The Use of Geographic Data Views to Help With Wide-Area Electric Grid Situational Awareness

Thomas J. Overbye, Jessica L. Wert, Komal S. Shetye, Farnaz Safdarian, Adam B. Birchfield
Dept. of Electrical and Computer Engineering
Texas A&M University
College Station, TX, USA
overbye@tamu.edu, jwert@tamu.edu, shetye@tamu.edu, fsafdarian@tamu.edu, abirchfield@tamu.edu

***Abstract*— The paper presents the use of geographic data views (GDVs) to help improve large-scale electric grid situational awareness for power flow and time-domain simulations. GDVs are electric grid display objects whose location is dynamically determined from geographic information embedded in an electric grid model. The paper provides examples using a 2000-bus and an 82,000-bus synthetic electric grid to show how GDVs can be used to help provide wide area understanding of values such as generator outputs, switched shunt values, voltages, and transmission line flows. It also shows the application of force-directed layout of GDVs and GDV summary objects.**

***Keywords*— wide-area electric grid visualization, geographic data views, situational awareness, power flow**

I. INTRODUCTION

The term situational awareness (also called situation awareness) (SA) was popularized in the electric grid literature as a result of its prominence in the North American August 14, 2003 Blackout final report [1]. As presented in [2] and discussed in [3], SA is intuitively defined as, “knowing what’s going on,” or more formally as, “the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning and the projection of their status in the near future.” In the blackout report lack of SA was one of the four causes of the event. The term is now widely used in electric grid operations and has been the subject of a variety of papers including [4], [5], and [6].

Associated with wide-area electric grids the concept of “knowing what’s going on” doesn’t just apply to operations, but also to the large number of engineering studies that are used to ultimately support the actual operations. These include many different studies and simulations done by many different people including the real-time support engineers, power marketers and traders, long-term planners, and the researchers developing new algorithms and techniques. While the concept of SA was originally introduced for dynamic systems, it has long been used in static situations as well, including by the military [7]. The focus of this paper is on techniques applied to larger scale systems to help people maintain SA during electric grid engineering studies such as power flow, contingency analysis, optimal power flow (OPF), and time-domain simulations.

The power flow is certainly one of the most widely used electric grid analysis tools, and maintaining SA during a power flow study is straightforward if the system is small. However, with electric grid models often having tens of thousands of buses it can sometimes become difficult for people to fully comprehend study results. This is not just due to the model size but also its complexity. The quantities of interest can get quite long, including the bus voltage magnitudes and angles, line flows, generator real and reactive power outputs, changes in automatic controls such as switched shunts and transformer LTC or phase positions, and sometimes other values such as those associated with geomagnetic disturbance studies (GMDs) [8]. The variables of interest expand further when the results include sensitivities or the study includes contingency analysis, OPF, security-constrained OPF, or time-domain simulations. As an aside, one of the motivations for the work presented here was a study by the authors looking at the power flow, contingency analysis and dynamic considerations of a potential ac interconnection of the North American Eastern and Western grids using a 110,000-bus model.

Of course over the years a number of different information management and visualization techniques have been developed to help engineers maintain SA during such studies. These include onelines, tabular displays, intelligent alarming, 3D displays, and color contouring. Examples of papers in the area include [9], [10], [11], [12], and [13]. The focus here is on new developments in the use of geographic data views (GDVs) for wide-area electric grid visualizations. The next section provides background on GDVs. Section III shows how force-directed algorithms can be used to improve them, while Section IV introduces the use of GDV summary objects to help improve SA.

II. GEOGRAPHIC DATA VIEWS

The purpose of GDVs, which were first presented in [14] and [15], is to provide a fast and flexible way to show large amounts of geographically-based information for larger-scale electric grids. In short, GDVs use geographic information embedded in an electric grid model to draw symbols on a display with the symbol’s appearance dynamically determined by the electric grid model object values. Hence a key requirement for the GDV approach is that at least some of the electric grid components have geographic coordinates such as the latitude and longitude of the substations.

Copyright© 2021 IEEE. Personal use of this material is permitted. However, permission to use this material for any other purposes must be obtained from the IEEE by sending a request to pubspermissions@ieee.org. Accepted for the 2021 IEEE Texas Power and Energy Conference (TPEC), College Station, TX, USA, February 2021.

For any real electric grid this information exists, though historically it was often not included in the transmission system models used for power flow analysis. This is now rapidly changing, partially because this information is needed for the now-required (at least in North America) geomagnetic disturbance risk analysis studies, and partially because of the now widespread availability of the grid information in geographic information systems. Geographically-based large scale synthetic electric grids are also now available with substation latitudes and longitudes [16], [17], and dynamic model parameters needed for time domain simulations [18].

Often wide-area transmission grid visualization is done using either a fully geographic approach (e.g., as done with Google Maps) or in a pseudo-geographic approach in which the geographic locations are only approximate (such as in an electric utility control room mapboard display). The advantage of the fully geographic approach is it allows easily coupling with other geographic information, such as weather or maps. A disadvantage is the electric grid equipment itself has a very small actual geographic footprint and often it can be quite densely packed in areas of interest such as urban centers. The pseudo–geographic approach sacrifices some geographic exactness for display clarity.

This paper demonstrates the use of GDVs using a 2000-bus (2K) synthetic grid covering a geographic footprint of the U.S. state of Texas from [19], and an 82,000-bus (82K) synthetic grid covering the Conterminous (Contiguous) U.S; both grids are available at [20]. Each grid has the buses mapped into electric substations (with 1250 substations for the 2K grid and 41,012 for the 82K grid) with geographic coordinates provided for each substation; they have 3206 and 104,125 transmission lines and transformers (branches) respectively. In addition the grids are divided into areas, with eight areas for the 2K and 76 areas for the 82K bus model.

The onelines for these grids are shown in Figure 1 and Figure 2 with the line color on the display used to show the transmission line's nominal voltage (blue for HVDC, green for 765 kV, orange 500 kV, red 345 kV, purple 230 kV, and black for lower voltages), and green flow arrows superimposed on the branches to show the direction and magnitude of the real power flow. While such onelines can certainly be helpful for electric grid study SA (with example useful techniques given in [21]), the premise of this paper is the SA can be enhanced through the use of GDVs.

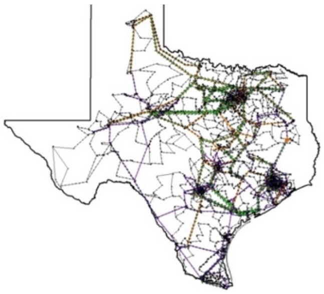

Figure 1: 2000-Bus System Oneline

For GDVs, usually the symbol's initial display location is based upon geographic information determined from the object associated with the GDV. For some objects this information is directly available, such as the location of a generator or substation. For others, such as an electrical area that is defined as a set of buses, its location needs to be derived (e.g., an area's location is the average of the location of its component buses). These initial locations might then be modified for display clarity.

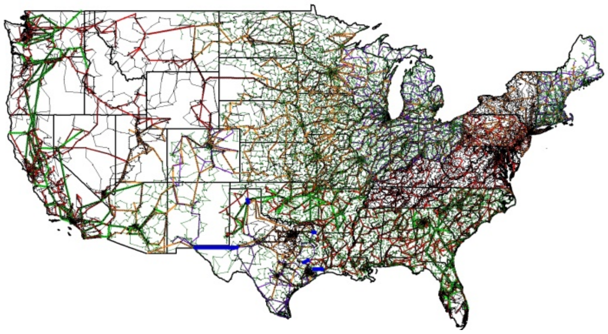

Figure 2: 82,000-Bus System Oneline

The GDV symbol display attributes are then dependent upon one or more field values from the linked electric grid object. Common display attributes include the symbol's size, fill color, border thickness, and border colors. The field values can be almost anything, with real power output being one example. Figure 3 shows a GDV display in which each symbol is linked to substation from the 2K system with the size of the symbol proportional to the amount of generation in the substation, and its color dependent upon the generator's percentage reactive power output (relative to its minimum and maximum limits). A total of 168 GDVs are shown, corresponding to the substations with non-zero generation. An advantage of this approach is that at a glance the location of the system generation is shown, including whether the generators are producing or absorbing reactive power.

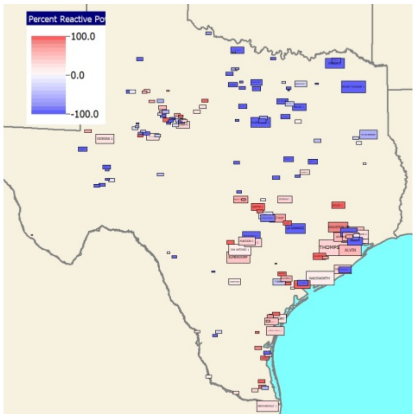

Figure 3: 2000-Bus System Substation Generation GDVs

A second GDV display for the same system is shown in Figure 4, this time with the GDVs showing the location of each of the 154 switched shunts. Here each GDV shows four device attributes: 1) its geographic location, 2) its nominal Mvar value (using size), 3) its status (using the border color of green for open and red for closed), and 4) its bus voltage (using the fill color, with the color key shown). Figure 5 shows an example of the use of GDVs to show the 76 areas from the 82K grid, with the size of each proportional to the area's total generation, and the color dependent upon whether the area is exporting (red) or importing (blue) power.

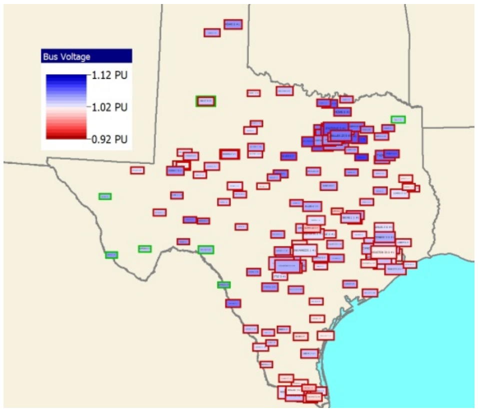

Figure 4: 2000-Bus System Switched Shunt GDVs

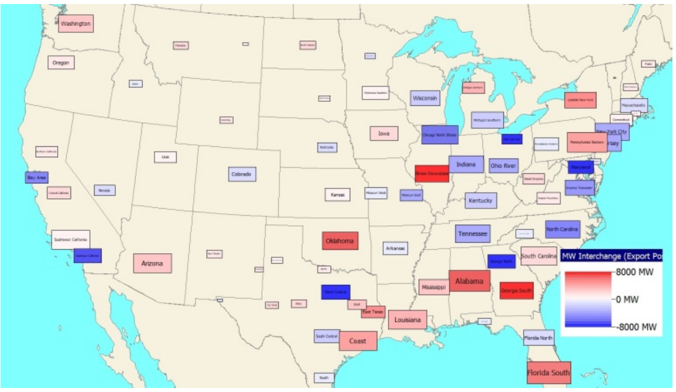

Figure 5: 82,000-Bus System Area GDVs

From a power flow SA perspective these figures illustrate how GDVs can be used to show information about important grid information across the entire system. During a power flow solution people usually know the changes that they explicitly made. The SA challenge is to understand the response of the sometimes quite involved automatic controls, including the changes in the generator real and reactive power outputs (Figure 3), the switched shunts (Figure 4), or area interchange (Figure 5). Other values that could be shown using GDVs include the LTC transformer tap changes or phase angle regulator changes. However, this is not to imply that all important values are best illustrated using GDVs. As noted earlier, regular onelines and tabular displays are important and often best for showing essential system-wide SA values such as total island load, generation, and slack bus output. Another important SA quantity, the per unit voltage magnitudes, could be shown using color contours [9].

While the concept of GDVs is general, before moving on it will be useful to present several particulars to our implementation and associated user interface (UI) that can be helpful from an SA persepctive. First, all of the GDVs are linked to their associated electric grid objects with the UI making it easy to get additional information about the object such as its dialog. Second, all of the GDVs are grouped into styles with the UI also making it easy to view the GDV's style dialog. The style defines all of the GDV attributes, such as what object values (e.g., MW) to map to what display attributes (e.g., display size or color). While a linear mapping is common, the actual implementation supports piece-wise linear mappings. The ability to quickly access the style provides several advantages such as a user being able to see the mapping used and, if desired, change it. Multiple styles can be used on a single display, though for paper clarity all the examples here only use a single style. Third, in the UI the GDVs can have up to three display lines, making it easy to show its ID and sometimes numeric field values.

Fourth, the UI makes it quite easy to create the GDV displays. For example, using predefined backgrounds the paper figures can each be created in just a few minutes. Fifth, while the GDVs are automatically placed on the displays using embedded geographic information, they can be manually repositions such as to avoid overlaps (though for this paper no manual changes were made). Sixth, while simple to create, the GDV displays can be stored to allow them to be used repeatedly. Seventh, in the approach implemented here the GDVs can be used to show either actual power system values, or differences between two solutions. Example usages include comparing the changes due to a power flow or OPF solution, or showing how quantities varied during a time-domain simulation. Last, the UI used here has been developed to allow GDV use with a large variety of different object types. For example, in a recent large system study we needed to gain better SA associated with a large number of contingencies and associated remedial action schemes (RASs) [22]. Since both could be placed geographically (by averaging the coordinates of their component objects) we were able to used GDVs quite effectively.

However, GDVs do have a potential shortcoming related to their use of display space. As is readily apparent in the previous figures, overlap can be a problem. For some object types, such as generators, multiple objects may be at the same geographic location. Even when the locations are different because of how the grid is structured often with a large number of devices in small geographic regions (e.g., urban areas) significant overlap can occur. There is an inherent tradeoff between the GDV's display size and this degree of overlaps. The next two sections provide some techniques for dealing with this issue.

III. USE OF LAYOUT ALGORITHMS WITH GDVS

GDV display placement involves a tradeoff between display clarity and geographic accuracy. As noted in the beginning of the previous section, the use of a pseudo-graphic approach, in which the display space itself it not strictly geographic, is one solution. The alternative is to keep the display itself geographic, but to be more approximate in the GDVs actual placement. Two such approaches are presented in [23] and [24], with Figure 6 showing a pseudo-geographic mosaic view (PGMD) from [23] for the Figure 4 GDVs. With the PGMD the display design goal changes from geographic accuracy to full utilization of the display (screen) space but with only a quite approximate geographic precision. In the figure the geographic orientation is the same (i.e., the top is north), and the rectangles are placed with a rough geographic correspondence (e.g., those of Houston, Texas, located in the southeast portion of Figure 4, are shown towards the bottom right). As with the other GDV displays all the GDVs are linked to their associated objects making it easy to get more detailed information and/or do control.

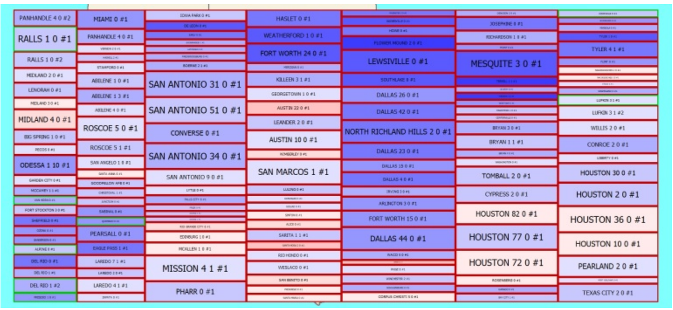

Figure 6: 2000-Bus System Switched Shunt GDVs Mosaic View

An alternative is to utilize a force-directed graph drawing algorithm to move the objects apart, sacrificing some geographic accuracy for improved display clarity. Force-directed algorithms are common in many domains, with the concept initially presented in [25] and some recent electric grid applications in [26], [27], and [28]. The idea is to better lay out the display objects by assuming each is subject to repulsive forces, pushing it away from its neighbors and attractive forces pushing it towards other objects or a fixed point. Then an iteration is run until an equilibrium is achieved.

Over the years, a number of different repulsive and attractive force functions have been proposed, with a Coulomb repulsive function common in which the force decreases with the square of the distance, and a Hooke attractive function that mimics the linear force of an ideal spring. These functions are used here, with the Coulomb "charge" of each GDV proportional to its area, resulting in the larger GDVs getting more display space. Given that each GDV has a geographic location, similar to what is done in [28], the attractive force is anchored there. In addition, a static friction force is applied if the GDV is at this location, causing a tendency for it to stay put. For objects at the same location separate initial perturbations are applied to separate them. Normalized scaling values are also provided on force each to allow the display's appearance to be easily customized.

Key to implementing this algorithm on larger displays is to reduce the otherwise $O(n^2)$ computation associated with computing the repulsive forces. By taking advantage of the typical electric grid structure of GDVs distributed fairly uniformly across the display and that the Coulomb force decreases with the square of the distance, the computation can be reduced substantially by just including in the calculation those GDVs within a given radius. Various heuristics can be used to determine this radius, but a value that gave reasonable results was four to six times the width of the largest GDV. The set of neighbors within this distance for each GDV can be determined with O(n log n) computation by setting up a k-d tree data structure. Optionally, the number of total neighbors could also be limited recognizing that the GDV densities could vary across a grid.

As an example, Figure 7 shows the results of using this forced-directed algorithm on the 154 GDVs on Figure 4. The algorithm takes about 0.5 seconds with an average of about 50 neighbors included in the Coulomb force calculation. An example of the algorithm separating GDVs at the same location is seen at the far top of the display. Boundaries and other constraints (such as water) can be optionally enforced during the algorithm by considering the figure pixel background color before doing the move. This is shown in Figure 8, again for the Figure 4 display.

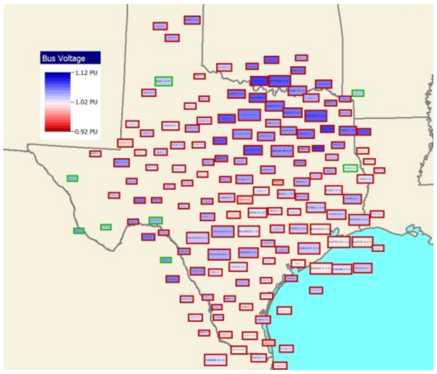

Figure 7: 2000-Bus System Figure 4 Layout with No Boundary Enforcement

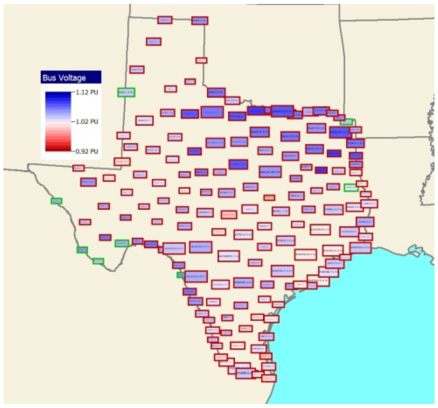

Figure 8: 2000-Bus System Figure 4 Layout with Boundary Enforcement

To demonstrate the algorithm computational scaling for larger systems, Figure 9 shows an initial display from the 82K grid showing the 4055 GDVs for the substations with non-zero generation with the color of each shaded based on its percentage reactive power output. Figure 10 shows the display after application of the force-directed layout algorithm with boundary enforcement. Overall the algorithm took about 12 seconds with an average of 119 neighbors per GDV considered for the Coulomb forces. While admittedly the individual substations are difficult to see in these small figures, on a computer screen with support for zooming and panning it is relatively easy to use the display to get a good feel for what is going on with respect to the overall generator reactive power outputs. Both figures use a selective color mapping in which only reactive power loadings above 80% of the maximum limit are shaded red and those below 80% of the minimum limit are shaded blue. This can enhance SA by making these outliers standout by taking advantage of pre-attentive processing [29]. One takeaway from Figure 10 is that the associated power flow has an unrealistic number of generators operating with low power factors.

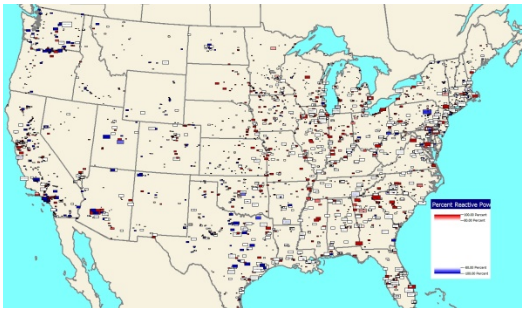

Figure 9: 82,000-Bus Grid Substation GDVs

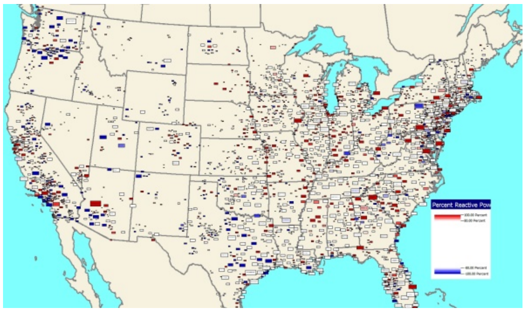

Figure 10: 82,000-Bus Substation GDVs with Layout

IV. GDV Summary Objects

However even with layout sometimes there are just too many GDVs to effectively display. In such situations the use of GDV summary objects can be helpful. These GDVs may either be derived from summary objects already existing in the electric grid model, such as the areas shown in Figure 5, or they may be dynamically determined. One quick approach is to just group the electric grid objects geographically and shown the summary GDVs based on an xy grid covering the entire system footprint. Such summaries could be used with actual values or with the previously mentioned differences between solutions. As an example Figure 11 uses a 25 by 15 grid of GDV summary objects to show the change in the generation during a time-domain study on the 82K bus system in which the initial contingency is the loss of about 2800 MW of generation in the Southwest U.S and the 60 Hz system response is integrated using a ¼ cycle time step. The size of each GDV is proportional to the change in generation while its fill color is set to red where generation is lost and blue where it is increased. The figure shows data for four seconds after the contingency. This use of the GDVs' summaries allows the system generator change pattern to be quickly determined.

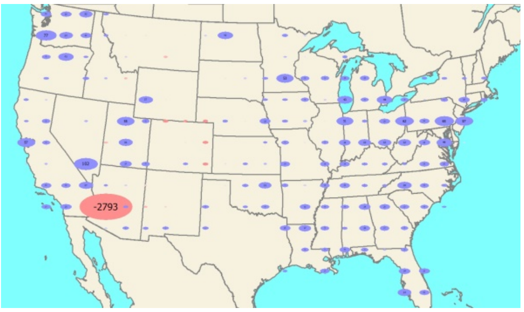

Figure 11: 82K System Generation Summary Objects using a 25 by 15 Grid

This concept can be extended to show the overall flow pattern of electricity in a grid. The challenge with summarizing branch flows for large systems is the sheer number of branches (e.g., Figure 2). Techniques such as using flow arrows [21] changing the thickness of the individual lines on the oneline [30] can be used for smaller systems, but have difficulty in scaling to extremely large systems. A newer technique from [31] visualizes electric grid flows as a vector field can be scaled to larger systems.

Complementing these approaches, GDV flow summary objects can be defined using the same xy grid approach as the regular summary object. Each of these flow objects can be configured to show the flow entering or exiting the summary object in the four different directions associated with the underlying grid. The amount of flow can be visualized by changing the thickness of the lines joining the neighboring flow objects and/or their color; arrows are superimposed to the lines to show the direction of flow. Figure 12 shows an example for the 82K system in which the system is partitioned into a 16 by 8 grid. At each grid location a regular GDV summary object is also added, here showing the net real power injection (with yellow for generation, magenta for load).

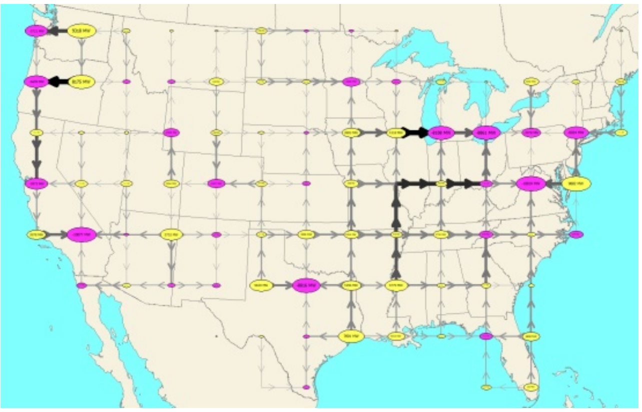

Figure 12: 82K Substation Flow Visualization with an Aggregate Line Flows (16 by 8 Grid)

In calculating the summary flow the impact of lines that both terminate in the summary location and pass through the location without terminating (such as a longer high voltage line) are considered. As with all GDVs the objects can visualize either actual values or the difference in flows from some base case. Given the aggregate nature of these summaries, the inclusion of a geographic background might be less useful, with Figure 13 showing the Figure 12 results except 1) the xy grid size is increased to 28 by 16, and 2) the background has been removed and the injection symbols have been removed, and 3) the color scale was changed. Such displays could be most useful in allowing for quick comparisons of different operating conditions.

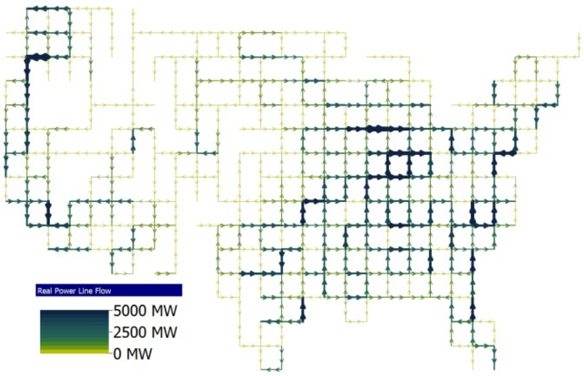

Figure 13: 82K Substation Flow Visualization with an Aggregate Line Flows (28 by 16 Grid)

V. ACKOWLEDGEMENTS

This work was partially supported through funding provided by the U.S. National Science Foundation in Award 1916142, the US ARPA-E, and the Power Systems Engineering Research Center (PSERC).

REFERENCES

[1] U.S Canada Power System Outage Task Force, Final Report on the August 14, 2003 Blackout in the United States and Canada, April 2004.

[2] M.R. Endsley, “Toward a theory of situation awareness in dynamic systems,” *Human Factors*, Vol. 37, pp. 32-64, March 1995.

[3] C.L. Wickens, “Situation Awareness: Review of Mica Endsley’s 1995 Articles on Situation Awareness Theory and Measurement,” *Human Factors*, Vol. 50, pp. 397-403, June 2008.

[4] C. Basu, M. Padmanaban, S. Guillon, L. Cauchon, M. De Montigny, I. Kamwa, “Situational awareness for the electric power grid,” *IBM Journal of Research and Development*, Vol. 60, Issue 1, 2016.

[5] J. Wu, K. Ota, M. Dong, J. Li, H. Wang, “Big Data Analysis-Based Security Situational Awareness for Smart Grid,” *IEEE Trans. Big Data*, Vol. 4, pp. 408-417, July-Sept. 2018.

[6] Y. Liu, W. Yao, D. Zhou, L. Wu, S. You, H. Liu, L. Zhan, J. Zhao, H. Lu, G. Gao, Y. Liu, “Recent Development of FNET/GridEye – A Situational Awareness Tool for Smart Grid,” *CSEE Journal of Power and Energy Systems*, Vol. 2, pp. 19-27, Sept. 2016.

[7] The National Research Council, “Modeling Human and Organizational Behavior,” The National Academies Press, Washington DC, 1998.

[8] T.J. Overbye, T.R. Hutchins, K.S. Shetye, J. Weber, S. Dahman, "Integration of Geomagnetic Disturbance Modeling into the Power Flow: A Methodology for Large-Scale System Studies," Proc. 2012 North American Power Symposium, Champaign, IL, September, 2012

[9] J. D. Weber and T. J. Overbye, "Voltage contours for power system visualization," *IEEE Trans. on Power Systems*, Vol. 15, pp. 404-409, February, 2000.

[10] P.C. Wong, K. Schneider, P. Mackey, H. Foote, G. Chin, R. Guttromson, J. Thomas, “A Novel Visualization Technique for Electric Grid Power Analytics,” *IEEE Trans. Visualization and Computer Graphics,* Vol. 15, pp. 410-423, May/June 2009.

[11] T.J. Overbye, J.D. Weber, "Smart Grid Wide-Area Transmission System Visualization," Engineering, Chinese Academy of Engineering, vol. 1, December 2015, pp. 466-474. Available online at http://engineering.org.cn/EN/10.15302/J-ENG-2015098.

[12] P. Cuffe, A. Keane, “Visualizing the Electrical Structure of Power Systems,” *IEEE Systems Journal*, Vol. 11, pp. 1810-1821, Sept. 2017.

[13] A.L. Figueroa-Acevedo, C-H. Tsai, K. Gruchalla, Z. Claes, S. Foley, J. Bakke, J. Okullo, A.J. Prabhakar, “Visualizing the Impacts of Renewable Energy Growth in the U.S. Midcontinent,” *IEEE Open Access Journal of Power and Energy*, Vol. 7, pp. 91-99, Jan. 2020.

[14] T.J. Overbye, E.M. Rantanen, S. Judd, "Electric power control center visualizations using geographic data views," Bulk Power System Dynamics and Control -- VII. Revitalizing Operational Reliability -- 2007 IREP Symposium, Charleston, SC, August 2007, pp1-8.

[15] T.J. Overbye, “Wide-area power system visualization with geographic data views,” Proc. 2008 IEEE PES General Meeting, Pittsburgh, PA, July 2008.

[16] A.B. Birchfield, K.M. Gegner, T. Xu, K.S. Shetye, T.J. Overbye, "Statistical Considerations in the Creation of Realistic Synthetic Power Grids for Geomagnetic Disturbance Studies," *IEEE Transactions on Power Systems*, vol. 32, pp. 1502-1510, March 2017.

[17] A.B. Birchfield, T. Xu, T.J. Overbye, "Power Flow Convergence and Reactive Power Planning in the Creation of Large Synthetic Grids," *IEEE Transactions on Power Systems*, vol. 33, pp. 6667-6674, November 2018.

[18] T. Xu, A.B. Birchfield, T.J. Overbye, "Modeling, Tuning and Validating System Dynamics in Synthetic Electric Grids," *IEEE Transactions on Power Systems*, vol. 33, pp. 6501-6509, November 2018.

[19] A.B. Birchfield, T.J. Overbye, K.R. Davis, "Education Applications of Large Synthetic Power Grids," *IEEE Transactions on Power Systems*, vol. 34, pp. 765-772, January 2019.

[20] Texas A&M Electric Grid Test Case Repository, https://electricgrids.engr.tamu.edu/.

[21] T.J. Overbye, J.D. Weber, “Visualization of Power System Data,” Proc. 33rd Hawaii International Conference on System Sciences, Wailea, HI, Jan. 2000.

[22] Glossary of Terms Used in NERC Reliability Standards, NERC, June 2020, online at www.nerc.com/files/glossary_of_terms.pdf.

[23] T.J. Overbye, J. Wert, A.B. Birchfield, J.D. Weber, "Wide-Area Electric Grid Visualization Using Pseudo-Geographic Mosaic Displays," Proc. 2019 North American Power Symposium, Wichita, KS, October 2019.

[24] A.B. Birchfield, T.J. Overbye, "Mosaic Packing to Visualize Large-Scale Electric Grid Data," *IEEE Open Access Journal of Power and Energy,* Vol. 7, pp. 212-221, June 2020.

[25] P. Eades, "A Heuristic for Graph Drawing", Congressus Numerantium, Vol. 42, pp. 149–160, 1984.

[26] S.C. Teja and P.K. Yemula, “Power network layout generation using force-directed graph technique,” in *Proc. 18th Nat. Power Syst. Conf.*, Guwahati, India, 2014.

[27] A. de Assis Mota, L.T.M. Mota, “Drawing meshed one-line diagrams of electric power systems using a modified controlled spring embedder algorithm enhanced with geospatial data,” *Journal of Computer Science,* Vol. 7, no. 2, pp. 234-241, 2011.

[28] A.B. Birchfield, T.J. Overbye, "Techniques for Drawing Geographic One-line Diagrams: Substation Spacing and Line Routing," *IEEE Transactions on Power Systems*, vol. 33, pp. 7269-7276, November 2018.

[29] C. Ware, *Information Visualization: Perception for Design*, Fourth Edition, Morgan Kaufmann, 2021.

[30] P.M. Mahadev, R.D. Christie, "Envisioning Power System Data: Concepts and a Prototype System State Representation," *IEEE Trans. on Power Systems*, Vol. 8, pp. 1084-1090, August 1993.

[31] S. Molnar, K. Gruchalla, "Visualizing Electric Power Systems as Flow Fields," Workshop of Visualization in Environmental Sciences, Brno, Czech Republic, June 2018.