# Inclusion of Geographic Regions in Electric Grid Power Flow Analysis and Visualization

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*Abstract*—This paper presents some benefits that can be achieved by directly incorporating geographic regions into power flow analysis and visualization. While traditional power flow analysis has not included explicit geographic information, this has recently changed. This allows the potential direct integration of geographic data to allow better association of system conditions with specific grid geographic regions, allowing for better assessment of grid vulnerabilities and improved situational awareness. This paper presents an approach for modeling geographic regions, visualizing the results, and then demonstrates the results on synthetic electric grids of sizes up to 82,000 buses.

*Index Terms*— Power flow analysis, geographic regions, power system visualization, situational awareness

## I. Introduction

In many fields the term situational awareness (or situation awareness) (SA) is used. Its formal definition is "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" [1], while its informal definition is "knowing what's going on" [2]. While this term was not widely used in the electric power industry prior to 2003, it has since become much more popular due to the August 14th 2003 North American Blackout report listing inadequate SA as one of the primary causes [3]. Since then there has been widespread agreement that adequate situational awareness is essential for the reliable operation of power systems [4], [5], [6], and that SA is needed not just in the operation of the grid but also in the large number of engineering studies that are used to design (plan) the grid [7]. For power system operations achieving SA means being able to determine the current and future states of particular portions of the grid, monitor the state of neighboring portions of the grid to identify corrective and preventive measures to restore and maintain system reliability, and be aware of the timeframe within which these actions must be implemented [5]. For more off-line engineering planning studies it can be equally challenging to true "know what is going on" with the vast amount of models, assumptions and computation that might accompany such a study. The purpose of this paper to show how the direct inclusion of geographic regions (Regions) into power system analysis tools can help enhance SA.

Achieving SA in power systems becomes significantly more challenging as they grow larger, more complex, and increasingly interconnected, and as data from a growing number of measurement devices must be processed [8]. In operations during disturbances this task is further constrained by the limited timeframe before automated remedial actions and protection devices are triggered. This timeframe significantly reduces the time-window for informed, real-time decision-making and coordinated responses in the control room [9]. While the timeframe is longer in planning type engineering studies, given the large number that often must be done, time efficiency is still paramount. While SA has many aspects, certainly it is paramount that data be effectively summarized and presented in way that highlights key information and enables operators to promptly detect changes in the power system's state and interpret real-time measurement data [10].

This paper shows how geographic regions (Regions) can be used to help in power system analysis and visualization, improving SA. Regions are a simple data structure defined strictly by geographic boundaries—using latitude and longitude—and represented as one or more simple polygons (subgroups). Power system objects (e.g., buses, generators, transmission lines and transformers) are automatically included in regions based on their geographic location. Regions summarize and group power system information within their geographic boundaries, independent of power system topology. Although Regions are not display objects, they can have associated one-line display objects for visualization. To demonstrate their utility, two example cases are presented: a synthetic 37-bus grid of the Hawaiian island of Oahu and an 82,000-bus synthetic grid covering the contiguous United States.

The remainder of this paper is organized as follows: Section II provides some background on electric grid modeling and visualization. Then Section III introduces the application of Regions in electric grid modeling while Section IV demonstrates its application on two synthetic example cases and Section V conclude the paper. All the computational results presented here have been done using PowerWorld Simulator version 24 [11].

## II. Grid Modeling and Visualization Background, and Example Grids

Over the last several decades there have, of course, been many advances in electric grid modeling and visualization with [12] providing a nice summary of the state-of-the-art from 50 years ago, and then [13] providing the current situation. Interestingly, much of the core power flow models have remainder relatively constant over the last 50 years. This can be seen by comparing the data structures of [14] with those of [15]. There are certainly more parameters, but the essence is the same. Of particular interest to this paper's focus on data aggregation using Regions, the two main ways of aggregating power system information, areas and zones, have remained the same. For both of these data structures, each bus is assigned to a particular area and a particular zone, with areas and zones then providing a means to summarize the bus information such as total load, generation, and losses. Areas also have the ability to do automatic generation control (AGC). The benefits of having

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Regions, and how they differ from areas and zones is discussed in the next section.

One more recent change in electric grid modeling, crucial for Regions, is the movement towards including bus geographic information. Historically, power flow models have not included geographic data since it is not required to do power system analysis such have power flow, and when digital power flows were initially introduced in the late 1950's and 1960's computers had very limited memory. However, this has changed due to 1) much more available computer memory and processing capabilities, 2) the ubiquitous availability of geographic information, 3) the visualization techniques that can leverage geographic information, and 4) the need for geographic information in a growing list of power system applications including geomagnetic disturbance (GMD) studies [16] and the direct inclusion of weather information in the power flow [17] . Examples of North American Electric Reliability Corporation (NERC) entities requiring the submission of geographic information for at least some applications include [15] and [ 18]. Large-scale synthetic electric grids with geographic information are now also widely available [19], [20].

Another change relevant to the application of Regions is the development of many new advanced power flow visualization techniques have significantly improved power system operations and planning, and certainly overall SA. Some examples of these techniques developed over the years are given in [21], [22], [23], [24], [25], [26]. For example, there are now a wide variety of techniques for visualizing raw or processed power system information, including showing it on top of a geographic layout. There are also a portfolio of techniques for intelligently grouping power system information, including approaches that take advantage of the underlying grid physics, and many that are very interactive, crucial for improved SA. Color contouring is also commonly used to show the patterns in large amounts of power system information such as bus voltage magnitudes and locational marginal prices [27].

Some of these techniques are used to show the two example cases that will be used in the remainder of the paper. The first, shown in Figure 1, is a 37-bus synthetic grid located in the US state of Hawaii (island of Oahu) that has a 138 and 68 kV transmission grid (Hawaii37). Here green flow arrows and dynamically-sized pie charts are used. The second, shown in Figure 2, is an 82,000-bus (82K-bus) grid that is geographically located in US 48 contiguous states plus the District of Columbia and hence is known as the CONUS_82K grid. In the figure different colors are used to indicate the different nominal voltage levels (with green for 765 kV, orange for 500 kV, red for 345 kV, purple for 230 kV, black for lower voltage AC, and blue for HVDC). Data for all the grids presented in this paper is publicly available at the repository described in [20].

Before concluding this section it is also important to mention Geographic Data Views (GDVs) [28], [29] since they are used sometimes with the Regions in the next section. GDVs are dynamic visualizations that combine power system data with embedded geographic information to map system quantities (such as power flows, generator outputs, and bus voltages) to graphic symbols. GDVs thus enable flexible displays that can represent multiple quantities and can be set to reflect changes in system conditions by changing the attributes, and thereby appearance, of the symbols accordingly. Attributes of a GDV include shape, size, color, etc. Readability of GDV displays, especially when many are shown, can be improved using GDV summary objects, which aggregate data according to user-defined criteria or existing groupings, such as zones and areas. An example of area GDVs coupled with the real power flow visualization technique from [25] is shown for the CONUS_82K in Figure 3.

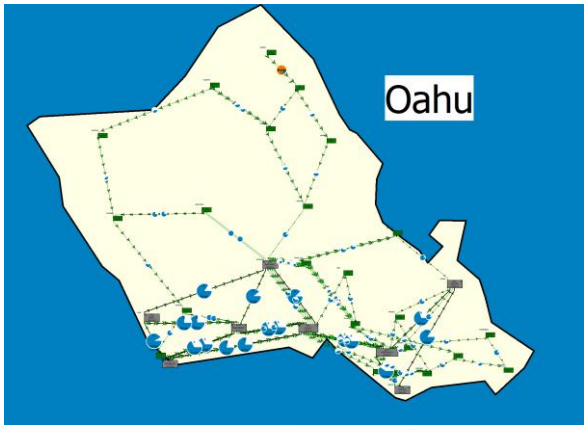


Figure 1: Hawaii 37-Bus Oneline

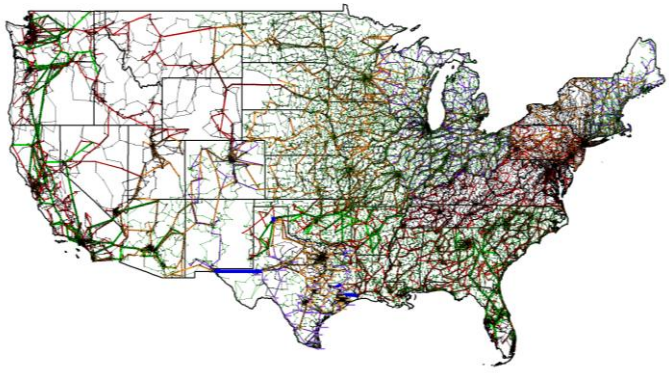

Figure 2: CONUS 82K-Bus Oneline

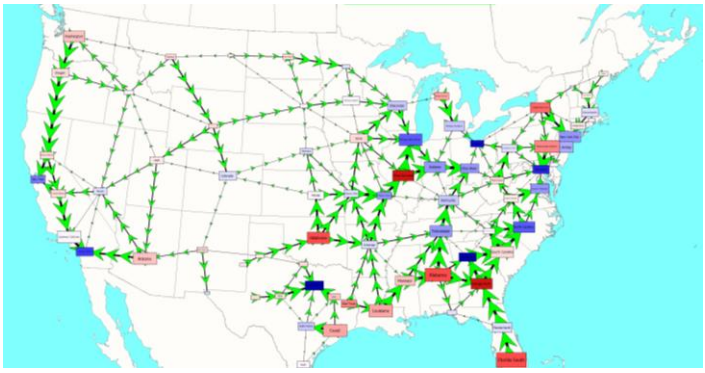

Figure 3: CONUS 82K-Bus Areas GDVs with Flow Visualization

## III. Geographic Regions

This section describes the key features of the Regions data structure and compares Regions to the area and zone data structures ubiquitously available in power system analysis tools. It also discusses how Regions can be used to create effective power system visualizations. A Region is a data structure defined by a set of simple polygons, each specified using geographic coordinates. A polygon is considered "simple" if it does not self-intersect and does not contain holes. Each simple polygon is regarded as a *subgroup*, and the Region's overall boundary is formed by the combined boundaries of all subgroups. This construct allows a Region to include disconnected areas, such as islands, and to represent highly detailed boundaries. As noted later the implementation of Regions presented here can be done in a computational tractable manner when used with Regions containing several million boundary points and with power systems with tens of thousands of buses.

Regions are strictly geographic constructs, and the inclusion of a power system bus in a Region depends solely on whether it lies within the Region's geographic boundaries. Regions are therefore only meaningful in the now common situation in which a power system includes geographic data providing geographic coordinates for its key components. Once a Region is defined, power system components are automatically associated with it based on their geographic coordinates. This makes a Region independent of power system topology and allows it to be used seamlessly across different cases. A Region groups and summarizes information about all power system components located within its boundaries, providing an intuitive and spatially meaningful way to analyze and visualize system data.

In the implementation presented here a Region contains buses, and from this set of buses essentially all other power system information can be aggregated, and if desired displayed. Thus a Region can provide comprehensive summary information that includes generation AGC values (such as maximum generation increase and decrease), reactive reserves, and geomagnetically induced currents (GIC) data. It also reports detailed generation mix information, broken down by fuel type, as well as aggregate metrics for load, generation, and shunt elements. Additionally, geographic characteristics such as boundary point count, subgroup count, and center latitude and longitude are included. Regions also list detailed data for each associated power system component, including buses, loads, substations, tie lines, and switched shunts, and support user-defined custom fields.

Regions are in some ways similar to the areas and zones mentioned earlier, and in someways they are different. Areas, zones, and regions all provide a means to group power system components and summarize information such as total load, generation, and losses. For differences each bus (and by extension generators, loads, switched shunts, and branches) can belong to at most one area and one zone, but can be part of multiple regions based on the bus's geographic location. Areas and zones are explicitly assigned components and are power system–specific structures that do not require geographic coordinates. In contrast, inclusion of a component in a region is automatic and determined solely by geographic boundary. This makes regions applicable to different cases that share overlapping geography. Additionally, areas and zones support operational functions such as automatic generation control (AGC) and interchange scheduling, whereas regions are intended mainly for data aggregation.

To complement Regions, there is also a need to visualize the results, here defined as Region Display Objects (RDOs). The RDOs allow users to overlay geographic boundaries directly onto one-line diagrams and can be fully customized with distinct fill colors, border styles, and stacking orders. Additionally, regions can be colored dynamically based on user-defined criteria—such as total generation, predominant fuel type, or renewable penetration—to differentiate them and improve interpretability. Regions can also be labeled to provide further geographic context and annotations. As noted in the next section, this can provide important SA enhancement benefits.

## IV. Regions Used with Example Cases

This section shows how Regions can be used with the two example cases. The Hawaii case illustrates how Regions can be defined using both hand-drawn boundaries and detailed GIS data. It also highlights the different visualization options available for representing regional power system data. The CONUS_82K case discusses some applications of Regions on a much larger synthetic grid.

The first example case is the Hawaii37 synthetic grid that covers the geographic footprint of the Hawaiian Island of Oahu. It is defined with a single area and a single zone. As a simple application of Regions, Figure 4 shows the oneline diagram of this network, as well as with three hand-drawn Regions that are labeled North, West, and East. These Regions are defined by a total of 14 geographic points, each with a latitude and longitude.

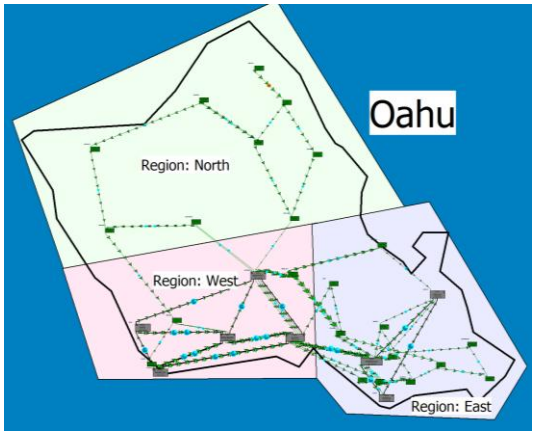


Figure 4: Hawaii37 Grid with Three Hand-Drawn Regions

Hand-drawing is the most basic method for defining a Region and is particularly useful when detailed boundary data is unavailable or when approximate delineations are sufficient for analysis and visualization. Since here the Regions don't overlap, and cover the entire footprint, they can be thought of as be quite similar to areas or zones. The key differences are 1) the buses are not assigned to a Region but rather are in a Region based on their geographic location, and 2) buses can be in multiple regions. Figure 5 shows an example of how a dialog can be used to summarize Region information; this is very similar to what could be shown for an area or a zone. As is the case with areas and zones, in the implementation used here the Region display is

interactive, so detailed information can be obtained for a Region just by using the mouse to click on it.

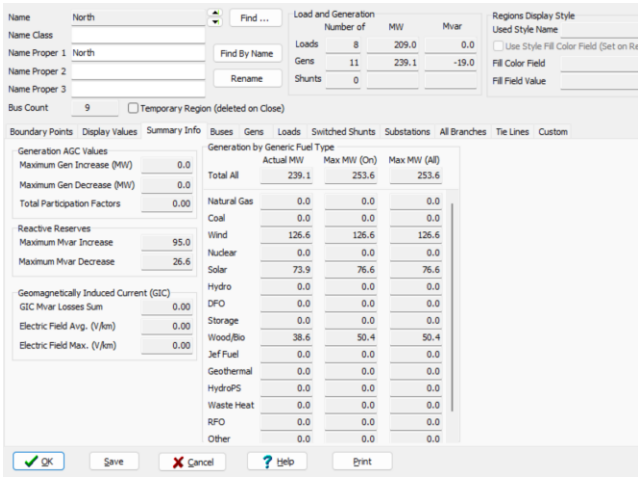

Figure 5: Region Summary Dialog for the Hawaii37 Grid North Region

An advantage of the Region data structure is since they can be simply defined (e.g. hand-draw), a Region can be created "on-the-fly" during a power system study, allowing an engineer to quickly gain insight into a particular portion of the grid. An example of how such a Region could be defined is shown in Figure 6 and then a view of the associated Summary Dialog is shown in Figure 7.

Figure 6: Temporary Region Being Defined in the Central Portion of the Hawaii37 Grid

Since Regions are just defined geographically, and hence are power system independent, much more detailed Regions can also be created by leveraging the vast amount of geographic information system (GIS) data that is available in the extremely popular shapefile format. For example, the US Census Bureau has a large amount of data available at [30]. An example of this is shown in Figure 8 using data provided in shapefile format. As shown in the figure, the Regions align with the boundaries of nine administrative districts on the island of Oahu and are distinguished by their unique boundaries and colors. This form of representation allows for an electric grid to be summarized using many different groupings.

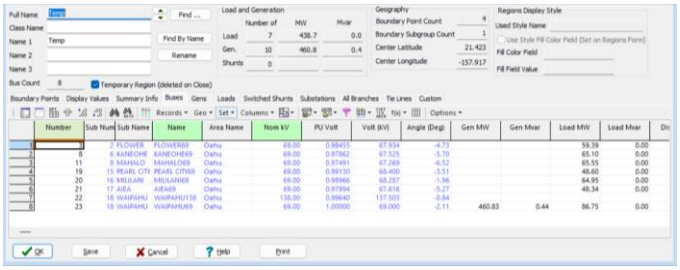

Figure 7: Summary Dialog (Buses Page) for the Figure 6 "Temp" Region Summary Dialog for the Hawaii37 Grid North Region

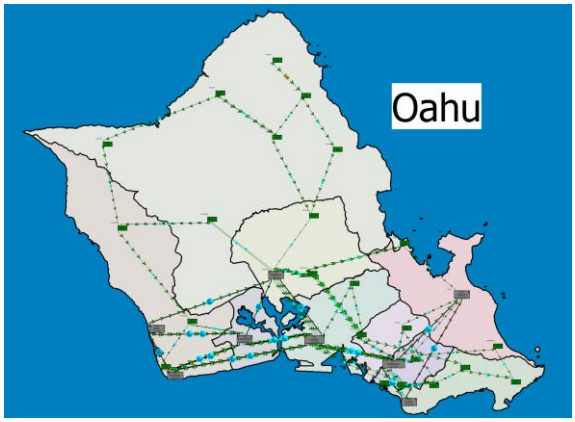


Figure 8: Hawaii37 Grid with Nine Regions Defined Using Oahu Districts

Because Regions can be defined as a set of subgroups, non-contiguous areas or disconnected sub-islands can be included within a single region. This capability is particularly valuable for accurately modeling power systems spread across fragmented territories, such as islands or separated service areas, as illustrated by the scattered sub-islands to the right of the main island in this case. In the Figure 8 example the nine Regions are defined to match each district; five of these are defined by a single subgroup, while the remaining four used 2, 8, 9, and 10 subgroups. A total of 22,741 geography point counts are used to achieve this level of detail.

The analytical utility and SA benefits of Regions can be further enhanced by making Region attributes, such as their background color, based on a user-defined metric rather than simply by geographic boundary. Figure 9 illustrates this capability by applying a customized display style that uses a geographic data view to represent total generation levels within each district. In this example, a continuous color gradient from pink (indicating low generation) to dark blue (indicating high generation) is used to visually differentiate regions according to their generation capacity. This type of data-driven visualization transforms static geographic boundaries into informative, dynamic displays that can be customized to reveal underlying system conditions.

The second example, CONUS_82K, applies Regions to a much larger electric grid. However, the same concepts from the smaller grid apply. However, now the grid's geographic footprint is much larger, meaning the need to utilize many more Regions is likely. For example, using the previously mentioned US Census Bureau shapefile data Regions are defined for each of the 48 CONUS states and the District of Columbia, and for each of the CONUS counties (known as parishes in the US state

of Louisiana) for a total of 3157 Regions, 1,055,591 geographic boundary points and 4795 total subgroups. Then, as before, Region attributes can be used to dynamically color the display, that, as before, is interactive so additional information can be obtained by clicking on a region.

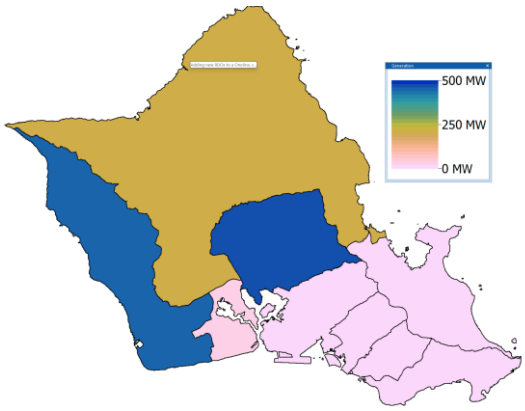


Figure 9: Hawaii37 Grid with Regions Colored Using Total Region Generation

An example of this is shown in Figure 10 in which the display attribute is based on the total power flow calculated wind power in each county. Shades of pink indicate lower levels of wind generation, while dark blue represents capacities of about 2,000 MW. Seemingly at a glance the Regions reveal a concentration of wind generation across the central U.S. (the Great Plains including Texas) and Midwest. The West Coast and parts of the Northeast also have significant wind capacity installed. In contrast, the Southeast and Gulf Coast have little to no wind generation.

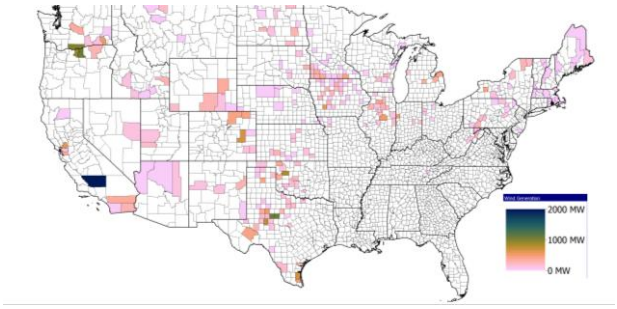


Figure 10: CONUS_82K Grid with Regions Colored by Wind Generation

In this context, Regions offers more than simply visualizing the geographic distribution of wind generation, which has been documented in prior analyses. Rather, their main advantage lies in aggregating power system data within geographic boundaries of interest and providing comprehensive summaries within power system analysis applications such as power flow that incorporate every wind farm in the electric grid. This allows people to analyze the distribution of wind generation from an operational and planning perspective rather than solely in terms of installed capacity. For example, Regions can be used to identify and group components in a network associated with a wind farm to support the analysis and monitoring of transmission constraints that may necessitate curtailment during periods of high generation output. Insight gained from the regions feature can thereby support planning efforts to integrate higher penetration levels of renewable generation as well as maintain reliability in operation.

Another geographic representation of the CONUS network is shown in Figure 11. Here the Regions are color-shaded based on their dominant generation fuel type in a particular power flow solution. As with the distribution of wind generation, the use of regions extends beyond merely providing an overview of the geographic distribution of generation resources within a network operator's area of responsibility. Summaries of power system components by Region can be used to analyze how generation fuel type influences the characteristics, dynamics, and reliability of the local network. Keep in mind the visualized data is associated with a particular power flow solution, and more detailed information (i.e., as in Figure 5) can be easily obtained, with good SA benefits.

This visualization can be further enhanced using the previously mentioned GDVs. Figure 12 demonstrates how GDVs can be used to display information summarized by the Regions. In this example, total county-level generation in the Pacific Northwest is shown using dynamically sized GDVs (e.g., the numbers shown in each Region, which while small in the figure are easily readable on a computer monitor). Figure 11 and Figure 12 underscore the importance of carefully designing visualizations to be clear and easily interpreted. If every county had been individually colored or less distinct color schemes had been used, the map would have been much harder to read, especially in real-time operational contexts.

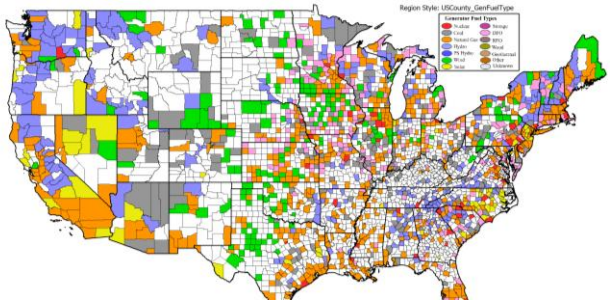

Figure 11: CONUS grid regions colored by generation fuel type

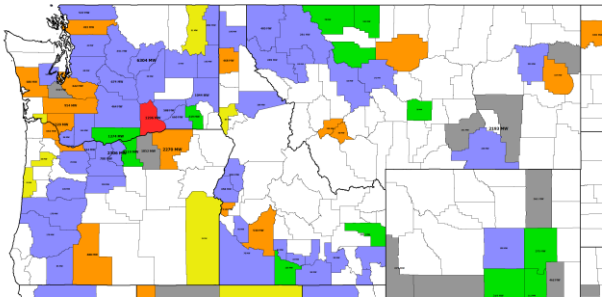

Figure 12: Pacific Northwest regions colored by generation fuel type and labeled by GDVs showing total generation

A final issue to consider is the computation required to keep the Region data structures up to date. Since Regions are power system independent, the buses in each Region needs to be recomputed anytime there is a change in either 1) the buses, 2) the geographic location of the buses, or 3) the Region boundaries. Checking if a point (i.e., a bus) is within a simple polygon (i.e., a Region subgroup) requires considering each

subgroup boundary segment and each bus. So in the worst case the required computation is the product of the two. For example, with the CONUS_82K grid with 82,000 buses and the US country example with about 1 million boundary points, this would require on the order of 82 billion comparisons. However, by take advantage of the well known speed-up of pre-screening the Regions by their bounding rectangle, this computation can be reduced significantly since the vast majority of buses are not the bounding rectangle for a Region. So with this example on a fast PC the buses in the Regions can be completely updated in about four seconds. Also, this computation only needs to be done if one of the previous three changes has occurred, usually a more rare situation.

## V. Conclusion

Situational awareness in power systems can only be achieved if engineers and operators are able to access and interpret relevant information in a timely manner. This requires continuous collection, analysis, and summary of large amounts of data to keep operators informed of the grid's condition at all times. As power systems continue to expand in scale and complexity, and as more measurement devices are deployed, this task becomes increasingly challenging. To address this, the Regions data structure is presented in this paper. Regions are designed to complement existing analytical and visualization tools by summarizing power system data within user-defined geographic boundaries. Once a region's boundaries are defined by geographic coordinates, all power system components located within that geography are automatically associated with it. This creates a spatial-based grouping of power system components that can be used for further analysis. Overall, Regions facilitate an approach to understanding and managing power systems from a geographic perspective. The paper demonstrates the application of Regions on two example grids, one with 42 buses and one with 82,000 buses.

## VI. Ackowledgements

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