Visualizations for Power System Contingency Analysis Data

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***Abstract*—Contingency analysis (CA) is critical in many routine power system and market analyzes to show potential problems with the system. Due to the tremendous and yet increasing amount of data computed by CA, effective visualizations are needed to present the CA results to assist the system operators and engineers to comprehend the static security status of the system in a quick and intuitive manner. The desirable functionalities of such visualizations include showing the overall system security status, showing the severity levels of the contingencies in terms of their associated limit violations, and showing the geographic connection between the violated elements and the contingent elements. The traditional EMS display of CA results is a tabular list of elements with limit violations. This paper explores interactive three-dimensional visualizations for contingency data. We visualize vulnerability levels of power system elements and severity information of outages separately. The overall situation of the whole system is conveyed "at a glance" by the overview visualizations, while more detailed information is displayed as needed.**

***Index Terms*—Contingency analysis, power system operations, power system visualizations, user interfaces.**

I. INTRODUCTION

CONTINGENCY analysis (CA), as a part of static security analysis, is critical in many routine power system and power market analyzes, 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 for each contingency to determine whether the system is secure.

With the global trend toward deregulation in the power system industry, the volume and the complexity of the CA results in the daily operation and system studies have been increasing. Not only has deregulation resulted in much larger system model sizes, but also CA is computed more frequently in the restructured power markets to monitor the states of the system under "what if" situations in order to accommodate the maximum number of power transfers. The net impact of these changes is a need for more effective and efficient visualizations for CA results to help with the comprehension of the essential security information, information which could be buried in the enormous and complex CA data sets.

The traditional display for CA results in an EMS is often a tabular list showing the violated buses and transmission elements, along with the corresponding contingency name, element value, limit and perhaps the percentage violation. However, when the number of elements in the list becomes excessive it can be difficult to build a mental connection between the violated elements and the contingencies causing the violations, or to understand the underlying problems in the system.

Thus better schemes to visualize the data computed by CA are needed. To help meet this need in [2] the authors introduced three-dimensional (3-D) visualizations of CA voltage results—voltage magnitudes at each monitored bus under base case as well as each credible single-element outage contingency. Similar results for transmission element flow values were presented in [3]. The purpose of this paper is to extend that preliminary work by presenting enhanced 3-D visualizations for the combined CA results—voltage magnitude results and transmission element loading results.

II. PREVIOUS WORK ON CONTINGENCY DATA VISUALIZATION

Surprisingly few visualization techniques have been presented in the technical literature aimed at assisting power system operators and engineers with contingency data visualization. The techniques that have been presented fall mainly in three categories: two-dimensional (2-D) visualizations based on the traditional one-line diagram, 2-D visualizations not based on the geographic network and 3-D visualizations without geographic environment.

The 2-D visualizations based on one-line diagrams have been relatively popular due to the familiarity of power operators with one-line diagrams and the importance of geographic information in power system operation and control. Example schemes include encoding the width [4]–[8], color [6]–[8] and arrow size [6] of transmission lines according to line performance indices (PIs) or post contingency loadings; augmenting the one-lines with the thermometers [4], [5] showing bus PIs and the pie charts [12] for contingent voltage angles.

In contrast to the one-line diagram based visualizations, the presentation of contingency data in a 2-D matrix [7]–[10] or bar charts [11] gives a clear overview of the system severity status, but at the expense of the loss of geographic information. Other 2-D visualizations not based on the geographical network can be found in [12] where high-level security risk levels were displayed by rectangular and oval meters and 2-D iso-risk curves displayed security level as a function of operating conditions.

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In addition to the 2-D visualization techniques listed, 3-D visualization without geographic background has been applied into power system CA results. In [7], a third dimension was added to represent time, allowing the display to show the time variation in contingency severity. Similarly, in [13] a 3-D manifold was used to display the percentage overload of the monitored transmission lines under each contingency by scaling the z axis in terms of percentage overload, assigning each point on the y axis a contingency, and each point on the x axis a monitored line.

This literature review indicates that power system CA visualization is still in its infantry, with a pressing need for better techniques. This paper first discusses possible 2-D visualization techniques for CA data and their drawbacks, and then presents a geographic 3-D approach.

III. FROM 2-D TO 3-D

The entirety of the CA results can be conceptualized as a set of 2-D matrices, perhaps one matrix for voltage results, and one for transmission element loading results. The loading matrix could have the columns correspond to the transmission elements while the rows correspond to the contingencies. The matrix entries are then the percentage loading of each transmission element for each contingency. Similarly, the columns of the voltage matrix may correspond to the buses and the rows correspond to the contingencies, with the per-unit voltage values being the matrix entries.

To aid in the interpretation of the results, a discrete color contour could be added to the background of the matrices, with the cell color based on the corresponding percentage loading or per-unit voltage value. This visualization technique has been applied to show the variation of bus marginal prices over time in [14]. If applied to contingency data, it gives a clear overview of the system static security status in terms of post contingency voltages and loadings.

Of course, if one is just concerned with the element/contingency pairs which resulted in limit violations, the size of the matrices could be reduced by limiting the columns to the set of elements with violations, and the rows to the set of contingencies causing limit violations. The disadvantage of this matrix approach is the absence of geographic information either for the power system elements (buses, transmission lines and transformers) or for the contingencies.

To add geographic information one might consider somehow displaying CA results using a 2-D 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 2-D color contour technique has been found to be intuitive and effective. Contouring has been used to visualize base case voltage magnitudes [15], LMPs [16], and line flow information [17]. However, the application of contouring to CA results has a significant disadvantage—the color for each power system element on the one-line contour can only be mapped to a single data point.

Nevertheless, 2-D color contouring still has some applicability within the CA context. For example, for contingency loading data, one could map the color of a transmission element according to some contingency related criteria, such as the worst overloading on the line for the entire contingency set, or the total number of possible contingent overloads on the line, or some more advanced contingency related PI. This approach can also be used to visualize bus information by contouring buses according to some contingency criteria associated with buses. But visualizing transmission element and bus information at the same time using 2-D color contoured one-line is problematic and would probably cause confusion. Moreover, in such an approach the transmission element/bus information (i.e., the columns from the above loading/voltage matrix) is being displayed geographically, while the contingency information (i.e., the rows) is not.

An alternative 2-D approach would be to present the contingency information geographically while presenting the transmission element loading and/or bus voltage 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 device outage, such as the number of limit violations caused by the contingent loss of that line.

In order to simultaneously display geographic information associated with both the power system elements and the contingencies, we propose expanding the display space from 2-D to 3-D. The goal in going to a 3-D visualization is the potential to include information of more dimensions within a display without creating excessive display clutter and confusion [18]. This property of 3-D visualization fits the CA requirement to effectively show the vast volume of multi-dimensional data. Due to widespread industry familiarity with one-line diagrams, the 3-D visualizations presented here are based on the one-line diagram, with the one-line drawn in the x-y plane.

IV. ORGANIZATION OF DATA

Because of the potential for CA to create a large amount of data, effective data organization is a prerequisite to the visualization of CA. The goals of CA results visualization include helping to extract the following essential information: 1) the extent of the limit violations in terms of low voltages (defined as voltage magnitudes lower than the voltage lower limit) and transmission element overloads (defined here as loadings above the limit of the corresponding transmission element) for the whole examined contingency set; 2) the identification of contingencies imposing loading and/or voltage violations; and 3) the set of power system elements inclined to contingent limit violations.

To better visualize the CA results geographically, one needs to differentiate between two different concepts: 1) the *severity* of each contingency and 2) the *vulnerability* of each power system element. The 3-D one-lines that primarily use geographic information based on the contingent element itself will be called contingency severity displays. The 3-D one-lines that primarily use geographic information based on the monitored elements will be called element vulnerability displays. Also, given the potentially large amount of CA data to display, this paper presents an interactive, hierarchical approach, with the data grouped into three levels: overview, middle, and detail level, based upon the desired degree of detail.

V. Issues in Simultaneous Voltage and Loading Visualization

In our previous work, we created separate visualizations for contingency voltage data [2] and contingency transmission element loading data [3]. The justifications are that power system operators might be interested in only one of the two aspects at a time and such separation reduces the complexity associated with the visualizations. When both contingency voltage results and contingency transmission element loading results are of interest, two windows may be shown simultaneously with one for voltage data and the other for loading data.

This paper extends that approach to allow simultaneous display of both sets of data on a single display. However, doing so presents two challenges: 1) How to differentiate the data sets and avoid interference? 2) With possibly many more limit violations than in the separate voltage/loading visualizations, how to avoid overwhelming users with too much information?

Inasmuch as people are sensitive to clusters and patterns created by colors [19], the approach proposed here is to distinguish voltage data from loading data using color. For example, the objects associated with voltage data could be shaded blue, while objects representing loading data could be shaded red. A solution to the second issue could be the application of transparency—the most severe/vulnerable contingencies/elements are made more solid, and hence more prominent. Less severe violations are still shown, but with varying degrees of transparency. This focuses attention on the more severe violations, but also provides context by still showing all the violations.

VI. Contingency Severity Visualization

The first type of displays, the contingency severity one-lines, show information about the severity of the contingencies in terms of the power flow loadings on the monitored transmission elements and voltage magnitudes at the monitored buses. Three categories of this display type are presented. First, the overview display summarizes the loading and voltage limit violations caused by each contingency by showing the number of violations and the approximate worst percentage overload and/or the lowest per-unit voltage in the system. Second, the middle-level display augments the overview display to also show the location of the violations. Third, the detail display shows the location and magnitudes of the violations for a single, specified contingency. Each of these categories is described in detail below.

A. Contingency Severity Overview Display

In the contingency severity overview display the one-line is used to show the location of the contingent devices, along with an indication of the violations caused by each contingency. An example of this visualization is shown in Fig. 1 for the IEEE 118 bus system. Overall the display shows results for 187 single line/transformer contingencies and 54 single generator contingencies. A total of 29 contingencies resulted in bus voltage and/or transmission element violations.

In the visualization, 3-D cylinders are located on the contingent devices that cause violations, with the cylinder shaded blue for low voltage violations and shaded red for transmission violations. The height of each cylinder is proportional to the number of violations caused by the contingency, while the shading and radius of the cylinder are proportional to the magnitude of the worst violation. The voltage cylinder is stacked on top of the transmission cylinder if a contingency causes both low voltages and overloads (which is the case for two of the contingencies shown in the figure). The doubling coding of the magnitudes of the worst contingent violations by color shade and cylinder radius helps to focus attention on these contingencies. A discrete color mapping is adopted from the consideration of its ease in distinguishing values in different small ranges over continuous color coding. The correspondence between the value ranges and the colors is shown by the color key.

Since only those problem contingencies that cause limit violations have associated cylinders, the overall static security status of the system is obvious at a glance. In the case of insecure status with contingent limit violations, the viewer's attention can be drawn to problem contingencies quickly with the geographic location of the contingency encoded by the display. Furthermore, one can quickly tell which kind of violations (low voltage or overload) each contingency would cause. The severity of the problem contingencies can be compared through the heights and radii of the cylinders. The encoded color of the cylinders would help to overcome the potential vagueness due to the perspective effect in 3-D visualization where a distant cylinder with larger width/height may seem thinner/shorter than another one closer but with smaller width/height. With the help of the color key, the per-unit or percentage range, in which the lowest voltage or the worst overloading lies under each problem contingency, can be read out from the color of the cylinders.

The take-away message from Fig. 1 is the visualization is presenting a significant amount of information, the results of 241 contingencies, in a single display. This same amount of information could not be presented as concisely using the traditional tabular approach, especially the spatial relationships between the various contingencies on the one-line. Of course, the new visualizations presented here could be used in tandem with existing methods. Furthermore, the approach could easily be extended to larger one-lines, with the key concern being the density of the 3-D symbols. Computationally, even displays with many hundreds of buses can be rendered quite quickly, allowing for highly interactive displays. For example, results from [21] indicate a 3-D one-line with 1600 buses can be rendered at around 7 frames per second using a 2.8-GHz Pentium machine.

The Fig. 1 color mapping was designed so more severe violations (lower voltage or higher loading) have darker or brighter colors while less severe violations have lighter colors. This helps to focus attention on the more severe contingencies. To give further attention to the most severe contingencies, one could also modify the transparency of the 3-D objects, according to the worst violation or some other severity index. Fig. 2 shows the severity overview visualization with transparency coded for the same IEEE 118 bus example system as in Fig. 1. The voltage cylinders representing a lowest voltage above 0.95 per unit are transparent, while the low voltage

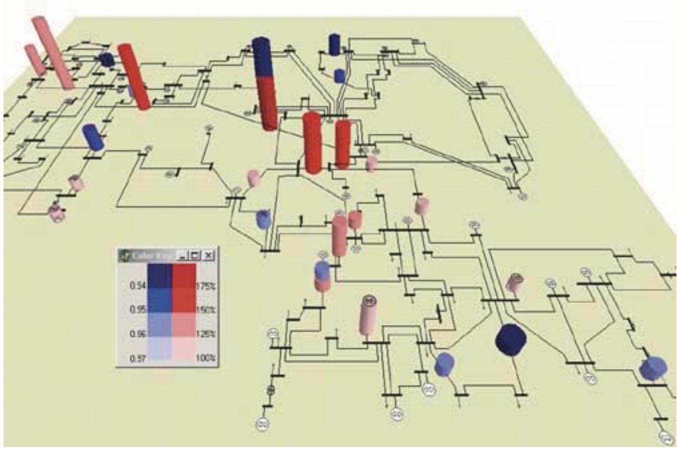

Fig. 1. Contingency severity overview visualization.

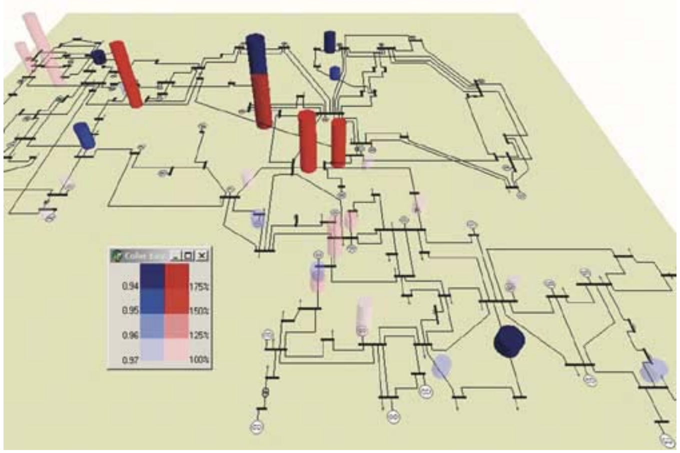

Fig. 2. Contingency severity overview visualization with coded transparency.

cylinders representing a lowest voltage below 0.95 per unit are solid. For overload cylinders, those with loadings above 150% are solid, while loadings below 150% are transparent. Of course, any number of different transparency mappings are possible.

B. Contingency Severity Middle-Level Visualization

While the top-level display shows only two pieces of information per contingency violation type (i.e., worst violation and total number of violations), through an interactive extension the geographic relationships between the contingent elements and the power system elements suffering violations could be displayed. One approach, designated here as the middle-level severity visualization, draws "link lines" between each contingency's cylinder and the violated elements from that contingency. To avoid excessive clutter, link lines might only be displayed for an interactively selected set of contingencies. This approach is illustrated in Fig. 3, with more detailed results shown for three of the more severe contingencies. Blue lines are used for bus voltage violations while red lines are used for flow violations. To highlight the starting points of the link lines, we designed so as to have all the link lines associated with a contingency radiating from the top cylinder of the corresponding 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, the colors used by the link lines could be modified to avoid using the same colors as those used on the one-line itself.

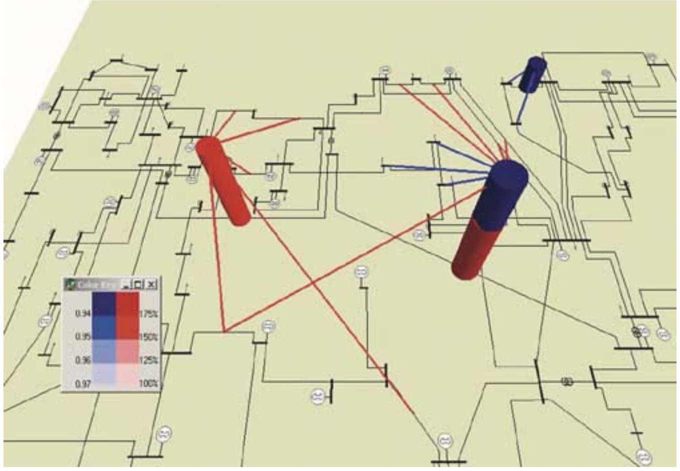

Fig. 3. Contingency severity middle-level visualization.

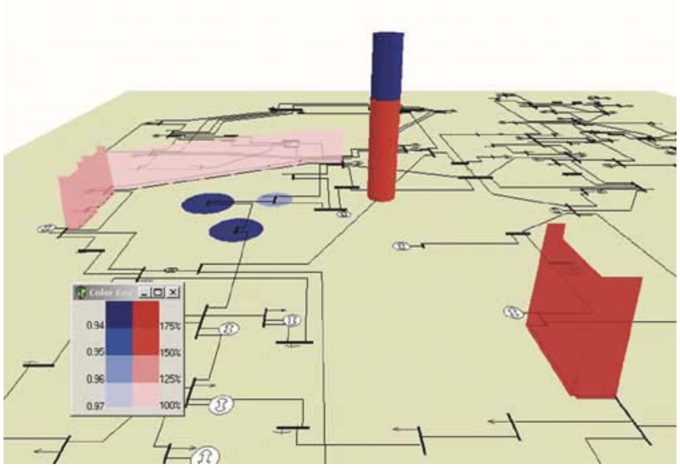

Fig. 4. Contingency severity detail visualization.

C. Contingency Severity Detail Visualization

When contingency voltage and loading results are visualized separately, detailed severity information for a specific contingency can be displayed using a 2-D color contour described in [15] and [17]. For voltage results, the one-line diagram could be contoured according to the post-contingency voltage at every bus under the selected contingency. For loading results, line contouring suffices by contouring transmission lines and transformers according to their post-contingency percentage loadings.

To integrate the voltage and loading results for a single selected contingency in the same display, we propose to supplement the 2-D bus color contour of post-contingency voltages with 3-D "transmission element terrains" to better show the post-contingency loadings. An illustrative example of this design is shown in Fig. 4. The one-line diagram in the x-y plane is contoured only for the buses with low voltages under the

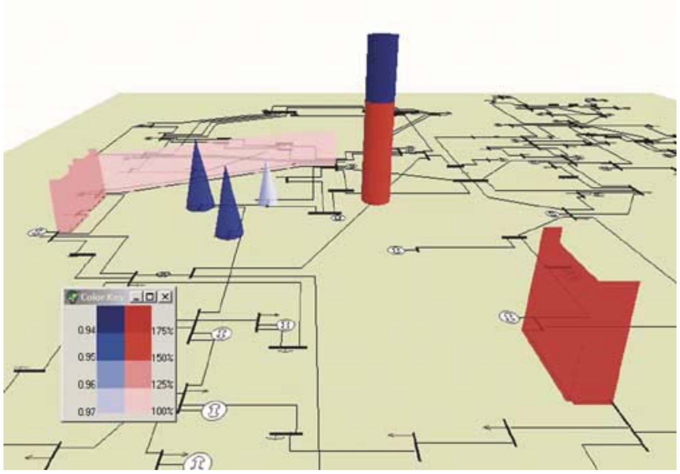

Fig. 5. Contingency severity detail alternative visualization.

selected contingency, with the contingent line indicated by its severity cylinder.

The overloaded transmission elements under this contingency are drawn as "terrains"—triangular prisms along the length of the line, with the height and color both coded for the percentage loading on the corresponding element. The width of the prisms 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 [20] for a 118 bus system example of such transmission line width variation).

It is noteworthy that the 3-D line terrain presented here enhances the 2-D line color contour [17] in that the loading of a transmission element is double coded by the height of the triangular prism in addition to its color. Thus, a severely overloaded short line will stand out in this 3-D visualization while it might be hard to perceive in a 2-D color contoured one-line. By looking for a dark blue contour and a tall dark red prism in the contingency severity detail visualization illustrated by Fig. 4, the viewers can easily identify the bus with the lowest voltage and the transmission element with the worst overload, under the contingency highlighted by its severity overview cylinder.

The similar color contour enhancement could also be applied to bus voltage contour, thus resulting in an alternative contingency severity detail visualization as shown in Fig. 5. The bus contour enhancement is achieved by extruding the color contour of buses along z-axis in cone shape with their height proportional to the difference between the nominal voltage and the actual voltage. From comparison between Fig. 4 and Fig. 5, it is apparent that the buses with low voltages look more prominent with 3-D cones, designated here as "bus terrain".

Such prominence not only provides valuable information in contingency data analysis, but also has the potential to aid with corrective controls. Corrective actions for voltage limit violations are often localized because reactive power does not travel well. The search for controllable equipments could be outward from the location of limit violations. Available controls, such as capacitors, could even be highlighted on the one-line. For example, in Fig. 5, capacitors could be shown using gray cylinders with heights proportional to the available reactive capacities.

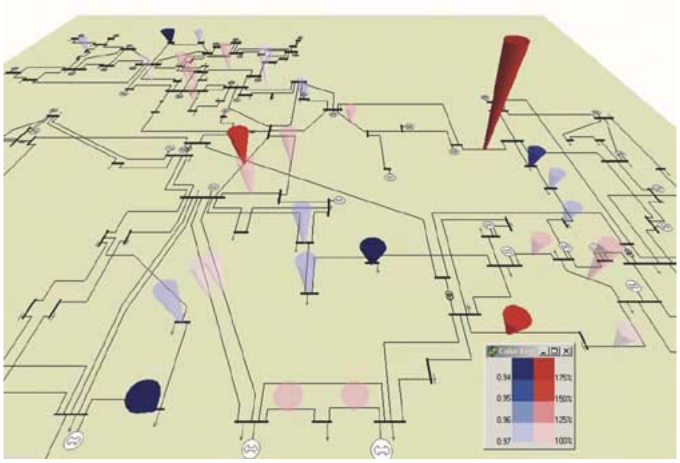

Fig. 6. Element vulnerability overview visualization.

VII. POWER SYSTEM ELEMENT VULNERABILITY VISUALIZATION

In contrast to contingency severity information, power system element vulnerability describes the vulnerability of buses and transmission elements in face of contingencies in terms of their post-contingency voltages or loadings. Hence, the primary focus here is on the violated element itself, with the different categories of visualizations showing sequentially more detail about the contingencies which cause violations on the element. Again, three different categories are presented: overview, middle-level, and detail.

A. *Vulnerability Overview Visualization*

The power system element vulnerability overview display is similar to the contingency severity overview display, with the following important change. Instead of severity cylinders for contingent elements, reversed cones are now drawn on buses and transmission elements to represent the information extracted from the voltage magnitudes at a bus or the loadings on a transmission element under all single failure contingencies examined. An advantage of using a reversed cone is it takes less one-line space compared to a cylinder. This can be important since the number of violated elements could be substantially greater than the number of problem contingencies shown in the last section on the contingency severity displays. Another advantage of reversed cones is their footprint on the one-line is much smaller; hence they do not cover their one-line elements, making it easier to see the association between the 3-D symbol and the one-line elements. Finally, by using a different symbol the element vulnerability displays and the contingency severity displays are readily distinguishable. Of course, other 3-D shapes could certainly be used.

To preserve consistency with the contingency severity displays the coding of the size, color and transparency is the same as from the previous section. That is, the upper radius and the hue of a reversed cone for buses (or transmission elements) convey the lowest voltage (or worst overload) the bus (or transmission element) will undergo under all contingencies while the height of each reversed cone is encoded to show the number of contingencies imposing voltage (or loading) limit violations on

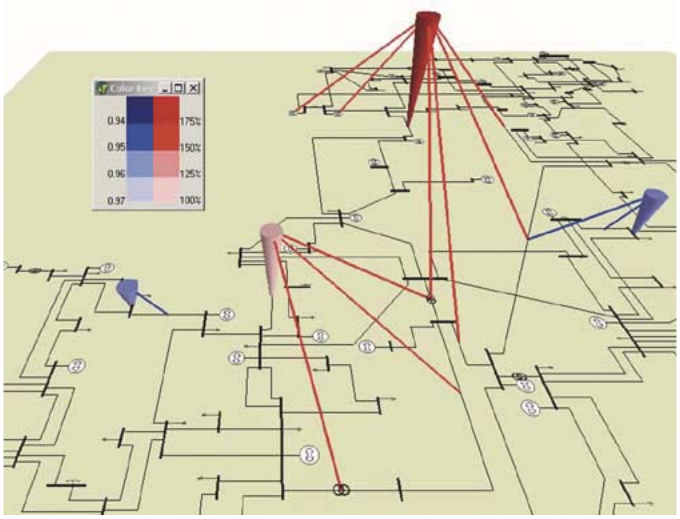

Fig. 7. Element middle-level visualization.

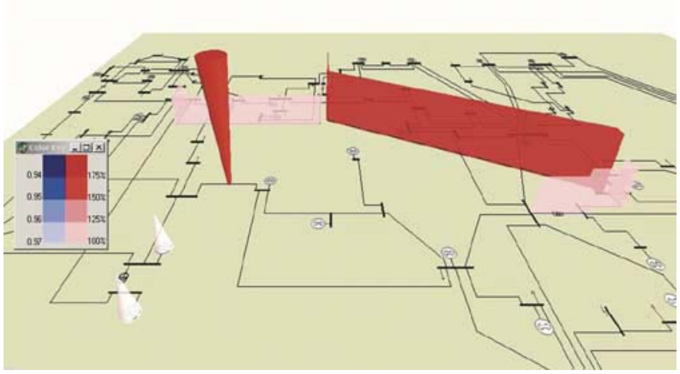

Fig. 8. Transmission element vulnerability detail display.

the bus (or the transmission element). The same discrete color mapping has also been used with the bus vulnerability cones colored blue and the transmission element vulnerability cones shaded red. A top-level vulnerability display is shown in Fig. 6, in which the transparency of the reversed cones is again coded according to the corresponding worst limit violation (lowest voltage for buses and worst overload for transmission lines or transformers) to accentuate the most vulnerable elements in the system.

As seen in Fig. 6, the vulnerable buses and transmission elements, which would suffer contingent limit violations, are highlighted by the reversed cones. The widest and highest dark blue cones pinpoint the most vulnerable buses in the system, while the widest and tallest dark red cones mark the most overloaded transmission elements. Moreover, the pattern formed by the color of the cones reveals the regions where low voltages and/or overloading are of most concern.

B. Vulnerability Middle-Level Visualization

As was the case with the middle-level contingency severity displays, the vulnerability middle-level visualizations use link lines to visualize the geographic connection between the violated elements and the associated contingencies. Again, an interactive process could be used to display the link lines for just a single selected violated element, or a set of violated elements. Such a display is shown in Fig. 7 for four selected elements. Here, the blue link lines connect the selected low voltage buses with the single-element contingencies that cause low voltages at those buses, while the red link lines connect the overloaded transmission elements.

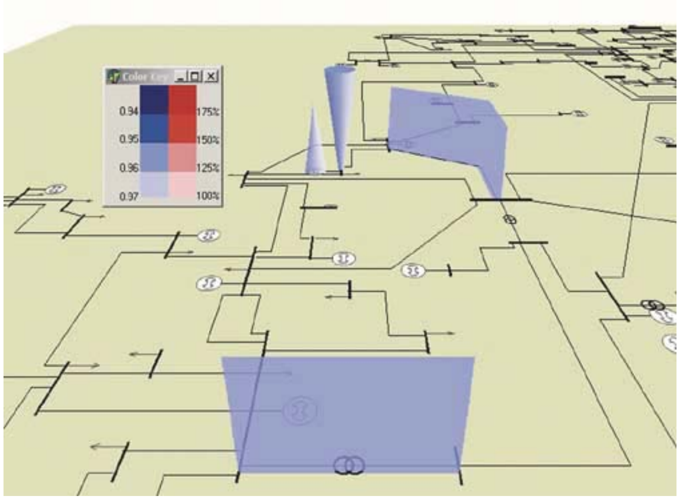

Fig. 9. Bus vulnerability detail display.

C. Vulnerability Detail Visualization

The vulnerability detail category visualizations can be used to provide more detailed information about a single specified bus or transmission element. The approach again uses the 3-D "terrain" visualization to show information about the device for each contingency causing a violation. Fig. 8 demonstrates the vulnerability detail display for a selected transmission line flagged by its red vulnerability cone. Each single-element outage which would impose overloads on the selected line has a terrain visualization (i.e., a triangular prism along the length of the contingent line or transformer, or a cone extruding from the contingent generator). The height, as well as the color of a prism or cone, are encoded according to the percentage loading on the flagged line.

Such visualization can also display vulnerability detail information for a bus as illustrated by Fig. 9. Here, the blue reversed cone signalizes the bus of concern and the blue terrains are associated with the contingent elements which would cause low voltages on the bus when outaged. The height as well as the color of each terrain are mapped to reveal the per-unit voltage at the selected bus for the terrain element contingency. By looking for tall terrains with the colors indicating severe limit violation in the vulnerability detail visualization illustrated by Fig. 8 and 9, one can readily identify the contingency resulting in the worst limit violation on the selected element signaled by the reversed cone.

VIII. DISCUSSION OF SWITCHING AMONG DIFFERENT VISUALIZATIONS

Separation of the contingency severity visualizations and the power system element vulnerability visualizations, along with the three-level hierarchy displays, necessitate an interactive interface to move between different displays of different detail

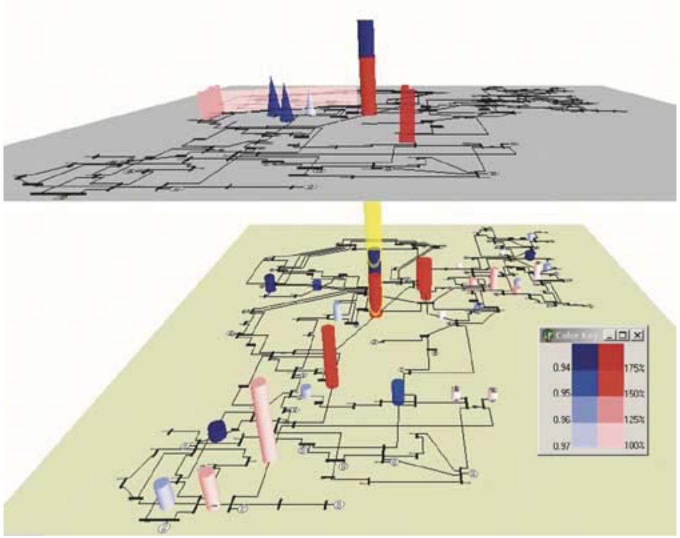

Fig. 10. Two-layer contingency severity visualization.

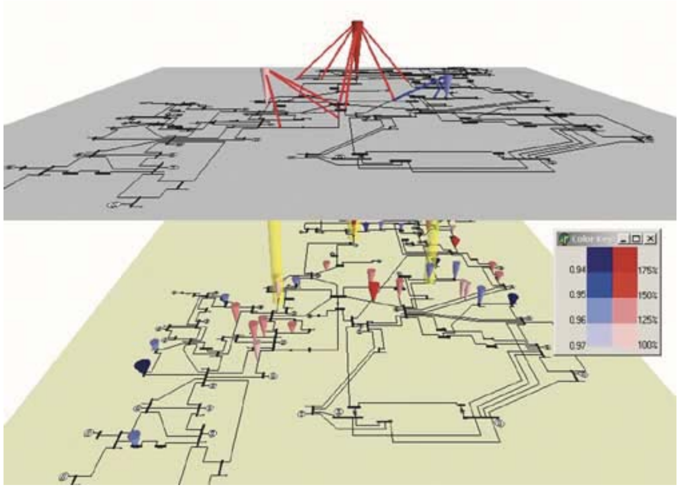

Fig. 11. Two-layer power system element vulnerability visualization.

levels. Typically, two different visualizations would be shown in different windows. However, there is no reason to preclude combining the two.

Fig. 10 shows an example of such a two-layer mechanism for a contingency severity display, where the lower layer visualizes contingency severity overview information, and the upper layer displays the detailed severity information of the selected contingency highlighted by the transparent yellow cylinder stretching from the lower layer to the upper layer. Similarly, in Fig. 11, the two-layer mechanism is used for power system element vulnerability visualization. The lower layer visualizes the vulnerability overview information and the upper layer shows the vulnerability middle-level display for the selected monitored elements again signified by the yellow cylinders.

IX. CONCLUSIONS AND FUTURE WORK

Additional CA result visualizations are needed to help power system engineers and operators more quickly understand the potentially overwhelming amount of data created by a CA study. This paper has presented several innovative 3-D visualizations to provide critical information in different detail levels. This information includes a global view of the system static security level in terms of the CA voltage magnitudes at buses and loadings on the monitored transmission elements, the locations of vulnerable power system elements and the severe contingencies, and the geographical relationships between contingent limit violations and the contingencies themselves.

The voltage violations visualized in this paper have only been for low voltages. Of course, high voltage violations could be displayed using the same approach. In situations where both high and low voltage violations are of concern, they could be distinguished by different colors, for example, blue for low voltages and violet for high voltages. The worst voltage violation for each contingency or each bus, as conveyed by the cylinder in contingency severity displays and the reversed cone for the bus in power system element vulnerability displays, could be defined as the voltage magnitude deviating from the nominal level the most for the contingency or at the bus.

It is worth noting that the visualizations presented here are certainly not intended to completely replace the traditional tabular displays for CA results, but rather to supplement such lists. Moreover, tabular displays can be integrated into these visualizations when numerical values are needed. For instance, one design could be through the use of popup dialogs showing the matrices discussed in Section III in the contingency severity or power system element vulnerability overview display. In middle-level or detail-level displays, the matrices could be reduced to only keep the rows corresponding to the selected contingencies or contingency, or the columns corresponding to the selected power system element(s).

Concerning directions for future research, one promising approach would be to augment the visualizations to include information about the location of candidate controls to correct the contingent limit violations. For voltage violations, candidate controls could be the reactive power reserve of generators, LTC transformers, and available switched shunts of SVC devices. Example controls for overload correction could include generators with controllable real output, phase shifters and other power electronics devices such as UPFC and IPFC.

A second extension would be the consideration of multiple device and sequential outage contingencies. One potential approach would be to just define additional one-line "elements" representing the multiple device contingencies. For example, if a contingency involves opening three lines sharing a single right-of-way, the new contingency element could be shown on the one-line parallel to the three lines.

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.

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