A bright full moon over a New York City skyline plunged into darkness during massive East Coast blackout

Time & Life Pictures/Getty Images

wired together

The irresistible surge in demand for power has laid bare a creaking electrical grid worldwide. **Philip Schewe**, chief science writer at the American Institute of Physics, considers historical and social aspects of the grid, **Laurie Wiegler** talks to Professor Massoud Amin, the founder of 'self-healing grid', and **Cheryl Knight** looks back at a year of power cuts in New York.

TEN CLIMBERS, hiking up a steep slope, rope themselves together, the strategy being that if one of them slips into a crevasse the others would be able to save him by concertedly pulling in the opposite direction. The danger is that the one falling might drag the other nine after him into the abyss.

The electrical grid is similar to this. Electrical networks are slung together not by rope but by high-voltage power lines. Super grids, encompassing dozens of utilities, serving tens of millions of people, and stretching a thousand kilometres or more, are now common, and when a disaster strikes, the results can be immense.

In August 2003, for example, some short circuits and software glitches (compounded by human errors) in Ohio unleashed a furious instability that rapidly spread to Michigan, into Canada, and back down into New York and beyond. Some 50 million people were left without power. Many Europeans gloated about how fragile the North American grid had become, until a month later when an even larger cascade blackout shot from France into Switzerland and down into Italy. This time 57 million people were deprived of electricity. In India, a blackout involving around 200 million people took place in 2001.

IS BIGGER BETTER?

How did the grid get so big, and why does it seem so vulnerable to hair-trigger disturbances?

Its size comes from economy of scale; from the investment point of view, and for the sake of energy efficiency, a utility traditionally gets more electricity for its money from

> 'In the US alone, the annual business losses stemming from the interruption of power are estimated to be $70bn or more'

larger generators. For much of the 20th century the graph of electricity output per fuel input keeps rising decade after decade. This 'law' ended in the 1970s, at least for conventional coal, oil and uranium power plants, at a level of about one-third efficiency. Higher efficiencies can be obtained by using the heat made along with power for warming homes and industrial processes, or by driving a gas turbine and a steam turbine at the same time.

The need for a sizeable grid is also enforced by the need to balance electric supply and demand moment by moment, which is a different kind of distribution challenge from those faced by any other commodity. If 100 light bulbs suddenly come on (or go off) at the same time, that increment of power has to be answered almost immediately. Sharing the electrical burden – meeting instantaneous load, as well as responding to emergency shutdown of generators or power lines – is better amortised by linking smaller grids into large grids.

An issue related to size and connectedness, but one which is poorly understood by the general public, is the absence of electrical provenance. The physics of grid electricity decrees that power flows over any path it can. Take, for example, a confederation of ten power plants serving a region with 100 cities. If all switches are open, no one city will be receiving power from any one plant, but rather from all ten plants. Conversely, the power from any one plant will not flow exclusively to one city but to all 100 cities. The electrical energy in the confederated grid is like the water in a lake fed by ten rivers. And the cities are like 100 campers pulling water from that lake. No one can tell, taking water out of the lake, from which river the water came; nor can you tell which campers (if they draw from the lake itself) received water from any one specific river.

A new power plant or new transmission line built hundreds of kilometres away has an impact on how you get your power. A grid upgrade or problem in one sector becomes, in effect, an upgrade or problem for the whole grid.

Large power plants, linked grids, multiple forking transmission paths: this is how the grid became a highly complex monolith. The operative word here is 'complexity': it has a general meaning, but in scientific and engineering terms, it means something specific. A system is complex if it consists of many rapidly interacting parts, some of which behave in a nonlinear way – changing the input might result in a disproportionately changed output.

The Big Apple immersed in darkness

SANDPILE EFFECT

A handy illustration of complexity comes in the form of a common conically-shaped sandpile. Grains added one by one to the top of the pile usually generate small spills involving only a few grains. Occasionally a new grain will initiate a medium sized slide. As the pile becomes steeper, the inter-grain strains grow larger and the pile becomes vulnerable to larger avalanches. You can't ever predict with certainty which new grain will set off a catastrophic avalanche – one bringing down the whole pile – only that such a collapse will eventually happen, all because of the deep-seated complex nature of the sandpile. ▶

'Super grids, encompassing dozens of utilities, serving tens of millions of people, and stretching a thousand kilometres or more, are now common, and when a disaster strikes, the results can be immense'

Sharing the huge electrical burden

Rex Features

◀ A graph of the likelihood of avalanches of a certain size will show a power-law fall-off – that is, the likelihood is proportional to the size of the avalanche raised to some negative power. Small slides will be common, larger slides rare. This is the case for all complex systems, whether it's sandpiles, or hurricanes, or forest fires, or earthquakes. The chance of a large flood or a large hurricane (as expressed in terms of homes damaged, people killed or businesses lost) is less than the chance of a small disaster but still not zero. We therefore arrive at the realisation that, even though the power grid is a human-built system, it is nevertheless a complex entity, and the spectrum of blackout immensity exhibits the same characteristic power-law shape as naturally-occurring disasters.

As if the underlying complexity of the electrical grid wasn't enough, the state of modern power delivery has been further complicated by the advent of a new business environment. First, in South America and Europe (especially Britain), and later in other continents, the power industry has undergone an immense reorganisation since 1990. Denationalisation, privatisation, liberalisation, unbundling of services, deregulation, and restructuring are some of the words used to describe the leaner business culture now in play. Even companies that continue to enjoy monopoly status in the supply of power in their service region are having to pinch pennies and streamline operations in order to stay competitive.

As early as the 1890s, Charles Merz pioneered in Britain the practice of making electricity at coal mineheads and then sending the power long distances to cities. This 'coal-by-wire' principle especially applies today, when electricity generated in one place might be shipped a thousand kilometres or more if a willing buyer can be found. The fulfilment of such transactions, however, is increasingly being compromised by congestion on the grid superhighway. Construction of new transmission lines has not kept up with increasing electricity consumption.

The result of this shortfall is predictable. The number of transmission loading relief events – occasions when sales of power could not be carried out owing to a lack of transmission capacity – has gone up dramatically in the past few years. More ominously, the number and size of blackouts is increasing. Most large power failures originate not at power stations but in the transmission grid.

HEAVY TOLL

People seldom die because of electrical outages. Nevertheless, their toll is still heavy in economic terms. In the United States alone, the annual business losses stemming from the interruption of power are colossal. Much of the loss comes not during the high-profile large blackouts, but from smaller events. This sort of rolling outage is particularly hard on customers in developing countries like India, where many businesses must use backup generators on at least a weekly, maybe daily, basis.

There are, needless to say, several other key issues concerning the electrical grid. Primary among these is sustainability – the ability to generate power for a burgeoning world population and global economy without also altering climate or irretrievably fouling the air, soil and oceans. Putting caps on carbon emissions is essential; nations that haven't yet done this should reconsider.

Efficiency is also a key issue – using less electricity to achieve the same aims, whether in manufacturing, services, or around the home. The cleanest, cheapest energy is energy that wasn't consumed in the first place. Regard for this principle needs to be inculcated at engineering schools, where those who design buildings (accounting for two-thirds of electrical consumption) are taught.

The use of renewables to decrease the fraction of generation performed using fossil fuel is vital. This issue only gets more important as international treaties, like the Kyoto Accord, are negotiated.

The issue of access must also register in the development of new electrical systems. One-third of the world's population has very little access to electricity, while another third has essentially none at all.

Decentralisation – the development of off-grid, localised networks – would put paid to a number of factors. Having reached an energy-efficiency plateau, large power plants are no longer necessarily the optimal production vehicle. Small plants, sometimes producing power and heat, or using a variety of energy sources, have been highly popular over the past decade.

A further innovation would be demand-side management, as customers, not just utilities, can do things to moderate energy use. For instance, for a reduction in rates a consumer might permit the utility to selectively reduce or switch off the customer's power during a temporary power shortage. Real-time metering will allow customers to see instantaneously how expensive power production is, allowing them to shift electric consumption to off-peak hours. ▶

FACTS & FIGURES: CON EDISON

- 2,000 primary feeders and 57 area substations
- 94,000 miles of underground cable
- 263,000 manholes and service boxes
- 34,000 underground transformers
- 36,000 miles of overhead cable
- 205,000 utility poles
- 46,000 overhead transformers
- The 94,000 miles of underground cable in the Con Edison system could wrap around the Earth 3.6 times.
- The company's 36,000 miles of overhead cable is enough to stretch between New York and Los Angeles 13 times.
- Customers in the Con Edison service area are using 20 per cent more electricity than they did 10 years ago.
- The utility company expects demand to rise another 10 per cent in the next decade.

NEW YORK: CAN THE GRID BEAR IT?

A YEAR AFTER tens of thousands of Con Edison customers in Queens were affected by a blackout during some of the hottest days of summer, 27 June saw another outage strike Manhattan and the Bronx.

The failure knocked out traffic lights, cut the subway service, and forced the evacuation of the Metropolitan Museum of Art on one of the hottest days of the year, with temperatures well over 90°F.

According to Con Edison, the blackout affected 136,700 customers in all. While the cause is still under investigation, the company's initial findings show that the event occurred quickly – in less than 10 seconds – and involved multiple transmission lines. Spokesman Chris Olert said the outage was the result of some sort of transmission disturbance.

Typically, the reasons for a power failure lie in a power station defect, damage to a power line or other part of the distribution system, a short circuit, or the overloading of electricity mains. Basically, when a transmission line fails, its load shifts to neighbouring transmission lines. Sometimes, those lines then overload and fail, and that unconfined overload cascades through the grid.

Con Ed's response to its electric grid problems has been to proactively implement system upgrades, and it plans to invest more than $7.5bn over the next five years to expand and upgrade. It will also pursue new energy-efficiency initiatives and conservation programmes as New York City and Westchester County continue to grow. To meet those needs, the company has filed a new electric rate proposal with the New York State Public Service Commission.

On a much smaller scale, another outage occurred on 7 June in Charleston, Illinois, where about 60 per cent of the city's power was knocked out by a breaker locking out at a substation. Ameren spokesman Leigh Morris said the power outage started at 4:18pm and left 5,902 of the 7,846 customers in the Charleston service area without power.

Morris said the outage appeared to be concentrated on the north side of Charleston and the area immediately beyond the city limits. The substation's large breaker will lock out like a home circuit breaker does when there is an electrical short in the system. It was not known why the breaker locked out.

New York energy suppliers are having to innovate after a series of disastrous outages

California has also seen its share of power outages over the past few years. One recent event happened on 21 July, when more than 120,000 Southern California Edison customers lost electricity due to an equipment failure.

One year previously, Pacific Gas & Electric transformers in California's Central Valley were out for more than four days. About 850,000 customers were deprived of electricity. At the same time, 30,000 customers served by the Los Angeles Department of Water & Power were also without electricity.

While these recent blackouts affected a large number of people, an outage on 14 August 2003 was the biggest in US history, affecting 40 million people in eight states (about one-seventh of the US population), and another 10 million in Canada.

A survey by the Electric Power Research Institute (EPRI) estimates the annual loss in the US from power outages and fluctuations at $100bn – 50 cents for every dollar spent on electricity. To address the shortcomings of the US power system, several initiatives are in the works.

On 27 June, the US Department of Energy (DoE) secretary Samuel W Bodman announced that the department will provide up to $51.8m for five cost-shared projects that will help accelerate much-needed modernisation of the grid. The goal is to advance the development and application of high-temperature superconductors, which have the potential to alleviate congestion on an electricity grid that is experiencing increased demand from consumers.

"Modernising our congested and constrained electric grid – through the development of advanced, new technologies – is vital to delivering reliable and affordable power to the American people," Bodman said. "As demand for electricity continues to grow, we must take steps now to identify potential problems, identify solutions, and deploy new technologies to provide a secure and steady energy supply."

The selected projects will help advance the future generation of power delivery equipment and aid the development of a highly efficient electricity grid system for the nation. Two of the research projects will help increase reliability and efficiency of power delivery cables, and the remaining three projects will place an emphasis on fault current limiters. The projects, which are expected to last two to five years, will be managed by DoE's National Energy Technology Laboratory.

With these projects, DoE plans to build on its past successes in superconductivity, which include operating two distribution-level voltage superconducting cables and utility grids. Superconductors – solid ceramic compounds that conduct electricity more efficiently than traditional copper wires – can be a key to improving the capacity, efficiency and reliability of electric power equipment. According to the DoE, a major challenge prior to commercialisation is to develop superconductors that can operate at relatively high temperatures, from approximately -320°F to -370°F, and in magnetic fields from 1 to 4 Tesla.

DoE's Office of Electricity Delivery and Energy Reliability (OE) will oversee the research projects. OE leads national efforts to modernise the electric grid; enhance the security and reliability of the energy infrastructure; and facilitate recovery from disruptions to the energy supply.

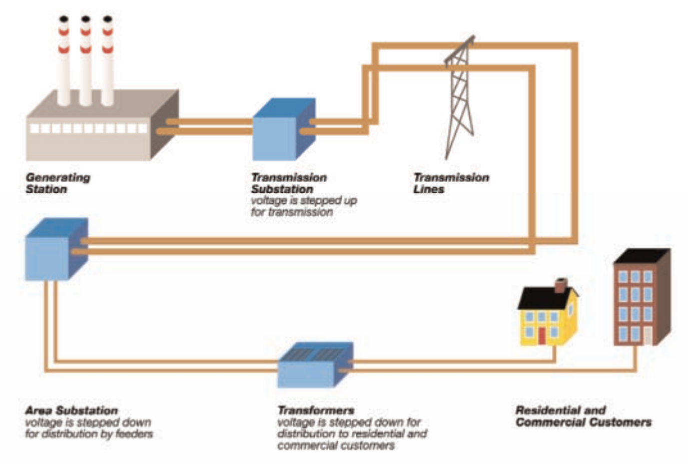
One OE project, called GridWorks, aims to improve the reliability of the electric system through the modernisation of key grid components: cables and conductors, substations and protective systems, and power electronics. The GridWorks multi-year plan includes near-term activities to incrementally improve existing power systems and accelerate their introduction into the marketplace. It also includes long-term activities to develop new technologies, tools, and techniques to support the modernisation of the electric grid for the requirements of the 21st century.

Another revolutionary initiative aimed at minimising defects in electric grids comes from IBM and Houston-based utility CenterPoint Energy. The partnership hopes to create the Intelligent Utility Network Coalition, to digitise electrical grids. Through the initiative, CenterPoint intends to invest about $750m over the next five years to upgrade its gear, including meters, switches, and equipment at power substations.

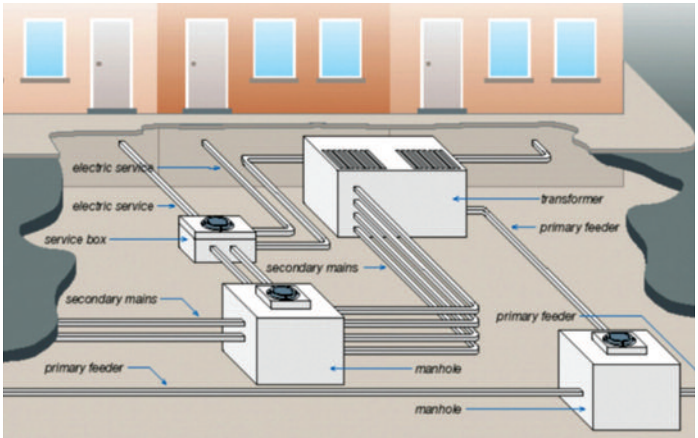
The utility is installing a broadband-over-powerline, or BPL, network over its Texas territory to gather and transport information such as real-time usage or overloaded distribution points.

"We expect that the intelligent grid will improve electric power line grid planning, operations, and maintenance, enabling us to deliver power more efficiently," said Tom Standish, CenterPoint Energy Group President, Regulated Operations. "We also expect the technology to contribute to fewer and shorter outages and higher productivity while maintaining our high level of data security."

'We should recognise that we are wired together, not just in our electrical connections, but in our consumption of raw materials, in our global economy, and in our collective international security'



When a transmission line fails, its load shifts to neighboring transmission lines



There are 94,000 miles of underground cable in the Con Edison system

◀ The final card up the sleeve of electricity providers is the development of new technology. If economic, political, and environmental factors dictate the continued use of coal and uranium for generating electricity, then extensive forms of carbon capture and long-term radioactive waste storage will have to be deployed. In tandem with the building of new transmission lines, a 'smart grid' is desirable – one in which the ongoing operation of the supergrid will resemble the flight of a fighter jet under the control of fast-acting, semi-autonomous computerised components. Such a system is needed to address the growing complexity of the grid and to anticipate terrorist threats.

Owing to the fact that electrical technology is a complex system, we must learn to prepare for system-wide disaster even as we work to mitigate such disasters through prudent investment and planning. In terms of life-expectancy, literacy rates, and nutritional levels, the human race is, in the aggregate, better off than ever. But this progress has necessitated the creation of a gigantic, complicated, cross-linked technological infrastructure, perched precariously on the edge of a precipice.

We will be more successful if we recognise that, in traversing the mountain of complexity, we are wired together, and not just in our electrical connections, but also in our consumption of raw materials, in our global economy, and in our collective international security. ■

innovation

MASSOUD AMIN'S SELF-HEALING POWER GRID

In May 2007, *Scientific American* published an article co-authored by Massoud Amin, professor of electrical and computer engineering at the University of Minnesota, on how a revolutionary technology called the 'self-healing grid' could alleviate the ubiquitous nature of power cuts. In the article, Amin explained how, by refashioning a power grid with digital technology, power could be assured on a large scale.

In a recent email conversation with *Engineering & Technology*, Professor Amin said the first step in building such a grid was to build a processor into each component of a substation. "Each breaker, switch, transformer, busbar, etc, has an associated processor that can communicate with other such devices. Each high-voltage connection to the device must have a parallel information connection. These processors have permanent information on device parameters as well as device status and analogue measurements from sensors built in the component."

During 1998 through to 2002, Professor Amin worked in tandem with the US Department of Defense (DoD) at the Electric Power Research Institute (EPRI). Here, they oversaw six university research groups comprising 108 faculty members and over 220 researchers in a joint EPRI and DoD programme, working towards the eventual Complex Interactive Networks/Systems Initiative (CIN/SI).

"We studied a broad spectrum of challenges to the power grid, energy and communication infrastructures and developed modelling, simulation, analysis, and synthesis tools for damage-resilient control of the electric power grid and interdependent infrastructures connected to it.

"This work showed that the grid can be operated close to the limit of stability, given adequate situational awareness combined with better, [more] secure communication and controls.

"As part of enabling a self-healing grid, we developed adaptive protection and coordination methods that minimise impact on the whole system performance (load dropped as well as robust rapid restoration); neither an agent, using its local signal, can by itself stabilise a system; but with coordination, multiple agents, each using its local signal, can stabilise the overall system."

According to Professor Amin, critical national infrastructure typically has many layers and decision-making units, and is vulnerable to various types of disturbance. Because of this, it is imperative that effective, intelligent control is designed to enable parts of the constituent networks to "remain operational and even automatically reconfigure in the event of local failures or threats of failure."

While it doesn't command the same high-profile coverage within the power sector, one threat that is as important as that of natural disasters or global warming-caused power outages is the very real concern of terrorist attack.

"In any situation subject to rapid changes, completely centralised control requires multiple, high-data-rate, two-way communication links, a powerful central computing facility, and an elaborate operations control centre. But all of these are liable to disruption at the very time when they are most needed," Amin commented.

While the self-healing grid is not yet in use, it is still more than a pipe dream.

"Developing the self-healing grid will be costly, but not prohibitively expensive in light of historic investment patterns. The incremental cost of both transmission and distribution transformation is about $13bn per year, or 65 per cent over and above current business-as-usual investments of about $20bn annually," professor Amin concluded.