A Virtual Environment for Interactive Visualization of Power System Economic and Security Information

Thomas J. Overbye
Senior Member

Raymond P. Klump
Member

Jamie D. Weber
Student Member

University of Illinois at Urbana-Champaign
Urbana, IL 61801 USA

Abstract

Simulation and analysis of power systems often involves modeling extremely complex systems. This is particularly true when the model involves not just the electrical power system, but also other networks layered on top of the power system, such as the accompanying financial transactions. Such layered networks can often involve interactions that are not at all obvious. Interactive visualization can be a very effective means for determining otherwise hidden relationships between various elements in the network. This paper describes a 3D virtual environment developed to allow users to interactively visualize such information and relationships. The paper describes the architecture used to develop this environment, and then provides several examples of how the environment is used to provide an interactive visualization of power system economic and security information.

Keywords: Power System Economics, Security, Visualization, Animation, Virtual Environments

1. Introduction

In analyzing power systems, one is usually confronted with a large amount of multivariate data. For example, in a simple power flow 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. In this paper we present some initial results on the development of a virtual environment to assist the user in analyzing this vast amount of information.

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 [1]. 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 [2]. Nevertheless, even PCs using standard displays, such as used for our research, can be quite useful for exploring the use of VEs.

Earlier results concerning the use of VEs for operator-training in power systems are described in [3] and [4]. In these applications the purpose of the VE was to train operators by simulating, as closely as possible, certain real-world conditions, such as the layout of a substation or a control panel. In contrast, the purpose of the work presented here is to use a VE to interactively visualize more abstract power system data. Thus this work is more akin to scientific visualization. An overview of using VEs for scientific visualization is given in [5]. As a caveat, we wish to make clear that we propose the use of VEs for power system visualization as a supplement to, not a replacement of, existing techniques such as two-dimensional one-line diagrams and tabular-type displays. Each has its own particular advantages and disadvantages.

2. Virtual Environment Architecture

The key design goal in the development of our virtual environment (VE) was to assist users in effectively visualizing, and hence interpreting, the vast amount of multivariate data generated by power system studies. However in meeting this goal several key issues had 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, we decided to keep our new VE as similar as possible to existing power system representations. Therefore the VE is based upon the common one-line representation. 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 to address was that, as mentioned in the introduction, power systems studies often generate a large number of different types of variables. Showing all of these variables simultaneously could quickly result in information overload for the user. To address this issue, the VE was designed to allow selective display of the information. The user is free to choose the set of variables to visualize.

The final major design issue was 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, we decided to use the widely available PC platform and to use standard input devices, such as a mouse and keyboard, for the initial 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 software the PowerWorld Simulator [6], [7], 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 [8]. 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 straightforward 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.
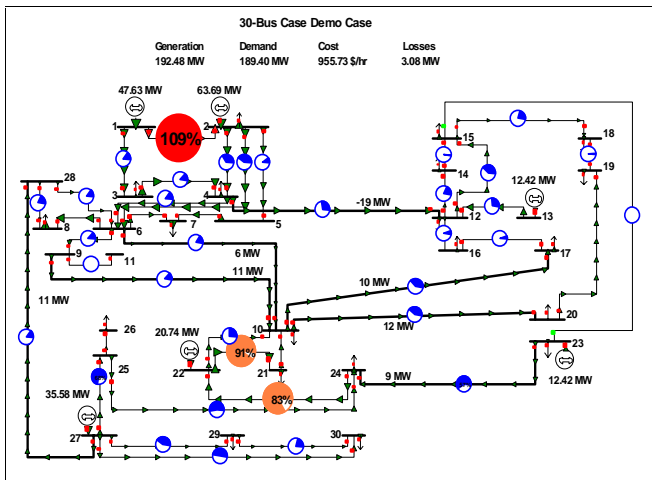

Figure 1: Traditional One-line View of Thirty Bus System

To introduce our VE, Figure 1 shows a traditional 2D one-line for a small thirty bus system. Figure 2 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 the Figure 2 example the height of each generator is proportional to its reactive power output. This issue will be addressed in greater depth in the next sections.
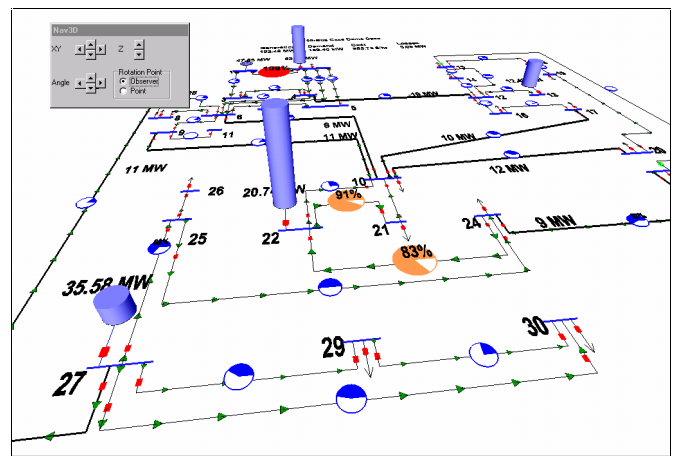

Figure 2: VE View of Thirty Bus System

The addition of a third dimension certainly adds new issues that must be addressed, the foremost of which is user navigation within the VE. The navigation of VEs has been a subject of significant research; interested readers should consult [1] and [9] for a much more thorough coverage of some of the issues involved. Here we provide brief coverage of some of the pertinent issues and details germane to our implementation. With a 2D one-line there are three degrees of freedom associated with viewing the one-line. That is, one may pan in either the x or in the y directions, and one may zoom in or zoom out. Thus the 2D one-line could be thought of as lying in the xy-plane, with the viewport "camera" located at some height above the one-line. Panning the one-line can then be thought of as moving the camera in the x and/or y directions, while zooming is simply changing the height of the camera above the one-line.

A 3D environment has these same three degrees of freedom, but also adds three more since now the camera itself can be rotated about each of its three axes. In order to simplify navigation, in our approach we allow the user only two additional degrees of freedom: the camera can change its angle with respect to the horizon (elevation) by rotating

about the axis passing through the camera from its sides, and the camera can rotate about the axis passing through the camera from top to bottom (azimuth). We do not allow rotation about the axis passing through the camera from front to back (twist). Movement in each of these degrees of freedom can be accomplished using either the mouse with a navigation toolbar shown in the VE, or using keyboard commands.

In addition, and perhaps more importantly, we've included several features that make rapid navigation much easier. In should be pointed out that the purpose of navigation in our VE is not to give the user a feeling of being in a "flight simulator." Rather, it is to allow the user to rapidly view the desired portion of the VE. To this end we've implemented features such as the ability to use the mouse to drag the camera view to the appropriate location, the ability to use the mouse to direct the camera to look at a particular location, the ability to rotate the camera about a fixed point, and the ability to move the camera directly towards or away from a fixed point. With these enhancements navigation to any point of interest, and the ability to view that point from any desired angle, becomes relatively straightforward.

Another issue that must be addressed in showing a 3D environment is lighting. While lighting at first may seem esoteric to visualizing power system data, it can actually be quite important to effective visualization. As an example, Figure 3 and Figure 4 show an identical view of the earlier thirty bus system with the viewport camera shifted so one of the generator cylinders is in the foreground. The only difference is that Figure 3 shows the scene with lighting, while Figure 4 shows the scene with fixed colors. As this example shows, lighting can be quite helpful in perceiving depths in objects since how an object looks depends upon how light reflects from it. OpenGL supports straight forward implementation of ambient, diffuse and specular light models [8]. Figure 3 was created using a combination of ambient light and a diffuse light source behind the viewport camera.
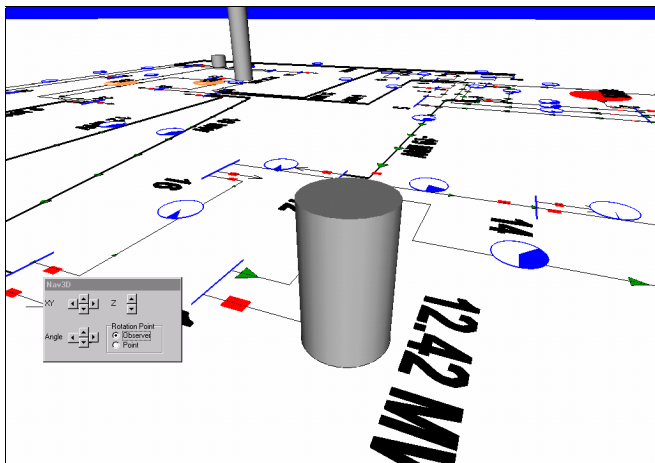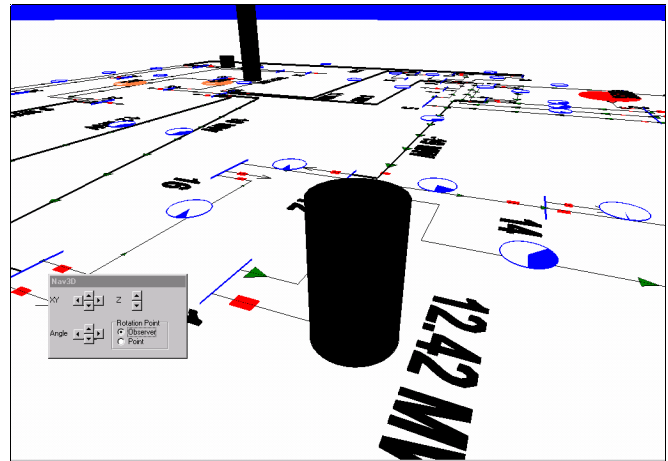

Figure 4: Thirty Bus System without Lighting

Another issue associated with the VE that needs to be addressed is performance. In order to give the user the feeling of interacting with a virtual environment it is crucial that the display refresh quickly and that there is little latency between the user issuing a command, such as desiring to change position, and the display being updated. How fast the display can be refreshed depends, of course, on a number of factors, including the speed of the computer's processor, the speed of the display card, whether the display card has hardware support for OpenGL, and software considerations such as the level of detail of the display and the lighting model employed. Given the recent trend to supporting OpenGL directly in the display card hardware, newer microprocessors with new commands to directly support 3D graphics and faster processors in general, we are quite optimistic that very good 3D performance will be available shortly even for relatively large systems. For reference, using a 200 MHz Pentium Pro machine without hardware support for OpenGL, display refresh rates of about 3 times per second are possible with the Figure 3 case and about 1 time per second for Figure 6.

3. Voltage and Reactive Power Visualization

In the next three section we present several examples of how a VE could be quite useful in the display of power system information. These include examples of both power system security and power system economic information. However, because of the inherent differences between a dynamic and colorful VE versus the static medium of ink of paper, we do request the readers forbearance and use of imagination in interpreting these examples. A key advantage of the VE approach is that the user is free to rapidly view the system from many different perspectives in a way which is impossible to completely convey in paper format.

The first example concerns the visualization of power system voltage magnitudes and generator reactive power outputs and reserves. It is well known that generator reactive power injections and bus voltage magnitudes are related. In studying the voltage security of a system one is

Figure 3: Thirty Bus System with Lighting

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. Of course if the system is extremely small all of this information could be shown numerically on a one-line.

An alternative for larger systems is to visualize the voltage magnitudes using a color contour [10], [11], [12], [13]. However a difficulty with using a color contour on a 2D display is it makes the display of other information difficult. An alternative approach is to use a VE with the voltage contour shown in the xy-plane (actually slightly below the xy-plane in which the one-line resides). The z direction can then be used to show generator or other reactive information. Such an implementation is shown in Figure 5 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 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 pu shaded. Important to the success of such a display is to avoid using excessive contrast in the color contours; rather we suggest the "smallest effective difference" approach of [14]. Figure 6 shows a similar representation for the IEEE 118 bus system.
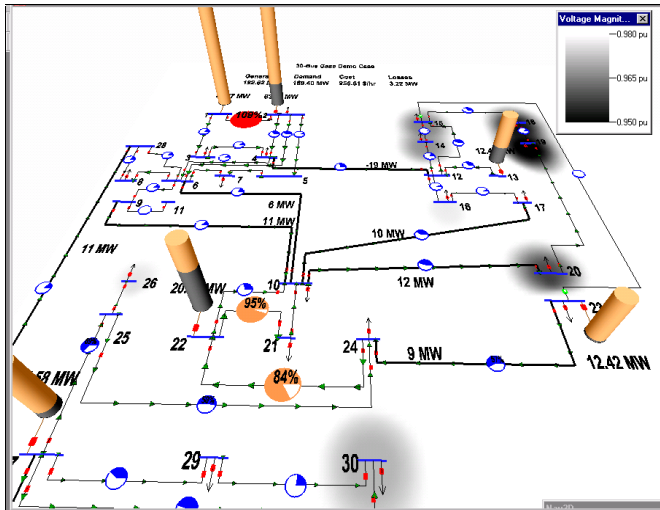

Figure 5: Thirty Bus System Generator Reactive Reserves

Note in both figures it is apparent, almost at a glance, the location of the sources of reactive power generation and the reactive power reserves. The figures also do a good job of conveying qualitative information about the magnitude of these values. What they do not do is convey quantitative information. Thus while one learns from Figure 5 that the reactive power generation at bus 20 is about 50% of its maximum, one does not learn what the actual var output is, nor the maximum var limit. In some situations this could be a significant limitation. We thus advocate the use of a VE to supplement, rather than to completely replace, existing one-line and tabular display formats.
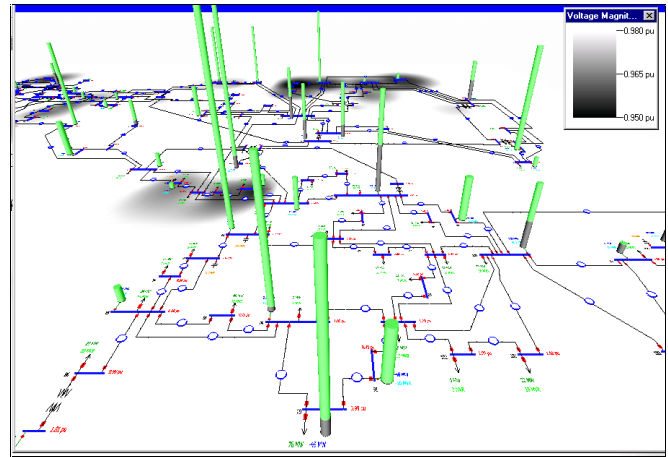

Figure 6: IEEE 118 Bus Generator Reactive Reserves

However, in support of the VE approach we would like to offer two observations. First, in many situations these qualitative relationships are sufficient. This is particularly true when one is studying a familiar system. For example utility operators already know the reactive limits of their generators; what they need to know is how close those generators are to their limits in a qualitative sense. And one needs to know the value for only a few generators in order to get acceptable estimates for the remaining generators by comparing their relative sizes. Second, there is nothing that prevents displaying numerical values of system quantities in the VE, just a bus numbers and some line flows are shown in Figure 5. A valid objection to this approach is that if the viewpoint is changed these fonts could be shown at unappealing angles, such as in Figure 3. However, this problem can be easily solved by having the VE automatically rotate the fonts so they are always facing the viewer, provided the one-line is designed with sufficient room for the fonts to rotate. The fonts could even be shown in the vertical plane, such as on the surface of the generator cylinders. An alternative approach, which we prefer and have implemented, is to allow the user to get additional information about system objects by selecting the object with the mouse. This allows the display to be relatively uncluttered, yet still allows rapid access to a large amount of quantitative information.

4.   Visualizing Available Transfer Capability

The second VE example is the display of 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 [15],[16]. ATCs set upper bounds on how much a market participant, for example a transmission-owning control area, can export to or import from another market participant, given the limited capacity of the transmission system.

While ATCs play a key role in helping mitigate congestion on the transmission system, the limits they

impose can have profound implications on days when system conditions are sufficiently stressed that a region has inadequate reserves to meet its load. For example, if a control area that has insufficient generation to meet its load also has inadequate ATC to import power from its neighbors, it will have to shed load to alleviate the deficiency. However, even if the deficient area does have positive ATC for importing power from a neighbor, it will be unable to receive support if that neighbor also has inadequate generation reserves. In this case, the area's import capability is limited by generation constraints rather than transmission constraints. ATC values do not convey this limit, because ATCs are purely transmission quantities.

One approach to visualizing this situation in a VE is to represent each of the operating areas using a bubble diagram approach. However, rather than showing the areas using ellipses in 2D space, they can be shown in 3D space as scaled cylinders whose heights are proportional to the generation reserves in each area. ATC for imports to, or exports from, a particular area can then be shown in the xy-plane using a contour. For example, Figure 7 shows the generation reserves for several areas in the Midwest portion of the North American Eastern Interconnect. The ATC values for imports to a particular area (Illinois Power in this example) are then shown using the contour. Thus Figure 7 provides the participant a single view of the system that considers both types of transfer capability limitations.
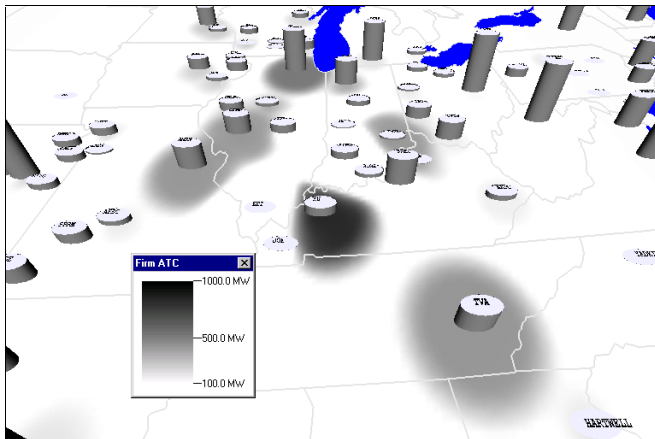

Figure 7: Visualizing ATC and Generation Reserves

One could employ similar views of transfer capability that provide equally valuable information. For example, a market participant, area A, might actually have excess capacity that it wishes to sell to other regions. A view that contours area A's export ATC in the XY plan and depicts generation costs along the Z axis would help match participant A with entities that would likely be most interested in purchasing its power for economic reasons. Alternatively, if power transfer distribution factors are contoured on the XY plane and import ATCs are represented as cylinders along the Z axis, area A can readily identify sources from which it can purchase energy without

being subjected to line-loading relief curtailments, which typically use PTDF values as the criterion for deciding which transactions to freeze, curtail, or prohibit.

5. Bus Marginal Price Visualization

The third example shows how a VE could be used to show the relationship between system pricing information and transmission system constraints. Electricity markets are increasingly moving towards spot-market based market mechanisms [17], 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. The marginal price includes components associated with both the cost of generating the power and transportation costs related to the transmission system. This means that spot-prices will vary more sharply when transmission constraints are present in the system. This marginal cost can be determined by using an Optimal Power Flow algorithm. A Newton-based OPF [18] is used for the following examples to calculate the spot-price at each bus in the network.

Regardless of how this price is determined, a market will contain a large amount of price information as well as system constraint information. As an example, consider a lossless version of the IEEE 118-bus system. With no constraints the marginal cost at each bus would be identical. Using illustrative economic data, we obtained a uniform bus marginal cost of 11.66 $ / MWhr. Now consider the same system with transmission line constraints added to the system, forcing the generators to re-dispatch to remove transmission line overloads. Enforcing these constraints results in different spot-prices throughout the system, shown using a 2D contour in Figure 8.
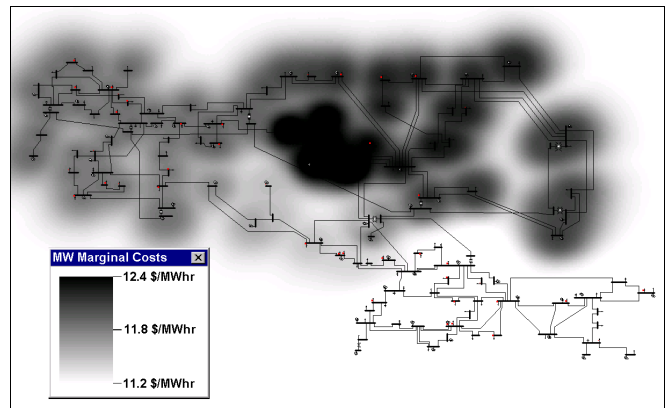

Figure 8 : IEEE 118 Bus Marginal Prices 2D Contour

This contour works well for showing price relationships alone, but it does not show the transmission line overloads that cause the price differences. To show the relationship between line overloads and prices, a VE that uses the z-direction to show overloads is employed. In Figure 9, the

xy-plane shows the system diagram along with a price contour, while the lines that require the OPF to redispatch to remove overloads are shown by vertical cylinders. The height of these cylinders is the marginal cost of enforcing the line limit. This marginal cost is also determined by the Newton OPF solution. Thus taller cylinders represent line limits that cost more to enforce, which will result in greater price variations.
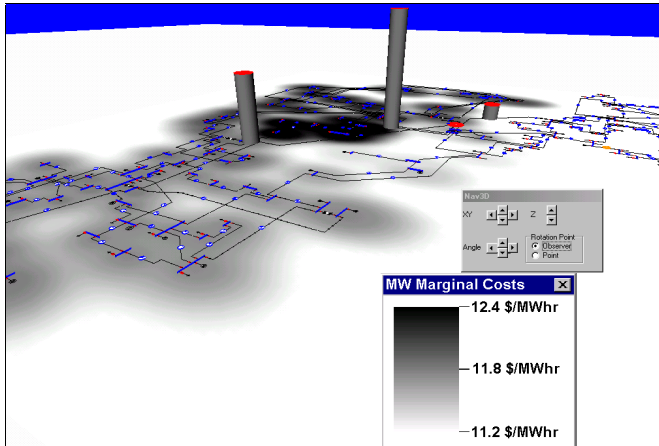

Figure 9: Marginal Cost of Line Constraint Enforcement

6. Conclusion

This paper has introduced a virtual environment (VE) that allows users to interactively visualize power system information. The VE approach provides power system analysts a means of interpreting the large quantities of multivariate data that typify today's system studies. By depicting data in three dimensions, the VE can illustrate qualitative relationships between system characteristics that traditional two-dimensional visualization techniques cannot convey. The examples described in this paper illustrate how the VE can help clarify system security and economics issues, but they only scratch the surface of what this technology has to offer. To exercise the power of the VE concept more completely, future research will strive to increase the user's capacity to interact with the environment. This work will enhance the user's ability to navigate through the system, to customize both the content and appearance of the data, and to manipulate the underlying system model in a manner similar to that employed in traditional two-dimensional environments.

7. Acknowledgements

8. References

[1]   John Vince, *Essential Virtual Reality*, Springer-Verlag, London, 1998.

[2]   S. Bryson, "Virtual Reality in Scientific Visualization," *Computers and Graphics*, vol. 17, pp. 679-685, 1993.

[3]   A.O. Veh, et. al., "Design and Operation of a Virtual Reality Operator-Training System*, IEEE. Trans. on Power Systems*, vol. 11, pp. 1585-1591, August 1996.

[4]   E.K. Tam, et. al., "A Low-Cost PC-Oriented Virtual Environment for Operator Training, *IEEE. Trans. on Power Systems*, vol. 13, pp. 829-835, August 1998.

[5]   H. Haase, F. Dai, J. Strassner, and M. Gobel, "Immersive Investigation of Scientific Data*," pp. 35-58,m Scientific Visualization*, IEEE Computer Society, 1997.

[6]   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.

[7]   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.

[8]   M. Woo, J. Neider, T. Davis, OpenGL *Programming Guide, Second Edition*, Addison-Wesley Developers Press, Reading, MA, 1997.

[9]   D. Hearn, M. P. Baker, *Computer Graphics C Version*, 2nd Edition, Prentice Hall, Upper Saddle River NJ, 1997.

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

[11]   *Advanced Graphics for Power System Operations*, EPRI TR-103633, Project 4000-13, Final Report, May 1994.

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

[13]   J.D. Weber, T.J. Overbye, "Voltage Contours for Power System Visualization, to appear *IEEE Trans. on Power Sys*.

[14]   E.R. Tufte, *Visual Explanations*, chapter 4, Graphics Press, Cheshire, CN, 1997.

[15]   North American Reliability Council, *Available Transfer Capability Definitions and Determination*, NERC, June, 1996.

[16]   L.R. Januzik, R.F. Paliza, R.P. Klump, C.M. Marzinzik, "MAIN Regional ATC Calculation Effort," *Proc. American Power Conference*, Chicago, IL, April 1-3, 1997.

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

[18]   Sun, D. I., Ashley, B., Brewer, B., Hughes, A., Tinney, W. F., "Optimal Power Flow by Newton Approach," *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-103, October 1984, pp. 2864-2880.