Power Systems Engineering Research Center

PSERC Background Paper

Power System Operations and Visualization

Thomas J. Overbye
Professor, Department of Electrical and Computer Engineering
University of Illinois at Urbana-Champaign

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Before the August 14th 2003 blackout most people gave little thought to the source of the power that comes out of the electric outlet. And why should they? The electric power grid had been designed as the ultimate in plug-and-play convenience – plug-in the toaster or any other electrical device, and it worked. When things work as expected, and they usually do, consumers receive all the electricity they need at (hopefully) a reasonable price. But behind that humble outlet lurks one of the largest, most complex machines ever created. Most of the entire electric grid in the eastern half of North America is really one big electric circuit called the "Eastern Interconnect." This grid encompasses billions of individual components, tens of millions of miles of wire, and thousands of individual generators. A large electric grid like the North American Eastern Interconnect supports energy businesses located hundreds of miles apart that can buy and sell electric energy, taking advantage of opportunities to produce and purchase generation cost-effectively. As a result, thousands of power transfers are occurring simultaneously.

Keeping the Electricity Flowing

But being an electrical circuit, the grid obeys the laws of physics. Electricity moves from generators through transmission and distribution systems (the wires) to customers at nearly the speed of light. Since today there is no way to realistically store bulk quantities of electricity, the total amount of electricity generated must be continually matched to how much is being used. In other words, total outputs of all the generators must be matched continuously with the total load. Thus, the electric grid represents the ultimate in "just in time" manufacturing, with "fresh" electricity delivered to customer power outlets within milliseconds of being "manufactured" by the generators. Customers control how much electricity is used at any point in time. They are never placed on hold, or told to "call back later."

As opposed to the positive control over when and how much electricity is used, there is little control over where electricity flows through the transmission system from the generators to customer loads. There are no “valves” engineers can open or close to control the flow of electricity down a particular line, short of cutting off the flow on the line completely by opening a circuit breaker. The electrons do not check a map (or a contract) to determine the shortest route from the generator to the load. Instead, electric power flows through the transmission system based on the relative resistance to power flows of each transmission line across the system, the locations where power is injected into the transmission network by generators, and where it is taken out to serve customers.

The challenge for people operating the electric grid is to keep everything in balance. For example, just like an extension cord from the local hardware store, each transmission line has a maximum electric current or power rating, usually expressed in either amperes or watts (or more typically megawatts, MW, with 1 MW equal to one million watts or, very roughly, enough power for 350 to 400 residential customers). A useful equation used by power engineers is that the total power flowing down a line is equal to the line’s voltage, expressed in volts or kilovolts (that is, 1,000 volts or kV) multiplied by the current. If the flow on a line gets too high, its wires start to heat, causing the line to sag. Although some sag is expected, excessive sag could possibly result in a short circuit (or “fault”) if the line comes in contact with something underneath the line, like a tree. Power system operators and engineers are also concerned about making sure the electric voltage stays high enough to avoid problems for customer equipment and about reducing the risk that cascading outages of transmission lines, generators, etc. occurs.

Control Centers in Power Systems

While the North American Eastern Interconnect is one big electric circuit, operationally it is divided into a number of much smaller control areas. Often each control area consists of the service territory of a particular utility, although sometimes the control areas span multiple utilities. Presently, there are more than 100 control areas in the Eastern Interconnect, with some being quite large, like the PJM area in Pennsylvania, New Jersey and Maryland, and some being quite small, with perhaps just a single generation plant or a medium-sized city. Each control area has a control center, staffed 24/7, charged with keeping the grid operating with no overloads.

With electric power industry restructuring, the control areas now operate under the oversight of North American Reliability Council “reliability coordinators.” The reliability coordinators may oversee just a single control area, such as PJM, or they may oversee many, such as with the Midwest Independent System Operator (MISO) that oversees more than twenty control areas.

Keeping transmission lines from overloading (and possibly triggering a cascading blackout) is a combination of good planning and good operations. Planning spans a timeframe of hours to decades. On the shorter hourly timeframe, operations planners must decide how many power transfers to allow to avoid any overloads. On the longer timeframe, planners must decide what lines to build and, to a lesser degree today due to the emergence of “merchant” generators, where generators can be located. This is a decision-making process with a long-term perspective since power transmission lines and generators cannot be built overnight. The process often requires coordination between various parties, since transmission lines can span the service territories of multiple utilities and may cross state lines.

In the here and now when the power system is actually operating (what engineers call “real-time”), the job of keeping the grid operating correctly is done by “system operators” working in control centers. These folks continually monitor the grid using a computer system known as SCADA (or supervisory control and data acquisition). SCADA allows operators to see the power flows and voltages throughout their portion of the electric network. Of course, if the planners have done their job and nothing unusual occurs, then everything should run just fine. The operators’ jobs would then consist mostly of routine tasks, such as taking electric lines out-of-service for regularly scheduled maintenance and doing other routine work.

On most days the grid works as expected. The operators’ jobs are filled with the routine. But on many days the unexpected does occur. Since much of the transmission grid consists of overhead wires, the grid takes its share of hits from the weather or a fast-growing tree might get close enough to a line to cause a short circuit. Large generators may also fail unexpectedly, substantially changing the power flows in the grid. The weather might also be hotter than forecasted, causing a large increase in customer loads.

Much of the power grid operation is automated. As described in other PSERC background papers, automatic protection systems are used to sense faults on the power system and disconnect the affected equipment in time, quicker than the blink of an eye. For example, if lightning strikes a transmission line causing a short circuit, the line is automatically opened to isolate the short circuit from the system, and then often returned to service several seconds later after the lightning-induced short circuit has gone away. Also, a system known as automatic generation control (AGC) is used to automatically change the output of the electric generators to match the changing load, while some other devices automatically change their settings to keep the electric system voltages within acceptable bounds. This automation is essential to keeping the grid working.

But the power grid is much less automated than many people realize. The human operators and engineers are very much “in the loop.” Unexpected events often require human judgment to determine the best course of corrective action. For example, operators might need to curtail power transactions, directly change the outputs of generators, open transmission lines, or, as a last resort, “shed load” by deliberately disconnecting customers. Fast, effective human actions are often essential. In addition, some responses to power system problems require coordination across control areas. Much of this operator-to-operator communication is by telephone today. The response may require curtailment of transactions (referred to as a “transmission line relief” or TLR). These actions are initiated by reliability coordinators.

Power System Visualizations

Increasingly visualization tools are helping operators and engineers figure out what is going on in a power system. Enhancements in these tools are occurring through research and development by PSERC researchers and its member companies, both alone and working with the U.S. DOE's Consortium for Electric Reliability Technology Solutions (CERTS) program. For example, key to understanding the state of the transmission grid is knowing the current flows and percentage loading of the various transmission lines. This can, however, be quite difficult to determine, particularly for large systems. Rather than looking at a whole bunch of numbers, a newer technique is to use dynamically-sized arrows to show how the power is actually flowing through a large portion of the system, such as shown in Figure 1.[1]

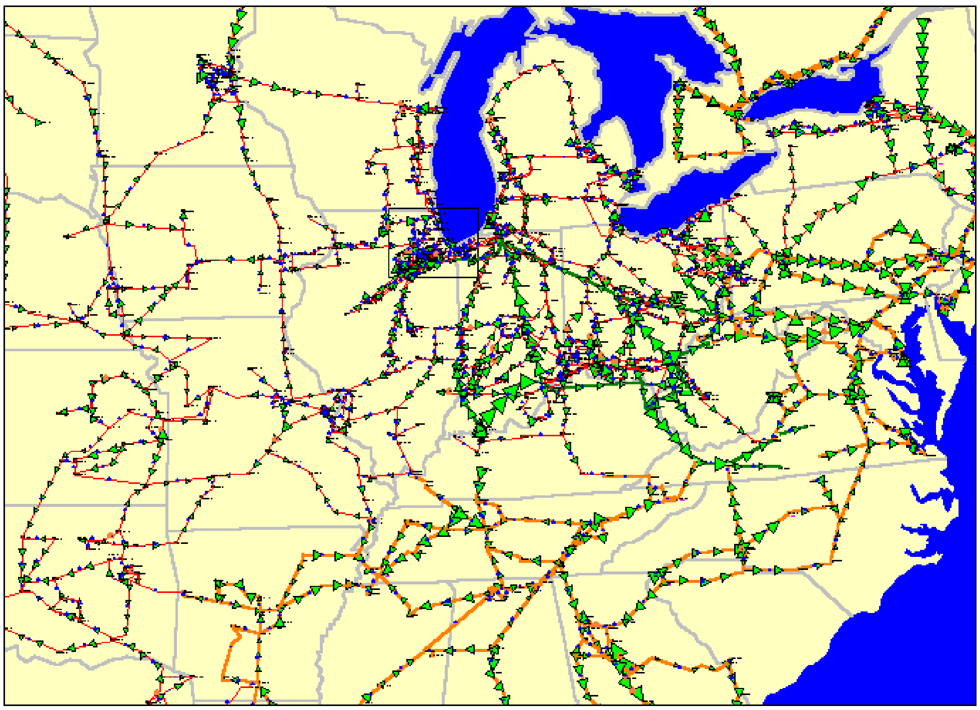

Figure 1: High Voltage Line Flows in Eastern U.S. This figure shows a one-line diagram of the high voltage (345 kV and above) transmission grid in a portion of the North American Eastern Interconnect. The arrows point in the direction of power flow with each arrow's size proportional to the MW flow on the line. This figure shows how interconnected the bulk power transmission grid is. Although there can be significant power flows on certain lines, these may not be the "congested" lines in a system. The power flow rating (or limit) on any one line can pose a bottleneck to transferring power between points in the system.

[1] For further reading on visualization, see Visualization of Power Systems, PSERC Report 02-36, November 2002, at http://pserc.org, or the Feburary 2001 *IEEE Spectrum* article, "Visualizing the Electric Grid," available online at http://www.spectrum.ieee.org/WEBONLY/publicfeature/feb01/egrid.html.

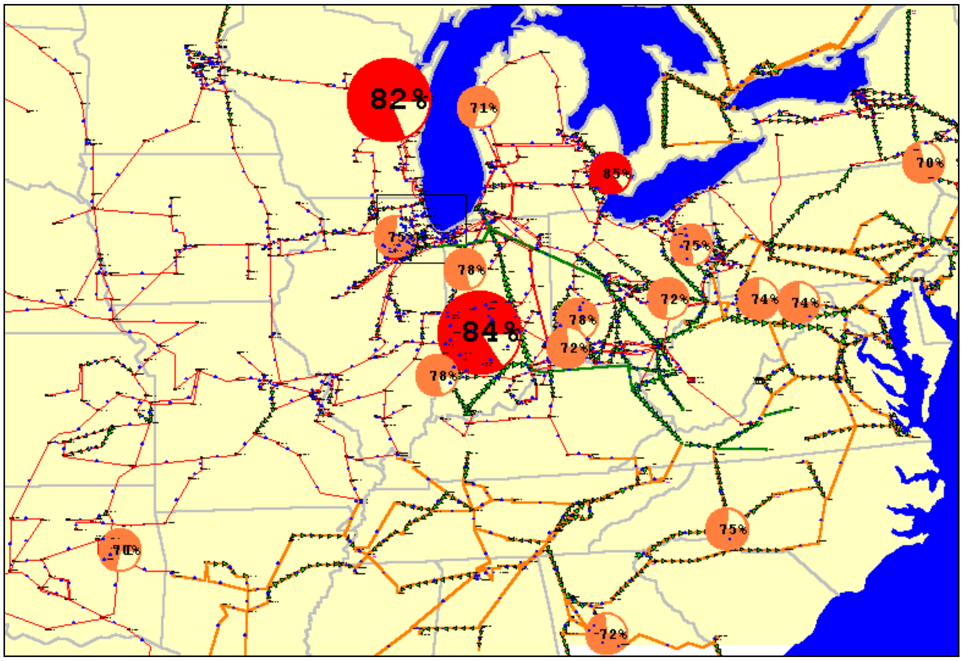

Figure 2: Pie Charts Showing Line Percentages of Line Capacity Being Use. This figure shows that multiple lines can be congested at the same time. When congestion is occurring in lines in the same region, that region can be more vulnerable to cascading outages; in other words, if a line fails in that region, it may be that one or more of the congested lines will subsequently become overloaded and fail, too.

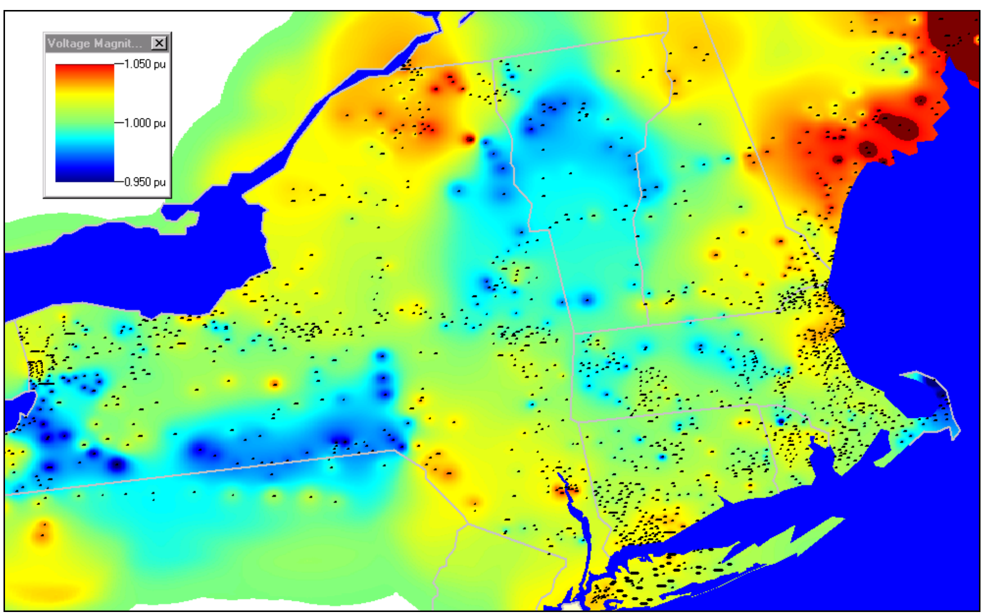

Figure 3: Voltages Magnitudes at 115/138 kV Buses in New York and New England. Transmission voltages are closely monitored in power systems. Equipment damage can occur if voltages get too low or too high.

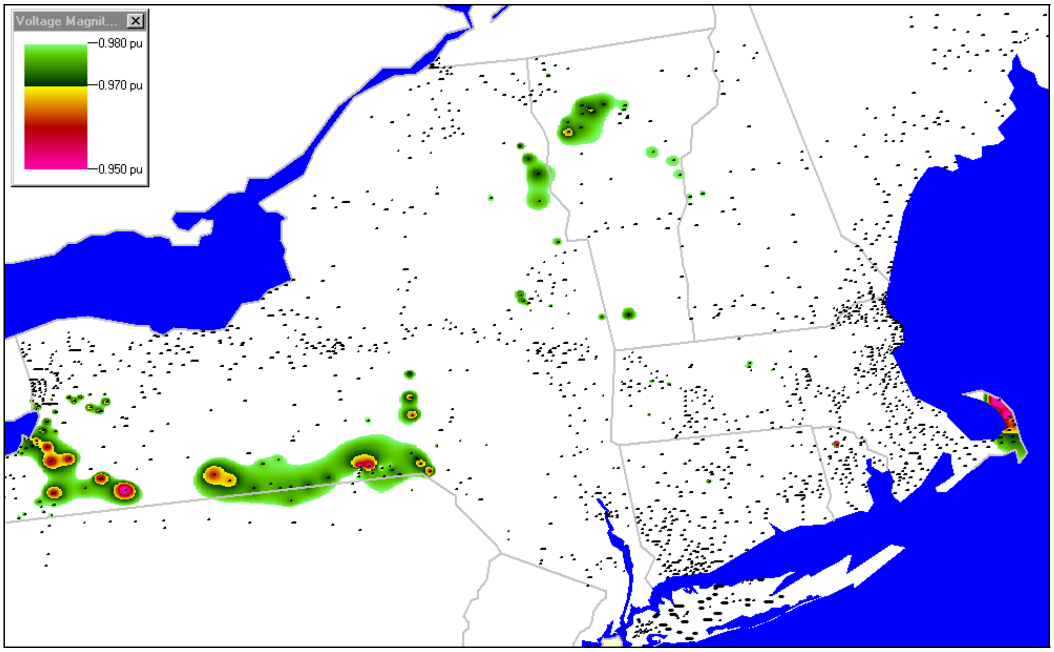

Figure 4: Voltage Magnitudes at 115/138 kV with Values below 98% of Normal. Some variation in voltages in a transmission system can be acceptable, particularly under high customer load conditions. Extreme variation requires an operator response. Low voltage is a particular problem in power systems because it can lead to excessive current flows that overheat transmission lines and can make the system more vulnerable to instabilities. Voltage collapse will lead to a blackout of a region or to "islanding" in which the interconnection system separates into sub-regions that are individually capable of generating enough power to meet the customer load in that sub-region. To solve a low voltage situation, operators may add generation, reduce customer load (that is, interrupt service to selected customers, perhaps some who may have agreed to an interruptible service contract), reduce power system transactions in the region (through transmission line loading relief) or actually disconnect certain transmission lines.

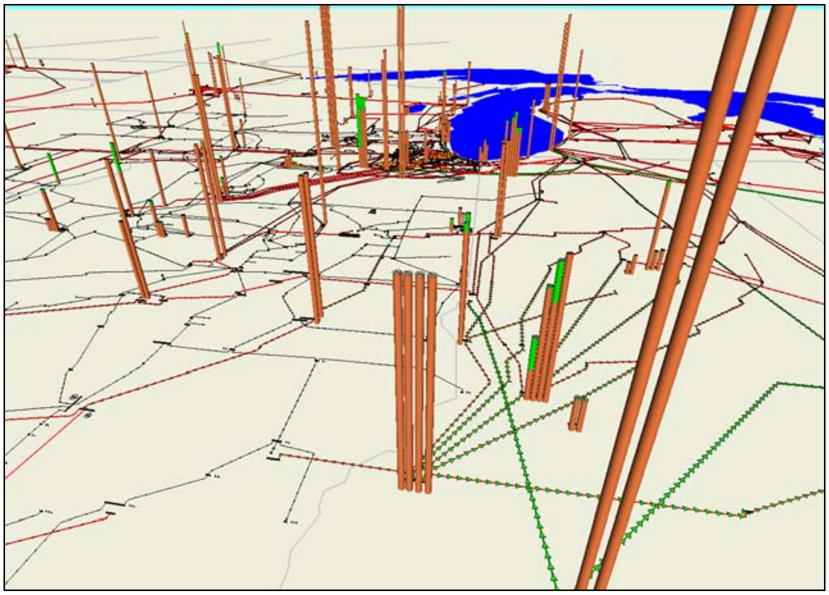

Figure 5: Three-Dimension View of the Midwest Power Grid with Generators. There is great diversity in types and sizes of generators in power systems. This figure shows the capacity of generating units that are operating at a selected moment in time; the taller the column, the higher the capacity. The green area is the reserve capacity, or the amount of generating capacity that is not currently being used at that moment. When one of these generating units trips (that is, no longer is connected to the grid), there can be major changes in transmission line flows

Figure 6: Commonwealth Edison Control Center in Northern Illinois. Control centers are busy places, with data coming from hundreds of sources that has to be quickly processed and interpreted. Visualization tools contribute to turning data into "information" useful for decision-making.

Contact Information

Thomas J. Overbye
Professor, Department of Electrical and Computer Engineering
1406 W. Green St.
Urbana, IL 61801
Phone: (217) 333-4463
Fax: (217) 333-1162
email: Overbye@ece.uiuc.edu

Power Systems Engineering Research Center
428 Phillips Hall
Cornell University
Ithaca, NY 14853-5401
Phone: 607-255-5601