliability investments and ensure that they are reimbursed, no investments will be made. None of the nineteen states that have implemented electric restructuring have figured out how to pay for investments to prevent low probability events such as blackouts.

Eight years ago, reacting to that summer's two large outages in the west, NERC's CEO wrote " [a new model] must include universal participation, more detailed and uniform reliability standards that can be put in place quickly, independent monitoring of reliability performance, and the *obligation* to support, promote, and comply with NERC's Policies." In 2002, NERC incorporated many of the new market participants that emerged after restructuring (such as brokers and aggregators) in developing its voluntary reliability standards. In 2003, NERC stated that "the existing scheme of voluntary compliance with NERC reliability rules is no longer adequate for today's competitive electricity market." However, both a 1998 Department of Energy report and a complaint to FERC in 1997 question NERC's authority to make its standards mandatory.

NERC has supported federal legislation which would establish an Electric Reliability Organization (ERO) with power to establish and enforce mandatory standards. This proposal had been first put forward in January 1997 by a NERC panel and eight months later endorsed by a task force chartered by the Department of Energy as a response to the 1996 blackouts; it was part of the energy bill which passed the House on April 11, 2003 and subsequently in Section 1211 of the conference committee language. The proposed ERO would be industry-led, and would be allowed to level penalties for violations of standards, but its authority over grid operations (as distinct from planning standards) is still to be defined.

Lessons from air traffic control

Electricity is not the only critical infrastructure in which safety conflicts with economics. It is instructive to consider the history of the air traffic control system as a guide to a framework which may reduce the errors leading to blackouts.

Air commerce expanded rapidly after a 1925 act allowed private carriers to transport mail by air. Few states took actions to increase air safety, leading President Coolidge to appoint a board to study federal regulation of air commerce. The 1926 Air Commerce Act charged the Department of Commerce with creating navigation aids and airways, as well as such regulations as required to give the public the perception that air travel was safe. Pilots and mechanics became federally licensed. In 1934 Congress created the Bureau of Air Commerce, assuming control of aviation.

Initially, air safety depended on each pilot spotting other aircraft and taking evasive action. This became impractical when the utility of air travel was increased by flying in clouds, where sight was limited. In 1934, the under-funded Bureau of Air Commerce asked a consortium of four airlines to develop the first air traffic control units to control and separate traffic. Participation by pilots was voluntary. Three years later, amid charges of favoritism (and after a crash which killed a Senator), the federal government took over the system and air traffic control became mandatory while flying in clouds. Later the Bureau was criticized for having both the responsibility to operate the system and to investigate the problem when things went wrong. It was dissolved, and its functions given to the new Civil Aeronautics Authority (CAA). The conflict of interest was fixed only in 1966 with the creation of the National Transportation Safety Board within the new Department of Transportation (but independent of the new FAA).

With its only data provided by airliners estimating their position and reporting via radio, the system muddled along for twenty years. Although radar had seen widespread use in World War II, and a 1948 report recommended its implementation for civil air control, it was not installed. A June 1956 crash between a TWA Constellation and a United DC-7 over the Grand Canyon killed all 128 aboard. The CAA denied responsibility, but the investigation found that the CAA's air traffic control system was "insufficient to offer positive separation to every airplane flying across the country." Congress approved a $1.6 billion (2002 dollars) modernization program, which provided position data on airplanes flying above 18,000 feet. All high-flying civil aircraft were to be separated by the federal air traffic control system. Although enhanced safety was the goal, radar also had the immediate effect of improving the capacity of the airways, since accurate data allowed the separation between aircraft to be decreased from 30 miles to 5.

During and after WWII, the Army successfully argued that the CAA should control only civil aircraft. Two parallel control systems – civil and military – persisted until 1958, when two collisions between military jets and civil aircraft killed 61. Later that year a single agency, the new Federal Aviation Authority (FAA), was established with a mandate to coordinate all civil and military air traffic at high altitude.

The data and control systems were still quite limited, since the sparse network of radar could not see congested areas near airports. Near-misses and warnings were followed by a crash on December 16, 1960 between two airliners over New York City, killing 136. The investigation blamed one of the airliners for poor navigation, but the board did not stop there. It also blamed an institutional problem, the lack of radar installations to collect data on aircraft at low altitude around busy terminals. Terminal radar facilities were approved and federally funded, with the first one serving New York.

In 1961 President. Kennedy charged the FAA with preparing a long-range plan for the air traffic network and performing associated research and development. The resulting study recommended a system that could monitor aircraft throughout their flight and improved the information displayed on screens to give operators better data and to make it much easier to interpret the information.

The 21 regional control centers have wide flexibility to formulate rules appropriate to their local conditions. By 1970 it was clear that a national coordination center was needed. As a result of the Air Traffic Control Command Center, airliners are held at the gate, not in the air, until it is safe to fly and they have takeoff and landing slots. Both the safety and efficiency of this large national network have been improved by federal standards for data, displays, and certification. In 1960, US air carriers had 44.2 fatalities per 100 million aircraft miles; in 2000 the rate was 1.2. Aircraft delays due to air traffic congestion fell by 2/3 after the opening of the national command center.

The improvements in air safety have been costly. Beginning with the Airport and Airway Revenue Act of 1970, funding for the system, as well as for improvements to airports, has been raised largely by taxes on airline tickets and fuel.

While the goal of preventing all air crashes will never be achieved, the increases in safety have been impressive because the incident investigations have sought ways to make the system safer, not just to blame the pilot in response to crashes or near misses.

We draw the following lessons from air traffic control:

- The federal government assumed control of a system that could not be handled by state and local government or by a voluntary system run by the airlines.
- The system had to move beyond a panic response to a crash to an overall system that included R&D and facilities to handle future issues.
- One agency should not be responsible for both operation and investigation.
- Comprehensive monitoring data are crucial, along with the ability to interpret the data in real time and take remedial action.

- While many of the actions are local or regional, a national coordination center is required to bring the controllers together.
- Finally, an extremely complicated and potentially deadly system of air transport has been made extremely safe, much safer than driving.

Reducing blackouts

Deaths from blackouts get less attention than those in air crashes, but in New York's 1977 blackout, two died and thousands were injured, including 400 police and 22 firemen.

We can apply lessons from the history of air traffic control and the causes of electric blackouts to control of the electric transmission system as a national asset. Just as in air traffic control in the early 1960's, the time for *ad hoc* fixes and finger pointing has passed. A national plan is needed, and it should be implemented through an organizational structure which recognizes that human beings make mistakes and that checks and balances are required.

A long range plan should take into account engineering improvements such as ways to control exactly where power flows through the lines, electrical compensation for the strain on the system caused when a customer spins up a large motor, and DC transmission lines (which reduce the loss in transmitting power long distances). Some would argue that technologies such as generation of electricity by relatively small plants located close to consumers, rather than large central generation plants, will reduce blackouts. This distributed generation holds promise, but for the foreseeable future the system will rely to some considerable degree on the existing transmission grid. Other technologies may be feasible in a decade, such as robust automatic control systems to take the load off of human operators (both central and distributed command have promise).

Long range planning should not distract us from the fact that very significant improvement can be made within the next few years. Some elements of such a near term plan are clear.

First, national standards for telemetry data on power flows and transmission system components are needed. Competitive pressures and changes in the way the grid is used have lead to a very sparse data system, and market pressures are not likely to lead to improvement. Operators can no longer be expected to make the right decisions without good data. The hodgepodge of individual capabilities resembles the rudimentary air traffic control system of 1934-37 operated by a few airlines. Control centers must have displays and tools which both allow operators to make good decisions and allow operators in different control areas to communicate without confusion. There must be backups for power and data, and clear indications to all operators that data are fresh and accurate. The emphasis should be on data and presentations which support decisions. The present representations of system state, particularly indicators of danger, are too complex. They stress accuracy over clarity. Grid operators need much clearer metrics of danger and suggestions for action (like collision avoidance alarms in aircraft and in air traffic control centers) even if they are a little less accurate. If the 157,000 miles of transmission lines were fitted with $25,000 sensors every ten miles which were each replaced every five years, the annual cost would be $100 million if financed at a 10% interest rate. This would increase the average residential electricity bill (now 10 cents per kilowatt-hour) to 10.004 cents per kWh, and the total would be roughly one-tenth the annual cost of blackouts.

Second, all grid operators must be periodically trained in contingency recognition and response using realistic simulators. These simulations must include all operations personnel in a way which exposes structural deficiencies such as poor lines of authority and insufficient staffing. The goal should be to recognize and act upon signs of extreme system stress which may be well outside daily operations experience. The description of flying as "years of boredom interrupted by moments of stark terror" applies also to grid operators, and they must have the systems and training that only realistic simulation using their specific control center configuration can provide. Federal standards for training, licensing, and certification of grid operators and control centers are warranted to ensure that a single weak control center does not bring down a large area. No federal entity now mandates such realistic training for grid operators, but the owners of nuclear generation plants proved (after Three Mile Island) that it can be done.

Third, operations control centers must have the ability to control. The patchwork of ability to shed load (some systems do it automatically, some cannot even do it manually from the control center) is not appropriate to the current inter-dependant transmission grid. Shedding of load in the near term will most probably be in the form of blacking out large areas. Some power companies have agreements now with customers who agree to be blacked out in emergencies, but this practice is not uniform. A decade hence it may be possible on a large scale to provide signals to consumers to shed parts of their load, in exchange for lower tariffs, but this partial shedding of load has not been economically feasible with current systems.

Fourth, just as air navigation aids are monitored and periodically flight checked, sensors, load shedding devices, and other system components must be checked on a much more systematic basis than at present. In a competitive environment, such periodic testing will be frowned upon by the chief financial officer unless mandated by national standards.

Fifth, industry standards for such items as tree trimming under transmission lines must be set with the costs of failures in mind, not just by the competitive constraints of the immediate marketplace. Penalties should accrue to companies which do not comply. These standards will vary by region, and should be set by regional bodies such as the RTOs.

Sixth, a national grid coordination center should be established and run as a national asset by a private body. It would stimulate R&D for the data needed for grid monitoring, and provide awareness of the situation at regional and larger scales, national flow control, and perhaps act as a backup for computer failures in individual control regions. As in air traffic control, the roles and responsibilities of the local and national centers will be neither perfectly optimum nor static, but they will complement each other to avoid the complete lack of situational awareness seen in so many blackouts.

Seventh, a permanent government investigation body including professional accident investigators who are trained to look for systemic causes as well as discipline-related causes should be constituted in a separate entity from the operators or regulators of the grid.

How can we evolve to such a system?

The current electricity reliability system was created and developed in an environment of voluntary participation. Trying to get all companies to participate and comply with the recommendations has meant that standards have not been stringent and, given the history of blackouts, have demonstrably not worked. Creating a better system is not simply a matter of making the current rules mandatory; this is necessary but not sufficient. In a time-limited process, we need to set rules for *operations* (the NERC standards here are very general, mandating general guides such as "return the system to a secure state") as well as for engineering by clarifying the goals of the transmission and generation systems and the responsibilities of each party. What emerges is unlikely to have policy or engineering purity or complete coherence, but it will be better than the present, fuzzy goals that provide little guidance on difficult tradeoffs.

The new rules for engineering and operations must be informed by the current state of technology and the technology improvements likely in the next few years. The size and complexity of any of the three US interconnection regions means that the new system has to be flexible and adaptive, since there is no mathematical formula which can be solved for so large a system. The need for innovative thinking suggests that an expert commission be created to advise the body setting mandatory standards. The commission should have experts from operating companies, systems operators, FERC, and academia to take a fresh look at how to design both engineering and operations standards that will satisfy the goals. Although this is analogous to the long-range air traffic control study President Kennedy ordered in 1961, the experience of the air traffic control system also provides insights for likely problems to avoid. While its operations have produced an admirably safe system, its investments in technology and infrastructure have been far from admirable. This suggests that infrastructure decisions be informed, but not dominated by current operations decisions. The electricity industry has its own technology issues; industry funding of its Electric Power Research Institute has dropped in half since restructuring began. Both R&D tax credits and detailed regulations have been proposed as stimuli for lagging innovation.

Industry is struggling to avoid detailed federal oversight (through FERC) of transmission and generation of electricity. NERC is not a federal entity, and FERC has very little authority to perform oversight of its voluntary policies. FERC has limited jurisdiction over both reliability issues such as reserve generation capacity requirements, and over the real time operations of the transmission grid. FERC is exploring its rather limited authority on reliability, and indicated in late 2003 that it would require public filings at FERC of any violations of the existing voluntary grid *reliability* standards, which are overseen by NERC. These standards deal with planning of adequate generation and transmission capacity to meet expected load. The new FERC proposal does not appear to require reporting of noncompliance with NERC's *operating* standards (which themselves do not require that data be collected on the status of the grid more often than every ten minutes). Even this innocuous-sounding FERC proposal was vigorously opposed on January 9, 2004 by the Edison Electric Institute (EEI), whose members (large utilities) want the industry's NERC, not the federal government, to have responsibility for standards. Three days later, FERC's chairman told the Wall Street Journal that "he intends to hire 30 engineers in coming months to conduct performance audits and bird-dog the work done by the reliability council."

If the legislation to create an ERO passes, the experiment of an industry organization chartered by the federal government to enforce with penalties standards it develops will be interesting to watch. The experiment aside, this provision is only a start. If a body such as the ERO is to make real progress, its authority should be expanded to include certification of transmission operators and systems to meet national standards of data and control, training, and periodic testing.

The FAA's certification and training standards, and its air traffic operations have been admirable. However, the FAA and its predecessors have found the management of new technology systems challenging, and upgrades such as better control center computers and precision upgrades for landing navigation systems have been decades behind schedule. It seems reasonable that a grid control system should be managed privately. Nevertheless, the past forty years have shown us that voluntary standards and individual operating practices are not appropriate for the grid. Just as the FAA sets standards for airlines and national standards for navigation data and control centers, a body (either the proposed ERO or a federal agency) should set operations requirements and police them. The same body could operate the national grid coordination center. A separate agency, such as the Department of Energy, should house the permanent investigation personnel.

The gross revenues of the electric sector and the airline sector are very similar. FERC is currently funded by user fees, and the improvements in the national grid control system that are required may be funded in a manner similar to the air traffic control system.

The best parts of the air traffic control experience can be incorporated and the worst parts avoided by implementing a strong set of mandatory federal rules and certifications covering the seven elements discussed above. Pending legislation misses most of the key points, and the battle between industry and FERC is not likely to be resolved without comprehensive attention to reliability in legislation, with the debate taking into account the lessons of related critical infrastructures.

A plan comprised of these elements, which recognizes that failures of complex systems involve much more than operator error, is not only enlightened but will also help keep the lights on.

Recommended reading

U.S.–Canada Power System Outage Task Force, Interim Report: Causes of the August 14th Blackout in the United States and Canada, November 2003. https://reports.energy.gov/

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