Visualization of the System State and 
Situation Awareness in Wide Area Transmission Systems for Electricity

C. SCHNEIDERS* J. VANZETTA J. F. VERSTEGE
Amprion GmbH University of Wuppertal
Germany

SUMMARY

During the past couple of years, the complexity of transmission system operation has increased significantly. Along with the liberalization of the electricity markets a broad range of new, varying tasks have arisen and with this a growing number of interfaces which the control centre operator has to cope with. Furthermore the substantial growth of volatile wind and solar energy sources and large-scale energy trades across wide-areas lead to frequently changing load flow situations. As a consequence of these huge load flows, the power system is operated ever closer to its security limits. The operator in the control room has to observe wider, external areas – with less operational experiences compared to the own grid – to fully evaluate system security. Along with the development of information technology and functionality of SCADA systems, the amount of on- and off-line data the operator has to monitor has augmented notably.

One major task of the control centre operator is to identify the global system state of the transmission system. This serves as basis for decision making. The growing complexity in the control centre poses new demands on the visualization concept according to cognitive principles. Therefore this paper describes the concept and implementation of an approach, how the increasing complexity can be prepared to assist the operator in the control centre.

The focus of this work is to develop a visualization of the global system state and to analyse and enhance situation awareness in wide area electrical transmission systems. In addition first versions of this new man-machine-interface (MMI) are implemented in the SCADA system of a German TSO. Thereby the study also enables usability engineering of variant new visualizations in the control centre. The proposed solution allows the operator to observe the global system state at a glance and enables intuitive situation awareness by improving visual perception like pattern recognition.

KEYWORDS

VISUALIZATION, SYSTEM STATE, CONTROL CENTRE, MAN-MACHINE-INTERFACE, PATTERN RECOGNITION, SITUATION AWARENESS, TRANSMISSION SYSTEM - OPERATOR

*christoph.schneiders@amprion.net
1. INTRODUCTION

Over the past couple of years, the complexity of transmission system operation has increased significantly. The main challenges are the integration of renewable energy sources - particularly wind and photovoltaic (PV) - and large-scale energy trades across wide areas [1]. Consequences are frequently changing load flow situations and huge load flows. The system is operated ever closer to its security limits. Along with the liberalization of the electricity markets a broad range of new, varying tasks have arisen and with this a growing number of interfaces which the operator in control centres has to cope with.

After the major disturbances 2003 in USA and 2006 in Continental Europe, inter-Transmission System Operator (inter-TSO) coordination has increased. For the security analysis regional approaches such as “Wide Area View” (NERC) [2] respectively “Observability Area” (ENTSO-E Region Continental Europe) [3] were introduced and several regional security initiatives have been founded (i.e. Coreso, SSC, TSC) [4]. This reflects that the operator in the control room has to observe wider, external areas – with less operational experiences compared to the own grid – to fully evaluate system security. Along with the development of information technology and functionality of SCADA systems, the amount of on- and off-line data the operator has to monitor has augmented radically. New visualization approaches to deal with the rapidly growing amount of data are necessary in order to enhance situation awareness in wide area electrical transmission systems.

One major task of the control centre operator is to identify the global system state of the transmission system. This serves as basis for decision making. The growing complexity in the transmission system control centre poses new demands on the visualization concept according to cognitive principles. An analysis of current visualization approaches shows that in most cases these are stand-alone systems, separated from ordinary SCADA systems in use. Furthermore the presentation types tend to suite better analysis rather than real-time operation objectives, so cognitive principles are often neglected. Therefore this paper describes the concept and implementation of an approach, how the increasing complexity can be prepared to assist the operator in the control centre.

2. SITUATION AWARENESS

The lack of situation awareness (SA) was identified as one of the main causes of recent large disturbances 2003 in USA and 2006 in Continental Europe [5, 6]. This shows that supporting and maintaining situation awareness play a major role to support the operator in the control room. The goal of this paragraph is to analyse and understand the cognitive process of an operator in the control room and to derive as an outcome requirements of new visualization displays for good state of awareness. While the transition of SA advances into the field of transmission system operation is still relatively new, in particular the experiences made in the area of air traffic control, military control, aviation and nuclear power can be taken into account [7].

One of the most common definitions, developed by Endsley, is described as “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” [8]. According to this definition, the following three levels are comprised:

1. Perception,
2. Comprehension and
3. Projection.

The model according to Endsley is illustrated in figure 1.
The first level of situation awareness includes the perception of significant objects in the current environment. This means, inter alia, that the operator in the control room must be able to see relevant displays or alternatively hear alarm sounds [7].

SA however goes far beyond perceiving data. Hence the comprehensive understanding and the meaning of information in relation to the goals play an important role in order to develop an overall picture of the current situation. As part of this, a good understanding of the current situation according to level 2, comprehension, aids the operator for instance in assessing the impact of an outage on other elements of the grid [7].

The third and highest level of situation awareness represents the projection of what is perceived into the future. In order to do this, the operator combines the current situation with his mental model of the system state and extrapolates the information forward in time to assess the future system state. Such a high level of SA is an essential foundation for effective decision making [7].

A state of the art analysis of current control rooms [7] shows that one major shortfall is data overload. The flood of data and the missing data integration of different systems is resulting in a high cognitive load of the operator, leading to a loss of situation awareness and thus to an higher error rate [7]. The operator has to scan continuously through a number of displays and merge them mentally for decision making. After analysis of the mental model, the operator derives high level information of the global system state [9, 10]. That high level information is based on the relationship of single values with each other. An example for high level information could be “high load flow from North to South due to high wind energy production”.

While enhanced visualization approaches taking into account ergonomic principles have been developed, for instance [11, 12, 13, 14], an overview of the current global system state is still missing in real-time system operation. Current developments are often focused on support in case of disturbances. Therefore the main focus of this work is the development of one graphical overall information platform, representing the current global system state and assisting in anticipating the future developments and trends in order to support proactive decision making to avoid disturbances.

3. HIERARCHICAL VISUALIZATION CONCEPT

In order to reduce data overflow, the visualization concept is based on a hierarchical approach, derived from the research and development presented in [9, 10]. The hierarchical principle is illustrated in figure 2. The basic idea behind this approach is to offer display levels with different degree of information. The top level, focus of this paper, tries to illustrate the global system state, showing the operator whether the system is in a desired operating state and if not, representing the amount of deviation.

The main aim of the top level display is to raise awareness in case of a deviation. Beside this, more detailed displays are required. These medium level displays are particular used to show more detailed information in case of deviations from desired values, to get an overview about certain system parameters - for instance the voltage profile - or to display trends in order to support proactive
decision making. Beside these kinds of overview displays, the operator needs to see detailed data i.e. using the classical single line diagrams for control tasks, too. Most visualization improvements in the last few years were applied in the bottom and medium display level, whereas the main focus of this research is on the top level display (figure 2).

Figure 2 Hierarchical visualization concept

4. GLOBAL SYSTEM STATE

Task Analysis

In the following step, the considerations in developing the global system state view are described. As mentioned previously, the operator in the control room has to combine and merge different information to high level information in order to get an idea about the system state. To understand which information the operator has to take into account to assess the current system state, a cognitive task analysis is carried out. The results of this task analysis show that the operator in the examined control room has to continuously monitor more than 20 different information readings for this purpose. As the capacity of the working memory with 5-9 elements of information, so called “chunks” [8], is quite low, it is obvious that the amount of key indicators forming the top level display has to be limited.

In particular the question how far the pre-assigned relevant system information may be condensed and integrated for the global system state representation has to be investigated. The highest level of aggregation could be a reduction to one single value, i.e. graphically coded as a traffic light. This kind of coding may be effective for applications as system monitors described in [4, 15], but discussions with operators showed that for presenting the own system state, the masking of information would be too high which leads to a loss of confidence into this kind of display. Therefore the system state display is subdivided into different key indicators. In order to build the global system state, information of different sources is integrated into one diagram. The task analysis showed that there are differences in the importance of the different system information. As the rating is consistent among the interviewed operators, prioritization is chosen as one data reduction possibility. It should be noted that these key indicators are the task analysis results carried out at among shift engineers of one TSO. As a matter of course they can look slightly different elsewhere. Furthermore the identified key indicators have to be validated in real-time operation.

The key indicators with highest priority identified are:

- **N-1, I**: N-1 security calculation with power flow security limit violation (current overloading);
- **N-1, V**: N-1 security calculation with voltage deviation;
- **Δf**: frequency deviation or information about system split;
- **ACE**: Area Control Error, is calculated as the sum of the power control error and the frequency control error;
- **Wind**: wind energy production, as an indicator for increased uncertainty regarding balancing and load flow situation and potential cause of high load flow situations;
- \( P_0 \): Power exchange program, the sum of all exchange schedules as an indicator of high energy exchange schedules, horizontal power transits and resulting high load flow situations.

The prioritization can be explained with the example of the power flow indicator (N-1, I): During real-time system operation, the presentation of the N-1 security calculation results have a higher priority than the presentation of the base case load flow results, as normally N-1 violations will appear first and thereby have an early warning or alert character for the operator.

**Graphical Representation of the system state**

In order to represent the global system state graphically, information of different sources are integrated into one integral circle diagram, in which each segment is representing one of the key indicators. Natural intuitive visual coding is used, as deviations are encoded combined by colour and shape. If all values are in nominal condition, a symmetrical circle is shown. Asymmetry, representing a deviation from normal conditions is recognized intuitively as human are sensitive to asymmetry.

Figure 3 shows the global system view, visualizing the highest priority indicators. In a second display (figure 4) a system state matrix is showing development over time of the key indicators, supporting SA level 3 and thereby proactive decision making. This diagram can also be extended by columns representing forecast information of the indicators, as the wind energy forecast of the next hour or results of the congestion forecast.

![Circle diagram for system state view](image1)

![System state matrix](image2)

The information is not arranged randomly. They are grouped in such a way to support pattern recognition and detection of causal links. Detection of correlations and determination of causal relationships between cause and effect are supported by representing direct (i.e. N-1 violation) and indirect information (i.e. wind energy production) in one diagram. The operator can assess intuitively operating situation such as “high wind energy production leading to huge load flows”.

**Multiple Displays**

To avoid masking of not shown information, the system state view was extended to a multiple display, organizing the within the task analysis identified information around goals [7]. The information is related to different tasks within the control room. Therefore they are grouped according to three working areas: grid, balancing and market related information. A global display shows the maximum deviation of each area. All further information of the three areas is shown in a second layer of the system state display (figure 5). If a deviation occurs, the second layer is shown automatically.
Initial results of usability tests resulted into a combination of both approaches. To avoid masking of information shown in the second layer, both views are combined to an advanced global system state view (figure 6). Therefore colour indicator fields are added to the centre of the circle diagram, indicating if a deviation in the second layer (grid, balancing, market) occurs which is not directly presented by the six highest priority segments.

The proposed solution allows the operator to observe the global system state at a glance and enables intuitive situation awareness by improving visual perception like pattern recognition.

**Coding of the key indicators**

Each key indicator of the system state diagram is composed in a transparent manner, enhancing its self-descriptiveness and conformance to user expectations. This is crucial because it increases confidence in information which forms a critical part of situation awareness [8].

By way of example, the power flow indicator (N-1, I) is calculated as the severest power flow security limit violation (current overloading) as result of the N-1 security calculation. The radius of this indicator field in the top level display increases depending on the percentage of the violated limit. Therefore two threshold values are defined. A warning threshold is defined, in order to draw up early attention when the loading has reached a certain value, the colour changes to yellow. If the overloading threshold is reached, the colour of the indicator changes to red in order to alarm the operator. Thereby overloads and pre-warnings are indicated. The operator can for example monitor easily the severity of the highest warning and is informed directly if the violation aggravates. To avoid misinterpretation or intransparent coding, a numerical index, summarizing several violations is discarded. The main aim of the top level view is to attract the attention of the operator. In case a violation occurs, the operator looks additionally to the more detailed medium level display, representing the results of the security analysis, which is introduced in the next paragraph (figure 8).

Regarding the projection on the radius, expressing the deviation of the key indicator, it has to be taken into account that the deviation is not projected linear on the radius but, according to human perception, projected on the surface area of the circle [16] which results into a logarithmic transformation.

**5. FURTHER MEDIUM LEVEL DISPLAY APPROACHES**

According to the hierarchical approach of the visualization concept, further overview displays are developed in addition to the representation of the global system state. Some of these displays are briefly presented in the following.

The projection of the future system state is additionally supported by new forward-looking trend representations which enhance proactive decision making i.e. to execute preventive countermeasures...
for ensuring system security. Therefore a time slice is representing the historical and forecast values of
the global state views’ key indices. In figure 7 the development over time of the power flow index
(N-1, I) is shown. In the same way the development of further key indices as wind energy production
and forecast, energy exchange programs, etc. can be presented. The visualization of data trends is
essential to assist the operator projection of the system state into the future (Level 3 SA).

This is complemented by a state of the art representation of the network security analysis (i.e. N-1
security calculation), showing the evolution of the results over time, sorted by severity (figure 8). The
way of presentation allows presenting at the same time the severity of violation and the development,
supporting thereby again SA. Beside the historical development, the display can be extended by
further columns, representing the results of the contingency forecast (i.e. Day-ahead or intraday
contingency forecast results).

Another way of intuitive coding is the use of Kiviat diagrams, respectively spider or star plots. Similar
to the circle diagram of the top level display, again intuitive visual coding is used. If all values are in
nominal condition, a symmetrical circle is shown. As an example figure 9 shows the deviation of the
system frequency in Central Europe during the disturbance in 2006 [5]. As the direction of axes is
geographically oriented, the representation allows an intuitive perception of the system split into two
areas in Central Europe.

Such kind of diagram can also be used to show a large number of values, for instance representing the
voltage profile. If applicable, again a hierarchical data reduction can be applied i.e. using different
diagrams per region and a top level Kiviat diagram representing their key values (i.e. minimum or
maximum deviation).
6. VISUALIZATION OF WIDE AREA TRANSMISSION SYSTEM

As described, the operators in control rooms now have to observe wider, external areas of the interconnected system to evaluate system security. The operational experiences of these external areas are always less compared to their own grid [1, 3]. In addition TSO staff is not responsible for external areas but the own grid may be affected by disturbances in the neighbouring grid. Also in this case, a data reduction is necessary, in order to avoid overwhelming the operator with information.

Until now many wide area overview displays in SCADA systems are based on a simplified grid representation defined i.e. on a control area or ownership structure. Hereunder the basic idea of a simplified representation of the grid, taking into account physical aspects (i.e. topology of the grid, generation pattern, etc.) are described [17, 18] and extended for an operational use in the SCADA system (figure 10-11). The display offers the possibilities showing in parallel different influencing factors on the load flow situation (i.e. amount and location of wind energy production, conventional generation pattern, commercial energy exchange, etc.), this form of presentation supports wide area situation awareness and aids faster and more reliable decision making. An application could be the visualization of grid congestions and support for congestion management (i.e. redispatch measures). In figure 11 the display is used to present the overall power flow situation together with the regional generation and load pattern. Depending on threshold values, recognizable load flow arrows, coded by colour and shape (size), are used to allow an easy identification of the main load flow direction and thereby supporting pattern recognition i.e. “High load flow, direction North to South”. In addition the balance situation of each area (import, export, neutral) is represented, using a diverging red-blue colour scheme (figure 11). A visual intuitive source-sink effect is achieved. This regional view can be considered as a new level between the high level control area view [15] and more detailed information displays offered in [11]. [15] is offering a European wide awareness system, based on control area structure. [11] illustrates situation dependent awareness displays especially for abnormal operating conditions.

Often colour sequences are used for representing geographical information. Regarding the use of colour it should be noted that the most common coding scheme, spectrum (rainbow) approximation, can be used for representing nominal scaled variables to enable rapid visual classification, but it is no perceptual sequence. This effect can be used representing system states, as the perceptual system trends to segment it into green, yellow and red [19]. For ordinal values and identification of differences, diverging colour scales - like red-green or red-blue schemes - should be used. Using for instance a red-blue colour scale enables pattern detection also for individuals with colour-deficient vision, which is not the case using a spectral colour scale [20]. Positive values - in this case “Export” - should be coloured in red, negative values - in this case “Import” - in blue and zero values in a neutral colour while the saturation of the colour depends on the magnitude of the value. Thereby the visual intuitive source-sink effect is achieved. The described principles for the use of colour are for instance applied in [15].

![Figure 10](image1.png) Simplified grid representation

![Figure 11](image2.png) Regional wide area view
7. IMPLEMENTATION INTO THE CONTROL ROOM

In the context of usability engineering, the operators are involved in the development and evaluation of the new visualization approaches from the early stage of design. Before implementation into the control room, the process of rapid prototyping is carried out. Therefore first visualization examples are developed using an off-line SCADA test system (figure 12). The different views are presented periodically to the shift engineers to get user feedback and adapt the different approaches. Outcome of this discussions are for instance the further enhanced system state views like the multiple displays and the system state matrix (figure 4-6). At figure 6 the frequency of switching to the second layer of the multiple display is reduced compared to figure 5.

The circle diagram in figure 12 (left) is extended by ex ante and ex post displays. Therefore the trend or - if available - forecast value is represented by an arrow. The colour is indicating the estimated category (green, yellow, red) of the next time step and the direction of the arrow is showing if the situation aggravates (increasing radius) or recovers (decreasing radius). Additionally the previous value is visualized by a dotted line. As already mentioned, the visualization of data trends is essential to assist the operator projection of the system state into the future (Level 3 SA).

In the next step, in order to validate the concept, different variations of the new visualization approaches are offered to the operator in the control room. Therefore first applications are implemented into the real-time SCADA system. The experiences gained by the operator of the control centre in real-time operation will be used to further adapt and improve the MMI. In particular the different variants of the global system state view are evaluated. Moreover, the identified key indicators with highest priority have to be validated and if necessary adapted. First views, the circle diagram and system state matrix, implemented in the control room are shown in figure 13. The back projection wall allows displaying the system state visualization at a fixed position, visible by all operators.
8. CONCLUSION

The paper presented a visualization concept based on a hierarchical aggregation of the information to be displayed. On the basis of a cognitive task analysis and a model of situation awareness applied in system operation, relevant system information indicators to determine the global system state are identified and prioritized. In particular the question how far the pre-assigned relevant system information may be condensed and integrated for the global system state representation was investigated. According to cognitive principles, a transparent and precise transformation of data is applied. As a result, a number of different global system state visualization variants (i.e. system state matrix, circle diagram) are presented and evaluated.

The proposed solution allows the operators to observe the global system state at a glance and enables intuitive situation awareness by improving visual perception like pattern recognition. According to the hierarchical approach of the visualization concept, further overview displays are developed in addition to the representation of the global system state.

Currently first visualization approaches are implemented into the SCADA system of a German TSO (figure 13). In the next step, experiences gained by operators of the control centre will be used to validate and further enhance this concept.

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