Visualization of Oscillation Mode Shapes and Participation Factors

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Abstract

Power system oscillations can cause a power system to become unstable if they are too large. The oscillation modes and participation factors are crucial data for the analysis of system oscillations. But on large systems, there can be thousands of data points to look at. The goal of this work is to take oscillation mode shape and participation factor data and display it, so that one can quickly obtain the important information. These displays allow system operators and others interested in the system oscillations to quickly determine which generators are contributing to the oscillations and how each generator's contribution compares to others. Because different users prefer different ways to visualize information, many options have been considered, including changing colors, sizes, and shapes. Both two-dimensional and three-dimensional displays will be demonstrated.

Keywords: Mode Shape, Participation Factor, Visualization

1. Introduction

Power systems possess large amounts of data that can be studied and analyzed to give engineers and system operators an understanding of the way the system behaves. Traditional tools usually display data such as one-line diagrams, tables, and charts. The goal of this work is to present yet another way to help get information quickly to the people who need it.

This paper deals with the visualization of oscillation mode shape and participation factor information. This information can be used to determine characteristics of the oscillation of the entire system. Additionally, visualization techniques discussed here could be applied to other power system data.

2. Mode Shape and Participation Factor

Oscillations are a characteristic of inter-connected power systems initiated by changes in system load. They can occur between areas, called inter-area oscillations, or between individual generators, called local oscillations. The oscillation mode and the participation factor are important for oscillation study.

The right eigenvector of a particular oscillation mode is called the mode shape. The mode shape is a good indicator of the relative activity of the state within a mode. The left eigenvector determines the amplitude of the oscillation. For a more detailed explanation of oscillation modes and mode shapes, see [1],[2].

Because the mode shape is an eigenvector, it has a magnitude and an angle. The magnitudes are normalized based on the largest in the set. This work examines two cases, one with about 100 generators and another with about 280 generators.

The participation factor is the sensitivity of the mode. It is a good indication of the importance of the state to the mode. Participation factors can be positive, zero, or negative. A positive participation factor associated with a particular generator means that generator is contributing to the oscillation of the system. A negative participation factor indicates a generator that is dampening the system oscillation. The participation factor data for this paper are all nonnegative and normalized.

Participation factors can be used to help determine whether a power system stabilizer (PSS) is needed to damp system oscillations. If the participation factors for many generators in an area are large, then a PSS placed in that area would dampen the oscillation of the system. However, if the participation factors for generators are negative, then adding a PSS would actually increase the oscillation [1], [3].

3. Visualization Techniques

Two-dimensional visualization techniques in power system applications are very common. Many software packages use 2-D one-line diagrams to run case studies on large power grids. We tried to expand on these methods for our 2-D applications.

Three-dimensional visualization techniques in power system applications also build on the 2-D one-line diagram. Some examples of 3-D power system visualization, such as reactive reserves, available transfer capability, and bus marginal prices, are presented in [4]. Building on these techniques, we present methods for visualizing the mode shape and participation factor. We ask the readers forbearance since one of the key strengths in 3-D visualization is the ability to navigate around the scene, which can hardly be conveyed on a printed page.

For the application of mode shape and participation factor visualization, three pieces of information need to be displayed, the mode angle, mode magnitude, and participation factor. In 2-D it can be difficult to show more than two pieces of information without overwhelming the person viewing the display. That is why we do not show all three pieces of data on the same display in 2-D. However, 3-D gives the viewer a feeling of looking at more volume, so showing more than two pieces of information is less overwhelming. In 3-D we will look at displays of only mode shape, only participation factor, and both mode shape and participation factor.

3.1 Visualization Environment

There are many tools, both software and hardware, available for visualization. A discussion of the different tools can be found in [5]. Many of these tools are for specialized applications, and are not common in ordinary offices where power systems are studied. That is why we use common hardware, such as the PC, a keyboard, and a mouse.

For the rendering of our visualization techniques, we wrote a program in Delphi, using OpenGL for graphics and 3-D effects [6],[7]. The program has a user-friendly interface that can be easily navigated, allowing the user to see as little or as much of the information as he or she desires. This visualization software and setup is similar to that discussed in [4]. Although the graphics displayed in these figures are very detailed, the program still has good performance. On a 400 MHz PC, the screens are updated at a rate of about 4 frames per second.

The background for our displays is a geographical map of the US. Therefore, shapes used to represent generators, such as circles, rectangles, and cylinders, are located on a map of the US, and they are placed in the approximate physical locations of the generators they represent. Displaying data in a geographical context is a great advantage when looking for patterns in data associated with location.

3.2 Mode Angle

The mode angles are in the range [-180°, 180°]. Two methods for visualizing mode angles were examined, a pie chart and an arrow, or "necktie", as shown in Figures 1(a) and 1(b), respectively. Both figures represent 120°.

The pie chart angles are positive if the right side of the circle is filled, otherwise the angle is negative. The angle is determined by how much of the pie is filled. In Figure 1(a) the angle of the shaded part is 120°.

The angles represented by the arrows are determined by the location of the tip of the arrow. If the tip is pointing in the upper half of the circle, the angle is positive. Otherwise the angle is negative. The arrow is pointing at 120° in Figure 1(b). Using arrows to represent directions for many different data points has long been a way to visualize vector fields. These are not vector fields in the mathematical
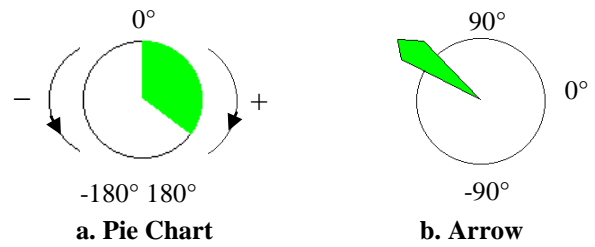
**a. Pie Chart**   **b. Arrow**
**Figure 1: Mode Angle Visualization**

sense, but they are complex numbers, which makes vector field methods applicable.

Color is used to group the generators by angle. The colors and group ranges can be user-defined. The default values are set to color the circle (2-D) or cylinder (3-D) red if the angle is in the range [-90°, 90°] and green otherwise. Angle grouping is important for this application because if too many mode angles are in one angle range, oscillation problems are likely to occur.

One of the main goals of visualization is to help the user see patterns in a large amount of data. Figure 2 shows a scene using arrows to show the mode angles, and Figure 3 uses pie charts. Patterns can quickly be recognized from Figure 2, whereas it takes longer in Figure 3. In 3-D the
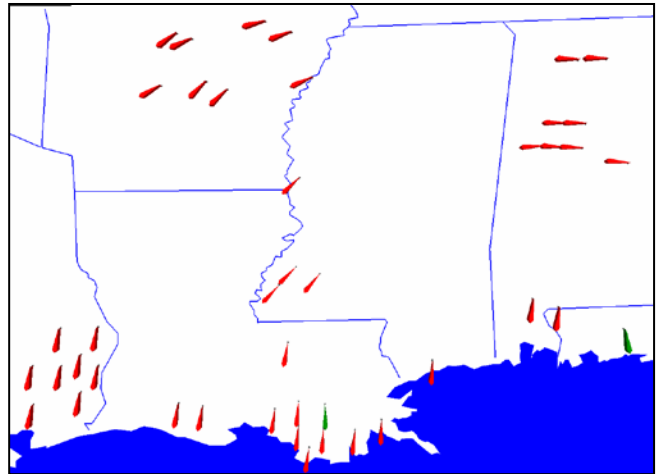
Figure 3: Mode Angle using Arrows
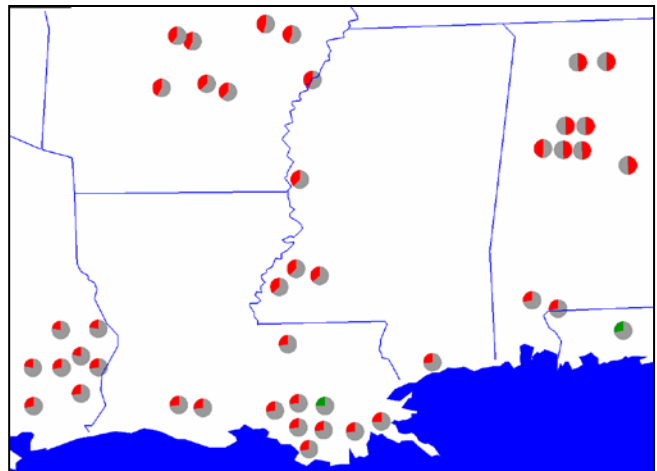
Figure 4: Mode Angle using Pie Charts

arrows also have an advantage over the pie charts. Compare the pie charts in Figure 8 to the arrows in Figure 9. The 3-D arrows stand out very well for a user who is looking at a scene from a far out perspective, while the pie charts seem to blend in and are more difficult to see.

Two interesting issues arise when using arrows to represent angles. When looking at a map in the normal direction so that north is up, we use right, or east, as the point of 0°. But what happens when the scene is rotated? Should an arrow pointing east according to a geographical map represent 0°, or should an arrow pointing towards the right side of the screen always represent 0° regardless of direction? We have tried both ways and found that although most people prefer the right side of the screen always being 0°, others would like the east direction according to geographical location to always be 0°. The major advantage to always having the right side of the screen be 0° occurs when the information being visualized is not associated with a geographical map, such as the standard IEEE 118 bus case.

The second issue occurs when the display is shown to people from a field where 0° is typically north, not east, such as aeronautics. Because this application is for power engineering and most power engineers are familiar with the complex plane convention of 0° being to the right, we choose to implement our arrows that way. But these are questions that must be considered in visualization design.

3.3 Mode Magnitude and Participation Factor in 2-D

The mode magnitudes and participation factors for all of the generators are normalized. Not only is it important to get a feel for the value of the data, but also how that value compares with surrounding values. To show this information in 2-D we use either two concentric circles or filled rectangles. For the circle method, the size of the inner circle is determined by the value it represents, and the outer circle is a unit circle. Using these two circles, a feeling for the value of the number, as well as how the number compares to the others, can be achieved. But a problem arises when trying to use circles to portray values. Should area or diameter be used to show the value? Consider Figures 4(a) and 4(b). Figure 4(a) uses radii to show the values, which means the ratio of the inner circle's radius to the outer circle's radius of (1) is 0.75. Figure 4(b) uses area to show the values, which means the ratio of the inner circle's area to the outer circle's area of (1) is 0.75. It is easy to see that although both circles in (1), (2), and (3) represent the same numbers, respectively, they look different. Not knowing the value, what value would you guess for these circles? This is another problem visualization designers must consider.

The circles shown in Figure 4(a) seem to match their corresponding values better than Figure 4(b) for most of the people who have discussed this issue with us. However, some do prefer area ratios to radius ratios. One of the ways to resolve this question is to let the user choose which representation he or she prefers, which would be most


(1)   0.75

(2)   0.50

(3)   0.25
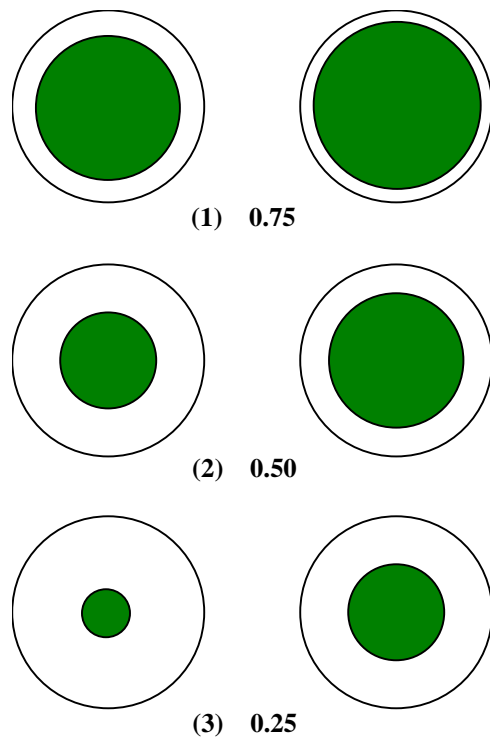
a. Radius   b. Area
Figure 4: Radius vs. Area

effective for a single user. But on a printout meant for other people's evaluation, one approach must be chosen and described. Another way to overcome this issue is to use a different shape, such as a rectangle, where the ratio of heights is the same as the ratio of areas.

Figure 5 shows the mode shapes for a group of generators in the southeastern US using circles where the radius ratio shows the value of the mode magnitude and arrows represent the angles. Figure 6 shows the participation factors for the same group of generators using rectangles where the height ratio shows the value of the
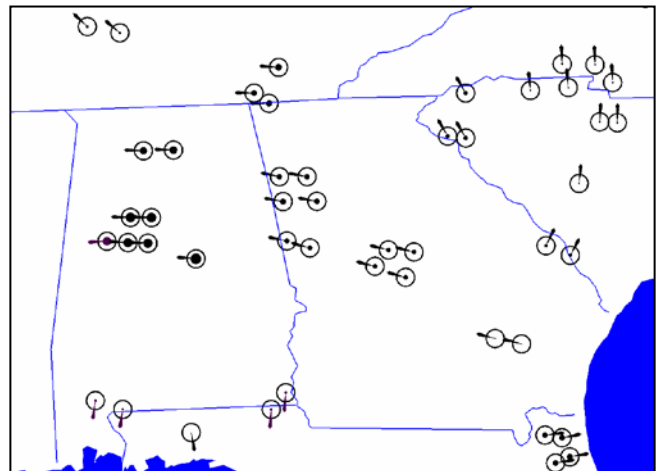

Figure 5: Mode Shape
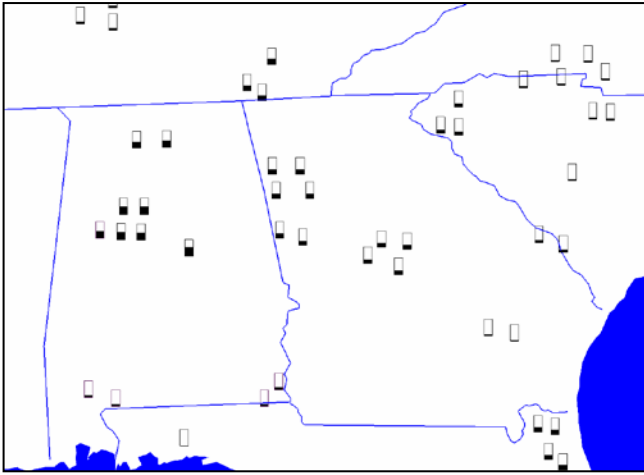
Figure 6: Participation Factors

participation factor. It is easier to guess the value represented by the rectangle, but on one-line diagrams, generators are typically shown as circles. Therefore, rectangles could be awkward for the representation of generator data.

3.4 Mode Magnitude and Participation Factor in 3-D

The same techniques will be used to display both mode magnitude and participation factor information in 3-D because they are both normalized sets of data. Because it is important to know the value as well as how the value compares to surrounding values, we introduce two different 3-D views, the magnitude view and the percent view.

The magnitude view, shown in Figure 7(a), uses the height of a cylinder to show the value of the number. The percent view, shown in Figure 7(b), uses two cylinders.
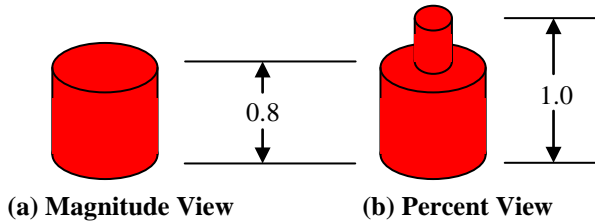
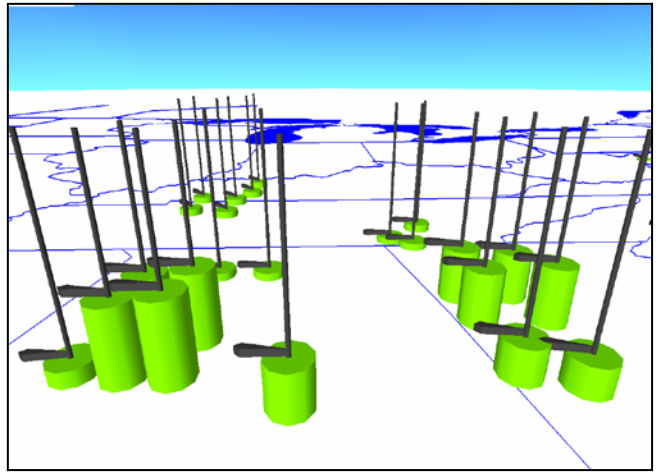**(a) Magnitude View**   **(b) Percent View**
Figure 7: Two Different 3-D Views

The bottom one represents the value of the number. The combined height of both the top and bottom cylinders is 1.0, representing the largest value in the set.

Both views have strengths and weaknesses. Figure 8 shows a view of mode shape data using the magnitude view. It is not easy to guess the values represented by these cylinders in this view, but it can be determined how one generator's magnitude compares to others in its surroundings. Looking at the percent view in Figure 9, the values represented by the cylinder heights can easily be guessed because of the top cylinder. This option also offers a feel for how that value compares with all values, not just surrounding values, because the largest value possible is 1.0. However, in a scene with many data points, the top
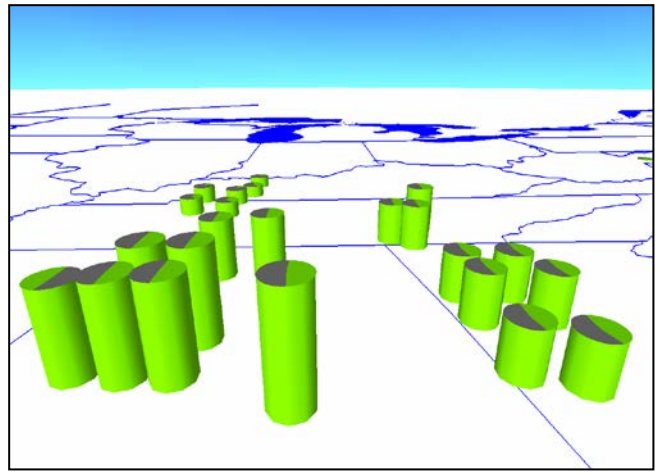
Figure 8: Mode Shape using Magnitude View

**Figure 9: Participation Factor using Percent View**

cylinders can block the view of data behind them. With the magnitude view, all cylinders can easily be seen.

3.5 Mode Shape in 2-D

One way to display both mode magnitude and mode angle in 2-D is shown in Figure 5. Another way is to use just an arrow. Arrows still point in a specific direction to portray the angle, but the size of the arrow shows the magnitude of the mode as in Figure 10. The outlines of the arrows around solid arrows are "unit" arrows because they represent the largest possible mode magnitude.

This method has many of the advantages of using arrows with unit circles, such as demonstrating size relative to both surrounding generators and all generators in the set and the mode angle. However, the unit arrow takes up much more space than the unit circle. To try something different, we took the unit arrow off the picture as shown in Figure 11, eliminating the advantage of showing size relative to all modes in the set. By doing this, we found another way to represent a magnitude and an angle.

3.6 Mode Shape and Participation Factor
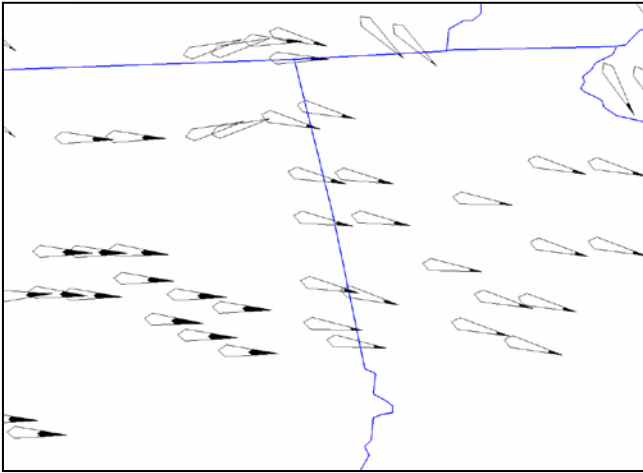
Figure 10: Using Arrows Only to Show Mode Shape
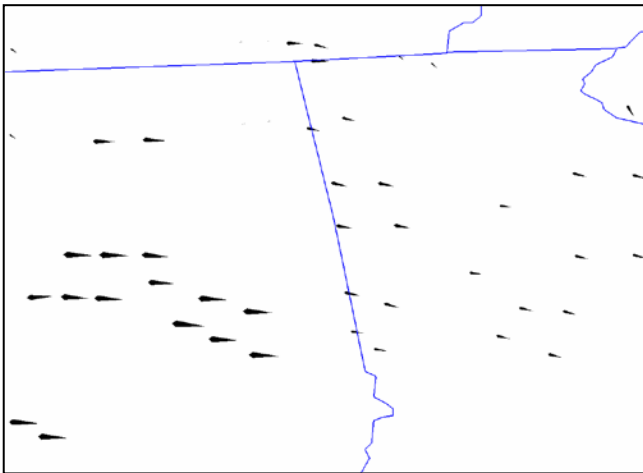
Figure 11: Arrows without the Unit Arrow Border

One of the advantages of 3-D over 2-D is the extra dimension. In 2-D we were able to show magnitudes using width, but how can you show two different magnitudes on one object? In Figures 12, 13, and 14 we tried to use this advantage to the fullest by displaying all three pieces of data: mode magnitude, mode angle, and participation factor.

In Figure 12, the cylinder height represents the mode magnitude, the arrow shows the mode angle, and the cylinder width represents the participation factor. This view makes it easy to see major contributors to the system oscillation by looking for tall, thick cylinders.

The height of the cylinders could represent the participation factor and the width could show the mode magnitude; just a reverse of the parameters used in Figure 12. As in Figure 12, it could also be determined quickly which generators are major contributors to the oscillation; cylinders that are tall and thick.

Figure 13 uses the arrow technique shown in Figure 10 for the mode shape and the height of the cylinder to show the participation factor. The arrow outline represents the 3-

D unit arrow. This method seems to also be effective for showing the data.
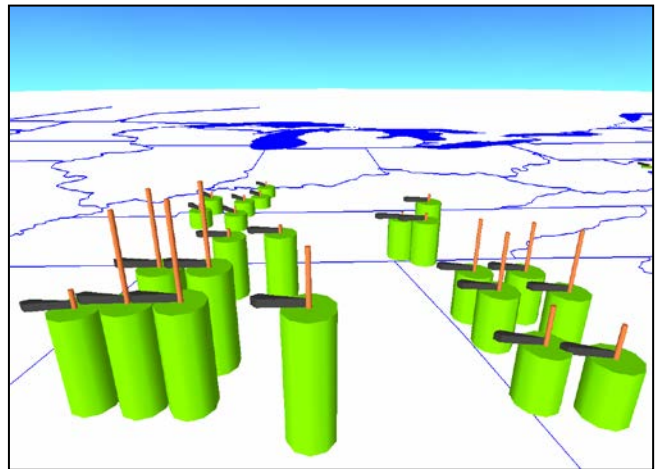
Figure 14 uses two cylinders stacked on each other to show this information, similar to the percent view. The height of the bottom, thick cylinder shows the mode magnitude, while the height of the top, thin cylinder shows
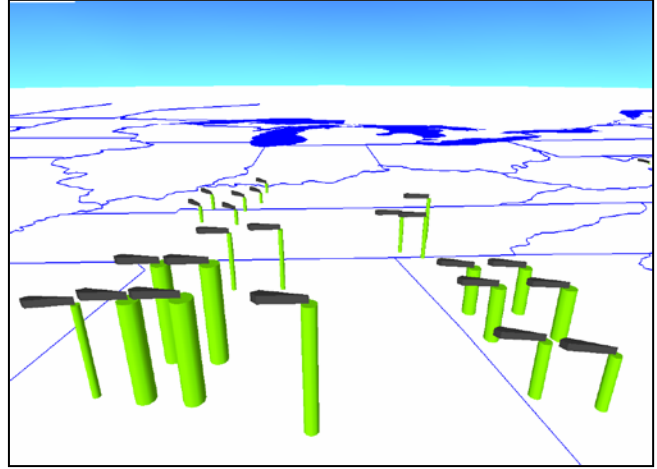
Figure 12: Mode Shape and Participation Factor I
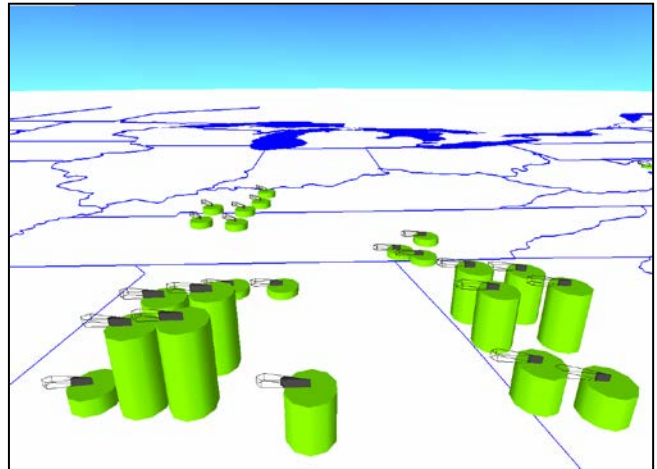
Figure 13: Mode Shape and Participation Factor II

Figure 14: Mode Shape and Participation Factor III

the participation factor. The sum of both heights is not 1.0 as in the percent view. This view seems to be less effective than Figures 12 and 13 for this application with mode shape and participation factor. But perhaps with different data, this method could be more useful.

The methods described above are just four ways of many to display this data, highlighting the versatility and promise for the future of 3-D displays in power system visualization.

3.7 More Data Points

At last, we need to discuss the issue of 2-D versus 3-D. Some people argue that for displaying the mode shape only, or any other data with an angle and a magnitude, the 2-D view as shown in Figure 5 is much easier to read than a 3-D view, as shown in Figures 8 or 9. This position seems to hold true for the case with only 100 generators, where three-dimensional viewing might be overkill. But for a case with more generators, a 2-D view can become filled quickly. This is where 3-D can help to relieve the user from feeling overwhelmed by too much information.

Figure 15 shows 280 generators in 2-D, while Figure 16 shows 280 generators in 3-D. These generators are the generators in the southeastern US that can produce at least 200 MW. Both figures are displaying a large amount of
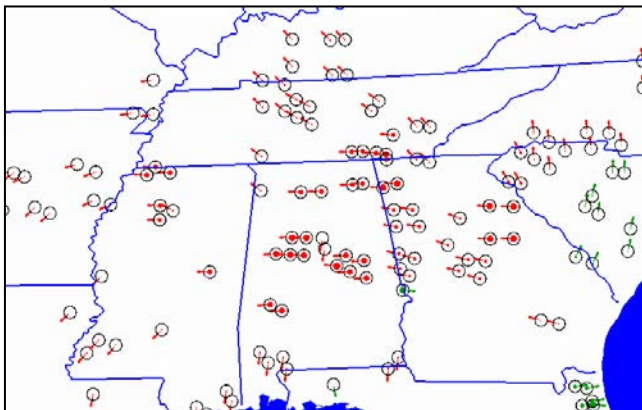

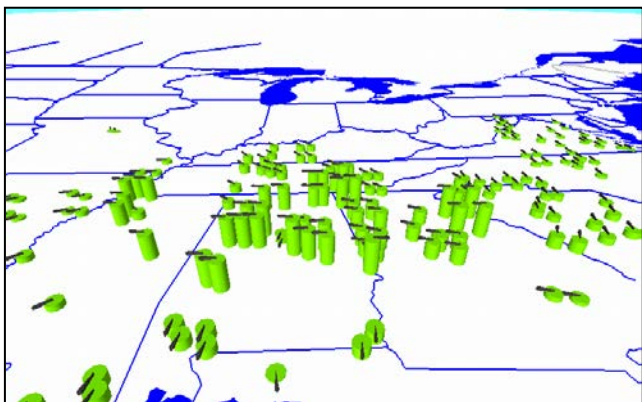**Figure 15: 2-D Mode Shape of 280 Generators**

Figure 16: 3-D Mode Shape of 280 Generators

information and therefore, both figures are successful visualizations of mode data.

Does Figure 16 relieve the viewer from being overwhelmed with data compared to Figure 15? Testing on this issue has not been performed yet, but is scheduled for fall 2000.

4. Conclusions

This paper has introduced ways to visualize oscillation mode shape and participation factor information in both 2-D and 3-D. Although extensive testing has not been completed, initial results of these techniques have been positive. Overall, people seem to be impressed by the 2-D applications and the versatility of the 3-D views.

In 2-D we have presented ways to display mode shape and participation factor data using circles, rectangles, and arrows. In 3-D we have shown the same data using cylinders in two different formats, the magnitude view and the percent view, as well as using arrows. We also discussed how more data points might be a reason for choosing 3-D displays over 2-D displays.

Although we have offered the reader many different views, we think all of them could have a place in the power system analyst's tool belt for effective visualization of data. Only mode shape and participation factor data have been visualized in this paper, but these visualization techniques could be applied to other data as well.

5. Acknowledgements

6. References

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