Chapter 17

AN ADVANCED DECISION-SUPPORT TOOL FOR ELECTRICITY INFRASTRUCTURE OPERATIONS

Yousu Chen, Zhenyu Huang, Pak-Chung Wong, Patrick Mackey, Craig Allwardt, Jian Ma and Frank Greitzer

Abstract A major failure in the electricity infrastructure would almost certainly lead to significant societal disruption and massive economic losses. The reliable operation of the electricity infrastructure is an extremely challenging task because human operators have to consider thousands of possible configurations in near real time to choose the best option. Nevertheless, the operation of the electricity infrastructure is largely based on operator experience with limited real-time decision support. This makes it difficult for operators to anticipate, recognize and respond to anomalies caused by human error, natural disasters or cyber attacks.

This paper proposes an advanced decision-support tool for electricity infrastructure operations. The tool converts large amounts of data into actionable information to help operators monitor the power grid status in real time. It performs trend analysis at the regional or system level to enable operators to foresee and discern emergencies; it performs cluster analysis to help operators identify the relationships between system configurations and affected assets; and it interactively assesses candidate actions to assist operators in making effective and timely decisions.

Keywords: Electricity infrastructure, decision support, visual analytics

1. Introduction

The U.S. electricity infrastructure has been called the most complex machine on earth [1]. However, much of the infrastructure was designed more than 50 years ago. A failure of the electricity infrastructure can lead to significant disruptions of people's lives and industrial and commercial activities, causing massive economic losses. Incidents such as the Western North America blackout of 1996 [4] and the Northeast blackout of 2003 [7] underscore the need to have a reliable power grid. The prediction, prevention and mitigation of blackouts have become the primary focus of the DOE Office of Electricity Delivery and Energy Reliability (DOE-OE) [8] as well as the central topic of power systems research.

The operation of the electricity infrastructure is an extremely challenging task due to its complex structure, geographical coverage, complex database and information technology systems, and highly dynamic and nonlinear behavior. The operation is also affected by a number of external factors, including physical attacks, cyber threats, human error and natural disasters. Because of the complex nature of the electricity infrastructure, large amounts of data and information have to be processed to gain adequate situational awareness and to adapt to emergency situations. Managing this complexity is a critical issue in electricity infrastructure operations.

Electricity infrastructure operations are largely driven by human operator experience and occur with little real-time decision support. The lack of effective systems that can manage the complexity of operations translates to an inability on the part of human operators to anticipate, recognize and respond to adverse and unexpected situations.

This paper presents an advanced decision-support tool that is designed to meet the immediate needs of electricity infrastructure operators. In particular, the tool improves situational awareness, enabling operators to recognize current and potential failures; it helps predict the consequences of potential failures; and assists in evaluating the effect of candidate actions. The tool has been successfully applied to real-world power grid models and data.

2. Enhanced Operational Framework

Electricity infrastructure operations involve highly complex computational processes and power grid models. Figure 1 presents a functional view of real-time power grid operations [2].

This paper focuses on two key functions: state estimation and contingency analysis. State estimation computes the various system parameters that are input to other operational functions, including contingency analysis. Contingency analysis studies "what-if" conditions in anticipation of potential power grid failures. It identifies operational violations that occur when certain operational limits, such as transmission line load capacity and substation voltage thresholds, are exceeded. The violations are presented to operators for review and to determine the appropriate candidate actions.

The North American Electric Reliability Corporation (NERC) operating standards [6] require that the loss of any single element in the power grid should not cause system instability. Networks that meet this standard are rated as "N-1 Secure." If the loss of one or more elements does not result in any limit violations, the system is deemed to be secure for the corresponding contingency. The contingencies that result in violations of operating limits are flagged and placed in a list for the operators to inspect. When contingency

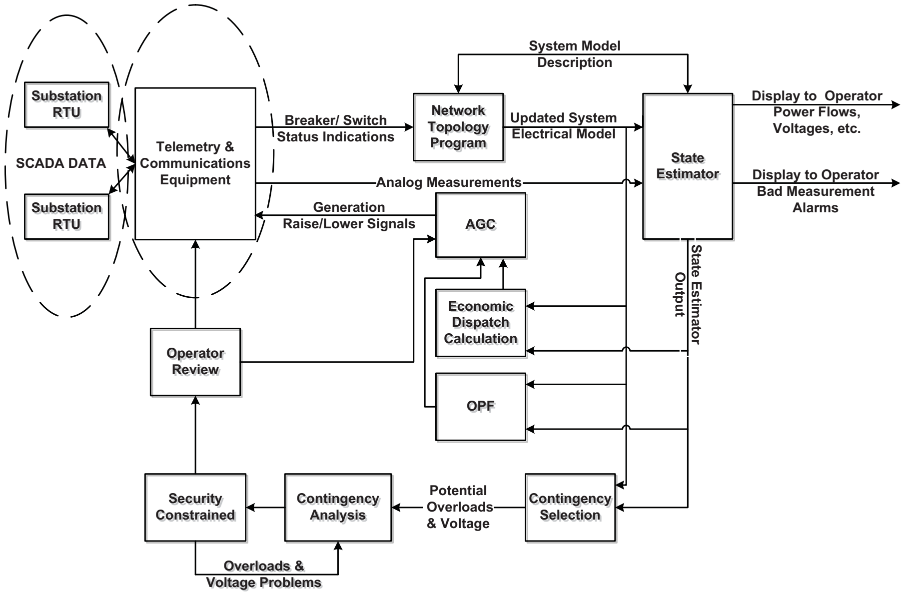


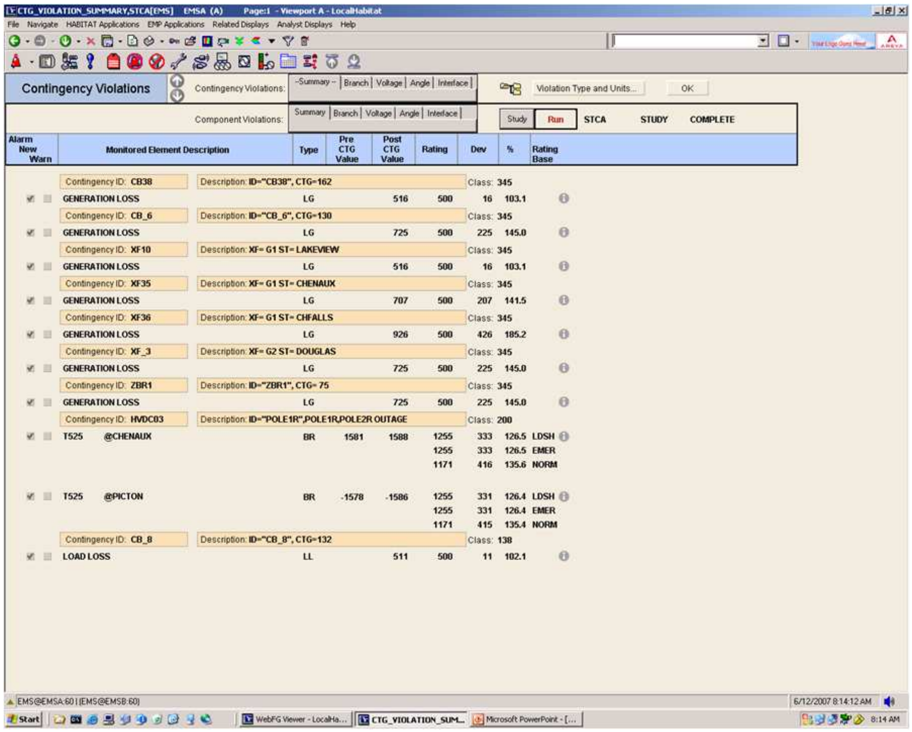
Figure 1. Electricity infrastructure operations.

violations occur, NERC mandates that operators take actions to mitigate the situation in a timely manner.

Due to the size and complexity of the modern power grid, the number of contingencies to be analyzed can be very large – it is not uncommon for several hundred contingencies or more to be examined. Conveying the contingency outputs to system operators in a meaningful and easy-to-understand manner is a real challenge. State-of-the-art commercial tools use a tabular form to display contingency violations (Figure 2). Each violation corresponds to a row in the form; note that no information is provided about the geographical context and relative severity of the violation. The tabular display may be adequate when few contingency violations are present. However, when the system is heavily stressed and there are many contingency violations, operators can be overwhelmed by the information presented in the tabular display. In such cases, it is almost impossible for operators to sift through large amounts of violation data and understand the system situation in minutes, let alone seconds. Of course, it is during these situations that operators need the information the most.

To address these challenges, we have developed an advanced decision-support tool that is intended to assist three important aspects of power grid operations:

- Improved situational awareness by visualizing and analyzing the change in risk levels as a result of violations.
- Prediction of the consequences of potential problems by analyzing the pattern of impact.



Alarm New Warn	Monitored Element Description	Type	Pre CTG Value	Post CTG Value	Rating	Dev	%	Rating Base
	Contingency ID: CB38	Description: ID="CB38", CTG=162				Class: 345		
☑ ☐	GENERATION LOSS	LG		516	500	16	103.1	
	Contingency ID: CB_6	Description: ID="CB_6", CTG=130				Class: 345		
☑ ☐	GENERATION LOSS	LG		725	500	225	145.0	
	Contingency ID: XF10	Description: XF= G1 ST= LAKEVIEW				Class: 345		
☑ ☐	GENERATION LOSS	LG		516	500	16	103.1	
	Contingency ID: XF35	Description: XF= G1 ST= CHENAUX				Class: 345		
☑ ☐	GENERATION LOSS	LG		707	500	207	141.5	
	Contingency ID: XF36	Description: XF= G1 ST= CHFALLS				Class: 345		
☑ ☐	GENERATION LOSS	LG		926	500	426	185.2	
	Contingency ID: XF_3	Description: XF= G2 ST= DOUGLAS				Class: 345		
☑ ☐	GENERATION LOSS	LG		725	500	225	145.0	
	Contingency ID: ZBR1	Description: ID="ZBR1", CTG= 75				Class: 345		
☑ ☐	GENERATION LOSS	LG		725	500	225	145.0	
	Contingency ID: HVDC03	Description: ID="POLE1R",POLE1R,POLE2R OUTAGE				Class: 200		
☑ ☐	T525 @CHENAUX	BR	1581	1588	1255	333	126.5	LDSH
					1255	333	126.5	EMER
					1171	416	135.6	NORM
☑ ☐	T525 @PICTON	BR	-1578	-1586	1255	331	126.4	LDSH
					1255	331	126.4	EMER
					1171	415	135.4	NORM
	Contingency ID: CB_8	Description: ID="CB_8", CTG=132				Class: 138		
☑ ☐	LOAD LOSS	LL		511	500	11	102.1	

Figure 2. Tabular representation of violation data.

- Assessment of the effects of candidate actions by interactively analyzing the collective severity level.

The advanced decision-support tool is designed to provide information about the status of the electricity infrastructure, analyze historical data, generate system-trending information for prediction, identify relationships between system configurations and affected assets, and interactively assess candidate actions to determine the best solution. The tool presents operators with actionable information about the current system status and trends, enabling them to comprehend the situation and identify the best candidate actions in a timely manner.

3. Improving Situational Awareness

Operator situational awareness is enhanced using visual analytic and graphical trending techniques. The visual analytic technique converts large amounts of raw operational data to actionable information. The graphical trending technique provides operators with information about system trends at multiple levels of abstraction, enabling them to foresee and discern emergencies. Interested readers are referred to [3] for details about these two techniques.

3.1 Visual Analytic Technique

The visual analytic technique involves two steps: (i) defining and computing the risk level of contingency violations; and (ii) converting the risk level to a contoured map by adapting a novel visual analytic technique developed by the National Visualization and Analytics Center [5].

Instead of using the tabular form in Figure 2 to convey the status of the power system, contingency data is converted into a quantitative risk level that is presented to operators. The risk level of contingency violations is given by:

$$R_{ik} \in \begin{cases} [0, R_T) & \text{Safe} \\ [R_T, 100) & \text{Alert} \\ [100, \infty) & \text{Violation} \end{cases} \tag{1}$$

where R_T is the pre-specified alert risk level (expressed as a percentage) for each transmission line and substation. Note that $R_T = 97.5\%$ in our study.

The risk levels (expressed as percentages) for transmission lines (Equation (2)) and substations (Equation (3)) are defined in terms of the capacities of their power loading and voltage level parameters, respectively:

$$R_{ik} = \frac{P_{ik}}{P_{imax}} \times 100 \tag{2}$$

$$R_{ik} = \left| \frac{(V_{ik} - V_{imin}) - (V_{imax} - V_{imin})/2}{(V_{imax} - V_{imin})/2} \right| \times 100 \tag{3}$$

where ik denotes the i^{th} line or i^{th} substation for the k^{th} contingency; P_{ik} is the loading in the i^{th} line for the k^{th} contingency; P_{imax} is the loading limit of in the i^{th} line; V_{ik} is the voltage of the i^{th} substation for the k^{th} contingency; V_{imin} is the lower voltage limit of the i^{th} substation; and V_{imax} is the upper voltage limit of the i^{th} substation.

Note that the risk level definitions apply to the tabular violation data shown in Figure 2. Also, they specify how close the operational parameters are to the corresponding limits, even when no violations exist.

Because each contingency generates a set of contingency risk levels as defined by Equations (1–3), there will be k sets of risk levels for k contingency cases. Across all the contingencies, the risk level of the i^{th} element is defined as the maximum value over the set of risk levels:

$$R_i = max(R_{ik}); \quad k = 1, 2, \ldots, K \tag{4}$$

Note that the tool permits the use of other functions (e.g., mean or sum) instead of maximum. Also, the risk R_{ik} can be multiplied by the probabilities of the contingencies to obtain the risks in combination with the likelihood of the occurrence of failures. For simplicity, this paper assumes a unit probability for all contingencies.

The next step is to convert the risk levels as defined in Equation (4) to a contoured map with colors indicating different risk levels. The system status

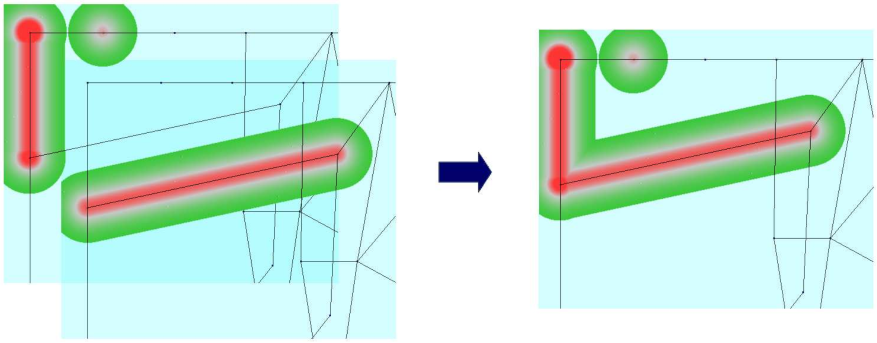


Figure 3. Collective risk area with superposition of individual risk areas.

is visualized as fading colors from the center as shown in Figure 3. The impact area of a substation has a circular shape, while that of a line has an elliptical shape. Individual risk areas are superimposed to form the collective risk area. The risk maps are overlaid to represent the collective risk of multiple possible configurations.

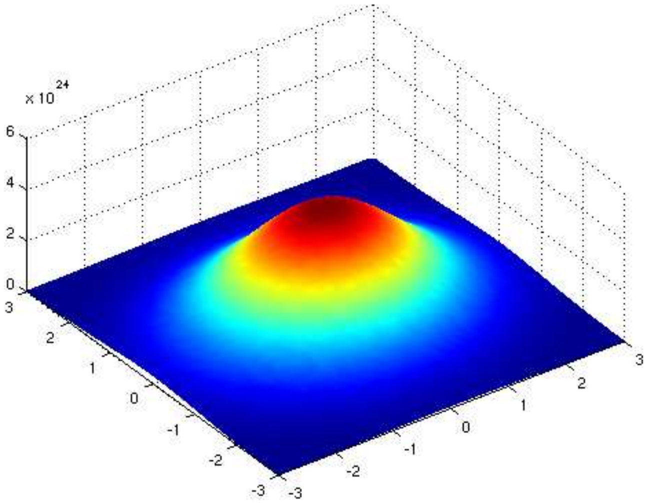


Figure 4. Gaussian color filter and color map.

The implementation uses a hash table to store all the pixels of the substations and lines, and a Gaussian color filter to display the collective risk. In the hash table, each pixel has a value determined by the contingency risk level of the substation or line. Only the largest value is retained in the table in order to represent the highest risk. The Gaussian color filter is circular with values conforming with a Gaussian curve (Figure 4). The output of the filter is the

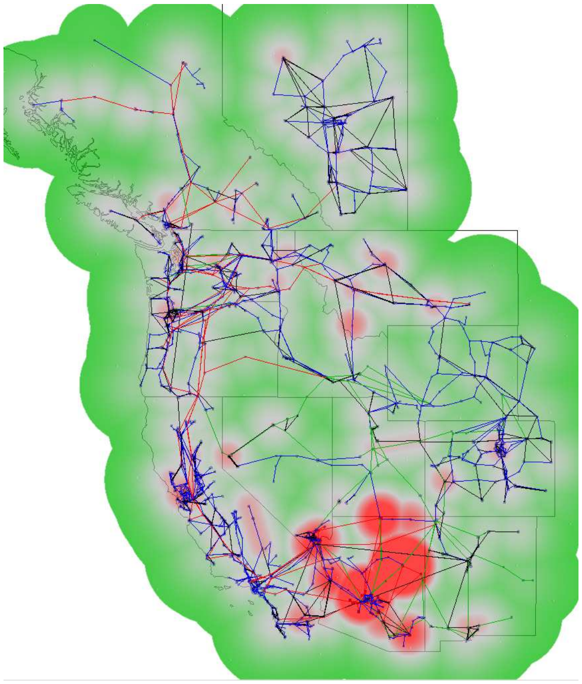


Figure 5. Risk map of the Western North American power grid.

output matrix M, which associates each point in the map with a floating point number (color value); each value is assigned to a color map to obtain the final contour. The colors, green, gray and red, in the color map correspond to the risk categories, safe, alert and violation, respectively.

The final visual representation uses HaveGreen [10] as the application framework, which provides an interface for navigating and zooming over the power grid. Figure 5 is created using the model and data from the 2005 HS2A Approved Operating Case of the Western Electricity Coordinating Council (WECC) [9]. The figure shows the Western North American power grid with 50 sets of contingency results overlaid on a single risk map to visualize the collective risk of the contingencies. Unlike the tabular representation in Figure 2, the color-contoured map enables operators to quickly identify the vulnerable portions of the power grid (represented in red).

3.2 Graphical Trending Technique

Trending analysis involves the observation and examination of the change in risk over time, and the prediction of whether or not the network is becoming more vulnerable, more compromised or more robust. Increases in the risk indices, which are expressed by the size of the region and color intensity in the risk map, indicate developing problems.

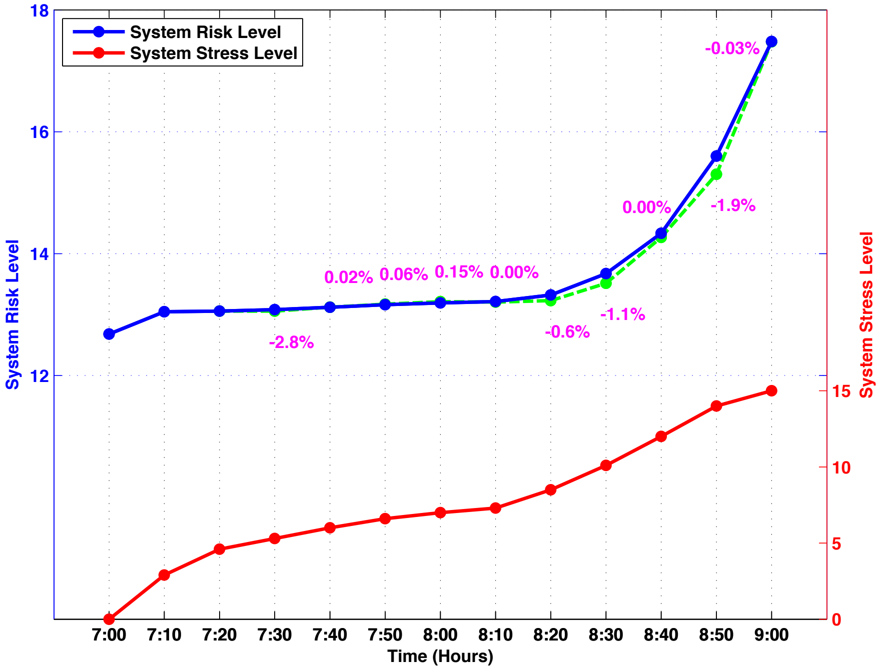


Figure 6. System risk level and stress level over time.

A trend analysis chart uses one line to represent the overall size and intensity of the critical regions in the power grid visualization; and multiple lines to represent the size and intensity of individual critical regions. A critical region is defined as a contiguous set of pixels where each pixel has a color value no less than a particular threshold. Each value is taken from the corresponding element in the output matrix M generated by the Gaussian color filter.

The first step in trending analysis is to find the calculated risk level for each individual region using a non-recursive breadth-first search. If the value of an element meets or exceeds the threshold, then all its neighboring elements are examined and marked if they meet the threshold. All the values in this contiguous region are added to produce the current regional risk value. After the breadth-first search is complete, a normalized regional risk value is obtained by dividing the regional risk value by the number of pixels in the image. Once all of the regions are found, the total risk value is calculated by summing the risk values of the individual regions.

Figure 6 presents the risk levels of the Western North American power grid during the morning load pick-up period. When the total power consumption is low at the beginning of the period, increasing the load does not increase the risk levels as much as when the total load is high (towards the end of the period). This is consistent with operational experience. To further validate the system risk levels, the contingency risk levels R_{ik} that are higher than 100% are

Table 1. System risk level and summation of contingency risk levels.

Time	**Risk Level**	ΣR_{ik}	**Time**	**Risk Level**	ΣR_{ik}
7:00	12.68	169.47	8:10	13.21	179.65
7:10	13.05	178.60	8:20	13.32	182.82
7:20	13.06	178.49	8:20	13.32	182.82
7:30	13.08	179.48	8:30	13.67	212.92
7:40	13.12	179.53	8:40	14.33	251.49
7:50	13.16	179.58	8:50	15.60	353.09
8:00	13.19	179.62	9:00	17.48	488.23

summed (Table 1). The results show that the system risk levels are consistent with the results of the contingency analysis.

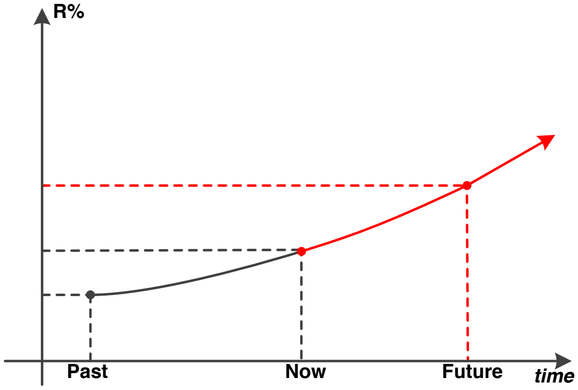


Figure 7. Illustration of visual trending analysis.

The next step is to conduct a visual trending analysis based on the system and regional risk levels. The trend is obtained by fitting a curve to the historical risk levels of the network or regions, and extrapolating them to predict the future system situation (Figure 7).

The green dashed line in Figure 6 is the predicted system risk level, where each point is computed based on the three preceding risk levels. Note that the prediction is reasonably close to the actual system risk level (i.e., within a 2.8% error range).

Complex evolving patterns may exist in the power grid network. As the risk values of different regions are computed, they are tracked to see how they relate to the previous risk regions. This helps determine if two new regions come from a previous region (defined as whether or not a region overlaps with a previous region). A region can originate from multiple regions, and a region can spawn multiple regions. This feature is depicted in the trend analysis chart as a line splitting into multiple new lines or combining multiple lines into one new line.

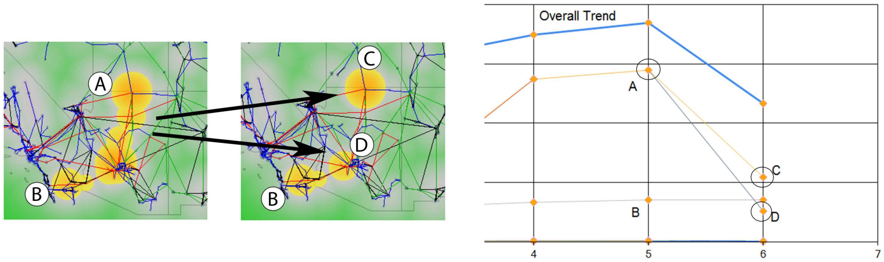


Figure 8. Complex evolving patterns of network risk impact areas.

Figure 8 shows an example of one area splitting into two areas (Region A splits to Regions C and D at Time 5). Note that the y-axis represents the risk level.

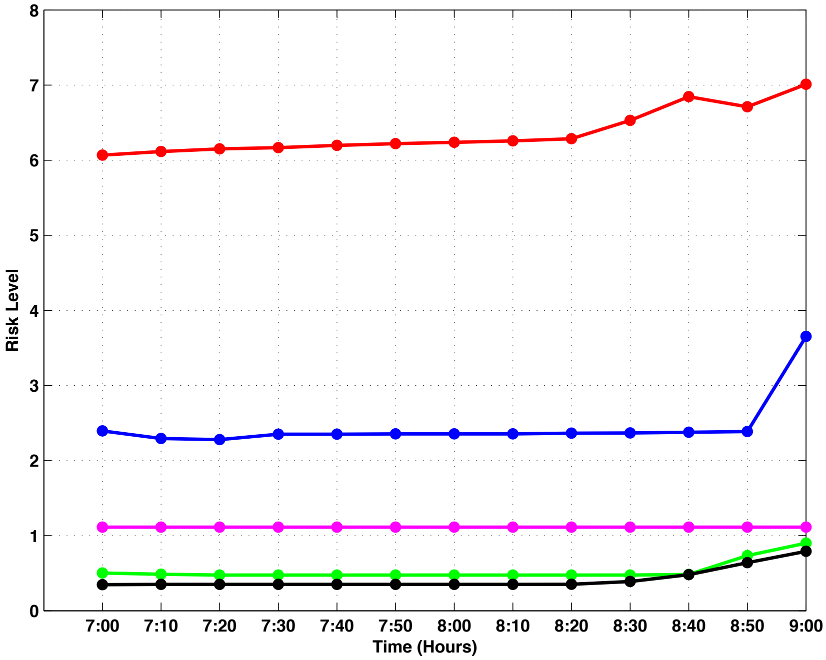


Figure 9. Regional risk trends in the Western North American power grid.

Figure 9 shows the trends for the five most critical regions for the same system conditions as in Figure 6. The overall system trend gives an overview of the system status. However, the system trend can be relatively flat because changes in different regions may cancel each other's impact. Therefore, it is important to observe regional trends to identify critical regions that demand immediate operator attention.

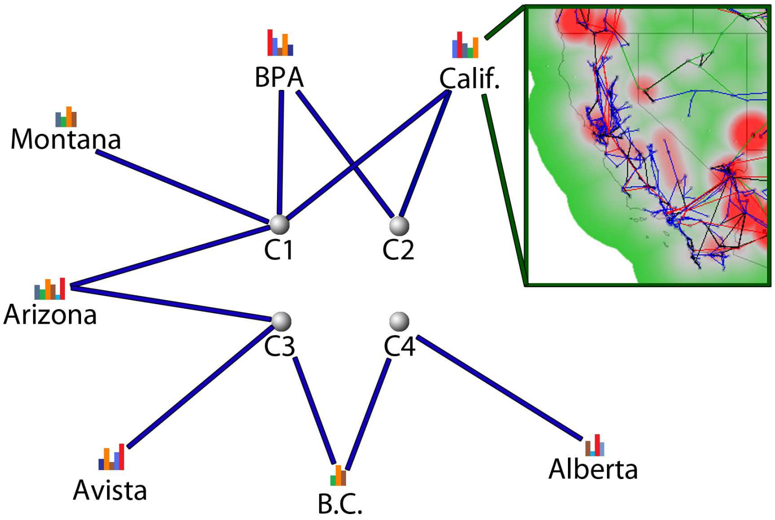


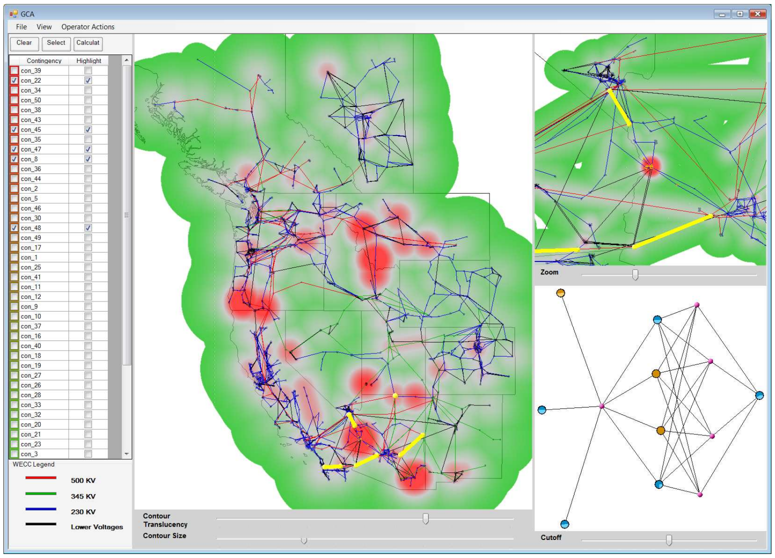
Figure 10. Clustering analysis.

4. Recognizing Failure Patterns

Power grids can have numerous configurations that result in stresses on substations and transmission lines. With the help of visual analytic techniques and visual trend analysis, operators can quickly gain wide-area situational awareness. To enable operators to focus on important information during network emergencies, clustering analysis is needed to identify system patterns and present them in association with the risk contour map. Clustering analysis can help operators identify the relationships between system configurations and affected assets. The criteria for configuration clustering are based on geographical characteristics, configuration types and impact types. Clustering analysis is combined with the contoured map to provide operators with a quick overview of the grid status while enabling them to drill down to the details if needed.

Figure 10 shows how clustering analysis can help reveal the relationships between network configurations and affected network assets. C1–C4 are critical contingency cases that cause violations (shown in the bar charts) in different locations. If an operator wishes to see more information in a specific area, he can go to a deeper level to investigate the contingency impact within the area. By applying the same method to multiple levels, a hierarchy of related contingencies from the area level all the way down to the individual configuration can be constructed. For example, in Figure 10, C2 causes violations in the BPA and California areas. An operator wishing to see more detail in the California area may use the hierarchy structure. At the same time, he has the option to study multiple configurations concurrently and to compare scenarios.

Figure 11 shows an example of clustering analysis. The yellow highlighted lines in the figure indicate the locations of the contingencies, which correspond



	Contingency	Highlight
☐	con_39	☐
☑	con_22	☑
☐	con_34	☐
☐	con_50	☐
☐	con_38	☐
☐	con_43	☐
☑	con_45	☑
☐	con_35	☐
☑	con_47	☑
☑	con_8	☑
☐	con_36	☐
☐	con_44	☐
☐	con_2	☐
☐	con_5	☐
☐	con_46	☐
☐	con_30	☐
☑	con_48	☑
☐	con_49	☐
☐	con_17	☐
☐	con_1	☐
☐	con_25	☐
☐	con_41	☐
☐	con_11	☐
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☐	con_28	☐
☐	con_33	☐
☐	con_32	☐
☐	con_20	☐
☐	con_21	☐
☐	con_23	☐
☐	con_3	☐

Figure 11. Clustering analysis function in the decision-support tool.

to the purple dots in the "spider web" plot in the lower-right corner. The location of a contingency is found by clicking the purple dot in the spider web. The blue circles in the spider web are the substation voltage violations, while the orange circles are the line loading violations. The shaded areas in the blue circles and orange circles indicate the severity of violations: the larger the shaded area, the more severe the violation. By clicking on different elements in the spider web, operators can easily identify the system patterns and focus on important information. The cutoff severity slider below the spider web can be used to change the minimum severity level to be shown, enabling only the more severe violations to be presented in a less crowded spider web.

The simple spider web example clearly shows how a contingency affects grid assets and how an asset is affected by various contingencies. A purple dot with many links to blue or orange circles indicates a critical contingency because it affects many power grid assets. These contingencies, if they occur, would have significant consequences; therefore, security enhancements or mitigation plans should be in place to ensure that the consequences are contained to acceptable levels. On the other hand, a blue or orange circle with many links to purple dots indicates a vulnerable asset because it can be affected by many contingencies. These assets should be protected by reliable backups or should be reinforced through new network development.

5. Assessing Candidate Actions

The interactive assessment of candidate actions provides additional decision support for power grid operators. With the help of visual analytic techniques, graphical trend analysis and clustering analysis, problems can be recognized and their consequences identified. Normally, there are multiple options for responding to a specific problem and choosing the best action is a challenging task for operators. Operators often make their decisions based on their experience because there is little decision support to enable them to identify the best option. Consequently, there is no guarantee that the action will be successful; in many cases, an action worsens the situation or causes new problems.

The interactive assessment of candidate actions helps determine the effect of operator actions. Operator actions may include power grid reconfiguration, generator re-dispatch, load shedding, etc. Before the operator chooses a specific action to implement, the candidate options may be tested in a model simulation, and the new grid status visualized in the color-contoured map. The collective severity level (CSL) is used to quantify the effect of the candidate actions and rank them in a prioritized list. The CSL is defined as:

$$CSL = \sum_{i=1}^{N} \left(\frac{max(P_{ik})}{P_{imax}} \right)^2 \text{ where } max(P_{ik}) > P_{imax} \tag{5}$$

Note that i denotes the i^{th} transmission line; k denotes the k^{th} contingency case; N is the number of transmission lines; P_{imax} is the capacity of the i^{th} transmission line; and P_{ik} is the power carried on the i^{th} transmission line for the k^{th} contingency case.

Figure 12 presents an example of interactive assessment. The figure shows a Western North American power grid risk map with an overlay of the results of 50 contingencies. For simplicity, only the line loading violations are shown. The power grid is clearly stressed because many violations exist (indicated by red regions). Note that only simple load shedding actions are considered as operator actions to illustrate the functionality of the tool. More realistic actions such as generator re-dispatch, reactive compensation and network reconfiguration will be investigated in future work.

Consider a situation where an operator has five candidate actions labeled A through E, which represent five different load reductions: –8.4%, –7.7%, –4.9%, –3.0% and –1.0%. The tool provides an interactive function as a menu item. An operator can select the menu item and simulate the candidate actions and update the contoured map. Figure 13 displays the results of the interactive assessment of the five candidate actions with line loading violations only. These actions are sorted based on their effectiveness from best to worst.

Table 2 lists the actions, their collective severity levels and rankings. By referencing Figure 13, an operator can easily identify A as the best action because it removes almost all the red color from the map and it has the lowest CSL (0.00). This is expected because a load reduction will better alleviate the system stress level.

The same methodology can be applied to other operator actions. Indeed, Figure 13 helps operators identify the violations that remain along with their locations, enabling them to judge if an option is satisfactory without relying solely on the CSL metric (Table 2). An operator can also choose to fine-tune the

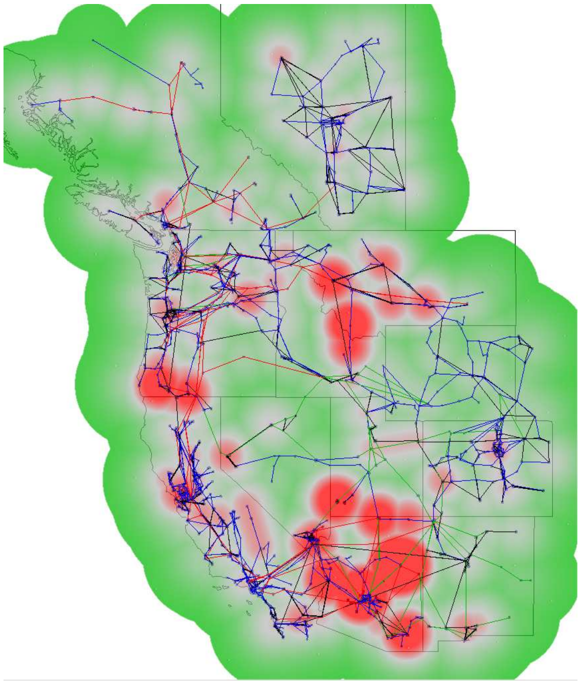

Figure 12. Western North American power grid risk map.

Table 2. Candidate actions and assessment results.

Option	**Description**	**CSL**	**Ranking**
A	8.4% load reduction off the current condition	0.00	1
B	7.7% load reduction off the current condition	53.30	2
C	4.9% load reduction off the current condition	74.03	3
D	3.0% load reduction off the current condition	90.28	4
E	1.0% load reduction off the current condition	117.23	5

options if none are deemed adequate. By adjusting the actions, the operator can reevaluate the option using the interactive function until a satisfactory option is determined.

6. Conclusions

Visual analytics techniques as implemented in the decision-support tool can significantly enhance power grid operations by converting large amounts of operational data into actionable information, translating the operational data into risk levels and presenting the risk levels in a color-contoured map. These features enable operators to quickly gain situational awareness of the power grid without sifting through large amounts of raw data. A predictive capability

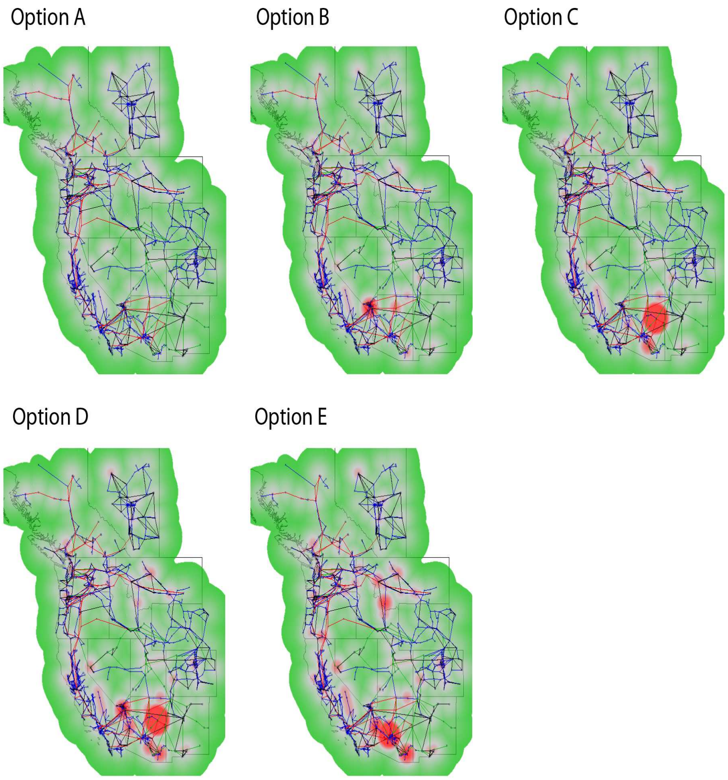

Figure 13. Sorted interactive assessment of candidate actions (from best to worst).

is established by analyzing network risk level trends using an approach that combines structural and statistical analyses; this assists operators in identifying system trends and foreseeing and discerning emergencies. The decision-support tool also performs clustering analysis to help operators identify the relationships between system configurations and affected assets. Additionally, operators can interactively evaluate candidate actions to identify the best action in a given situation.

The tool has received favorable reviews from power grid operators. It is currently being evaluated in collaboration with the WECC, which oversees the Western North American power grid. The results of the evaluation will be used to drive the refinement of the tool prior to its use in power grid control centers.

The decision-support tool engages a generic framework. Thus, it can be applied to other applications such as system planning and sensor data quality assessment. The tool can also be extended for use in other complex networks, including gas pipeline systems, telecommunications systems and aviation networks. Our future work will implement the hierarchical organization chart for clustering analysis, apply more realistic actions for interactive assessment, conduct usability studies to validate the utility of the tool, and integrate the tool with current commercial tools.

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