Visualization of Flows and Transfer Capability in Electric Networks

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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. This paper presents several power system visualization techniques to help in this task. These techniques include animation of power system flow values, contouring of transmission line flow values, data aggregation techniques and virtual reality data visualization. Results are shown for several large scale power systems.

Keywords: Power System Visualization, Transfer Capability, Contouring, Animation, Large System Simulation

1. Introduction

The electric power business throughout the world is restructuring its institutional arrangements to allow more competition, especially amount suppliers of electricity. This has resulted in the entry of many new players into the electricity marketplace, such as non-utility generators, brokers, marketers and load aggregators. While their interests are diverse, what facilitates the market for electricity, and yet binds and constrains its players is the requirement that they share a common high voltage transmission system. Indeed, what sets the electricity market apart form all other markets is this common transmission system.

In order to participate in this electricity market, it is important that the various players understand the operation and constraints imposed by this common transmission system. That is, the ability to participate in the electricity market depends upon the availability of transmission capacity between a buyer and a seller. Whether or not such capacity exists depends upon a coupling between the physical capacity of the transmission system, including the need to consider plausible contingencies, and already existing power transfers. In the United States this capacity of the transmission system to support additional transactions has been defined by the North American Electric Reliability Council (NERC) as available transfer capability capacity (ATC).

Determining ATC has proven to be an extremely difficult task. This is due primarily to four factors. First, since ATC is directly dependent upon the current or assumed system operating point, it is constantly changing as either the system state changes or as new transactions are implemented. Second, for any given transmission system there is not a single ATC value. Rather, ATC is dependent upon the set of buses where the power is assumed to be injected, the source, and the set of buses where the power is being withdrawn from the system, the sink. A particular combination of source and sink is known as a direction. Usually on a large system a substantial number of directions must be considered. Third, determination of ATC requires considering not just one particular operating state, but rather the operating state and a set of plausible contingencies. The ATC for any direction is practically always limited by one of the contingent conditions. Finally, once a set of ATC values has been determined, they must be updated anytime a new transaction in a particular direction is implemented. The complicating issue here is that the ATC for each direction is dependent, to varying degrees, upon the transactions in all directions.

An example of the specific requirements for an ATC calculation is discussed in [1] for the Mid-America Interconnected Network, Inc. (MAIN). MAIN is one of ten NERC regional reliability councils. MAIN is entrusted with ensuring safe, reliable operation of the interconnected transmission system covering most of Illinois and Wisconsin, the eastern part of Missouri, and the upper peninsula of Michigan. Thirty times each week MAIN calculates ATC values for over 200 directions using a 14,000 bus power system. For each direction about 1300 different contingencies must be considered. Once a study has been completed, the text-based results of each direction must be analyzed by engineers from the transmission providers for accuracy. Finally the results of the study, consisting of nearly 20,000 numbers are posted to the MAIN OASIS (Open Access Same-Time Information System).

The net result has been that transmission providers and market participants are being overwhelmed by tidal wave of data about ATC, but have gained little insight into the mechanisms impacting their ability to get transmission service. Without this insight it is near impossible for participants to make informed business decisions regarding the interaction between their desired transactions and the constraints imposed by the transmission system. For example, when electricity market players need transmission service they must determine whether to pay a higher premium and purchase non-recallable transmission services, or whether they can get by with less expensive recallable transmission services. Also, with either type of service they must develop a feel for the likelihood of curtailments. These situations require business decision about managing the risk associated with the transmission system. The successful market participants will be the ones who understand the underlying transmission systems, and can thus make fully informed decisions. In this paper we present results using several visualization methods to assist in the analysis of this data.

Much work has, of course, been done in the area of developing useful visualization techniques to aid in interpreting power system data. Several recent examples are described in [2]-[7]. This paper addresses several additional methods of visualization of power system data, with the goal of providing electricity market participants with better insights into transmission system operation. These techniques include animation of power system flow values, contouring of 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] - [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 that are violating their limits.

Here we propose that such representations be supplemented through 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. In order 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. Of course the impact of such animation is impossible to convey using ink on paper, so we require the reader's forbearance and use of imagination. 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 one-line objects gives the user the ability to easily study the flows in a large system.

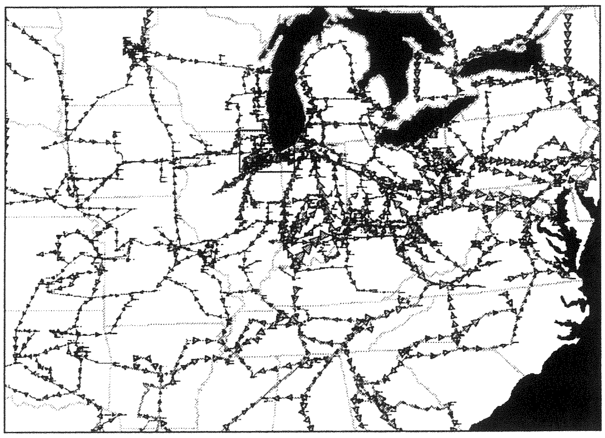

Figure1: High Voltage Transmission System Flows in Eastern North America

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.

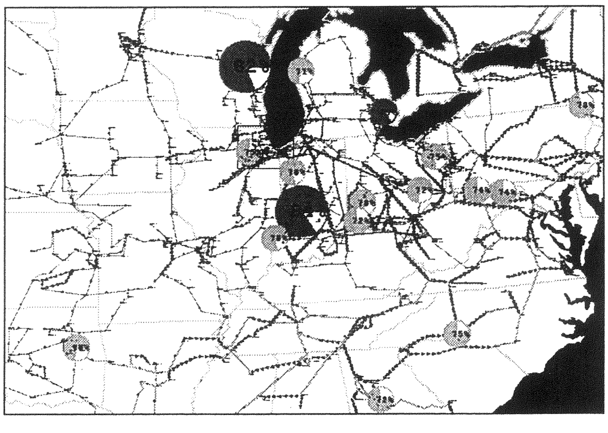

Figure 2: Pie Charts Showing Line MVA Percentages

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. For example 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 was investigated: contouring.

3. Contouring

Building on the work done in [12]-[13], this sections looks at the use of contouring visualization in the analysis of transfer capability. 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 to find a patterns in the power system. In order to overcome this problem for studying system voltages, the use of bus voltage contouring has been developed [12].

The creation of a contour for a bus-based value involves representing the *virtual value* throughout the two-dimensional contour region by a weighted average of the bus values near each point. An example virtual value point along with six buses with associated values is shown in Figure 3. The calculation performed to determine the virtual value at each point in the contour is given in (1).

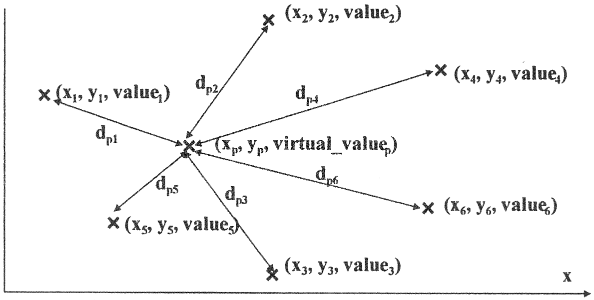

Figure 3: Calculation of the Virtual Value

$$v_p = \frac{\sum_{i=\text{all buses}} \left(v_i \frac{1}{d_{pi}^{\alpha}} \right)}{\sum_{k=\text{all buses}} \left(\frac{1}{d_{pk}^{\alpha}} \right)} \tag{1}$$

where v_p = value for virtual position p
v_i = value for bus i
d_{pi} = distance from p to bus i
α = parameter controls weighting

By adjusting the parameter alpha, one can control the relative weighting of close versus far buses. A value of alpha equal to 2 is used throughout the contouring shown here because it provides the fastest computation time and the nicest results.

Once these virtual values are calculated, mapping each virtual value to a colored pixel creates the contour. A color-map is defined which performs this number to color conversion. The choice of this color-map is discussed further in the following section, but for bus values a mapping which shows high values in red, middle values in green, and low values in blue is used. We refer to this color map as the RGB map. Several issues regarding recommended ways to use contouring when showing bus values are discussed in [12]. Issues regarding numerical techniques used to greatly accelerate the calculation of contours are covered in detail in [13].

An example of the use of contouring visualization to represent the voltages at approximately 400 of the 161 kV buses in the Tennessee Value Authority (TVA) system in the United States is shown in Figure 4.

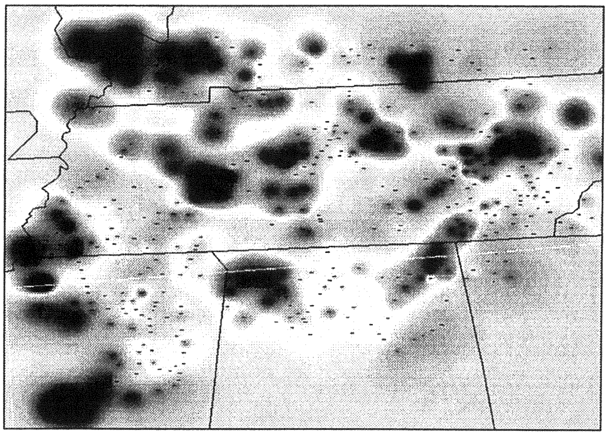

Figure 4 Bus Voltages in the 161 kV system in TVA

As one can see, an overview of the voltage profile of the entire TVA 161 system is found at a glance using the contouring visualization

4. Line Flow Contour Visualization

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 such as shown in Figure 5

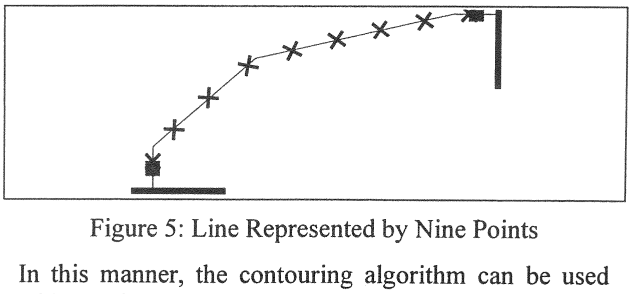

Figure 5: Line Represented by Nine Points

In this manner, the contouring algorithm can be used with no further modification to determine the virtual values throughout the contour.

This method was tested on a display showing the MVA line loading percentages throughout a system, but the results were disappointing. Using the RGB color map, most of the screen shows up blue, making it difficult to locate the heavily loaded lines. The reason for this problem is the nature of line-based values: high line loadings are important to show, but low line loadings are of less importance. This differs from information such as bus voltage magnitudes where both high and low voltages may be of interest. Essentially, line limits are a "single-sided" limit, while bus voltages are a "double-sided" limit.

In order to create line-based contours that are useful, a more appropriate color map needed to be developed. The authors have found that choosing an appropriate color map is an essential step in creating a useful contour. To determine an appropriate color map, we looked to commonly recognized color-maps used in weather forecasting for guidance. In situations where both high and low values are important (e.g. Bus Voltage Magnitudes), the use of a color-map that mimics temperature forecast is useful. This is what the RGB map does. In situations where only high values are important (e.g. Transmission Line Loading), the use of a color-map that mimics the precipitation radar forecast is useful. This color-map represents low values as showing nothing on the contour (areas with no precipitation do not need to be displayed), medium values as light to dark green (light to heavy rain); then when values cross a limit, the color-map changes to yellow in order to highlight them (thunderstorms). As the values move higher they then transition to orange, then red, and then magenta to show more severe violations. We refer to this color map as the Radar High Limits color map.

Besides the use of a more appropriate color map, it has also proven useful to completely remove lines that are below a specified value from the contour calculation. For instance, one may want to completely ignore line loadings below 50% when calculating a line loading contour. Making these changes to the contouring routine resulted in very useful contour plots. An example showing the percentage line MVA loadings in the entire Eastern Interconnection is shown in Figure 6.

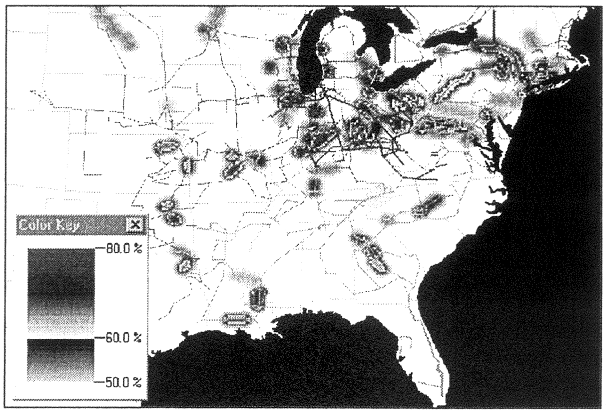

Figure 6 Eastern Interconnection Line MVA Percentage

Again, from a brief glance, the user is able to determine where the line MVA loadings throughout the entire region are high.

Line contouring can also be used to visualize transmission line power transfer distribution factors (PTDFs) for a large system [15]. 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 7 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.

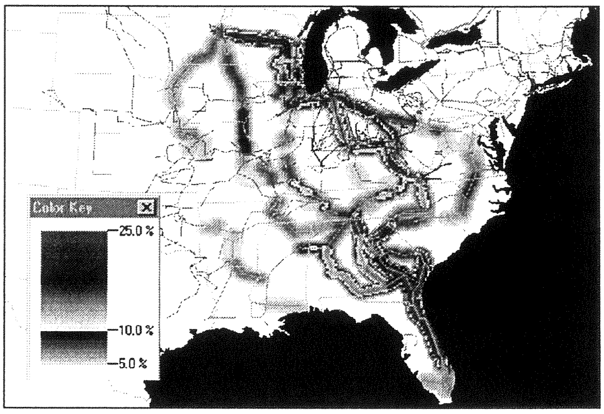

Figure 7: Transmission Line/Transformer PTDFs for a Transfer from Florida to Wisconsin

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. Contour Animation

The creation of single image contours has proven to be extremely useful in the visualization of power system information. However because of the speed of contour calculation it is also possible to implement the contouring as animation or to allow the contour to be dynamically redrawn as the system information changes. This has been done and the results are dramatically more interesting than those produced by a single snapshot contour. In a simulation, the contour can be updated dynamically and the user is able to view the voltage profile or flow changes as they occur, enabling the determination not only of the location of the present problems, but also to see where new problems are developing.

6. Flowgate Visualization

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 into ways that enable a smaller set of data to be analyzed. This process is called data aggregation. One such data aggregation technique is the flowgate idea currently advocated by the North American Electric Reliability Council (NERC) [14]. 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 draw 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 8 shows the flowgate PTDF values for a transfer from Commonwealth Edison in Chicago, Illinois to TVA in Tennessee in the United States Eastern Interconnect.

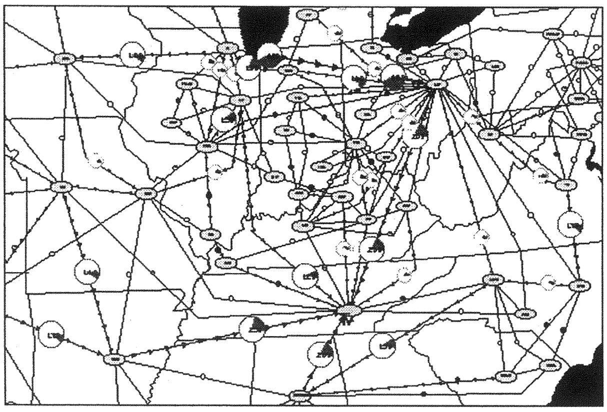

Figure 8: Pie Chart Visualization of Flowgate PTDFs

The use of flowgates can also be coupled with the line-based contouring techniques. An example showing the PTDF values for a transfer from is shown in Figure 9. These contours are also very useful.

Extending this technique to the contouring of values determined by ATC calculation may prove to be more difficult however. This is due to the fact that even areas which are not directly connected with have an ATC associated with them. The number of "links" from one area oval may become much larger. In order to overcome this problem, an investigation of the use of virtual reality to display the power system using three dimensional graphics is presented next.

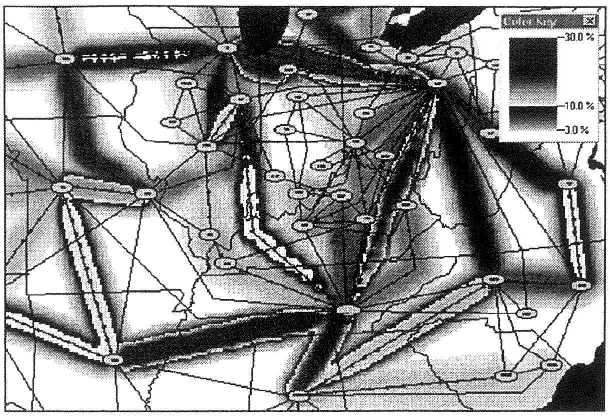

Figure 9: Contour Visualization of Flowgate PTDFs

7. Virtual Reality Data 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 often in power systems the relationships between a number of layered systems need to be considered. A pertinent example is the relationship between the actual transmission system flows and the scheduled contractual flows. Here we provide some initial results on the use of virtual reality to visualize such systems.

Virtual environments, or virtual reality (VR), provide a fully three-dimensional interface for both the display and control of interactive computer graphics [16]. Thus the main idea behind VR systems is to give the user the feeling that they are immersed in a three-dimensional world, populated by computer generated objects. The most compelling illusions are achieved through the use of wide-field-of-view strereoscopic head-tracked display systems [17]. Results concerning the use of VR for operator-training in power systems are described in [18] and [19].

For the results presented here, PowerWorld Simulator was modified to allow three dimensional drawing and interaction using OpenGL. OpenGL itself is a software interface, originally developed by Silicon Graphics, for graphics hardware that facilitates the modeling of three-dimensional systems [20]. Similar to [19], the PowerWorld Simulator implementation uses a regular PC type display to provide a less-ambitious, but nevertheless quite compelling virtual world. Key to achieving a virtual reality illusion is to provide the user with the ability to move about freely in three dimensions, and to look in any desired direction. Of course this affect is impossible to achieve using figures in a paper, and again need to request the reader's forbearance and imagination.

As an example, Figure 10 shows a one-line for a thirty bus, except with the modification that the one-line has been mapped into a 3D view, and that bus "height" and color is now proportional to the bus voltage magnitude. When the simulation is running the flows on the transmission lines are also animated. By moving about in this virtual world, the user begins to feel more as if he/she is within the one-line, rather than just looking at it. This allows the potential to gain a much better intuitive appreciation for the relationship between different power system quantities, such as voltage magnitude and flows in this example.

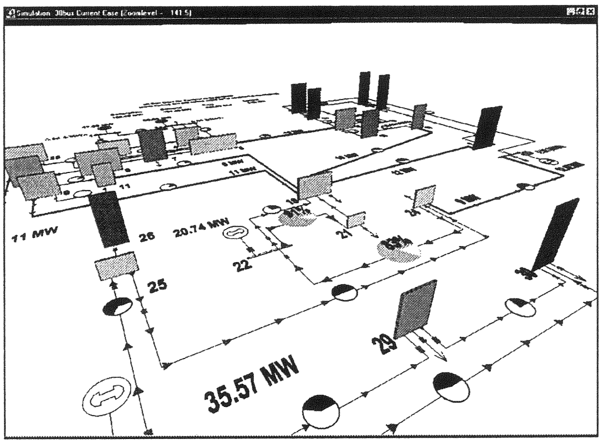

Figure 10: Three-Dimensional View of a Thirty Bus System

The potential for VR systems to show relationships between the actual flow of power and the scheduled flow of power is illustrated in Figure 11. This example uses an area display similar to the one shown in Figure 8 for illustrating the actual flow of power between different operating areas. However by using VR the system scheduled flows can also be added to the display as trajectory arcs between the different areas. Here the height of the arc is proportional to the scheduled MW flows between the areas, with the movement of the spheres superimposed on the trajectories used to indicate direction of the transaction. Note that in a standard two-dimensional layout it could be very difficult to show the scheduled flows since they often go between non-contiguous areas. In a similar manner such an approach could be used to indicate available ATC along a number of different directions.

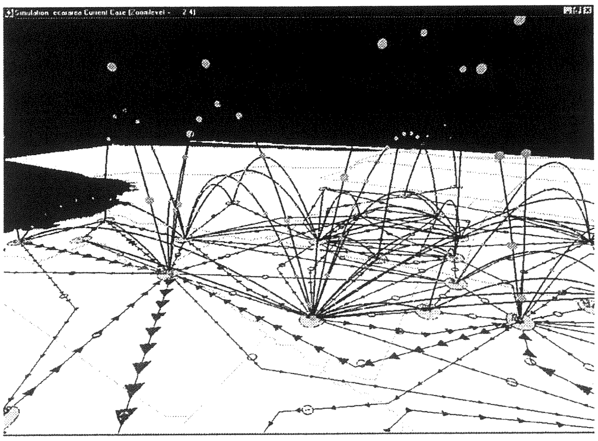

Figure 11: Relationship between Actual and Scheduled Flows between Areas

VR systems can provide an extremely effective method for visualizing power system data. However we would like to conclude this section by noting that they are usually best for describing relationships qualitative relationships between different variables. For exact quantitative results text based displays are better. Therefore we recommend using the proposed visualization techniques to supplement, but certainly not replace existing techniques.

8. 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 large systems. We believe that animation, contouring, data aggregation and data visualization using virtual reality 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. Hopefully future research and continued improvements in computer technology will lead to new innovations in these areas.

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