Christine Mikkelsen, Jimmy Johansson and Mikko Rissanen. Interactive Information Visualization for Sensemaking in Power Grid Supervisory Control Systems. In: Proceedings of the 15th IEEE International Conference on Information Visualization (IV), London, UK, July 13-15, 2011, pp. 119–126. IEEE. DOI: 10.1109/IV.2011.100

DRAFT

Interactive Information Visualization for Sensemaking in Power Grid Supervisory Control Systems

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Abstract Operators of power grid supervisory control systems have to gather information from a wide variety of views to build situation awareness. Findings from a conducted field study show that this task is challenging and cognitively demanding. Visualization research for power grid supervisory control systems has focused on developing new visualization techniques for representing one aspect of the power system data. Little work has been done to demonstrate how information visualization techniques can support the operator in the sensemaking process to achieve situation awareness. To fill this gap, and with support from a field study, we propose solutions based on multiple and coordinated views, visual interactive filtering and parallel coordinates.

Keywords Human supervisory control systems, sensemaking, information visualization, power grid visualization, field study

I. INTRODUCTION

Human Supervisory Control (HSC) system is a general term for systems that include an automation layer between the human operator and the system [15]. HSC systems can be found within a wide range of application domains and in this paper we will focus on control systems used for supervision of power grids. The main objective for an operator of such control system is to make sure that the power grid runs in ”normal mode”. That task involves information and data gathering from several different views of the power grid. The gathered information is used for building a mental model of the situation, a concept referred to as situation awareness [3].

Today’s sophisticated and extremely complex power grids generate large amounts of data which needs to be analyzed by power system operators. Analyses of recent blackouts have shown that power grid operators ability to understand the situation is crucial and that problems with situation awareness have been one major factor that has affected the propagation of failures [4].

In recent years, sensemaking has been introduced as a process that should be considered while designing decision support systems for power grid supervision [4].

”Sensemaking is the active process of building, refining, questioning and recovering situation awareness.” [7]

Sensemaking is related to situation awareness [3] and the conceptual model of sensemaking presented in [10], [11] defines situation awareness as the product of the sensemaking process. Their model is intended to describe the process of how situation awareness is achieved when the available information is uncertain or conflicting, and maintained or recovered after a surprising event, which are typical situations that an operator of a HSC system has to deal with. The metaphor frame is used to describe how humans start with some form of framework to make sense of data and events. This framework can, in the beginning of the sensemaking process, be minimal but it expands and becomes more elaborate when more data is acquired. The frame is a hypothesis about the connections among data and sometimes new information confirms the hypothesis but sometimes new data forces the user to reject the frame and thus the user has to replace it with another.

In this paper, we present findings from a comprehensive user study that describes how operators have essential problems with navigation and interaction with data in the system. Even if new visualization techniques that present data in a more intuitive way are used, there is still a need for intuitive navigation and interaction techniques that support the sensemaking process so operators can understand the situation and make the right decisions.

We propose visualization solutions for interactive analysis of data in a control environment that support sensemaking. The solutions have been influenced by the Visual Information-Seeking Mantra [16]: *”overview first, zoom and filter, then details on demand”* and are based on coordinated and multiple views (see [1] for a survey and user guidelines) and dynamic visual queries using parallel coordinates [8]. The proposed solutions are the result of an extensive user study with 76 participants from 16 different power utility control rooms in USA, India, Sweden, United Arab Emirates and Oman.

The remainder of this paper is organized as follows. Section II describes the fundamental views in the targeted system. In section III related work on interactive information visualization methods for power grid supervisory systems is discussed. Details of the method used for conducting the user studies are presented in section IV and the findings from the field studies are together with the proposed solutions presented in section V. The proposed solutions and future work are discussed in section VI.

II. BACKGROUND

An HSC system for power grid supervision usually includes the following fundamental views:

- Geographical overview - This is an overview of the power grid's geographical area, see Figure 1a. It includes, for example, transmission lines and substations that are mapped to their geographical location on the overview. The purpose of the view is to show overall status of the grid, for example voltage levels and if there are reported alarms in substations.

- Single line diagrams (SLD) - In addition to the geographical overview there is also a schematic view, called single line diagram (SLD), over the whole system showing more details, see Figure 1b. This schematic view focuses on the connectivity in the grid and does not maintain geographical distance between devices. The schematic view is also divided in subviews showing individual substations with more details about devices and their status.

- Alarm and event lists - One of the most important views is the alarm list, see Figure 1c. The alarm list is usually a vertical list that represents reported alarms in the power grid. Each alarm that is reported to the alarm list has a number of alarm attributes that can be used for sorting and filtering. When a device in the power grid report a value that exceeds one of its limits then an alarm is sent to the alarm list. Usually a device has a number of different alarm limits and the first level is supposed to be used for alerting the operator about potential problems in the future if the value continues to increase or decrease. In addition to the alarm list there is usually an event list that includes recorded manual operations and other types of system events.

- Detailed information views - The single line diagrams display a subset of available information about devices in the power grid. The displayed information is typically numerical values which operators constantly need to supervise. Other information that the operator needs occasionally is displayed in separate detailed information views, see Figure 1d.

- Automatic support function views - The supervision of a power grid system is supported by automatic functions. One example is a function called contingency analysis which analyzes the effect of losing one or several transmission lines, due to damage or overload. The results from the automatic support functions are, in some cases, displayed on the schematic views or on the geographical overview but in some cases only in tabular lists, see Figure 1e.

Figure 1 shows an example subset of views that operators use while supervising a power grid system. Due to the size and complexity of the physical power grid system the information and data is spread over thousands of various views in the HSC system. The views represent different aspects of the system and are used for supervising the status and for performing manual operations. Most of the tasks performed by an operator involve some kind of decision making and thus the process of making sense of information to understand the current situation is very important.

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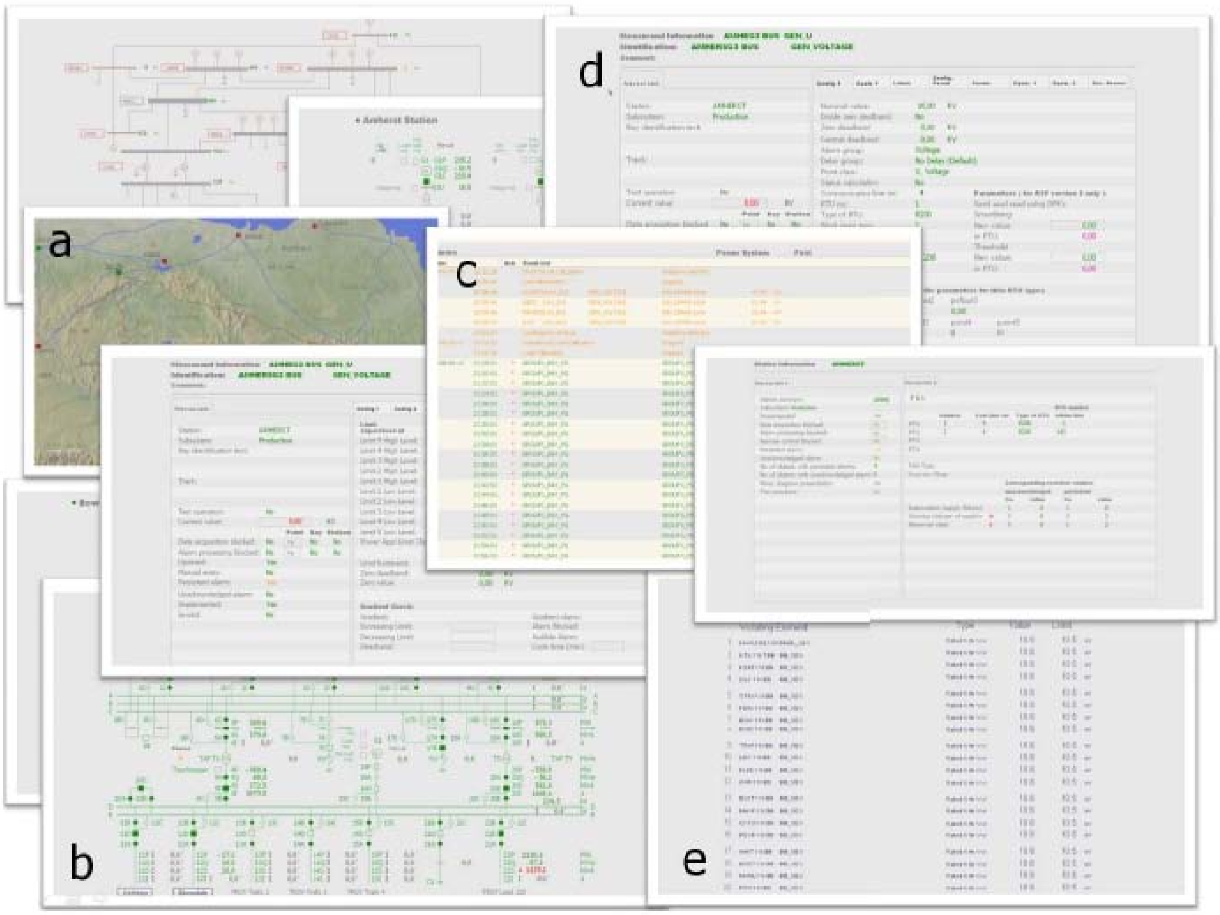

Figure 1. The wide variety of views in HSC systems for power grid supervision: (a) geographical overview, (b) single line diagram, (c) alarm list, (d) detailed information view and (e) automatic support function view.

III. RELATED WORK

During the last decade, research within power grid operations has focused on how to enhance situation awareness. Several visualization techniques have been developed to improve the representation of power grid data.

One early proposed technique for visualizing power system data is colour contouring [18]. Colour contouring is described as useful for representing voltage levels in the power grid. This technique has been validated in a follow-up study on the human factors aspects [13]. The study showed that the colour contouring display attracts the users’ attention to the worst voltage violations quicker than the numerical display, but at the cost of worse performance when used for solving or removing the voltage violations. Overbye et al. also found that combining the numerical display with colour contouring resulted in worse performance in some situations, than just colour contours or numerical display alone, and their proposed explanation is that users are not able to ignore one dimension (numbers) while using another (colour contours).

Two other presented visualization techniques are static or animated arrows that represent power flow, and pie charts that represent the transmission lines' load percentage [12].

There are several attempts to utilize 3D views by mapping power system data to a three dimensional shape that is placed onto a tilted geographical map or schematics of the power grid. In some cases the tilted map is a terrain map representing additional aspects of the power grid. [2] used a results of power flow analysis and state estimation.

One example of visualizing the result of a contingency analysis is presented in [20]. In this case the presented solution also utilizes a third dimension by mapping attributes (height, colour and orientation) of bars, cones and other 3D shapes onto a tilted 2D plane with a single line diagram.

Thus, different kinds of 3D visualization techniques have been presented as solutions to enhance the way power system data is presented to the operator but few user studies have been performed to validate that 3D visual representations actually improve the performance. The user study presented in [19] only concludes that 3D displays could potentially be valuable tools but that more studies are needed. However, a number of situations where 3D can add value are presented. In particular they highlight 3D representations as a tool for improving the speed of high level judgments of current operating levels in relation to upper and lower limits.

Evaluations of 3D displays in comparison to 2D displays have been done for various other domains with mixed results. The reason for the variety of conclusions in previous conducted evaluations is discussed in [17] and Smallman et al. present their own comparison study where they found that information about a third dimension can be better obtained in a well-designed 2D display.

The fact that data in a power grid supervisory system has a spatial nature is the background for the work presented in [14]. They suggest several visualization techniques for different problems that would benefit from a geographical view. Their main idea is to map power system data onto different types of 2D icons within a geographical map, a similar solution as one of the solutions presented and compared in [17].

Some of the techniques summarized above, such as colour contours, animated arrows, 3D bar graphs on tilted 2D display and pie charts, have been implemented in power grid supervisory systems as solutions to fill the need for more intuitive displays that provide operators with better situation awareness.

The above summary of previous work shows that research within visualization for power grid operations has been focusing on developing visualization techniques that map power system information to one separate view for exploring a specific aspect of the data. There is little research about how these proposed techniques would fit into the whole decision making process to support sensemaking in situations when information needs to be gathered from several views.

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IV. METHODOLOGY

To investigate what operators need in their supervisory role, and how they operate and make decisions in dynamic and complex systems, the best way is to observe them in their real environment [21]. Thus a number of field studies were conducted in 2008 and 2010 covering 16 different power utility control rooms in USA, India, Sweden, United Arab Emirates and Oman. During each visit a selection of users, having different roles, were observed and interviewed.

The goal was to gather as much information as possible about the different users' tasks and how they were using the system. How they navigated and interacted with information in the system to perform their tasks and making decisions was of special interest. Different types of control rooms (managing transmission (EMS) and/or distribution (DMS) power grids) located in three different continents was covered to capture differences between them. Figure 2 illustrates the role and geographical location distribution of the 76 studied users.

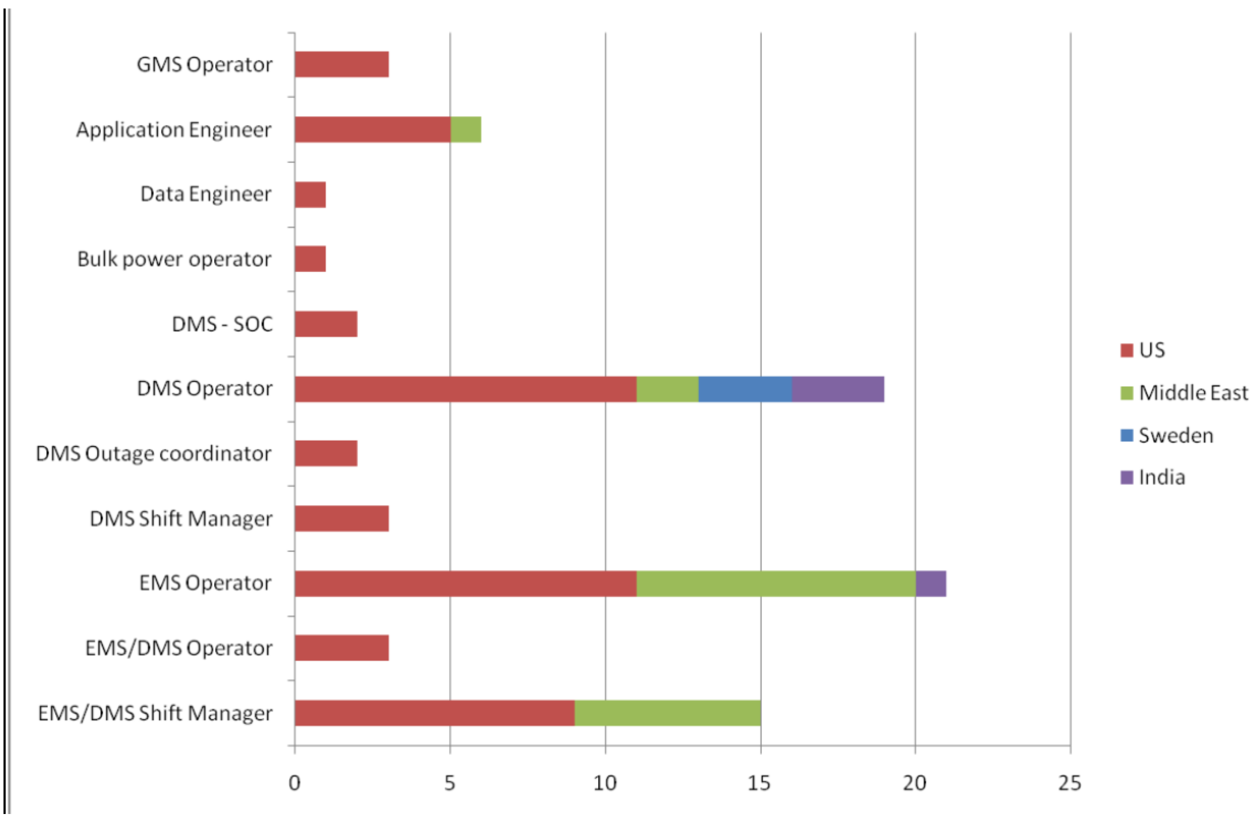

Figure 2. Distribution of studied users (roles and geographical location)

We chose to do field studies instead of laboratory studies since it is difficult to replicate a true realistic situation with all interruptions and conflicting events that are going on in a control room. In addition, all control rooms have their own variations of the system and we were interested in finding out whether those variations affected the users' way of working. Another issue with laboratory testing is that it is difficult and expensive to get subjects with the right background to travel to the laboratory site.

The drawback of field studies is the lack of control. The opportunities for conducting the interviews with operators were strongly affected by the control rooms' organization and schedule and we had to adjust our methods depending on the available time in the control room and with the different users.

Generally a variation of different protocols for cognitive task analysis was used. In some cases a modified bootstrapping protocol [5] was enough to get the overall picture of the users' main tasks. In some cases we had the opportunity to observe a user while performing a task where he had to carefully analyze the situation and make critical decisions. In those cases an adapted version of the critical decision making method [6] was used to get a deeper understanding of the decisions the user had to make.

We aimed for an individual interview with each user, combined with naturalistic observations but in some cases the interview had to be done at the same time as the user was in operation due to the fact that replacement operators were not available. Thus the interview was constantly interrupted, but that also gave us additional and important information about how the system is used. The individual interviews together with the different cognitive task analysis protocols gave us deeper knowledge about the users' decision making process. Through the naturalistic observations we captured basic problems that users had with navigation and interaction with information in the system.

The information we got from the interviews and the conducted observations were mainly recorded with pen and paper and in some cases, with permission, they were audio recorded.

During the following phase, proposed solutions for dealing with the general findings were developed and implemented in a prototype. Finally the prototype was used in a qualitative validation of the results.

V. RESULTS

Several findings could be drawn from the field study, however in this paper we focus on the issues concerning the navigation between overview and details and alarm management.

A prototype was created in order to test and verify the proposed solutions during the development phase and in order to get qualitative response from end-users. The prototype was developed with C# as programming language and Windows Presentation Foundation (WPF) was used for the graphical user interface. The GAV Framework [9] provided us with the parallel coordinates control component.

A. Overview and details

Having an overview of the situation in the power grid has been highlighted by basically all types of users as critical and the most common views chosen for that purpose are the alarm list, in

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combination with single line diagrams (SLD). To have a complete overview the operators also have to find detailed information in many different views and it takes a lot of time and effort to just find the right views and place them on the available displays. One operator commented on moving from one alarm in the list to the station SLD and to find the right device is one of the most time-consuming tasks that operators face. Even if this statement came from a single operator it could be confirmed by observing other operators.

Another observation was a problem with the current function that takes the user directly from one alarm to the corresponding device on an SLD. The new view is opened on top of the alarm list and the user has to rearrange the views on his available displays to avoid hiding important information on the alarm list. Thus this function is not used very often.

Our proposed solution to the above findings is to implement a system based on the concept of multiple and coordinated views. Figure 3 displays an alarm list view coordinated with an SLD view. A selection of one alarm in the alarm list will make the SLD diagram view automatically display the matching SLD for the device raising the alarm and with the device highlighted to guide the operator to directly understand where the device is located. Other alarms related to the same device is also highlighted in the list and gives the user an instant way to understand if the alarm is recurring or what the previous alarm from the same device was about.

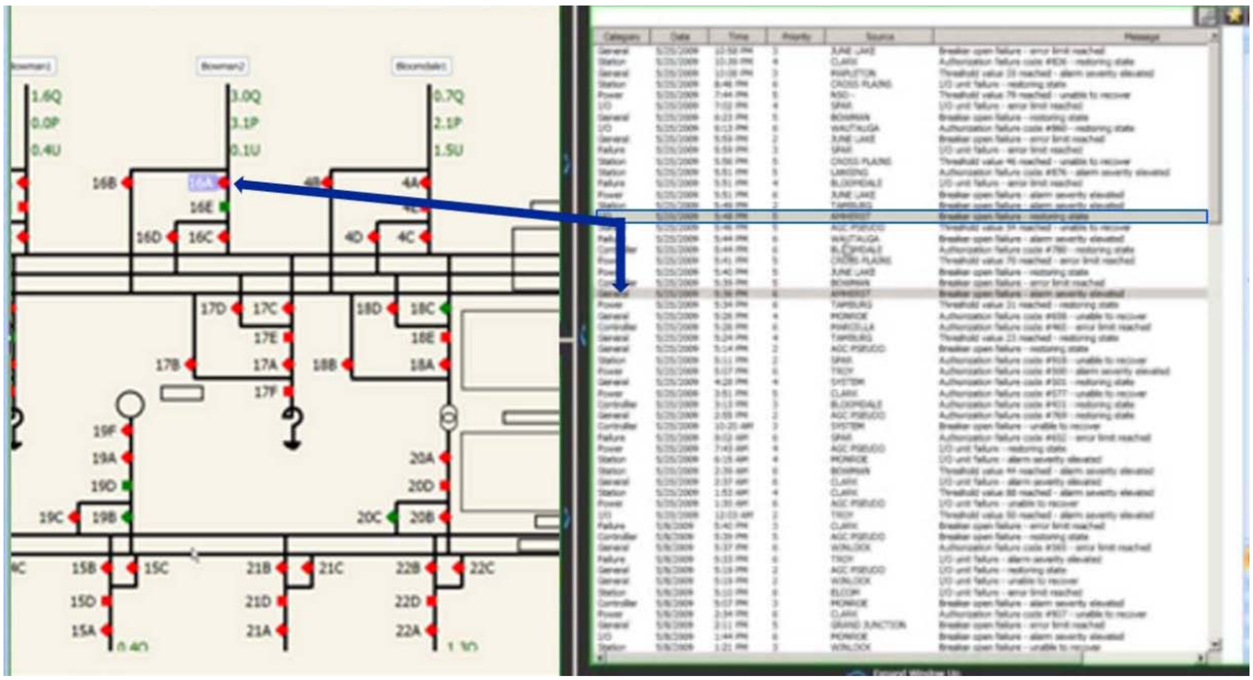

Figure 3. Selection of one alarm in the alarm list automatically displays the matching SLD and the device causing the alarm is highlighted. Other alarms related to the same device is also highlighted in the list

The geographical overview could also be coordinated with the alarm list and then a selection of one alarm in the list would highlight the related station in the geographical overview. Figure 4

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demonstrates that the coordination should also work in the opposite direction and a selection of a station in the geographical overview would highlight the related alarms in the alarm list and the matching SLD would be displayed in the SLD view.

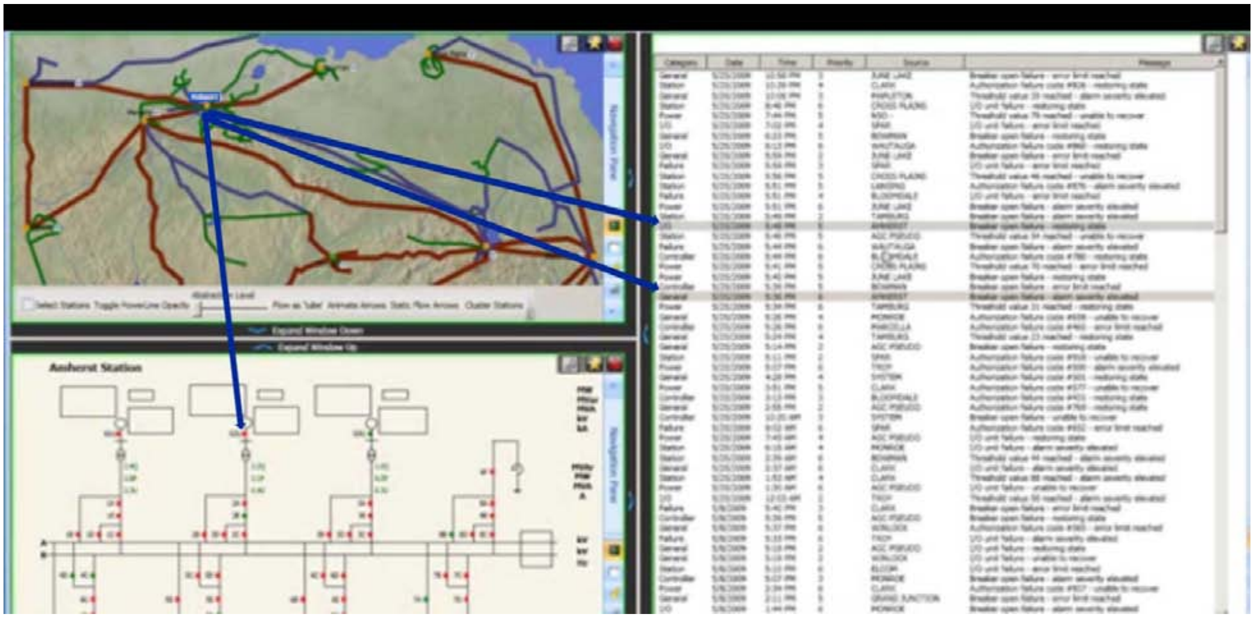

Figure 4. Substation selection in geographical overview highlights alarms in alarm list and displays the corresponding SLD with the alarming devices highlighted

The field studies also revealed a need to show more information about alarms in some kind of overview. This was specifically mentioned by operators in American control rooms. Several operators explained that when they receive a new alarm they have to find the right information in different places and often scroll down large tabular lists before they know what to do and how they should act. One operator would like to be able to extract more information from the overview and mentions which device has caused an alarm as an example. Today, he can only see that information in the SLDs if he zooms in on the right area. Also other operators said that details about devices are hard or slow to find. According to one operator, the SLD should show the details about breakers already in that view instead of another level of windows on top of a station's SLD. Others suggested that if the station name is clicked, the operators should see more detailed data on that station.

The above findings are all related to overview and details on demand and these problems could also be solved with the implementation of multiple and coordinated views since it provides a direct relation between the overview and details about objects and devices. Instead of mapping detailed information onto the geographical overview display or onto the SLDs, making them more cluttered, the user can easily find more information about an object by selecting it on the overview or SLD. The coordinated detailed view would then show more information about the object, see Figure 5. If the user selects another object the detailed view would automatically display the related information.

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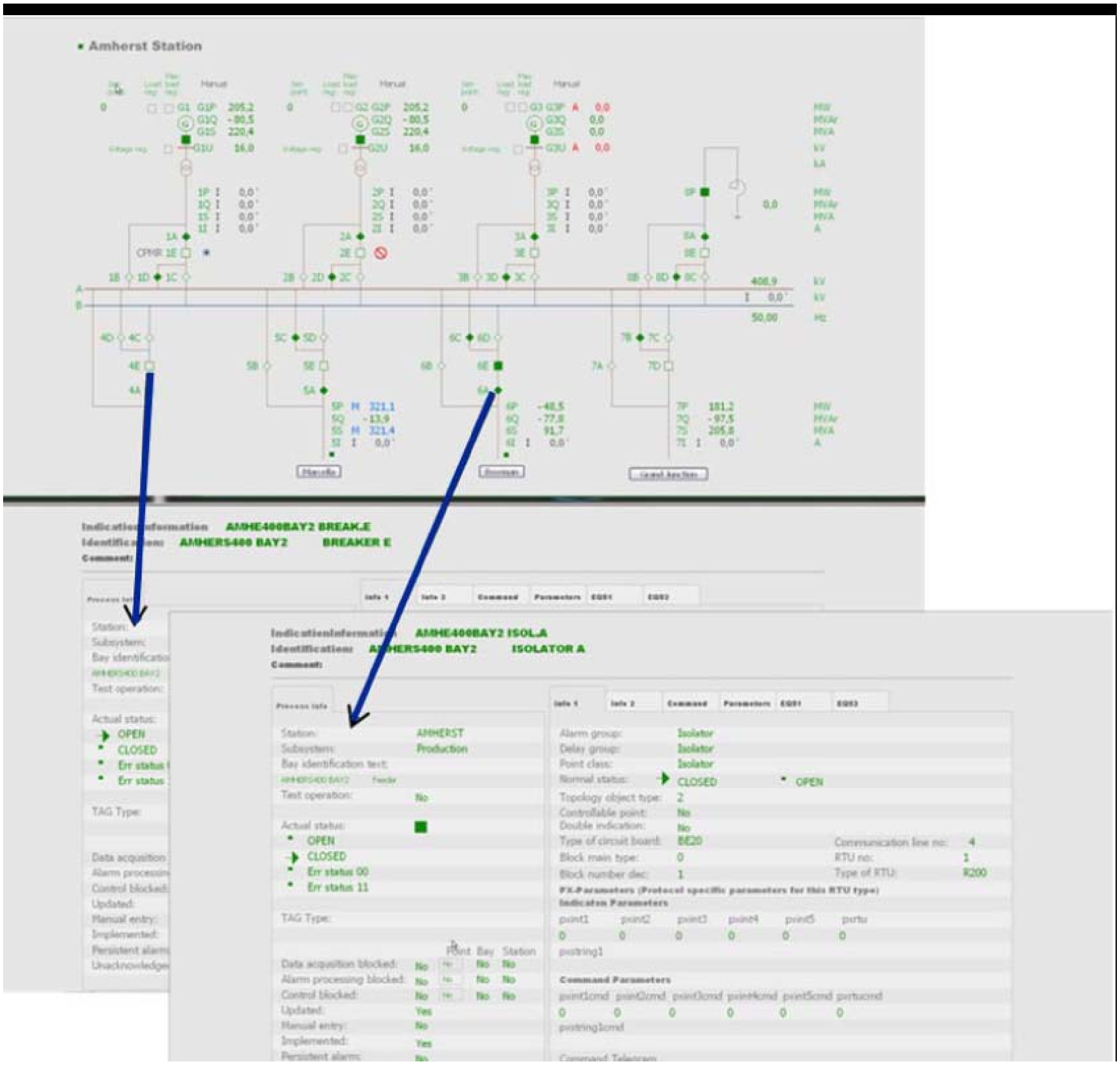

Figure 5. Selection of a device on SLD automatically display its detailed information view

Another problem that operators expressed is that they *”cannot measure disturbance”* in general. The overall disturbance must be deduced by using a number of different views of the system, which is cumbersome. One operator also said that *”we have to read all values in SLDs instead of seeing relevant things directly”*. Even if this statement came from one single operator the observations of the others confirmed this issue. These findings underpin the need for having good situation awareness.

Because of the complexity of the system it is difficult to have all needed information in one single view. Instead the operator has to navigate through different disconnected views and put the pieces of information together to a complete picture. The alarm list view is, for example,

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suitable for identifying the most recent alarms, since it is usually sorted chronological, and get more detailed information about them. But to find out where the alarms are located the operator has to first look at the alarm list and then find the interesting alarm on the geographical overview or on the SLDs. Thus, to understand where the most recent alarms are located the operator has to put information from the different types of views together and this is a cognitively demanding process.

By coordinating the displays the operator can easily answer the following questions: Where are the most recent alarms? How are alarms distributed in the power grid? Is there a specific part of the grid that is affected? The operator can select an alarm in the list and the geographical display highlights the station having the alarms selected and the operator can directly see where those alarms are located on the SLD.

Coordinated views also solve the problem of cumbersome exploration of various lists in the system. The alarm list is one example but there are many more. The items in the lists usually refer to one object in the system and the normal procedure is to navigate from one item in the list to a detailed view of the object in the SLD. This is done either using a function reached through the context menu that appears when right-clicking on the item or with a direct link. As a result the first view, the list, is either hidden or replaced by the new view, the SLD. The user must therefore re-arrange the views in order to monitor the list and get more detailed information at the same time or use backward and forward interaction to switch between the list and the details. If the user wants more information about another item in the list the same procedure must be performed again and this makes exploration of information a time consuming process.

Thus the proposed solution of implementing multiple and coordinated views is addressing both the problem with detailed views hiding the overview and the cumbersome way of navigating between overviews and details. The solution also addresses the problem of information scattered in different places in the system and the need to navigate through a number of views to build a mental model of the situation. Multiple and coordinated views support the operator in the sensemaking process by providing an intuitive way to explore data from different views and understand relationships among data.

B. Alarm management

One of the most critical issues that was found from the field studies were the information overflow that operators experience in critical situations. One operator described a specific situation when he received over 60 pages of alarms in 30 seconds. During that situation they missed important alarms about a transmission line that had a high load.

A major event in the system can be followed by a large number of alarms and events reported and the only view that operators can rely on in that situation is the alarm list. From the alarm list the operator needs to prioritize and find the root cause or causes of the problems and understand how the current situation can be resolved. Thus a large portion of the operators’ daily work is going through pages of alarms.

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It was also observed that too many alarms seems to make operators regularly ignore some of them and they need to trust their experience to identify the alarms that are essential. The need to manually narrow down alarms was expressed by several operators. In every control room except one, it was specifically mentioned that alarm filtering must be improved from their existing implementation.

Even if the users clearly expressed the need to narrow down the alarm list they also highlighted the fact that it is risky to filter alarms and filtering rules must be considered carefully since it is crucial that operators not miss important information. It is not possible to only look at the order of the alarms to detect the root cause alarm and filter out the rest. The alarm limits may also have been configured incorrectly, which makes it risky to use as the only filtering attribute.

Today each alarm is traditionally represented with a row in the list and has a number of different attributes that are divided in different columns. Examples of attributes are time, type and priority. The alarm list can be sorted by the different attribute columns and there is also a possibility to filter the list by entering limits to the attributes in a separate dialogue window. This functionality is not used according to the field studies and one explanation for that is that operators are afraid of missing important information. For example, if the list is filtered to only show alarms of priority 1-3, there is a risk that important information is passing by without notice since alarm limits may have been calibrated incorrectly. Each alarm that is reported to the alarm list has to be acknowledged by the operator to tell the system that it has been noticed. Only when it has been acknowledged and when the cause of the alarm has been cleared it disappears from the list.

One comment from an operator was: *”Every alarm counts in some way”*. This comment indicates that operators somehow use alarms that they, at first impression, seem to ignore. Even if the operator acknowledges some alarms without any further analysis they are still used in the creation of the mental model of the situation. Observations show that operators need the information hidden in the vast amount of alarms but also that they need an intuitive way to identify the alarms that they should focus on.

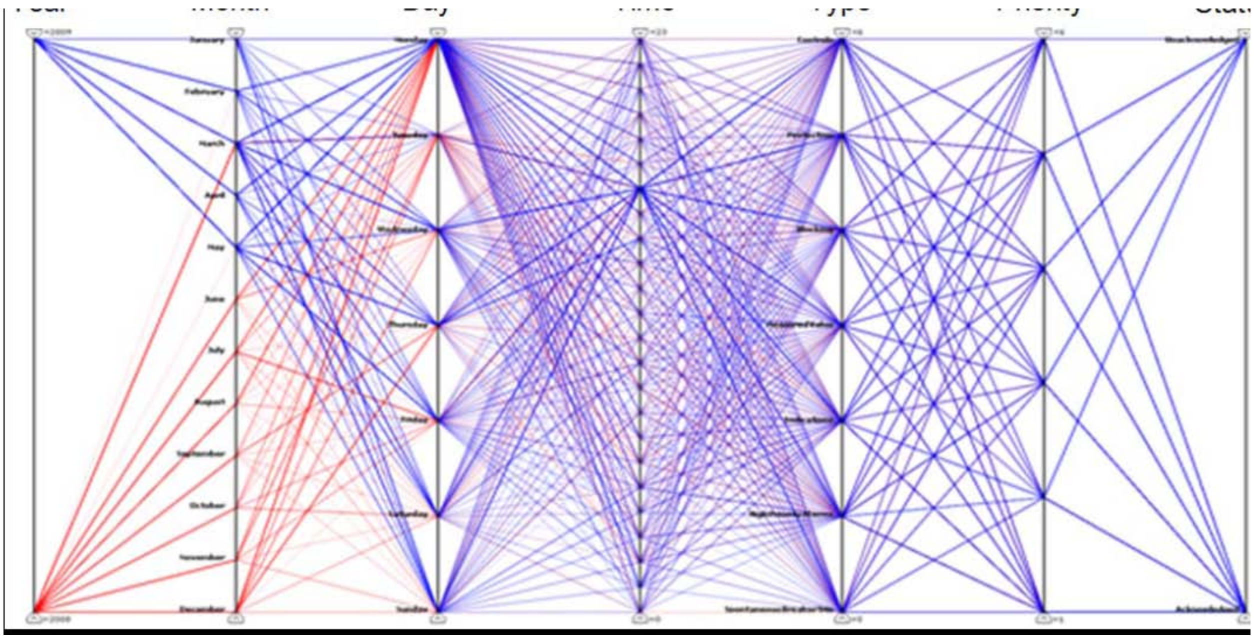

Figure 6. Parallel coordinates display showing alarm items as horizontal lines crossing alarm attributes values mapped to the vertical parallel axes

Thus operators need a more efficient and interactive way of filtering alarms without the risk of removing important information. The proposed solution is to coordinate the alarm list with a visualization technique that also can be used for interactive filtering of the alarm list. The suggested technique is parallel coordinates, see Figure 6, since it also can reveal hidden patterns in the huge number of alarms. In the parallel coordinates display, each alarm attribute is represented by a parallel axis and each alarm is represented with a line crossing through the vertical axis at the alarm’s corresponding attribute value. From this view it is possible to explore alarm patterns and find out if there seems to be a correlation between some of the attributes, for example alarm type and time.

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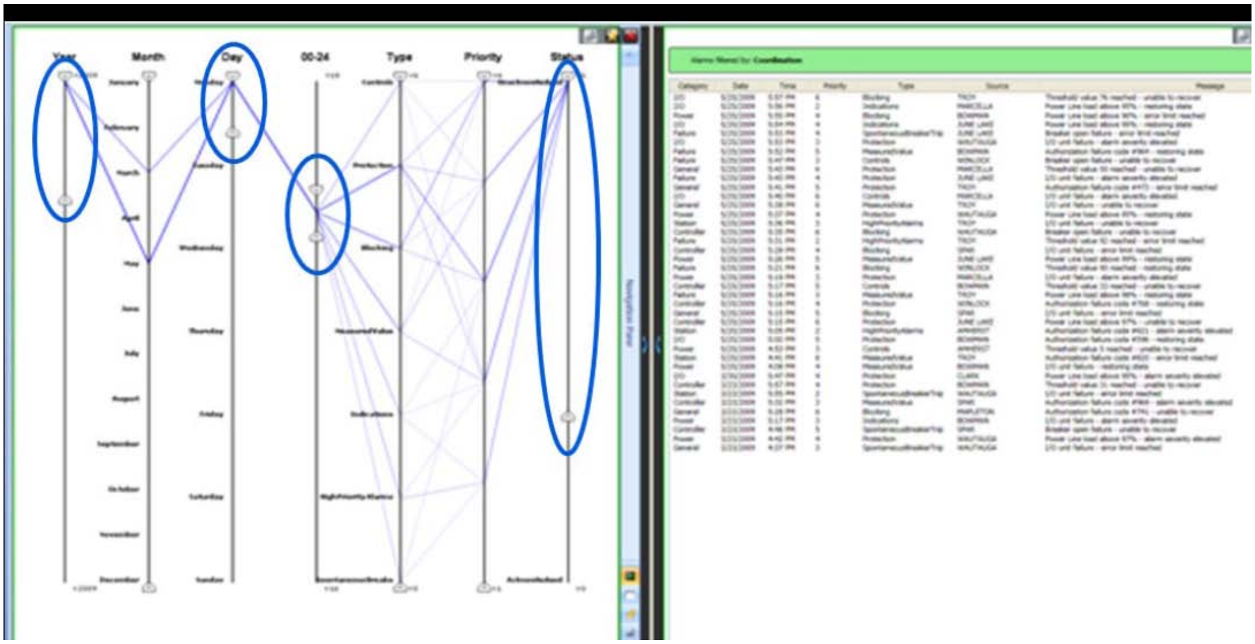

Figure 7. Interactive visual filtering of alarm list using the sliders in the coordinated parallel coordinate graph

Figure 7 demonstrates how the alarm list can be narrowed down by using the sliders on the vertical axis, in the parallel coordinate graph, representing the alarm attributes. Depending on the situation the user can have the option to either remove or fade the filtered alarms from the list and from the parallel coordinates display. The reason why the filtered out alarms should be faded out instead of removed is the risk of losing important information that is hidden in the alarms. The user can focus on a selection of the alarms but still keep the overview of all alarms and identify patterns.

Parallel coordinates is not a suitable representation for all alarm attributes. The location of the object that is sending the alarm is, for example, better shown on a SLD or on a geographical map. The solution with coordinated views solves this issue since an SLD and a geographical map can be coordinated with the parallel coordinates display and the alarm list, see Figure 8. Then the operator can carry out filtering operations by selecting regions of the map or of the single line diagram and look at alarms only from that specific region.

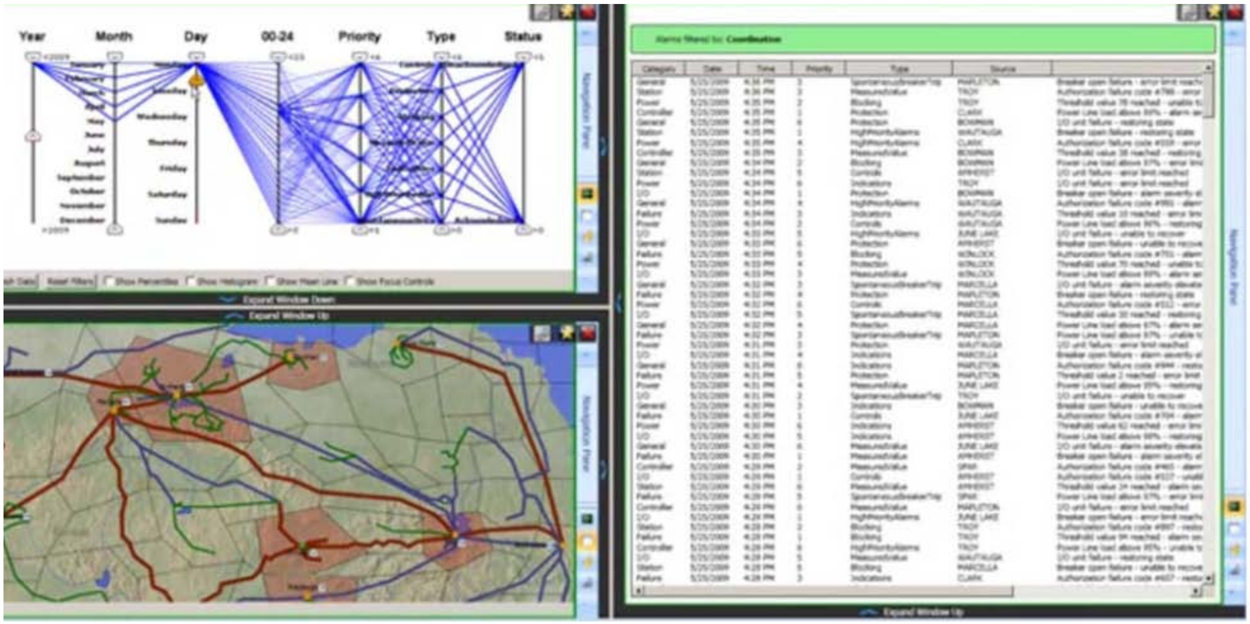

Figure 8. A coordinated geographical view provides a way to interactively filter out alarms based on regions

Thus, the final solution to coordinate the alarm list with a parallel coordinates display, a geographical overview and/or a SLD provide the operator with an intuitive way of exploring many alarms and detecting patterns. It addresses the need for narrowing down the number of alarms so that operators can focus on specific areas without the risk of losing important information.

VI. DISCUSSION AND FUTURE WORK

The field studies have shown that today the sensemaking process of reaching situation awareness is cumbersome. Operators are required to put pieces of information together from disconnected views in the system and the navigation between overview and details is especially challenging.

The developed prototype was presented to end-users during three focus groups meetings in USa, India and Denmark (including end-users from the Nordic countries). During the focus group session the end-users had the opportunity to try out the proposed interactive visualization techniques. The qualitative feedback from the end-users was gathered and will be used to refine the proposed solutions.

Overall the users were impressed by the proposed solutions and asked if they will be implemented in the real system. The users were also asked to fill in a questionnaire about how they felt about the different solutions. The answers from the questionnaire, in combination with verbal feedback, indicate that the multiple and coordinated views and parallel coordinates, in particular, have the potential to enhance the way operators interact with data in the system.

High learning threshold is usually listed as one of the major drawbacks of parallel coordinates. Thus one of the objectives with the qualitative analysis of our proposed solutions was to find out if the end-users understand the visualization technique and how it can be used. Observations of the users while trying out the prototype, together with verbal feedback and the answers in the questionnaires show that users understand the parallel coordinates display. They started to discuss how it could be used for representing other types of data in the system. One operator said: -*"I am a part of a group that meets every week to discuss alarm patterns and parallel coordinates would therefore be very good for us. I mean having this tool for figuring out what the data is trying to tell you."* Another statement made by an operator was: -*"The parallel coordinates would be very good; it would be possible to use this in real time."* These statements indicate that the visualization technique is understood and can probably be used for identifying patterns in the alarms.

Another identified issue were the need to narrow down the number of alarms in the alarm list. The proposed solution, using parallel coordinates for representing alarms and providing a visual way to filter the coordinated alarm list, was evaluated in a quantitative and qualitative user study. Preliminary results, so far, indicate that the parallel coordinates display coordinated with the alarm list outperformed the alarm list alone in terms of execution time, correct answers to tasks and other usability attributes, in particular for tasks rated as difficult. The user study did not compare filtering alarms and selecting a subset of alarms in the parallel coordinates display alone. Thus the improved performance cannot be derived from only the parallel coordinates display but in coordination with the alarm list. However, subjective user responses were recorded and comments about the alarm list's strength when it comes to sequential sorting and the level of details in comparison with the parallel coordinates display were mentioned. This implies that the solution of coordinating multiple views support the user in the sensemaking process by providing a way to combine the strength of both representations.

Section III demonstrates the tendency to believe that new visualization techniques are the solution for problems with situation awareness. Visualization techniques play an important role but a single view containing all possible information an operator needs, to have complete situation awareness, would be to cluttered. The evaluation of colour contours showed, for example, that the combination of colour contours and numerical values had the worst performance [13]. When they were separated each of them was effective but for different situations. This underpins the fact that the best solution is to create visualizations that are effective for representing some aspect of the data and coordinate them together to build a complete mental model of the situation.

Adoption of the concept of multiple and coordinated views opens up a new way for exploring information and supporting the operators' sensemaking process to build situation awareness, not only from one view but from several. This makes it promising to continue to develop customized visualization strategies for efficient identification of specific aspects of the system and by coordination find relationships between them.

The proposed solutions are based on results from field studies in the power grid system domain. It is possible that the proposed solutions could be applicable to other human supervisory control systems, used in other domains, where data and information is spread over a vast amount of various views, and where operators need intuitive way of navigating between overview and details.

Based on the results obtained in this work we will continue to investigate how multiple and coordinated views in combination with existing and new visualization techniques can improve operators' sensemaking process to achieve situation awareness in human supervisory control systems. Qualitative and quantitative evaluations of the proposed solutions in real world situations are discussed as the next step, both in the power grid system domain and in industrial process control.

ACKNOWLEDGEMENTS

We wish to thank the project leader Dilip Kota for arranging the field study and making things happen and Martin Naedele, Claus Vetter and Magnus Larsson for supporting this work.

We would also like to thank Missy Cummings and her researchers in the Humans and Automation Laboratory (HAL) at Massachusetts Institute of Technology (MIT), and Matthew Cooper at Linköping University for valuable input and discussions.

This work was partly supported by the ABB Industrial Software Systems program and partly by the Swedish Research Council in the Linnaeus Centre CADICS.

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