Challenges in Reliability, Security, Efficiency, and Resilience of Energy Infrastructure: Toward Smart Self-healing Electric Power Grid

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Electric power systems constitute the fundamental infrastructure of modern society. Often continental in scale, electric power grids and distribution networks reach virtually every home, office, factory, and institution in developed countries and have made remarkable, if remarkably insufficient, penetration in developing countries such as China and India.

The electric power grid can be defined as the entire apparatus of wires and machines that connects the sources of electricity, the power plants, with customers and their myriad needs. Once "loosely" interconnected networks of largely local systems, electric power grids increasingly host large-scale, long-distance wheeling of power from one region to another. Likewise, the connection of distributed resources, primarily small generators at the moment, is growing rapidly. The extent of interconnectedness, like the number of sources, controls, and loads, has grown with time. In terms of the sheer number of nodes, as well as the variety of sources, controls, and loads, electric power grids are among the most complex networks made.

Global trends toward interconnectedness, privatization, deregulation, economic development, accessibility of information, and the continued technical trend of rapidly advancing information and telecommunication technologies all suggest that the complexity, interactivity, and interdependence of infrastructure networks will continue to grow.

The existing electricity infrastructure evolved to its technology composition today from the convolution of several major forces, only one of which was technologically based. During the past 10 years, we have systematically scanned science and technology, investment and policy dimensions to gain clearer insight on current science and technology assets when looked at from a consumer-centered future perspective, rather than just incremental contributions to today's electric energy system and services.

Because of the way the electrical grid grew organically in response to customers' demands over decades, today's system has inherent resistance to new enabling technology assimilation. At best, this incumbent electric energy system can grow and possibly improve performance through incremental technology adoption—a diffusion dynamic that may not be fast and effective enough to meet the needs of the 21st century. 'Pushing harder' will likely have limited effect on this dynamic. In contrast, the system best meeting the various consumers' needs for the 21st century will need to be:

- Scalable, Robust, and Multimodal
- Able to rapidly and effectively exploit technology breakthroughs
- Capable of meeting diverse consumers' needs and give them service choices
- Ready to provide market dynamics such as elasticity between price and performance
- Economically and politically aligned to give simultaneous incentives to the major providers, users, and stakeholders.

A model or metaphor for the development of the existing and 21st century electric energy providing systems is the "Wintel" vs. MAC models[1], respectively, for personal computing. Windows and Intel were the major driving forces for the existing personal computer (PC) system. The dynamic was based on supply side engineering and limited by technology improvement and the economics of consumers' ability to absorb new products. The MAC approach, in this metaphor, was, from the start, based on consumer needs and choices and the development dynamic was to

[1] "Wintel" refers to the Windows operating system running on Intel microprocessors; a term often used to indicate the close alliance between Intel and Microsoft.

assemble the appropriate technology to meet those needs. This could be a model for a path to the perfect 21st Century electricity enterprise.

In addition, the electricity grid faces (at least) three looming challenges: its organization, its technical ability to meet 25 year and 50 year electricity needs, and its ability to increase its efficiency without diminishing its reliability and security. These three are not unrelated, as the grid's present organization reflects an earlier time when electrification was developing, objectives and needs were simpler, and today's technology was still over the horizon.

To understand the challenges we face in the immediate and distant future, it is helpful to give an overview of the current system. Currently, in North America we operate over 240,000 miles of high voltage electric transmission lines while electricity demand increased about 25% since 1990, construction of transmission facilities decreased about 30% (OE). In a report from the Edison Electric Institute, "Meeting U.S. Transmission Needs" (July 2005), the planned transmission lines (230 kV or greater) for the period 2004—2013 total approximately 7000 miles.

According to the Energy Information Administration (EIA), 281 GW of new generating capacity will be needed by 2025 to meet the growing demand for electricity; on the basis of current needs, this implies a need for about 50,000 miles of new HV transmission lines.

There are approximately 15,000 power plants ('generators') in the U.S., with an average thermal efficiency of approximately 33%. In addition, there are about 5,600 distributed energy facilities, representing about 6% of the U.S. power capacity in 2001. The voltage of the power produced varies significantly among the generators, but a typical figure is 25 kV. The size of the generators also varies, but 300 MW is typical. In 2002, the installed generating capacity in the U.S. was 981,000 MW. If the power plants ran full time, the net annual generation would be 8590×10^6 kWh; the actual net generation was 3840×10^6 kWh, representing a 'capacity factor' of 44.7%.

Chief Grid Problems

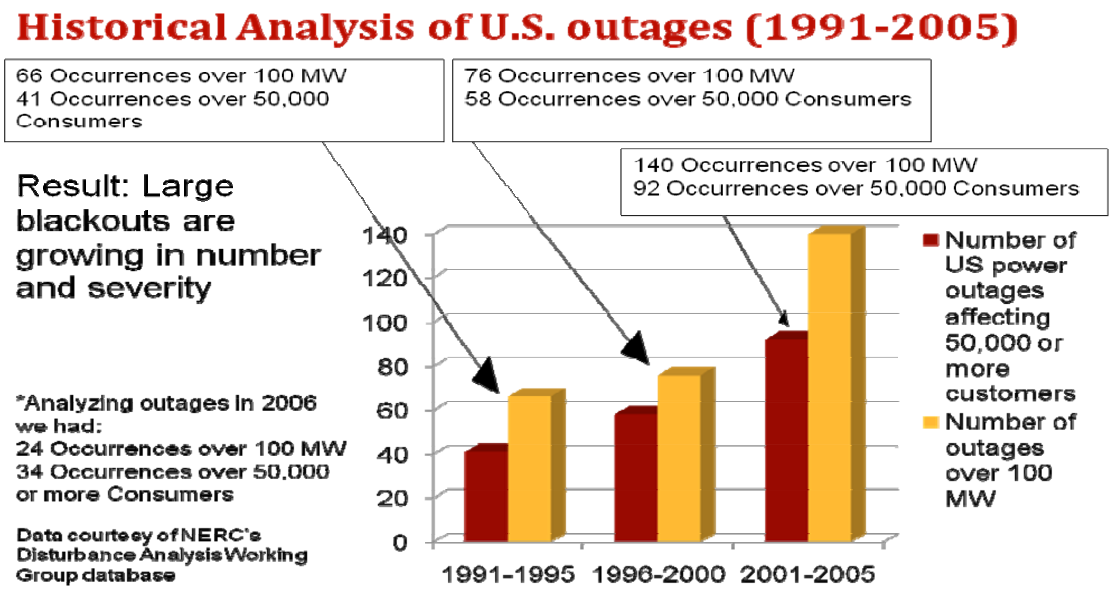
Several cascading failures during the past 40 years spotlighted our need to understand the complex phenomena associated with power network systems and the development of emergency controls and restoration. In addition to the mechanical failures, overloading a line can create power-supply instabilities such as phase or voltage fluctuations. 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.

According to data from the North American Electric Reliability Council (NERC) and analyses from the Electric Power Research Institute (EPRI), average outages from 1984 to the present have affected nearly 700,000 customers per event annually. Smaller outages occur much more frequently and affect tens to hundreds of thousands of customers every few weeks or months, while larger outages occur every two to nine years and affect millions. Much larger outages affect seven million or more customers per event each decade. These analyses are based on data collected for the US Department of Energy (DOE), which requires electric utilities to report system emergencies that include electric service interruptions, voltage reductions, acts of sabotage, unusual occurrences that can affect the reliability of bulk power delivery systems, and fuel problems.

Coupling these analyses with diminished infrastructure investments, and noting that the cross-over point for the utility construction investment vs. depreciation occurred in 1995 (Figure 1), we analyzed the number and frequency of major outages along with the number of customers affected during the decade 1991-2000; splitting it into the two time periods 1991-1995 and 1996-2000. Based on EPRI's analyses of data in NERC's Disturbance Analysis Working Group (DAWG) database, 41 percent more outages affected 50,000 or more consumers in the second half of the 1990s than in the first half (58 outages in 1996-2000 versus 41 outages in 1991-1995). The average outage affected 15 percent more consumers from 1996 to 2000 than from 1991 to 1995 (average size per event was 409,854 customers affected in the second half of the decade versus 355,204 in the first half of the decade). In addition, there were 76 outages of size 100 megawatts (MW) or more in the second half of the decade, compared to 66 such occurrences in the first half. During the same period, the average lost load caused by an outage increased by 34 percent, from 798 MW from 1991 to 1995 to 1067 MW from 1996 to 2000. In summary, the most recent outage data from NERC show that:

- 1991-1995:
  66 Occurrences over 100 MW
  41 Occurrences over 50,000 or more Consumers
- 1996-2000:
  76 Occurrences over 100 MW
  58 Occurrences over 50,000 or more Consumers
- 2001-2005:
  140 Occurrences over 100 MW
  92 Occurrences over 50,000 or more Consumers

These data from the NERC's Disturbance Analysis Working Group (DAWG) are a subset of the total outages that are required to be reported to DOE's EIA. Going through the more comprehensive data sets from DOE's EIA, during 2001-2005 there were 162 outages of 100 MW or more, and 150 outages affecting 50,000 consumers or more.



In addition, analyzing outages in 2006 (NERC's Data), in one year we had: 24 Occurrences over 100 MW and 34 Occurrences over 50,000 or more Consumers.

In this presentation, we focus on the technical, policy and economic aspects of these challenges: Improving existing technology through engineering and sound policy. For example, imagine what services electricity will be expected to provide in the next 20–50 years. A partial answer is: digital power, plug-in hybrids, communication, smart control of manufacturing (like current semiconductor fabrication plants) personal computers, phones, and entertainment. Some of these will rely on materials advances that will improve present technology (e.g., stronger, higher current overhead lines), some will enable emerging technology (e.g., superconducting cables, fault current limiters, and transformers), and some will anticipate technologies that are still conceptual (e.g., storage for extensive solar or wind energy generation).

Self-Healing Smart Grid

The North American electric power system developed over the last hundred years without a conscious awareness and analysis of the system-wide implications of its current evolution under the forces of deregulation, system complexity, power-market impacts, terrorism, and human error. The possibility of power delivery beyond neighboring areas was a distant secondary consideration. Today, the North American power network may realistically be considered to be the largest machine in the world. With the advent of deregulation and competition in the electric power industry, new ways are being sought to improve the efficiency of that network without seriously diminishing its reliability and security.

How to control a heterogeneous, widely dispersed, yet globally interconnected system is a serious technological problem in any case. It is even more complex and difficult to control it for optimal efficiency and maximum benefit to the ultimate consumers while still allowing all its business components to compete fairly and freely. We presented a brief overview of some of the key issues and the context in which the electricity infrastructure is being operated under the above forces; in this part we present a strategic vision of a self-healing smart grid, an "electrinet," extending to a decade, or longer, that would enable more secure and robust systems operation, security monitoring and efficient energy markets.

The first step in making the smart self-healing grid is to build a processor into each component of a substation. That is, 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 analog measurements from sensors built into the component.

When a new device is added to a substation—the new device automatically reports to the central control computers such data as device parameters and device interconnects. The central control computers thus get updated data as soon as the component is connected and do not have to wait until the database is updated by central control personnel.

The joint Electric Power Research Institute (EPRI) and U.S. Department of Defense (DOD) program, through the Complex Interactive Networks/Systems Initiative (CIN/SI) involved studying a broad spectrum of challenges to the power grid, energy and communication infrastructures and developed modeling, 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 secure communication and controls.

As part of enabling a self-healing grid, we have developed adaptive protection and coordination methods that minimize impact on the whole system performance (load dropped as well as robust rapid restoration).

Note that while computation is now heavily used in all levels of the power network, e.g. for planning and optimization, fast local control of equipment and processing of field data, coordination across the network happens on a slower time-scale, based on a system of operation developed in the 1960s . Some coordination occurs under computer control, but much of it is still based on telephone calls between system operators at the utility control centers, even-or especially during emergencies.

In any situation subject to rapid changes, completely centralized control requires multiple, high-data-rate, two-way communication links, a powerful central computing facility, and an elaborate operations control center. But all of these are liable to disruption at the very time when they are most needed (i.e., when the system is stressed by natural disasters, purposeful attack, or unusually high demand).

When failures occur at various locations in such a network, the whole system breaks into isolated "islands," each of which must then fend for itself. With the intelligence distributed, and the components acting as independent agents, those in each island have the ability to reorganize themselves and make efficient use of available local resources until they are able to rejoin the network. A network of local controllers can act as a parallel, distributed computer, communicating via microwaves, optical cables, or the power lines themselves, and intelligently limiting their messages to only that information necessary to achieve global optimization and facilitate recovery after failure.

The EPRI/DOD CIN/SI aimed to develop modeling, simulation, analysis, and synthesis tools for robust, adaptive, and reconfigurable control of the electric power grid and infrastructures connected to it. In part this work showed that the grid can be operated close to the limit of stability given adequate situational awareness combined with better sensing of system conditions, communication, and controls and. Grid operators often make quick decisions under considerable stress. Given that in recent decades we have reduced the generation and transmission capacity, we are indeed flying closer to the edge of the stability envelope.

However, these technologies will require sustained funding and commitment to Rⅅ given the state of art in electricity infrastructure security and control as indicated in this article, creating a smart grid with self-healing capabilities is no longer a distant dream; we've made considerable progress. The cost of a self healing smart grid will not be cheap --- some estimated are as much as $10-$13 billion per year needed for a period of ten years or more for real-world testing and installation. But then the price of electrical failure, an estimated over $80 billion per year, is not cheap either.

There are signs too that Congress and the government recognize the need for action. Recently the White House OSTP and the U.S. Department of Homeland Security (DHS) declared the Self-healing Infrastructure as one of three strategic thrust areas for its National Plan for R&D in Support of Critical Infrastructure Protection. But considerable technical challenges as well as several economic and policy issues remain to be addressed. At the core of the power infrastructure investment problem lie two paradoxes of restructuring, one technical and one economic. Technically, the fact that electricity supply and demand must be in instantaneous balance at all times must be resolved with the fact that new power infrastructure is extraordinarily complex, time-consuming, and expensive to construct. Economically, the theory of deregulation aims to achieve the lowest price through increased competition. However, the market reality of electricity deregulation has often resulted in business-focused drive for maximum efficiency to achieve the highest profit from existing assets and not resulting in lower prices or improved reliability. Both the technical and economic paradoxes could be resolved by knowledge and technology.

Given economic, societal, and quality-of-life issues and the ever-increasing interdependencies among infrastructures, a key challenge before us is whether the electricity infrastructure will evolve to become the primary support for the 21st century's digital society—a smart grid with self-healing capabilities—or be left behind as an 20th century industrial relic.

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