Delaunay Triangulation Based Wide-Area Visualization of Electric Transmission Grids

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Abstract— **This paper presents a Delaunay triangulation based technique to develop planar visualizations to better show the overall flow of power in large-scale electric grids. One of the challenges with analyzing large-scale electric grids is maintaining an understanding of the overall electric grid state, including the grid's flow pattern. The paper's algorithm addresses this by first aggregating the buses into groups. Then a Delaunay triangulation is used to create a planar graph, followed by a mapping of the transmission line flows onto this graph. Finally the flows are visualized with dynamically sized line thicknesses and/or flow arrows. Results are demonstrated using several example systems ranging in size from seven to 82,000 buses.**

Keywords—**wide-area electric grid visualization, electric grid aggregation, delaunay triangulation, power flow**

I. INTRODUCTION

A challenge in doing engineering studies associated with large-scale electric grids is for the person doing the study (the user) to well understand what is going on. The term situational awareness (SA) is used to convey this concept [1], [2], with electric grid applications of the term given in [3], [4], [5], [6]. Example engineering applications include power flow, contingency analysis, sensitivity analysis, optimal power flow (OPF), and time-domain simulations.

The SA challenges associated with doing these studies depend upon a number of factors including the size of the electric grid, and, most importantly, the ultimate purpose for the user doing the study. To aid with SA, electric grid analysis software usually utilizes a number of different information presentation techniques including tabular displays and graphical visualization. These different approaches are often used synergistically to achieve overall SA. The purpose of this paper is to focus on an aspect of SA associated with the user understanding the overall state of a large-scale electric grid, with a particular focus on the graphical visualization of the overall transmission system flow patterns.

II. BACKGROUND

A quite common graphical visualization used with positive sequence simulations is the single-line or one-line diagram (oneline), so named because the devices associated with assumed balanced three-phase system are shown using a single line. Onelines have several different applications in electric grid operations and planning. In the context of this paper's focus on wide-area visualization of larger scale systems, the purpose of the oneline is to provide an overview of all, or a significant portion of an electric grid.

The paper presents an algorithm to better visualize oneline information. The results are demonstrated on four different example systems, ranging in size from seven buses to 82,000 buses. Overview onelines for these systems are shown in the first four figures. Figure 1 shows the oneline for the seven-bus grid of [7] except with the addition of a transmission line between buses 4 and 6, Figure 2 the oneline for the 37-bus electric grid from [8], Figure 3 the oneline for a 500-bus synthetic grid [9] from [10], and Figure 4 the online for the synthetic 82,000-bus (82K) system [10].

Figure 1: Seven Bus System Oneline

Figure 2: 37-Bus System Oneline

All of these displays have been created utilizing the visualization techniques originally presented in [11] and [12], such as the use of green arrows to show the direction of real power transmission flow, the use of pie charts to indicate percentage line loading, and in the last two figures different line colors are used to indicate different nominal voltages

(e.g., green for 765 kV, orange for 500 kV, red for 345 kV and black for 138 kV).
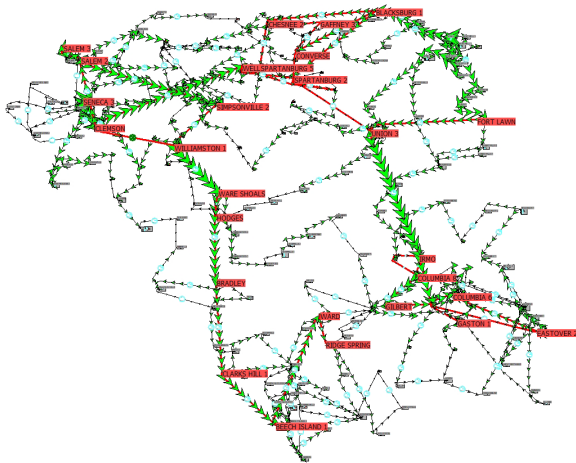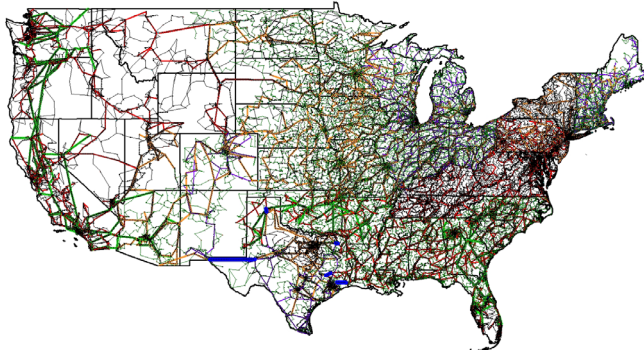

Figure 3: 500-Bus System Oneline

Figure 4: 82,000 Bus System Oneline

Broadly speaking the information shown on a oneline can be divided into two general classes: 1) that associated with the buses, and 2) that associated with the branches, with the term branches used here to indicate the flow on AC transmission lines or transformers, and also HVDC transmission lines. The bus information includes values for the bus itself (e.g., voltage magnitude and angle), values for devices attached to the bus (e.g., generators, loads and shunts), and values for bus aggregations (e.g., substations, operating areas, zones). The branch data includes real and reactive power flows, percentage loading and sometimes values such as LTC tap positions.

Over the years various techniques have been developed to help with wide-area visualization, particularly for oneline bus related data. One is color contouring [13], a technique that is widely used in the electric industry particularly for the display of locational marginal cost information [12], [14]. A second is the use of geographic data views (GDVs) [15], [6] in which geographic information embedded in the electric grid model is used to draw symbols on a display in which the symbol's appearance can be dynamically modified to show model object values. Our experience is that all of these techniques can be quite useful, with the most important design aspect being the ability to easily get more information on anything that seems important. To quote [16], [17], "Overview first, zoom and filter, then details on demand."

However it is much more difficult to do effective wide-area visualization of branch flows. This is partially due to the sheer number of branches, and partially due to the many overlapping branches that occur in large-scale grids with parallel branches common. This difficulty becomes more apparent when contrasting the smaller systems in Figures 1 and 2, with the larger ones in the Figures 3 and 4; as systems grow it becomes more difficult to show specific details such as the individual bus voltage magnitudes or the specific outputs of generators. Some of this can be helped through zooming and panning, but zooming does come with the loss of seeing the overall system.

To address this the paper presents an algorithm to take the flows on a potentially large number of electric transmission lines, which could be either AC or DC, and visualize them using a planar graph. In general the high voltage transmission system is not planar, with line crossings common, particularly when the lines are at different voltage levels. Nevertheless the premise of this paper is a planar graph structure can be used to effectively visualize some aspects of such grids. The aesthetics of graphs is discussed in [18], [19], [20] including the potentially competing properties of symmetry, minimal crossing, and minimal bends. Prior work in the area of planar electric grid visualizations includes [21], which transformed the transmission flows into a vector field, and [6], which required that the grid be visualized using a rectangular grid. The approach presented here is general and can be applied to quite large systems.

III. ALGORITHM WITH SEVEN BUS EXAMPLE

The algorithm to do this layout is straightforward and quite computationally tractable, allowing for interactive design even on large systems. As a starting point, assume that in the portion of the electric grid to be visualized there are n buses, m bus groups, and b branches. Further assume that each bus is included in a bus group and that each bus group has a unique associated spatial location, where the spatial location could be its geographic location (latitude and longitude) or an XY value associated with its position on a oneline. If multiple bus groups have the same location then they can either be combined to form a single group, or their locations can be slightly perturbed to make them unique. The bus groups can be essentially anything including existing data structures (e.g., substations, areas, zones) or ones developed based on say a clustering approach such as with a latitude and longitude grid. If desired, a layout algorithm could be used to improve the oneline aesthetics [22], [23], [6].

The first step in the algorithm is to map each branch to the bus groups associated with its terminals. Often this is already setup with the grid data structures (e.g., a branch knows its buses, and each bus knows its associated substation, area and zone). Branches that do not have both their terminal buses in the set of bus groups are ignored, with an example being when only a portion of the grid is to be visualized. Computationally this is at most O(b).

The second step is to do a Delaunay triangulation of the bus groups [24]. Computationally this can be O(m log m), and

given that m is usually relatively small, this step is usually very fast. As an example assume that for the seven-bus system from Figure 1 the buses are grouped into five zones (i.e., $n = 7$, $m = 5$ and $b = 12$), with buses 1 and 2 in Zone A, buses 3 and 4 in Zone B, bus 5 in Zone C, bus 6 in Zone D, and bus 7 in Zone E. Define the set of line segments (segments) added as the result of the Delaunay algorithm as S, and of course by definition the Delaunay layout will be planar. The results from applying the Delaunay algorithm are shown in Figure 5, and S contains seven segments. In the figure each zone is visualized using a GDV, so their locations were automatically determined based upon the coordinates for their buses. For convenience the GDVs are also showing the total generation and load in each zone.

The third step is to determine for each branch a segment path between its terminal bus groups, and then to add it to the list of branches maintained by each segment along the path. There are three different types of paths with the first two being trivial to determine. First, if the branch's terminals are in the same bus group then the path is empty and the branch is ignored. For the seven bus case the branch between buses one and two is an example since both are in Zone A. Second, if the branch's bus groups are directly connected then the path just contains a single segment and the branch is added to the list for that segment. The branch between buses one and three is an example of this, going between Zones A and B. Otherwise an algorithm is required to quickly compute a path between the two bus groups. Various algorithms exist for doing this, with [25] providing a good coverage of different approaches. The results presented here used the Greedy Routing of [25], which is guaranteed to find a path. A Figure 5 example of this is for the branch between buses four (Zone B) and six (Zone D), which has a segment path from Zone B to A to D.
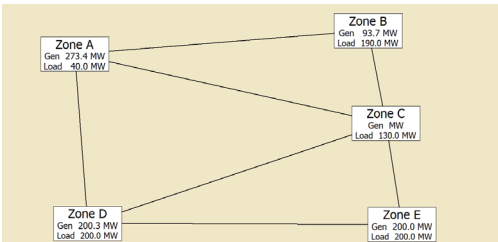
Figure 5: Seven Bus System Zones with Delaunay Triangulation
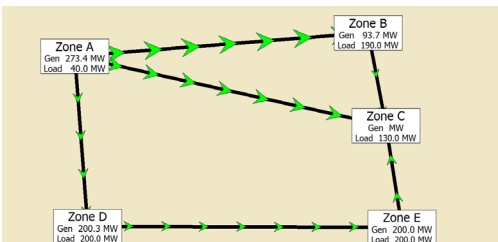
Figure 6: Seven Bus System Overall Transmission Flows Visualized

For electric grids, because branches are usually relatively short, the path sets are usually quite small. Overall the computational complexity of this step is $O(b)$. Commonly at the end of this step those segments without any associated branches are removed. In the example this occurs with the branch between Zones C and D.

The last step is to visualize the results. This is shown in Figure 6 for the seven bus system utilizing dynamically size flow arrows and segments thicknesses [11], [26]. If desired the actual flow numeric values could be shown, but in some cases the "details on demand" approach of [16], [17] would be preferred. In the approach implemented here the flow details are always available by right-clicking on the desired line segment to show the details. An example of this is shown in Figure 7 for the segment between Zones A and B. Overall the algorithm has taken twelve branches (all ac transmission lines here) and mapped them into six Delaunay segments. The number of branches in each segment ranges from one to four, and number of segments for each branch ranges from zero (for branches within a bus group) to two.

Figure 7: Seven Bus Details on Demand Dialog for Zone A to B Segment

IV. LARGER SCALE EXAMPLES AND APPLICATIONS

This section demonstrates the algorithm on the three larger systems from Figures 2 to 4. The first example applies the technique to the 37-bus system, here setting up the bus groups based on the system's 27 substations, with the individual substations containing between one and three buses. Figure 8 applies the algorithm from the previous section to visualize the overall MW flows. In the figure the substations are shown using GDVs in which their size is proportional to the absolute value of the net injection for the substation (total generation minus total load) and the GDVs color is magenta if the net injection is positive and yellow if negative.
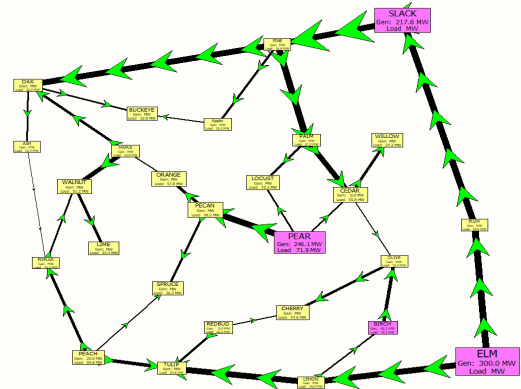

Figure 8: 37-Bus System Substation-Based Visualization

In the figure the segment flows are again shown using arrows and the thickness of each line thicknesses proportional to the overall MW flow. In comparing the original oneline

(Figure 2) it is clear that they are complimentary, with Figure 2 showing more details, but with Figure 8 meeting this paper's goal of providing an easy to understand visualization of the overall system flows. Here the flows on 57 branches have been mapped into 34 segments, with at most three branches in a segment. For the branches 14 are within the bus groups (primarily the transformers) and hence not mapped to a segment, 36 are in a single segment, six in two segments and one in three segments. While the reduction from the number of branches to segments is rather modest here, it is easier to see the overall power flows. This approach could be particularly helpful in comparing different operating conditions. The clearer layout also permits showing multiple flows types per segment and/or showing the numeric values. An example is shown in Figure 9, which extends the Figure 8 example to include blue reactive power flow arrows and labels on each segment to show the MW flow.
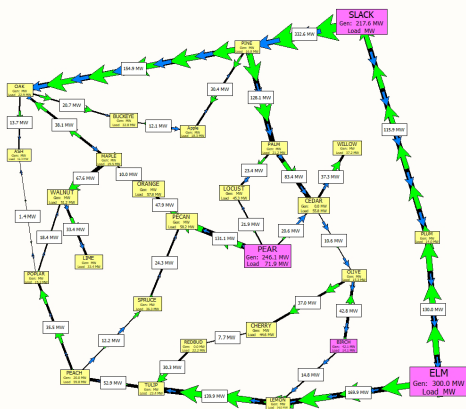
Figure 9: Extension of Figure 8 to include Reactive Power and MW Labels

The next example demonstrates the approach for the 500-bus, 208-substation system from Figure 3. If the goal is to show all the substations then the reduction in display complexity is rather modest, partially because Figure 3 already uses variable object sizing so the substation details only become apparent on zooming. An example is shown in Figure 10, in which 599 branches are mapped into 311 segments with a maximum of six branches in a segment, and a maximum of six segments per branch. Again substation GDVs are used to show the net power injections.
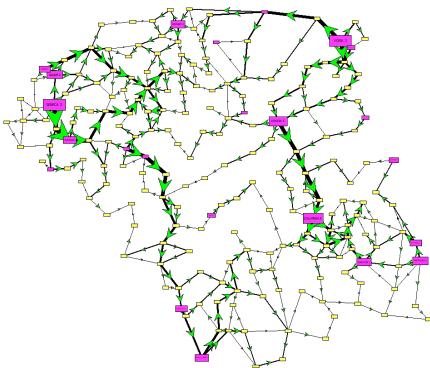
Figure 10: 500-Bus System Substation-Based Visualization

However, an advantage of the paper's algorithm is it can be used with any type of bus grouping. An example for the 500-bus system is shown in Figure 11 using the geographic grid approach of [6] in which the bus groups are defined using a geographic grid and then a GDV summary object is drawn based upon the objects within each grid element. The grid dimensions are arbitrary, with a six by six grid used here. The number of buses in each grid element ranged from zero to 18 with the eight GDV summary objects with no buses not shown. Hence in the figure there are 28 GDVs (i.e., $m = 28$), with each having three text fields showing its total generation, its total load, and its minimum bus voltage. To emphasis the minimum voltage the GDV's background color is also shaded using a red/blue color mapping with the key shown in the figure; also the size of each GDV is based on its overall net power injection. The paper's algorithm is then applied to these 28 groups, with the 599 branches now mapped into 49 segments with a maximum of ten branches in a segment, and each branch being in at most three segments. Now the overall power flow in the grid is readily apparent. If precise flow values are desired labels can be added to each segment (shown as the small white rectangles with the exact values not important for the example).
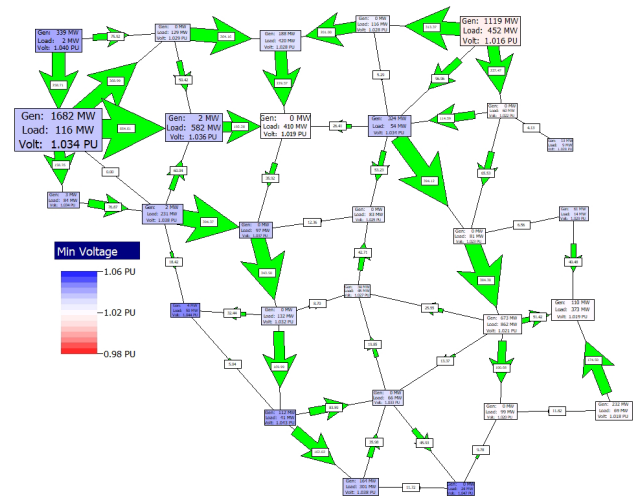

Figure 11: 500-Bus System Shown Using a 6 by 6 Geographic Grid

As a final example the remaining figures demonstrate the approach using the 82K-bus, 76 area grid from Figure 4, which contains 104,125 branches spanning the contiguous US. The number of buses in each area ranges from 91 to 3229. Because of the large number of buses and branches little information about the grid's actual operation is apparent from Figure 4. The next several figures show how this information can be shown using several different bus grouping approaches.

As a starting point Figure 12 shows the initial Delaunay triangulation using the system's 76 areas as the bus groups. The size of each area GDV is proportional to the area's generation and its color based on the amount of MW exports (with red for net exports, and blue imports). The figure also shows the initial 213 segments with the number of branches in each segment ranging from zero up to 161 (for illustrative

purposes the zero branch segments are included in the figure, but normally they would be removed). The number of segments per branch ranged from zero to two, with only 114 branches being in multiple segments. Computationally the algorithm took less than one second. Figure 13 shows the same system except with the zero branch segments removed and green arrows used to visualize the MW flows.
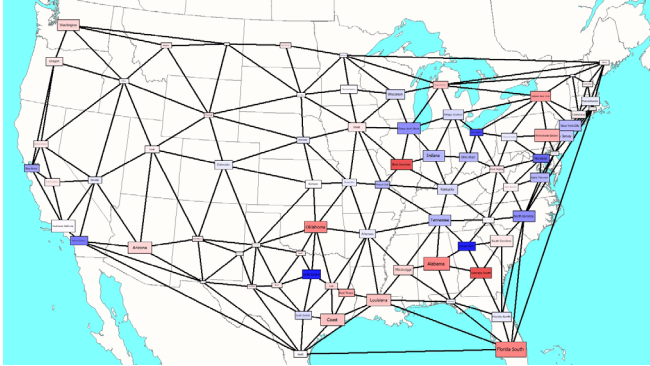

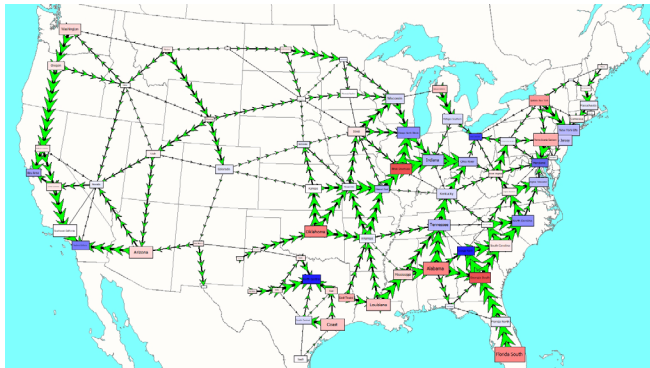Figure 12: Initial 82K System Area Delaunay Results

Figure 13: 82K System Area Full Visualization

It is important to contrast the approach presented here with the visualizations that were introduced more than 20 years ago for showing flows between areas (see for example [27]). The two approaches are complimentary. The earlier area to area visualizations showed the actual flow between the areas and hence could have intersecting segments. The focus of this paper's algorithm is to provide a planar graph visualization, so the flows shown in Figure 13 are not necessarily the flows between the two connected areas (though actually in this example they are quite similar since very few branches are in multiple segments).

The final three figures demonstrate the algorithm on different types of bus groups or with different flow values. Figure 14 shows the same system but now uses a 10 by 16 latitude and longitude grid to group the buses and define the bus groups. To aid in comparison the same arrow sizing is used as with Figure 13. Figure 15 again uses the areas as the bus groups, but rather than showing the MW flows it visualizes power transfer distribution factors (PTDFs). To further illustrate that this approach can be used for very wide area visualization, it shows the PTDFs for an unrealistic coast-

to-coast power transfer from Maine to Washington state. The magenta flows show the PTDFs with white labels added to show the percent on each segment.
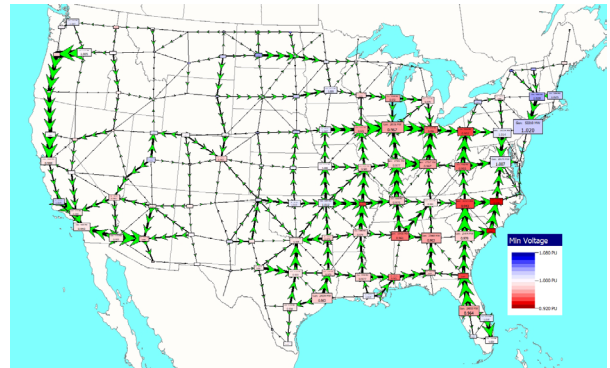

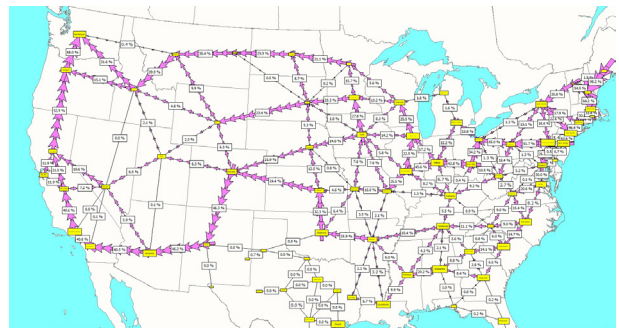Figure 14: 82K Bus System Flows Visualized with a 10 by 16 Grid

Figure 15: 82K System Area Visualization showing PTDFs

The last figure demonstrates how the approach can be used to visualize geomagnetically induced currents (GICs), which could be caused by a geomagnetic disturbance [28]. The integration of GICs into the power flow and their visualization is given in [29]. Because GICs can affect a wide area, they are an ideal candidate for this paper's visualization technique. The results are shown in Figure 16 in which the earlier 10 by 16 grid is used, with the GDVs how showing the net injections for GICs into the ground (with magenta net into the ground and yellow out of the ground) and the segments are used to show the flow. The results are shown for an assumed North-South electric field scaled by the geomagnetic latitude.
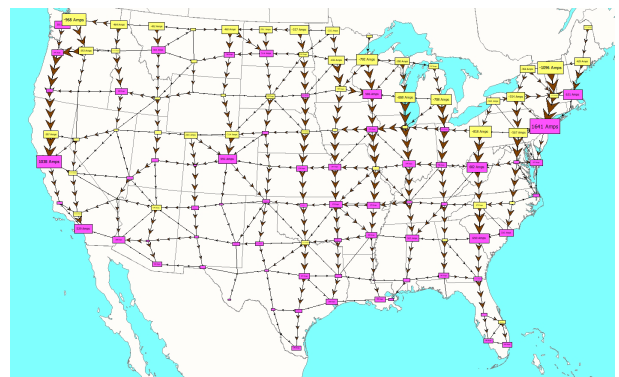

Figure 16: 82K Bus System Grid-Based Visualization of GICs

V. Summary And Future Directions

This paper has presented a Delaunay triangulation based technique for visualizing flows in high voltage electric grids. The algorithm assumes a set of n buses and b branches joining the buses where the branches can include ac transmission lines and transformers or dc lines, and that the n buses have been grouped into m bus groups with geographic information available for each bus group and that each has a unique location. The paper's algorthim then creates a Delaunay triangulation for the bus groups, and maps each of the branches into a group of the Delaunay segments. These aggregated branch flows for each segment are then visualized. The algorithm is introduced with a seven bus grid and then further demonstrated on grids with 37, 500 and 82,000 buses. Future directions include deciding the best ways for setting up the bus groups and design issues associated with what and how the electric grid information is visualized using the paper's algorithm.

VI. Ackowledgements

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