Visualization of Power System Data on Situation Overview Displays

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Abstract

Findings from field studies in power system control rooms show that overview displays are needed to aid operators to achieve shared situation awareness. The existing overview displays are often cluttered, with a lot of detailed information and with overuse of colors. There is no 'best practice' in the field and it is up to power system utilities to design their own displays. This work presents a survey of previously proposed mappings of power system data to visual representations and based on this analysis a set of alternative mappings are demonstrated.

Keywords— **power systems, situation awareness, information visualization, power grid visualization, overview displays**

1 Introduction

The focus system in this paper is a human supervisory control system for power grids. The system gathers measurements from the physical grid and with advanced applications a complete system status is calculated and presented to human operators through a number of different displays. The operators use the information to operate and maintain a safe, reliable and robust grid. Understanding the current system status is crucial and visualization plays an important role [1]. The type of data operators have to deal with is multivariate, temporal (continuous and discrete), spatial and uncertain and the size of the systems continues to grow.

The last 10-20 years, the need to improve how information from control systems for power grids is visualized has resulted in a few new proposed solutions. Around 1993 Mahadev et al. were among the first to present new ideas how to map data from the power system to visual representations [2][3]. A few years later Weber and Overbye et al. presented a collection of alternative solutions [4][5][6]. Since then surprisingly few real new ideas on how to make use of the human vision's capability to detect patterns has been presented.

This paper is a survey of the previously proposed techniques and the idea is to bring new light into this interesting application area and demonstrate the need for future research by information visualization experts. A number of new proposed mappings of data to visual representations are presented and the objective is to develop a first attempt of a "best practise" for designing overview displays.

One part of this work was to determine what is actually needed on an overview display and the second part was to develop a set of mappings that does not conflict with each other from an information visualization perspective. As part of this work, the following information has been identified as important to present on an overview display and to each one of them we present a proposed visual mapping:

1. Nominal voltage level
2. Actual voltage level p.u
3. Actual active and reactive flow including direction
4. Generation reserve
5. Breaker/switches status (open/closed)
6. Transmission line status (energized/de-energized)
7. Abnormal equipment status
8. Uncertainty

The proposed solutions should so far be seen as inspiration for future research. They have not yet been validated, which must be done before implementing in a real system.

2 Background

Control systems for supervision of power grids are complex and consist of many different applications used for different tasks. Operators use different views in the system to perform their tasks and it is important to understand the objective of the tasks in order to develop efficient displays. This work focuses on overview displays supporting the task to provide operators and other users with a shared situation awareness.

2.1 Status overview displays

A control room for supervision of a power grid usually has a number of work stations divided in areas of responsibility. One operator is thus normally responsible for monitoring and controlling a part of the power grid. To understand the system status in their area of responsibility they monitor a number of different displays with information from the control system. To reduce the amount of information they have to deal with, the information is often filtered to their specific area of responsibility. But the responsibility areas are interconnected and the operators must also have an overview of the overall situation in the power grid. One problem in one area can very fast propagate into other areas and one operation can have an effect on the whole power grid.

To overcome this problem it is common that control rooms also have a large wall display unit called the power wall or the video wall with an overview display of the current status in the power grid. What the overview visualizes varies but typically it is either a large single line diagram (SLD) of the part of the power grid supervised by the control room or a geographical map over the same.

When first introducing the power wall it replaced the former used large static board, displaying a static map of the power grid. The only dynamic information reflecting the system status was small light bulbs indicating alarming conditions. The introduction of digital displays enabled more dynamic information to be visualized and in many cases as much information as possible is added to the displays. Colors are used for both differentiating static information like for example nominal voltage levels, areas of responsibilities, equipment types etc. and at the same time for highlight alarming conditions in the power grid.

In control rooms for supervising industrial processes the problem with overuse of colours has been brought up and the more and more established solution is to only use colors for information that needs operators' attention [7]. This rather obvious solution has not yet been recognized in the power system industry and there is a need to evaluate how it would affect the ability to achieve situation awareness.

The need to provide the operators with a shared situation awareness is not fulfilled in many control rooms today. The utility companies creates their own overview displays and the result is often overuse of colors. The urge to display everything clutters the picture with a lot of detailed information and it is difficult for the operators to detect patterns of important information about the overall status in the grid.

2.2 Energy Management System and the State Estimator

The energy management system (EMS) is the part of a power network control system that supervises the transmission network which typically means voltage levels of 110 kV and above. The EMS consist of a number of applications, were some are more fundamental and some are optional. One of the most fundamental applications is the State Estimator (SE).

The State Estimator (SE) calculates a more comprehensive system state based on information from several sources in the system like measurements and load curves etc. The result is a best guess of the system status and it is presented in tabular displays and on electrical schematics, called Single Line Diagrams (SLDs).

The calculated values coming out from the SE are compared with predefined limits and if a value exceeds a limit a violation is reported. The violation is presented to the operator in the form of an alarm in the power system alarm list and in additional tabular lists filtered on specific violations. There is for example a list with current voltage violations in the system.

The SE is normally running cyclic with a predefined interval. The result from the SE can be used both for detecting violations in the network but also for detecting bad data. Bad data can be caused by measurement errors and device/communication failures but it can also be caused by manual operation mistakes or intentional so called cyber attacks [8].

Depending on the available input to the SE the results are more or less reliable. In some cases the SE results are uncertain and it is important for an operator to know if that happens. A loss of a measurement unit can for example result in a more uncertain SE result in an area around it.

2.3 Visualization to achieve Situation Awareness

Situation Awareness is an accepted term within the field of human supervisory control systems and a common used definition is Endsley's *"Situation Awareness is the perception of the elements in the environment within a volume of time and space, the comprehension of their meaning, and the projection of their status in the near future"* [9].

The applications in the system generates huge amount of alarms and warnings and it is possible to set up an alarm system for all kind of situations. A fully automatic system is not possible and it is necessary to have a human in the loop acting in critical situations and tuning the system to prevent failures. The problem is that operators can not deal with the amount of information generated by the system. Visualization is a powerful tool to aid operators digest the information and in particular overview displays of the current situation is important. The problem is to identify natural visual coding for the quantitative information that do not conflict the human vision's pre-attentive process []. The contribution in this paper is both a survey of previously proposed techniques and a new set of mappings to move one step forward to more efficient overview displays.

3 Method

To understand operators need and to identify problems with current used visualization techniques of power system data a number of field studies were conducted during 2008 and 2010. In total 16 different power utility control rooms in USA, India, Sweden, United Arab Emirates and Oman were visited. Qualitative data was gathered using cognitive task analysis methods and bootstrapping protocols [10].

Previous published visualization methods for power system data have been analysed and the benefits and the drawbacks with each one of them have been identified.

To demonstrate problems with previous proposed solutions and to present the new suggested visual mappings of data we have used the IEEE 118-bus system. A one-line diagram replica of the 118-bus test system one-line diagram from the IIT Power Group was created in Processing. The first "raw" version of the one-line diagram is shown in Figure 1. The black lines represents the 118 buses and the gray lines are the 186 branches (transmission lines). This one-line diagram was then used as a test bed and data from the IEEE 118-bus system was mapped to our proposed visual representations.

The results have been demonstrated for domain experts who provided valuable qualitative feedback discussed in section 5.

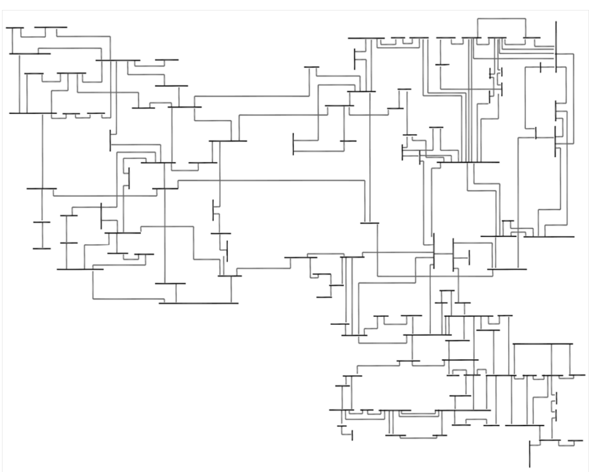

Figure 1: IEEE 118-bus test system

4 Visual mapping of power system data

Some of the techniques summarized below, such as color contours, animated arrows, 3D bar graphs on tilted 2D displays and pie charts, have been implemented in power grid supervisory systems as solutions to fill the need for more intuitive displays providing operators with better situation awareness. The problem is that few studies proving their effectiveness have been presented. This survey summarizes the previously proposed techniques and highlights the benefits and drawbacks with each one from a visualization perspective. The next step is to benchmark the previously proposed techniques with our new set of proposed mappings.

4.1 Bus voltage nominal value

The nominal voltage of a bus or a transmission line is information experienced operators normally know. It is thus not the most critical information operators need on an overview display. But an overview display might also be used by other roles without the same natural feeling about the voltage levels in the power grid and the information should be mapped to the one-line diagram without distracting more important information.

4.1.1 Color coding

To separate transmission lines and buses with different nominal voltage levels it is common to use color coding. One voltage level is represented with one color and another voltage level with another. Figure 2 (left) shows an example how two nominal voltage levels are coded with green and magenta. The benefit of using this type of mapping is the clear separation of the different transmission lines. The disadvantages with this technique are many. First, color is no natural mapping for different voltage levels. The operator has to learn what the colors mean. Second, the choices of colors are typically random and it is no inherited order relating to the order of the voltage levels 110 kV, 230 kV, 400 kV etc. The biggest disadvantage is probably that colors should be used for attracting the operator's attention to critical areas in the one line diagram and using colors for other information results in conflicts. If, for example, a transmission line is overloaded it should turn red to get the operator's attention and then it is not possible to see what nominal voltage level it has.

One possible solution is to use only gray scale colors to differentiate the voltage levels. Normally there are only a few different voltage levels displayed in the same one-line diagram and it should be possible for the human eye to separate them. Even with a small variation as in Figure 2b it is possible to identify the transmission lines with the higher voltage level. This alternative color coding solves the problem with visual clutter but it does not solve the problem with conflicting coding.

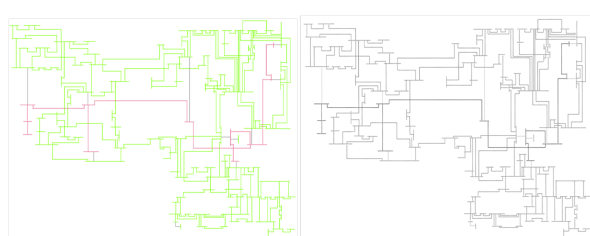

Figure 2: (left) Nominal voltage level mapped to colors (right) Nominal voltage level mapped to gray scale colors

4.1.2 Proposed new mapping - Line width

A natural coding of nominal voltage level would instead be to map it to the width of the lines. Mahadev et al. proposed to use the line width to represent the actual power flow [2]. Their proposal was to map the magnitude to a continuous width but this resulted in quite wide lines cluttering the one-line diagram. But to map the nominal voltage level to the lines in the one-line diagram would only require a few different discrete widths and it should be possible to compare them to relatively understand if one transmission line has higher nominal voltage value than another. The result using two widths with only 2 pixel difference is shown in Figure 3. In this example the same color is used so there is no double coding of information. One big advantage of this method is that color coding is saved to more important information and it does not clutter the view. Possible disadvantage is that it could be difficult to differentiate the lines if they do not have the same color. User studies are required to identify how big the difference between the lines must be to be able to differentiate them from each other.

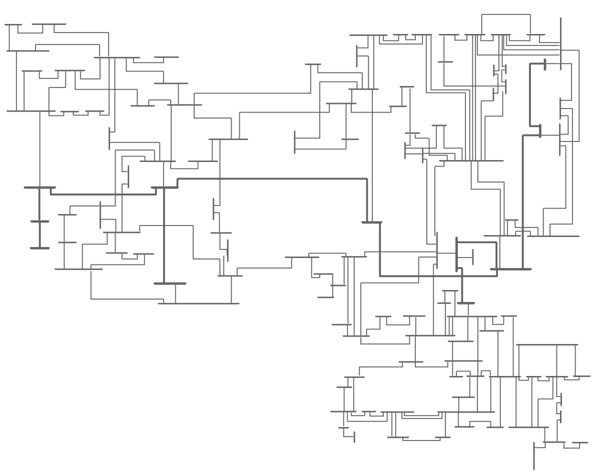

Figure 3: Nominal voltage level mapped to line thickness.

4.2 Actual voltage magnitude and limits

The current voltage level at buses and transmission lines is normally measured as the fraction of the nominal base value for the unit and the expression is called per-unit (pu). The per-unit expression makes it possible to compare units regardless of the voltage level. Information about low voltage levels (values below, for example, 0.96 p.u) and high voltage levels (values above, for example, 1.04 p.u) are very important for an operator and the result from the state estimator list all current voltage violations in the grid.

4.2.1 Bars (thermometers)

Mahadev et al. [2] presented a solution to map current bus voltage levels to what they called ”thermometers”. First they had tried to map it to a color contour (see Section 4.2.2) but they were not satisfied with the result. The second attempt was to use a continuous color code where the hue represented bus voltage. Since it required a separate key they found it less effective and instead they proposed to map the current voltage to a bar placed next to the bus. The bar is coloured according to the voltage level and the top of the bar represent the high voltage limit and the bottom the lower limit. Since a low voltage typically is more important they uses two contrasting colors to also draw attention to bars closer to the lower limit. In addition they also propose to change the color and outline the bar if a value exceeds a limit.

The disadvantages with this mapping are several. The voltage magnitude is important both for the buses and the transmission lines. Adding an extra geometry for every single bus and branch will clutter the display. Another drawback is that it does not use the human eyes capability of pre-attentive process information and to get a feeling of the voltage levels in the system the operator has to scan the whole display. One possible solution to the clutter problem would be to only show the bars representing violating voltage levels but it will still not result in an easy detected pattern.

4.2.2 Color contour

Colour contours was early considered by Mahadev et al. as a potential technique for visualizing voltage levels in a power system [2]. They did not believe in this technique since they did not consider it to be a natural coding of the information. Weber et al. [4][5][6] had an opposite view and presented their solution a few years later. The algorithm used for the contouring is described in [4] and later a technique taking advantage of the GPU is presented [11].

The idea with color contours is to use the same principle as temperature maps for weather forecasts. The voltage levels at the available discrete spatial locations are used for calculating values in between to create a continuous map. To highlight the most important information they suggest to only contour voltage levels above or below the limits.

One problem with this mapping is to decide what colors to use. The authors uses a color scale ranging from blue to red and demonstrate examples when low voltages are mapped to blue and high voltages to red and vice versa. The first mapping seems to be the most natural coding since we tend to relate cold colors to low values and vice versa. For a domain expert this can be conflicting since low voltages are more critical and should be represented with red. The authors realized this conflict and left the decision to the ones implementing and configuring the system. It is not clear which alternative is best and if there is a better color map to use. Another problem, which is not as obvious, is that it is impossible to see which nominal value the buses and transmission lines have. It is interesting for an operator to know if a potential voltage collapse is in a 110 kV part of the grid or in a 400 kV region, for example.

The color contour technique was validated in a follow-up study on the human factors aspects [12][13]. The study showed that the color 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 color contouring resulted in worse performance in some situations, than just color contours or numerical display alone, and their proposed explanation is that users are not able to ignore one dimension (numbers) while using another (color contours). The result of this study underpins the importance of conducting more studies and develop other solutions.

4.2.3 3D Bars

A third proposed mapping presented by Meliopoulos et al. in [14] is the use of a third dimension by mapping the voltage level to the heigh of 3D shapes placed on a tilted 2D SLD. Figure 4 demonstrates the drawback with this choice of mapping. In the example the pu voltage level in the IEEE data set is mapped to the height of 3D bars. Since the differences between the p.u voltages are so small it is not possible to detect any pattern from this view.

One alternative could be to map the voltage levels to discrete heights as in Figure 5. In this example pu voltage levels above 1.04 is mapped to a height of 50 pixels and pu voltage values below 0.96 is mapped to a height of 10 pixels. In this view it is easier to identify buses with high voltage levels and the ones with low but it is the high voltage levels that stands out and not the more important low values. Another problem is that it is not feasible to use the same approach for visualizing the p.u. voltage of the transmission lines since it would clutter the display even more.

4.2.4 3D Contour map

In [13] the voltage level is mapped to a continuous 3D terrain map and a color contour is used as a redundant mapping. The distance from the elements in the SLD and the underlying surface representing the voltage level makes it impossible to relate the information. The surface clearly indicates peaks and valleys of voltage levels but it is not

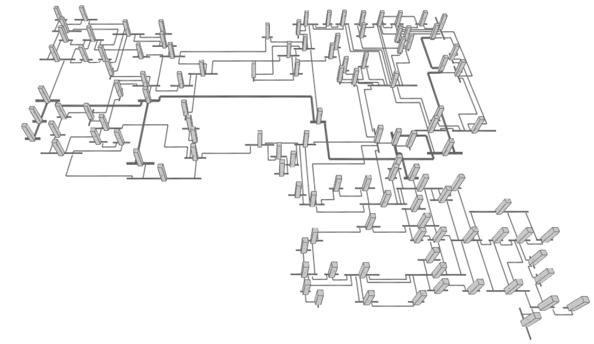

Figure 4: Per-unit voltage mapped to height of 3D bars.

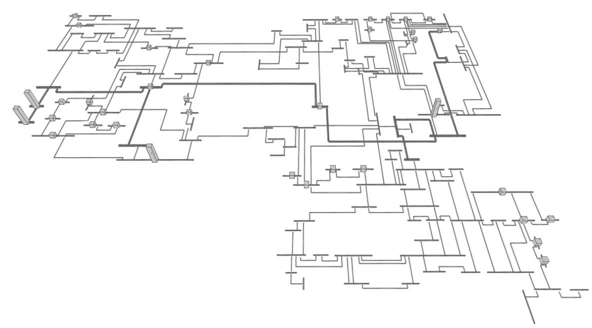

Figure 5: Per-unit voltage mapped to discrete height of 3D bars.

possible to see which buses they belong to. Since a low voltage level is more critical than a high voltage level it is also a bad idea to map the most important information to valleys since they will be hidden in a 3D view.

4.2.5 Proposed new mapping - Discrete color coding

Mahadev et al. tried to use a continuous color scheme to map the actual voltage level to the buses but disregarded this technique since it required a separate color key. Our suggestion is to instead of a continuous color scheme use a discrete scheme to only color the buses that need the operators' attention. The alarm management system is normally configured to trigger warnings when a voltage level exceeds the first limit. A new warning is sent when the voltage level exceeds the second limit and finally an alarm is triggered if the value exceeds the third and critical limit. These three limits could be color coded with three warm colors for high voltages and three cold discrete colors for low voltages. An example of the result is demonstrated in Figure 6. The figure clearly shows a pattern with a few areas with high voltage problems and some more areas with low voltage problems. Since thickness instead of color is used to code voltage capacity it is also possible to see the nominal voltage levels in the problem areas. The thick blue line in the middle should probably get the operator's attention since it represents a low voltage problem at a line with high nominal voltage.

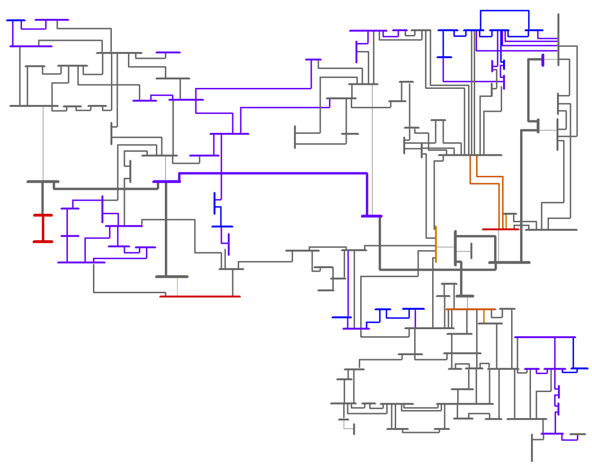

Figure 6: Per-unit voltage mapped to discrete colors of bars. Blue ≤ 0.96 and Red ≥ 1.04

4.3 Active and reactive flow (capacity, limits, actual and direction)

4.3.1 Thickness and arrow

Mahadev et A. proposed to map the active power flow limits and the current amount of active power flow (MVA) to the thickness of the transmission lines [2]. The idea was to use the absolute MVA and not the percentage of loading since it would give a better idea of the magnitude of a voltage problem. They also suggested using color to highlight when a line is overloaded. The scale they used in the example resulted in very wide lines and visual clutter. One reason for using this scale could be to be able to have a wider range since the mapping is continuous. On an overview display there is no need to have that level of detail. It is enough to know if a line is overloaded or close to overload.

4.3.2 Arrows (static and animated)

In addition to the loading of a transmission line an operator needs to understand the direction of the flow in the power grid. The direction can be deduced from the sign of the ingoing and outgoing side on a transmission line. To understand the overall flow from reading numerical values is cognitive demanding. Mahadev [2] realized the obvious mapping to represent the flow direction with an arrow on the transmission line and Overbye et al. [5][6] extended this mapping to distribute flow arrows along the transmission lines. They also suggest mapping the amount of flow to the size of the arrows and as an additional feature they

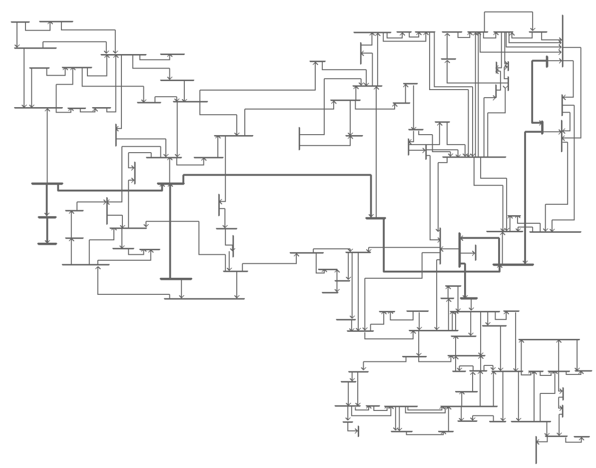

Figure 7: Active flow direction indicated with static arrows.

present animation as a way to further enhance the flow. The problem with the animated arrows is the animation itself and a common comment from the users is that they turns of the animation. The remaining static arrows is often enough to display the flow, see Figure 7.

A study comparing numeric value display with static and animated arrows is presented in [15] and the general conclusion was that the animated arrows could be helpful for some tasks but great care must be taken since the moving arrows draws the user's attention and it must be relevant for the task. If the only task was to understand the flow in the system it could be a good alternative but since the task is usually more complicated the moving arrows are likely to distract the user.

One complication with the flow is that both the active power flow in MW and the reactive power flow in MVAR are important and these can sometimes be in opposite direction and usually with different magnitude. No known solution to this problem has been presented other than by user interaction switch between the two types of flow and use the same visual representation.

4.3.3 Pie charts

An alternative solution to visualize the magnitude of line loading was presented by Overbye et al. in [5][6]. Their suggestion is to map the magnitude to a pie chart and the tecqnique is demonstrated in Figure 8. The idea is that a pie chart will appear on the one line diagram on the transmission line if it is overloaded or is close to overload. This will draw the operator's attention to the problem and this is probably the biggest advantage. They also suggest that the pie charts should be resized dynamically when the problem is above a certain threshold. The drawback with resiz-

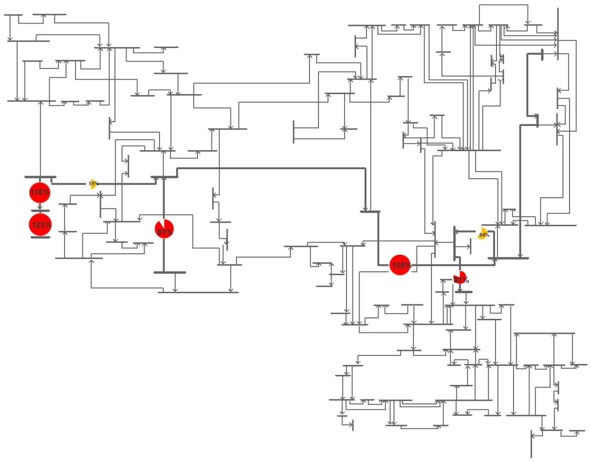

Figure 8: Active flow magnitude mapped to pie charts.

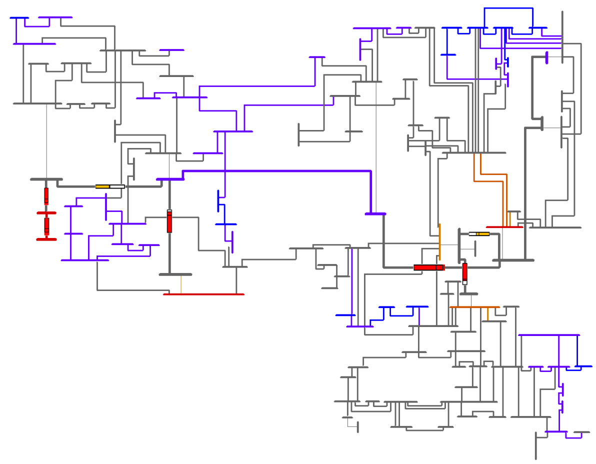

Figure 9: Active flow magnitude mapped to bars.

ing the pie chart in relation to magnitude of the problem is that the pie charts could hide important information. In some of the figures presented in [5][6] it is impossible to see what line some of the pie charts actually belongs to. This problem is mentioned by the authors and there are also other problems. The proposed techniques has a lot of redundant coding cluttering the display. Both the numerical values and the fill of the pie chart represent the same data. The size and the color also represent similar information. A pie chart is coloured red if the percentage exceeds 75% and the size is dynamically increases if the percentage is above the same threshold. The need for using resizing for attracting the operators attention to the most severe violations is due to the overuse of colors. If colors only were used for highlighting important information it would probably be enough to color the pie chart red to draw the operator's attention to the transmission lines with highest percent overload.

A problem that is not as apparent is what happens if the display shows both 220 kV lines and 400 kV lines. A 400 kV line loaded to 74% is probably more interesting than a 220 kV line loaded to 76%. Mahadev's solution with mapping the loading to the thickness of the line is in that sense a better mapping.

4.3.4 Proposed new mapping - Bars

The idea with pie charts appearing when a line is close to overload is probably a good way to attract the operators attention but a pie chart is not a natural mapping of flow. A similar but more natural mapping would be to represent the flow with a filled bar. If the bar is filled in the direction of the flow it will both map the percentage of flow and the direction in the same representation. Figure 9 displays an example with data from the IEEE 118 test system mapped to voltage levels and flow magnitude. The idea is to only display the bars for lines with flow exceeding the limits. For other lines it is enough to know the direction and for now we have no better alternative than using arrows since it is a natural coding of flow. Care must be taken to reduce potential visual clutter and the arrows should therefore have the same color as the transmission lines. We also propose to only use two discrete sizes on the arrows on the overview display. One larger for lines close to reach the first limit and one smaller for the others. In detailed displays operators use for operation it is possible to use a more continuous scale of the arrow sizes but on an overview display the focus should be to have as clean display as possible.

4.4 Generation reserves

To know the current generated power and the available generation reserves is also important information. In today's power grids a large variation of generators are available. Some are relatively small and produces only a few MW but some are very large and can produce hundreds of MW.

4.4.1 3D Bars

Overbye et al. [6] suggest to utilize a third dimension by mapping shapes onto a tilted 2D plane with the SLD. The maximum capacity generation is mapped to the cylinder's height and the different colors represent the current reactive power output and the available reserve. A human factors study of this approach is presented in [16]. The result indicated a faster solution time compared to a 2D representation and numerical values but the study could not verify increased accuracy compared to the other two display types. In the study it does not seem to be overlapping generation cylinders in the 3D view but in a real system this problem can not be neglected. Figure 10 demonstrates this

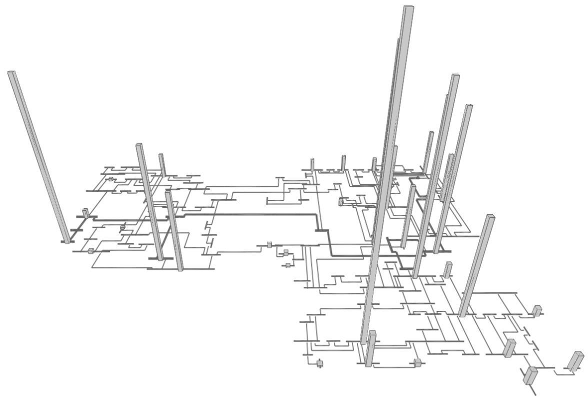

Figure 10: Generation mapped to continuous height of 3D bars.

problem. Another issue is the wide range of generation capacity. Our example only map the current power generated but it is possible to understand that it will be difficult to see the available reserves for the smaller generation units due to the wide range.

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.

4.4.2 Proposed new mapping - Pie chart

The study in [16] compares 3D cylinders with what the authors calls a graphical ”thermometer” which basically is a 2D bar. This could be an option but since we suggest to map the power flow to a bar this representation is already ’taken’. Instead we propose to use pie charts. The filling grade of the pie chart represents the current power generation and the remaining piece is the reserve. Neutral colors should be used as long as the generators is not in an alarming mode. One issue to solve is how to map the maximum generation capacity of one generator. One suggestion is to map the size of the generation pie chart to a discrete radius. For example could generation units up to 50 MW be represented with one size of the pie chart, units between 50 and 400 MW with one size and units above with a third.

4.5 Equipment status (open/closed)

Other important information in an overview display is to see the current status of breakers and switches. This binary open/closed information is in some cases mapped to colors. Colors are not a natural way to code this type of information since operators without any training cannot understand what a specific color mean. Instead we argue for using two variations of the symbols. This is already done in many systems today and the symbols can vary. In many cases a closed breaker is represented with a filled square and an open breaker with an unfilled square. The color of the symbol should be the same color as the transmission line unless there is an alarm. In that case the symbol should be red to attract the operator’s attention.

4.6 Equipment status (Energized and energized)

Transmission lines can also have different status and it should be obvious for an operator if a line is energized or de-energized. This information is also sometimes mapped to different colors and again color is no natural coding for this type of information. Instead we propose to use solid lines for representing energized lines and dashed lines for representing de-energized lines.

4.7 Equipment status (Normal or Abnormal)

Some equipment in a power system can be considered to be in normal mode or in an abnormal mode. Breakers for example can be normally or abnormally closed if an operator has re-routed the power due to maintenance work. One other example is power lines that can be normally or abnormally de-energized. In some cases it is interesting to know if equipment is in normal or abnormal mode but few solutions how to visually identify the equipment status have been presented or discussed.

The question is: What is a natural coding of an abnormal condition? Abnormal is not equal to a problem and should not automatically attract the user’s attention. If the abnormal mode at the same time is critical the use of colors to highlight alarming conditions will instead draw the operators focus to the interesting area. But it should still be possible to see if an alarming equipment is in abnormal mode.

Our suggestion is to in this case use two colors. Red for indicating the alarm and another more neutral color for representing the abnormal condition. A voltage violation on a transmission line that is abnormally energized would be represented with a solid line with altering red and and another color. If the equipment is in a abnormal mode without an alarm it should be coloured with the abnormal color.

The color used for representing abnormal condition is not trivial. It must contrast well to both cold blue toned colors, warm red toned colors, grey tones and it cannot be a green tone since green typically indicates ok. One possible color is a brown tone. A brown color is also good since it is a discrete color and does not draw too much attention.

4.8 Data uncertainty

Finally it is important to know how reliable all previous information is. The information comes from the State Estimator and the quality of the data depends on the available input data. If the system is undetermined the result is just a best guess and it is important to know when this happens and where in the system. In current systems this is typically done with an index after the numerical displayed values. This solution makes it difficult to see a pattern of areas with uncertainty. Our proposed solution is to use a gray scale contour map as a background in areas with uncertain results. One example to demonstrate this idea is shown in Figure 11. A similar approach was proposed in [18] where they used a red colour map for representing SE residuals (difference between the SE result and the measurements). They red map is too strong and take over other important information. A more discrete gray toned map does not clutter the view and the observer can direct relate the information about violating elements to the background. In our example the low voltage violations in the area in the upper right corner might not exist in the reality. It could be a consequence of uncertain data and the operator need to analyse this further before making any actions.

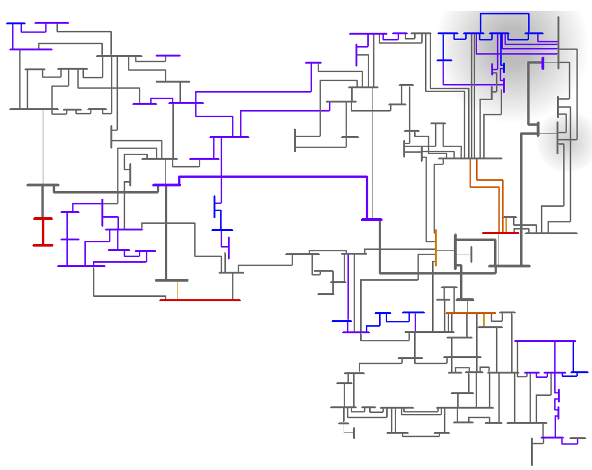

Figure 11: Gray color contour representing uncertain information.

5 Discussion and future work

The main purpose and contribution of this paper are the survey and analysis of previous proposed mappings. The proposed solutions should so far be seen as suggestions and inspiration to open up for new ideas. We will continue with benchmarking tests to evaluate the efficiency of the proposed mappings and the goal is to be able to formulate a ”best practice” guidance for the industry.

Some general conclusions, in addition to the ones already presented, can be drawn.

Overview displays are about providing operators and other roles in a control room a shared situation awareness. It is not intended to give detailed information about voltage levels at individual lines etc. Thus no numerical values should be shown. Instead mapping of information to visual representations should result in visual patterns. The mappings should be natural and the users should not have to remember what the mapping mean. Colors should be used with care and only for highlighting information and patterns and not for static information like type of equipment. In many cases it is possible to simplify and group a range of values together to simplify the visualization and continuous mappings should be minimized.

Color contours is a good example of a mapping resulting in a strong visual pattern. The problem is that it is too strong. It hides other important patterns and information. For specific tasks it fills its purpose but for a display with a lot of equally important information a better balance is needed.

3D shapes on a 2D display is popular mapping of quantitative data on a spatial 2D map, in this case a SLD. In some situations this mapping could be very valuable as some studies shows. If there is a strong pattern it could potentially be found in this type of mapping. In Figure 12 we have for example used this mapping to visualize the phase angle difference between one bus (the one in the top left corner) and the others. It is clear that the phase angle difference increases with distance from the reference bus and in this case the 3D shape mapping could serve its purpose. But the problem comes when the bars hide other bars. Then the user must rotate the view to see it from another angle. An overview display on a large power wall is supposed to be shared between many operators and other roles and relying on interaction to be able to see the information is not the best approach.

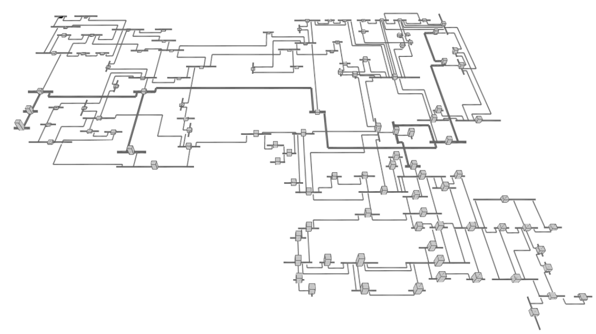

Figure 12: Phase angle difference mapped to height of 3D bars.

One thing not discussed in this paper but must be taken into consideration and is a suggestion for future work is change blindness and how it affect operators ability to get situation awareness. The SE application runs cyclic and the result last for a few minutes and is then replaced with a new result. To discover a trend in the data the operator must compare the snapshots and remember information from previous results. This is not only true for the SE result but also for the measured values but these are changing more continuously so it is easier to see if a value increases or decreases. The only proposed solution for this problem is to animate historical values and use the same visual mapping but it has shown that animation could be more time consuming and less accurate for exploratory tasks [19] and is probably not the best option when operating a time and safety critical system. Since it also would require interaction it is not a good solution for an overview display.

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