Visualization of Power System Data

Thomas J. Overbye
overbye@ece.uiuc.edu
University of Illinois at Urbana-Champaign
Urbana, IL 61801 USA

Jamie D. Weber
weber@powerworld.com
PowerWorld Corporation
Urbana, IL 61801 USA

Abstract

Effective power system operation requires power system engineers and operators to analyze vast amounts of information. In systems containing thousands of buses, a key challenge is to present this data in a form such that 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 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 virtual reality data visualization.

1. Introduction

Deregulation is, and will continue to have, a tremendous impact on power system analysis and operations. In many regions deregulation has resulted in the creation of much larger markets under the control of an independent system operator. 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, system 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 software and the EMSs 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.

Much work has, of course, been previously done in the area of developing useful visualization techniques to aid in interpreting power system data. Several recent examples are described in [1]-[7]. This paper addresses several methods of visualization with the goal of power system analysts gain better insights into transmission system operation. 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 techniques presented here have been implemented in PowerWorld Simulator [8]; earlier versions of this package have been described in [9], [10], [11].

2. Line Flow Visualization

Key to understanding the state of the transmission system is to know the current flows and percentage loading of the various transmission lines. However, this can be quite difficult, particularly for large systems. By far the most common means for representing transmission system flows is through the use of the one-line diagram. Traditionally MW/Mvar/MVA flows on transmission line/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. In a typical EMS system this representation is supplemented with alarms to call attention to lines violating their limits.

One newer technique is to supplement such representations though the use of animation to illustrate how power is actually flowing in a system [10]. As an example, Figure 1 shows a one-line diagram of the high voltage (345 kV and above) transmission system in the Eastern Interconnect in North America. The actual power flow model itself contains over 30,000 buses and 41,000 transmission branches. However only the small number of high voltage buses and transmission 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 with the size of the arrow proportional to the MW flow on the line. The advantage of this one-line approach is that 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 computer equipment, animation rates of greater than ten times per second have been achieved when using a relatively fast PC, even on large systems such as shown in Figure 1. Smooth, almost continuous, animation is achieved by updating the display using bitmap copies. 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.

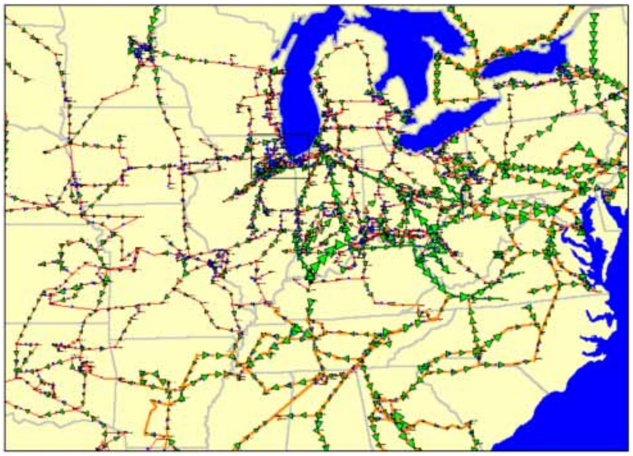

Figure1: High Voltage Line Flows in North America

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 to indicate loading on each transmission line. As an example, Figure 2 again shows the Figure 1 system with pie-charts used to indicate the loading on each transmission 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 2 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.

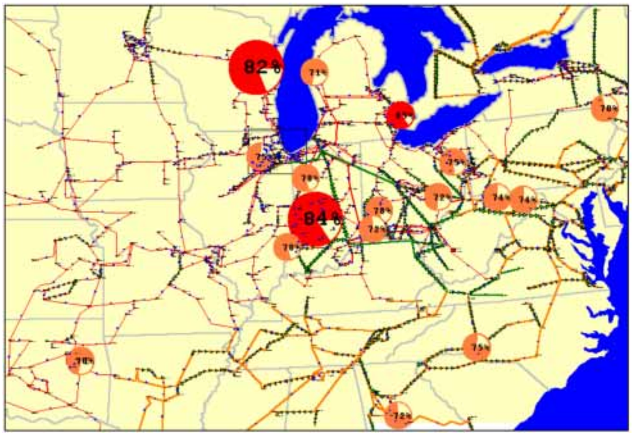

Figure 2: Pie Charts Showing Line MVA Percentages

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 that it not useful when one wants to examine the values at more than a handful of buses, say to find a patterns in the power system. In order to overcome this problem the use of contouring is presented [7], [12], [13].

Contours have, of course, been used extensively for the display of spatially distributed continuous data. One common example is the contour of temperatures shown in many newspapers. The problem with displaying power system data with a contour is that it is not spatially continuous. For example 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 (the details are discussed in [13]). 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. One common mapping is to use blue for lower values and red for higher values.

An example of the application of contouring to power systems is shown in Figure 3, 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, an overview of the voltage profile of the entire region is available at a glance using the contour. Of course other contour mappings could be used. For example, Figure 4 shows the same case, but with a color mapping such that only those buses with voltage magnitudes below 0.98 per unit are highlighted.

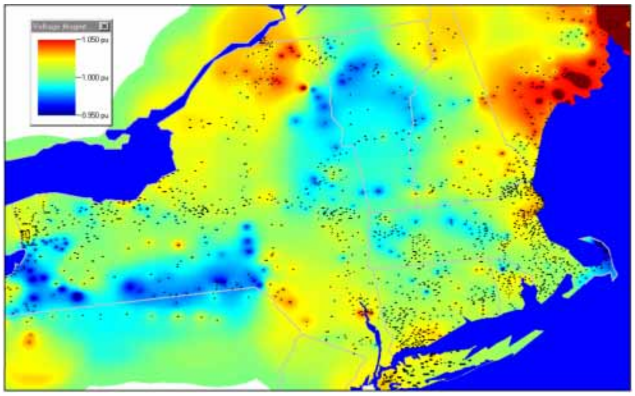

Figure 3: Voltages Magnitudes at 115/138 kV Buses in New York and New England

Finally, contouring need not be restricted to bus voltage magnitudes. Electricity markets are increasingly moving towards spot-market based market mechanisms [14] with the United Kingdom, New Zealand, California Power Exchange in the Western US, and PJM Market in the Eastern US 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 network. Contouring this data could allow EMS operators and market participants to quickly assess how prices vary across the market. As an example, Figure 5 plots the actual locational marginal prices (LMRs) in the PJM market on 2:00 pm, Friday August 20, 1999. Similarly, the technique could be used to contour the LMRs generated by an OPF study. For example Figure 6 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. [15] . In this study marginal prices were calculated for 5774 buses, with approximately 2000 of these values using in creating the Figure 6 contour.

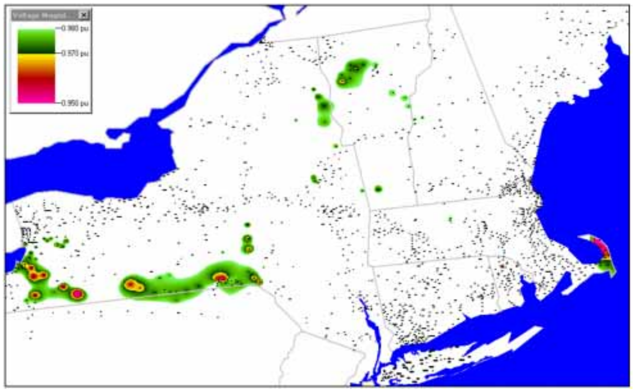

Figure 4: Voltage Magnitudes at 115/138 kV with Values below 0.98 per unit

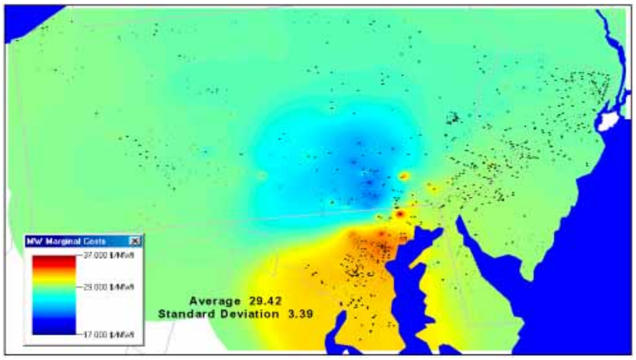

Figure 5: Locational Marginal Prices in PJM at 2pm on August 20, 1999.

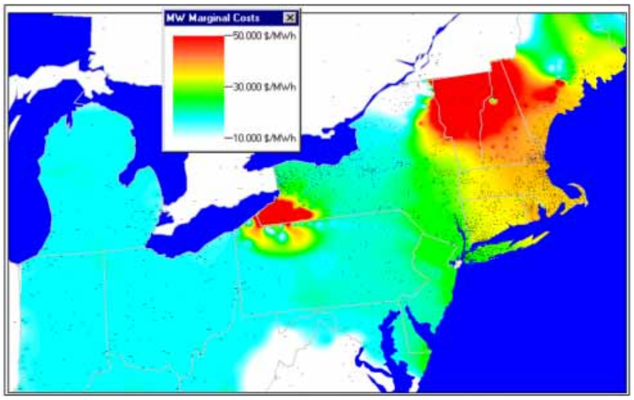

Figure 6: Locational Marginal Prices for Northeast U.S.

4. Contouring Line Data

Besides being useful to represent bus-based values, contouring can also be applied to line-based values. In order to accomplish this, a line is represented by a user-specified number of points in the contour. In this manner, the contouring algorithm can be used with no further modification to determine the virtual values throughout the contour. As an example, Figure 7 shows about 1400 of the 345 kV and above transmission lines/transformers of the U.S. portion of the North American Eastern Interconnect. Superimposed on the one-line is a contouring highlighting the lines and transformer 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 4 case, the key to the successful application of contouring on such a large 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. Of course in an actual EMS implementation this threshold percentage might be significantly higher.

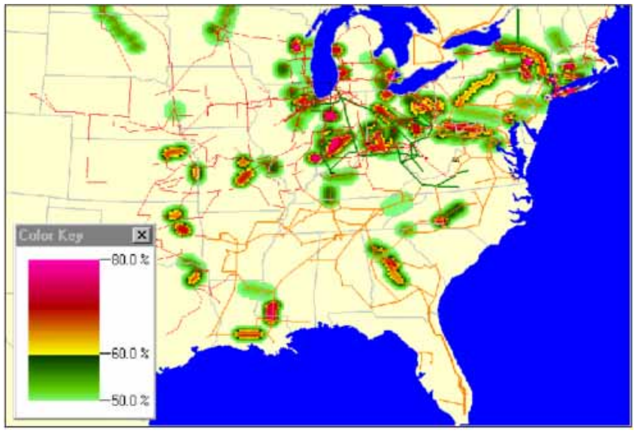

Figure 7: Eastern Interconnection Line Loading Contour

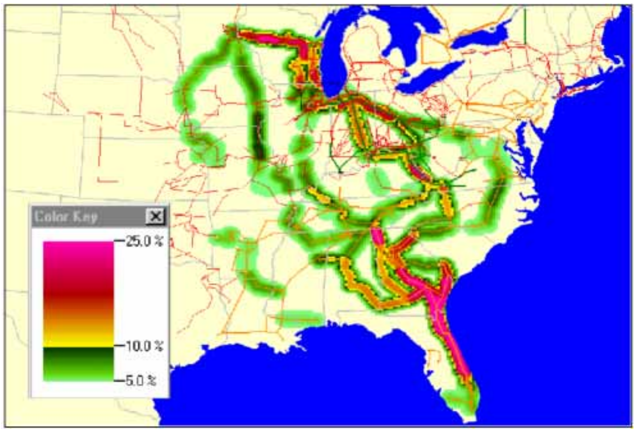

Figure 8: Transmission Line/Transformer PTDFs for a Transfer from Florida to Wisconsin

Line contouring can also be used to visualize transmission line power transfer distribution factors (PTDFs) for a large system. In short, a PTDF value shows the incremental impact a power transfer from a specified source to a specified sink would have upon each power system element. For example, if a line has a PTDF value of 10% that means that 10% of the power transfer would flow on that line. Thus if the power transfer is 300 MW, the line's MW loading would change by 30 MW. Figure 8 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.

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 grouping the information in the power system to enable a smaller set of data to be analyzed. This process is called data aggregation. One aggregation technique is the flowgate idea currently advocated by the North American Electric Reliability Council (NERC). Such data aggregation can be extremely important when calculating ATC values.

A flowgate is simply a collection of transmission system branches. A flowgate is able to serve as a proxy for a combined limitation on the flow on the branches. Grouping the branches into a flowgate reduces the amount of information that must be monitored when performing economic analysis of the system. A common flowgate is the sum of the tie line flows between two areas. To represent this information, ovals are drawn which represent a control area, 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 9 shows the flowgate PTDF values for a transfer from Commonwealth Edison in Chicago, Illinois to TVA.

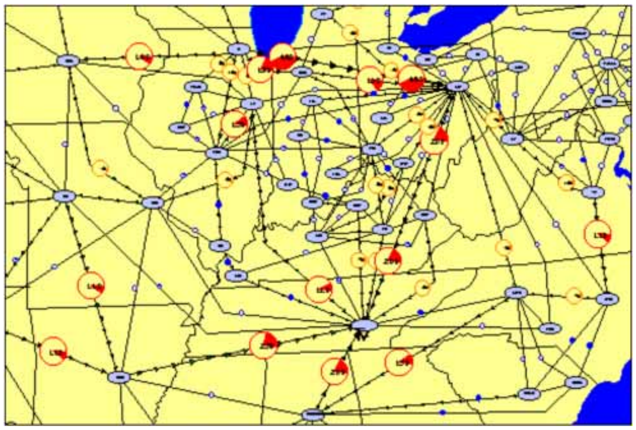

Figure 9: Pie Chart Visualization of Flowgate PTDFs

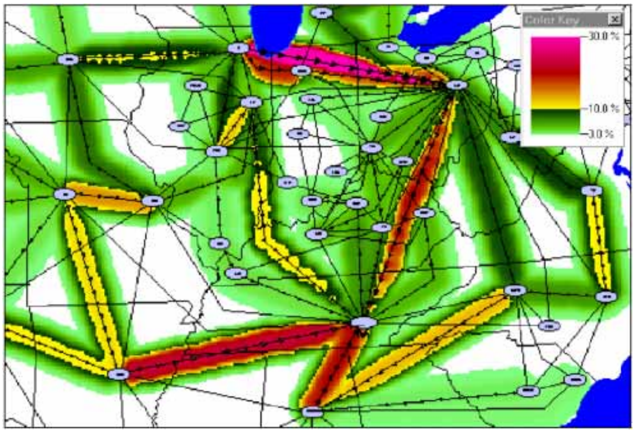

Figure 10: Contour Visualization of Flowgate PTDFs

A difficulty with using pie charts to display PTDF values is since many of the PTDF values are small, it is difficult to accurately visualize the PTDF value just using the pie chart. For example 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 10 shows the same data as Figure 9, except the data in Figure 10 is represented using a contour.

6. Virtual Environment 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 transmission line voltages or bus voltages. However in EMS one is usually confronted with a large amount of multivariate data. For example, 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 a virtual environment to assist the operator in analyzing this vast amount of information are presented.

Virtual environments (VE), or virtual reality systems, are simulation systems that use real-time computer graphics in such a way to make the user believe he or she is part of a virtual domain [16]. Thus the main idea behind VE systems is to give the user the illusion, at least to some degree, of being immersed in real-time in a three-dimensional (3D) world populated by computer-generated objects. The degree to which the illusion is achieved depends, in part, upon the hardware and software used, with the most compelling illusions achieved through the use of wide-field-of-view strereoscopic head-tracked display systems [17]. Nevertheless, even PCs using standard displays can be quite useful for exploring the use of VEs.

In order to investigate the application of virtual environments for EMS visualization a prototype VE was developed [18]. In implementing a VE for EMS type applications several key issues must to 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 var 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 VEs for operator training, in which the VE seeks to mimic, as closely as possible, an existing physical environment. It also differs from the use of VEs for some types of scientific visualization, in which the purpose of the VE is to visualize physical phenomena, such as flows in a wind tunnel or molecular interactions. To address this issue, a VE based upon the common one-line representation is proposed. The VE differs from the one-line in that a one-line is two-dimensional representation, whereas the VE is three-dimensional. How this third dimension can be exploited is covered in the following sections.

The second issue is the VE 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 major design issue is a decision on the hardware and software to use to implement the VE. For pragmatic reasons, such as budget constraints and the ability to use existing software, the prototype VE originally described in [18] was based upon the widely available PC platform and used standard input devices, such as a mouse and keyboard, for the VE control. A benefit to this approach is that it allows the potential to make this VE available to a wide variety of users, without requiring new hardware. Furthermore, there is nothing that precludes augmenting the VE to include more specialized hardware, such as 3D mouses, shutter glasses to simulate steroscopic vision, and head-mounted displays. For EMS applications a more elaborate implementation may ultimately prove more useful.

For software the PowerWorld Simulator [9], [10] was modified to allow 3D drawing and interaction using OpenGL. OpenGL itself is a software interface, originally developed by Silicon Graphics, for graphics hardware that facilitates the modeling of 3D systems [19]. 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 two-dimensional (2D) one-lines, that could then be seamlessly used as the basis for the 3D VE, and also allowed the environment to be interactive so that, for example, when the user clicked on a circuit breaker in the VE a power flow is solved, resulting in a new system state. This provided a good prototyping environment for application of the VE to an EMS.

To introduce the VE, Figure 11 shows a traditional 2D one-line for a small thirty bus system. Figure 12 shows the same one-line in the VE, with the exception that now generators are represented using cylinders of potentially varying heights. Note that the one-line has been mapped into 3D using a perspective projection, in which closer objects appear larger. In the VE the one-line can be thought of lying in the xy-plane (horizontal plane), while the generators extend in the z (vertical) direction. This ability to extend objects in the z direction is an important advantage of using 3D space since it permits the visual display of additional information by making the height of the object potentially proportional to some variable. In Figure 12 the height of each generator is proportional to its reactive power output.

One of the advantages of the VE is its ability to show the relationships between variables. 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. Such a situation is illustrated in Figure 13 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 var reserves. The bus voltage values are indicated using a color contour, with only voltage values below 0.98 shaded.

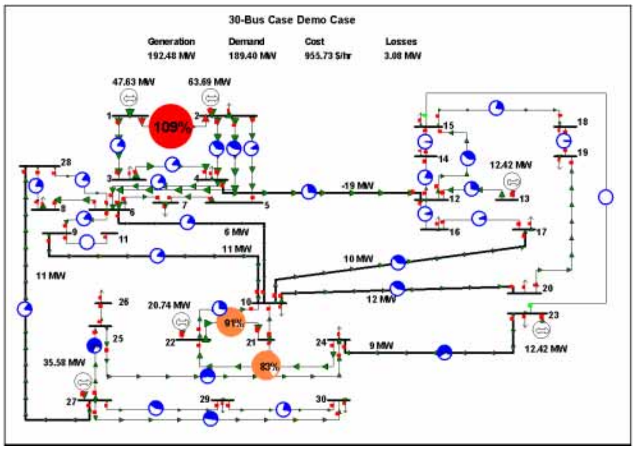

Figure 11: Traditional One-line View of 30 Bus System

Figure 14 illustrates how the VE could be used to show available transfer capability (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 14 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.

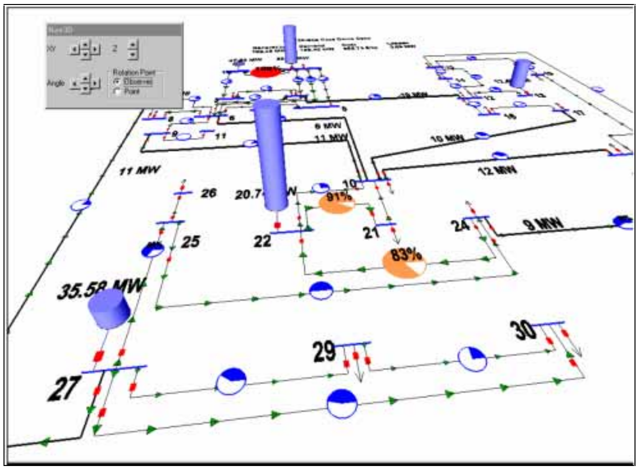

Figure 12: VE View of 30 Bus System

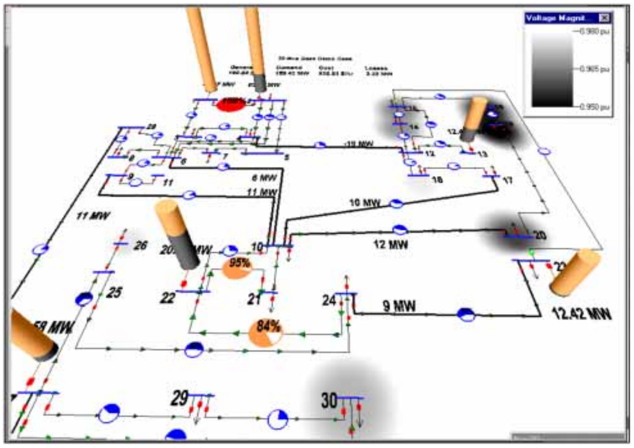

Figure 13: 30 Bus System Generator Reactive Reserves

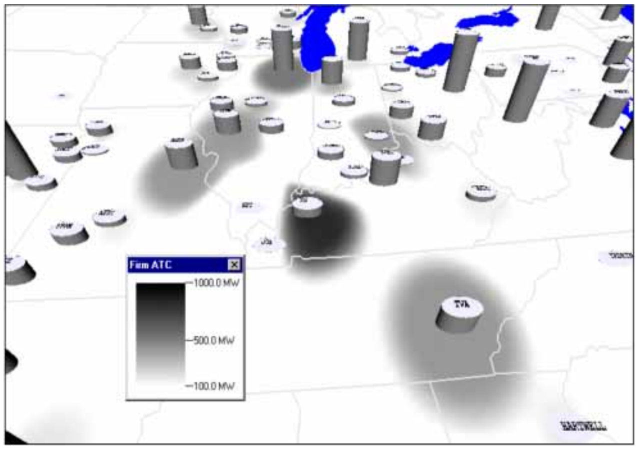

Figure 14: Visualizing ATC and Generation Reserves

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.

8. Acknowledgements

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9. References

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