Human Factors Aspects of Power System Voltage Contour Visualizations

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***Abstract*—This paper presents experimental results associated with human factors aspects of using color contours to visualize electric power system bus voltage magnitude information. Participants were divided into three groups: the first group saw only one-line numeric data, the second only one-line contour data, while the third saw both. The purpose of the experiment was to determine how quickly participants could acknowledge low-voltage violations and perform corrective control actions. Results indicated the contour only visualization resulted in the quickest voltage violation acknowledgment, while the numeric data only visualization resulted in the quickest solution times. Testing was done using a modified version of the IEEE 118-bus system.**

***Index Terms*—Contouring, human factors, power system operations and planning, voltage visualization.**

I. INTRODUCTION

DEREGULATION is having, and will continue to have, a tremendous impact on the design of power system operations and analysis software. In many regions, deregulation has resulted in the creation of much larger markets under the control of an independent system operator (ISO). This has resulted in even more buses to monitor and control. Simultaneously, the entry of many new players into the market and the increase in power transfers has resulted in more engineering studies to perform and more data to manage. Finally, system operators and engineers have come under increased scrutiny since their decisions, such as whether to curtail particular transactions, can have a tremendous financial impact on market participants. Accurate answers to rather complex questions are needed quickly, often in hours or minutes rather than in the previous days or weeks. Engineering analysis software and energy-management systems (EMSs) will need to be modified in a number of different ways to handle these new challenges. One such modification concerns how system information is presented to the user.

Traditionally, the information associated with power systems has been represented either as numerical fields on one-line diagrams, or by tabular list displays. Additionally, in a utility control center, an overview of the system has usually been available on a static map board with the only dynamic data shown using different colored lights. While these approaches may have been adequate to meet the needs of a vertically integrated utility, with restructuring they are increasingly inadequate.

To meet this need, over the last several years, a number of new visualization techniques have been developed with several of the more recent examples described in [1]–[7]. However, very little empirical research has been presented in the literature evaluating the effectiveness of these techniques (with the usability test described in [4] being one notable exception). The purpose of the present paper is to help address this shortcoming by presenting the results of a recent human factor experiment. The goal of these ongoing experiments is to provide the power system community with the results of carefully controlled studies to aid in the evaluation of the effectiveness of different visualization techniques, and thereby to provide guidance for the development of better power system visualizations. The present paper considers the use of color contouring on one-line diagrams to visualize bus voltage magnitudes.

II. APPLICATION OF CONTOURING TO ONE LINES

The earliest mention of color contouring to visualize voltage magnitude information on one-line diagrams is provided in [8] with results presented for the IEEE 118-bus system. A more detailed description, along with results applied to larger systems, is described in [9] and [10]. The application of contouring to visualize additional bus information, such as locational marginal prices (LMPs), and line flow information is presented in [11] and [12]. Finally, while integrated one-line contouring has been available for several years in offline study tools, its application to the real-time control center is more recent. Since summer 2001, contouring of real-time bus voltages magnitudes has been implemented in the Commonwealth Edison and Tennessee Valley Authority (TVA) control centers [13], [14].

The use of color contouring on one-line diagrams attempts to capitalize on the well-known benefits of color coding in the human factors literature. For example, color can be used as a highlighting feature that attracts attention to a particular area within a display, thus reducing the size of the search space [15] and for facilitating target detection [16]. Furthermore, the mental stage at which color codes are interpreted generally occurs early during perceptual processing whereas the interpretation of numeric codes generally occurs at a much later and more effortful cognitive level of processing [17]. Therefore, the speed in which color codes can be interpreted and compared is often faster than numeric processing. Thus, color contouring on one-line diagrams may facilitate the detection and comparison

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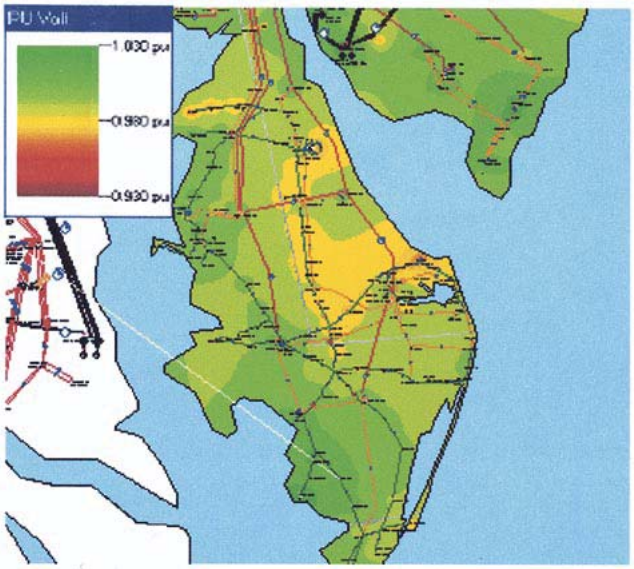

Fig. 1. Delmarva 69-kV voltages before IR2 outage.

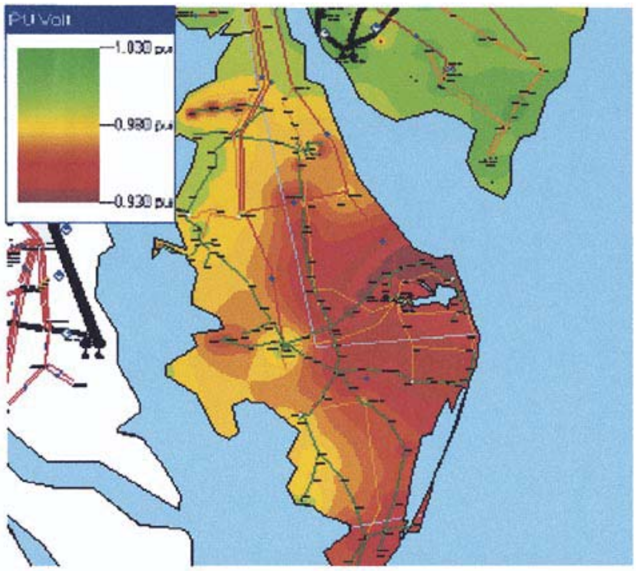

Fig. 2. Delmarva 69-kV voltage after IR2 outage.

of voltage violations in large power systems compared to traditional numeric coding.

As an example, Figs. 1–3 illustrate the use of contouring to show the variation in the per unit voltage magnitude at approximately 100 of the 69-kV buses on the Delmarva Peninsula (located in the U.S. Northeast). Fig. 1 contours the estimated July 6, 1999 voltages immediately before the loss of the 85-MW Indian River 2 Generator (IR2) at 10:35 A.M., while Figs. 2 and 3 show the estimated voltages immediately after the outage [18]. The first two figures use a continuous color mapping in which each bus voltage value is contoured, while Fig. 3 uses a color mapping in which only buses with voltages below a specified threshold are contoured (0.96 p.u. in this example) [10]. Such a mapping can be quite effective in highlighting the location of limit violations. Thus, Figs. 2 and 3 show the same information but use a different color mapping (Figs. 1 and 2 use the same mapping). Of course, color mappings could be tailored for individual preferences or needs. For example, some users might prefer red to show high voltages and blue to show low voltages, while colorblind users would need to use only color variations that they could perceive.

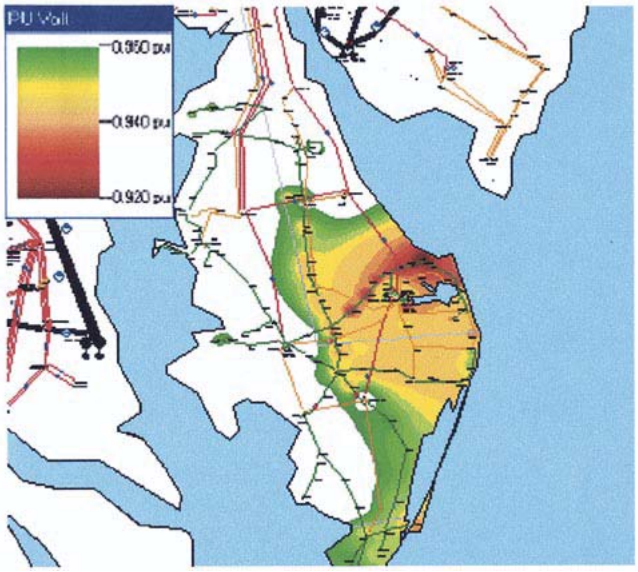

Fig. 3. Fig. 2 Case using limit highlight mapping.

There may; however, be certain costs and limitations to the use of color contours. For example, the number of colors that can be optimally used on a display are bounded by the human limits of absolute judgment. In using color contours, a user needs to differentiate between colors to understand what voltage value a color represents. Absolute judgment experiments have typically shown that errors begin to be made in discrimination tasks when five or six different stimuli exist. For example, [19] found that this guideline applied specifically to color as well when colors represented a value or meaning. Therefore, to avoid incurring costs, only five or six colors should be used to represent colors that must be categorized. A further cost associated with color is that no natural continuum exists. There is no inherent meaning that guides people to judge one color being greater or less in value along some dimension [17]. Finally, the issue of clutter is often involved with the use of color. Color, if not used carefully, can unintentionally conceal or hide important aspects of a display. This occurs by overlapping, blending, and inundating the display with multiple colors. Contours in one-line diagrams can often be of different sizes and invoke a number of different colors, which may inadvertently cover up numeric bus voltage fields or other one-line elements.

III. EXPERIMENTAL SETUP AND PROCEDURE

The purpose of this paper is to provide experimental results on the usefulness of such color contours. In a previous study by the authors, the benefits of color contouring on a one-line diagram were examined using a 30-bus power system [20]. In that study, color contouring was shown to have an effect on the strategy participants adopted for acknowledging voltage violations. Specifically, participants using a one-line display with contouring generally acknowledged the bus with the worst violation more often than the equivalent buses when the informa-

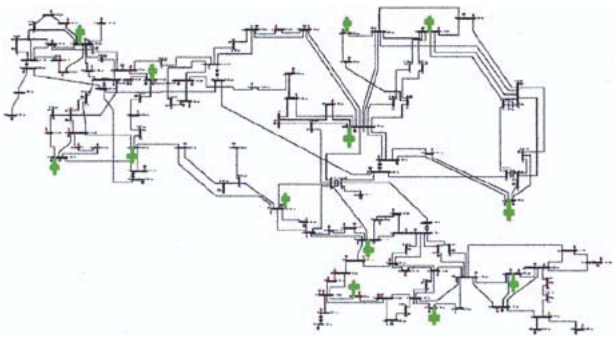

Fig. 4. One-hundred eighteen bus one line with capacitors.

tion was presented either with a tabular display or as numeric fields on a one-line diagram display without contours. Thus, the contours did prove beneficial for attracting attention to the bus with the worst (lowest) voltage magnitudes. Still, whether such benefits occur when larger and more realistic power systems are employed needs to be determined. Indeed, with an increase in grid size comes an increase in the potential cost associated with contouring, such as the possibility of exceeding the user's ability to process and compare multiple contour colors, as well the potential for increased clutter produced by multiple contour locations.

This paper addresses these issues by examining the impact of different voltage visualizations on the participant's ability to detect and resolve voltage violations. The study system consisted of a modified version of the IEEE 118-bus system, with the system augmented to include 13 switched capacitors. A one line of this system is shown in Fig. 4. During the experiment, the participants were each presented with a sequence of 30 different contingencies, with each contingency causing low voltages at one or more buses (with low defined here as being below 0.96 p.u.). The contingencies consisted of line and/or generator outages. The number of voltage violations per contingency ranged between one and 13 with an average of 5.2.

Following each contingency, the presence of voltage violations was indicated both audibly (having the computer beep) and visually on the one line, using one of the three display conditions described in Section IV. The participants were then required to perform two consecutive tasks. First, in the detection task, they had to acknowledge the bus with the worst (lowest) voltage magnitude. This task indicated that they had identified the location of the worst voltage violation. A bus voltage violation was acknowledged by clicking on the one line at (or near) its bus symbol.

Upon acknowledgment of the correct bus, the audible alarm was terminated and the second or solution task begun. In the solution task, participants had to take corrective control action to restore all of the bus voltages to values above 0.96 p.u. The voltages were corrected by closing one or more capacitors, with all capacitors initially in the open state at the start of each contingency. Elapsed time and level of accuracy for both the detection and the solution tasks were recorded.

The study used 43 participants (38 men and five women), which is a typical sample size for human factors laboratory research. All participants were students who had been recruited from electric power systems classes at the University of Illinois at Urbana-Champaign (potential participants who identified themselves as being colorblind were not included in the study). Each participant was required to have either completed, or be currently enrolled in, at least one class in the electric power systems area. Therefore, all participants had at least some familiarity with basic power system terminology and the use of one-line system models. The participants worked independently and were each presented with the exact same sequence of the 30 contingencies. They were told that accuracy and speed were important, and were paid U.S.$12 for their 1-h participation. The experiment was conducted using a graphical power system analysis package using an underlying full ac power-flow model of the system. Graphical one-line results were presented on a 20-in color monitor with all user input done with a mouse.

To assess the effectiveness of one-line voltage contours, the participants were randomly assigned to one of three groups: the number-only group ($n = 15$), the contour-only group ($n = 14$), or the number-plus-contour group ($n = 14$). Random assignment was used to ensure that group members were, on average, virtually identical in all respects, such as age, education, and experience with electrical power systems. The only difference between the groups, therefore, was the display condition used to show the voltage violations. The participants in each group were provided with specific instructions about their display and their tasks. They were asked to read through the entire instructions and inform the experimenter when they were ready to proceed or to ask questions that they had.

The 30 contingency trials were divided into four practice trials and then 26 experimental trials, with only the results of the experimental trials used. Following the fourth practice trial, the participants were again given an opportunity to ask questions. Each trial began with the same base case condition, characterized by no voltage violations. Then, after a time delay of between five and 15 s, a contingency occurred, signaled by both the computer beeping and one of the display conditions described in Section IV. The same buses incurred voltage violations across the three display conditions during each trial, but the buses that incurred voltage violations changed from trial to trial. Participants were requested to be quick and accurate in acknowledging and solving the voltage violations. After all of the voltage violations for a trial have been successfully corrected, a pop-up screen informed the participant of the successful solution. Participants then proceed to the next trial by clicking "OK." Testing was terminated at the completion of all 26 trials.

IV. DISPLAY CONDITIONS

Participants in the study completed the task using one of three display conditions, all of which were derived from the one-line diagram shown in Fig. 4. The different display conditions were 1) number only: a one-line diagram with numbers showing the per unit voltages; 2) contour only: a one-line diagram with color contours showing the per unit voltages; and 3) number plus contour: a one-line diagram with both numbers and color contours.

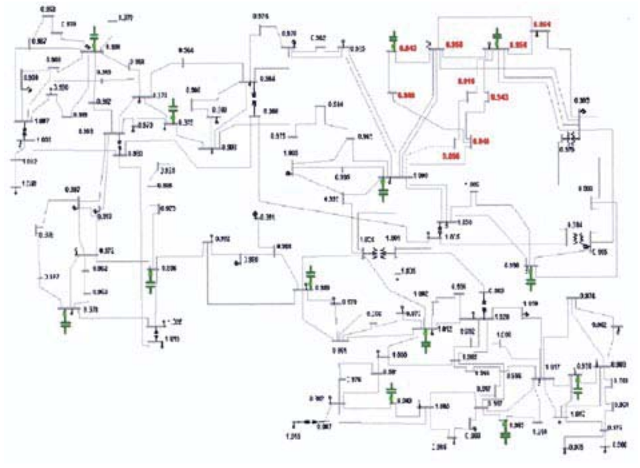

Fig. 5. Number-only one line.

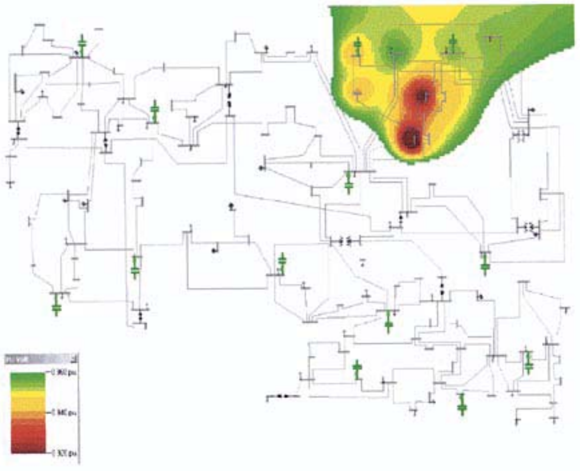

Fig. 6. Contour-only one line.

A. Number-Only

In the number-only group, the Fig. 4 one line was augmented to include numeric bus voltage magnitude fields for each of the 118 buses. The bus voltage values were shown as black numbers beside the associated buses, each with three digits to the right of the decimal point. Voltage values dynamically changed as the system state varied. Initially, all of the voltages were above the 0.96-p.u. limit. Then, following the contingency, one or more of the voltages would be below this limit. Voltage values below the limit were shown using a larger, bolded red font, with their height on the one line changed from 2 to 4 mm. Fig. 5 shows an example of the number-only display. Following the contingency, the participants were first requested to acknowledge the bus that has the worst (lowest) per unit voltage by clicking the one line on either the bus symbol itself or the associated red numeric voltage field. Once the worst voltage violation had been acknowledged, the beeping would stop.

Then, the participants were asked to correct the low voltages by switching in one or more capacitors, an action performed by clicking on the capacitor symbols. When a capacitor was open, its small circuit breaker symbol (shown on the bus side of the capacitor) was an unfilled green rectangle. When the capacitor was closed, the circuit breaker changed to a red-filled rectangle. Participants were not able to perform capacitor switching until the worst voltage violation had been acknowledged. As the participants switched the capacitors, a power flow was automatically solved, with the one-line display updated with the new voltage values. Power-flow solution and the display refresh took less than 0.1 s. When all of the voltage problems were fixed, a popup window told the participant that the trial was complete; the next trial began when they clicked the "OK" button on this window.

B. Contour Only

In the contour-only group, the Fig. 4 one line was augmented to include a color contour of the voltage values; no numeric voltage fields were shown. The contour color mapping used was identical to that shown in Fig. 3. That is, as long as there were no voltage violations, there was no contour. But when a voltage limit violation occurred, the region surrounding the bus experiencing the low voltage became shaded using a contour pattern that ranged from green to yellow to orange to dark red, with the dark red indicating the lowest voltage. The size and the color of the contour were scaled according to the severity of the bus voltage. A color key was shown on the bottom left-hand side of the display. No contours were shown for buses with acceptable voltages. Fig. 6 shows an example of this display condition.

Voltage violations were acknowledged by clicking directly on the symbol of the bus with the worst violation or on the darkest part of the contour. Once the worst violation was acknowledged, the beeping would stop. Then, in a nearly identical procedure to the number-only group, the voltage violations were corrected by capacitor switching. The difference with this group was that as the participant switched the capacitors, the contour would be dynamically updated to indicate the new voltage values. Due to the additional processing associated with redrawing the contour, the power-flow solution/display update step took slightly longer, approximately 0.35 s. Again, when all the voltage problems were fixed, the trial would automatically end.

C. Number Plus Contour

The one-line diagram with both numbers and color contours was a combination of the first two display conditions in that the voltages within limit were shown in small black numbers, and when the voltage violations occurred the voltages below limit, would turn to large bolded red font surrounded by a white box, and, at the same time, the region surrounding the bus experiencing the low voltage became shaded using the same contour pattern used with the contour-only group. Acknowledging and solving voltage violations was identical to the procedure for the other two conditions. Fig. 7 shows an example of this display condition. The time for the power-flow solution/display refresh was similar to the contour-only group, approximately 0.35 s.

V. RESULTS AND DISCUSSION

The experiment examined the impact of the display conditions on acknowledgment time and accuracy, and on solution time and accuracy. Due to the varying complexity of the contingency trials, defined here as the number of contingent voltage violations, the trials were subdivided into three groups with metrics calculated for each group. The three groups were low (those

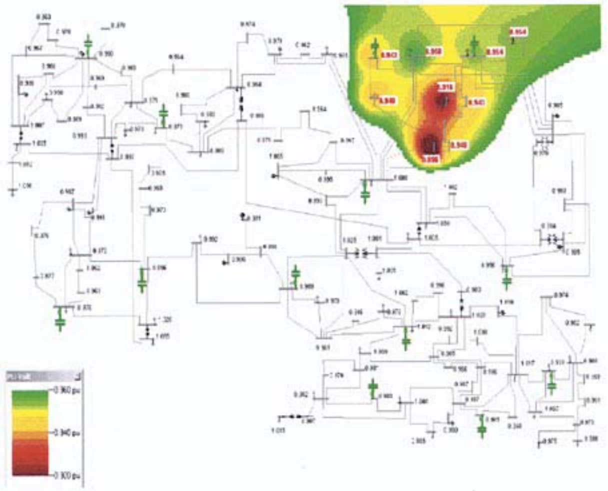

Fig. 7. Number-plus-contour one line.

TABLE I
AVERAGE ACKNOWLEDGEMENT TIME IN SECONDS PER CONTINGENCY

Display	Complexity Group			All
	Low	Medium	High	
Number	2.49	3.68	5.74	3.81
Contour	2.33	2.47	2.33	2.37
Number & Contour	2.58	3.23	3.38	3.00

TABLE II
AVERAGE NUMBER OF ACKNOWLEDGEMENTS PER CONTINGENCY

Display Condition	Complexity Group			All Groups
	Low	Medium	High	
Number	1.01	1.11	1.28	1.12
Contour	1.06	1.06	1.03	1.05
Number & Contour	1.06	1.06	1.06	1.06

trials causing less than five voltage violations), medium (between five and eight violations), and high (greater than eight violations). The number of trials in each group were 11, 7, and 8, respectively.

Statistical analysis revealed that acknowledgment times did not differ significantly across display conditions for the low complexity trials. However, as shown in Table I, acknowledgment times consistently increased with complexity for the number-only group, yet increased only slightly for the number-plus-contour group, and did not increase at all for the contour-only group. Therefore, acknowledgment times did differ significantly ($p < 0.05$) between display conditions for the medium and high complexity trials. Specifically, the average time for the contour-only group was significantly less on both medium and complex tasks than that of the number-only group and the number-plus-contour group. Although the average acknowledgment time for the number-plus-contour group was also generally less than that of the number-only group, this difference was particularly significant ($p < 0.05$) only for the high complexity trials.

The number of acknowledgments that participants made per trial was used as a measure of acknowledgment accuracy, with fewer acknowledgments reflecting a greater level of accuracy. As shown in Table II, acknowledgment within the contour-only and number-plus-contour groups differed only slightly across different complexity levels, but the number of acknowledgment for the number-only group increased consistently with trial complexity. Statistical analysis revealed that for the high complexity trials, the number of acknowledgment for the number-only group was consistently higher ($p < 0.05$) than for those of the contour-only group and the number-plus-contour group, whereas the number of acknowledgments for the number-plus-contour group was not significantly different from that of the contour-only group. Note, on the 30 contingent trials considered here, the use of three digits to the right of the decimal point ensured the bus with the lowest voltage magnitude was always uniquely identifiable for number-only and number-plus-contour groups. The higher level of wrong acknowledgments for these groups was not due to two buses having the same apparent voltage value displayed on the one line.

The finding that participants performed the voltage acknowledgment task both quicker and more accurately with just the contours is noteworthy because previous reaction-time research has shown a *speed–accuracy tradeoff*. That is, as people respond more rapidly, they tend to make more errors [21]. This reciprocity between response latency and errors; however, was not evident in the contour-only group. This finding indicates that participants in this group were not just quickly and haphazardly attempting to located the bus with the lowest voltage magnitude. Rather, the contours allowed them to quickly and consistently focus their attention on the bus with the lowest voltage.

A second noteworthy finding is the independence of the contour-only group between acknowledgment time and contingency complexity. Regardless of the number of voltage violations (at least up to the maximum of 13 considered here), the contour-only group was able to quickly and accurately identify the lowest voltage bus, performing the task in less than half the time of the number-only group. This is exactly the type of performance one would like from a visualization, particularly for use in an EMS.

While most EMS operations are usually characterized by routine events with perhaps a few simultaneous alarms, events such as the near voltage collapse on July 6, 1999 of the Delmarva Peninsula highlight the need for effective power system visualizations [18]. In the July 6th event, the loss of the 85-MW Indian River 2 generator resulted in approximately 85 low-voltage alarms within the first 2 min. Had the operators not immediately shed load, a voltage collapse of the peninsula was a distinct possibility.

While experimental results presented here did not include such widespread voltage violations, a visual comparison of Figs. 3 with 7, coupled with the results of Tables I and II, appear to support a hypothesis that color voltage contours could be quite effective in focusing the user's attention on the areas of the system with the most depressed bus voltages. This benefit should occur both in online application and in offline study analysis. In the offline context, response time to any particular problem is, of course, less critical. Nevertheless,

TABLE III
AVERAGE SOLUTION TIME IN SECONDS PER CONTINGENCY

Display Condition	Complexity Group			All Groups
	Low	Medium	High	
Number	2.26	3.52	5.11	3.48
Contour	3.36	5.60	8.63	5.58
Number & Contour	4.78	8.63	7.80	6.75

TABLE IV
AVERAGE SOLUTION TIME IN SECONDS PER CONTINGENCY AS A FUNCTION OF CAPACITOR COVERAGE

Display Condition	Capacitor Status		Both States
	Uncovered	Covered	
Number	3.64	2.93	3.48
Contour	5.38	6.26	5.58
Number & Contour	5.78	9.96	6.75

with the need for engineers to often perform many power-flow studies, coupled perhaps with extensive contingency analysis, the use of contours to help them quickly assess the extend of voltage problems could be a welcome enhancement.

The second task in the experiment examined the impact the display conditions had on solution time and accuracy. Here, the solution task required the participant to close one or more capacitors to correct the contingent voltage violations; usually the contingent violations could be corrected with the insertion of one or two capacitors. The results revealed that solution times for the number-only group were significantly faster ($p < 0.05$) than for the number-plus-contour group and the contour-only group. However, solution times were not significantly different between the contour-only and the number-plus-contour groups. As shown in Table III, except for the number-plus-contour group, solution times increased as the contingencies became more complex.

This finding was surprising, given the exact numeric voltage values were not needed to remedy the problem. One possible explanation was that the contours created display clutter that hindered solution times by covering up the capacitors necessary to solve the violations. This explanation is also consistent with comments in a post-experiment questionnaire, in which some noted display clutter as a problem.

To examine this hypothesis, the scenarios were parsed according to whether the contours significantly covered the capacitors ($n = 6$) or did not cover any capacitors ($n = 20$). As shown in Table IV, the differences in solution times between the groups were much less on trials in which the capacitors were uncovered than on trials in which they were covered. Nevertheless, solution times were still significantly faster for the number-only condition. It should be noted that, as mentioned in Section IV, the presence of the contour on the contour-only and number-plus-contour displays did impose a slightly increased refresh time (0.35 versus 0.10 s for number only). This time delay may have contributed at least partially to the increased times for the contour display conditions.

The number of capacitors used per trial to solve the voltage violations was examined as a measure of performance efficiency, with fewer capacitors closed reflecting more judicial use of system components. As shown in Table V, the average number of capacitors used per trial for the number-only group was significantly lower than that of the number-plus-contour group and the contour-only group. But the number-plus-contour group did not significantly differ from the contour-only group.

TABLE V
AVERAGE NUMBER OF CAPACITOR SWITCHINGS PER CONTINGENCY

Display Condition	Complexity Group			All Groups
	Low	Medium	High	
Number	1.16	1.45	1.98	1.49
Contour	1.23	1.84	2.04	1.64
Number & Contour	1.24	1.87	2.01	1.65

TABLE VI
AVERAGE NUMBER OF CAPACITOR SWITCHINGS PER CONTINGENCY AS A FUNCTION OF CAPACITOR COVERAGE

Display Condition	Capacitor Status		Both States
	Uncovered	Covered	
Number	1.52	1.40	1.49
Contour	1.59	1.83	1.64
Number & Contour	1.54	2.00	1.65

Solution accuracy was also analyzed as a function of the capacitor status (covered versus uncovered) to explore issues of contour clutter (Table VI). As expected, the number of capacitors used to solve the contingency did not significantly differ between the display conditions for the uncovered trials, but did differ significantly for the covered trials. Specifically, on the covered trials, the number of capacitors used to solve for the number-only group was significantly less than that of the number-plus-contour group and the contour-only group. The number-plus-contour group did not significantly differ from the contour-only group.

The significance of the increased solution time between the number-only condition and the contour-only conditions depends upon the application. In an EMS implementation, in which switching is usually performed on a detailed substation one line, the impact might not be significant. The contour could be used on a system overview display, helping to quickly show the operator the areas of concern. Then, by perhaps poke points, the operator could switch to the pertinent, detailed substation one line, which would not contain a contour, to take the actual corrective action. In offline study analysis, only the acknowledgment functionality might be needed—the user might only be required to determine the extent of problems without taking corrective action. If such action is required, it could be accomplishing by dimming out or completely removing the contour, thereby gaining the advantages of contouring in problem detection without its detriments in problem correction.

VI. CONCLUSION

Color contouring was expected to attract users' attention to the worst voltage violations, thereby facilitating both acknowledgment speed and accuracy compared to a numeric display. This hypothesis was generally confirmed, particularly when a large number of violations simultaneously existed within the power grid. However, the benefits of contouring also came with a cost—contouring generally slowed the speed and accuracy by which users could solve or remove the voltage violations within the system compared to the numeric display. An in-depth analysis revealed the nature of this cost was due, at least in part, to the increased display clutter associated with the contouring. The contours were covering up the relevant capacitors thereby delaying their selection.

Remedying this cost/benefit tradeoff between contours and numbers does not appear to be as simple as combining the two display features. Indeed, under certain conditions, the combination of these features in the display was found to produce worse performance than either display feature individually. Apparently, users are not able to ignore one dimension (e.g., numbers) while using the other (e.g., contours). An alternative option may be to incorporate dimming features that can be used to make the relevant color or numeric code more salient, or a toggling feature that allows users to switch each feature on or off depending on the particular task. Still, whichever features are chosen, the present study underscores the need for formal usability and human factors research to test the effectiveness of specific visualization techniques.

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