Wide-Area Electric Grid Visualization Using Pseudo-Geographic Mosaic Displays

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***Abstract*—This paper introduces a new technique for wide-area visualization of information about electric power grids known as a pseudo-geographic mosaic displays (PGMDs). The PGMD approach uses dynamically created geographic data view (GDV) objects to show information about the attributes of different electric grid objects, and then arranges them on the screen to maximize the used display space. The paper presents the PGMD algorithm and then discusses design approaches to maximize their usability. Results are presented for several large-scale electric grids.**

***Index Terms*—power grid visualization, wide-area transmission visualization, interactive control, mosaic displays, treemaps**

I. Introduction

The design and operation of large-scale electric grids requires the use of models with many thousands of buses, and results in the creation of large amounts of data. Electric power system visualization helps the human users make sense of all this information. Over the last several decades good progress has been made in this area. For example, about twenty years back most operational information about the grid and the results from engineering studies, such as power flow and transient stability, was conveyed using either substation-based one-line diagrams with numeric fields or tabular displays. The use of graphics to display electric grid information was quite limited, with just dashed lines to show out-of-service devices and perhaps a varying font color and/or blinking to indicate different dynamic conditions such as limit violations. System over view information might be available on a static mapboard with perhaps different colored lights.

Driven by advances in computers and display technology, over the last 20 years newer techniques have gradually emerged to supplement these existing techniques, particularly for wide-area power system visualization. The goal of wide-area visualization is to quickly provide the user, potentially an operator in a control center or an engineer doing a study, with the pertinent information about the state of the electric grid without excessive extraneous clutter. Techniques that have been utilized on such displays include the use of color contours for data such as bus voltage magnitudes [1], [2] and locational marginal prices [3], the use of dynamically sized system elements such as pie charts to indicate transmission line loading [4] (taking advantage of preattentive processing [5 ,pp.152-161]), and for some applications animated transmission flows [6]. The use of interactive 3D for power system visualization was presented in [7], though it is not currently widely used. Animation of time-varying power system information is discussed in [8] and [9], [10] presents some approaches for showing electric grid structure, while [11] and [12] show some approaches for showing electric grid dynamics information.

Usually wide-area electric grid information is conveyed using either a geographic or a pseudo-geographic approach, often utilizing a power system one-line diagram. In the geographic approach the electric grid information is drawn on a map display as accurately as possible, recognizing that often there are tradeoffs since the electric equipment itself will have a very small geographic footprint. Sometimes the electrical information is super-imposed on satellite images (e.g., Google Maps), though these run the risk of background camouflaging the electric grid information of interest. Usually a more minimalist background approach is preferred, such as just showing state boundaries and other major features. Advantages of the geographic approach is it provides a familiar context, it can be coupled with other information (i.e., weather or other infrastructures), and is useful when presenting results to outsiders. An early example of this approach is shown in [6] with more details given in [13].

In the pseudo-geographic approach the display positions of electric grid elements have some relationship to their actual geography, but the overriding design consideration is display clarity. The pseudo-geographic approach is often used in control center mapboard displays. The use of a pseudo-geographic approach will be presented here, but leveraged with the ability to morph between the two.

Any geographic approach requires the availability of electric grid models with embedded geographic coordinates. Histor-

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ically, most electric grids have been analyzed without the benefit of bus geographic coordinates. As noted in [14] in the analysis of electric grids geographic does not explicitly matter, but as any electric grid planner knows geography is implicitly embedded in the grid model, and is often the key design constraint.

Luckily large-scale grid models with embedded geographic coordinates are now widely available. For actual grids this was driven in part by the need for geographic information to do geomagnetic disturbance analysis (GMD) (see [15] for a discussion of the integration of GMD with the power flow). For the broader research community large-scale, public synthetic electric grids with geographic coordinates are now available for power flow, GMD and transient stability analysis [16], [17], [18], [19]. Figure 1 shows an example of the use of a 2000 bus synthetic system for undergraduate education [20] using an interactive, transient stability level power system simulation [21]. Synthetic electric grids with up to 82,000 buses are freely available at [22], with the oneline for the 82,000 bus grid shown in Figure 2.

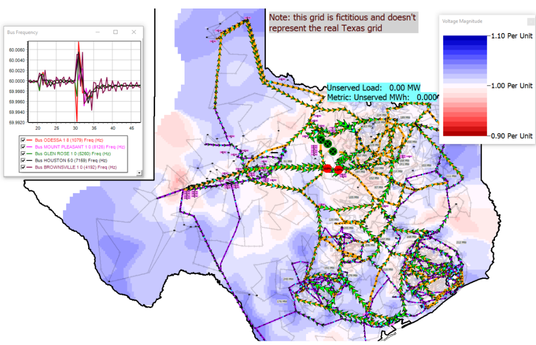

Figure 1. Example 2000 Bus Texas Synthetic Electric Grid

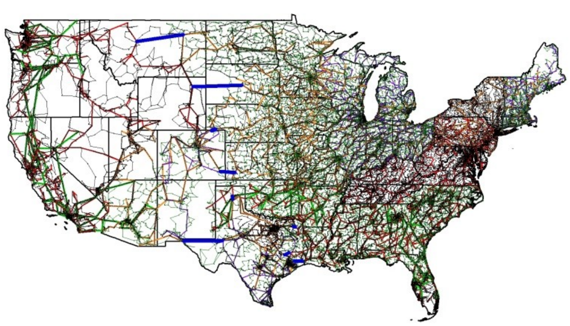

Figure 2. 82,000 Bus Synthetic Electric Grid Oneline

Wide-area onelines such as those of Figures 1 and 2 have advantages and disadvantages. Advantages include the ability to see the entire system and to show different types of data (e.g., a voltage magnitude contour with line flows and potentially some generator information). However, there are several disadvantages. First, the need to initially draw the display and keep it up-to-date, recognizing that automatic layout algorithms can be helpful (in these figures the approach of [23] was used for determining the line routing). Second, the locations of potentially greatest interest electrically, such as substations in the high load urban areas, can have a relatively small geographic footprint. Third, such pre-designed onelines can only show a rather limited number of types of information.

This paper presents a complimentary approach that addresses these disadvantages known as pseudo-geographic mosaic displays (PGMDs). Originally introduced in [24], mosaic displays use a subdivided rectangular space to show the relationships between multiple objects in which the area of each subdivision (also a rectangle) is proportional to an object attribute. Here the row and column locations will approximate the objects geographic location, hence the pseudo-geographic name. As will be shown, the PGMDs utilize an automatic layout approach that will maximize the display usage. The PGMDs are in-turn based on the use of an earlier visualization technique known as geographic data views (GDVs) [25] that utilize embedded geographic information in the electric grid model to automatically layout the display. So before introducing the PGMD approach it will be helpful to briefly review the use of GDVs.

II. Geographic Data Views (GDVs)

Originally introduced in [25], the idea behind the GDV approach is to automatically create a power system visualization by joining results from a power system model with geographic information embedded within that model. The product is a geographic display that utilizes graphical symbols to represent power system values of interest with the location of the symbols determined from the embedded geographic information. Typically the symbol attributes can be data dependent. Attributes could include shape, size, fill color, rotation, and border color. Important to this approach is to allow the attributes to be easily customized on-the-fly to display the desired power system quantities. Since each GDV is linked to its power system object, the objects information dialog can be shown by right-clicking on the GDV object.

Figure 3 shows a GDV automatically derived from the Figure 2 grid in which the GDV objects show information about each of the 76 areas in the grid (where an area is defined as a group of buses, here containing between 91 and 3229 buses). The display size of each area GDV is proportional to a value denoted here as the size metric. In this example the metric is proportional to the areas total MW generation, and the GDV fill color is based on the areas total MW exports using the color key shown in the figure, and a GDV text string shows the areas name. The location of each GDV on the oneline is then auto-determined based upon the average of the location of that areas buses.

A second example GDV is shown in Figure 4, with the GDVs now corresponding to the individual generators, with their size proportional to the generators MW output and their color dependent upon the percentage of the generators reactive power output relative to the minimum and maximum reactive power limits

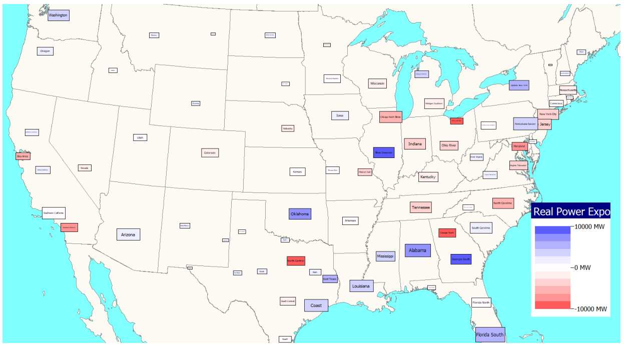

Figure 3. 82,000 Bus Synthetic Electric Grid Area GDV

The power of the GDV approach is that because the GDV objects are automatically placed, the displays can be created quickly. And a wide variety of different object attributes can be shown. In the approach implemented here, essentially any object field can be used as a GDV attribute parameter. A piecewise linear approach is utilized to map the object field to the GDV attribute. For example, mapping generator MW output to the GDVs display size (recognizing that display size needs to be a non-negative value).

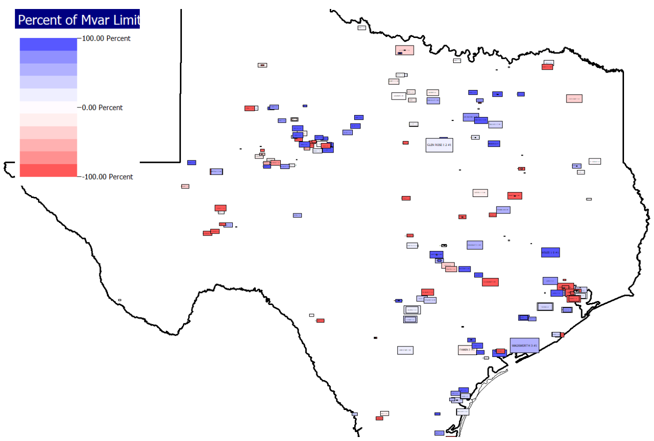

Figure 4. 2000 Bus Grid Generator GDVs

However, there are tradeoffs inherent in the GDV approach. First, because the objects are automatically placed, the potential for overlap exists. While not a significant concern in Figure 3, overlap is clearly an issue in Figure 4. Of course algorithms could be used to minimize this overlap, albeit with some loss of geographic accuracy. Second, because of the nature of the electric grid the GDV objects tend to be clustered in small areas (e.g, urban areas when showing load). Last, the GDVs do not tend to make effective use of display space, with most of the image consisting of empty background.

Figure 5 shows an example of the limits of GDVs, here trying to visualize the line (i.e., transmission line and transformers) flows in a 10,000 bus, 12,706 line synthetic system. In the figure the size of each GDV is proportional to the lines flow, whereas a color mapping is used to show the lines loaded above 70% of their limits, with white used for lines below their limit. The figure has excessive overlap, and even on a high resolution monitor it looks extremely cluttered. The next section presents pseudo-geographic mosaic displays (PGMDs) to address these shortcomings.

III. Pseudo-Geographic Mosaic Displays

The gist of the PGMD approach is to place and size the individual GDVs to maximize the display usage, while sacrificing some geographic accuracy. Hence it is a pseudo-geographic approach. An example of a PGMD for the Figure 3 GDVs is shown in Figure 6. As noted earlier, this is a type of mosaic plot [24], with the row attribute being the areas approximate latitude and the column attribute being the areas approximate longitude. As was the case in Figure 3 the screen space size of each area GDV is proportional to its total real power generation, and its color remains dependent upon its real power exports. The key difference is the PGMD uses all of the display space for showing these GDVs, with the result being most area names can now be read in the figure (and even more so on a high resolution monitor).

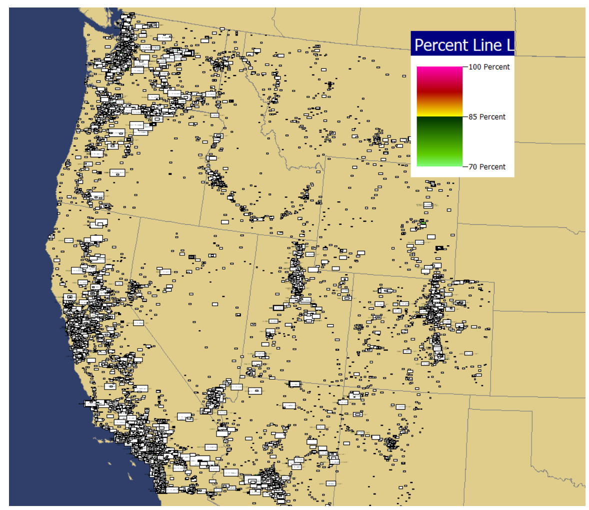

Figure 5. 10,000 Bus Electric Grid Line Flow GDVs

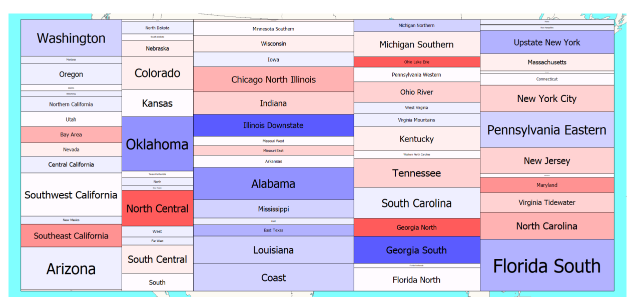

Figure 6. 82,000 Bus Synthetic Electric Grid Area PGMD

However, there is a sacrifice in geographic precision. For someone unfamiliar with such displays this could result in the potential for confusion with respect to what is actually being shown. Therefore in our implementation of the PGMDs we have included the ability for people to smoothly transition between the original GDV display and the PGMD, and if desired to transition back. Figures 7 and 8 illustrate this transition, with Figure 7 being 25% transitioned from Figure 3 to Figure 6, and Figure 8 being 60% transitioned. This ability to easily and smoothly transition between the GDV and PGDV reduces the initial unfamiliarity of the approach. With maps in general such animated transitions are commonly used in showing cartograms, in which a map is distorted based on an underlying attribute. An example of a cartogram animation is shown in [26].

In creating the PGMD, the size and the location of the GDVs need to be modified to fill the rectangular region. This is accomplished by the layout algorithm. While the approach presented here is best described as a mosaic display, the approach is also similar to a treemap display in which a set of nested rectangles is used to visualize a tree structure [27], albeit here there would just be a single level to the tree.

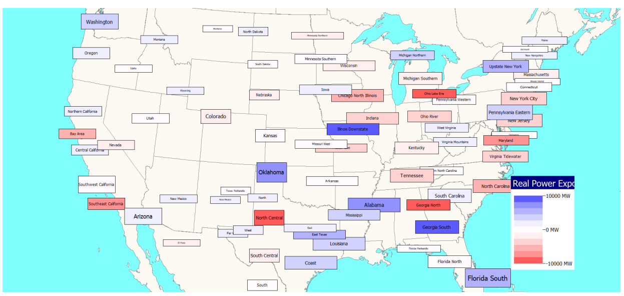

Figure 7. 82,000 Bus Area PGMD 25% Transitioned

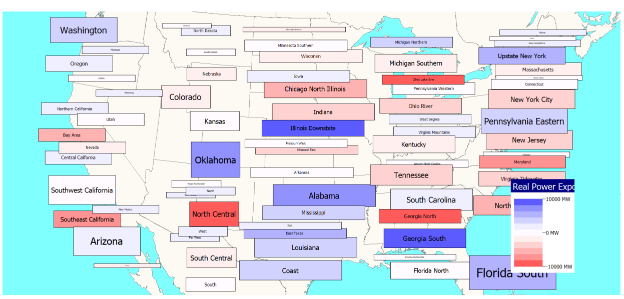

Figure 8. 82,000 Bus Area PGMD 60% Transitioned

Numerous layout algorithms exist, with tradeoffs between algorithm complexity, computation, and the aesthetics of the resultant layout. An important design goal is to have a reasonable aspect ratio for the rectangles. That is, avoiding long and skinny, or short and wide rectangles. In a mosaic display it is common to have the objects arranged in columns (i.e., column objects all have the same width); this is seldom the case with treemaps. Whether the column approach works well depends upon the nature of the underlying data and the application of the visualizations. For the pseudo-geographic electric grid data visualization presented here, in which the rectangle sizes are similar (at least to say two orders of magnitude) and uniformly distributed, and the desire is to quickly recreate a display after perhaps a power flow solution, the column approach works well and hence is used.

With this approach, the design considerations are how many columns to use and how to assign objects to the columns. Currently our implementation assigns approximately the same under of objects to each column, with the number of columns set to maintain a user specified row count to column count ratio. The default value of three times the rows to columns was used with Figure 6. The width of each column is then dependent upon the sum of the size metrics of the column GDVs, with the height of each object in its column dependent upon its size metric relative to the sum of the metrics for all the objects in the column.

IV. Design Considerations and Tradeoffs

In developing the PGMDs there are a number of design considerations and tradeoffs. A key consideration in the design of the layout algorithm is whether one would like to maintain a consistent row and column assignment of the GDVs. Of course, this is application dependent. If the goal is to show say a figure in a paper to someone who will only be looking at the image once, then whether Figure 6 has four, five or six columns doesnt matter much, and a layout algorithm could be used to maintain a consistent aspect ratio. In contrast, if the goal is to use the PGMD is a setting in which the user gains familiarity with the location of the GDVs, such as an engineer doing many power flow studies, then consistent display placement could be more paramount. This approach is used in the examples presented here. This can result in some loss of a uniform aspect ratio, manifested in Figure 6 by the second column being substantially narrower than the third column. However, with wide-area electric grid data the approach seems to work well. This is illustrated in the next two figures.

Figure 9 is the PGMD associated with Figure 4 with the GDV size attribute the real power output of each generator, a value that could change substantially between power flow solutions. Overall the display shows data for 544 generators, though some are off-line and hence do not appear. With the approach of maintaining a constant column assignment, the width of each column varies with changing generator outputs, but the location of each individual generator would stay relatively constant, only varying slightly within its column. Here the left three columns are thinner than the rest because they are mostly showing smaller wind farms in West Texas.

Figure 10 show the PGMD for the 12,706 GDVs shown in Figure 5. While the small figure in this paper doesnt fully do it justice, on a high resolution monitor it can be quite effective in showing the overall flow pattern and percentage line loading for the system as a whole. Again, a selective color mapping is used to only highlight lines loaded above 70(with the color map shown in the upper left corner of the figure). Because the elements are GDVs, the associated objects dialog can be shown by right-clicking on it. To help illustrate the high resolution of the display, Figure 11 shows a zoomed view of the upper left-hand corner of Figure 10.

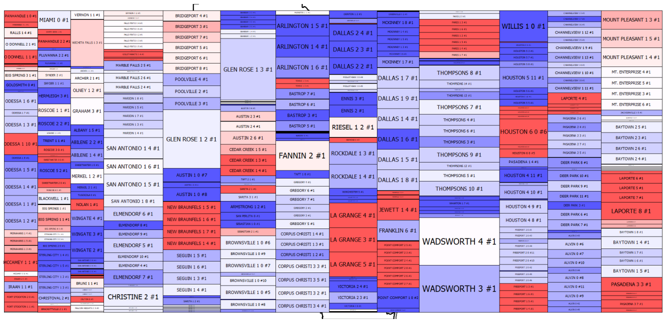

Figure 9. 2000 Bus Grid Generator PGMD

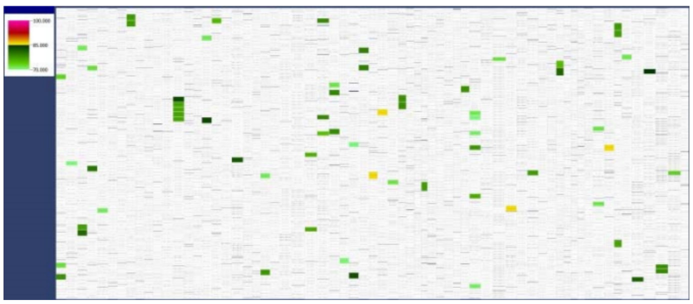

Figure 10. 10,000 Bus Electric Grid Line Flow PGMD Showing Data for 12,706 Lines

Figure 11. Zoomed View of Upper Left Corner of Figure 10

By default the size of each PGMD is sized to be equal to the computer window (with optional margins on the size). However, the size can be normalized based upon a specified total metric value for all the objects on the display. This can be quite useful when comparing between different operating conditions (e.g., power flow solutions). For example, the size of the Figure 10 would vary based on the system loading condition, with its size increasing for heavily loaded conditions, and shrinking for more lightly loaded conditions.

An advantage of GDVs and PGMDs is they can be used to simultaneously visualize multiple display attributes. For example, most of the previous figures showed two attributes in addition to geography. Figures 12and 13 show the switched shunts for the 2000 bus system, now displaying three attributes: 1) the shunts nominal Mvar value with the size metric, 2) the shunts regulation voltage error (with the fill color, using a color mapping that is blue if the voltage is too high, red if it

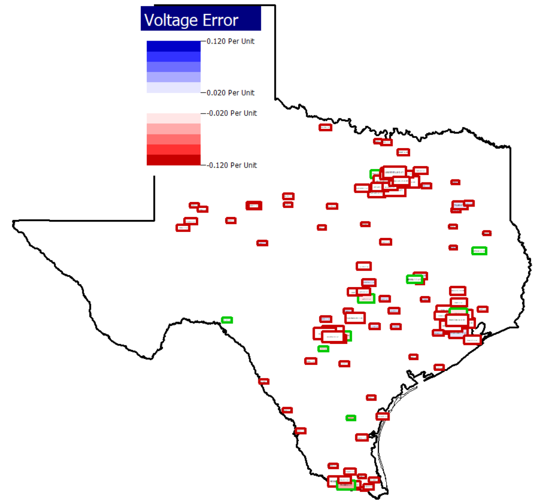

Figure 12. 2000 Bus Multi-Attribute Switched Shunt PGDV

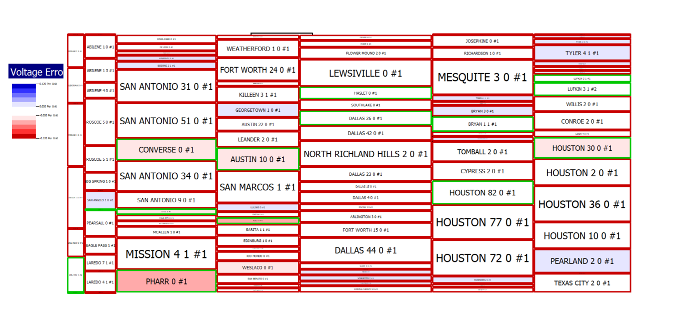

Figure 13. 2000 Bus Multi-Attribute Switched Shunt PGDV

is too low, and a white color deadband if the voltage is close to its regulated value), and 3) the switch shunts status using the border color (red for in-service, green for out-of-service). Hence this display could be used for reactive power control.

V. Summary and Future Directions

This paper has presented a new visualization technique for showing information about a potentially large number of objects for large-scale electric grid. The papers approach is to arrange geographic data view objects using a pseudo-geographic layout to maximum the use of the display space. Results have been demonstrated for several different applications on a variety of different electric grids.

However, there are many future applications and enhancements to the approach that are currently being researched. One is to develop animation loops using the PGDVs to show changes during dynamic simulations such as occur in transient stability studies and with phasor measurement unit (PMU) data. The use of animation loops to show frequency contour during transient stability studies is discussed in [9] and [9]. PGDVs could be used to show multiple attributes, such as both frequency and bus voltage magnitude deviation during the simulations. A second future direction is to explore the many different power system parameters and states that could be displayed using PGDVs. A final future direction would be to explore layout algorithms for the GDVs that make different tradeoffs between the percentage of the screen space utilized and geographic accuracy.

VI. Acknowledgements

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