Voltage Contours for Power System Visualization

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Abstract

Power system engineers are presented with vast amounts of information to analyze during daily operations. In systems containing thousands of buses, it can be very difficult to assess the state of the power system in an intuitive and rapid manner. The paper discusses the use of contours for visualizing power system voltage data. Also, because of the low computation requirements of the contouring algorithm, the algorithm is implemented into a real-time animation of the voltage profile of a power system. The contouring routines are implemented into the PowerWorld™ Simulator software package, with results shown for systems with up to several thousand buses. Experiments and interviews with system engineers are also discussed to measure the applicability of voltage contouring as an add-on to practical EMS systems

Keywords: Visualization, Voltage Contouring, Power System Operations

1. Introduction

As computing power continues to grow, engineers are both aided and burdened by the volumes of information these tools create. Within the electric utility industry, this is especially apparent as power engineers are confronted with analyzing and studying information regarding thousands of electrical nodes. Although extensive work has been done over past decades in developing new ways to manipulate greater and greater amounts of data, less work has been done in developing methods to aid in understanding and interpreting this data. However with the advent of new hardware and software, this has begun to change. Specifically, much work has been done recently in developing effective graphical user-interfaces (GUI) for energy management systems within present day control centers, with several examples described in [1]-[6].

When developing effective GUI's for any application, it is important to first consider the interaction between the computer and the user. These topics have been studied in detail in recent papers [7]-[8]. The investigations have found relatively good representations for power system information relating to branch data, such as line MVA flows, MW flows, line limits, etc., but have had less success in developing effective tools to visualize bus related parameters such as voltage magnitudes and angles.

As a result, most power system engineers still rely on text-based displays for studying bus-related information. While this data is extremely accurate, the user can have a very difficult time perceiving patterns in large amounts of text. As an extension of this to a graphical environment, one-line displays have been created using digital numerical displays to provide bus-based information. While this is an improvement, it is still extremely difficult to quickly comprehend large amounts of data.

2. Previous Voltage Visualization Work

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 [9]-[12]. A simple thermometer is shown in Figure 1. In this example, more gray signifies a lower voltage.

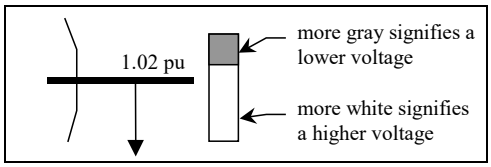

Figure 1 Basic Thermometer Graphic

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 [8]-[10], 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 [8]:

- Natural encoding of information
- Task specific graphics

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- No gratuitous graphics

A contour plot meets all these requirements. First, it provides a natural 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 lower temperatures, while red signifies higher temperatures. Likewise, 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 journal 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. Including only informative graphics was an integral part of the work done in [4]. For example graphics could be limited to the buses, transmission lines, and the contour plot. Other graphics would 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 must be addressed: 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 [13]. 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 the paper help to show the effectiveness of the contouring approach. The contouring algorithms in this paper have been implemented using the PowerWorld Simulator package [14].

3. Overview of Contouring Basics

Much of the data within a power system is referenced to the system buses. This includes information such as loads, generation, voltage magnitudes and angles, and bus spot prices. Buses, however, are only defined at discrete points within a power system. Therefore, a power system can be visualized as a two-dimensional region that has discrete values at points throughout the space. Thus the contour algorithm must map this discrete data into a continuous region. Conceptually, this can be thought of as low pass filtering 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.

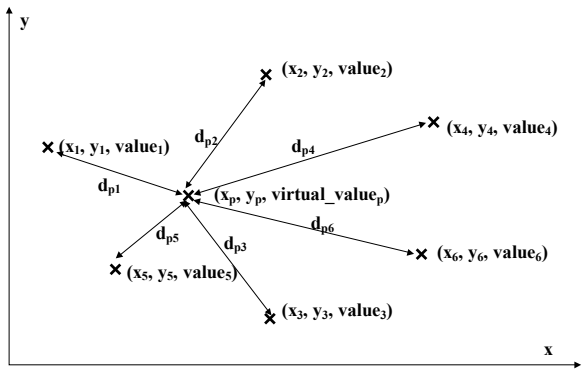

Figure 2 Calculation of the *Virtual Value*

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 2, the virtual value at the point (x_p, y_p) should weight the value at (x_1, y_1) more than the value of a more distant point such as (x_6, y_6). The method presented in [13] 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).

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

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,

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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 3. Here white equates to higher and black to lower voltages. It is obvious at a glance what areas have high and low voltages.

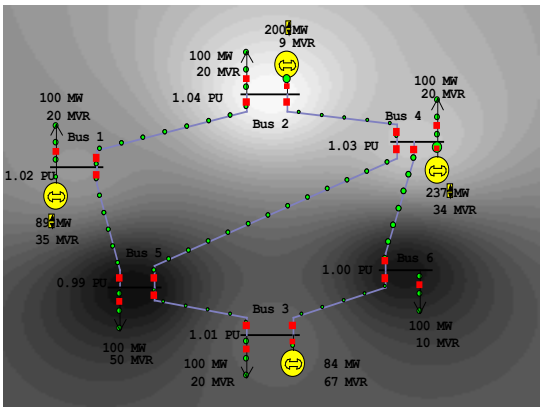

Figure 3 Sample Voltage Contour of Six Bus System

Now that a method of calculating the virtual values across a two-dimensional area has been defined, it is important to consider how this value gets mapped to a color for display. To create the color-mapping, values were mapped to one of potentailly 16.7 million different colors on a computer monitor. This corresponds to a value of between 0 and 255 for red, green and blue. A common method for achieving this is shown in Figure 4. This is similar to the mapping used in Matlab's "Jet" color-map [15]. All values below some minimum value are mapped to dark blue and all values above some maximum value are mapped to dark red.

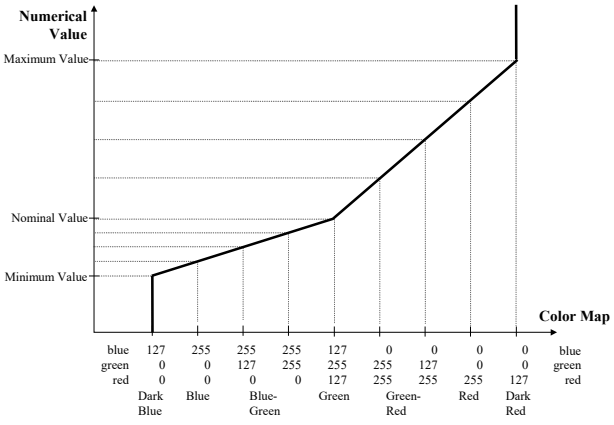

Figure 4: Color-Mapping for Red = High, Blue=Low

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 5. Figure 6 shows the Figure 3 system with these discrete color changes implemented.

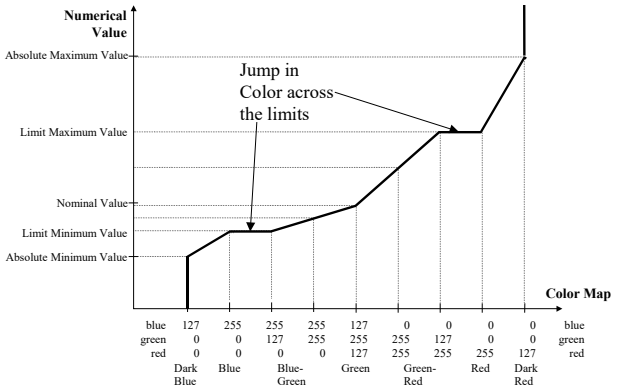

Figure 5: Discrete Change at Limits Color-Mapping

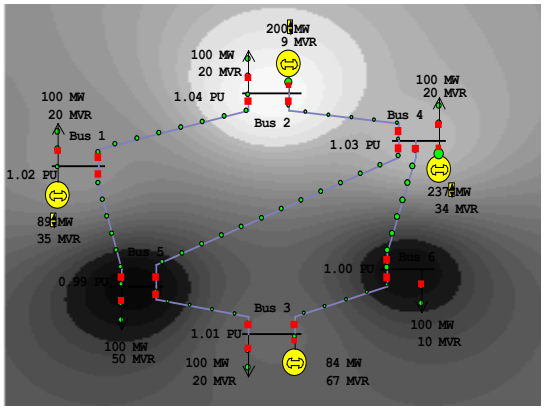

Figure 6: Voltage Magnitudes with Limits Highlighted

In Figure 6, 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.

Of course any color-mapping is possible. For this paper, four voltage magnitude 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 6.

4. Fast Contouring Algorithm

The numerical algorithm used to calculate the contours initially reported in [13] was quite successful; however calculation times to contour large systems took from 10-15 seconds on a 200 MHz Pentium Pro based PC. While this was adequate for creating snapshots of the voltage profile in a power system, it was far too slow for realistic

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implementation of real-time animation of the contours. As a result, a new technique is presented here. In this technique each bus is processed in turn, with a conceptual circle drawn around the center of the bus to represent the influence region of the bus, as shown in Figure 7.

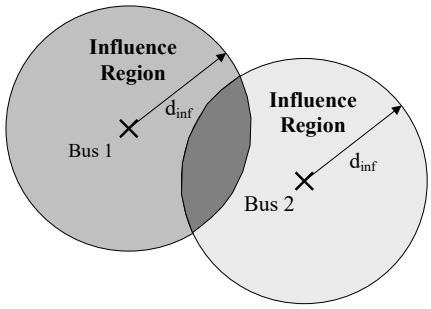

Figure 7 Bus Influence Regions

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 = (-dinf+x1) to (dinf+x1)
  For y = (-(dinf^2-x^2)^0.5+y1) to ((dinf^2-x^2)^0.5+y1)
    UpdateVirtualValue at (x,y) with value Vj
  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.

While this technique improved the computation time greatly, a further speed up is still possible 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 considering only the shaded piece of the influence region shown 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 a factor of eight.

5. Contouring in 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 is now possible to implement the contouring as an animation. 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.

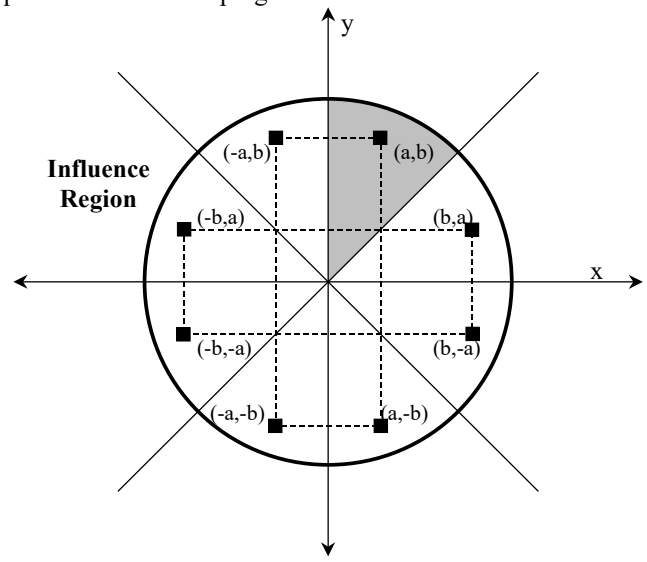

Figure 8 Reduction of Computation by a factor of 8

While the animation itself can not, of course, be presented in a paper format, the next three figures can be used to judge the effectiveness of contouring on several large systems at least from a static perspective. All three figures can be re-contoured in less than one second to show either a changing system operating point, or results of a contingency. Figure 9 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. Here the contour voltage limits were minimum of 0.98 pu, maximum of 1.05. Figure 10 shows the 345 kV buses for an 11,000 bus ECAR model, while Figure 11 shows the 500 kV buses for a 6400 bus WSCC model. For all figures a darker color indicates a lower voltage.

6. Usability Test

Ultimately the intended users must judge the usefulness of any visualization technique. Because of the limitations of the journal paper format, this may be difficult for the readers to access. To aid in this process, as was done in [10], a simple test was developed and then presented to eight power system engineers and system operators from three different utilities. For this test, the IEEE 118-Bus system was used as a starting point. Then two different operating points were developed which had voltage problems in different regions. These two systems are shown in Figure 12 and Figure 13, with the contours based upon the color mapping shown in the following table. The discrete jump in color is seen in both figures, illustrating that voltages below 0.95 per unit exist in highlighted portion of the system. For both systems the voltage problems can be fixed by switching in a capacitor bank in the region which is experiencing low voltages.

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Abs. Min	Limit Min.	Nominal	Limit Max.	Abs. Max
0.90 p.u.	0.95 p.u.	1.00 p.u.	1.05 p.u.	1.10 p.u.

In order to help measure whether the contour did indeed result in a faster response to voltage problems, the following test was given. For each system the individual was asked to identify the bus voltages which were being violated. After doing this they were asked to determine a corrective procedure that would remove the voltage violations.

The results of this test indicated that using voltage contours was found to be useful by all participants. Using the contours all participants were able to identify the violated buses within less than 5 seconds. Contours did indeed provide an "at a glance" overview of the voltage profile of the system. Once the violations were located, the user took from 20 to 30 seconds to fix the problem by switching in a capacitor bank located in the region. This varied due to adeptness at using the pan/zoom capabilities of PowerWorld Simulator.

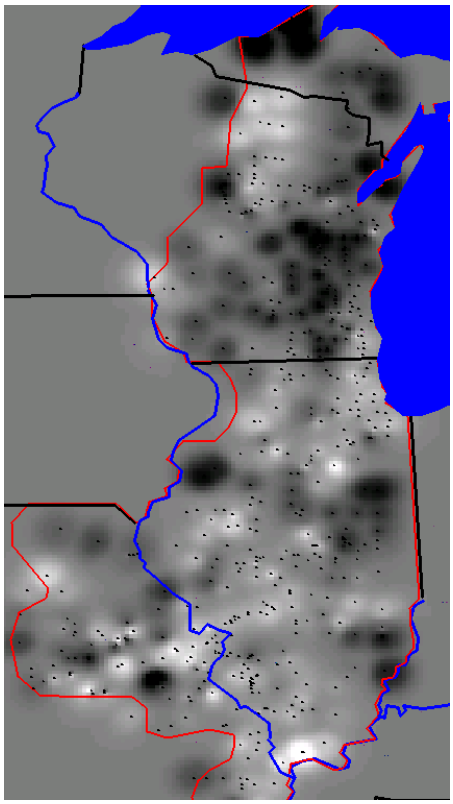

Figure 9 MAIN 115/138/161 kV buses

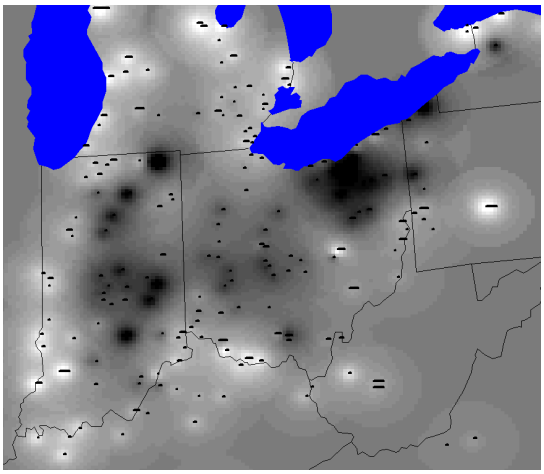

Figure 10 ECAR 345 kV buses

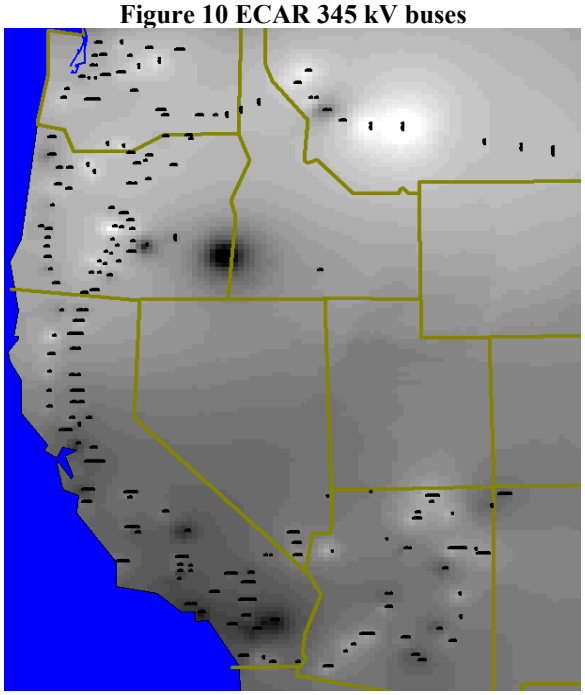

Figure 11 WSCC 500 kV Buses

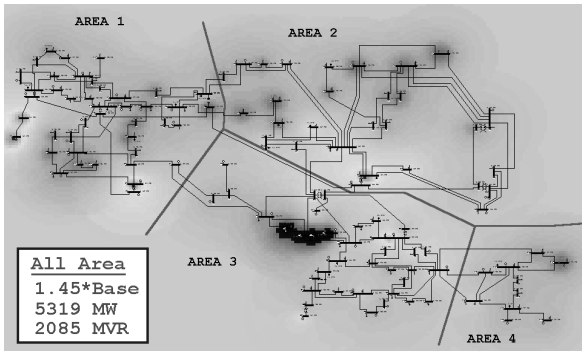

Figure 12 First Test Case with IEEE 118 Bus System

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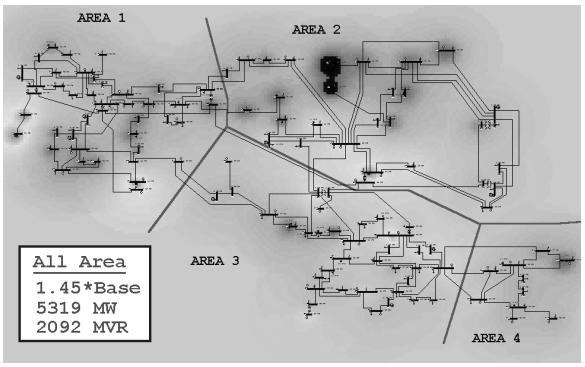

Figure 13 Second Test Case with IEEE 118 Bus System

Without the contours, the participant was allowed to use a display that listed all the buses in a system above or below a specified limit. Essentially, this described an alarm-list in a present-day EMS system. Using these instead of the contours, the time to find the voltage violations varied between 20 and 120 seconds with an average time of 65 seconds. While this may have largely been due to an unfamiliarity with the test system used, all participants felt that the use of the voltage contour would be useful even for a user with a great deal of experience with the system. Upon finding the violations in this test, the user had already pan/zoomed into the correct area of the one-line diagram and was able to quickly switch a capacitor bank in within 5 to 10 seconds of finding the voltage violations.

Before these tests were performed the participants, along with many other people at each utility, were presented with a brief background on how the contours were created. Following this background, they were asked whether the contours were useful and how they might be used. All respondents felt that the contours were definitely a useful tool. In addition to their use for general system monitoring, several other uses were suggested. These included the following

- Good aid in distribution system operation. Contours could aid in determining capacitor switching actions to correct voltage problems on a distribution system. (Note: This was only a good use if the utility presently monitored distribution system voltages on a large scale which is not always done)
- Good for monitoring parts of a system that an operator is not familiar with. Contours could be helpful as OASIS information becomes more detailed. Engineers and operators will be faced with studying data for systems for which they have little experience. One utility interviewed was going through a merger that would make their transmission system 2-3 times larger.
- Possibly a good tool for contingency analysis. Contours could be used to highlight contingencies with the most severe voltage deviations. This information could help to quickly determine the weakest spots in the transmission system.
- System Planning Studies. Contours could be a good way to quickly determine which parts of a transmission system need more support. They could help determine which plans should be seriously considered and which could be ignored.

7. Acknowledgement

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Biographies

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