Visualization of Large Scale Power Systems

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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, or even tens of 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 paper presents several power system specific visualization techniques to help in this task. These techniques include animation of power system flow values, contouring of various power system values including voltage magnitudes and transmission line percentage loadings, and brief coverage of a data aggregation technique. Results are shown for several large scale power systems.

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

1 Introduction

The electric power industry throughout much of the world is in a period of radical and rapid restructuring. While the future structure of the industry is not yet completely determined, it is clear that the future system will be more competitive as many new players, such as non-utility generators, brokers, marketers and load aggregators enter the business. 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 from 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. However a key difficulty in achieving this goal is the fact that the capacity of the transmission system has a finite, but not easily determined value. Furthermore, determination of this capacity requires analysis of large systems, often containing thousands or tens of thousands of buses. Such analysis creates the need to sift through tremendous amounts of data.

Much work has, of course, been done in the area of developing useful graphical user-interfaces (GUI) to aid in interpreting this data. Several recent examples are described in [1] - [6]. 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..

The techniques presented here have been implemented in PowerWorld Simulator [7]; earlier versions of this package have been described in [8] and [9]. In a nutshell, Simulator is an innovative power system analysis package designed from the ground up to be extremely user-friendly, and highly interactive. Simulator is actually a number of products integrated together. At its core is a power flow package capable of efficiently solving systems of almost any size. Yet it can be used as a time-domain simulation mode using a constant frequency model to simulate power system operation over time frames of minutes to days. The main interaction between the user and Simulator is through a GUI whose most important component is the one-line diagrams. An important aspect of Simulator is its ability to update these one-lines quite quickly using smooth bitmap copies. This allows for very quick panning and zooming on the one-lines, and also makes Simulator a very useful platform for power system visualization research. The remainder of the paper describes techniques for visualization of large power systems. Techniques described include power system line flow animation, contouring of data, and data aggregation.

2 Line Flow Visualization

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 analog 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. More recently in [6] a width encoding is used to indicate line flow direction and loading. With this encoding the width of the line is varied to indicate the real and reactive loading on the line. Such an encoding permits more rapid comprehension of flow on a larger number of lines, albeit with some loss of precision.

However, one of the consequences of industry restructuring has been an increasing need for market participants to analysis larger and larger systems. Recent examples of this phenomena in the United States include a proposal to develop a "Midwest ISO" that would cover parts of thirteen states [10], the proposed merger between American Electric Power Company, and Central and SouthWest Corporation [11], and recent FERC Form 715 filings in which systems with over 30,000 buses are modeled. In this section several methods for visualizing such large systems are discussed.

The first such method is the use of animation to illustrate how power is actually flowing in a system [12]. As an example, Figure 1 shows a one-line diagram of the high voltage (345 kV and above) transmission system in the southern portion of the WSCC (Western Systems Coordinating Council) system in North America. The actual WSCC model itself contains about 6400 buses. 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 an animation is impossible to convey using ink on paper, so we require the reader's forbearance and use of imagination. Using PowerWorld Simulator 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. The package updates the one-line using bitmap copies resulting in a smooth, almost continuous animation. During the animation the "flow" of the arrows along each line can be either proportional to the actual flow on the line or proportional to the percentage loading on the line. That is to say, lines which either have a greater actual MW flow or a greater percentage flow appear to be flowing faster. 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. For example, Figure 2 shows the same WSCC system, except with the one-line zoomed into the San Diego area. Note that underlying 230 kV transmission lines are now visible.

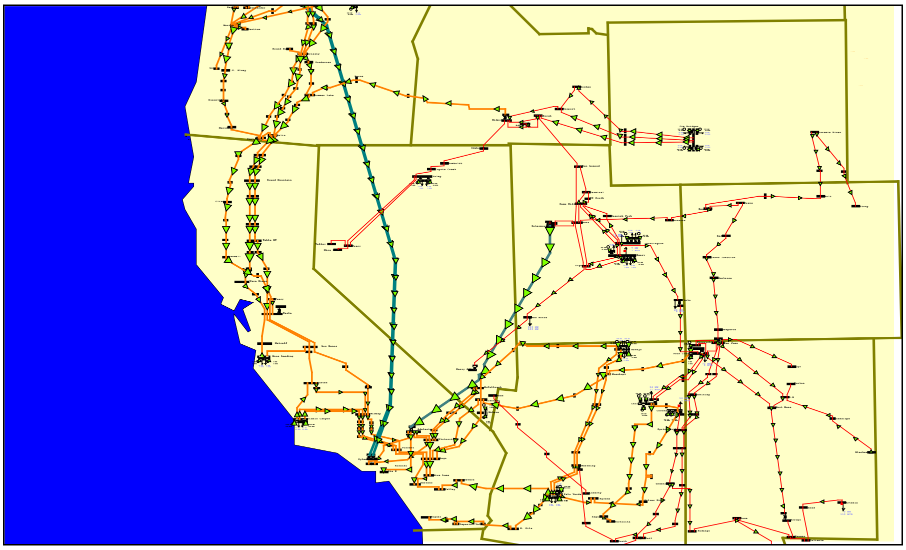

Figure1: Southern WSCC High Voltage Transmission System

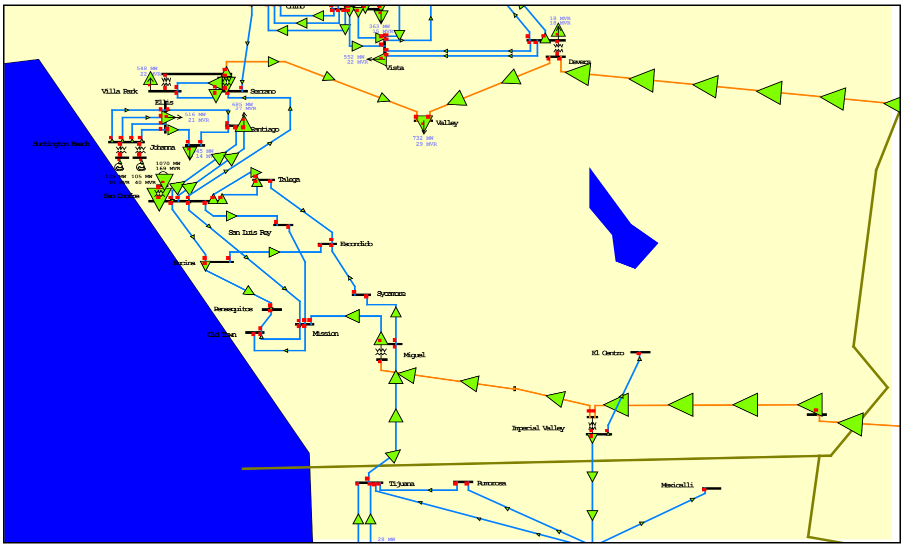

Figure 2: WSCC Zoomed View of San Diego Area

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 3 again shows the southern portion of the WSCC system with pie-charts used to indicate the loading on each transmission line; for this example the animated flows have been suppressed. 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 3 case the user was only concerned with those lines at or above 75% loading. By specifying that the pie-chart increase in size by a factor of 5 if above 75% or a factor of 7 if above 90%, it is easy, even in a large system, to see the heavily loaded lines.

3 Contouring

Another important visualization technique for large scale power systems is the use of contour plots to show voltage magnitudes, and possibly line flow values. Traditionally the most common representation of voltage magnitudes on one-lines has been a digital numeric display of the voltage next to the bus. While this representation is certainly accurate, the user can have a very difficult time perceiving patterns in the voltages at more than a handful of buses.

An initial improvement on numerical displays has been to place an analog type display next to each bus. As an example, for bus voltage magnitudes approaches based on placing a "thermometer" next to each bus have been used [13] – [16]. A simple thermometer is shown in Figure 4. In this example, more gray signifies a lower voltage.

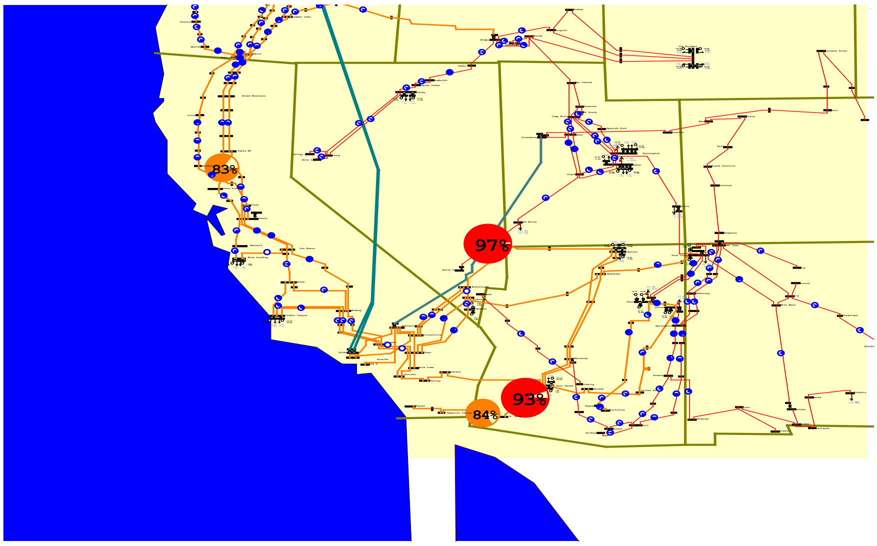

Figure 3: Southern WSCC with Heavily Loaded Lines Highlighted

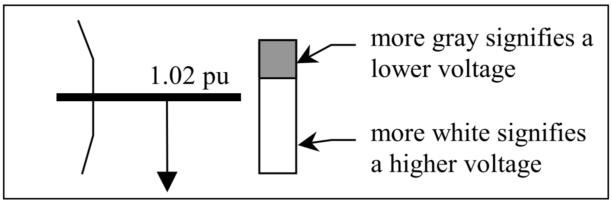

Figure 4: Basic Thermometer Graphic

The thermometer-based representation was definitely an improvement over the digital displays when looking at hundreds of buses, but it is still not easy to analyze vast amounts of information this way and to see patterns.

As mentioned in [6], [13], [14], possibly the first representation one thinks of for visualizing voltage information is the contour plot. However before discussing contour plots in detail, it is useful to consider three guidelines of what constitutes a good graphical representation [6]:

1. Natural encoding of information
2. Task specific graphics
3. No gratuitous graphics

A contour plot meets all these requirements. First, it is a nature encoding of information. Anyone who has seen a temperature-forecast map on the evening news is familiar with this type of representation. For example on the temperature map blue may signify low temperatures, while red signifies hot temperatures. Likewise, for power systems a contour could be developed where blue signifies low voltage magnitudes, while red signifies high voltage. Of course a gray scale can also be employed, and is indeed preferable when presenting results in a paper printed in black and white, or to color-blind users.

The second and third guidelines can be satisfied by using customized one-line diagrams in which all the gratuitous graphics have been removed. For example graphics could be limited to the just the system buses and the contour plot. Other graphics could make the display too busy and the user unable to distinguish between the different types of information being displayed.

While contour plots in general meet these guidelines, a key question that must be addressed is, are contour plots an effective means for showing voltage information? Some potential objections include:

1. Voltages are defined at discrete points in a power system, not a continuum as assumed in a contour plot.
2. Tap-changing transformers may introduce sudden changes in voltage. Contour plots normally imply a slow variation in value.
3. Voltages that are near one another on a diagram may not be "near" one another electrically. This is especially true for different voltage levels.

While these objections certainly have merit, we believe each can be adequately addressed [17]. The first is addressed by recognizing that the primary purpose of the contour is to aid in data interpretation. Contours let the user see the trends in voltages across a region. If desired, the contour can be augmented with traditional text-based information either from a printout or via numerical displays on the one-line diagram.

The second objection is a valid concern. Tap-changing transformers can introduce some problems in interpreting contour plots. However, this problem can be overcome by setting up a contouring in which only a single voltage level is contoured at a time. The third objection is also overcome by only plotting one voltage level at a time and by judicious construction of the contouring diagram. For example if a strictly geographical layout is used, normally buses of the same nominal voltage that are near each other geographically are also near electrically. The example plots towards the end of this section show the effectiveness of the contouring approach.

3.1 Contouring Algorithm

To create a contour the power system can be visualized as a two-dimensional region that has discrete values at points throughout the space. For bus voltage contouring these discrete points consist of the per unit voltage magnitude at the particular bus. The contour algorithm then must map this discrete data into a continuous region. Essentially this can be thought of as low pass filtering of the data. Upon doing this filtering, a contour can be created which effectively displays the voltage profile of the system.

Of course for implementation on a computer this continuous space is represented by a grid of data points, in which the size of the grid is dependent upon the desired resolution on the computer screen. The job of the low pass filter then is to calculate the *virtual values* of each point in this grid. These values can then be mapped to a color and the resulting contour plotted.

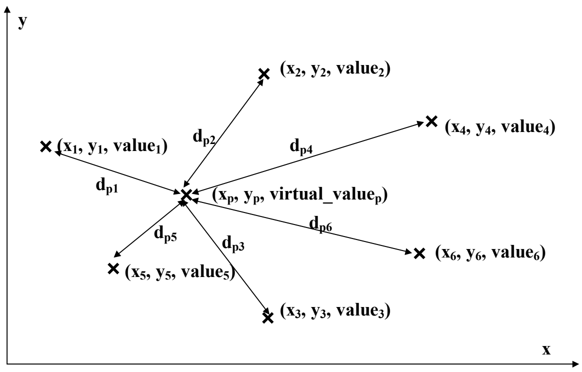

Figure 5: Calculation of the *Virtual Value*

In the calculation of these virtual values, buses that are closer to the virtual point should be weighted more than those that are farther away. Referring to Figure 5, the virtual value at the point (x_p, y_p) should weight the value at (x_1, y_1) more than the value at (x_6, y_6). The method presented in [17] for implementing this was to calculate a simple weighted-sum of the buses in the system for each virtual position as shown in Equation (1).

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

where v_p = value for virtual position p

v_i = value for bus i

d_{pi} = distance from p to the center of bus i

α = parameter controlling weighting

By adjusting the parameter α the user can control the relative weighting of close versus far buses. As α grows, buses that are closer receive higher weights, and as α grows toward infinity, only the bus that is closest to the virtual point is given any weight. For this paper and for general purposes, using a value of $\alpha = 2$ is best as it provides for the fasted computation time (computers calculate x^2 much faster than say $x^{1.5}$).

Calculating contours in this manner makes the basic assumption that buses near one another on the one-line diagram (i.e. near geographically) are "near" one another electrically. A sample contour plot of the per unit voltage magnitudes for a six bus system is shown in Figure 6. Here white equates to higher and black to lower voltages. It is obvious at a glance which areas have high and low voltages.

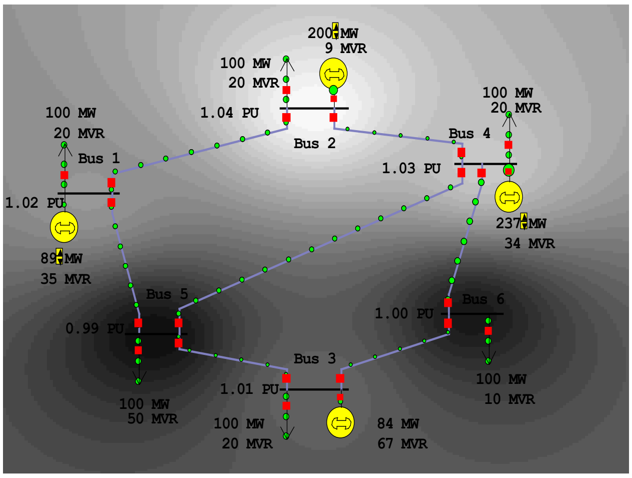

Figure 6: Sample Voltage Contour of Six Bus System

Using this algorithm to contour large systems with hundreds of buses took from about 10 to 15 seconds on a 200 MHz Pentium Pro based PC. While this was adequate for creating snapshots of the system voltage profile, it was far too slow for realistic implementation of real-time animation of the contours. To achieve substantially faster results, the algorithm was modified from processing each screen pixel in the outer loop to processing each bus. This is accomplished by drawing a conceptual circle about the center of the bus to represent the influence region of the bus, as shown in Figure 7.

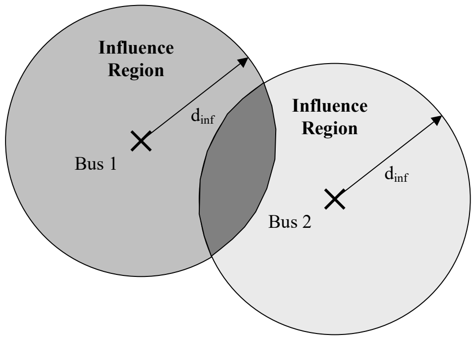

Figure 7: Bus Influence Regions

Then only the virtual values that lie within this influence region for each bus need be updated. The update involves simply adding one additional term to the summations in (1). Thus the inner loop for each bus j at location (x_1,y_2), assuming a voltage value of V_j, looks something like a double integral over a circular region as follows:

For x = $(-d_{inf}+x_1)$ to $(d_{inf}+x_1)$
  For y = $(-(d_{inf}^2 - x^2)^{0.5}+y_1)$ to $((d_{inf}^2 - x^2)^{0.5}+y_1)$
    UpdateVirtualValue at (x,y) with value V_j
  Next y
Next x

An array with an entry for each point in the two-dimensional region of the contour is used to store these sums until all buses have been processed. Then the two sums are divided as shown in equation (1) to calculate the virtual value. Further speedup was achieved by recognizing that if the pixel regions within the influence region are square, then the computation can be further reduced by a factor of eight. This can be seen by consider only the shaded piece of the influence region seen in Figure 8. When calculating the influence of a bus on the virtual values, if the pixel regions are square, then the influence at the point (a,b) is the same as the influence at (b,a), (b,-a), (a,-b), (-a,-b), (-b,-a), (-b,a) and (-a,b). Therefore, instead of "integrating" over the entire circle, it is only necessary to integrate over a pie slice one-eighth the size of the circle. This reduces expected computations by almost a factor of eight.

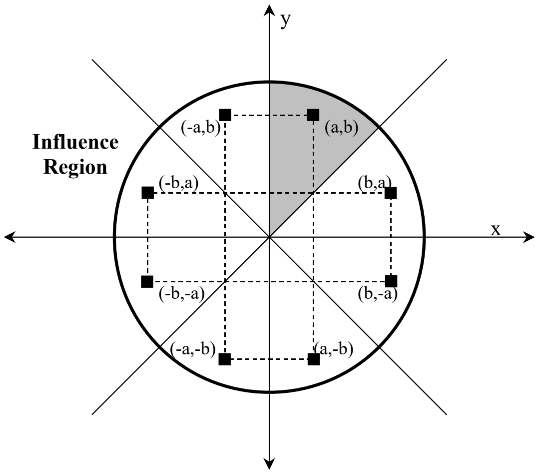

Figure 8: Reduction of Computation by a factor of 8

3.2 Contour Color Mapping

Once the virtual value has been computed, it must be mapped to a color for display. To create the color-mapping, values were mapped to one of potentially 16.7 million different colors on a computer monitor. This corresponds to a value of between 0 and 255 for red, green and blue. Of course a wide variety of different color mappings are possible, with the most appropriate mapping dependent upon the application. One common mapping is shown in Figure 9. This is similar to the mapping used in Matlab's "Jet" color-map [18]. All values below some minimum value are mapped to dark blue and all values above a maximum value are mapped to dark red. Another useful color mapping is black to white; this scale was used for most of the figures in this paper.

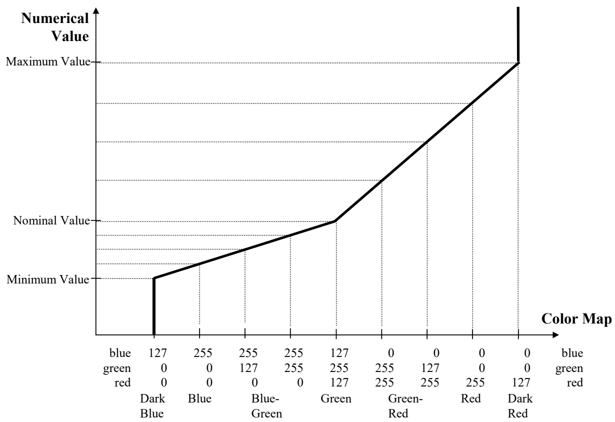

Figure 9: Color-Mapping for Red = High, Blue = Low

Within a power system, it is typical to maintain values within a specified limit. Thus when viewing system data it may be helpful to highlight any violations in these limits. This can be achieved by varying the color-mapping to include a discrete jump in color when the limit is crossed as shown in Figure 10. Figure 11 shows the Figure 6 system with these discrete color changes implemented. The bus at the top of the figure and the two at the bottom left and right are outside their respective limits, and are subsequently highlighted.

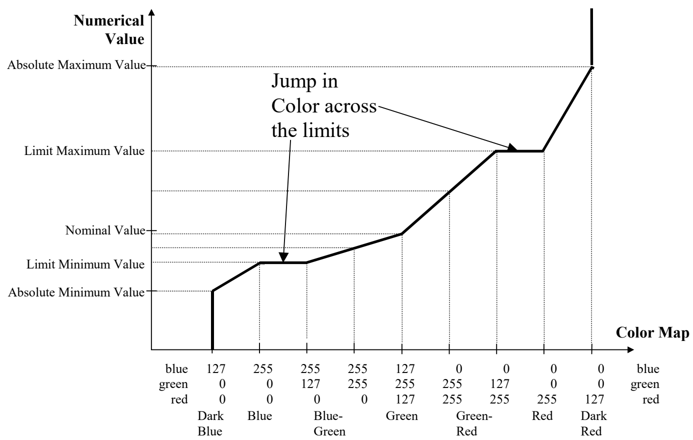

Figure 10: Discrete Change at Limits Color-Mapping

Another useful color mapping is a one-sided mapping for which only values below a some specified threshold, or a above a specified threshold are mapped. All other values are shown using a default background color. This type mapping could be very useful in highlighting only those buses that have voltage magnitudes below a specified value. Examples of these different mappings are shown starting with Figure 12.

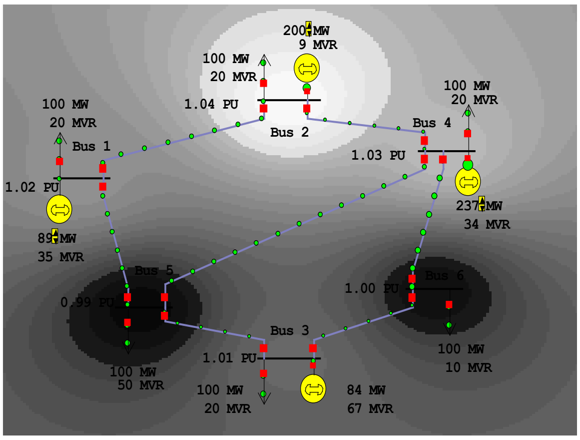

Figure 11: Voltage Magnitudes with Limits Highlighted

3.3 Contouring Animation

The use of the fast contouring algorithm decreased the time necessary to calculate a contour, even for a large system, to less than a second. With this order of magnitude decrease in computation time, it was possible to implement the contouring as an animation or to allow the contour to be dynamically redrawn as the user pans or zooms the one-line. This was done for this paper and the results were 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 as it changes, enabling the determination not only of the location of the voltage problems but also where voltage problems are developing.

3.4 Example Voltage Contours

While the animation itself can not, of course, be presented in a paper format and is much more dramatic when shown using a color monitor, the next several figures can be used to judge the effectiveness of contouring on two large systems, at least from a static perspective. All cases can be re-contoured in about one second to show either a changing system operating point, or results of a contingency. Figure 12 contours the voltage levels of approximately 500 of the 115 kV, 138 kV and 161 kV buses in a 4000 bus model of the Mid-American Interconnected Network (MAIN) in North America. Here rather restrictive voltage limits were chosen, with a minimum of 0.98 pu and a maximum of 1.05 pu, to highlight the voltage variation in the case. Figure 13 shows a contour of about 440 of the 161 kV buses in the TVA region of the United States using a 23,000 bus model using more realistic limits, with a minimum of 0.95 pu and a maximum of 1.10 pu. For this case the discrete change at limits color mapping of was used to highlight voltages below 0.95 per unit. For the case shown in Figure 13 there are no violations; the contour can be used to show the gradual variation in voltage across the region. In contrast, a contingency was modeled in the Figure 14 case, with a one-sided color mapping used to highlight only those buses with voltages below 1.0 per unit. For this case the area of low voltage is very apparent even in a black and white figure (results for a color display are more dramatic).

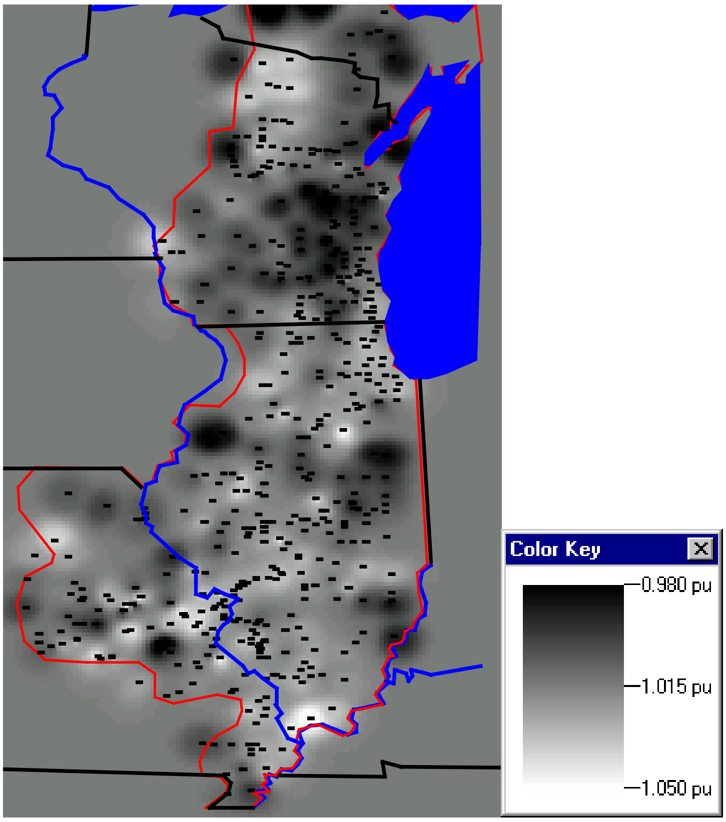

Figure 12: MAIN 115/138/161 kV buses

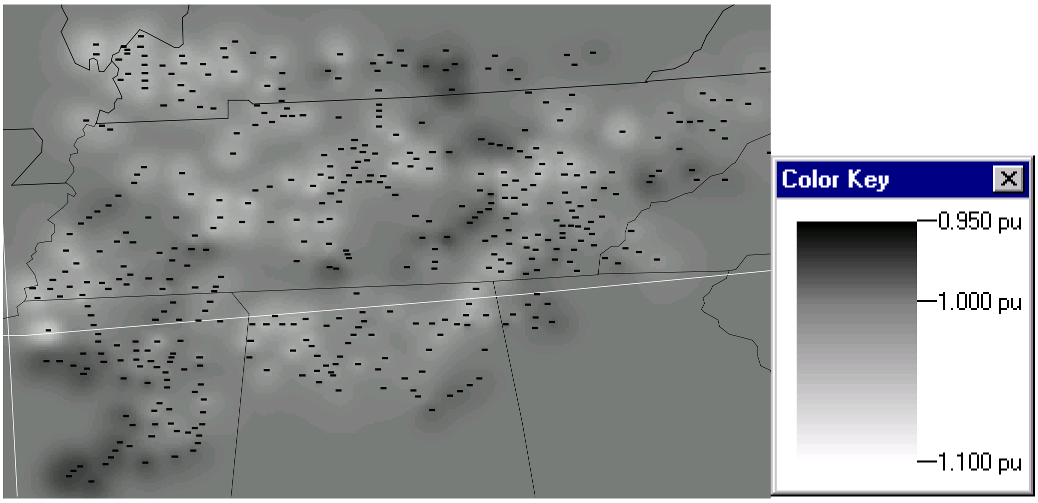

Figure 13: TVA 161 kV Buses

3.5 Line Flow Contours

Contouring can be applied to other types of power system data as well. For example Figure 15 shows about 1400 of the 345 kV and above transmission lines/transformers of the U.S. portion of the Eastern Interconnect. Superimposed on the one-line is a contour highlighting the transmission line and transformer flows that are above 65% of their MVA rating. The advantage of the contour approach is at a glance it is possible to determine the location of potential congestion, even in a very large system. This figure was produced using the same contouring algorithm discussed for bus voltages, with the slight modification that a transmission line is represented by a number of points.

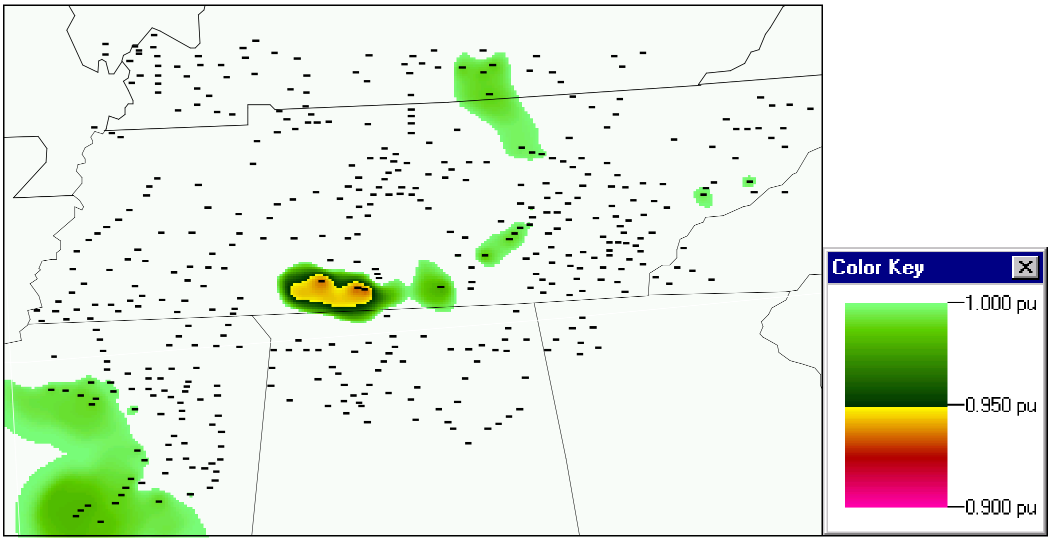

Figure 14: TVA with Only Low Voltages Shown

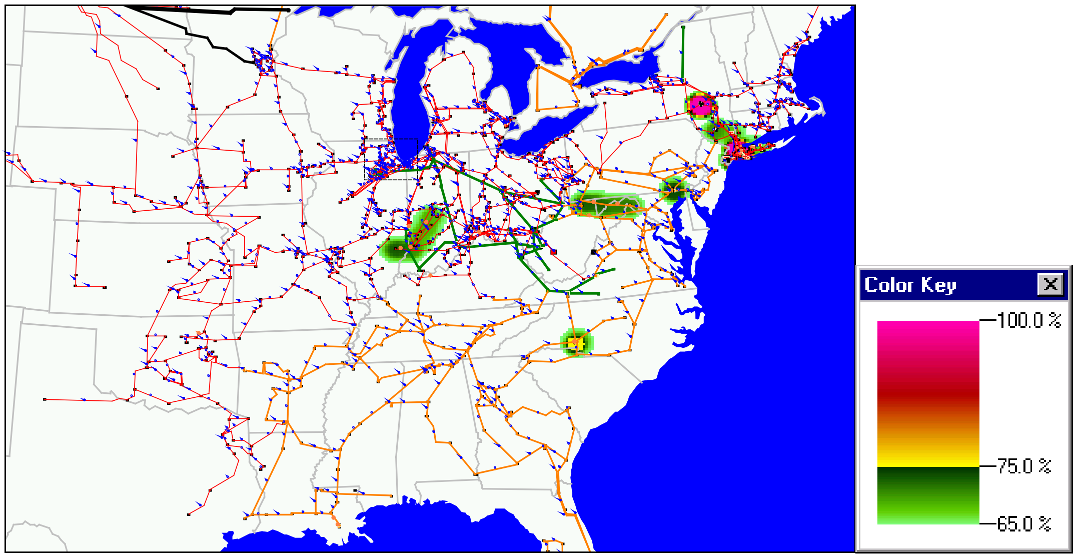

Figure 15: Eastern United States Transmission System

4 Data Aggregation

Previous visualization ideas can be quite useful for conveying detailed information about system state and should prove to be quite useful to aid in visualizing the network power transfer problem. Additionally, it is important to consider methods for data aggregation, viewing the system at an operating area or zone level, rather than at the bus level considered earlier. One such promising field for investigation is the flowgate idea currently being advocated by North American Electric Reliability Council (NERC). Flowgates are designated as subset proxies for transmission limitations and transmission service usage on the power system networks [19]. By monitoring the smaller subset of flowgates one can insure system or capture the directional flow associated with various commercial transactions. A flowgate is usually defined as being the sum of the flows through a specified group of transformers, transmission lines, or area to area interfaces.

As an example consider the 30,000 bus, 41,000 line model used earlier in the Figure 15 case. This case includes just about every operating area in the Eastern Interconnect, along with practically the entire transmission system. This makes the model useful for studying transactions throughout the interconnected system. Consider an example where one is simply interested in understanding the flow of power between the different operating areas. For this case only the net flow of power on the interfaces between the different areas would need to be visualized, rather than the individual line flows. Figure 16 shows the net flows on the 311 area to area interfaces joining the 119 areas shown on the one-line. As was the case for lines in Figure1 and Figure 2, animated directional arrows are used to indicate this flow. The use of such aggregation techniques, particularly when coupled with animation, make it relatively easy to get a feel for the flows, even in a very large system.

Such aggregation techniques can also be used to show the incremental impact of a particular power transfer, defined by NERC as the power transfer distribution factors (PTDF)s. The PTDF values provide a linear approximation of how the power flows would change for a particular power transfer between different values. In NERC's interim Interchange Distribution Calculator (iIDC) [20] these values are provided in list format, making it difficult to show the system-wide impact of a transaction. In contrast, Figure 17 uses the area to area flow diagram from Figure 16 but rather than showing the actual flows Figure 17 shows the incremental impact of a power transfer, in this case from Southern Company to the New York Power Pool (NYPP). The pie-charts show the percentage of the transfer carried on each interface, with the animated flows proportional to the PTDF for the interface. Representation on the one-line makes it relatively easy to see how this transaction has significant impacts throughout a large portion of the system. Note that these PTDF values could also be shown for the individual lines using a one-line similar to Figure1. However a difficulty with this approach is that since the PTDF value on each line would be quite small a pie chart would probably not be an appropriate means for showing the value. This is because it would be difficult, using a pie chart, to distinguish between small percentage values. This is another application where contouring might prove useful; sample results are shown in Figure 18.

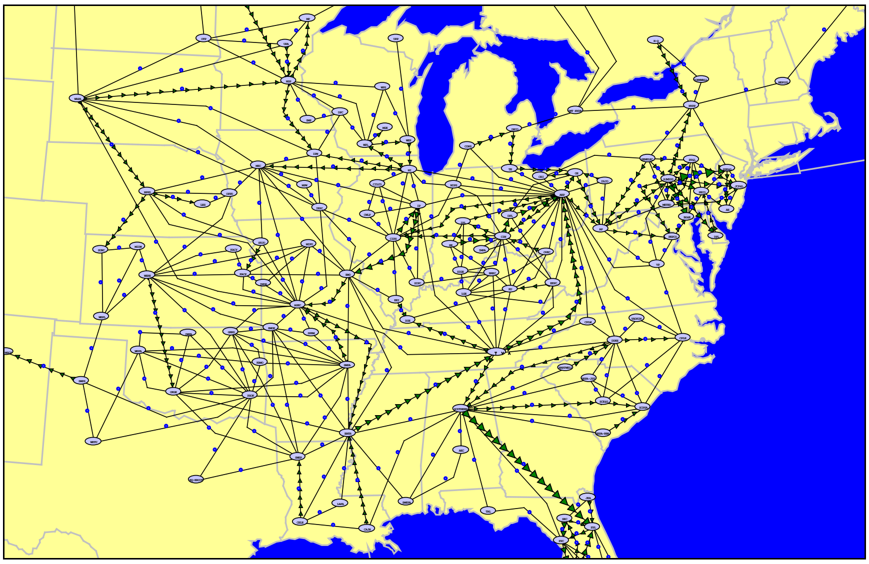

Figure 16: Area to Area Flows

5 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 and data aggregation 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.

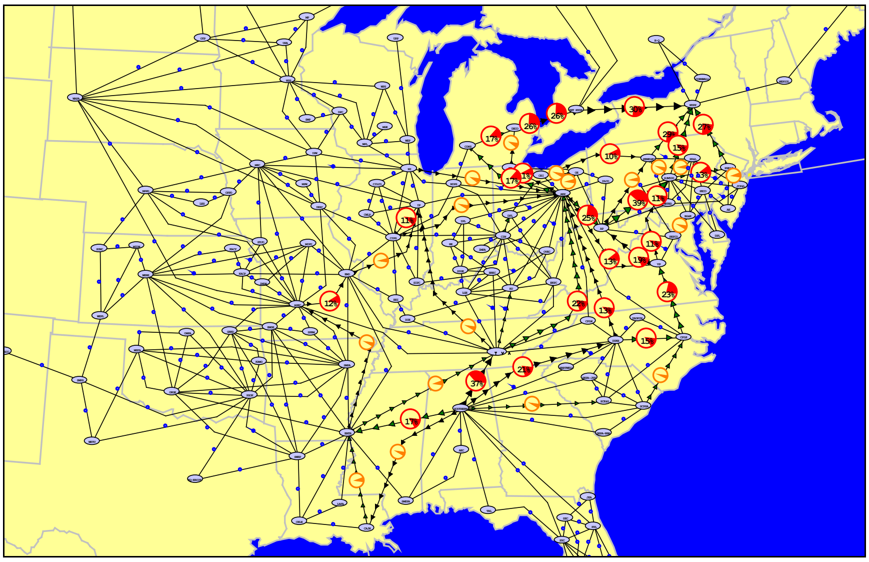

Figure 17: Southern to NYPP PTDFs

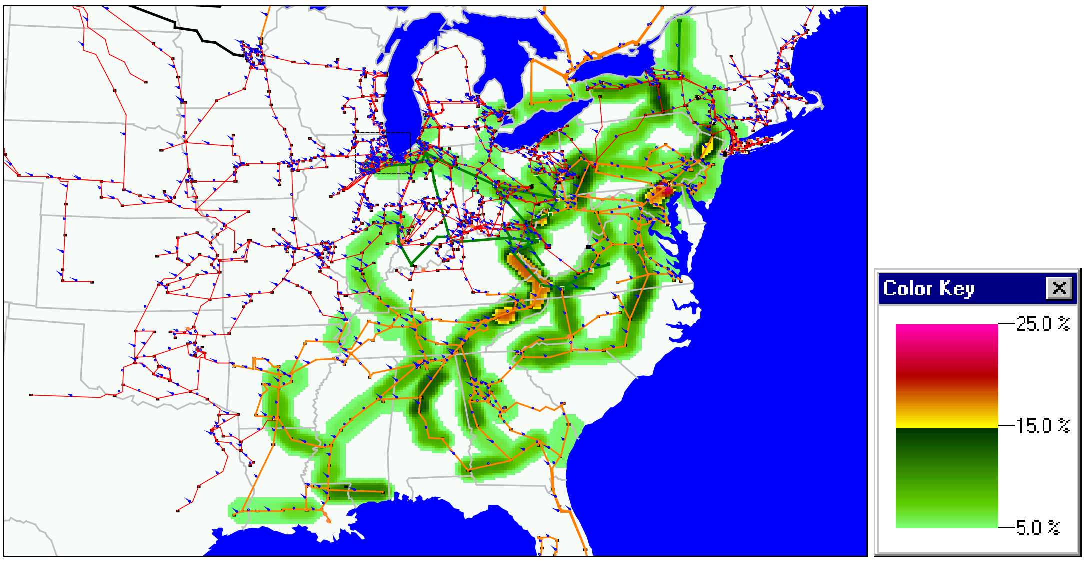

Figure 18: Southern to NYPP Transmission Line PTDFs

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