Keeping the Lights On Across the Continent

Work domain analysis and ecological interface design combine to hone the prototyping of an improved graphical layout for power system monitoring.

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FEATURE AT A GLANCE:
Operators need new visualizations to help them monitor increasingly complex power grids at wider geographical scopes. We developed a work domain analysis of power grid operations from interviews, focus groups, and observations. The work domain analysis helped determine information requirements for a wide-area monitoring design concept that follows ecological interface design principles. We validated the design concept in a usability evaluation, achieving an above-benchmark System Usability Scale score of 77 out of 90. This work domain analysis and ecological interface design process will equally apply to the design of other power grid monitoring displays.

KEYWORDS:
power grid, ecological interface design, work domain analysis, cognitive engineering, interface design, electrical power, human factors, focus groups, energy management system, power failure, design concept, design prototyping

On August 14, 2003, 50 million people lost electrical power in the United States and Canada (US-Canada Power System Outage Task Force, 2004). A power transmission line in Ohio contacted an overgrown tree, launching a cascading failure across an interconnected power grid spanning multiple states and an international border.

The reliability coordinators (RCs; see sidebar at the end of the article) who manage regional electric reliability had failed to anticipate the event with their energy management systems (EMSs). The ensuing investigation (US-Canada Power System Outage Task Force, 2004) revealed problems including inadequate monitoring capability and poor information sharing with neighboring utilities about events preceding the failure. Operators had insufficient tools for wide-area monitoring; that is, visualizing the power grid over a large geographical scope beyond, but connected to, their jurisdictions.

WIDE-AREA MONITORING

The blackout drew attention to the threat of cascading failures posed by lack of wide-area monitoring in North American EMSs. Regulatory organizations such as the North American Electric Reliability Corporation (NERC) have since mandated data sharing and wide-area views (NERC, 2006) so that operators can detect and respond to incidents in other jurisdictions. The recent increase in intermittent renewable generation (Obradovich, 2011), market deregulation (Sanderson, Memisevic, & Wong, 2004), and cybersecurity risks (Ten, Liu, & Manimaran, 2008) have increased power grid operations' complexity and thus information processing required of operators and EMSs.

To adequately display information, EMS design must satisfy both technical constraints of power grid operation and requirements of human operators. One approach to this challenge is *ecological interface design* (EID; Rasmussen & Vicente, 1989; Vicente & Rasmussen, 1992), which is used in complex systems to support human performance and error recovery. The method for creating ecological displays involves systematically eliciting information requirements using *work domain analysis* (WDA; Burns & Hajdukiewicz, 2004). Although previous wide-area power grid visualization projects cited EID guidelines (Hoffmann, Promel, Capitanescu, Krost, & Wehenkel, 2011; Rantanen, Winkle, & Overbye, 2008), this project is the first to draw information requirements from a WDA of the power grid operations domain (Hilliard, Tran, & Jamieson, 2017).

Our project objectives were to understand human factors issues in power grid control, analyze operator work, and design and evaluate wide-area visualizations. We collaborated with Ontario's Independent Electricity System Operator to study its control room (Figure 1) and explore future implementations of wide-area visualizations that will help it comply with the NERC regulatory standard.

Context of the design. Wide-area views visually represent the power grid at large geographical scopes. They are a central monitoring feature of an EMS to help operators detect abnormal events at both system (e.g., Ontario only) and multijurisdiction (e.g., Ontario and its neighbors) levels (Overbye & Weber, 2015). The design concept presented here was scoped to Ontario's power grid.

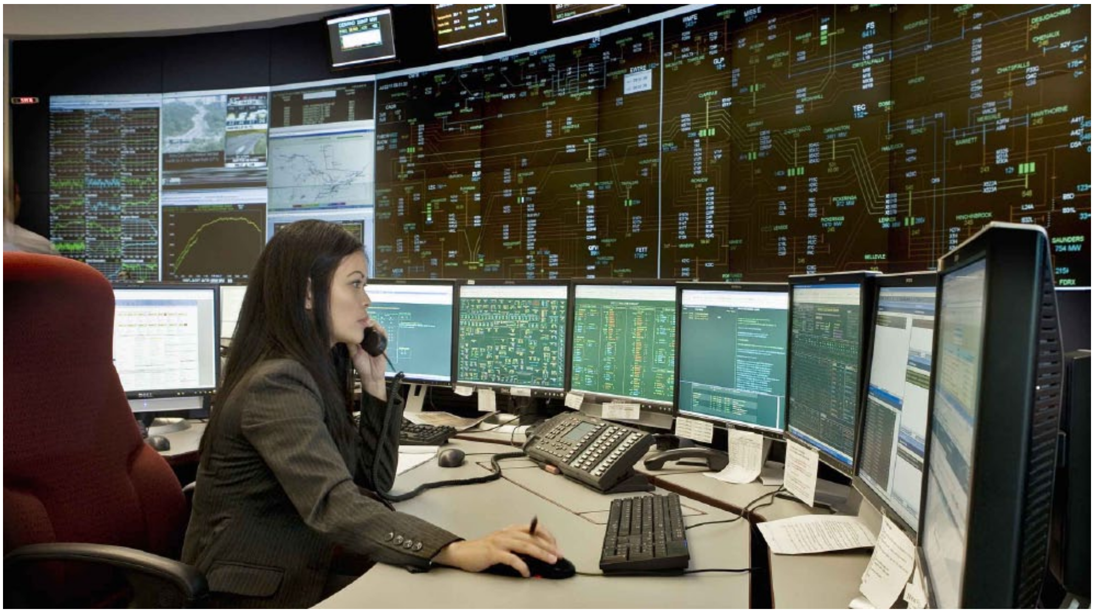


Figure 1. Human operators monitor and control the grid with the aid of an energy management system, which takes real-time operational data and displays the information on the computer monitors and wallboard in the control room (Independent Electricity System Operator, n.d.).

One design challenge was provincial population concentration in the south of the province, meaning the geographical representation used in other wide-area visualizations (e.g., Hoffmann et al., 2011; Legatt & Parker, 2015) would produce both information clutter and white space if applied to Ontario.

The WDA abstraction hierarchy lends itself to resolving scale issues. The layout had to be more functionally than geographically based, and the WDA helped determine functional groupings. We expected that higher (purposeful) levels of abstraction would help represent wider scope (e.g., an entire continent's grid).

CRITICAL INCIDENT STUDY

We conducted critical incident interviews and focus groups with control room operators and observed their work over 60 nonconsecutive days. We supplemented our operator interactions with a scoping study (Arksey & O'Malley, 2005) and documentation review to understand the current state of wide-area monitoring research and development.

The critical incident interview questions were adapted from Flanagan's (1954) *critical incident technique*, a method for eliciting critical incident recounts to understand operator work and identify information gaps in existing tools. Eight operators described incidents that they had experienced firsthand in the control room, totaling 27 separate incidents. The top two issues mentioned were displays that did not clearly communicate operational data and lack of visibility to predict consequences of a control action. Operator reports suggested a need for displays to highlight unusual activity and aid problem solving for unanticipated events. EID has been shown to improve operator performance in such work (Burns et al., 2008; Jamieson, 2007; Vicente, 2002).

In focus group sessions, crews of operators discussed critical incidents and brainstormed challenges in daily operation. Forty-two operators participated. The top-voted challenge was switching between multiple screens to complete a single task or diagnose a problem – a symptom of poor wide-area monitoring tools. Operators expressed concern that the information layout on current displays has changed little in recent decades despite the increasing complexity of the power system. Extended training and additional computer monitors have partly compensated for design deficiencies but were not viewed as viable long-term solutions.

WORK DOMAIN ANALYSIS

Our knowledge elicitation informed a WDA of power grid operations (Hilliard et al., 2017). The WDA describes power grid operations concepts in four ways: at different levels of the abstraction hierarchy, from high-level purposes down to the physical state of electrical equipment; means-ends links between abstraction levels; the system decomposition; and topographical links between power grid elements.

Figure 2 illustrates the abstraction hierarchy and means-ends links between power grid elements. Table 1 summarizes the system decomposition.

INFORMATION REQUIREMENTS

Another focus group finding was how operators defined wide-area monitoring within the power grid operations

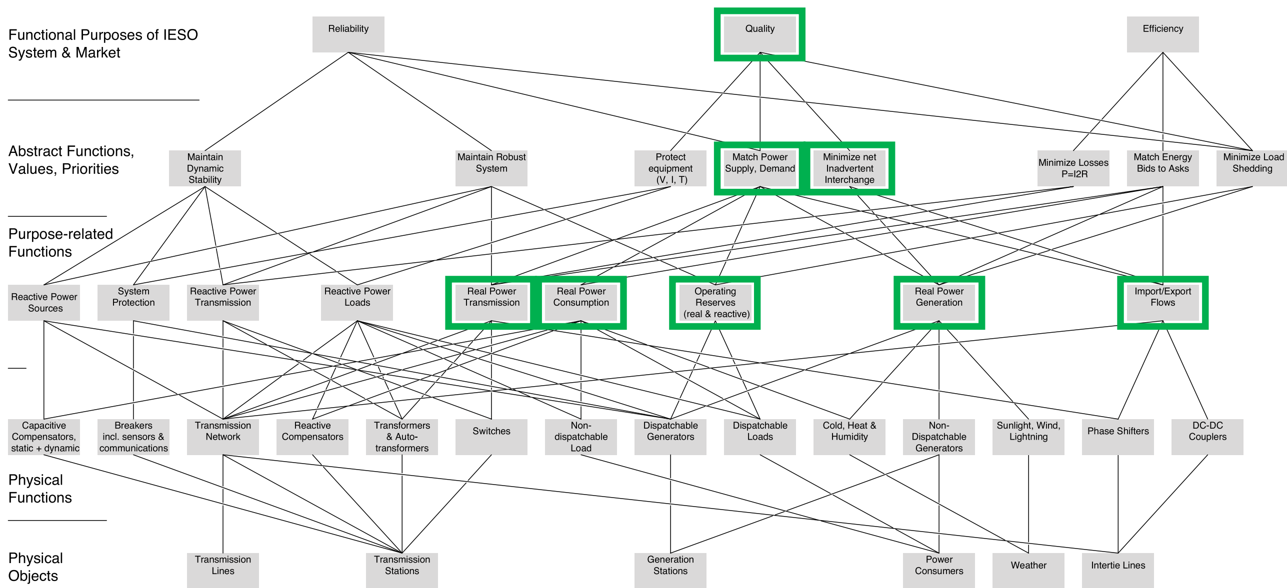


Figure 2. Abstraction hierarchy for power grid operations (Hilliard, Tran, & Jamieson, 2017). Green boxes highlight elements pertaining to the scope of wide-area monitoring.

Table 1. System Decomposition of Power Grid Elements

Level of Abstraction	Decomposition Description
Functional purposes	Defined by the regulatory requirements and concepts they represent.
Abstract functions, values, and priorities	Defined by the regulatory requirements and concepts they represent.
Purpose-related functions	Power flow, either • Between individual lines, • Grouped as system operating limits that operators monitor to determine whether power flows are within acceptable limits, or • Grouped systemwide as area control error, a summary metric that compares a whole jurisdiction's power balance with schedule, plus a small "bias" obligation to maintain frequency.
Physical functions	Equipment grouped by function within an area and connectivity with other components.
Physical objects	Individual pieces of equipment grouped by transmission yard, and lines grouped by their shared transmission towers.

domain. The abstraction hierarchy elements most relevant to wide-area monitoring were the two abstract functions "match power supply and demand" and "minimize net inadvertent interchange of power" (Figure 2). These two abstract functions help achieve the overarching purpose of high-quality service and are supported by real power transmission, real power consumption, operating reserve, real power generation, and import/export flows between jurisdictions. For designing a high-level overview, we omitted lower abstraction levels describing physical functions and physical objects.

We established information requirements for wide-area monitoring from this subset of the abstraction hierarchy. Table 2 lists the measures and constraints required at each abstraction level.

PRELIMINARY DESIGN AND TABLETOP DISCUSSIONS

Starting with these information requirements, we sketched preliminary design concepts for each of the three in-scope abstraction levels. Functional purposes were represented by the dashboard, abstract functions by the dashboard and wide-area view (Figure 3), and purpose-related functions by the system view (Figure 4). In tabletop discussions with four

Table 2. Wide-Area Monitoring Information Requirements Established From the Abstraction Hierarchy

Level of Abstraction	Measures (Units)	Constraints
Functional purposes	Area control error (MW)	Ideally at or close to 0 MW (i.e., power balance according to schedule and acceptable transmission frequency).
	Frequency (Hz)	Ideally at or close to power line frequency (e.g., 60 Hz in North America). Power grid components are designed for this operating frequency.
Abstract functions, values, and priorities	Power supply (MW)	Total power generation capacity installed and connected to the grid.
	Power demand (MW)	Transmission and distribution systems that deliver power to consumers have voltage and current limits.
	Net interconnect power transmission flows (MW)	Transmission infrastructure connecting jurisdictions and power flows within each jurisdiction.
	Scheduled import/export flows (MW)	
Purpose-related functions	Power transmission flows within jurisdiction (MW)	System operating limits developed in engineering simulations.
	Power consumed (MW)	Power generated and connected to the grid.
	Operating reserve capacity (MW)	Requirements set by regulatory organizations.
	Spare generation capacity (MW)	Total power generation capacity installed and connected to the grid.
	Power generated (MW)	Total power generation capacity at that generator or group of generators.
	Tie-line power transmission flows (MW) Tie-line import/export schedules (MW)	Transmission infrastructure connecting two jurisdictions and power flows within each jurisdiction.

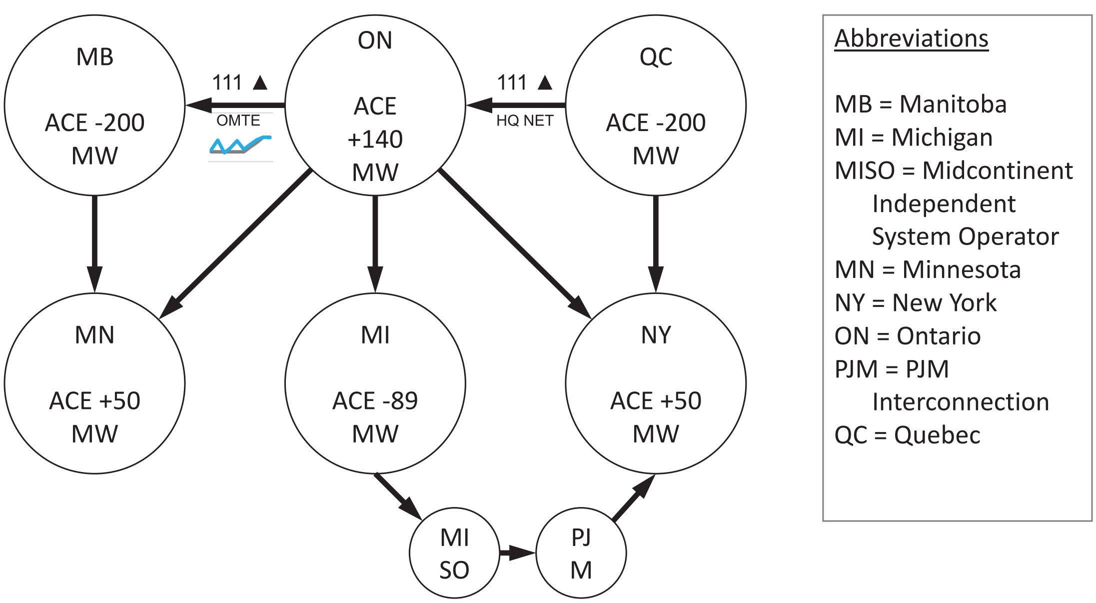


Figure 3. Preliminary concept for wide-area view: External jurisdictions connected to Ontario.

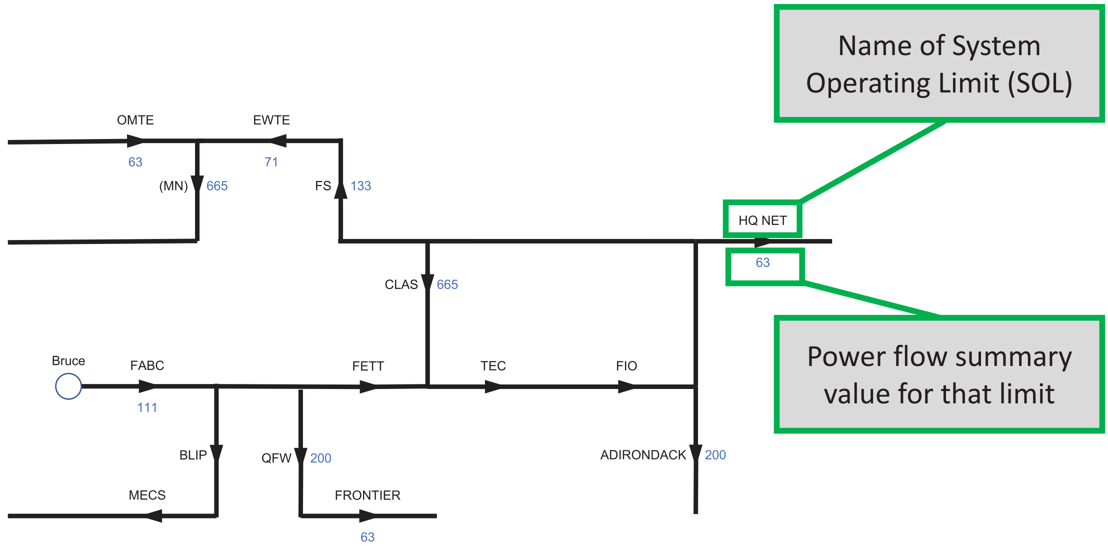


Figure 4. Preliminary concept for system view: One-line diagram showing links between Ontario's most critical power flow limits.

Table 3. Critical Parameters of System Operation

Parameter	Included in Prototype?
Frequency	Yes
Major interface flows	Yes
Area control error values	Yes
Limits (internal and external)	Somewhat (external model missing)
Topology (critical infrastructure)	Somewhat (required at lower levels)
Generation	
Total generation	Yes
Total load	Yes
Total wind, solar generation	Yes
Major generating stations	Yes
Largest contingency–operating reserve relationship	Yes
Flow gates	Yes
Boundaries (circuits that make up each interface)	No (for simplicity)
Any interfaces phase shifted	No
Voltages (perhaps compared with historical)	No (mixed opinions on necessity)
Automatic generation control	No (mixed opinions on necessity)

operators, we clarified operators' information needs and sought feedback on the preliminary designs.

Table 3 lists critical parameters for power grid operation according to participants. Most parameters were implemented into the next design iteration; however, because of information unavailability at the time of design, risk of excessive detail at the wide-area level, and mixed opinions among participants, some parameters were not implemented.

The preliminary wide-area view summarizes power flow between Ontario and connected jurisdictions and shows each province's and state's area control error (ACE). Participants suggested adding two more RCs that, although including states not directly connected to Ontario, have jurisdictions large enough to affect Ontario's power grid. Participants clarified that not all jurisdictions calculate ACE for their grid (e.g., Quebec); this factual inaccuracy was corrected in the interactive prototype.

The preliminary system view is a one-line diagram of the most critical power flow limits in Ontario for large-scale reliability (interconnection reliability operating limits [IROLs]). Tabletop discussions revealed an existing display that divided the province's grid into zones. Its stick-and-circle model suited zonal summaries better than the one-line diagram and was adopted in the next iteration (Figure 5).

We explored the idea of voltage color contours (Overbye, Wiegmann, Rich, & Sun, 2003) to help operators detect deviations. Contours were not implemented in the prototype because of limitations of the prototyping software; however, supplementing the prototype with a voltage map was reported as useful.

WIDE-AREA MONITORING DESIGN CONCEPT

The preliminary designs were refined into an interactive prototype, addressing user feedback from tabletop discussions and

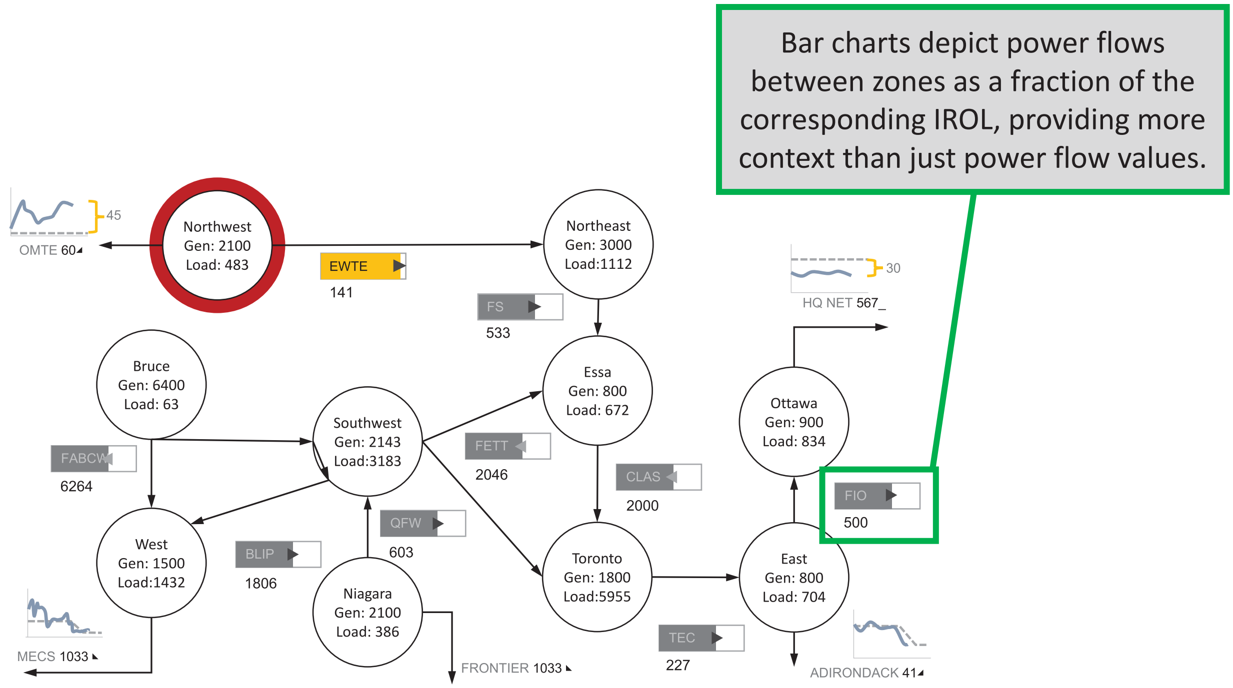


Figure 5. After tabletop discussions: Stick-and-circle layout for modeling zones in the system view.

covering all measures and constraints in the information requirements. This section describes the interactive prototype iteration after the usability evaluation (detailed in the next section).

In this design prototype, operators navigated the power grid model starting with the wide-area view (Figure 6). For more detail, they could click to go to the system view (Figure 7) and, from there, a detailed overview of a zone (Figure 8). Further detailed views are outside the wide-area monitoring scope.

To illustrate the behavior of the design concept and simulate the usability evaluation task, the prototype depicts a scenario in which an unplanned outage occurs on the M24L transmission line in northwest Ontario.

Dashboard. At the top of all screens is the dashboard (Figure 6) with many of the critical parameters from Table 3. The dashboard partly satisfies functional purpose information requirements (Table 4).

Wide-area view. The wide-area view (Figure 6) is a high-level overview of power flow relationships between jurisdictions. Each jurisdiction is represented as a circle, as in the preliminary sketch. The wide-area view indicates abstract functions from the abstraction hierarchy (Table 5).

System view. The system view (Figure 7) shows the jurisdiction divided into zones, power flows between zones and their relevant limits, and generation per zone. The system view displays purpose-related function information from the abstraction hierarchy (Table 6).

Detailed views. Finer levels of detail beyond the system view were not the focus of this work. However, a zonal display was created for the usability evaluation scenario (Figure 8).

USABILITY EVALUATION

We validated the interactive prototype in a usability evaluation with nine current or former operators. Participants ranged between 4 and 26 years of experience in power grid control (mean = 13.1 years).

Participants were shown the prototype and were asked 11 questions about the M24L unplanned outage scenario. To help gauge learnability of the display, no training session was provided. However, participants could ask clarifying questions during the task. After task completion, participants answered qualitative questions about their impressions of the display. Finally, they completed a usability questionnaire.

RESULTS

Of 11 task questions, 9 were correctly answered by most participants (Table 7) on their first time seeing the prototype and without instruction. Some had difficulty navigating to a system generation view, which was later integrated into a single system view as per participant feedback.

Two design features of the system view were unclear to most participants. First, hovering over a power flow prompted a visualization of how it affected other flows in the system. Without models to calculate flow relationships, the feature

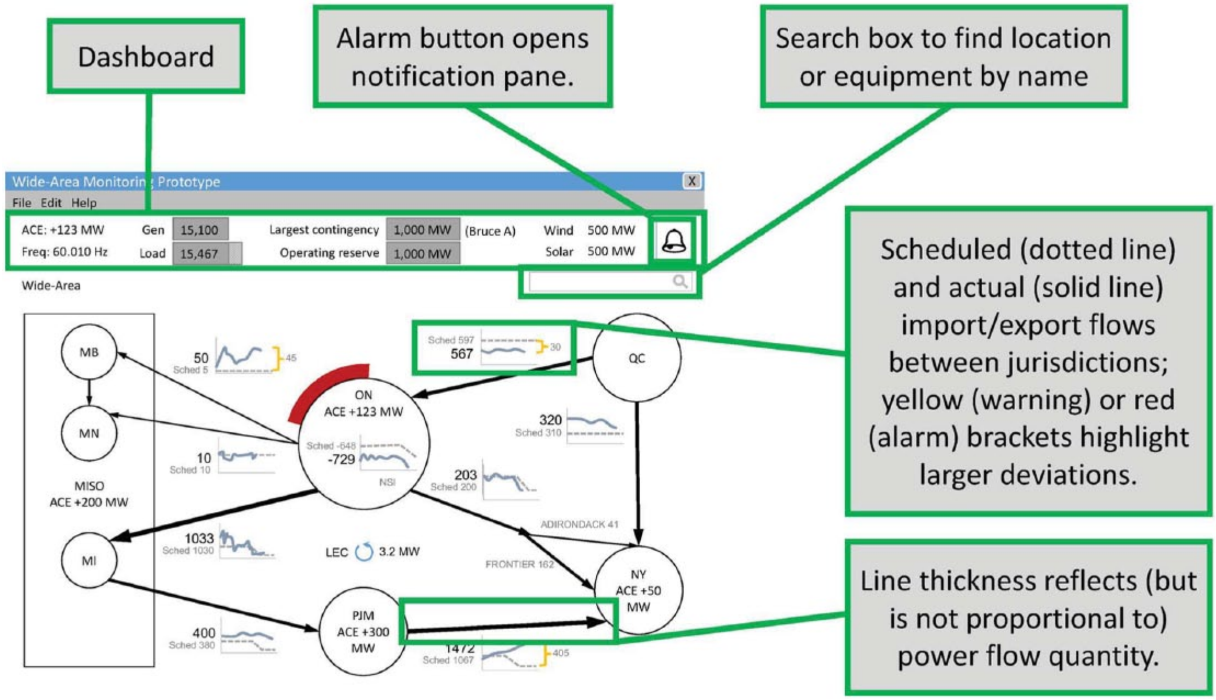


Figure 6. Wide-area view showing the jurisdiction (e.g., Ontario) and its neighbors. The top dashboard displays the area control error, frequency, total generation, total load (+ dispatchable load), largest contingency versus operating reserve, and current renewable generation.

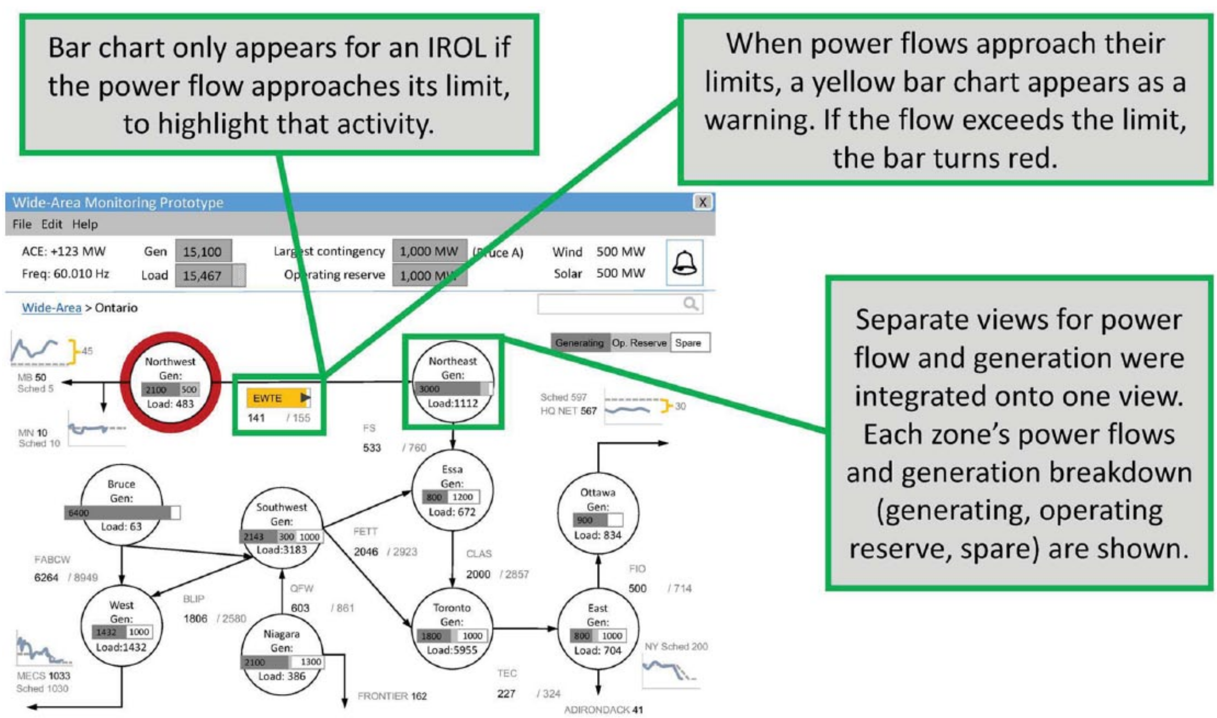


Figure 7. System view of the Ontario power grid. Changes between before (Figure 5) and after (Figure 7) usability testing are labeled.

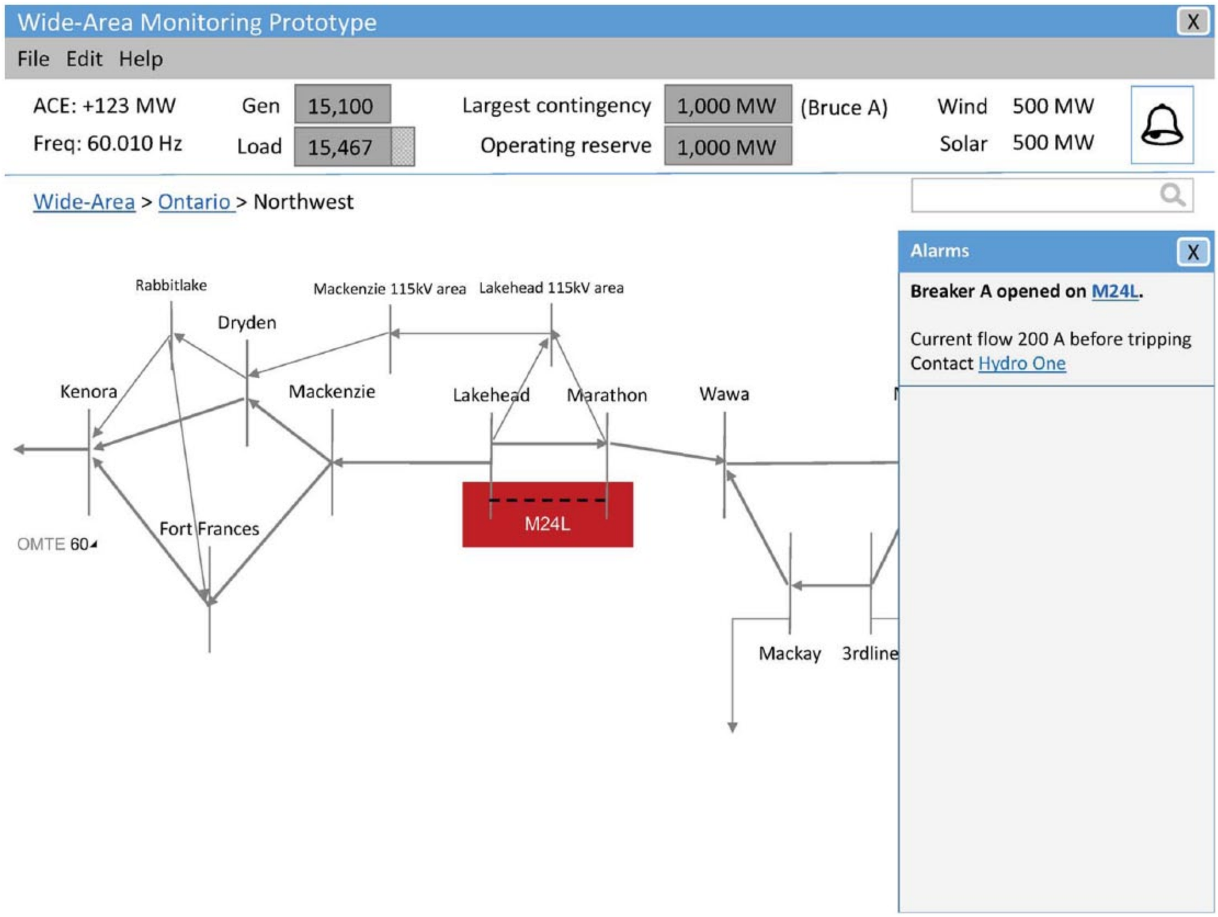


Figure 8. Northwest zone overview within the Ontario power grid. A red background flashes to highlight the unplanned outage in the scenario.

Table 4. Information Requirements From Functional Purposes to Features on the Dashboard

Measure	Prototype Feature
Area control error (ACE) (MW)	System ACE in the top left corner in the dashboard. ACE for each jurisdiction displayed in the circle on wide-area view.
Frequency (Hz)	System frequency in the top left corner in the dashboard.

was removed in the next iteration. Second, a triangular icon in IROL bar charts indicated whether a flow was decreasing, stable, or increasing. When asked the trajectory of a flow, some participants did not realize the purpose of the triangular icon; however, after the triangle was pointed out to them, its meaning was clear.

Participants felt the display had a minimalist design with a low risk of information overload. They cited the wide-area overview as particularly useful for a shift superintendent monitoring at a high level. Participants liked that the single display allowed them to see all alarms and power flows, spot discrepancies between scheduled and actual intertie flows, and monitor generation summary numbers graphically. In contrast, this information was spread across separate screens in their current interface.

Suggestions included placing digital readouts next to bar charts to help compare a power flow with its acceptable limit, adding context to alarms so users can click to discover the location and cause, and displaying only power flows approaching their limits rather than all flows.

The questionnaire included 9 of the 10 System Usability Scale (SUS; Brooke, 1996) questions; the question on tool

Table 5. Information Requirements From Abstract Functions to Features on the Dashboard and Wide-Area View

Measure	Prototype Feature
Power supply (MW)	A bar chart for total MW generating in the top left corner in the dashboard.
Power demand (MW)	Total MW of load in the top left corner in the dashboard. The bar chart also shows the amount of dispatchable load available (crosshatched).
Net interconnect power transmission flows (MW)	Arrows show the direction of power flow between jurisdictions. The thickness of the arrow depends on the magnitude of the total flows between two regions, though not in a linear relationship, so that small flows are not hidden.
Scheduled import/export flows (MW)	Trend charts compare import/export schedules with actual flows, so that operators can determine whether net imports and exports are following predetermined schedules for the day, and whether they need to take control actions to mitigate inadvertent net interchange. A yellow (warning) or red (alarm) bracket appears on the trend chart in the event of a discrepancy between scheduled and actual flows.

Table 6. Information Requirements From Purpose-Related Functions to Features on the System View

Measure	Prototype Feature
Power transmission flows within jurisdiction (MW)	Net power flows between each zone, each corresponding to an IROL. Both the flow and the limit are shown so that the operator can ensure that flows do not exceed limits.
Power consumed (MW)	Load numbers are in each circle.
Operating reserve capacity (MW)	A stacked bar chart shows the summary breakdown of generation status within each region. Light gray represents the proportion that is operating reserve.
Spare generation capacity (MW)	White section of the stacked bar chart for generation status.
Power generated (MW)	Dark gray section of the stacked bar chart for generation status.
Tie-line power transmission flows (MW)	Trend charts showing actual versus scheduled import/export flows at the tie-lines. These are also shown in the wide-area view.
Tie-line import/export schedules (MW)	Trend charts showing actual vs. scheduled import/export flows at the tie-lines. These are also shown in the wide-area view.

Note. IROL = interconnection reliability operating limit.

integration into a system was not applicable for this prototype stage. As such, the SUS score was derived from 90 possible points. The prototype received a mean score of 77/90 ($SD = 7$), normalized to 86/100. The prototype exceeded the average benchmark score of 68/100 (Sauro, 2011) and ranks within the upper quartile of studies that applied the SUS (Bangor, Kortum, & Miller, 2009).

Figure 9 shows mean responses per question. Overall, responses were strongly positive. Participants mildly agreed that the prototype was consistent with other tools (e.g., color scheme) and that they felt confident using the prototype.

Relative to their existing tools (Figure 10), participants thought the prototype was clearer and easier to use. They believed it would help detect outages, deviations from interchange schedule, and limit violations faster. Furthermore, search and navigation seemed easier.

FUTURE OPPORTUNITIES

We have described the design process of the first published example of a wide-area monitoring display based on WDA. The WDA abstraction hierarchy was straightforward to apply to design for wide-area monitoring because wide-area views are high-level overviews matching higher levels of abstraction, and the abstraction hierarchy maps how higher-level goals of power grid operation are met by the functionality of grid components. Operator tabletop discussions and usability evaluation helped us to translate the WDA into information requirements and to develop usable design concepts. The positive reception by operators in the usability evaluation indicated the pressing need for wide-area views in the control room and the promise of applying an EID process to meet that need.

Table 7. Number of Participants Who Answered Each Task Question Correctly During the Usability Evaluation (*N* = 9)

Question	Number Correct
Which Ontario region is generating the most MW right now?	9
Which IROL power flow is close to the limit?	9
How many MW are flowing between Ontario and New York, and in what direction?	9
The power flow to Quebec has (a) decreased, (b) remained stable, or (c) increased?	8
How does the power flow to Quebec compare to schedule?	8
How does the power flow to New York compare to schedule?	8
How does the power flow to Manitoba compare to schedule?	7
An alarm just sounded. Which circuit tripped?	7
How much spare generation do you have in the West?	6
How many MW of the EWTE flow are attributed to the OMTE intertie flow?	2
The flow into Ottawa is (a) decreasing, (b) stable, or (c) increasing?	1

Note. IROL = interconnection reliability operating limit; EWTE = East–West Transfer East (flow that is functionally related to the power flows between Ontario and Manitoba, and Ontario and Minnesota); OMTE = Ontario–Manitoba Transfer East.

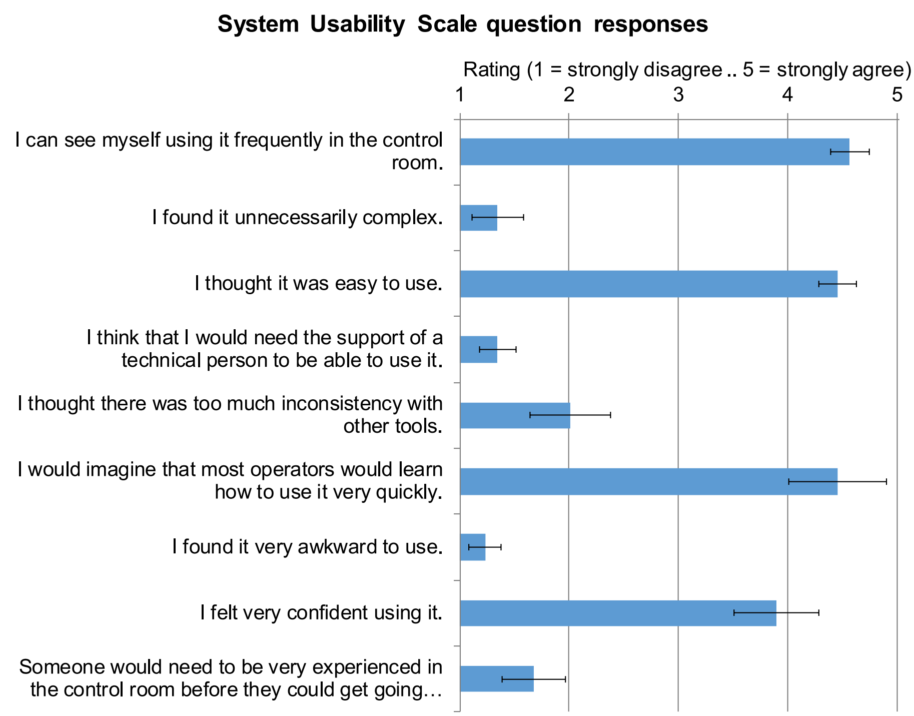


Figure 9. System Usability Scale questionnaire responses. Error bars indicate standard error.

Time and resource constraints on the academic–industry partnership limited the analysis of power grid operations to the first stage of cognitive work analysis (CWA; Vicente, 1999), WDA. The other four stages of CWA could have studied operator tasks, control strategies, organizational structure, and operator characteristics to inform a broader control room redesign.

The study was limited to the context of Ontario power grid operations, which may affect the suitability of the design for jurisdictions with different grid topologies, scopes of work, and regulatory and policy frameworks. However, Ontario was an appropriate topological use case, as its irregular shape and highly concentrated population required a design largely

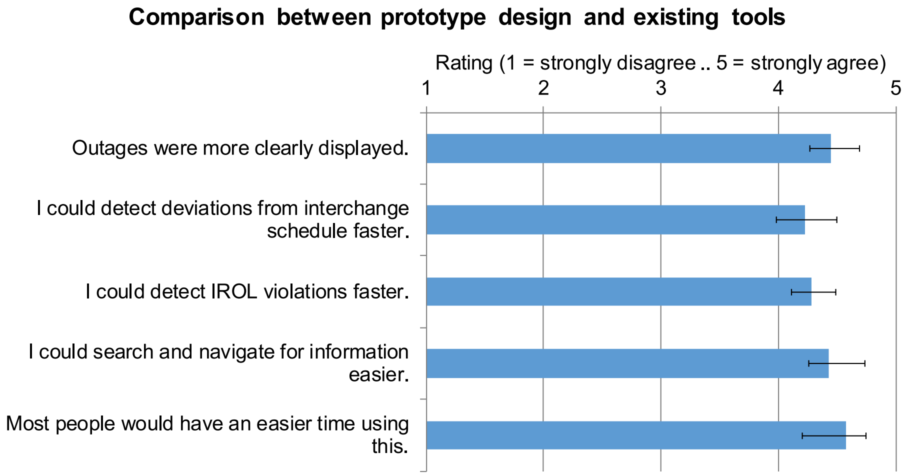


Figure 10. Usability comparison between prototype and existing tools, rated by participants. Error bars indicate standard error.

detached from the geographical representation employed in other wide-area monitoring designs.

Wide-area monitoring is a broad concept; the design concept described here focused on power flows between and within jurisdictions but may be expanded to support other areas of power grid operation. Voltage monitoring, such as described by Cuffe and Keane (2015), would help operators detect and respond to voltage deviations that may precipitate cascading failures. Market information and pricing visualizations would help validate constraints on dispatch prices between the system and market sides of operation.

Software implementation of the design will require links to more detailed views and database structures that support wide-area monitoring displays. Operators, developers, engineers, and managers must be involved in discussing implementation feasibility, regulatory compliance, technical constraints, and execution planning. The design must also ensure coverage of broader scenarios that may not have been captured during the scope of our study.

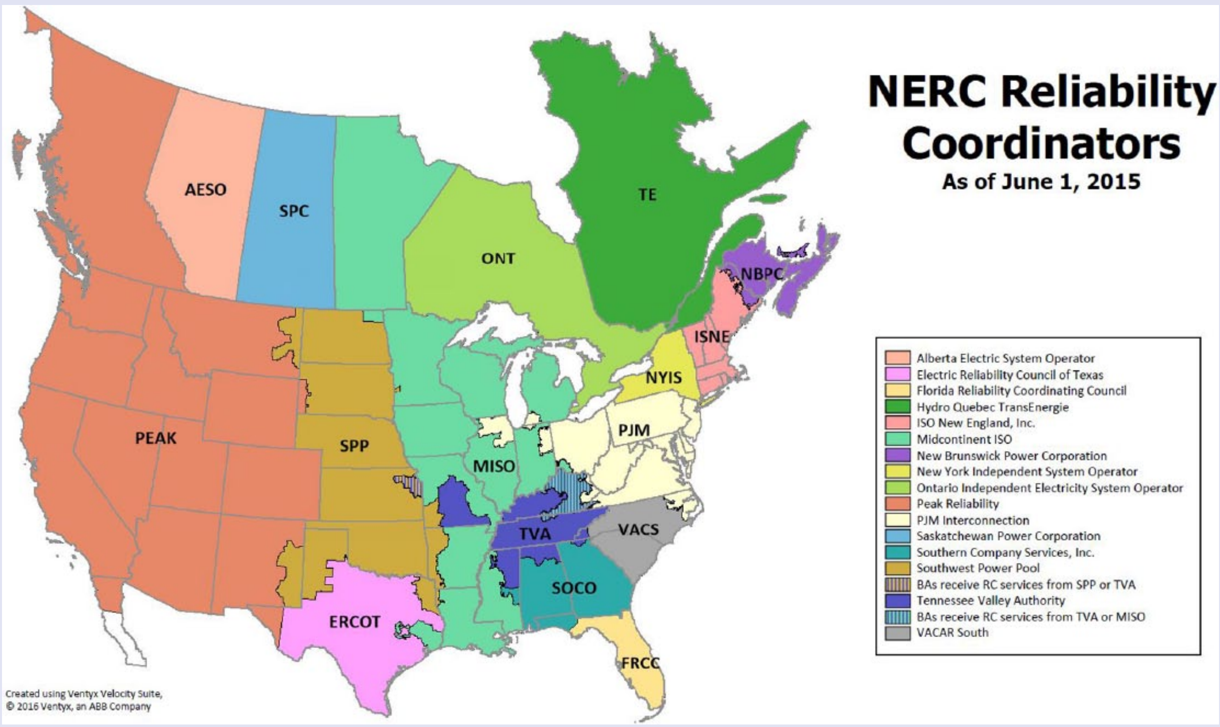
CONCLUSION

Power grids continue to grow in complexity, and operators need modern tools that enable them to quickly and effectively problem-solve during abnormal events. Large-scale blackouts such as that in North America in 2003 have highlighted this need and inspired regulatory standards requiring that RCs have wide-area views of their surrounding power grid.

We have developed the first published WDA of power grid operations and the first known wide-area monitoring design concept based on a WDA. The high SUS score of the prototype demonstrates the promise of the WDA and EID process described here, which may also be applied to design other wide-area power grid control displays.

Reliability coordinators (RCs) control and monitor power transmission and wholesale electricity markets for each region of the U.S. and Canadian power grids. The goal of power grid operations is to ensure a reliable and stable electricity supply for consumers.

Human operators at the RC monitor the grid through an automated energy management system and balance real-time supply with demand for electricity within their region. Because the power grid is interconnected between regions and spans large geographical areas, operators must be aware of events outside their jurisdiction, making adequate wide-area monitoring tools essential.



Map of North American reliability coordinators (North American Electric Reliability Corporation, 2016).

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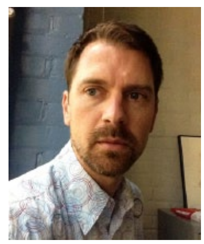

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