Contouring Method Considerations for Power Systems Applications

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***Abstract*—Contouring can be used to enhance engineers' situational awareness during power system studies and events. This paper compares two contouring methods (Shepard and Delaunay-based) for power system applications. Power system case studies are presented to demonstrate and discuss contour choices in various steady-state and transient applications. Discussion is centralized around the following features: relative computation speed, realism, contour boundary, and smoothness.**

***Index Terms*—Visualization, Contour, Situational Awareness, Shepard, Delaunay**

I. Introduction

Situational awareness is essential when operating a grid or analyzing the results of a study and, when considering the volume of data associated with regional power system models, presents a unique challenge of how to represent the system data. Visualizations serve as an excellent tool to aid situational awareness, but with such large amounts of data available, strategic choices must be made to design effective visualizations to capture the state of the grid at any operational snapshot. When designed and used effectively, visualizations can yield quicker human response times to the data presented than numerical representations of the data [1].

Contours serve as one such visualization system [2]. Contours make use of data at discrete points (such as buses or nodes in a system model), approximate the values at intermediate locations, map these values to a hue from a colored gradient, and present the region of the system with a layer representing the values of the metric being contoured. Contours are often used in conjunction with geographic or pseudo-geographic grid models to provide insights to the values of the contoured parameter across the geographic footprint of the system.

This type of visualization appeared in power systems two decades ago as a means to visualize voltage throughout a system [3]–[8]. Since, contours have been used to visualize other system attributes, such as locational marginal prices [9], phasor measurements [10], and bus frequency [11]. In practice during simulation, contour calculations can be performed using either GPU or CPU, with tradeoffs that must be considered situationally [12].

In essence, contouring is a data interpolation method [13]. There exist a variety of interpolation methods, each with its predominance in different fields, neatly compared in [14]. This paper discusses Shepard's contouring method [15] and Delaunay-based contouring method for power system applications. Within power systems, Shepard's method has been viewed by some as a "default" contouring method as it yields visually pleasing data visualization. Some have chosen to perform interpolation using the Delaunay-based method, favoring its fast computation [16], [17]. Section II discusses the Shepard and Delaunay-based contouring methods in depth while demonstrations on power system applications are shown in Section III.

While there is no singular correct contour design choice, some selections may be better suited to the intended application and audience than others. Each study has different intended users and intentions which must be considered in the contour selection and design process. The design choices made impact various attributes of the user experience. For example, the contour method selected when creating an animation or an interactive visualization should be fast to allow for minimal delay in the user experience.

II. Overview of Contouring Methods

The topology of a power system is naturally a network graph, with nodes like buses, generators and loads, and edges like transmission lines. Measurements like voltage magnitudes, angles, and frequency from nodes and edges can be visualized as scattered discrete points throughout a two-dimensional space. The purpose of contouring is to find a continuous function that matches each scattered point smoothly and thus fill the area with extra interpolation points to provide the viewer a better global perception. This section presents two types of contouring algorithms (regular mesh-based methods and Delaunay Triangle-based methods) that are used in the power system associated applications.

As one critical regular mesh-based method, Shepard's method and its variations can be found in power system analysis tool [3], [4], [18], Energy Management System [19] and some online monitoring tools [20], [21]. The basis of this method is for the value of an interpolation point, to calculate the weighted average from the measurement points. The weighting function is:

$$w_i = \frac{h_i^{-p}}{\sum_{j=1}^{n} h_j^{-p}} \quad (1)$$

where p is the weighting exponent with normally a defaulted value 2, and h_i is the distance function for the interpolation point defined as:

$$h_i = \sqrt{(x - x_i)^2 + (y - y_i)^2} \quad (2)$$

The default Shepard's method is a global method, which makes its computation on large region and large dataset considerably expensive. The calculation of weights is also sensitive to distant outliers. As a result, modified version using an influence region is proposed [22] and used in some power system analysis tool [12]:

$$w_{k,FL}(x,y) = \begin{cases} \left[\frac{(R-d_k)}{Rd_k}\right]^2 & ,d_k < R \\ 0 & ,d_k \geq R \end{cases} \quad (3)$$

where R is the influence radius, or influence distance, within which the observation points are used for computing the weights. R being set too low results in bull's eye shapes and set too high, there can be a blurring of information, particularly in geographically dense urban areas.

The Delaunay-based method, on the other hand, is a very efficient contouring algorithm. The first step is to construct the Delaunay triangles. Several algorithms for generating the triangles have been proposed [23], [24]. Then for each triangles, linear interpolation will be done on each edges:

$$F(x_i, y_i) = \begin{cases} f_0 + (x_i - x_0)\frac{f_1 - f_0}{x_1 - x_0} & ,x_1 \neq x_2 \\ f_0 + (y_i - y_0)\frac{f_1 - f_0}{y_1 - y_0} & ,x_1 = x_2 \end{cases} \quad (4)$$

where (x_i, y_i) is the interpolation coordinates and f is the values at the given node. The complexity for triangle generation in the method used in this paper is $O(n^2)$, the same as the default Shepard's method; some triangle generation algorithms have a complexity of $O(n * ln(n))$ [25]. Because the triangle generation is based on the location of measurement points and it only has to be run once in the whole period of application, this Delaunay-based method's complexity is normally $O(n)$, which generally means with this method things can be much faster on large systems than the Shepard's method. The triangle generation can be done in the pre-process to further reduce the initialization time.

The following features should be considered when selecting a contouring method:

- **Computation time**: The time taken for each algorithm to generate the contour represents the speed of the algorithm. In this study, the computational complexity of each algorithm is used to facilitate a comparison of these methods for various applications.
- **Realism**: Evaluate the realism of the shape in the context of power systems. Also test whether a specific area of interest stands out during an event.
- **Contour Boundary**: Test whether the the generated contour lost fidelity in the boundary.
- **Smoothness**:

  Snapshot: Evaluate whether the contour has unpleasant shapes or distribution.

  Animated: Test whether contours between two consecutive snapshots demonstrate continuity. Also consider changes that may be emphasized or, conversely, lost in the animation.

III. POWER SYSTEM STUDIES

In this paper, two synthetic transmission networks are used as test cases to demonstrate the differences between the Delaunay-based and Shepard's contouring techniques. These synthetic power systems are created to reflect the structural and functional characteristics of the actual power grids, but contain any confidential information on critical energy infrastructure.

Case Studies 1 and 2 make use of a 2000-bus synthetic transmission network on the footprint of Texas, ACTIVSg2000. Case Studies 3 and 4 use an 80,000-bus synthetic transmission network on the combined footprint of the Western and Eastern Interconnects in the United States to demonstrate the techniques for contouring the results of transient stability studies.

Each case includes detailed modeling of power system elements such as generators, loads, and transmission lines [26], [27]. Time series and scenarios are also developed to represent wide spectrum of system operating conditions [28], [29].

Figure 1 shows the one-line diagram of the 2000-bus synthetic network used in Case Studies 1 and 2. The 500-kV, 230-kV, and 115-kV networks in this case are represented as the orange, purple, and green lines respectively. The total electric load is 67 GW and the total generation capacity is 100 GW.

Figure 2 shows the one-line diagram of the 80,000-bus network used in Case Studies 3 and 4. The 765-kV, 345-kV, 230-kV, 161-kV, 138-kV, and 69-kV networks in this test case are represented as the bright green, red, purple, orange, thin black, and thin dark green lines in the one-line diagram, respectively. The total electric load is 746 GW and the total generation capacity is 766 GW.

The computation times reported for contouring results are based on measurements from a system using an i9-9880H 4.80 GHz CPU. For the 2000-bus system used in Case Studies 1 and 2 the Delaunay-based method took 0.10 seconds to produce a medium-resolution contour on average whereas Shepard's method took 0.15 seconds. For the 80,000-bus system used in Case Studies 3 and 4, the Delaunay-based method took 0.37 seconds to produce a medium-resolution contour on average whereas Shepard's method took 4.43 seconds. The Delaunay-based method provides advantage of fast computation time in the applications of transient stability simulations, where visualizations need to be refreshed at least every few seconds.

A. Case Study 1: Power Flow Voltage Contour

Case Study 1 looks into the differences between Shepard's method and the Delaunay-based method with a focus on

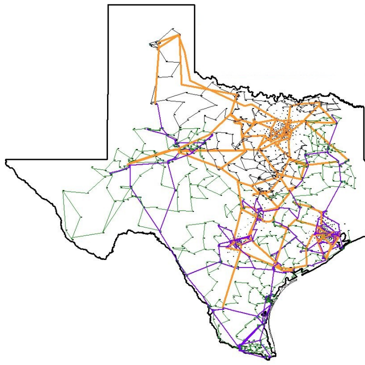

Fig. 1. One-line diagram of the ACTIVSg2000 synthetic transmission network

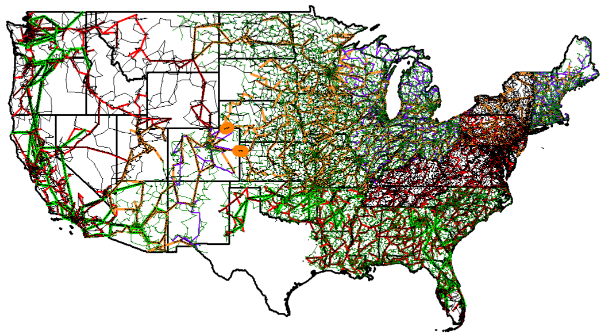

Fig. 2. One-line diagram of the 80,000-bus synthetic transmission network

steady-state voltage contours. In this study, a double line outage of 230 kV transmission lines is implemented. The contingency occurs for the two circuits located at the southern tip of Texas. This transmission capacity loss results in low voltages at several buses in the southern geographic region.

Figures 3 and 4 show the voltage contour of the low voltage region using the two contouring methods. Both methods provide straightforward visualizations of the buses with low voltages. As the Delaunay-based method uses at most three data values for each contour point, it is noticeable that there are more straight lines in Figure 3. Comparing the two figures, the Shepard's method depicts the low voltage region with a red-shaded patch that has smoother boundaries. The color transition within the red-shaded patch is also more gradual for Shepard's method. Similar observations can be made in the Northwest portion of the contour, where the blue-shaded area represents buses with relatively higher voltage magnitudes.

B. Case Study 2: Power Flow Voltage Contour

Case Study 2 also focuses on steady-state voltage contours. In this study, a 230-115-kV transformer and a 115-kV transmission line in East Texas are taken out of service for this study. The two-element contingency caused more than 10 voltage violations in the eastern region. Figures 5 and 6 contour the same power flow voltage solution using the Delaunay-based method and Shepard's method, respectively. Similar to the observations made in Case Study 1, Shepard's method depicts the low voltage region with smoother

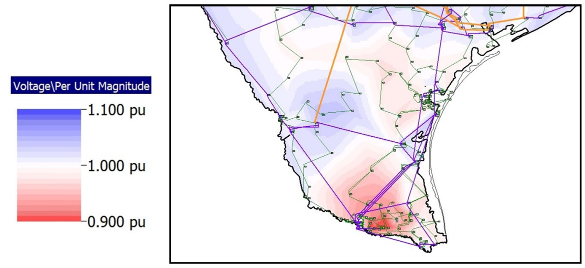

Fig. 3. Case Study 1: Delaunay-based method's Voltage Contour

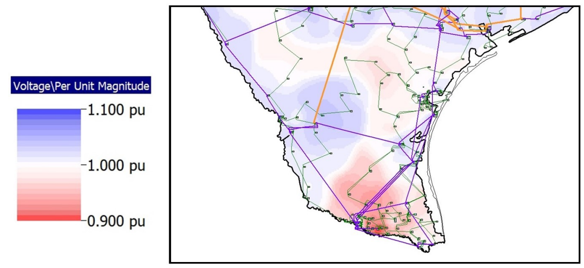

Fig. 4. Case Study 1: Shepard's Method Voltage Contour

boundaries and more gradual color transitions. However, it is noticeable that in this specific case study, Delaunay-based method is able to represent the low voltage region with more continuity and integrity, while Shepard's method depicts the low voltage buses as two disconnected red-colored patches and plots a "tail" to the south of the actual bus region.

In addition, as the Delaunay extrapolation outside the convex hull only depends upon the closest boundary point, some straight lines can be observed in Figure 5 heading off the eastern edge. Whereas in Shepard's method there can be unusual artifacts such as the sudden changes in voltage on the geographic boundaries.

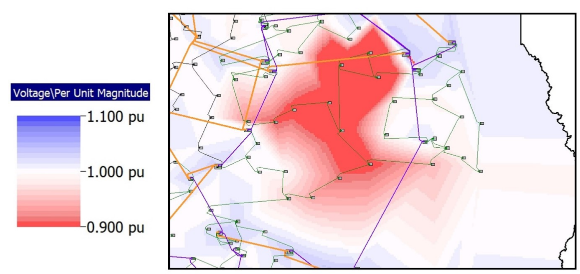

Fig. 5. Case Study 2: Delaunay-based method's Voltage Contour

C. Case Study 3: Transient Stability Frequency Contour

Case Study 3 simulates the transient response of the synthetic system after the loss of its largest generator (located in Mississippi). Besides comparing the differences between the two contouring techniques in terms of steady-state snapshots, this case study also focus on contour plots' ability to capture the trend of time-varying values. Figure 7 shows a zoomed-in view at the source of disturbance in Mississippi, where

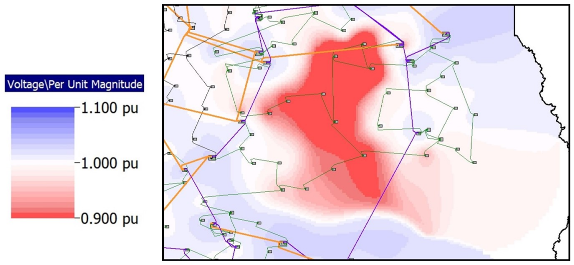

Fig. 6. Case Study 2: Shepard's Method Voltage Contour

the largest generation in the system is located. Using the Delaunay-based method and Shepard's method respectively, Figure 7 depicts the the propagation of disturbances right after the outage, at four time points 0.1 seconds apart. Both methods show the trend of frequency response, where the drop in frequency first started with buses towards the center of the view, and quickly spread.

As was observed with the voltage contours in the previous case studies, the boundaries of the low frequency region depicted using Shepard's method is smoother compared to the Delaunay-based method. The contours experience better continuity in the Delaunay-based approach which is particularly noticeable when comparing the southwestern tip of the blue low-frequency region in the second and third images of each contouring method.

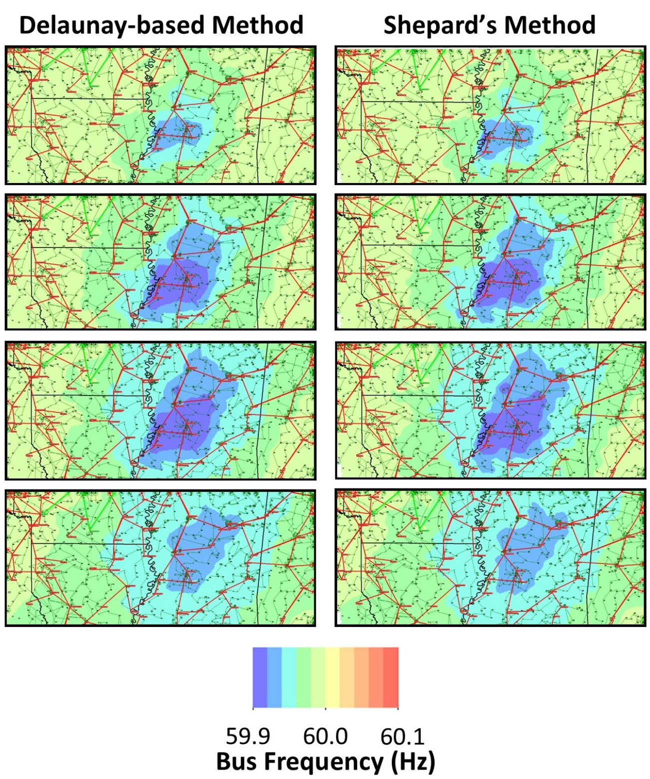

Fig. 7. Transient Stability Frequency Contours for Case Study 3

D. Case Study 4: Transient Stability Frequency Contour

Case Study 4 simulates the frequency response of the synthetic system after the loss of its largest generator in the synthetic Western Interconnect (located in Arizona). Figure 8 shows a view of the system. Using the Delaunay-based method and Shepard's method respectively, Figure 8 depicts the the propagation of disturbances to this specific region from 0.15 seconds after the contingency happened, at four different time points 0.3 seconds apart.

Both contouring techniques communicate the general trend of time-varying frequency, showing a voltage drop that spreads from the location of the contingency. The most immediately apparent difference between the two contouring methods is that in the Delaunay-based method, the contour covers the entirety of the display area whereas the contour presented using Shepard's method includes some white space. This is a good example of the influence distance used in Shepard's in juxtaposition with the Delaunay-based method which constructs triangles to from the buses with data to fill the display space.

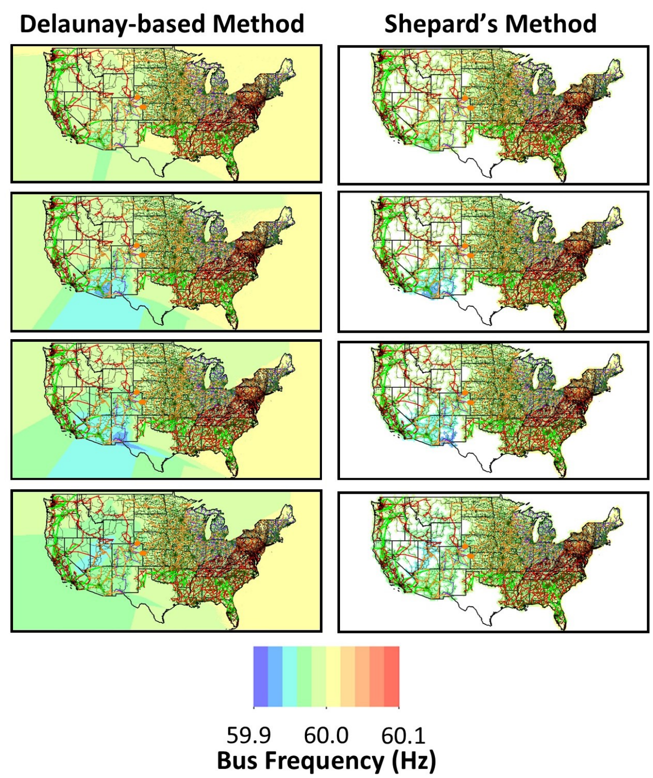

Fig. 8. Transient Stability Frequency Contours for Case Study 4

IV. Summary

This paper evaluates the Shepard and the Delaunay-based methods for applications in power system contour visualizations. Visualization in electric grids is motivated by the need for situational awareness for researchers, engineers, and operators who work with large power system models. Shepard and Delaunay-based interpolation methods are formulated and their strengths and weaknesses are discussed. To demonstrate the interpolation methods in power systems, four case studies were presented on 2000-bus and 80,000-bus synthetic grids. These case studies display Delaunay-based and Shepard contours to depict bus voltage and bus frequency in both steady-state and transient applications. The goal of these examples is demonstrate the design choices involved in contour selection as motivated by specific applications for and context of the visualization. The discussion around these applications is grounded in the use of features including relative computation speed, realism, contour boundary, and smoothness. Readers should note that each contour choice is application- and audience-dependent and thus contour method selection should be considered carefully, though the Delaunay-based contour method may be sometimes better-suited to power systems applications as it is consistently faster and may provide more reasonable interpolation than Shepard's method.

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