Transactions on Energy Systems and Engineering Applications

Article

Visualization Proposal for Power System Control Rooms Based on Situational Awareness

Daniel Betancur*, Eros D. Escobar, Anderson Quintero, Jorge W. González, Gabriel J. López and Idi A. Isaac

Research Group on Transmission and Distribution of Electric Power, Universidad Pontificia Bolivariana, Medellín, Colombia.
* Correspondence: daniel.betancurtr@upb.edu.co

Received: 21 December 2021; Accepted: 6 July 2022; Published: 27 July 2022

Abstract: Due to the increasing size of electric power systems and their monitoring and operation needs, people in control rooms face complex situations, analyzing great amounts of information, protocols, operation states, alarms, and control parameters. Additionally, new renewable energy sources data is taking place nowadays, hindering the process of quickly reading and interpreting information. This is known as the loss of Situational Awareness, SA, of system operators. This work presents proposals for displaying useful information in control rooms and visualization techniques to support accurate SA. Grid data displays, maps, trending graphics, lists, bar graphics, table plots, hierarchical levels, proximity regions, and connections are also proposed and analyzed, presenting an application case in a microgrid control room.

1. Introduction

The growth of electric power systems and consequent increase in their operation and monitoring complexity, in conjunction with the processing of a great amount of information and implementation of new operating protocols and cyber-security, made it necessary to include a high level of situational awareness (SA) in the operators control rooms. The core idea is to perform proper and effective decisions based on different grid scenarios, incidents, and contingencies [10, 18].

In general, SA has been identified as a mental state implying updated knowledge around situations, objects, or ideas, based on the perception of the working memory at the present time [10]; this way, SA applies to various environments where people perform tasks involving perception, understanding, and projection. Thus, electric power utilities, especially grid operators, are not exempt from these challenges. They must ensure clear and relevant information within operating environments to assure the security of their systems [4].

How to cite this article: Daniel Betancur, Eros D. Escobar, Anderson Quintero, Jorge W. González, Gabriel J. López and Idi A. Isaac. Visualization Proposal for Power System Control Rooms Based on Situational Awareness. *Transactions on Energy Systems and Engineering Applications*, 3(2): 442, 2022. DOI:10.32397/tesea.vol3.n2.442

SA concepts drew attention in 2004 in the frame of the USA-Canada power system blackout, since the main cause was attributed to human errors related to information overload and difficulty in data collection, that is to say, to the loss of SA [26].

In control rooms, various software applications are typically used. These spread out over several screens and video walls showing different data types [23]. Thus, when the information is combined with contingency analysis, alarms, and state estimation calculations, data to be processed by the operator get to exceed its mental capacity, whereas on average, the human brain has a short-term memory of 7 ± 2 elements for 10 seconds [28]. Likewise, software diversity, similar colors for different data, confusing iconography, different sizes, fonts, fuzzy contrast between text and backgrounds, and false alarms, among other aspects, deter the process of reading and interpreting information, leading to the loss of SA conception [18].

At present, different companies develop custom Supervisory Control And Data Acquisition (SCADA) software for control rooms of electrical power systems [12, 17, 1, 11]. In general, commercial SCADA systems present extensive use of colors, graphs with hard-to-read names, displays of meteorological variables, and highly detailed and irrelevant information.

This work identifies as a research problem the failures in power systems due to human error, caused by low levels of SA in control rooms, presenting the contribution that visualization interface design methodologies could offer to the improvement of the SA of operators.

The content of this paper is organized as follows: in Section 2 a description of SA and its main concepts is shown, and Section 3 presents some design methodologies based on SA and Section 4 applies these concepts to electric power systems; Section 5 contains a case study where these concepts are applied to a real campus microgrid, Section 6 presents a discussion of the proposed designs and its implementation; finally, Section 7 presents some conclusions and future work derived from this document.

2. Situational awareness concept

2.1. Situational Awareness Definition

In [8, 7] the authors define SA as the conscious perception of the environment elements in a defined space and time, the understanding of their meaning, and projection of near-future states. Thus, we base SA on three basic levels[23]:

Perception: Corresponds to the sensory detection capacity of the environment´s significant signals, either a human being using external senses or a machine based on its sensors.

Comprehension: Refers to the global understanding of acquired information, its dimension, impact, and immediate risks.

Projection: It consists of processing information received, projecting it towards a future time to foresee consequences, and following events.

2.2. Team Situational Awareness (TSA)

Team Situational Awareness (TSA) is the awareness degree required by each member of a team to carry out their assignments [10]. Hence, the SA of each individual composing the unit determines the TSA, requiring active participation of its parts [20, 15].

2.3. Human Factors

Human factors influencing SA of the person cover a wide range of areas, including perceptive, physical and mental abilities, interaction and working environment effects on people, equipment and systems influence on human performance, organizational characteristics related to work safety, etc. Therefore, within human factors, five aspects determine SA conservation [15]: Attention, perception, working memory, long-term memory, and decision automatism.

3. Visualization interfaces based on Situational Awareness

Implementation of visualization interfaces based on SA methodologies greatly facilitates information processing and decision-making of individuals, especially during alarms and high responsibility situations. User interfaces in a control room should consider that data displays shall be designed for specific tasks according to the application environment, including color-coding schemes and representation of proper information and lighting [16, 7]. Relevant factors to consider in SA-based information presentation are set out below.

3.1. Levels

Proper use of levels in the display allows reducing the time employed by an operator to respond to different situations presented by electrical systems. We propose the following levels with their respective elements:

Level 1 (Overview): Includes key indicators, priority alarms, general equipment condition, trends, and abnormal situations. *Level 2 (Control Unit):* Includes visualization of control and monitoring parameters, such as control directions, values, alarms, trends, and specific states of equipment. The present work will focus on this level, due to its greater impact on the operator. *Level 3 (Detail Unit):* Presents the detail of parameters indicated in level 2, for each equipment or situation. *Level 4 (Support Unit):* Integrates documents, support information, guides, and procedures.

3.2. Colors

The use of colors in the displays of electric grids control rooms becomes relevant as each color is able to indicate a system state, e.g., red: heat and danger, yellow/orange: warning and alert, blue: obligation, attention or information, among others [19]. However, the designers must consider that color excess generates confusion, and visual noise, and makes it difficult to recall the coding scheme [2].

For critical elements, design colors must ensure the contrast between objects and the background. For backgrounds, and during normal operation states, SA principles recommend light colors, e.g., alice blue, beige, and grey. This allows identifying important details without needing to place them in the foreground [29].

3.3. Appearance attributes

Visual aspect attributes are necessary to simply express as much information as possible. Thus, at the time of planning information displays, SA methodologies recommend assuring that in a stable state or normal operation, the data presented is not highlighted and is considered boring [9].

On the other hand, changes in appearance attributes draw attention in order to indicate an alert state. Shape attributes related to information design and display are associated with orientation (trends, data types), movement (intermittency) [2], contour line size (important information distinction) [13], bar length (quantitative information) [9], size and shape of objects (visual classification), markings (iconography, symbology), analog shapes (bars, trend graphs) and dynamic shapes (alternating between colors and texts, fillings) [13].

3.3.1. Grouping Information

Principles of perception reveal visual characteristics that incline individuals to group similar objects or data. Thus, it is possible to group these principles into five: proximity, similarity (color, size, shape, and orientation), confinement (visual boundaries), continuity, and connection [9].

3.3.2. Texts

In [2], some specific text fonts are recommended to facilitate observation and reading of information. Among the highlights are the monospaced Sans-Serif, Verdana, and Tahoma fonts. In addition, [13] recommends using the same type of text in visualization, using dark colors (avoid black) and being consistent with abbreviations. To ensure good visibility, ANSI/ISA-18.2-2009 recommends limiting a minimum text size of 2.8 mm and a maximum of 4.1 mm, to a typical distance of 24 inches (0.61 m) from the projection surface.

3.3.3. Tables

Designers should take care to ensure tables provide useful information and not only present unnecessary data. Including limits or deviations in tables, the use of the same quantity of decimal places, and non-centralization or left alignment of data, allows for reducing cognitive load and contributes to the information understanding [21].

4. Visualization proposal for power systems

Electric network control rooms have a series of common monitoring and control parameters that allow for maintaining grid stability. Hence, these parameters are usually visualized in information displays such as single-line diagrams, voltage control, and reactive power graphs, dispatch and generation control displays, frequency control, security conditions, etc. [19, 27]. Besides, with the increase of renewable energies, it has become necessary to add new signals comprising, to a greater extent, intermittent sources monitoring, frequency, and reactive power backups, system inertia [24], compensations availability, and indicators such as Rate Of Change of Frequency (ROCOF), Voltage Ride-Through (VRT), generation ramps, Area Control Error (ACE), rate of change of demand [16], among others.

Regarding the visualization proposal of this work, it is established the use of greyish colors as a standard palette, achieving a sober appearance in the normal state of operation. Voltage levels differentiate by the contour or size of symbols. Iconography is used to give more information about each element and its state. For states of warning (near defined limits) or alarm (exceeding limits), orange and red colors are respectively used. Each diagram proposal preserves the same symbology, fonts, and colors, to display electrical parameters in control rooms, as shown below:

4.1. Maps

This type of graph allows the geographical identification of system anomalies. For an electrical grid operator, a map display grants identification of substations under special conditions, or visualization of meteorological parameters (solar radiation, wind speed and direction, cloudiness, and temperature). For voltage monitoring and parameters such as VRT, this type of illustration will allow geographical recognition and its effects on nearby grid elements.

A voltage map display is presented in Fig. 1, where circumferences size allows quick identification of the substation voltage level (1), and its color indicates the current system state (2). These designs use the red color for critical states, orange for high abnormal states, and purple for critically low voltage. In the case shown, the map displays a state of no communication or no data. Likewise, the graph integrates,

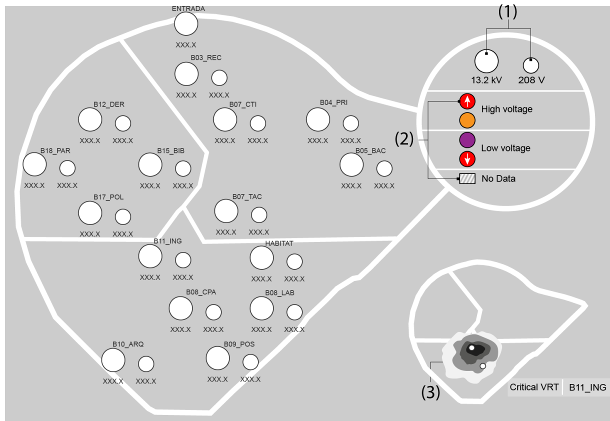

Figure 1. Map graph under SA concepts for displaying voltage states and voltage limits.

as a heat map, a simulation result of the most critical low voltage hole (3), and its influence on nearby grid generators/substations, allowing operators to be aware of the effects of the greatest possible voltage disturbances in the power system. This design allows to easily determine the geographical position of the substations, avoiding visual overload with terrain, roads, towns and city names, water sources, and other useless physical data.

Sometimes control displays use purple color as an index of restoration status of the system as in [22], however, this will greatly depend on the structure and definition of colors determined for display visualization.

4.2. Trend plot

This type of graph represents visualization by continuity grouping. Fig. 2 exhibits a trend chart display, which allows appreciating the parameter history, its current state, and past and projected values. In (1) is located the name of the vertical axis with its units; in (2) the name of the general parameter to be visualized; in (3) different complementary or related line graphs are shown; in (4) the trend plot integrates an uncertainty range of projected or forecast values using darker grey, and in (5) appears the time frame of the plot. This trend plot also includes warning (orange) and alarm (red) states described in the Variable generation section. Trend plots may present parameters such as:

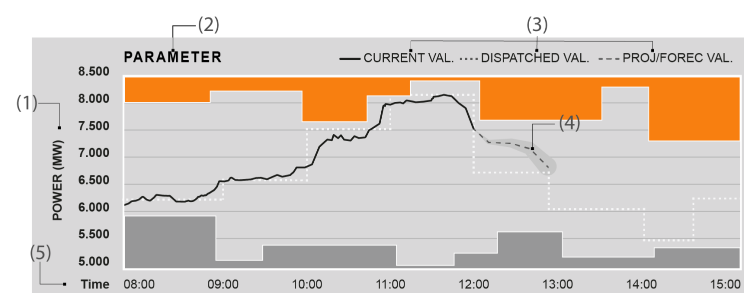

Figure 2. Trend plot under SA concepts for displaying electrical parameters.

4.2.1. System generation and demand

Trend graphs could display generation history, generator dispatch, total and gross demand, including distributed and renewable sources. Hence, this plot allows operators to work with a guide based on historical data, projections, and forecasts (e.g., solar and wind power) for proper operation.

4.2.2. Variable generation (solar and wind power)

Allows the incorporation of warning and alarm limits, which when crossed, would generate changes in the colors of the graph, as shown in Fig. 2. Renewable generation trend plots are crucial for microgrid supervision and control, as it is key to have clear information about current and forecast energy availability for the Energy Management System (EMS) operation. Trend plots implementations in electric microgrids are available in [3, 5, 6].

4.2.3. Inertia

Given the massive incorporation of variable renewable energy sources into modern power systems, the monitoring of grid inertia has become crucial. Consequently, operators must attend rapidly sudden generation loss scenarios and the visualization schemes must contribute to this task, balancing inertia [14] or increasing other generation sources and compensation devices.

4.2.4. Frequency and ROCOF plots

Frequency variation monitoring allows adding useful historical and projections to available data for a control room operator, as well as limits that generate alarms indicating a possible future risk for the electric grid. Likewise, the increased power share of variable energy resources displacing classic synchronous generators, makes it decisive for operators to be aware of the current and projected ROCOF to support system stability [16].

4.2.5. Rate of change of demand

Indicates the active power change of demand in a given period, accounting for required sources dispatch orders to preserve grid stability. This type of graph can be limited by tolerance zones defined by system characteristics, combining a trend line plot with color alarms in the approximation or surpassing of limits, as shown in Fig. 2.

4.3. Lists and bars plots

Lists and bar graphs allow visualization, in a grouped environment, of detailed numerical information for an element. In this case, we propose to display three parameter classes under this type of plot: Generation, Compensation, and Frequency.

Fig. 3 presents a generator state display under SA graphic concepts. The most relevant generation systems or those with operation anomalies would be portrayed. This type of graph exhibits specific use of colors, icons, or shapes to distinguish different generator states (red-alert, orange-warning, blue-information, or gray-normal state) (1), operating states and characteristics (2), number of available generation units (3), generator type (hydro, thermal, renewable) in (4) and generator power operating range (V1-V4) (5), dispatched power value (V3) and current output power value (V2). Finally, a graph of generation power trend and forecast is presented in (6).

The triangles presented in (1) can be replaced by iconography that symbolizes the type of generator, compliance with dispatches, failure, or maintenance status. Now, due to the integration of variable energy sources, with mostly active power generation, it becomes necessary to add reactive power compensators monitoring in control rooms.

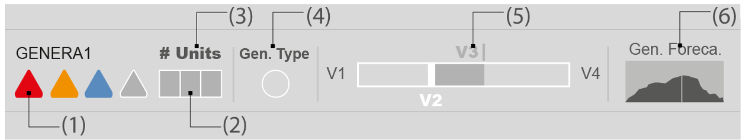

Figure 3. Lists and bars plot under SA concepts for a generator state display.

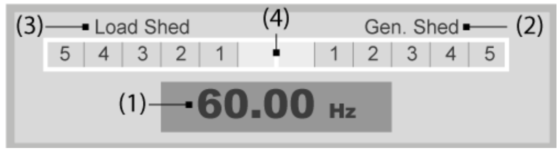

Figure 4. Bar plot for monitoring frequency and load/generation shedding/curtail states.

Besides generation and compensation plots, for wind power sources, bar charts allow adding more useful information related to generator characteristics such as wind speed, cut-in, and cut-off/out speeds, the number of developed VRT protocols in a time frame, alarm-alert states, among others.

Another display proposal is presented in Fig. 4 for visualization of the current frequency value (1). There are different stages of generation shedding/curtailment because of high frequency (2) and load shedding by low frequency (3). Given the approximation of the mobile frequency indicator (4) to its limits, indicative box (1) would get orange (alarm state) or red (emergency state) when it exceeds regulated limits. In case of entering any curtailment state, each phase background box shall be positioned in an alert state (red color) indicating system accessing to the corresponding operation scenario.

4.4. Tables plots

Although information visualization through tables is not recommended due to the difficulty of differentiating data between rows and columns, this type of plot is useful for visualizing a few parameters with low information. Hence, Fig. 5 shows the system's capability to increase or decrease active and reactive power, based on the capacities of generators and compensators. Likewise, given the increase of intermittent sources, it is necessary to monitor the reactive power reserve, as in [24, 12]. Besides, the right side of this graph displays the reserves ramp, that is, the grid's ability to increase or decrease certain active power megawatts in one minute.

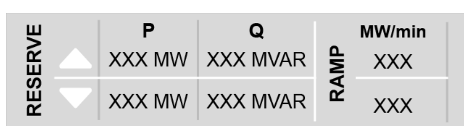

Figure 5. Visualization under SA concepts of active and reactive power reserves, as well as the power change ramp.

4.5. Hierarchical levels and grouping by proximity, confinement, and connection

Using levels for visualization and monitoring of electrical systems permits the hierarchy and logical organization of information. Based on SA methodology, the first level indicates alarms associated with abnormal variations in equipment status; the second level displays single-line diagrams with topological indications of affected substations and system status; at the third level, available and affected substations and measuring instruments are enunciated; at the fourth level, operative protocols and equipment documentation are available.

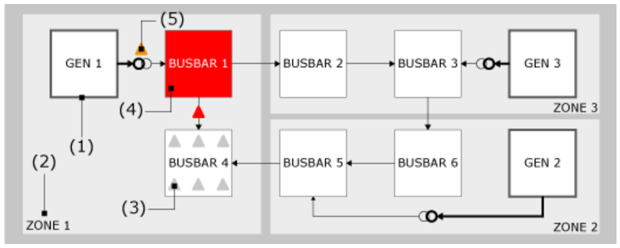

Figure 6. Second level visualization of IEEE 9-bus system under SA concepts for a monitoring and control room.

Figure 6 presents a single-line diagram of the standard IEEE 9-bus system, displayed in the second level of visualization. The diagram integrates nine busbars, composed of three generation busbars (Gen 1, 2 and 3), three transmission busbars (Busbar 1, 3 and 5), and three load busbars (Busbar 2, 4, and 6). Hence, when applying SA criteria, a sober single-line graph is observed, allowing quick identification of anomalies within the system based on color-coded highlighting of elements and specific iconography. Likewise, the thickness of transmission lines and substations containing boxes (1) characterizes the voltage of grid zone (2); thinner lines represent a lower voltage than thicker styles. Each substation is a square, including a short and easily related name, e.g., geographical location, function, type of connection, or electrical zone. This facilitates additional representative iconography about substation characteristics (3), and visualization of different operational states of substations (4), lines, and transformers (5). Similarly, the single-line diagram of Fig. 6 serves as an example of grouping by proximity (voltage level), confinement (grid zone), and connection (transmission lines).

On the whole, these designs framed in SA methodologies enable to establish differentiating factors like voltages, operational states, element types, and relationships like zones and electrical links. It is easy to set up groups of intuitive identification for operators, achieving visual and cognitive flexibility and evading colors that attract attention during normal states.

5. Case study: UPB microgrid control room

The design of real-time graphical interfaces based on SA concepts has been widely applied in the monitoring and control system of the UPB microgrid, located at the Universidad Pontificia Bolivariana, Medellin, Colombia. In the microgrid control room presented in Fig. 7, there is a large-format screen (videowall) integrating various displays for the visualization of different operating parameters, focused on maintaining an appropriate SA of the operators.

Figure 7. UPB microgrid control room.

Due to the distributed electric generation of the microgrid, it is necessary to divide the information of power, energy, and demand in different areas, allowing to locate issues in generation systems and characterize the demand curve. Fig. 8 shows the Energy and power display, integrating techniques of map

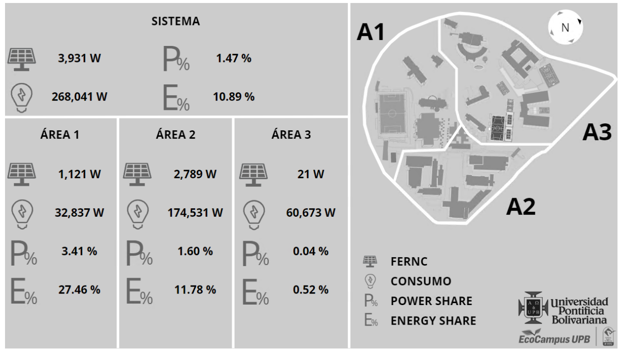

Figure 8. Energy display at UPB microgrid control room.

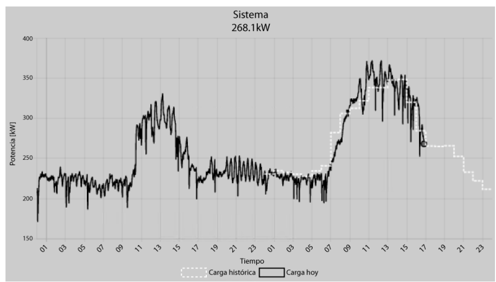

Figure 9. Demand display at UPB microgrid control room.

charts, table plots displays and information grouping by proximity proposed in sections 4.1, 4.4 and 4.5, respectively; and Fig. 9 shows the Demand display, including demand trend plots proposed in section 4.2.1.

There is also a voltage monitoring display, where it is visualized the geographical position of the substations on the campus and their voltage status. The voltage display is shown in Fig. 10, integrating low and high voltage alarms and applying techniques of map charts proposed in section 4.1.

6. Discussion

The design methodology of the proposed interfaces is based on the concepts and theory of SA, widely implemented and validated in various fields, as explained in sections 1 and 2. Thus, the proposed displays are supported by design logic that has been shown to be useful in improving advanced SA, and, currently, work is being done on indicators that allow quantitative analysis of the contribution of such designs to the performance of operators in control rooms.

A possible approach to objectively evaluate the performance of a display is an indicator to qualify the improvement in the SA of power system operators, due to the implementation of the design methodologies described in this work. An indicator of the system failures due to operator errors, related to the total network failures of any cause, is a good starting point to evaluate the effect of these design methodologies on the network operation performance, compared to classical designs available in commercial SCADA systems. Energy service quality indicators like SAIFI (System Average Interruption Frequency Index) and SAIDI (System Average Interruption Duration Index) could be a tool, already used by grid operators, and helpful to evaluate the effectiveness of the designs.

Nowadays, several public grid operators and private electrical systems in Colombia integrate situational awareness concepts into the display designs of their control rooms. The UPB microgrid presented in this paper, the National Dispatch Center of the Colombian grid and market operator XM[25, 30], and the control rooms of grid operator EPM and generation plants operator CELSIA are some real-world applications of these methodologies.

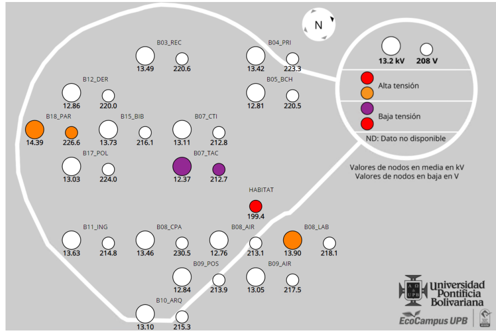

Figure 10. Voltage display at UPB microgrid control room.

7. Conclusions

The application of SA concepts to the design and visualization of displays in the control rooms of power systems enables standardization of signals, icons, and elements with which operators interact, avoiding confusing diversity of colors, diagrams, and shapes provided by commercial suppliers in software tools.

When designing interfaces for power system control rooms, it is crucial to avoid factors that can induce loss of SA like data ambiguity, distraction, high memory and workload, operators fatigue and stress, information overload, communications losses, and lack of a defined work plan.

Developing custom tools for the monitoring and operation of electric systems allows research projects to evolve according to specific needs and goals, rather than relying on commercial software availability. Each display has a purpose in the control room visualization system, so it is designated as an alarm, informational, control, or mixed interface. It is necessary to establish the purpose of each display to avoid misinterpretation of the information.

SA-oriented design of display interfaces for control rooms of power systems leads to a significant advantage in information organization, perception, processing, and decision-making of operators. Application cases, like the UPB microgrid supervision and control room interfaces, show a significant improvement in grid monitoring and data processing speed and efficacy.

Acknowledgments

The authors would like to thank the support of the project: “Estrategia de transformación del sector energético colombiano en el horizonte de 2030” and the Research Group on Transmission and Distribution of Electric Power (T&D) at Universidad Pontificia Bolivariana.

Funding: This research was funded by the program: "Estrategia de transformación del sector energético colombiano en el horizonte de 2030" financed by the research call 778 of MinCiencias Ecosistema Científico. Contract FP44842-210-2018.

References

[1] Alstom. Innovation in Distributed Energy Resources Management Solutions (DERMS) Based on Pilot Project Experiences European Utility Week, Amsterdam. Technical report, Alstom, 2015.

[2] Larry Arend, Alex Logan, and Galina Havin. Using Color In Information Display Graphics, 2015.

[3] E. Ariza, A. Correcher, C. Vargas, and F. Morant. Supervision, condition monitoring and fault diagnosis system in a hybrid renewable energy systems (HRES) laboratory. *Renewable Energy and Power Quality Journal*, 1(13):208–212, 2015.

[4] Paranietharan Arunagirinathan and Ganesh K. Venayagamoorthy. Situational awareness in an electric utility's control center of its generators' damping capabilities. In *2017 IEEE Power and Energy Society Innovative Smart Grid Technologies Conference, ISGT 2017*, 2017.

[5] Paula De la Hoz, Elvin Jimenez, Ingrid Oliveros, and Andrea Silva. UniGRID: Photovoltaic Study Case for the Universidad del Norte Renewable Energies Laboratory. *15th International Conference on Electrical Engineering, Computing Science and Automatic Control*, 2018.

[6] Dario Dosen, Matej Znidarec, and Damir Sljivac. Measurement Data Acquisition System in Laboratory for Renewable Energy Sources. In *2nd International Conference on Smart Energy Systems and Technologies*. IEEE, 2019.

[7] Mica R Endsley. Toward a theory of situation awareness in dynamic systems. *Human Factors: The Journal of the Human Factors and Ergonomics Society*, 37(1):32–64, 1995.

[8] Mica R. Endsley and Erik S. Connors. Situation Awareness: State of the Art. In *2008 IEEE Power and Energy Society General Meeting - Conversion and Delivery of Electrical Energy in the 21st Century*. IEEE, 2008.

[9] Stephen Few. *Information Dashboard Design*. O'Reilly Media, 2006.

[10] José Figueroa Martínez. *Integración de los requerimientos de conciencia situacional y grupal al desarrollo de sistemas colaborativos y dinámicos usando un enfoque basado en modelos*. PhD thesis, Universidad de Granada, Granada, 2012.

[11] GE Power. Advanced Distribution Management Solutions (ADMS), 2018.

[12] Green Eagle Solutions. Soluciones SCADA para parques eólicos y plantas solares, 2019.

[13] Bill R Hollifield, Dana Oliver, Ian Nimmo, and Eddie Habibi. *The High Performance HMI Handbook*. 360 Digital Books, Houston, 2008.

[14] Hydro-Québec Transmission System. Transmission Provider Technical Requirements for the Connection of Power Plants To the Hydro-Québec Transmission System. Technical report, Hydro-Quebec: Direction Planification des actifs, Quebec, 2009.

[15] David B Kaber and Mica R Endsley. Team Situation Awareness for Process Control Safety and Performance. *Process Safety Progress*, 17, 1998.

[16] Debra Lew, Drake Bartlett, Andrew Groom, Peter Jorgensen, Jon Osullivan, Ryan Quint, Bruce Rew, Brad Rockwell, Sandip Sharma, and Derek Stenclik. Secrets of successful integration: Operating experience with high levels of variable, inverter-based generation. *IEEE Power and Energy Magazine*, 17(6):24–34, 2019.

[17] Mattia Marinelli. Key requirements for future control room functionality. Technical Report 609687, Technical University of Denmark, 2015.

[18] Jim McCarthy, Otis Alexander, Sallie Edwards, Don Faatz, Chris Peloquin, Susan Symington, Andre Thibault, John Wiltberger, and Karen Viani. Situational awareness for electric utilities. Technical report, NIST, 2019.

[19] Christine Mikkelsen, Jimmy Johansson, and Matthew Cooper. Visualization of Power System Data on Situation Overview Displays. In *Information Visualisation (IV), 2012 16th International Conference on*, Montpellier, 2012. ABB Corporate Research, Industrial Software Systems.

[20] K L Mosier and T R Chidester. Situation assessment and situation awareness in a team setting. *Designing for Everyone*, 1991.

[21] OPTO 22. Building an HMI that Works: New Best Practices for Operator Interface Design. Technical report, OPTO 22, Temecula, 2014.

[22] Mathaios Panteli. *Impact of ICT reliability and situation awareness on power system blackouts*. Degree of doctor of philosophy, The University of Manchester, 2013.

[23] Mathaios Panteli and Daniel S. Kirschen. Situation awareness in power systems: Theory, challenges and applications. *Electric Power Systems Research*, 122:140–151, may 2015.

[24] M Power, N Singh, M Sanchez, C Roggatz, G Ivkovic, E Garrigan, V Pandey, and I Aronovich. Challenge in the control centre due to distributed generation and renewables. *Cigré*, 2013.

[25] Jorge Esteban Tobón. Conceptos y ejemplos de la Conciencia Situacional aplicada en operación del sistema eléctrico colombiano. Technical report, cigre, 2017.

[26] U.S. Secretary of Energy, Minister of Natural Resources Canada, and U.S.-Canada Power System Outage Task Force. Final report on the August 14, 2003 blackout in the United States and Canada: Causes and recommendations. Technical report, U.S.-Canada Power System Outage Task Force, 2004.

[27] C A Vanegas, R. A. Bolaños, J. E. Tobón, and S. Ardila. Prototipos funcionales de aplicaciones visuales para la toma de decisiones en el centro nacional de despacho Colombia. *XVII ERIAC*, 37(3), 2018.

[28] Øystein Veland, Magnhild Kaarstad, Lars Åge Seim, and Nils Førdestrømmen. Principles For Alarm System Design. Technical report, Norwagian Petroleum Directorate, Kjeller, Noruega, 2001.

[29] Colin Ware. *Information Visualization: Perception for Design*. Morgan Kaufmann Publishers, San Francisco, 2004.

[30] XM S.A. E.S.P. Nuevo Centro de Control del Centro Nacional de Despacho. Technical report, XM S.A. E.S.P., 2018.