# Human Factor Aspects of Power System Flow Animation

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***Abstract*—This paper presents experimental results associated with human factor aspects of using animation to display electric power system flow information, including transmission line megawatt flow and power transfer distribution factor (PTDF) values. The paper's results are based on two experiments performed at the University of Illinois at Urbana-Champaign using electric power system students. The results indicate that animated motion of power system flows can be used successfully in displays to improve both the speed and accuracy of certain tasks. This effect was most apparent on displays showing PTDFs. However, the results also show that motion may not provide a clear advantage in the visualization of transmission line flows for uncomplicated analysis tasks.**

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

## I. INTRODUCTION

IN MANY regions around the world, deregulation has resulted in the creation of much larger power markets, often under the control of an independent system operator (ISO). For example, in North America, PJM oversees the operation of a single control area that supplies electric power to over 25 million people, while the Midwest ISO (MISO) oversees the operation of more than 20 control areas with over 150 000 km of transmission lines. The net result has been an increased need for power system operators and engineers to quickly process a vastly increased amount of information. To meet this need, engineering analysis and energy management system (EMS) software will need to be modified in a number of ways, including how system information is presented to the users.

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. Over the last several years, this pattern has begun to change as new visualization techniques are developed and integrated into utility control centers. For example, [1] and [2] describe the online usage of animated flows, voltage contours, dynamically sized pie charts, and interactive 3-D displays.

However, very little empirical research has been presented in the power system literature evaluating the effectiveness of these newer techniques. Over the last decade, the only such papers known to the authors addressing the effectiveness of power system visualizations are [3], which looked at voltage profile visualization, and [4]–[6], which looked at the applicability of bus voltage contouring. The purpose of this paper is to present the results of human factor experiments looking at the power system flow animation.

## II. BACKGROUND ON FLOW VISUALIZATION AND ANIMATION

Power engineers have long been concerned with studying how power (real, reactive, and complex) flows through the transmission network. As the transmission system models have increased in size, with large models now having tens of thousands of buses and lines, the question of how to represent the results has grown in importance. Numeric fields on one-lines and tabular listings showing the exact power flows and percentage loadings can be crucial. However, for medium to large systems, such approaches need to be supplemented to give an overall view of the system. More recently, due to the growing popularity of power transfer distribution factors (PTDFs) [7], [8], the flow representation issue has also been expanded to include PTDFs. PTDFs are used extensively in the operation of the North American electric grid.

Several approaches have been suggested in the literature to supplement numeric fields for transmission flow visualization, including dynamic sizing of the transmission line size on the one-line [9], [10], animated flows [11], [12], and dynamically sized pie charts to show the percentage loading of the lines. This paper focuses on the application of animation.

A survey of the broader human factors literature is promising, since animated displays have been shown to improve operator performance in other disciplines in a variety of ways [13], [14], [27]. For example, motion can help operators interpret displays by directing their attention to the most important information for a particular task or situation, by helping them extract high-level information that requires integration of multiple display elements and by enhancing the operator's understanding and knowledge of the current state and behavior of the system. Studies have also shown that people can selectively direct their attention to only the moving items in a display and can quickly find a unique feature among the moving items, such as red arrows among green arrows [15]. They can also quickly find

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fast-moving elements among slower-moving elements [16], an effect that is enhanced by greater differences in movement speed [17]. In addition, viewers respond faster to the sudden onset of a moving indicator if it is moving faster [18], [19].

Research has demonstrated that the human eye has specialized detectors that differentiate between translating, rotating, expanding and contracting, and deforming motion [20], which suggests that these patterns could be used in displays to direct a viewer's attention. Expansion and contraction lend themselves well to displaying power flow data because they appear to be moving faster than, and may be detected more easily than, translation at the same real speed [21]–[23] and because they are orthogonal motions that can be used to indicate positive and negative values unambiguously. The motion patterns created by multiple moving elements are perceived as a single object when they move at similar speeds and in similar directions [24], [25], an effect called common fate, which can still operate when the elements' trajectories diverge or converge [26], as in expansion and contraction.

Researchers have also stated that motion can aid in the understanding of the dynamic behavior of a system. Quoting from [13, p. 676], "[animated mimic] displays can improve real-time performance by (1) contributing to an individual's ability to assess current system state and the causal factors that underlie that state, (2) illustrating alternative system resources that can be used to avoid or recover from the violation of system goals, and (3) providing immediate feedback regarding the effectiveness of control input." This has been confirmed by studies in computer-based instruction showing that participants performed better on tests of electronic troubleshooting after being instructed with displays showing current flow, circuit device behavior, and troubleshooting procedures with animation rather than with static displays that indicated current flow with arrows or did not indicated current flow at all [27].

However, motion should be used in displays with care, since it may not always improve performance. Motion and dynamic changes in task-irrelevant areas of displays can cause distraction and increase search times, especially if the motion is incoherent, moving in multiple directions, or at different speeds [15], [28]. It has been shown that this problem can be reduced if moving distracters can be differentiated from moving targets by some feature, such as color [29]. For instance, overloaded lines can be indicated by both faster moving arrows and by highlighting the arrows with a color that indicates an abnormal condition.

## III. EXPERIMENT OVERVIEW

This paper investigates the use of motion to indicate power flow in power systems displays by presenting results of two human factor experiments. The first experiment examined the usefulness of animation for transmission line flow visualization. The experiment compared line overload detection and resolution performance using a 30-bus system, with the power flow indicated on a one-line by either numeric fields, stationary arrows, or moving arrows. Hence, this experiment might mimic, at least to some extent, the task a power system operator may need to perform during an emergency situation of determining the extent of transmission system overloads and of initiating preventative control.

The second experiment examined the usefulness of animation for PTDF visualization by comparing subject performance in analyzing power transactions. In this experiment, subjects needed to determine buyers and sellers, and a common path between them, utilizing a one-line diagram that indicated the PTDFs using either stationary arrows, arrows that moved at a uniform speed, or arrows that moved at a speed proportional to the PTDF value on each line. Here, the experiment seeks to simulate (again to some extent) the task of a power system analyst of determining the impact of proposed power transactions on the grid.

A key difference between the two experiments is the relationship between the flow on elements incident to the same node. With the PTDF experiment, in which power is assumed to be injected into the network at a single location (i.e., the seller) and withdrawn at a single location (i.e., the buyer), the PTDFs appear to radiate from the buyer to the seller. In contrast, in the first experiment, in which there are a number of sources of power (i.e., the generators) and a number of sinks (i.e., the loads), the line flows appear to be much less ordered. Our supposition is that the PTDF display, with its animated expanding pattern of arrows out from the seller and the contracting pattern of arrows into the buyer, will focus attention on these points. Such patterns, which are known as configural displays, can support both detection and diagnosis tasks due to the ability to direct attention to either the high-level or low-level information [30].

## IV. FIRST EXPERIMENT SETUP AND PROCEDURE

The study system used in the first experiment had 30 buses, 43 transmission lines, and 10 generators. A one-line of this system is shown in Fig. 1. During the experiment, the participants were each presented with a sequence of 29 trials (each received the same contingency sequence). A trial initially started with no transmission line overloads. Then, following a delay of between 2 and 15 s, a contingency occurred, causing overloads on one or more of the transmission lines. All contingencies were either single or multiple line outages. Following the contingency, overloads were indicated visually on the one-line using one of the six different display types discussed in the next section. Half of these display conditions included transmission line loading pie charts (as shown in Fig. 1), and half did not. Overloads were also indicated audibly by a continuous, beeping alarm.

After each contingency, the participants acknowledged either the worst power violation, for the displays with pie charts, or every violation, for the displays without pie charts. This was done by clicking on either the appropriate line's numeric display of the line loading, on the line's pie chart, or on the line itself. After acknowledging the violation(s), participants solved each violation by adjusting the megawatt output of one or more of the generators. This was done by clicking on the up or down arrows in the highlighted generator megawatt fields shown by each generator (see Fig. 1). Each trial continued until either all violations were solved, or it timed out after 120 s.

The experiment had 88 participants, 70 men and 18 women, with self-reported normal color vision. All participants either had completed or were currently enrolled in power system

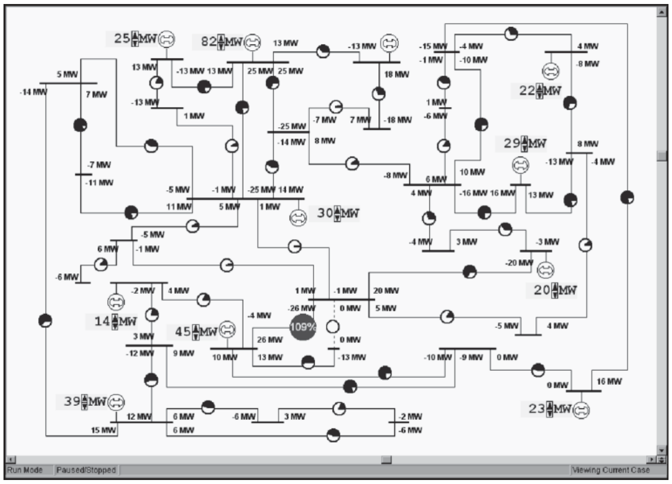

Fig. 1. Experiment 1: 30-bus system.

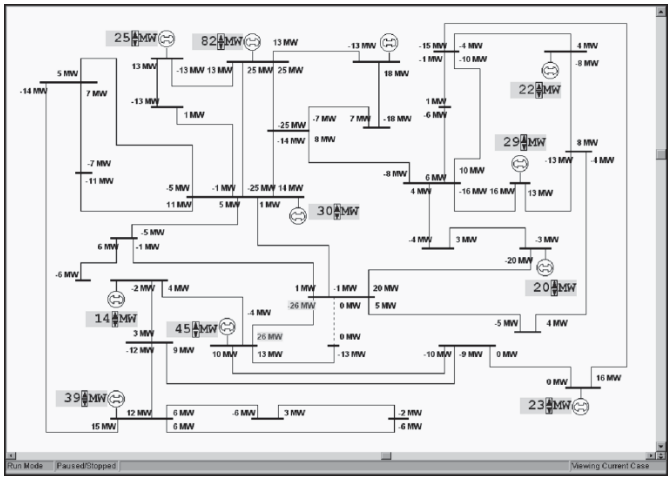

Fig. 2. Digital-only one-line.

classes taught in the Department of Electrical and Computer Engineering (ECE), University of Illinois at Urbana-Champaign (UIUC); the gender percentages are roughly proportional to the enrollment in the UIUC ECE power classes. Participants were randomly assigned to one of the six display groups discussed in the next section, except that the 13 participants who had participated in previous electric power systems display experiments were distributed as evenly as possible. Each group had either 14, 15, or 16 participants. The experiment consisted of four practice trials and 25 experimental trials, which were completed in less than one hour. After the final trial, the participants completed a post-experimental questionnaire, which included the NASA-TLX subjective workload assessment [31].

## V. FIRST EXPERIMENT DISPLAY TYPES

Participants completed the experimental tasks using one of six display types, with each display type based upon the 30-bus system shown in Fig. 1. The display types are 1) the digital-only display, 2) the digital-with-pie-charts display, 3) the stationary-arrows-only display, 4) the stationary-arrows-with-pie-charts display, 5) the moving-arrows-only display, and 6) the moving-arrows-with-pie charts display. The digital-only (see Fig. 2) and digital-with-pie-charts (see Fig. 1) displays indicated power flow with numeric fields (digits) at the end of each line showing the megawatt flow into the line (negative values indicated flow out of the line into the bus). The stationary-arrows-only (see Fig. 3) and stationary-arrows-with-pie-charts (see Fig. 4) displays indicated power flow with stationary arrows superimposed on each line, with the arrows pointing in the direction of power flow, having a size proportional to the magnitude of megawatt flow. Hence, these displays did not use numeric fields to indicate the magnitude of the power flow. The moving-arrows-only (see Fig. 3) and moving-arrows-with-pie-charts (see Fig. 4) displays were identical to the corresponding stationary display types, except that the arrows were animated with the speed of the arrows proportional to the magnitude of the power flow on each line.

Transmission line overloads were indicated slightly differently on the six displays. In the digital-only display, overloads were indicated when the power flow digits associated with a line turned from black to red with a yellow background. The stationary-arrows-only and moving-arrows-only displays indicated overloads when the arrows associated with overloaded lines changed from green with a thin, black outline to red with a thick, yellow outline. In the three displays with pie charts,

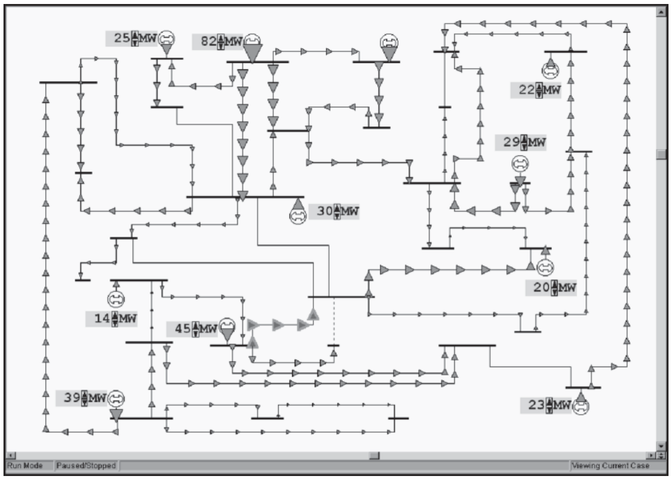

Fig. 3. Stationary- or moving-arrows-only one-line.

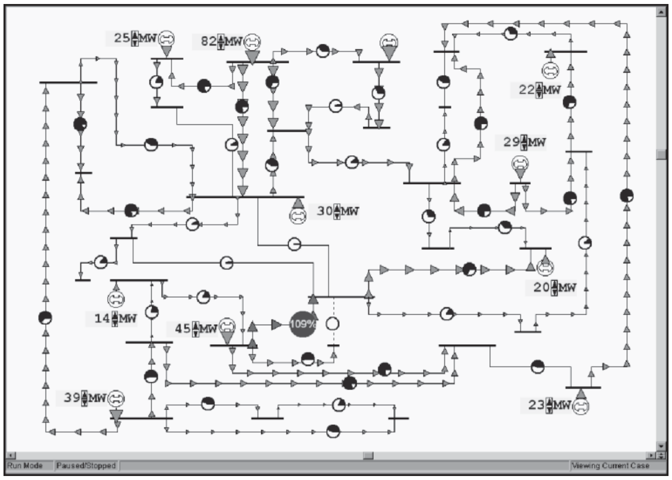

Fig. 4. Stationary- or moving-arrows-with-pie-charts one-line.

TABLE I
SOLUTION TIME IN SECONDS

| **Problem Complexity** | **Display Type** | | |
|---|---|---|---|
| | Digital | Static Arrows | Moving Arrows |
| Single Viol. | 8.5 | 9.8 | 11.3 |
| Multiple Viols. | 23.6 | 21.8 | 20.4 |

TABLE II
NUMBER OF GENERATORS USED PER TRIAL

| **Problem Complexity** | **Display Type** | | |
|---|---|---|---|
| | Digital | Static Arrows | Moving Arrows |
| Single Viol. | 1.43 | 1.52 | 1.58 |
| Multiple Viols. | 2.59 | 2.60 | 2.42 |

the pie charts on overloaded lines enlarged and turned from blue to red with centered yellow digits indicating the loading percentage. In addition, the arrows associated with overloaded lines in the stationary- and moving-arrow displays changed from green to red. The contingent opening of a transmission line was indicated on all six displays by a dashed line and the pie chart, if present, becoming completely empty.

It is important to note that the size and speed of the arrows in the stationary- and moving-arrow displays were proportional to line's megawatt flow, not its percentage loading. Hence, a low-capacity line could be in violation with much smaller and slower arrows than a high-capacity line loaded below its limit. Their reason for making the arrows' size and speed proportional to the megawatt flow was because the experiment was testing the validity of replacing the megawatt fields in Fig. 2 with the arrows—the arrows needed to represent the same information.

## VI. FIRST EXPERIMENT RESULTS AND DISCUSSION

For reporting the results, display types 1) and 2) are grouped as "Digital," 3) and 4) as "Static Arrows," and 5) and 6) as "Moving Arrows." Also, the trials are differentiated based upon whether the contingency caused a single violation or multiple violations (i.e., problem complexity). Table I shows the mean solution times per trial by display type and problem complexity. The presence of pie charts did not significantly affect solution times. Solution times were fastest in the moving arrows display groups, followed by the stationary arrows and digital display groups for multiple violation trials. In addition, the increase in solution time as the number of violations increased—from single to multiple—was lowest for the moving arrows display followed by the stationary arrows and digital displays ($p = .018$).

Table II shows the mean number of generators used to correct each trial, again as a function of display type and problem complexity. Participants in the moving arrows display groups used fewer generators in multiple violation trials than those in the other groups, and the increase in the number of generators used as the number of violations increased was lowest in the moving arrows display groups ($p = .044$). Pie charts, however, as shown in Table III, improved efficiency in multiple violation trials and reduced the difference from single violation trials ($p = .015$).

Also, an analysis of the "adjustment error" indicated that participants using pie chart displays made fewer errors (mean of 1.69 per trial) than those using displays without pie charts (3.09 per trial). Here, an adjustment error is defined as a generator megawatt adjustment that increased the load on at least one already overloaded transmission line that did not also decrease the load on any other overloaded lines or that could have produced those effects in the case of an attempt to adjust a generator already at its minimum or maximum output.

TABLE III
EFFECT OF PIE CHARTS ON NUMBER OF GENERATORS USED PER TRIAL

| **Problem Complexity** | Without Pie Charts | With Pie Charts |
|---|---|---|
| Single Viol. | 1.48 | 1.58 |
| Multiple Viols. | 2.65 | 2.43 |

TABLE IV
NASA-TLX WORKLOAD SCORES EXPANDED ACROSS PIE CHART PRESENCES AS A FUNCTION OF DISPLAY TYPE

| **Pie Charts** | **Display Type** | | |
|---|---|---|---|
| | Digital | Static Arrows | Moving Arrows |
| Without | 28.8 | 36.3 | 39.8 |
| With | 35.6 | 32.9 | 29.6 |

Workload, as assessed subjectively for mental demand, physical demand, temporal demand, performance, effort, and frustration level, by the participants on a scale from 0 to 100, using the NASA Task Load Index (TLX), was affected both by the display type and the presence of pie charts, as shown in Table IV. Participants rated workload as lowest with the digital display when pie charts were not present but rated workload as lowest with the moving arrows display when pie charts were present, with the stationary arrows display workload scores falling in the middle of both cases ($p = .037$).

For the more complex trials, the arrows aided the participants in resolving violations by reducing the amount of time required to determine the power flow patterns compared to the digital display, which required mental conversion of the numbers or exploratory generator adjustments to determine power flow directions. Adding motion reduced solution times further and helped the participants determine the best generators to use by displaying power flow directions and magnitudes dynamically, as predicted by [13] and consistent with the results of [27].

The presence of pie charts in the displays improved generator use efficiency and reduced the number of adjustment errors because the digital values indicating the percentage loading on the overloaded lines were more sensitive to generation adjustments than changes in arrow size or speed and were easier to monitor than the digital values in the digital displays, due to their large size and unique shape and coloring. In the displays without pie charts, the participants could have adjusted a generator in the wrong direction, increasing the overloads on lines for many adjustments before realizing that the power flow digits were increasing or that the arrows were increasing in speed and/or size on the overloaded lines, whereas increases in the numbers on the pie charts were easy to detect. In addition, the pie charts provided unique information about the magnitudes of the overloads that was not provided by the arrows or digital power flow values. The overload information allowed the participants to see which violations were most critical and determine which lines were near their upper capacity limit to avoid overloading new lines while adjusting generators.

The presence of pie charts modified the effect of display type on workload. Without pie charts, workload was rated highest for the moving arrow display and lowest with the digital display, perhaps due to distraction caused by the moving arrows throughout the moving arrow display and by the changes in the arrow sizes in the stationary arrow display, as discussed in [29]. Apparently, the pie charts overrode this distraction effect and even made the tasks easier when combined with arrows and motion. This may have been due to the earlier-mentioned fact that the pie charts were more sensitive to the effects of generator adjustments than the arrows and provided information that the arrows did not.

## VII. Second Experiment Setup and Procedure

The second experiment also looked at flow animation but with the focus changed to PTDF visualization. The study system was a 55-node 148-branch system that was a rough equivalent of much of the electric grid in the eastern part of North America. The nodes corresponded to different operating areas, while the branch reactances approximated the equivalent impedance between the areas; resistive losses were ignored. A one-line diagram of this system is shown in Fig. 5. Again, during the experiment, the participants were presented with a sequence of trials. However, rather than showing actual megawatt flows, the one-line was used to visualize the PTDFs for transactions between various buyer/seller pairs. Each trial initially started with no transaction. Then, following a delay of between 2–12 s, a transaction between a buyer/seller pair was shown on the one-line. The transaction was indicated visually using one of the three different display types discussed in more detail in the next section. All display types used magenta-colored arrows on the branches to indicate the direction and magnitude of the PTDFs; the display types were differentiated based upon the type of arrow animation.

For each trial, participants were required to perform up to two consecutive tasks. First, they needed to search for and select the buying and selling area (in any order). The buying area was indicated by inbound arrows on all the branches connecting it to other areas, while the selling area was indicated by outbound arrows on all its incident branches. If the buyer and seller were directly connected, the trial ended as soon as both were selected. Otherwise, the participant's second task was to select any set of areas that formed a complete path between the buyer and seller. The participants could select any areas other than the buyer and seller, and the trial ended as soon as any subset of the selected areas formed a complete path.

The experiment included 49 participants, 41 men and 8 women, who were again recruited from UIUC ECE power systems classes. Once again, an entrance questionnaire was used to screen out colorblind participants (two in this experiment). Each participant was randomly assigned to one of the three display types, with either 16 or 17 in each.

Each participant was administered four practice trials and 50 experimental trials. The 50 experimental trials were divided by buyer-seller connection type into 15 trials where the buyer and seller were directly connected to each other and 35 trials where the buyer and seller were not directly connected. The trials were identical across the three display types. The participants were allowed a maximum of 60 s to complete each trial. When the buyer and seller had been selected, and, if they were not directly connected, a path connecting them had been selected, or time had run out, the trial ended. After the final trial, the participants completed a post-experimental questionnaire, which included the NASA-TLX subjective workload assessment.

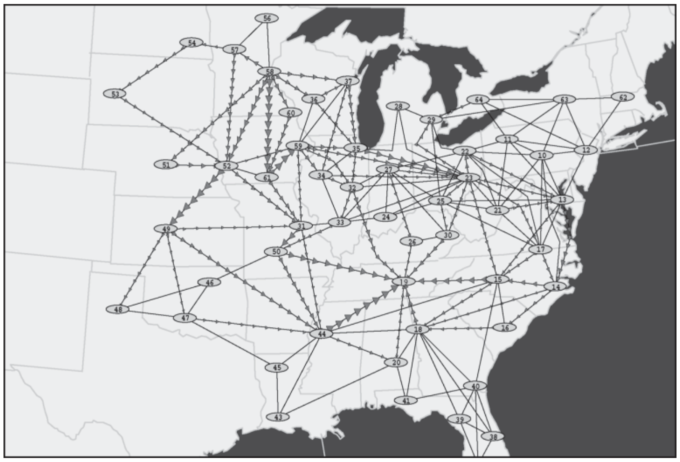
Fig. 5. PTDF display used in Experiment 2.

## VIII. Second Experiment Display Types

Participants completed the experimental task using one of three display types. Each display showed the areas connected by branches with the PTDF magnitude and direction visualized using magenta arrows, with the size of each arrow proportional to the PTDF for the branch. For the first display type, no-motion, the arrows were stationary. For the second, uniform-motion, the arrows on all the branches were animated with uniform speed. For the third, proportional-motion, the animation speed for each branch was proportional to the PTDF for that branch.

After an area was selected, it was color-coded to show the participants which areas they had already selected. All areas began as light blue. When selected, the seller's node turned to green, and the buyer's node turned to red; prior to the selection of the buyer and seller, the other areas did not change color if they were selected. After being selected, the buyer and seller remained red and green, respectively, throughout the remainder of the trial. During the path selection task, each selected area turned from light blue to white and remained white until the completion of the trial. An example is shown in Fig. 6, with area 37 the seller, area 32 the buyer, and area 35 the selected path element.

## IX. Second Experiment Results and Discussion

The mean times for participants to select both the buyer and the seller are shown in Table V. The results show a clear advantage for the motion displays over the no-motion display, especially in indirect connection trials ($p = .011$). However, the differences between the two motion displays were not significant ($p = .417$, direct; $p = .249$, indirect). In addition, we measured the time required to select the path between the buyer and seller

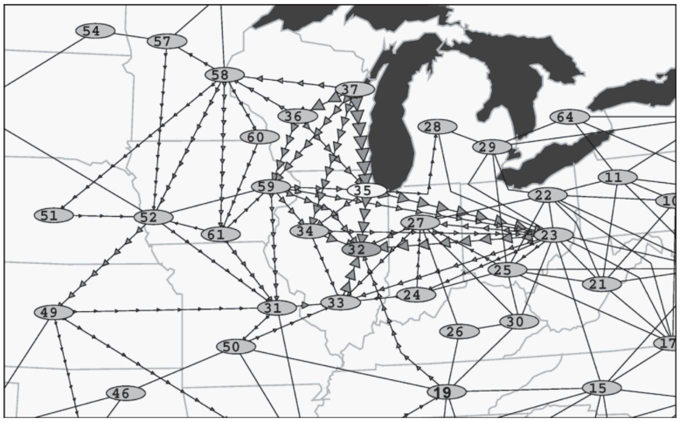

Fig. 6. Close-up showing the completion of practice trial 2.

TABLE V
MEAN BUYER-SELLER SELECTION TIMES IN SECONDS

| Connection Type | Type of Motion (Display Type) | | |
|---|---|---|---|
| | None | Uniform | Proportional |
| Direct | 6.75 | 4.54 | 4.14 |
| Indirect | 10.42 | 6.88 | 6.08 |

TABLE VI
MEAN ERRORS PER TRIAL

| Connection Type | Type of Motion (Display Type) | | |
|---|---|---|---|
| | None | Uniform | Proportional |
| Direct | 0.40 | 0.08 | 0.07 |
| Indirect | 1.26 | 0.58 | 0.35 |

in indirect trials and counted the number of nodes in each path but did not find significant differences among the display groups for either measure ($p = .788$, time; $p = .716$, number of nodes).

Table VI shows that participants also committed fewer errors, defined as attempted selections of areas that were neither the buyer nor the seller, while using the motion displays than with the no-motion display, an effect that was marginally enhanced in the indirect connection trials ($p = .075$). As for selection times, the differences between the two motion displays were not significant ($p = .794$, direct; $p = .258$, indirect).

The participants' reported mental workload, assessed with the NASA-TLX, is shown in Figs. 7 and 8. The workload rating was lowest for the proportional-motion display group followed by the uniform-motion and no-motion groups ($p = .103$). Only the individual difference between the no-motion and proportional-motion display groups was significant ($p = .043$). As shown in Fig. 8, the temporal and mental demand were the most significant contributors to overall workload, receiving scores higher than effort and performance ($p = .076$).

Motion apparently aided the participants in finding the buyer and seller by directing attention to the most relevant areas of the displays. The larger—and faster, in the case of the proportional-motion display—arrows tended to be located near and flowed between the buyer and seller in both motion displays, perhaps leading the participant's attention from the seller to the buyer. The arrows were configured uniquely for the buyer and seller, since they were the only nodes in the displays where all arrows flowed either in or out. Motion probably increased the visibility of these configurations significantly, since humans are sensitive to expanding and contracting patterns [21], perceive those patterns to be moving faster than linear motion [22], [23], and can perceive the pattern as a single object [15], [24]–[26]. That error rates followed a pattern very similar to selection times indicates that the participants were not trading accuracy for speed with the motion displays but were truly able to perform faster and more accurately.

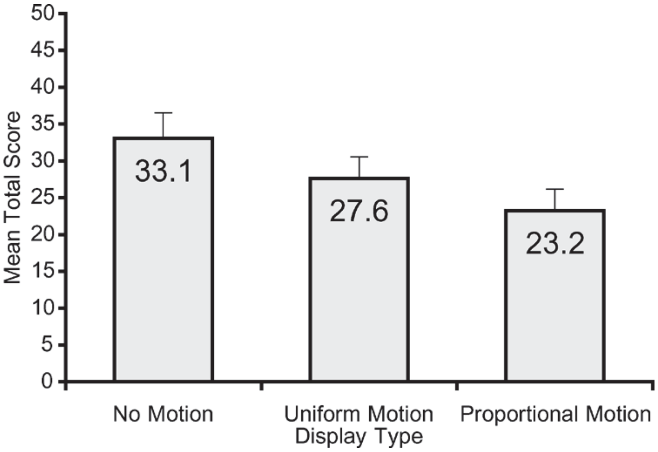

Fig. 7. NASA-TLX as a function of display type.

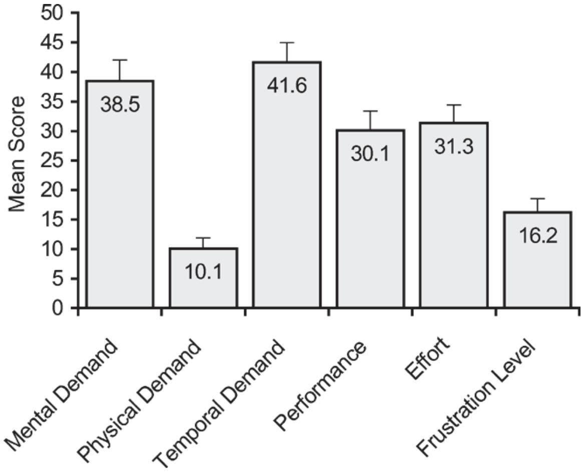

Fig. 8. NASA-TLX as a function of workload dimension.

Motion may also have aided the participants' understanding of the behavior of the power network. This effect might improve users' performance in a task such as the path selection task in helping them detect power flow patterns with less mental conversion than required with the no-motion display, as shown in [27]. The unstructured nature of the path selection task, however, may be the primary reason for the lack of significant differences among the displays for that task. Participants were instructed to choose any path, rather than choose an optimum path, making the task simple. We might have seen effects had the correct path been more difficult to determine and dependent on finding a pattern in PTDF magnitude and direction of flow, which the motion information would have directly supported.

For all display groups combined, the seller was selected first in a significant proportion of trials ($p = .010$). For individual display groups, the proportion of trials in which the seller was selected first was significantly greater than chance only for the no-motion group ($p = .019$) and the proportional-motion group

TABLE VII
PERCENTAGE OF TRIALS IN WHICH SELECTED FIRST

| | Type of Motion (Display Type) | | |
|---|---|---|---|
| | None | Uniform | Proportional |
| Buyer | 44% | 48% | 39% |
| Seller | 56% | 52% | 61% |

$(p = .016)$, though the trend was in favor of selecting the seller first in the uniform-motion group as well, as shown in Table VII. That this preference was present with the no-motion display suggests that the participants may have consciously looked for the seller first but happened to see and select the buyer while searching for the seller on some trials. It is unclear why this preference effect was significant with the no-motion and proportional-motion displays but not with the uniform-motion display. A possible explanation is that the expansion and contraction surrounding the seller and buyer in each trial were easiest to find in the uniform-motion display, in which motion was most coherent, so that even though participants may have preferred to search for the seller first, the buyer may have popped out during search for the seller more frequently than participants happened to see it in the no-motion display and more frequently than it popped out with the less-coherent contracting motion in the proportional-motion display.

## X. CONCLUSION

Motion can be used successfully in displays to aid understanding of the behavior of systems and aid search if the display is configured so that motion provides information that is directly relevant to the user's tasks and draws the user's attention to the areas most relevant to the current task. Task-relevant areas of displays can be highlighted with higher-speed motion or moving elements that configure themselves into moving patterns that are easily grouped together and separated from the rest of the display, such as expansion, contraction, rotation, and deformation. This result was most clearly shown in experiment 2 in which the PTDF motion displays had a clear advantage in terms of speed, accuracy, and reduced mental workload. Proportional motion was also slightly better than uniform motion for such displays.

However, our results do not show a clear advantage for encoding real power flow with motion speed, suggesting that care should be taken to ensure that the resulting incoherence of the motion will not overpower the advantage of highlighting with motion and will not weaken the perception of patterns in the flow. In addition, there may be no advantage to incorporating motion in displays to support tasks requiring integration of information when the integration task is simple.

In displays similar to one-lines, where the user monitors power flows and resolves contingencies affecting flow patterns, it appears that indicating flows graphically with arrows that move at a speed proportional to power flow can reduce contingency resolution times and increase efficiency in terms of the number of resources used, compared to displays without motion or arrows. For displays where the user must analyze flows to determine the locations of flow sources and sinks, such as in PTDF analysis, it appears that the best configuration is to use arrows that move at a uniform speed, reducing search times, error rates, and workload compared to displays with nonmoving arrows. We expect that these differences will be even more pronounced for larger networks and contingencies that affect more components, as could be the case in real systems.

Finally, this study underscores the need for further usability and human factor research to test the effectiveness of power system-specific visualization techniques, in addition to motion. With the ongoing advances in computer visualization hardware and software, the visualizations that can be performed on the power system data sets are (almost) limited only by the human imagination. However, the development of new visualization techniques must proceed hand in hand with usability assessment and human factor research. Further experiments are needed using both academic participants, such as was presented here, and practicing power system operators and engineers.

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