Electric Power Control Center Visualization using Geographic Data Views

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Abstract

This paper introduces a new technique for power system visualization known as geographic data views, or GDVs. The impetus behind the development of GDVs was to use dynamically created visualization in order to show a wider range of power system information than is possible using the existing geographically based wide-area visualizations that are becoming common in electric power control centers. With the GDV approach power system visualizations can be dynamically created by operators or engineers using power system information along with geographic information imbedded in the power system model. This paper demonstrates the approach for several sample data sets.

Introduction

Over the last decade or so there have been significant advances in the area of power system visualization. For example, prior to the year 2000 in practically all power system control centers operational quantities, such as power flows and voltages were represented either as analog fields on substation one-line displays or as numeric fields on tabular displays. Dynamic display of system information was quite limited, such as the use of dashed lines to represent device status and font color for limit violations. An overview of the system had only been available on a static map board with the only dynamic data shown using different colored lights.

However since 2000 many power system control centers have adopted more advanced visualization techniques particularly for wide-area displays. For example, now the use of color contours to show voltage magnitude variation across large regions is common. Animated arrows may be used to show line flow direction, while dynamically sized pie charts are used to indicate transmission lines and transformers that are close to or are exceeding their limits, or are out-of-service. A more detailed discussion of these techniques are provided in [1] and [2]. Figure 1 shows an example of these techniques being used in the TVA

Regional Operations Center, where the large overview display in the background is a geographically-based visualization that includes these techniques.

Figure 1: TVA Regional Operations Center (ROC), 2006

The Need for Geographic Data Views

Typically such wide-area displays are based upon a predefined graphical one-line format. The use of these techniques on predefined displays can be particularly effective for power system monitoring. Being geographically-based they can rapidly provide system operators and engineers with an overview of current system conditions, letting them quickly focus on problem areas. Since the displays are predefined, they also have the advantage of providing a consistent and known view of the system. Panning and zooming can be used to provide more detail as needed.

However, when the task switches from monitoring to corrective control or analysis, one potential short-coming of this approach is that it can be quite difficult to design a priori a single display, or even a set of displays, that contains all the information needed to make effective, corrective control decisions. For example, consider the common application of generation re-dispatch to remove a line overload, either for an actual violation or for a contingent violation. The two most important pieces of information for deciding which generators to change are 1) their control sensitivity with respect to the overloaded line, and 2) their effective real power (MW) control

range. While one could design a display to show this information (indeed Figure 10 of [2] shows the use of control sensitivity contours), it would be difficult to construct beforehand since it would require the simultaneous display of sensitivity information that is device dependent, along with generator MW control ranges. Also, showing this information on an existing display designed for system monitoring could result in slow display performance and a more cluttered appearance.

The need to extend the power system visualization methodology is also apparent in engineering applications. An example of such a need occurred in the development of test cases for the research project that funded the development of tools described in this paper. The starting point for the development of these cases was a 43,000 bus MMWG power flow case of the entire Eastern Interconnect along with a one-line diagram showing the 161 kV and higher voltage transmission system (shown in Figure). Overall the one-line contained more than 7100 buses and about 9500 transmission lines and transformers. Such a one-line could have been quite useful if one were simply interested in seeing which lines were overloaded, or with producing voltage contours.

Figure 2: Eastern Interconnect One-Line Diagram

However, the design goal for the development of the test cases was to create a much smaller equivalent case, centered on TVA, with a strong north to south power flow pattern. Therefore it was necessary to both determine which nearby areas should be retained and which more distant ones should be deleted, and to visualize the importing and exporting areas in order to create the desired power flow pattern. For this task the one-line was much less useful.

The insightful moment in the development of the concept that became known as geographic data views was the recognition that while the Figure 2 one-line did not show

the desired information, the one-line, along with the underlying power system model, did contain the necessary information. The trick was to provide a way of dynamically extracting it, a technique known as geographic data views (GDVs).

Overview of Geographic Data Views

The idea behind GDV displays is to dynamically create power system visualizations by combining information derived from a power system model with geographic information that is embedded within the power system model. The resultant visualizations usually contain graphical symbols to represent power system quantities, with the location of the graphical symbols determined from the embedded geographic information. Typically one or more symbol attributes are dependent upon the values for the underlying power system data. Example attributes include size, color, rotation, and shape.

The key to an effective GDV implementation is to allow these dynamic displays to be easily customized to display the desired power system quantities. For wide-area visualizations the most important geographic information will be the bus locations, or at least the locations of the substations containing the buses. Once the location of the buses (or their substations) are known, the location of some other objects, such as operating areas can be estimated. Transmission lines could be dynamically drawn either by embedding the actual coordinates for the lines with the model, or by approximately their paths just from the location of their terminal buses. Depending upon the application, geographic display information about the location of devices modeled within a substation, such as generators, switched shunts, and loads, could either be stored explicitly, or just default to their bus's location. Simple overlap avoidance algorithms could be used to avoid overlapping display symbols.

To illustrate the GDV approach, again consider the Figure 2 case in which the initial design goal was the creation of a smaller equivalent system, centered on TVA. This was to be accomplished by retaining all the buses in some electrical areas, and equivalencing all the buses in others. Overall the model had 144 areas, some with well known names like NYISO that easily denoted their geographic location, but also with many that were quite cryptic such as SETH, a name that was not geographically helpful (at least to the authors). Some contained large amounts of generation and load, while for others the amounts were quite small. The power system model contained information about the operating areas themselves, such as their names and what buses they contained. From the list of buses an area's electric characteristics, such as total

generation, load and interchange could be easily determined.

In order to create the GDVs the power system model was augmented to assign every bus to a substation, and then to provide each substation with a geographic location. While this step obviously takes a significant amount of work, it is a step that only needs to be done once in its entirety since substations do not move. Furthermore, if a detailed one-line diagram is available, substation geographic coordinates can be automatically determined from the one-line. With all the data in place, a GDV can be created "on-the-fly."

Figure 3 shows a GDV in which cyan colored rectangles are used to show the location of the various operating areas from the Figure 2 case, with the size of each rectangle proportional to the area's total generation. Black text is centered on each symbol is used to show the area's name. For this example the geographic location of each rectangle was determined by a simple averaging of the locations for the area's buses. To provide a geographic context, the rectangles are shown superimposed upon a map of the US state boundaries.

Figure 3: GDV of Eastern Interconnect Operating Areas with Size Proportional to Area Generation

However, the point of emphasis about GDVs is that they can literally be created from scratch within seconds. This allows for quick visual display of almost any power system data. Also, by combining different graphical element attributes, multi-attribute visualizations are possible. For example, Figure 4 extends the Figure 3 GDV by making the rectangle color dependent upon the area's interchange, with blue shades corresponding to exporting areas, and red importing areas.

Before moving on to the details on a GDV implementation, the issue of which geographic coordinates showed be implemented within the power system model needs to be considered. Traditional utility

control center map boards and other wide-area displays have usually been constructed using pseudo-geographical coordinates at best. That is, while the displays have some relationship to the actual geographic location of the modeled devices, the need to show the one-line in a readable format tends to be the dominate design factor. A pure geographic representation, as might be done in a geographic information system (GIS), is seldom practical since locations of great interest electrically (e.g., substations) usually have a very small geographic footprint. Also, transmission lines sharing a common tower would be indistinguishable in a true GIS representation. Finally, some one-line elements, such as aggregate loads, are often spread over a large geographic area. Therefore it is expected that most GDV models would use such a pseudo-geographic approach.

Figure 4: Figure 3 Display with Rectangle Color Based on Area Interchange (Exports are Blue, Imports are Red)

However, there may be times when having a visualization that contains the exact geographic location of the power system elements could be useful. For example, one might wish to superimpose power system information with weather radar images, lightning strike data, or show the exact location of a transmission line fault. Or perhaps a substation level GDV could be used to show the exact equipment locations. Therefore it might prove useful to design GDV models so buses, lines and other elements (e.g., breakers), are modeled using two coordinates systems. One coordinate system would contain the pseudo-geographic location for the device, with the design goal being display clarity, while the second coordinate system would contain its exact latitude and longitude. Which coordinate system to use would then just become another option when the display is created. Morphed displays could also be created in which the coordinates change gradually from one system to another as a display parameter, such as the zoom level, is modified. All of the GDVs shown in this report were created using a pseudo-geographic approach.

GDV Implementation

To better illustrate the GDV approach this section describes an initial implementation of the concept. Of course, a wide variety of different implementations are possible, and the implementation shown here is certainly still a work in progress. But key design goals would be to make it easy to select the information to visualize, and to make it easy to customize the GDVs. For the GDVs shown here the approach was to have the objects and initial field to be displayed selected from tabular "case information displays." An example of such a display is shown in Figure 5[1], in this case with the display showing all of the electrical substations within Entergy, Southern and TVA, with the list sorted by generator real power output. Key functionality of these case information displays is their ability to allow filters to limit the objects displayed, and allow easy sorting.

Figure 5: Substation Case Information Display Showing Entergy, Southern and TVA Generation Substations

To create a GDV of a particular set of objects one would select the desired objects within the column corresponding to the initial field to show. As an example, the 163 substations with on-line generation were selected, with the initial field to display set to generator MW. Right-clicking on the selection, and selecting the appropriate option from a local menu results in the display of the GDV Customization Dialog, shown in Figure 6.

The GDV Customization Dialog has two main pages, corresponding to its two main tasks. The first task is to specify the background for the new GDV. Currently several options for US state borders and Canadian provincial borders are implemented, along with the more

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[1] The information shown in this figure, along with that shown in several other figures in this paper has been deliberately blurred at the request of the data providers. Since the purpose of these figures is to show how information is presented, not the actual values, the authors do not believe this blurring unnecessarily distracting.

common option of using a specified template file which could include any desired predefined background.
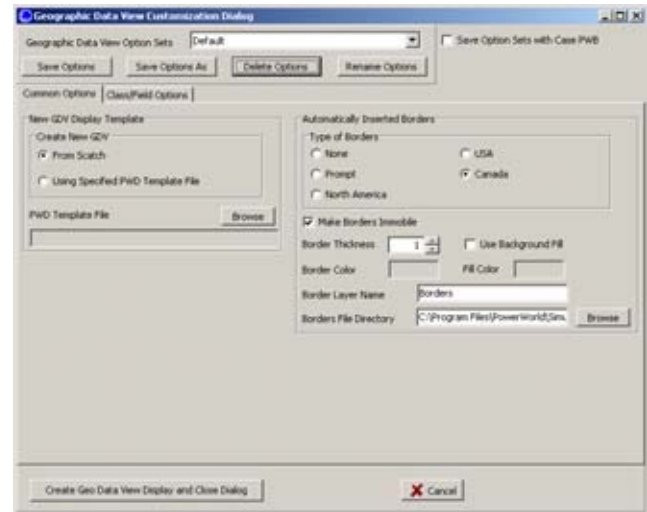

Figure 6: Geographic Data View Customization Dialog, Common Options Page

The second page, the Class/Field Options, is used to specify how the object field data is displayed on the GDV. The page itself contains a number of subpages, with the General Display Options page shown in Figure 7. This page has a number of general options such as what symbol to use (rectangle, triangle, oval, etc), its default border color, border thickness, fill color, and whether identifier information should be shown on the symbol (e.g., its name and/or number). This page also provides an option to automatically determine a default size for the objects on the new GDV display. This can be quite useful since it can be quite difficult to determine a priori what size to make the objects to create a useful display. A display created using the default values, except that the border and fill colors have been changed, for the 163 substation example is shown in Figure 8.

By itself Figure 8 does little more than show the geographic locations of the generation substations. While useful, especially since each display object is automatically linked to the underlying substation object allowing easy display of additional substation information, the real value of the GDV approach is in its ability to customize the visualization based upon the field values. In the implementation presented here this can be done either when the GDV is initially created or after the GDV has been created. For both approaches the object appearance can be dynamically updated by using the First Field Formatting and Second Field Formatting pages from Figure 8. Examples of these pages are shown in Figures 9 and 11.
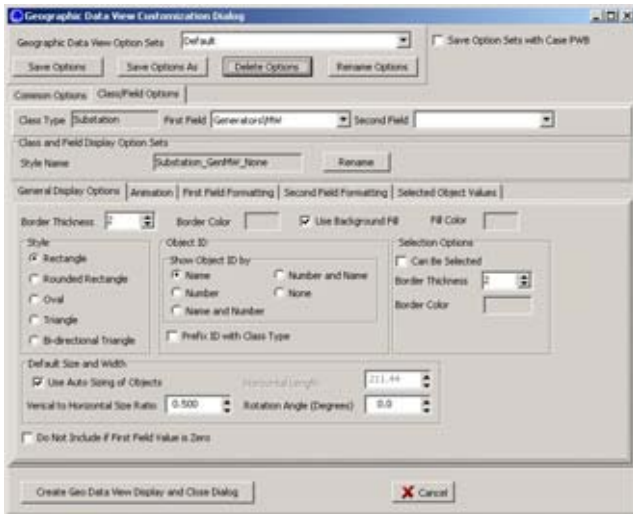
Figure 7: Geographic Data View Customization Dialog, Class/Field Options Page
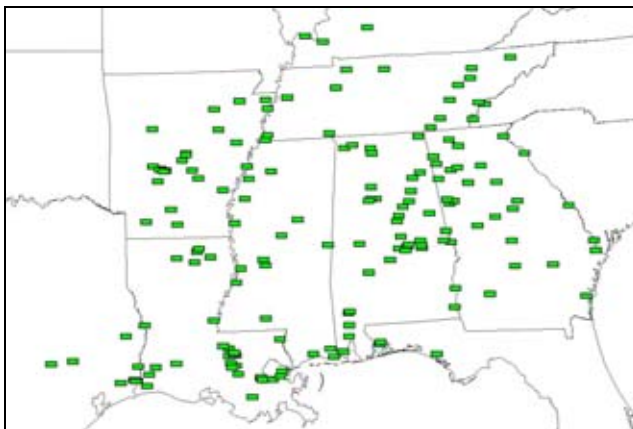

Figure 8: A Default Geographic Data View Showing the 163 Generation Substations

The main idea for both of these formatting pages is to change the appearance of the screen object based upon the value of one of the object's fields. The field itself is selected at the top of the dialog, with the generator real power output set as the first parameter in the Figure 9 example. Once the field has been selected, various attributes can be customized based upon the field value. While a variety of different attributes are possible, only four are currently available: Fill Color, Total Area, Border Color, and Rate of Rotation. Once the attribute has been selected, the right side of the page is used to map the field's values to a characteristic value for the attribute. For Total Area and Rate of Rotation this is accomplished using a piece-wise linear mapping from the field value to a real number. In the Figure 9 example the total area (size) of the display symbol is set to be proportional to the total substation generation, with the mapping going from 81 square display units if the generation is at or below 6 MW to 40080 square display

units if the generation is at or above 3456 MW. Again intelligent default values are used to simplify this process. The results of this modification are shown in Figure 10. Now the locations and relative amounts of generation are available at a glance.

Additional insight is possible by simultaneously associating other attributes with other field values. The current implementation only allows the dynamic display of two independent attributes. Certainly higher numbers of independent attributes could be possible, however one would need to avoid using too many to maintain display clarity.
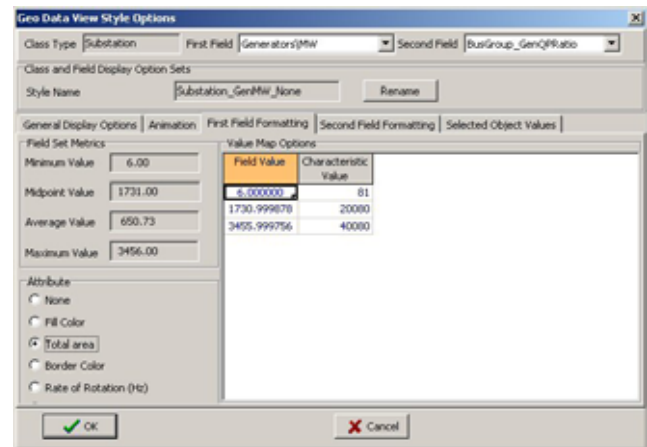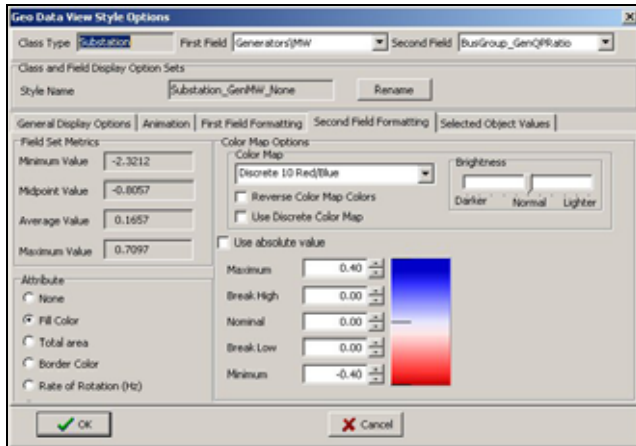

Figure 9: Geographic Data View Customization Dialog, First Field Formatting Page

Figure 10: Figure 8 Visualization with Size Proportional to Substation Generation

Figure 11 shows an example in which fill color is being mapping to the ratio of the generators' reactive power output to real power output (i.e., the Q/P ratio). For the color-based attributes (fill color or border color) the right side of the page is used to select a color mapping between the field values (with a Q/P ratio range of between -0.4 and 0.4 for this example) and a color. The color mapping

was chosen so generators producing reactive power are shown with a blue shade, while those absorbing reactive power are shown with a red shade. The result of the simultaneous visualization of total substation generation and generator Q/P ratio is shown in Figure 12. Of course many other substation fields could be visualized as well, with the current implementation allowing about one hundred. Figure 13 shows just one additional possibility, in which the color mapping is changed from showing the Q/P ratio to showing the generator reactive power reserves.

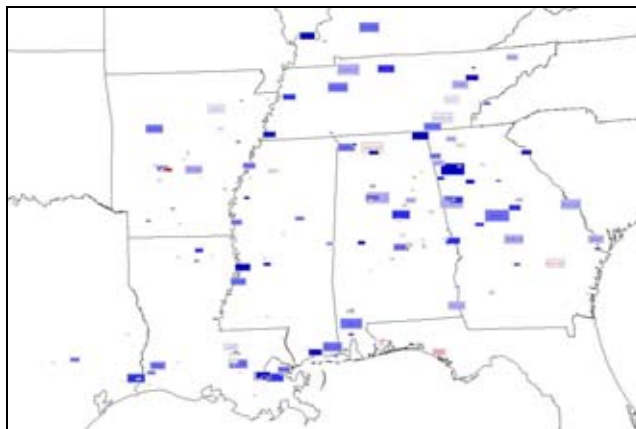Figure 11: Geographic Data View Customization Dialog, Second Field Formatting Page

Figure 12: Figure 10Visualization with Fill Color Proportional to Generator Q/P Ratio

While the GDV have been designed to be quickly created and customized, it is certainly not outside the realm of reason to expect that certain GDVs would be reused. Therefore two options for quickly recreating these displays are available. First, the GDV itself can be saved just like the predefined visualizations mentioned in the beginning of the chapter. This allows the GDV to be easily used to monitor the system state, albeit showing the same objects as when it was first created. Second, the

customizations used to create the GDV can be saved. This allows very quick creation of new GDV but possibly with different fields. For example, the Figure 13 display could be recreated showing the generation for a different subset of substations.
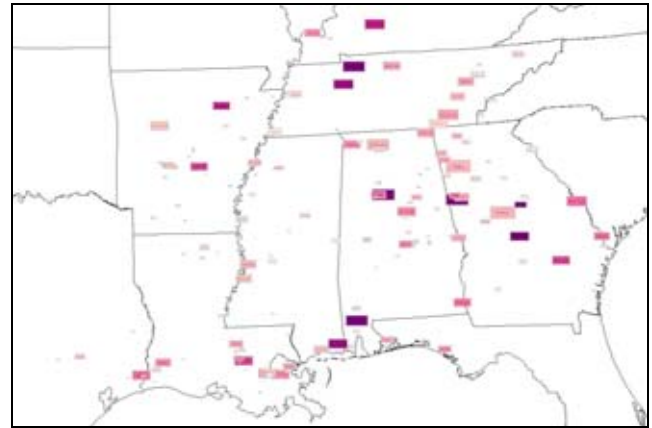

Figure 13: Figure 10 Visualization with Fill Color Proportional to Reactive Reserves

Application of GDVs to the Line Overload Problem

This section considers a specific example of how GDVs can be applied in an embedded context to help with corrective control. As was mentioned earlier, a common operator task is the redispatch of generation to remove a line overload, usually under contingent conditions. This task requires a knowledge both of what generators are available to participate in the redispatch, and the impact each generation change would have on the flow of the overload line (i.e., the line flow sensitivities). The design criteria for this application was to provide the operator with options on how a particular line overload could be corrected, while minimizing the amount of numerical calculations they needed to manually perform. Hence the goal was to have the computer do much of the underlying math, assisting but not replacing, the operator in the decision-making process. This section describes how this can be accomplished using the Line Overload Correction Form (LOCF).

To begin the development of the LOCF it is helpful to first focus on the two types of information needed, the available generators, and their line flow sensitivities. Information about the generators available to participate in the redispatch, or specifically the available correction range for each generator, is independent of which line(s) is violated. From a visualization perspective this is a relatively straightforward problem since there is only one set of information that needs to be shown, and that information is usually readily available. This information

could be shown either in a tabular list format or more graphically. Figure 14 shows an example of the latter in which the information is visualized using a GDV with objects to represent the generation available for re-dispatch, either up or down, within the TVA footprint (aggregated at the substation level). This is done using vertically symmetric quadrilaterals, denoted here as "kites," that merge two isosceles triangles, an upward pointing one whose area is proportional to the amount by which the generation can be increased, and a downward pointing triangle whose area is proportional to the amount by which the generation can be decreased.

Figure 14: Available Generation Shown with Kites

However, in contrast to available generation range, the line flow sensitivities depend upon which line is violated. Therefore they need to be calculated with knowledge of the specific line whose flow should be corrected. In the current LOCF implementation this information is obtained when the LOCF is initialized by requiring the operator to "click" on either a transmission line or transformer on a one-line diagram, or on its associated pie chart.

The LOCF was designed to allow the option to show the information needed to assist with the correction of line overloads in either a textual format or graphically using an embedded GDV. An example of the textual format option is shown in Figure 15, while the GDV approach is shown in Figure 16. The LOCF itself has three main sections. The first section, which is in the upper left, contains identifier information for the overloaded device.

The second section, which comprises the bottom 75% of the form, contains the generator sensitivity information that has been designed to help the operators make the decision about which generators to change to correct the line overload. This section of the form contains three tabbed pages that present the generator to line flow sensitivity in three different ways. The first two pages present the sensitivity information in the text-based

format (Figure 15) with data provided for individual generators on the first page, and for generators aggregated by substation on the second page. The third page presents the generator information using a GDV aggregated by substation (Figure 16).
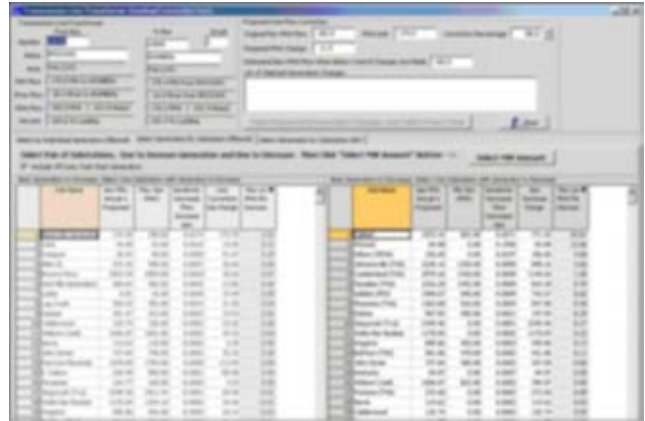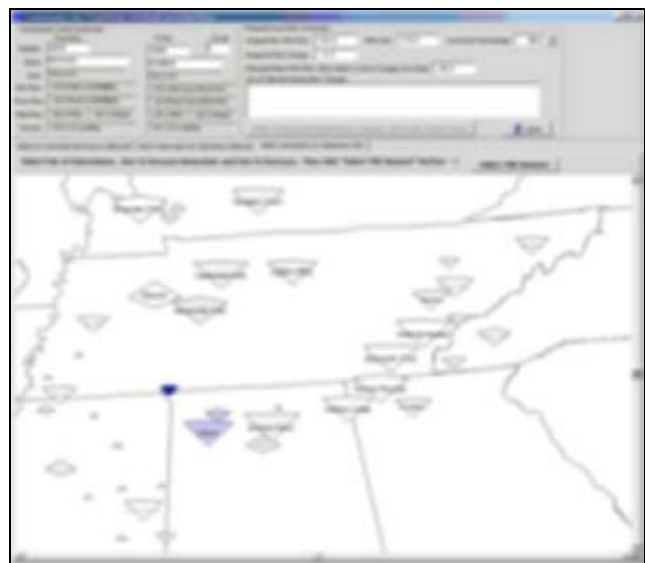

Figure 15: Text-Based LOCF Page

Figure 16: LOCF showing GDV Option

It is interesting to contrast the text-based approach with the GDV approach. Regardless of approach the purpose of the LOCF is to assist the operators in selecting pairs of substations at which the generation should be changed to remove the line overload. The generation at one substation is to be increased while at the second the generation should be decreased by a similar amount (in order to maintain a constant area interchange). Hence selecting the generators requires three key pieces of information: 1) the generator identifier information, 2) available generation MW control range, and 3) sensitivity information that tells how the line's MVA flow would change if the generator's MW output were increased.

In the text-based approach this information was presented in a tabular format, with an additional column added to show the product of the available MW control range with the line flow sensitivity. The values were then sorted based upon this last column.

In the GDV approach the three key pieces of information were presented using one graphical "kite" symbol with the identifier information shown as text superimposed upon the kite. The size of the kite showed the available generator MW control range (both up and down). The line sensitivity information was shown by applying a color mapping to the fill of each kite so its color was proportional to the sensitivity of the line's MVA flow with respect to change the substation's generation. The color mapping was such that red represents locations where the generation should be increased and blue where it should be decreased. Therefore to correct the line overload one would be looking for red upward pointing kites and blue downward pointing kites. The beauty of this approach was a large amount of information could be quickly presented in a relatively intuitive way. Of course, the disadvantage is the user no longer sees the exact numeric values.

Human Factors Considerations

Both the text-based and the GDV view of the LOCF tool were evaluated against established human factors guidelines as well as demonstrated to experienced power system operators at TVA's ROC facility. A total of eight operators with years of experience in various power systems operations—including several in TVA's reliability coordination—performed line overload correction tasks on three different scenarios presented on a power system simulator using each of the LOCF interfaces. Their comments were recorded and analyzed for evaluation of the LOCF designs

For a formal evaluation of these interfaces we used a human factors checklist modified from [3]. This checklist represents an exhaustive review of human factors guidelines and standards pertinent to air traffic control (ATC) systems. As the ATC task environment has much in common with generic control room task environments and human supervisory control settings, the checklist was easy to modify for development and evaluation of electric power transmission control room displays. Both displays were in compliance with the majority of the items in the checklist (over 225 individual items) with only few necessary recommendations for improvement.

The operators had a very favorable reaction to both the level of automation of the LOCF tool (a computer performs all calculations for the operator, including 'what

if' scenarios and exploratory solutions the operator may try) and the visual interfaces. The operators did not, however, express clear preferences for either the text-based or GDV view of the LOCF. Several explanations for this ambivalence can be postulated, which also elucidate the respective pros and cons of each approach.

The main reasons the operators were so comfortable with the tabular, text-based LOCF interface are their domain expertise and familiarity with textual information. There are several other displays in the control center (e.g., the main alarm display) which use tabular presentation and cryptic (to the uninitiated) labeling of substations, generators, etc., but with which the operators are intimately familiar. The tabular interface also was much more information rich than the GDV display, with several accurate numerical values associated with each component of the system and multiple ways of sorting and filtering these data according to the operator's purposes. Finally, simultaneous display of this much 'raw' data allowed the expert operators quickly verify the solution recommended by automation, helping them to stay 'in the loop' of decision-making and properly calibrate their trust in automation.

The GDV view of the LOCF, on the other hand, was ecologically extremely compelling. As one operator put it: 'If you give me a regional map and I know my system well enough that I know where my units are, logistically, I can figure out what's going to do what…'. We may assume that the GDV view could be particularly advantageous in emergency situations or when the operators are under severe time pressure. The scenarios employed in this study did not allow testing this hypothesis, however. There are also some other issues that warrant further study and refinement. For example, the hue of the color of the 'kite' symbol was proportional to the sensitivity of the line's MVA flow with respect to change the substation's generation; small differences in sensitivity, however, resulted in hue differences that were below perceptual thresholds for most of the operators. Proper scaling of hue increments will therefore be necessary

In conclusion, automation—such as the line overload correction calculations by computer and display of (computer) recommended solutions—supports inexperienced operators at all times, and experience operators in tasks performed under intense time pressure. The ecologically valid GDV interface also allows for operator creativity in seeking solutions to line violations. Therefore, GDV displays warrant further research with respect to decluttering algorithms, optimal choice of colors and sizes of the visual elements, and provision of numerical raw data on demand.

Conclusion

This paper has introduced the concept of GDVs, in which new visualizations are created on-the-fly based upon power system information coupled with embedded geographic information. A key advantage of GDVs is they can be used to visualize a wide variety of different power system field values with the ability to use different display attributes to simultaneously show different fields. However, it should be emphasized that GDVs are not intended to replace existing text-based and predefined object visualizations. Rather they are intended to supplement existing techniques, with the major uses expected in the areas of power system analysis and corrective control particularly for wide-area visualizations.

Acknowledgments

References

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