Power System Visualization through Contour Plots

James D. Weber Thomas J. Overbye
jd-weber@uiuc.edu overbye@uiuc.edu
Department of Computer and Electrical Engineering
University of Illinois at Urbana-Champaign
Urbana, IL 61801

Abstract
As the amount of data power system engineers need to study continues to increase, a new problem arises: how to analyze and visualize all this data. In this paper we propose using contour plots to help see variations of bus parameters across a large power system. This paper will concentrate on visualizing bus voltage magnitudes, but will also introduce the visualization of bus voltage angles and spot prices. Numerical issues of the calculation of these plots in a timely manner are also discussed. The contouring routines introduced are implemented into the POWERWORLD™ Simulator software package.

Keywords
Human-computer interface, power system visualization, contour plots, voltage visualization, spot pricing visualization

1. Introduction

Over the past several decades the computer has aided engineers in collecting and creating larger and larger amounts of data. This has been especially true for power engineers, who while studying, operating, and controlling the electric power system are confronted with the largest machine in the world. With typical systems having thousands of buses, engineers may be confronted with interpreting thousands of data points at a time. Fortunately, the computing technology that has helped create all this data is helping in its interpretation. Inexpensive, as well as easily implemented, hardware and software platforms have been developed that allow engineers to create graphical interpretations of the data. Much work has been done in creating effective graphical user-interfaces (GUI) for the energy management systems (EMS), with several recent examples described in [1]-[3].

In order to develop a good GUI for power system applications, it is important to understand the interaction between the computer and the human user. This has been studied in detail in several recent papers [5]-[6]. These studies have found good representations for power system parameters which are related to power system links: line MVA flow, line limits, etc., but all have found difficulty in creating good representations of data which is related to individual buses: voltage magnitude, voltage angle, spot price, etc.

Without graphical display, bus-related data must be studied by looking at text-based computer output. While this data is very accurate, it is also very difficult to interpret or see patterns in a large amount of data. With a limited graphical output available, one-line diagrams can be supplemented with digital numerical fields next to each bus. While this maintains the accuracy of the text-based data, the interpretation of large system remains difficult.

As GUI's have continued to improve, more work has been done regarding the visualization of bus-parameters. This has been especially true for bus voltage magnitudes for which many different approaches, centered on a thermometer analogy, have been tried as an alternative to the digital numerical displays [7]-[9]. A very simple thermometer is shown in Figure 1. For this sample, as the graphic became more "red", it would signify a higher voltage.

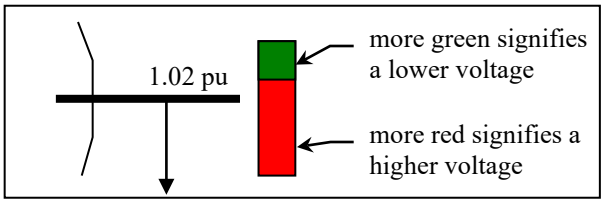


Figure 1: Basic Thermometer Graphic

While the thermometer-based representation certainly can aid in data interpretation, it is difficult to use this approach to rapidly interpret very large amounts of data and to easily see data trends. As mentioned in [6] and [7], possibly the first representation one thinks of for displaying system voltage magnitudes is the contour plot. Some objections with representing voltages as a contour are apparent from the outset however:

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

As a result, [6] and [7] dismissed this idea as being an unnatural coding. While these objections are partly valid, the objections should not be used to completely dismiss the contour plot approach. Section 3 will address these objections individually and show that they can be overcome. In this paper, we will show contour plots can effectively supplement existing methods of visualizing bus parameters. Special attention will be paid to visualizing bus voltages.

As mentioned in [6], graphic representations need three key components to be effective.

- Natural encoding of information
- Task specific graphics
- No gratuitous graphics

A contour plot can meet all these requirements.

A contour plot of system voltages creates a coding which is natural to anyone who has ever watched the weather forecast on the evening news. On a weather map, blue signifies cold while red signifies hot. For our application, blue can signify a low voltage while red can signify a high voltage. An unfortunate problem for anyone writing about visualization is that most conference and journal papers are printed in a gray scale. While color is preferred for contour plots, a gray scale can also be employed.

While looking at the contour plot, it is also possible to remove all graphics that are not needed for the specific task. For the task of plotting system bus parameters, one could determine that only the system buses are necessary. In this case the graphics would be limited to the buses and the contour plot. In this paper for the smaller systems shown in Figures 4, 7, 8, and 12 the additional graphics were retained for illustrative purposes. For the larger systems, the additional graphics created clutter and were therefore not shown.

The remainder of the paper discusses the basics on contouring (Section 2), interpretation and use of contour plots (Section 3), numerical issues in calculating the contour plots (Section 4), and finally, conclusions made (Section 5).

2. Contouring Basics

A majority of power system data is referenced to the system buses. System voltage magnitudes, voltage angles, loads, generation, and MW spot prices are several examples of this. Given a spatial distribution of the buses, the power system can be viewed as a two dimensional space with discrete values throughout the region. For the six-bus system shown in Figure 2, these values are shown in Figure 3 as (x_i, y_i, $value_i$).

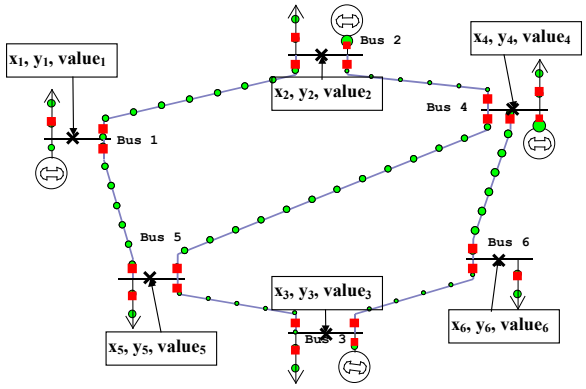


Figure 2: Sample Six-Bus Power System

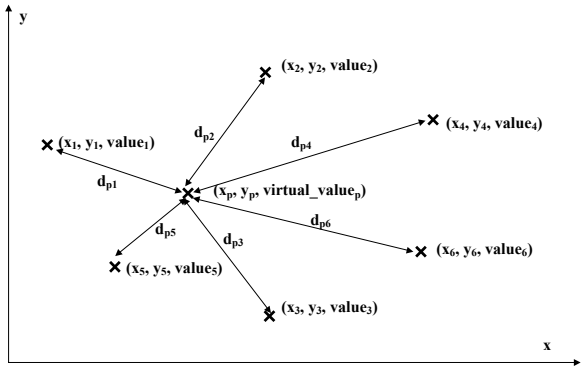


Figure 3: Visualization of Six-Bus System for Contouring

A contour plot assumes that values exist throughout the two-dimensional space. Therefore, in order to create a contour plot of the system data, it is first necessary to filter the data in a way that converts it from discrete points to a continuous spread of values. Essentially this can be thought of as a low pass filter process.

In order to achieve this, actual contour lines could be calculated. However, this is often not necessary. Instead, if a grid of data points are created containing *virtual values* at all points in the two dimensional space and these values are mapped to colors and plotted, the user will cognitively fill in the contour lines. These *virtual values* should weigh values that are closer to the virtual position (x_p, y_p) more than those values that are further away. A simple way to implement this is by performing a weighted-sum over all the buses in the system for each virtual position as shown in Equation (1).

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

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 grid size for the data points, a user can control the resolution of the contour plot. For this paper, all plots are made using a 200 by 200 grid of data points.

This method also gives a user control over the relative weight of close buses. As α increases buses that are closer receive higher weights. In the limit as $\alpha \rightarrow$ infinity, only the closest bus is given any weight. For this paper however, all plots are made with α=2.0, which has the advantage of using the familiar Euclidean distance and of faster computation than other values of α.

It should be noted that the calculation of contours in this manner makes the assumption that buses near one another on a one-line diagram are "near" one another electrically. This may not always be true, but the objection is addressed in Section 3.

A contour plot of per unit system voltage magnitudes for the Figure 2 system is shown in Figure 4.

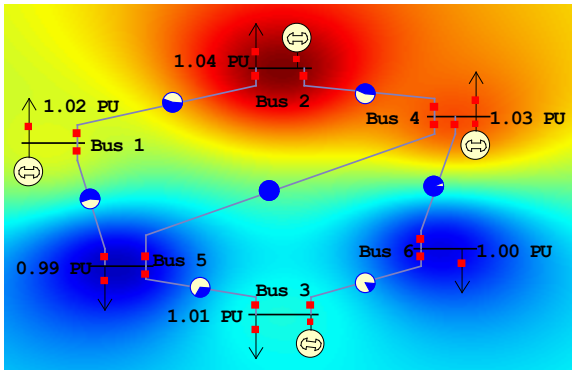


Figure 4: Voltage Magnitudes for Six-Bus System

For this figure red equates to higher voltage and blue to lower voltage. This simple picture shows the key advantage of contouring. At a glance the high and low voltage regions of the system are apparent. Once a user is familiar with the color-map key, there often may be no need to look at the actual values shown in the picture.

Several color-mapping options have been implemented for this paper. The authors' preference is to map red to high values and blue to low values. To create this color-mapping, values must be mapped to one of 16.7 million colors on a monitor. This corresponds to a value of between 0 and 255 for red, green and blue. A common method for achieving this is by mapping values as shown in Figure 5 [11]. This is similar to the mapping used in Matlab's "Jet" color-map. All values below some minimum value are mapped to dark blue and all values above some maximum value are mapped to dark red.

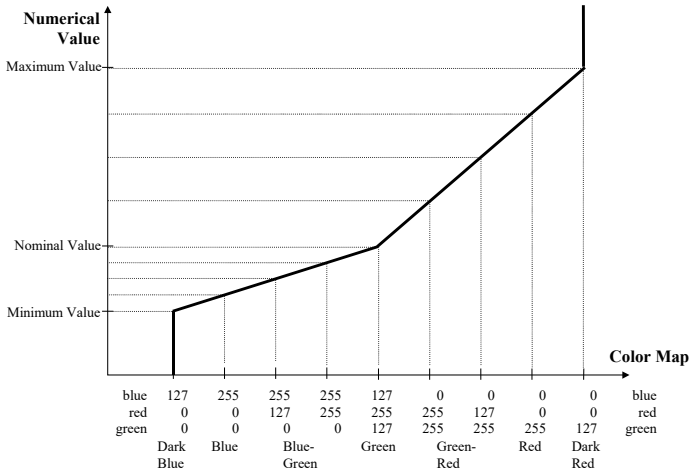


Figure 5: Color-Mapping for Red = High, Blue=Low

Within a power system, it is typical to maintain values within a specified limit. When viewing system data, is would therefore be helpful to highlight any violations in these limits. This can be achieved by varying the color-mapping to include a discrete change in color when the limit is crossed as shown in Figure 6. Figure 7 shows the six-bus system with these discrete color changes implemented.

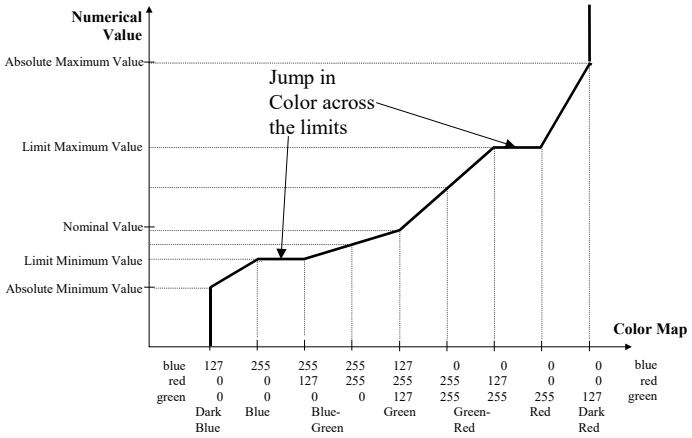


Figure 6: Color-Mapping with Discrete Change at Limits

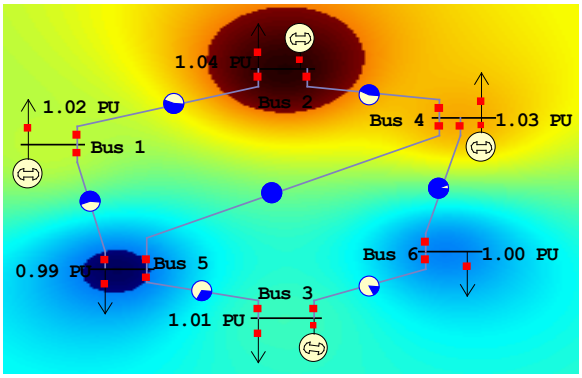


Figure 7: Voltage Magnitudes with Limits Highlighted

In Figure 7, the bus at the top of the figure and the two at the bottom left and right are both outside specified limits, and as a result they are highlighted more. Compare Figure 4 and Figure 7.

Any color-mapping is possible. For this paper, four color-mappings were implemented:

- Blue=Low, Red =High
- Red =Low, Blue=High
- Black=Low, White=High
- White=Low, Black=High

Each of these mappings also had the option to highlight the limit violations as done in Figure 7.

3. Interpretation and Use of Contour Plots

Overcoming Objections to making Contour Plots of Voltages Magnitudes

Prior to discussing applying a contouring algorithm to system voltages, it is import to address the objections mentioned in the introduction:

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

The first objection is only valid if one is concerned with complete numerical accuracy of the contour plot. In this application, however, the contour plot is only meant to aid in data interpretation. We are only concerned with helping the user identify where high and low voltage regions exist. If necessary, the exact numerical value can be shown in more conventional ways, such as a text-based lists of all voltages or displaying numeric values on top of the contour as done in Figures 4, 7, and 8.

The second objection is a valid concern. Tap-changing transformers can introduce some problems in interpreting the contour plots. When creating a contour, one assumes that a continuous change in the values occurs. This can be violated with the introduction of tap-changing transformers. Figure 8 shows this effect.

Absolute Minimum	Nominal	Absolute Maximum
0.99 p.u.	1.02 p.u.	1.05 p.u.

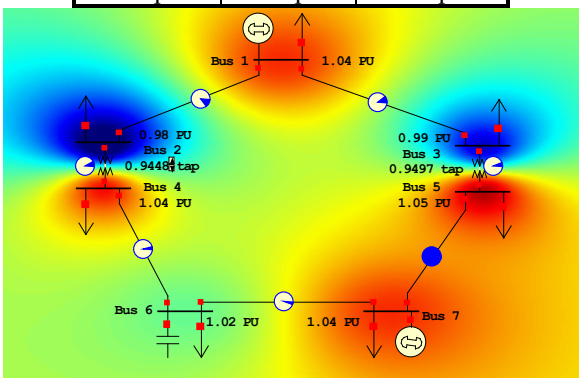


Figure 8 Tap-Changing Transformer Effects

In Figure 8, the buses at the upper-right and upper-left have tap-changing transformers connected to them. This results in having two buses next to one another with very different voltages. In the contour having a dark and a light spot right next to one another depicts this. It is sometimes hard to see this effect, so caution must be used when looking at systems with a large number of tap-changing transformers. It is probably preferable to avoid this problem by only contouring the buses at certain voltage level.

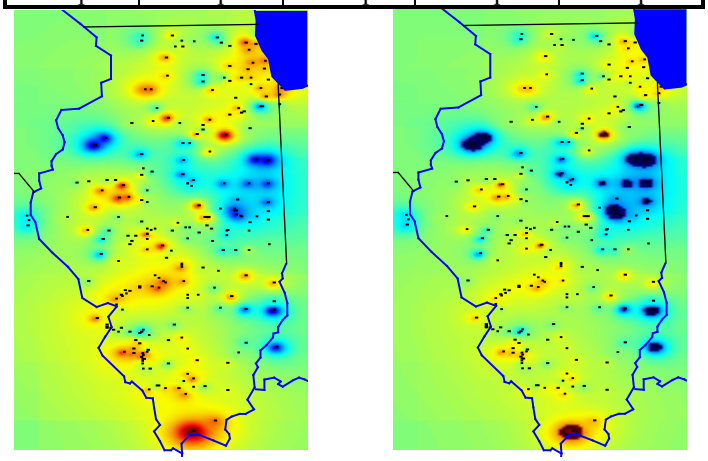
The third objection is also a valid one. In performing the calculation of the voltage contours it is assumed that buses which are near one another on the one-line are near electrically. This, of course, depends upon how the one-line has been designed. If the one-line is done geographically, then there certainly could be problems, particularly when different voltage levels are involved. As a result, it is normally good practice to only include buses that are at the same voltage level. In this way we ensure that buses are near both electrically and geographically.

Thus as a result of both the second and third objections, it may be advisable to only perform voltage contouring on one voltage level at a time. Of course, individual users of the contour plot will need to design a one-line display that highlights voltages in a manner that will be of use to them.

Contour Plots of Voltage Magnitudes

Following the guideline set forth in the previous section, a map of a large portion of the 115/138/161 kV transmission system buses in Illinois was made with over 250 buses displayed. Figure 9 shows contour plots of this system. The user-specified limit values shown in the table are quite restrictive, but were chosen for illustrative purposes only.

Absolute Minimum	Limit Minimum	Nominal	Limit Maximum	Absolute Maximum
0.98 p.u.	1.00 p.u.	1.015 p.u.	1.04 p.u.	1.05 p.u.



Without Limits Highlighted With Limits Highlighted

Figure 9: 4000-Bus System with 250 Buses Displayed

Through the use of these contour plots, the user can obtain a quick overview of the voltages in a large power system. Also, Figure 9 again shows voltage violations can be easily highlighted by introducing a discrete change in color when this occurs.

Contour plots of voltage magnitudes may be most useful when very large systems are studied. Once a one-line with appropriate graphics has been developed and a color-mapping for the contour plot has been settled upon, the experienced user would rapidly become familiar with the expected voltage contour. Unexpected low and/or high voltage patterns would be readily discernable from the contour plot. Upon noticing unexpected patterns, the experienced user could then consult text-based computer output or digital numerical displays for more detailed information regarding the voltage magnitudes.

With open access, very large power system markets will be open, allowing many new market participants access to system data. New visualization techniques, such as contouring, could be especially helpful to these new participants for accessing voltage conditions. For example, if a reactive power market is created, the voltage information could provide guidance to a trader for locating reactive power reserves.

As another example of a larger system, Figure 10 and Figure 11 show 500 of the 115 kV, 138 kV and 161 kV buses in the Mid-American Interconnected Network (MAIN) control area. The user-specified limit values user where as shown in the following table. Again, these were chosen for illustrative purposes only.

Absolute Minimum	Limit Minimum	Nominal	Limit Maximum	Absolute Maximum
0.98 p.u.	0.99 p.u.	1.01 p.u.	1.03 p.u.	1.04 p.u.

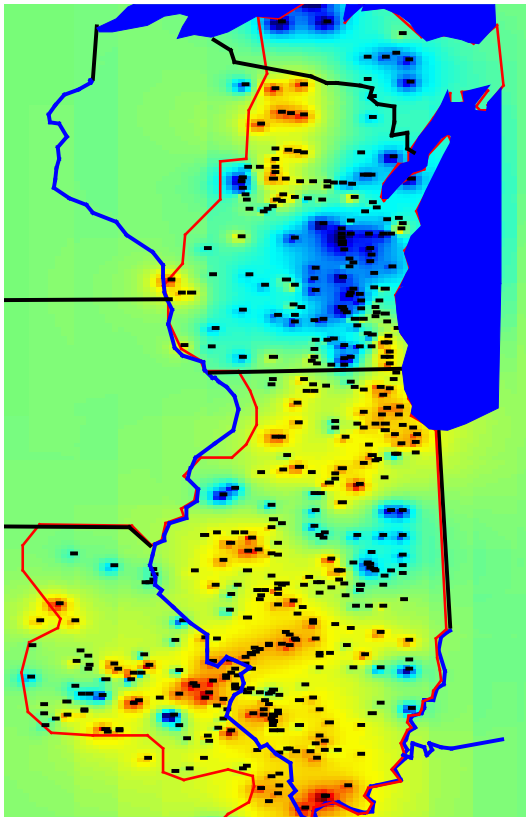


Figure 10: 500 Buses Display Without Limits Highlighted

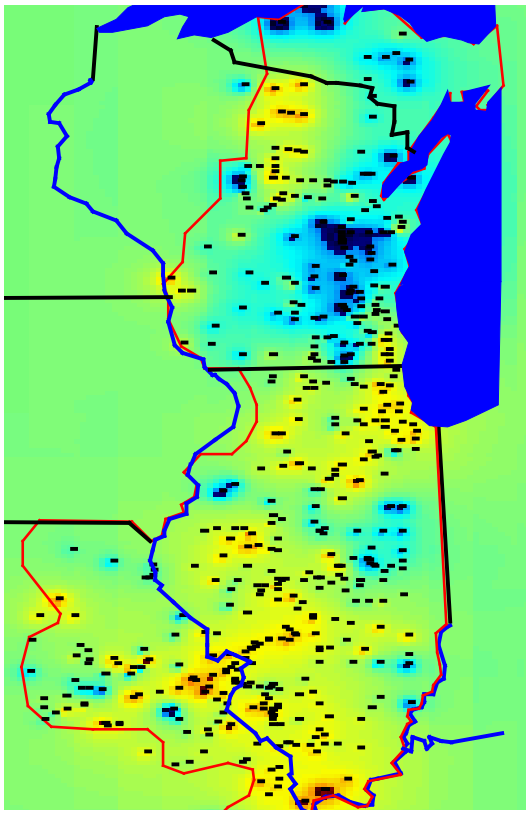


Figure 11: 500 Buses Display with Limits Highlighted

System Marginal Costs

Thus far, only voltage magnitudes have been contoured. As mentioned before, any system parameter that is based around a bus can be made into a contour using the same technique. An example bus parameter that is of use is the marginal cost of power at a bus. Using an optimal power flow program, which has been implemented in the POWERWORLD Simulator [12], the marginal cost of power ($/MWhr) at each bus can be calculated and these values can then be contoured. Figure 12 shows a three-area, 23-bus power system for which this has been done.

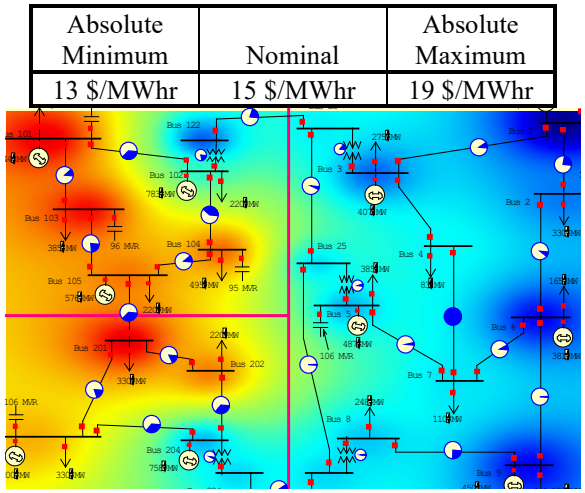


Figure 12: Marginal Cost of Power for Three-Area System

From a quick glance at Figure 12, it can be seen that the marginal cost of power in the right area is lower than that in the other areas. For larger systems this can give a market overview at a glance.

4. Numerical Issues

Bus Grouping

While the basic idea discussed thus far works effectively, as the number of buses displayed increases the amount of calculations increases dramatically. This is because at each virtual point, all buses on the display are included in the calculation of the virtual voltage. This means that the calculations are on the order of P*N where P is the number of grid data-points (40000 for a 200 X 200 grid) and N is the number of buses displayed. However, the number of calculations can be decreased by recognizing that buses that are a large distance away from a virtual point can be ignored since their weight in the sum of Equation (1) will be very small.

In order to decrease computation time, prior to beginning the calculation of the contour, a grid is conceptually laid across the entire map and buses are grouped according to this grid with each bus going into one of the grids. The user specifies the number of grids in the horizontal and vertical directions. Figure 13 portrays a five by five grid for grouping the buses.

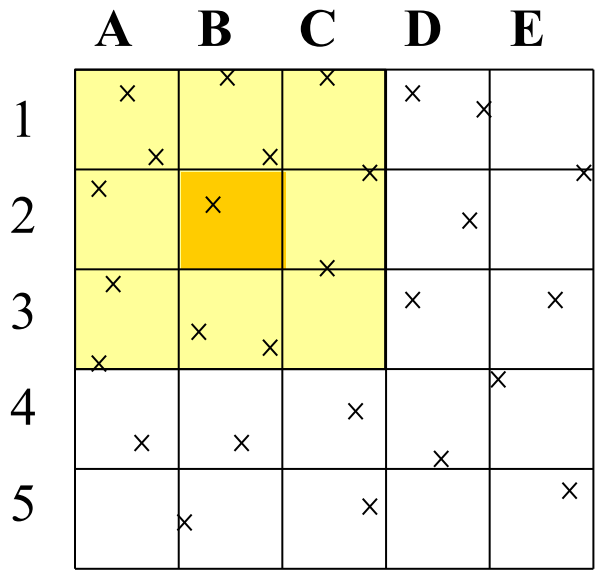


Figure 13: Conceptual Grid for Bus-Grouping

While calculating the contour, only buses that are within a user-specified number of grids are used in the weighting of a virtual value. For example, in Figure 13, a specification of one grid neighbor would mean that while calculating the virtual values in grid B2, only buses which fall in grids A1, A2, A3, B1, B2, B3, C1, C2, and C3 would be used (see shading in Figure 13). In this way only the closest buses are used for the calculations, but the determination of which buses are closest does not have to be performed at each virtual point (all this is done up front in applying the conceptual grid).

Assuming that the user chooses an appropriate size for the conceptual grid and number of neighbors, the calculations will be reduced to order P*β where P remains the number of pixels and β is the average number of buses used in the calculation of a virtual value. The parameter β will be relatively independent of the number of buses displayed. As the number of buses increases, presumably the user will change the conceptual grid size and the average number of buses involved in the calculation of each virtual value will remain relatively constant. This means that the calculations have been reduced from being a function of the number of buses to being a constant that is independent of the number of buses.

This technique of grouping buses prior to contour plot calculation was used on many of the plots shown in this paper. Table 1 shows the parameters used for several of these plots.

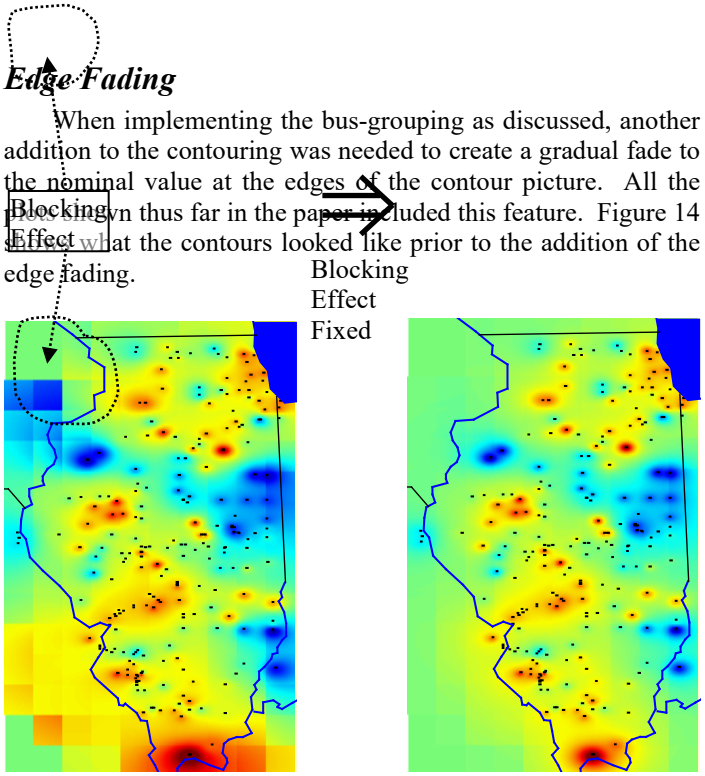
Table 1: Bus Group Parameters

Figure	Horizontal Grid Size	Vertical Grid Size	Grid Neighbors	Bus Influence Distance
Figure 9	10	15	2	200
Figure 10	10	20	3	100
Figure 11	10	20	3	100

The computation time for calculating the contour plots in Figure 9 was reduced from 10 seconds down to 1.5 seconds, while the computation time for calculating the contour plot shown in Figure 10 and Figure 11 was reduced from 15 seconds down to 2.0 seconds. Tests were done on a 200 MHz Pentium Pro machine with 32 MB of RAM.

Edge Fading

When implementing the bus-grouping as discussed, another addition to the contouring was needed to create a gradual fade to the nominal value at the edges of the contour picture. All the plots shown thus far in the paper included this feature. Figure 14 shows what the contours looked like prior to the addition of the edge fading.



Without Fading (Problems Circled) With Edge Fading Added

Figure 14: Fading to Nominal Voltage at the Edges

Because the plot was made weighting buses within 2 grids of the bus, near the edge of the display, it is possible that only one or two buses will be included in this weighting. This can create a sudden change in the color creating a strange blocking effect. The dark and light blocks at the left of Figure 14 were due to this problem.

In order to correct the problem, one extra data point was included for every calculation. This point was the nominal value at a user-specified distance from the virtual point. Any bus that was further away than this bus would be weighted less than this extra data point. This specified distance essentially determines the influence distance of a given bus and is thus given the name Bus Influence Distance.

The contouring discussed has been implemented into the POWERWORLD Simulator [10] using the Borland Delphi Developer software development package.

5. Conclusions and Future Work

Plotting contours of power system bus parameters has been shown to be very useful in giving a qualitative feel for the state of the power system. Using some numerical techniques, the calculation of these contours can be done on-line and provide useful data to the user of the power system software.

As mentioned in Section 3, for voltage magnitude plots, it is recommended that contour plots only be made of buses at the same voltage level. In this way misinterpretation of the plots due to "nearness" assumptions and tap-changing transformers will be largely avoided.

It is also recommended that users of a contour plot routine settle on a specific color-map and value levels (i.e. the user-specified values for the contour plots.) In this way, users would quickly get a feel for what is normal for their system. The use of

discrete changes in color could also be implemented as an extension to present "alarming" routines. During contingencies/emergencies contours could make it easy to rapidly interpret the extent of system problems regarding voltages.

As shown in the paper by example of system spot prices, any bus parameter can be made into a contour plot in the manner presented. This could include bus voltage angle or bus load. In the future, contours of bus parameter values regarding voltage collapse and voltage stability might be especially useful.

6. Acknowledgements

This work was funded in part by the Power Affiliates Program at the University of Illinois. The authors would also like to thank PowerWorld Corporation for the use of their software.

7. References

1. Mahadev, P.M., Christie, R.D., "Minimizing User Interaction in Energy Management Systems: Task Adaptive Visualization," *IEEE Transactions on Power Systems*, Vol. 11, No. 3, August 1996.
2. Christie, R.D., "Toward a Higher Level of User Interaction in the Energy Management Task," Proceedings of the IEEE International Conference on Systems, Man and Cybernetics, San Antonio, TX, October 2-5, 1994.
3. D'Amour, P.R. and Block, W.R., "Modern User Interface Revolutionizes Supervisory Systems," *IEEE Computer Applications in Power*, January 1994.
4. Ghoshal, K., Douglas, L.D., "GUI Display Guidelines Driving Winning SCADA Projects," *IEEE Computer Applications in Power*, April 1994.
5. de Azevedo, G.P., de Souza, C.S., Feijo, B., "Enhancing the Human-Computer Interface of Power System Applications," *IEEE Transactions on Power Systems*, Vol. 11, No. 2, May 1996.
6. Mahadev, P.M., Christie, R.D., "Envisioning Power System Data: Concepts and a Prototype System State Representation," *IEEE Transactions on Power Systems*, Vol. 8, No. 3, August 1993.
7. Mahadev, P.M., Christie, R.D., "Case Study: Visualization of an Electric Power Transmission System," Proceeding of Visualization 1994, October 17-21, 1994, Washington D.C.
8. Thiyagarajah, A., Carlson, B., Bann, J., Mirheydar, M., Mokhtari, S., "Seeing Results in a Full Graphics Environment," *IEEE Computer Applications in Power*, July 1993.
9. Huang, J.A., Galiana, F.D., "An Integrated Personal Computer Graphics Environment for Power System Education, Analysis, and Design," *IEEE Transactions on Power Systems*, Vol. 6, No. 3, August 1991.
10. Overbye, T.J., Gross, G., Laufenberg, M.J., Sauer, P.W., "Visualizing Power System Operations in an Open Market", *IEEE Computer Applications in Power*, January 1997.
11. Reference Guide for MATLAB. The Math Works Inc. Natick, Mass. Copyright 1992.
12. Weber, J.D., *Implementation of a Newton-based optimal power flow into a power system simulation environment*, Master's Degree Thesis, University of Illinois, Department of Electrical and Computer Engineering, January 1997.