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THREE DIMENSIONAL VISUALIZATIONS FOR POWER SYSTEM CONTINGENCY ANALYSIS VOLTAGE DATA

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ABSTRACT

Contingency analysis (CA) as an inherent function of system security assessment is critical for detecting underlying problems in a power system. More frequent CA computation is required in the deregulated power markets to monitor the state of the system under "what if" situations in view of the fact that the power systems are now operated closer to their limits imposed by the increasing number of power transfers. The traditional EMS display of CA results is a list of violated elements for each contingency examined. Due to the tremendous amount of data computed and the traditional lack of a geographic connection between the violated elements and the contingency elements, interpretation of the contingency results is often time consuming. To aid power system operators with this interpretation, this paper explores several innovative and interactive 3D visualizations of CA voltage violation data. We visualize vulnerability levels of buses and severity information of outages separately and create a three-level visualization for each category. The overall CA results are conveyed at a glance by the top-level visualizations, while more detailed information can be displayed at the user's request.

1 INTRODUCTION

Effective power system operation requires power system engineers and operators to analyze vast amounts of information. Among them, of particular interest are results of contingency analysis (CA), which is critical in many routine power market analyses, such as ATC evaluation, security assessment and transaction arrangement. A typical CA models single element outage (one-transmission line or one-generator outage), multiple-element outage (two-transmission line outage, one transmission line and one generator outage, etc), and sequential outage (one outage after another) [1]. Limit checking is done after each contingency to determine whether the system is secure. As a part of static security analysis, CA is computed more frequently in the deregulated power markets to monitor the states of the system under "what if" situations in view of the fact that the power systems are now often operated closer to their limits to maximum transmission system utilization. Due to the huge amount of data generated from CA, there is a need for efficient and effective visualizations of the results to allow the user to access system security in a quick and intuitive manner.

The traditional display for CA results in an EMS has been a list of violated buses and transmission elements, with their corresponding values, limits and perhaps percentage violation. As might be imagined, when the number of lists exceeds 8-12, it is difficult to build a mental connection between the violated elements and the contingency, or to understand the underlying problems in the system.

Several different visualization approaches have been proposed in an effort to present base case and/or contingency data more effectively. In [2] and [3] the width of the transmission lines shown on a one-line varies according to the transmission line performance indices (PIs) while a thermometer approach was used to show PIs for bus voltages. Reference [4] colored the elements in a contingency-branch flow matrix to show the level of overloading. Additionally, a modified bar chart was used to show the voltage of every bus in a specified voltage level. In [5] an image-based visualization is used that could include all branch MW values or bus voltage values that results from the contingencies by assigning each value a distinct color-pixel in the pixel matrix of a computer screen.

However, the research on contingency data visualization is still in its infancy, with the need for better techniques pressing. To help address this need, in this paper we explore several innovative visualization techniques for contingency data. Our focus here is on the visualization of voltage magnitudes of every bus in the system in the base case as well as under each credible single device outage (i.e., transmission lines, transformers and generators). Visualizations for transmission line loadings and contingency data for multiple device contingencies will be considered in future work.

2 FROM 2D TO 3D

The entirety of the CA bus voltage magnitude results can be conceptualized as a two-dimensional (2D) matrix, with the columns corresponding to the bus numbers while the rows correspond to the contingencies. The matrix entries are then the voltage magnitude at each bus for each contingency. To aid in the interpretation of the results, a discrete color contour could be added to the background of the matrix, with the cell color based on the corresponding per unit voltage value. This visualization technique has been applied to show the variation of bus locational marginal prices over time in [6]. If applied to contingency bus voltage data, it gives a clear overview of the system static security status.

Of course, if one is just concerned with the bus voltage/contingency pairs which resulted in limit violations, the size of the matrix could be reduced by limiting the columns to the set of buses with voltage violations, and the rows to the set of contingencies with violations. The disadvantage of this matrix approach is the absence of geographic information either for the buses or the contingencies.

To add geographic information one might consider somehow displaying CA results using a 2D one-line diagram. The one-line has the ability to at least approximate a geographic location and is certainly familiar to power system operators and engineers. To incorporate various kinds of power system data into one-line diagrams, the 2D color contour technique has been found to be intuitive and effective. Contouring has been used to visualize base case voltage magnitudes [7], locational marginal prices [8] and line flow information [9]. However, the application of contouring to CA results has a significant disadvantage – the color for each bus on the one-line contour can only be mapped to a single data point.

Nevertheless, 2D color contouring still has some applicability within the CA context. For example, one could map the bus color according to some contingency related criteria, such as showing the lowest voltage magnitude at the bus for the entire contingency set, or showing the number of contingent voltage violations for the bus, or contouring some more advanced contingency related performance index. In such approach the bus information (i.e., the columns from the above matrix) is being displayed geographically, while the contingency information (i.e., the rows) is not.

An alternative 2D approach would be to present the contingency information geographically while presenting the bus voltage magnitude information in an aggregate form. For example, if one only considers single device contingencies then we could contour the contingent device itself with information related to that particular contingency, such as contouring the line values based upon the lowest voltage caused by the contingent loss of that line.

In order to simultaneously display geographic information associated with both the buses and the contingencies in this paper we propose expanding the display space from 2D to 3D. The goal in going to a 3D visualization is the potential to include more information within a display without creating excessive display clutter [10]. This property of 3D visualization fits the CA requirement to effectively show the vast volume of data. Due to popularity of and the operators' familiarity with the power system one-line diagrams, our 3D visualizations targeted at contingency voltage data are based on the one-line diagram with the one-line itself still drawn in the x-y plane. In the following sections, we first describe data separation and issues associated with hierarchical visualization, and then present various 3D implementations.

3 SEPERATION AND HIERARCHY OF DATA

Effective data organization is a prerequisite in the visualization of CA results due to the immense amount and complexity of the data. Our 3D visualizations are aimed at helping the users to extract the following essential information: 1) the extent of the voltage limit violations under all credible contingencies, 2) the identification of contingencies imposing abnormal voltages, and 3) the set of buses inclined to voltage limit violations. Also, given the potentially large amount of CA data to display, we propose an interactive, hierarchical approach, with the data grouped into three levels: top, middle, and lower level, based upon the desired degree of detail.

To better visualize the CA results geographically we need to differentiate between two different concepts: 1) the *severity* of each contingency and 2) the *vulnerability* of each bus. The 3D one-lines that primarily use geographic information based on the contingent element itself will be called contingency severity displays; these displays are discussed in Section 4. The 3D one-lines that primarily use geographic information based on the buses will be called bus vulnerability displays; these displays are discussed in Section 5.

4 CONTINGENCY SEVERITY 3D DISPLAYS

4.1 Top-Level Severity Visualization

The contingency severity 3D one-line displays show information about the severity of the contingencies in terms of the bus voltage magnitudes. The top-level severity information is conveyed through the height, radius and color of a 3D cylinder associated with the contingent element. For example, such cylinders could be located at the middle point of the longest line segment for transmission lines and transformers, or at the centers of the circular generator symbols. The height of each cylinder could be proportional to the absolute value of the difference between the nominal voltage magnitude and the lowest off-limit voltage in the whole system under the corresponding contingency. At the same time, the radius of each cylinder could be coded according to the number of voltage violations in the system under the associated contingency. This allows use of the integral display dimensions of height and width [11] to convey the combination of the number of violations and the magnitude of the worst off-limit voltage imposed by a contingency. Moreover, the lowest voltage resulted from a contingency is double coded by the color of the cylinder using a discrete color mapping shown by the color key.

Since only those contingencies which cause voltage limit violations have associated cylinders, the viewer's attention can be drawn to problem contingencies quickly with the geographic location of the contingency encoded by the display. The severity of the problem contingencies (causing voltage limit violations) can be compared through the heights and radii of cylinders. The encoded color of the cylinders would help the viewers to overcome the potential vagueness due to the perspective effect in 3D visualization where a distant cylinder with larger height may seem shorter than another one closer but with smaller height. With the help of the color key, the small range, in which the worst voltage lies under each contingency, can be read out from the color of the cylinders. A discrete color mapping is adopted from the consideration of its ease in distinguishing over continuous color coding. Figure 1 shows the top-level severity visualization for the IEEE 30 bus example system.

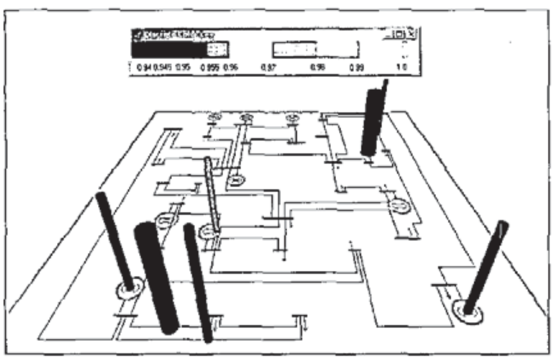

Figure 1: Top-level severity visualization

4.2 Middle-Level Severity Visualization

While the top level display only shows two data points per contingency, through an interactive extension the geographic relationships between the contingent elements and the violated buses could be displayed. For example, in the top-level severity display, right clicking on a contingency's cylinder could invokes the middle level severity visualization where the problem contingencies and the consequent buses with low voltages are connected by blue link lines. Link lines are drawn from the center of the top of the cylinder associated with the outaged element to the centers of the buses, which will experience low voltages under the correspondent contingency. In a one-line diagram of a system with multiple voltage levels, the transmission lines are traditionally color coded according to their nominal voltage levels. In this case, we modify the classical color mapping for voltage levels by reducing the hues of the transmission lines and we reserve the pure blue for link lines. This makes link lines easy to be distinguished from and more attracting than transmission lines.

When clutter is not a problem, middle-level severity information for more than one contingency could be displayed simultaneously. This is shown in Figure 2 where the cylinders convey the same top-level information for each one-element outage as in the previous section with link lines pointing out the locations of buses with consequent voltage violations. Only the top-level severity cylinders associated with the contingencies being selected for middle-level visualization are shown to avoid display clutter.

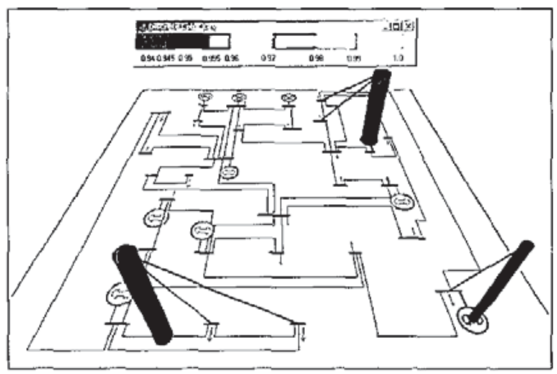

Figure 2: Middle-level severity link lines visualization

4.3 Lower-Level Severity Visualization

Lower-level severity information for a specific contingency (the bus voltage at each bus under the contingency) can be displayed using the 2D color contour described in [6] by contouring the one-line diagram according to the post-contingency voltage at every bus under the selected contingency. To enhance the 2D color contour, we also bring forth a 3D lower-level severity "bus terrain" visualization shown in Figure 3 where the voltage magnitude of every bus under the selected contingency is represented by the height and the radius as well as the color of the cone sitting on it. The height and the radius of a cone are proportional to the absolute value of the difference between the nominal voltage and the voltage magnitude of the bus the cone is on. The color is mapped according to the same discrete color mapping as in section 4.1. The link lines from the middle level display are kept to pinpoint the buses with off-limit voltages.

This visualization not only provides valuable information for operators in contingency data analysis, but also has the potential to aid in corrective controls in the face of voltage limit violations. Corrective controls for voltage limit violations include raising or lowering the output of controllable reactive power sources (or the voltages of voltage controllable buses), and adjusting tap ratios of tap-changing transformers. Because reactive power does not travel well, corrective actions for voltage limit violations are often localized. The search for controllable equipments could be outward from the location of limit violations.

In the lower level severity visualization, the geographical relationship between buses with voltage limit violations and the causing outage can be easily established due to the attraction of large cones. When controllable reactive sources are highlighted, by gray cylinders with heights proportional to the available reactive capacities for instance, operators can continue to search for closest control candidates to restore voltages to normal values based on identification and location of voltage limit violations.

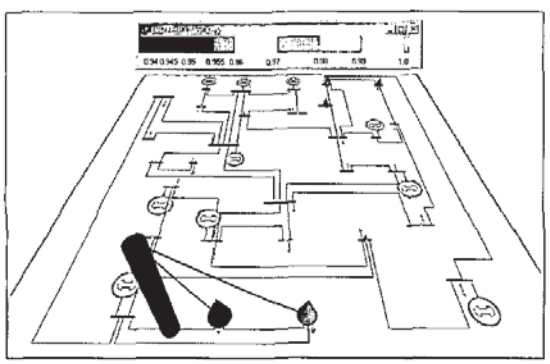

Figure 3: Lower-level severity bus terrain visualization

5 BUS VULNERABILITY 3D DISPLAYS

5.1 Top-Level Vulnerability Visualization

The top-level bus vulnerability display is similar to the contingency severity display, with the following important change. Cylinders are now drawn on buses to represent the information extracted from the voltage magnitudes of a bus under all single failure contingencies examined. The height and the hue of the cylinder convey the worst voltage the bus will undergo under all contingencies while the radius of each cylinder is encoded to show the number of contingencies imposing voltage limit violations on the bus. A top-level vulnerability display is shown in Figure 4.

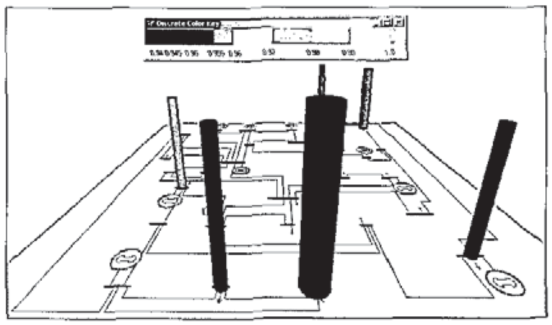

Figure 4: Top-level vulnerability visualization

The vulnerable buses, which will have off-limit voltages under certain contingencies are highlighted by the cylinders. The vulnerabilities among buses can be compared the same way the severities of contingencies are compared in section 4.1. The widest and highest cylinder pinpoints the most vulnerable bus in the system. This information can be utilized in search for voltage support equipments in the corrective control and in planning for adding reactive power sources into the system.

5.2 Middle-Level Vulnerability Visualization

To build the connection between bus voltage problems and the incurring contingencies, viewers can access the visualization for middle-level vulnerability information for a specific bus (the locations of contingent elements causing low voltages at the bus) by again right clicking on its cylinder. Only the cylinder of the selected bus shows up in the middle-level vulnerability display to highlight the clicked bus.

The middle-level vulnerability visualization shown in Figure 5 is similar to the one for middle-level severity information with link lines. Here, however, the blue link lines connect the selected vulnerable buses with the single element outages, which will cause the bus low voltages. The middle-level vulnerability information for several buses may be shown at the same time when desired.

5.3 Lower-Level Vulnerability Visualization

To display detailed voltage magnitude value of a bus under every one-element outage, we create the 3D "line terrain" visualization. Only the top-level vulnerability cylinder of the selected bus is drawn to highlight the selected bus. We then extrude the circle of every generator along z-axis with the height and the color indicating the voltage magnitude the selected bus will experience when this generator is outaged. For transmission lines, we use the height and the color of a transparent, triangular wedge lying along every transmission line to reveal the voltage of the selected bus with this transmission line outaged. Obviously, if a line were not included in the contingency set then it would not have an associated wedge.

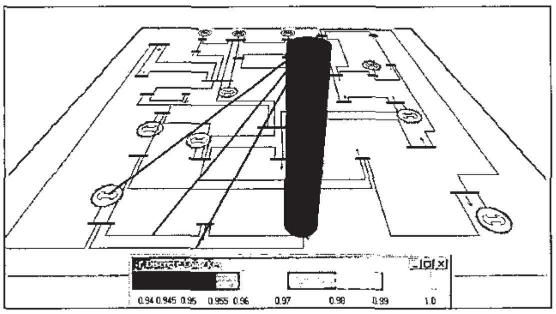

Figure 5: Middle-level vulnerability link lines visualization

The link lines in the middle-level visualization are kept, thus pinpointing the outages imposing voltage violation on the selected bus. The width of the wedges has not been coded here in recognition that in medium to large systems there is often insufficient space on the one-line for significant variation in line thickness (see in [12] for a 118 bus system example of such transmission line width variation). The 3D visualization presented here enhances the 2D line color contour [9] in that the voltage value of the selected bus under each outage is double coded by the height of the triangular columns or cylinders in addition to their color. Moreover, a severe outage of a short line will stand out in this 3D visualization while might be hard to perceive in a 2D color contour.

By looking for tall wedges and tall generator cylinders in the lower-level vulnerability visualization illustrated by Figure 6, the viewers can easily identify the contingencies resulting in the worst bus voltages.

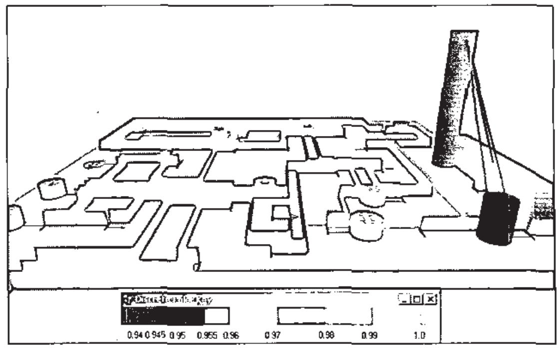

Figure 6: Lower-level vulnerability line terrain display

Separation of the contingency severity visualization and the bus vulnerability visualization, and the three-level hierarchy displays necessitate an interactive interface for viewers to move between different displays of different level. Typically the two different visualizations would be shown in different windows. However, there is certainly no reason to preclude combining the two. As an example Figure 7 shows a two-layer visualization where the lower layer visualizes top-level severity information of the system and the upper layer displays in "bus terrain" the lower-level severity information of the selected contingency highlighted by a transparent violet cylinder around the corresponding top-level severity cylinder stretching from the lower layer to the upper layer. Similarly, the two-layer mechanism can be used for combining middle and lower level, or top and middle level severity displays, or vulnerability visualizations of different detail levels.

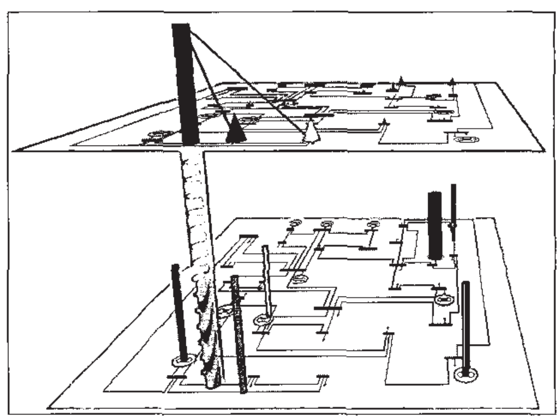

Figure 7: Two-layer visualization scheme combining top, middle and lower level severity display

6 CONCLUSION AND FUTURE WORK

Effective and efficient visualizations for contingency analysis results are in great demand due to the overwhelming volume of the data. Interactive and innovative 3D visualizations have been presented in this paper to provide power system operators and engineers critical information in different detail levels visually. The information includes the global view of the system security level in terms of bus voltage magnitudes, locations of vulnerable buses and severe outages, geographical relationships between voltage violations and the causing outages.

However, more research is certainly needed. For example, one avenue for future would be to augment the visualizations to include information about the location of candidate controls to correct the contingent voltage violations. Example controls could include the reactive power reserve of generators, LTC transformers, and available switched shunts of SVC devices. A second extension of the present work would be to consider overloaded transmission lines and transformers. A third extension would be the consideration of multiple device and sequential outage contingencies. Finally, the performance of these candidate visualizations needs to be assessed by formal human factor experiments and, of course, through implementation in actual power system software.

7 ACKNOWLEGMENTS

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