

The Distributed Storage-Generation "Smart" Electric Grid of the Future

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By 2050, North America will need somewhere between 15 and 20 Terawatt hours/year of electric power (DOE/EIA estimate¹). The storage, transmission, and distribution technologies of the smart grid of the future—a web-enabled, digitally controlled, intelligent delivery system—must be able to deliver that amount of power to all corners of the continent efficiently. Millions of generation and storage points, both remote and locally distributed, from many different energy sources will be needed to supply that amount of electricity. A continental-scale grid will be needed to interconnect remote gas, coal and nuclear generation with wind, solar, geothermal and other renewables, in both centralized (deserts, offshore) and distributed (house, block, community, business, town) facilities.

Such sources cannot be simply added to the existing grid – it is not smart enough. The management of the grid will require digital control, automated analysis of problems, and automatic switching capabilities more familiar to the Internet (like the routers sold by Cisco that break messages into packets and send them over several different routes to relieve congestion, only to reassemble them at the destination into your next e-mail). In addition, most renewable energy sources are intermittent, variable, and unpredictable. Large-scale storage of electricity to accommodate the erratic nature of such green power sources will be required in elevated reservoirs; in superconducting batteries, flywheels and magnets; and in underground compressed air and natural gas caverns [see also paper by Berry]. In short, the present U.S. electric grid will not work on any scale—local, state, national or international—at the higher loads and more diverse generation sources required in the future.

Why? At present, the grid is not even equipped to deal with the large increases in congestion and electricity traffic being stimulated by the long-distance demands of the new power trading and deregulation of U.S. electricity markets. Slow response times of mechanical switches, lack of automated analysis of problems, inability to "see the whole grid," are contributing to a noticeable increase in failures of the grid. These problems which have caused a dramatic increase in blackouts and brownouts since 1998, will propagate cascading failures of the grid more and more frequently unless we migrate to a new "smarter" or more intelligent grid control system because decision speeds increasingly are becoming too fast for humans to manage. As demand, sources of energy, and distances between demand and supply increase, the grid will become increasingly vulnerable not only to blackouts set off by equipment failures and weather, but also to terrorist attacks.

In order to be able to utilize massive amounts of renewable energy sources, it is necessary to first modernize the grid by installing digital controls, electronic switches, and higher capacity transmission lines, within the next ten years or so.

10 Year-out Technology Needs

The northeastern United States blackout of August 14, 2003, was not an isolated event. With any complex machine like the electric grid, there will always be the occasional failure. Since 1998, the frequency and magnitude of blackouts has increased at an alarming rate, however, deviating from the stable, predictable “fractal” pattern of the previous 15 years.² Blackouts in Chicago, Delaware, Atlanta, New Orleans, and New York in 1999, San Francisco and Detroit in 2000, and the infamous California “problems” of 2001 deviated from the predictable behavior of the previous 15 years in the United States. When examining the frequency of outages against the number of customers affected by each, we should have perceived clearer warnings that the system was going unstable long before August 14, 2003 (Figure 1).

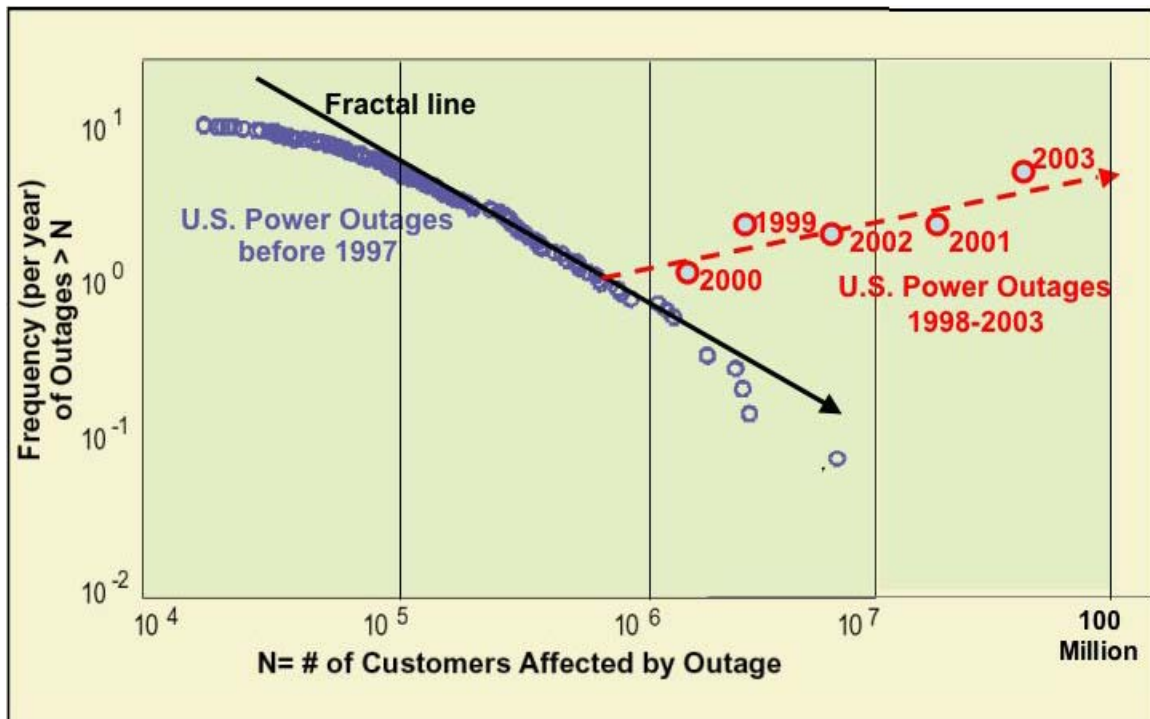


Figure 1. The U. S. electric grid has become more unstable since 1998, with more failures that affect large populations of customers than extrapolating of the previous 50 years would predict (Background plot from Amin, IEEE Computer Applications in Power, 2001).

A computerized control capability could be used to model and better understand the electric grid, yet none exists to date that can visualize the entire North American grid. Such computer assistance is particularly needed because the grid is exhibiting more and more behavior characteristic of chaotic systems. Since electricity on the grid is free flowing, it moves as power pulses at nearly the speed of light (10^{10} cm per second). However, in reality, electrons flow back and forth between the power plants and the consumers at speeds slower than the flow of these power pulses. The electrons can “only” move along the copper and aluminum wires and transformers of the transmission

grid at velocities between 10^7 and 10^8 cm per second.³ This disparity produces the “non-linear” behavior of the system affecting the flow of electricity in unpredictable ways.

In addition to computer software more akin to the internet or air traffic control systems, new hardware is needed to provide buffers to the cascades of failures that are caused by congestion and disruptions of the flow of electricity—failures that propagate across the grid. Power switches that combine thyristors (the electrical equivalent of transistors which direct information in the computer) to redirect flow with capacitors to provide buffering storage would give the grid operator the option of redirecting electricity around obstacles and disturbances at the speeds needed to forestall failures. Currently flow can only be redirected through the use of mechanical circuit breakers at speeds adequate for most present, but not future, conditions. There are a few of these experimental devices installed in the United States but their cost is currently too great for large-scale usage.

On top of such electronic aid, distributed storage and generation hardware such as High Temperature Superconductivity (HTSC) storage must be added to the transmission grid to provide the capability to smooth out intermittent and unpredictable flow from large-scale wind and solar farms. HTSC's have no resistance to electricity flow at supercritical temperatures, but if heated up, for example, by an electricity spike, HTCS become resistive and limit the propagation of the power surge. Surges and sags in power could then be dealt with in fractions of a second without shutting down the whole system. This technology is currently too expensive (see table 1), as well as being improperly incentivized to gain widespread use today. For example, regulators do not allow utilities to recover the costs of purchasing such equipment through consumer electricity rates. Yet these large-scale storage systems must be in place before we can decentralize the grid to accommodate significant amounts of smaller distributed generation (DG) and distributed storage (DS) capabilities. These kinds of new grid hardware, e.g., HTSC, thyristors, and capacitors—commonly grouped into the term “power controllers”—together with DG and DS, will make the overall grid network more efficient and stable by flattening out peak-demand spikes and load variability.

These power controllers would also allow operators to charge a higher fee for high quality power while no additional fees would be charged to users that don't need completely stable power. The ability, provided by power controllers, to switch the flow of electrons is required for this type of dual power system, in which higher quality, more reliable power can be delivered at an added cost only to those consumers that need it, while lower-quality, less reliable, less expensive power could be delivered to the rest of us. The home is little affected by momentary brownouts, but such brownouts wreck a semiconductor assembly line. Added revenue sources, such as from a dual system, are needed to attract the private capital that is needed to upgrade and maintain the long-distance transmission system so that it can accommodate vast new wind and solar “farms.” Presently, we all get the same high-quality, expensive power (99.999% of the time it is within a strict range of voltage and frequency, called “5 9's” in the power business).

Technology	Function	Timing	Unsolved Issues
Smart Grid Control Center: real time digital management of unpredictable electricity flow.	Automatic fault detection and rerouting power around congestion. Deliver of both high and low quality power on same grid.	Immediately needed. All other Smart Grid technologies require this.	Visibility across entire Grid. Human/Machine interaction. Will people be in the control room at all?
Digital Power Controller Substations: Thyristors, HTSC power limiters, capacitors, digital transformers.	Rerouting of power flow at the electronic command of the Control Center.	Near-term , next 10 years.	Cost too high by a factor of 10. Miniaturization of electronics. Security.
High Temperature Superconducting (HTSC) Storage: No-friction Flywheels, loop storage, surge limiters	Small-scale and large-scale storage of electricity, elimination of cascading surges and voltage sags.	Mid-term , next 20 years.	Cost too high by a factor of 100. Reliability
HTSC / Hydrogen Pipelines: Liquid Hydrogen Pipeline with HTSC transmission wires inside.	Enable combined electricity/hydrogen fuel distribution system.	Mid-term, next 20 years.	Cost too high by a factor of 1000. Reliability Security
Quantum Nano Transmission Wires: stronger than Kevlar, lighter than Polypropylene, 10X higher electrical conductivity than Copper	Increase efficiency and speed of delivery while virtually eliminating line losses. Can be buried without shielding or special trenching.	Long-term, next 30 years.	Cost unknown. Mass Production will require special-made petrochemical size plants. Weaved into "rope"

Table 1. Major new components of the new distributed Storage-Generation Smart Grid of the future.

20-30 Year-out Technology Needs

There is great promise that high temperature superconductivity and nano-meter scale technologies will deliver several breakthroughs that could revolutionize the grid 20-30 years out. The high temperature superconductor/liquid hydrogen (HTS/LH₂) super energy highway newly proposed by EPRI and DOE might provide the clean and green energy in both electrical and chemical forms to power urban transportation and electricity needs simultaneously. This “Super Grid” would use a high-capacity, superconducting power transmission cable cooled within a liquid hydrogen pipeline, with the hydrogen used in fuel cell vehicles and generators. The Super Grid would accelerate the deployment of HTSC technology by relaxing the stringent requirements and removing a major cause of failure of existing superconductors. At present HTSC costs are excessive because of the insulation requirements to keep HTSC devices cold. Placing the HTSC inside liquid hydrogen pipelines would eliminate the need to insulate them. In such a system, electricity and hydrogen provide a joint pathway for us to become progressively less dependent on fossil fuels, reducing GHG and pollutant emissions, and increasing the capability of the grid to accept large contributions of renewable energy sources.

Nano-scale transmission wires, called quantum wires (QW), might revolutionize the grid even further. QW has electrical conductivity that is higher than copper at one sixth the weight, and twice the strength of steel. A grid made up of such transmission wires would have no line losses or weather dependencies, eliminating the need for

massive emergency generation capacity, and the grid could be buried without any special handling. The transmission wires of the grid, if made from such QW would be virtually immune to weather-induced outages, especially if laid underground. QW will perhaps be spun into polypropylene-like rope that is non-corrosive and can be buried “forever” with no fear of corrosion and no need for shielding of any kind. However, massive factories will surely be required to “weave” the QW in the quantities needed by the grid. There are more than 700,000 miles of transmission lines in the United States alone at this time.

Barriers to Success

A smarter grid is required to provide efficient, clean, plentiful, safe and secure energy to power continued economic development with lessened environmental impact. It could even be a web-enabled, digitally controlled, intelligent delivery system for both power and transportation services.

How we get there from here is a much harder question. Currently, there are no incentives for fixing the grid beyond short-term patches like laying additional transmission wires around congestion. That strategy is much like urban highway construction – the more lanes a city provides, the more traffic the road attracts, producing more congestion, requiring more lanes, etc.

I believe we must create several national test beds to experiment with how to deploy new smart grid technologies on a large scale and in an integrated way. Such test beds would combine promising technologies (see Table1) in various configurations and experiment with how the system is improved through their use. Designing a smart grid is difficult to do if individual technologies are deployed in isolation. Such test beds MUST already be in operation within 10 years if we are to meet the power needs of the continent 20-30 years out. The grid cannot be experimented with “live.” We must be certain that the grid is capable of handling each new technology BEFORE it is deployed. It is not an option to connect new gadgets directly to the grid, and accidentally cause massive, cascading blackouts. The problem with creating such national test beds is that the electricity industry has among the lowest R&D expenditures of all companies (Technology review, 2003). The federal government must recognize the electric grid as vital to our prosperity and national security. A DARPA-like organization is required. DARPA (Defense Advanced Research Projects Agency) funded, among other developments, the Internet and super computers. Such an effort, dedicated to modernization of the electricity grid, is needed within the U.S. Department of Energy.

¹ U.S. DOE. 2003. *National Electric Delivery Technologies Vision and Roadmap*.

November. 2003. Available for download at: <http://www.energetics.com/electric.html>

² A relationship between two variables is defined as being “fractal” if it is linear when examined in exponential or “log-log” space...that is, the same across many scales.

³ Termed the Fermi velocity.