New Methods for the Visualization of Electric Power System Information

Thomas J. Overbye
University of Illinois at Urbana-Champaign
overbye@ece.uiuc.edu

Jamie D. Weber
PowerWorld Corporation
weber@powerworld.com

Abstract

One area in need of new research in information visualization is the operation and analysis of large-scale electric power systems. In analyzing power systems, one is usually confronted with a large amount of multivariate data. With systems containing tens of thousands of electrical nodes (buses), a key challenge is to present this data in a form so the user can assess the state of the system in an intuitive and quick manner. This is particularly true when trying to analyze relationships between actual network power flows, the scheduled power flows, and the capacity of the transmission system. With electric industry restructuring and the move towards having a single entity, such as an independent system operator or pool, operate a much larger system, this need has become more acute. This paper presents several power system visualization techniques to help in this task. These techniques include animation of power system flow values, contouring of bus and transmission line flow values, data aggregation techniques and interactive 3D data visualization.

1. Introduction

One area in need of new research in information visualization is electric power system operation and analysis. Most people give little thought to the source of the power that comes out of the electric outlet. And why should they? The electric power grid has been designed as the ultimate in plug-and-play convenience. The regulated monopoly structure of the electric utility industry meant that consumers had no choice but to buy power from their local utility. Electric utilities were vertically integrated "natural" monopolies serving captive markets. That is, the electric utility did everything in a particular geographic market, from owning and operating the generation, owning and controlling the transmission grid in that market, to providing the wires that actually connected to the customer. Hence there was little competition within the industry and little need for new visualization techniques.

But the times they are a-changin. The electric power industry in the United States and throughout much of the world is in a period of radical and rapid restructuring. The ultimate goal of much of this restructuring is lower prices, to be achieved through the development of competitive markets for electricity. The regulated monopoly structure is rapidly being replaced by a paradigm of "open access" by all to the transmission grid. In the United States Congress passed the Federal Power Act in 1992. This legislation required opening the transmission grid to competition. In 1996 to implement this competition the Federal Energy Regulatory Commission (FERC) issued Orders 888 (Promoting Wholesale Competition Through Open Access, Nondiscriminatory Transmission Services by Public Utilities), and 889 (Open Access Same-Time Information System). Thus the means to achieving the goal of lower costs is to superimpose a highly competitive market on the existing high voltage transmission grid.

Easier said than done. The humble wall outlet is actually a gateway to one of the largest and most complex man-made objects ever created. For example, in North America the entire electrical grid is really just one big electric circuit, excepting a few islands and other small isolated systems. This grid encompasses billions of individual components, tens of millions of miles of wire and thousands of individual generators with power outputs ranging from less than 100 kW to more than 1000 MW.

But being an electrical circuit, the grid obeys the laws of physics. However, these physical laws are often at odds with the artificial rules being imposed on the grid to facilitate competitive markets. The result: high price volatility and increased potential for widespread blackouts [1]. An extreme example of this new volatility in prices occurred during the later part of June 1998. For several days electricity spot market prices in the Midwest soared *three hundredfold* from typical values of 2.5 cents per kWh to $7.50 per kWh. Because the affected utilities were only able to charge their customers fixed rates of less than 10 cents per kWh, they lost a lot of money very quickly. And, of course, others made money. Other markets have experienced almost as much volatility both during 1998, 1999 and most recently in summer of 2000.

Most germane to the information visualization issue is the cause of this price volatility. During the June 1998 price spike generation was in short supply in the Midwest due to high electric demand from hot weather. It was, however, available elsewhere on the grid. But because of thermal overloads on just two devices – a transmission line in Northwest Wisconsin and a transformer in Southeast Ohio – no additional power could be transferred into the Midwest from either the West or the East. The reason: loop flow. The electric power flow associated with a transaction between two utilities does not flow along a path specified by a legal contract. Rather, it spreads out through a significant portion of the grid, looping around so to speak. In the event of an overload of a transmission system device new power transactions are not allowed if any of the transfer would flow through the overloaded device in the direction to increase the device's loading; existing transactions may also need to be curtailed.

For example, the shaded region in Figure 1 contours the utilities (shown with the small ovals) that could not sell additional power to a utility in Northern Illinois because of the two overloads mentioned above. The contour indicates the percentage of the power transfer that would have flowed through the overloaded devices. Shaded utilities on the left could not sell because of the overload in Northwest Wisconsin, those on the right because of the overload in Southeast Ohio.

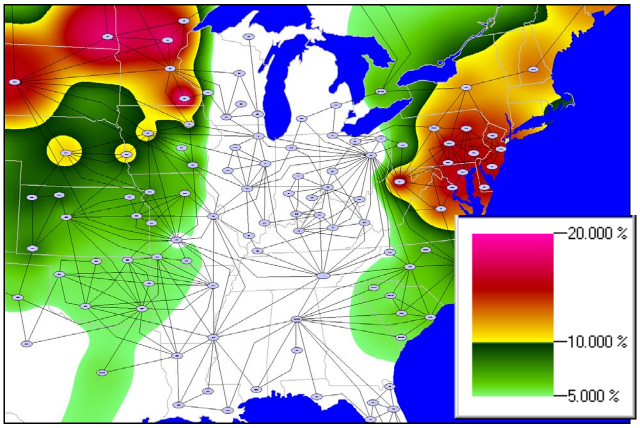

Figure 1: Utilities Unable to Sell Power to Northern Illinois during June 1998 Price Spike

The extreme economic consequences of overloads in the transmission grid has served as a wake-up call to the electric power industry concerning the need for better methods for visualization of power system economic and engineering information. For the most part, visualization tools for power engineering have evolved little beyond the "one-line diagram[i]." The one-line diagram is a roughly geographic representation of all the transmission lines, transformers, generators and major load centers within the grid. Great latitude is often given from exact geography, since areas with a high concentration of electric facilities (e.g., urban areas) are usually greatly expanded. In a typical utility control center, system quantities, such as power flows and voltages, are usually represented with analog fields on a set one-line diagram consisting of all the utility's substations. Other values are usually shown with tabular numerical fields. An overview of the system is usually only available on a static map board with the only dynamic data shown using different colored lights.

This needs to change. Restructuring is resulting in the creation of much larger markets. Rather then transacting with their neighbors, utilities are buying and selling in a transcontinental market. Restructuring is resulting in the creation of much larger markets under the control of a single system operator. For example, the proposed Midwest Independent System Operator will be responsible for the operation of the grid in portions of eleven states [2]. This will result in even more buses and other devices to monitor and control. Simultaneously, the entry of many new players into the market and the increase in power transfers will result in even more data to manage. Finally, electric grid operators will come under increased scrutiny since their decisions, such as whether to curtail particular transactions, can have a tremendous financial impact on market participants. Power system analysis will need to be modified in a number of different ways to handle these new challenges. One such modification is in how system information is presented to the user. In this paper several new techniques for the visualization of system information are presented.

Earlier work has, of course, been done in the area of developing visualization techniques to aid in interpreting power system data, although few have actually made it into the hands of practicing engineers. Several recent examples are described in [3]-[9]. This paper addresses several methods of visualization for helping users extract useful information associated with grid operation from the tidal wave of power system data. These techniques include animation of power system flow values, contouring of bus and transmission line flow values, data aggregation techniques and 3D visualization. Results are shown for several large scale power systems. The

---

[i] So named because the actual three conductors of the underlying three phase electric system are represented using a single equivalent line.

techniques presented here have been implemented in PowerWorld Simulator [10]; earlier versions of this package have been described in [11], [12], [13].

2. Line Flow Visualization

Key to understanding the state of the grid is knowing the current flows and percentage loading of the various transmission lines. This can, however, be quite difficult, particularly for large systems. By far the most common means for representing transmission grid flows is through the use of the one-line diagram. Traditionally MW/Mvar/MVA flows on transmission line and transformer (lines) have been shown using digital fields. Such a representation provides very accurate results, and works well if one is only interested in viewing a small number of lines.

One newer technique is to supplement such representations with animation used to illustrate how power is actually flowing in a system [12]. For example, Figure 2 shows a one-line diagram of the high voltage (345 kV and above) transmission grid in the Eastern Interconnect in North America. The actual power flow model itself contains over 30,000 electrical nodes (buses) and 41,000 high voltage lines. Only the small number of high voltage buses and lines are initially shown on the one-line. To indicate the direction of real power flow (MW), small arrows are superimposed on each transmission line, with the arrow pointing in the direction of the flow and the size of the arrow proportional to the MW flow on the line. The advantage of this one-line approach is even when using a static representation, such as a figure in a paper, the reader can quickly get a feel for the flows throughout a large portion of the system.

However a much more dramatic affect is achieved when the flows are animated. With modern PCs animation rates of greater than ten times per second can be achieved even on large systems such as shown in Figure 2. The effect of the animation is to make the system appear to "come to life". Our experience has been that at a glance a user can gain deep insight into the actual flows occurring on the system. The use of panning, and zooming with conditional display of objects gives the user the ability to easily study the flows in a large system.

Another visualization idea that has proven useful for quickly indicating the loading on a large network has been the use of dynamically sized pie-charts. Figure 3 again shows the Figure 2 system with pie-charts used to indicate the loading on each line; for this example the animated flows have been reduced in size. The percentage fill in each pie-chart is equal to the percentage loading on the line, while the size and color of the pie-chart can be dynamically sized when the loading rises above a specified threshold. Assume in the Figure 3 case the user was only concerned with those lines at or above 70% loading. By specifying that the pie-chart increase in size by a factor of 5 if above 70% or a factor of 7 if above 80%, it is easy, even in a large system, to see the heavily loaded lines. Using pie charts to visualize these values is helpful, but this technique also runs into difficulty when a large number of pie charts appear on the screen. To remedy this problem, an entirely different visualization approach is useful: contouring.

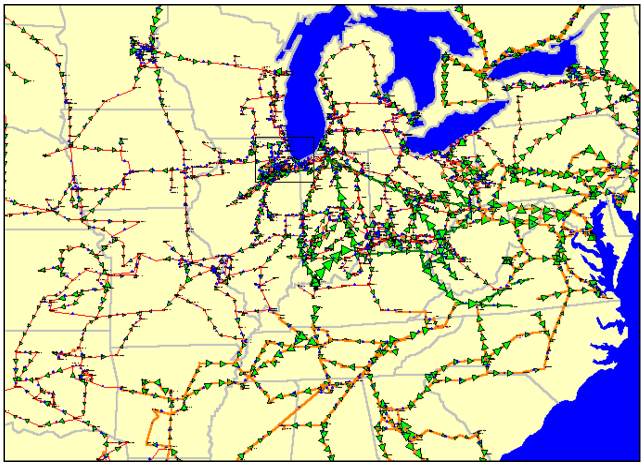

Figure 2: High Voltage Line Flows in Eastern U.S.

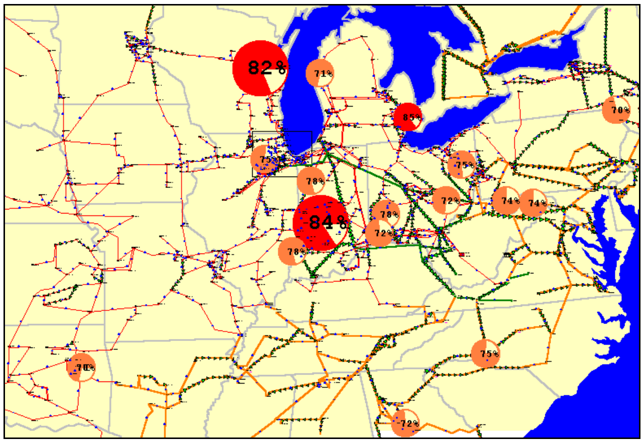

Figure 3: Pie Charts Showing Line MVA Percentages

3. Contouring Bus Data

For decades, power system engineers have used one line diagrams with digital numerical displays next to each bus to represent bus-based values. The advantage of this numerical display is that the results are highly accurate and are located next to the bus to which they refer. The disadvantage of this display is it is impractical when one wants to examine more than a handful of buses, say to find a patterns in the power system. To overcome this problem the use of contouring is presented [9], [14], [15].

Contours have, of course, been used extensively for the display of spatially distributed continuous data. The problem with displaying power system data with a contour is that it is not spatially continuous. Voltage magnitudes only exist at buses. Therefore virtual values must be created to span the entire two-dimensional contour region. The virtual value is a weighted average of entire by data points with different averaging functions providing different results [15]. Once these virtual values are calculated a color-map is used to relate the numeric virtual value to a color shown on the screen. A wide variety of different color maps are possible, with one common mapping being the use of blue for lower values and red for higher values.

An example is shown in Figure 4, which contours the voltages at approximately 1000 of the 115 and 138 kV buses in the New York and New England regions. As can be seen, the contour provides an overview of the voltage profile of the entire region. Of course other contour mappings could be used. Figure 5 shows the same case, but with a color mapping such that only those buses with voltage magnitudes below 0.98 per unit are highlighted.

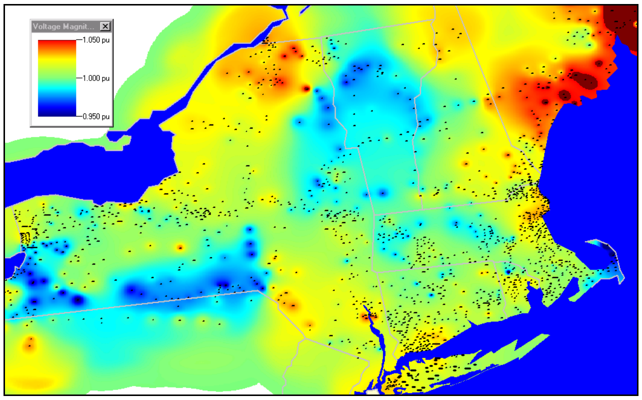

Figure 4: Voltages Magnitudes at 115/138 kV Buses in New York and New England

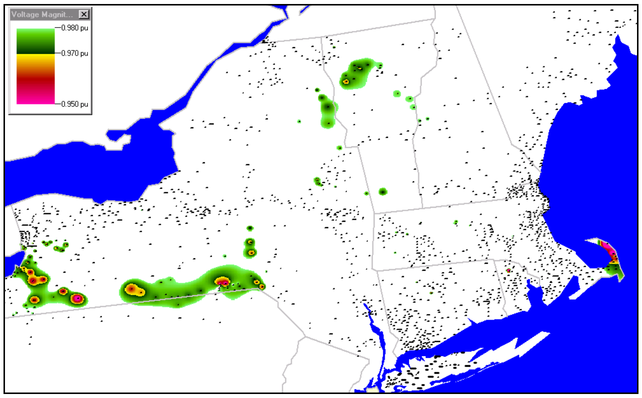

Figure 5: Voltage Magnitudes at 115/138 kV with Values below 0.98 per unit

Finally, contouring need not be restricted to bus voltage magnitudes. Electricity markets are increasingly moving towards spot-market based market mechanisms [16] with the United Kingdom, New Zealand, California Power Exchange in the Western U.S., and PJM Market (covering parts or all of Pennsylvania, New Jersey, Maryland, Delaware, Virginia and the District of Columbia) in the Eastern U.S. as current examples. In an electricity spot-market, each bus in the system has an associated price. This price is equal to the marginal cost of providing electricity to that point in the grid. Contouring this data allows market participants to quickly assess how prices vary across the market. As an example, Figure 6 plots the actual locational marginal prices (LMPs) in the PJM market on 2:00 pm, Friday August 20, 1999. The variation in prices is due to constraints in the transmission grid. In this case, lower priced electricity is available in Pennsylvania, but transmission constraints prevent electric users in Maryland and the District of Columbia from obtaining this power.

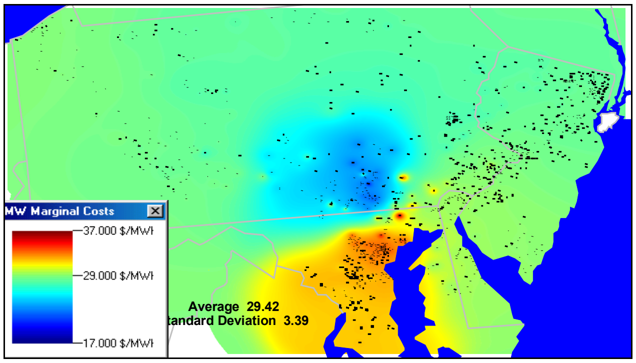

Figure 6: Locational Marginal Prices in PJM at 2pm on August 20, 1999.

Similarly, the technique could be used to contour the LMPs generated by an optimal power flow (OPF) study. Figure 7 shows the same contouring technique applied to the OPF results of a study using a 9270 bus system to model bus marginal prices in the Northeast U.S. [17] . In this study marginal prices were calculated for 5774 buses, with approximately 2000 of these values used in creating the Figure 7 contour. The contour is superimposed on a map of the high voltage transmission lines in the Northeast. Pie charts are used to indicate the constrained transmission lines (i.e., those loaded to 100% – note the price differential between New York and New England caused by a constrained line on Northern New York/New England boundary.

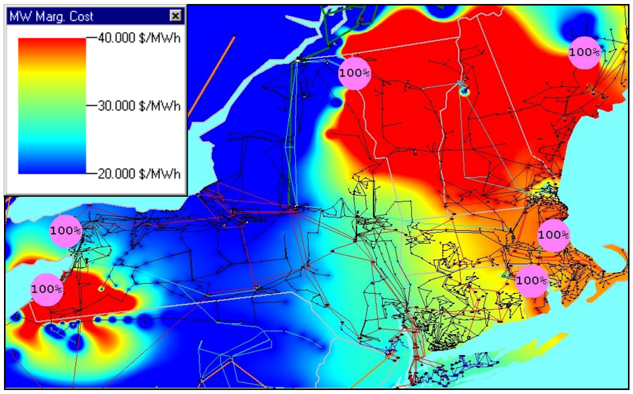

Figure 7: Locational Marginal Prices for Northeast U.S.

4. Contouring Line Data

Besides being useful to represent bus-based values, contouring can also be applied to line-based values. As an example, Figure 8 shows about 1400 of the 345 kV and above lines of the U.S. portion of the North American Eastern Interconnect. Superimposed on the one-line is a contouring highlighting the line flows that are above 50% of their MVA rating. Again, the advantage of the contour approach is at a glance it is possible to determine the location of potential system congestion even in a very large system. Similar to the Figure 5 case, the key to the successful application of contouring on the data set is to only contour the information of interest to the user, in this case lines loaded above 50% of their limits. Less heavily loaded lines are not of interest and hence not included in the contour.

Line contouring can also be used to visualize transmission line power transfer distribution factors (PTDFs). In short, a PTDF value shows the incremental impact a power transfer, from a specified source of the power to a specified sink for the power, would have upon each power system element. For example, if a line has a PTDF value of 10% for a particular power transfer, then 10% of that power transfer would flow on that line – if the power transfer is 300 MW, the line's MW loading would change by 30 MW.

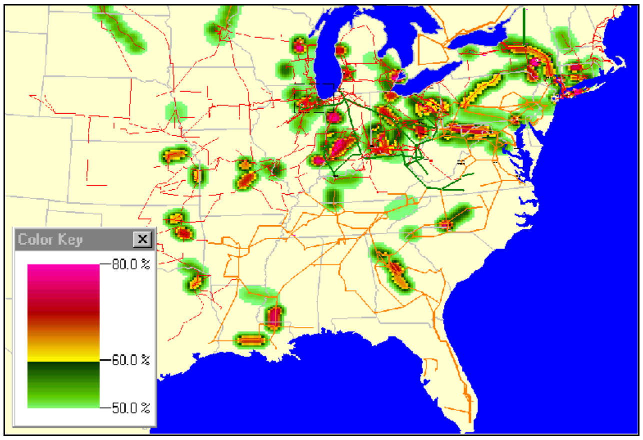

Figure 8: Eastern Interconnection Line Loading Contour

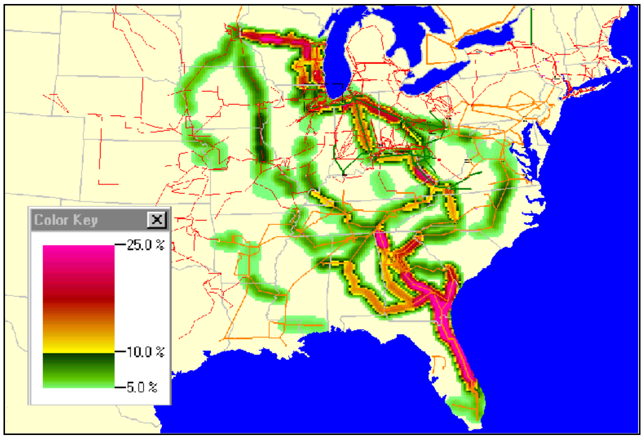

Figure 9: Transmission Line/Transformer PTDFs for a Transfer from Florida to Wisconsin

Figure 9 shows the PTDFs for a proposed transaction from Florida to Wisconsin. The PTDFs are calculated using the 30,000 bus, 41,000 line model used earlier. From the figure it is readily apparent how the transfer flows throughout the system. PTDF contours are especially useful because of their more continuous nature. One can quickly look at this contour map and see which parts of the system experience increases in line loadings.

The 5% contouring threshold was chosen because the North American Electric Reliability Council (NERC), the watchdog group charged with insuring the reliable operation of the North American power grid, may require that a power transfer be curtailed if *any* of the transmission lines with PTDFs above 5% for that transaction are overloaded. For the Figure 9 case at least 5% of the power transfer would flow on over 250 different lines. Thus a market participant would find the information shown in Figure 9 to be quite valuable in considering the transaction.

5. Data Aggregation with Flowgates

While previous techniques have proven to be extremely useful in analyzing the large amounts of data found in the electric power system, it is also useful to consider ways of aggregating the data. One such approach is the flowgate idea currently advocated by NERC. Such data aggregation can be extremely important when calculating the capacity of the transmission grid to undertake additional power transfers (known as Available Transmission Capacity or ATC).

A flowgate is simply a collection of transmission system lines that usually serve as a proxy for limits other than the line thermal limits. For example, voltage or transient stability constraints might be implemented using a flowgate. Grouping the lines into a flowgate reduces the amount of information that must be monitored when performing economic and/or operational security analysis of the system. A common flowgate is the sum of the tie line flows between two utilities. To represent this information, similar to Figure 1 ovals are drawn which represent the individual utilities (actually the ovals represent control areas, which may consist of a single utility or may represent a grouping of utilities operating as a "pool"), while lines are drawn between the ovals to represent the flowgate. Line flow animation and pie chart visualization can then be used on this type of display. Figure 10 shows the flowgate PTDF values for a transfer from Commonwealth Edison in Northern Illinois to the Tennessee Valley Authority (TVA) .

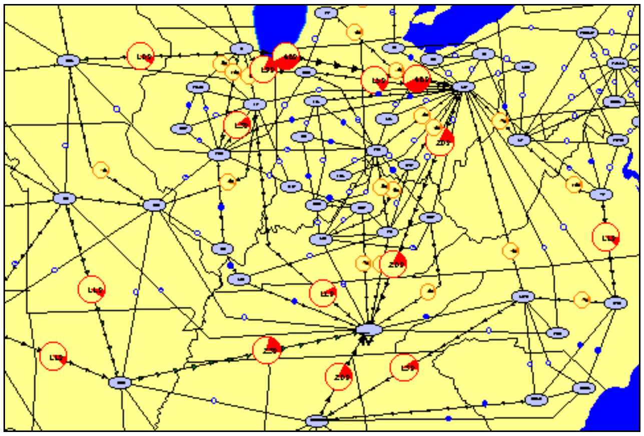

Figure 10: Pie Chart Visualization of Flowgate PTDFs

A difficulty with using pie charts to display PTDF values is many of the PTDF values are small, making it difficult to accurately ascertain the PTDF value – a pie chart that is 5% filled looks quite similar to one that is 10% filled, yet the later has twice the value of the former. This difficulty can be overcome through the use of line based contouring techniques. Figure 11 shows the same data as Figure 10, except the data in Figure 11 is represented using a contour.

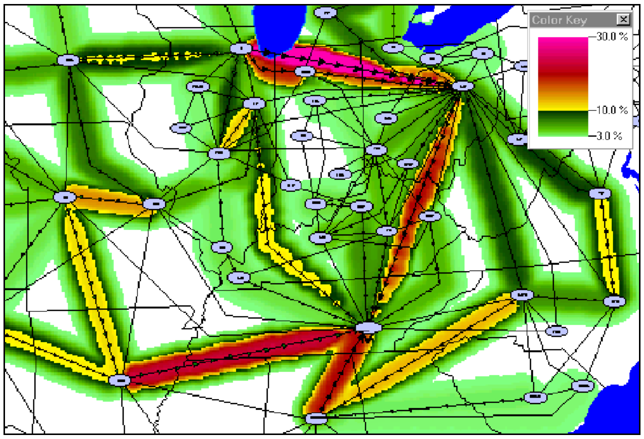

Figure 11: Contour Visualization of Flowgate PTDFs

6. Interactive 3D Visualization

The previous data visualization techniques can be quite useful when one is primarily concerned with visualization of a single type of spatially oriented data, such as bus voltages or transmission line flows. However in power system analysis one is usually confronted with a large amount of multivariate data. Data of interest could include a potentially large list of independent and dependent variables, such as bus voltage magnitudes, transmission line loadings, generator real and reactive reserves, transformer tap and phase positions, scheduled and actual flows between areas, and interface loadings. In more advanced applications, such as the optimal power flow (OPF), contingency analysis, and available transmission capacity (ATC) calculations, this list of variables is even longer. This section presents results on the use of an interactive 3D visualization environment to assist in analyzing this vast amount of information [18].

In developing such an environment several key issues must be addressed. First and foremost, in visualizing power system data there is usually no corresponding "physical" representation for the variables. For example, there is no physical representation for the reactive power output of a generator, or for the percentage loading of a transmission line. Rather, these value are typically shown as a numerical value on either a one-line diagram or in a tabular display. This contrasts with the use of interactive 3D for power system operator training, in which the 3D environment seeks to mimic, as closely as possible, an existing physical environment. It also differs from the use of interactive 3D for some types of scientific visualization, in which the purpose of the environment is to visualize physical phenomena, such as flows in a wind tunnel or molecular interactions. To address this issue, an environment based upon the common one-line representation serves as a starting point. The new environment differs from the one-line in that a one-line is a 2D representation, whereas the new one is 3D. How this third dimension can be exploited is covered in the following sections.

The second issue is the 3D environment must be highly interactive. In power systems there is simply too much data to simultaneously display all the data that may be of interest. Rather the user should be able to quickly and intuitively access the data of interest.

A third issue is the decision on the hardware and software to use to implement it. For pragmatic reasons, such as budget constraints and the ability to use existing software, the environment described here is based upon the widely available PC platform and used standard input devices, such as a mouse and keyboard, for the interactive control. A benefit to this approach is that it allows the potential to make it available to a wide variety of users, without requiring new hardware. Furthermore, there is nothing that precludes augmenting the environment in the future to include more specialized hardware, such as 3D mice, shutter glasses to simulate steroscopic vision, and head-mounted displays.

For software the PowerWorld Simulator [11], [12] was modified to allow 3D drawing and interaction using OpenGL. With OpenGL, most of the software modifications necessary to support a 3D environment, such as viewpoint perspective transformations, hidden surface removal, lighting, and the transformations for stereoscopic viewing, are handled almost transparently. Building upon the PowerWorld Simulator platform allowed easy development of 2D one-lines, that could then be seamlessly used as the basis for the 3D environment and also allowed it to be interactive so that, for example, when the user clicked on a circuit breaker a power flow is solved, resulting in a new system state.

To introduce the environment, Figure 12 shows a traditional 2D one-line for a small thirty bus system, augmented using animation to show the system flows. Figure 13 shows the same one-line in the 3D environment, with the exception that now generators are represented using cylinders of potentially varying heights. The one-line has been mapped into 3D using a perspective projection. The one-line is now oriented in the xy-plane (horizontal plane), while the generators extend in the z (vertical) direction. In Figure 13 the height of each generator is proportional to its reactive power output.

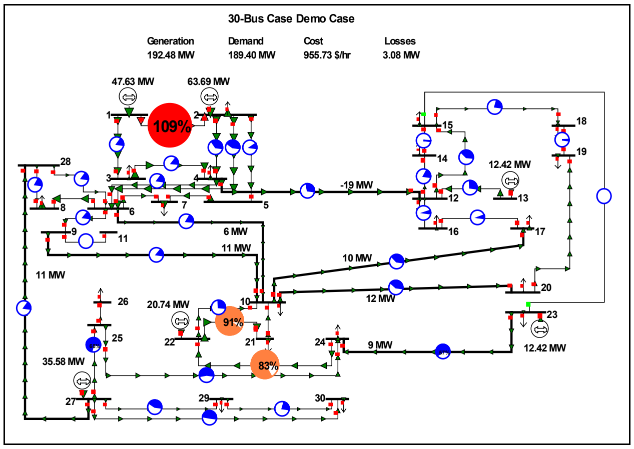

Figure 12: Traditional One-line View of 30 Bus System

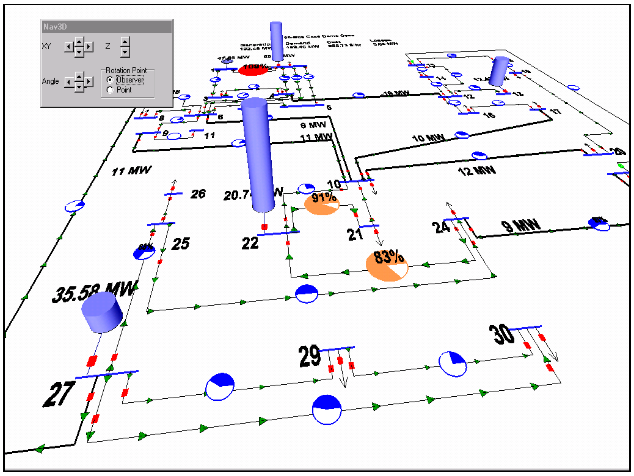

Figure 13: VE View of 30 Bus System

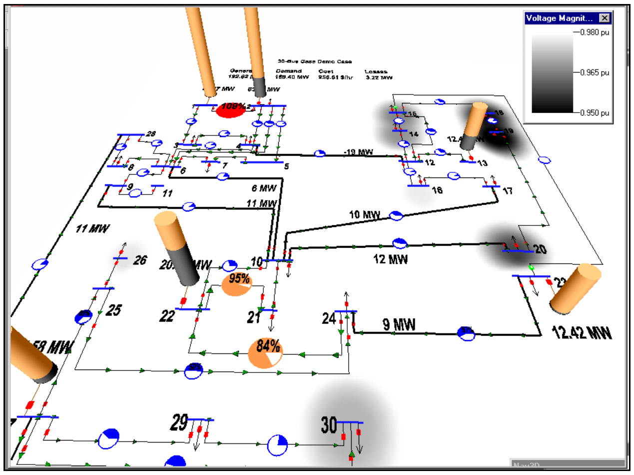

Figure 14: 30 Bus System Generator Reactive Reserves

One of the advantages of 3D is its ability to show the relationships between variables. For example, in studying the voltage security of a system one is often interested in knowing both the location and magnitude of any low system voltages, and also the current reactive power output and the reactive reserves of the generators and capacitors. Such a situation is illustrated in Figure 14 where the height of each generator cylinder is proportional to the maximum reactive capacity of the generator; the darker region on the lower portion of the cylinder is proportional to the current reactive power output, while the lighter top portion represents the reactive power reserves. The bus voltage values are indicated using a contour, with only voltage values below 0.98 shaded.

Figure 15 illustrates how the 3D environment could be used to show available ATC and generation reserves. ATC measures the ability of an energy market participant to transact power with other market participants given the limited capacity of the transmission system. However to be meaningful there must also be sufficient generation reserves. ATC values do not convey there reserves, because ATCs are purely transmission quantities. In Figure 15 the ATC values for imports to a particular area (Illinois Power in this example) are then shown using the contour while the height of the area is used to convey the generation reserves. Finally, Figure 16 shows how the 3D environment can be used to combine the PTDF from Figure 9 with cylinders showing the heavily loaded transmission lines. This immediately allows market participants to know whether their transaction is likely to run into grid congestion.

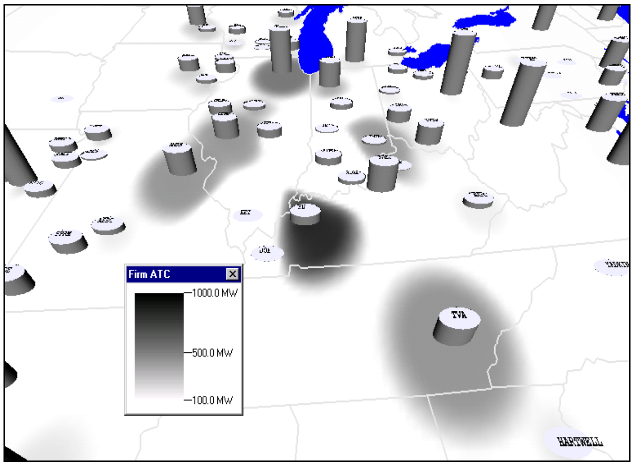

Figure 15: Visualizing ATC and Generation Reserves

7. Conclusion

Restructuring in the electricity industry is resulting in a need for innovative new methods for representing large amounts of system data. This paper has presented an overview of several new visualization techniques that could be quite useful for the representation of this data. Animation, contouring, data aggregation and virtual environments are techniques that should prove to be quite useful. Nevertheless, significant challenges remain. The key challenges are the problem of visualizing not just the current system state but also the potentially large number of contingency states, and the problem of visualizing not just the impact of a single proposed power transfer but of a large number of such transactions.

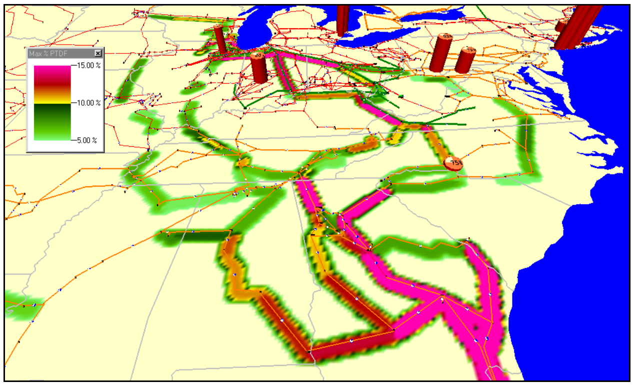

Figure 16: 3D View of Figure 9 with Heavily Loaded Lines Highlighted

8. Acknowledgements

The authors would like to acknowledge support of NSF through its grants NSF EEC 98-13305 and EEC 96-15792, the University of Illinois Power Affiliates program, and PSERC (Power System Engineering Research Center).

9. References

[1] Final Report of the U.S. Department of Energy's Power Outage Study Team, March 2000, http://www.policy.energy.gov/electricity/postfinal.pdf.
[2]http://www.midwestiso.org/whoweare.htm
[3] P.M. Mahadev, R.D. Christie, "Minimizing User Interaction in Energy Management Systems: Task Adaptive Visualization," *IEEE Transactions on Power Systems*, Vol. 11, No. 3, pp. 1607-1612, August 1996.
[4] L.D. Christie, "Toward a Higher Level of User Interaction in the Energy Management Task," *Proceedings of the IEEE International Conference on Systems, Man and Cybernetics*, San Antonio, TX, October 2-5, 1994.
[5] P.R. D'Amour, W.R. Block, "Modern User Interface Revolutionizes Supervisory Systems," *IEEE Computer Applications in Power*, January 1994, pp34-39.
[6] K. Ghoshal, L.D. Douglas, "GUI Display Guidelines Driving Winning SCADA Projects," *IEEE Computer Applications in Power*, April 1994, pp. 39-42.
[7] G.P. de Azevedo, C.S. de Souza, B. Feijo, "Enhancing the Human-Computer Interface of Power System Applications," *IEEE Transactions on Power Systems*, Vol. 11, No. 2, pp. 646-653, May 1996.

[8] P.M. Mahadev, R.D. Christie, “Envisioning Power System Data: Concepts and a Prototype System State Representation,” *IEEE Transactions on Power Systems*, Vol. 8, No. 3, pp. 1084-1090, August 1993.

[9] M.D. Anderson, H.J. Pottinger, C.M. Schroeder, R. Adapa, “Advanced Graphics Zoom in on Operations,” *IEEE Computer Applications in Power*, pp. 25-28, April 1993.

[10] http://www.powerworld.com

[11] T.J. Overbye, P.W. Sauer, C.M. Marzinzik, and G. Gross, “A User-Friendly Simulation Program for Teaching Power System Operations,” *IEEE Trans. on Power Sys.*, vol. PWRS-10, pp. 1725-1733, November, 1995.

[12] T.J. Overbye, G. Gross, M.J. Laufenberg and P.W. Sauer, "Visualizing Power System Operations in the Restructured Environment," *IEEE Computer Applications in Power*, pp. 53-58, January 1997.

[13] T.J. Overbye, P.W. Sauer, G. Gross, M.J. Laufenberg and J.D. Weber, “A simulation tool for analysis of alternative paradigms for the new electricity business,” *Proc. 20th HICSS*, pp. V634-V640, Maui, HI, Jan. 1997.

[14] J.D. Weber, T.J. Overbye, "Power System Visualization through Contour Plots," *Proc. of North American Power Symposium*, Laramie, WY, October 13-14, 1997.

[15] J.D. Weber, T.J. Overbye, “Voltage Contours for Power System Visualization,” to appear, *IEEE Trans. on Power Systems*.

[16]F.C. Schweppe, M.C. Caramanis, R.D. Tabors and R.E. Bohn, *Spot Pricing of Electricity*, Kluwer Academic Publishers, Boston, 1988.

[17] T.J. Overbye, D. R. Hale, T. Leckey, J.D. Weber, “Assessment of Transmission Constraint Costs: Northeast U.S. Case Study,” IEEE PES 2000 Winter Meeting, Singapore, January 23-27, 2000, pp. .

[18] T.J. Overbye, R.P. Klump, J.D. Weber, “A Virtual Environment for Interactive Visualization of Power System Economic and Security Information,” PES 1999 Summer Meeting, Edmonton, Canada, pp. 682-687, July 1999.