Case Study on Design Considerations for Wide-Area Transmission Grid Operation Visual Storytelling

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***Abstract*—Effectively communicating the behavior of an electric grid is an important pursuit in education, research, and industrial applications. This paper presents considerations for visual storytelling as a means for interpreting and communicating the behavior of the grid for simulations ranging in duration from seconds to days. By framing the issue of communicating the vast amounts of data associated with wide-area transmission grid operation as a story to tell, those tasked with presenting this data are encouraged to consider what makes an effective story and, in turn, create compelling and understandable stand-alone narratives. Demonstrations are presented for cases of various scales including a 37-bus case, a 2000-bus case, and a 24,000-bus case. Narrative techniques including non-linear time and alternative path storytelling are shown.**

***Index Terms*—wide-area electric grid visualization, electric grid simulation, storytelling**

I. Introduction

The large-scale grids that supply electricity to much of the world are some of the largest and most complex machines ever created [1]. An ongoing engineering challenge is to analyze, understand, control, and explain their operation to a variety of different audiences. To partially address these challenges, over the years, a number of different power system visualization techniques have been presented with some of these summarized in [2]. Certainly many of these techniques are useful and are now widely applied. However, power systems visualization is challenging, partially because of the variety of information that needs to be presented, the size of the systems, the lack of a way to naturally "see" an electric grid, and the sometimes proprietary nature of information about the grid.

Also electric grid visualization shares a challenge with general information visualization, which as noted in [3] is that while there has been much progress in developing techniques to work with large amounts of data, solid knowledge about the best ways to present and communicate data is still lacking. Or as noted in [4], while much has been done to develop sophisticated visualization tools, when such tools are demonstrated, it is not unusual to get feedback such as, "fancy visuals, cool interactions, but what does this mean?"

To address these shortcomings there has recently been a large amount of interest in what is commonly called visual storytelling [3]–[8]. While the term "storytelling" often invokes its colloquial meaning of orally communicating a story, more broadly it is defined to encompass a variety of different means of presentation, including the video visualization approach considered here. Then, as noted in [7], stories have long been used to entertain, educate, and instill moral values in a way that presents information in a compelling manner. This is exactly what is desired with information visualization. Here from a visualization perspective a story can then be defined broadly as an ordered sequences of steps, with an emphasis here on the visualization steps [3]. Recent examples of scientific visualization stories include [9]–[12].

Of course stories have been widely used in the electric power industry, with applications ranging short stories informally shared usually verbally between practitioners, sometimes to entertain and sometimes to educate, to much longer stories that are usually written and are sometimes designated as reports or articles. For instance, [13] tells the story of the August 14, 2003 black whereas [14] presents the story of when the North American Eastern and Western grids were interconnected. However, stories could also be much shorter and expressed mostly or entirely as visualizations. For example [15], which describes the FNET systems, also mentions quite short computer animations that tell the story of how a frequency disturbances propagates through an electric grid (with more recent FNET-based animations available at [16]) while [17] presents how movies can be created for utility control room usage to tell how the system changes over time, [18] describes how computer simulations with oral commentary can tell the story of electric grid operations, and [19] presents the use of animation to describe study results.

The focus of this paper is to present case study considerations of how storytelling can be used with visualization of the electric grid transmission operations over time periods ranging from seconds to days. The next section provides background on the techniques used in developing these stories and the associated case study grids. The following section then presents the case study results with the resultant videos available at [20], whereas the last section provides directions for future work.

II. Background

When applying storytelling to transmission operations there are a number of issues that need to be addressed. The first is the source of the information that is used to create the story. This can include historical information about actual electric grid operation, simulations done using models of actual electric grids, or simulations using models of synthetic electric grids [21]. Of course what is displayed depends on the application, and the different sources would have different amounts of data that could be used to develop the story. Here the case studies are presented using three synthetic electric grids: 1) the 37-bus one from [22] with its oneline shown in Figure 1, 2) the 2000-bus (2K) grid from [23] (Figure 2), and 3) the 24,000-bus (24K) grid from [24] (Figure 3).

The second issue is the intended audience. Example audiences could include utility managers who want a summary of the operation of their grid from the previous day, control room personnel who want a summary from the previous shift, engineers presenting study results or describing the behavior of a particular control system, policymakers, engineering educators who wish to explain the operation of the grid, researchers, or the general public education. In designing the stories the different degrees of familiarity of the audience with the material would, of course, need to be considered, as well as their different information requirements.

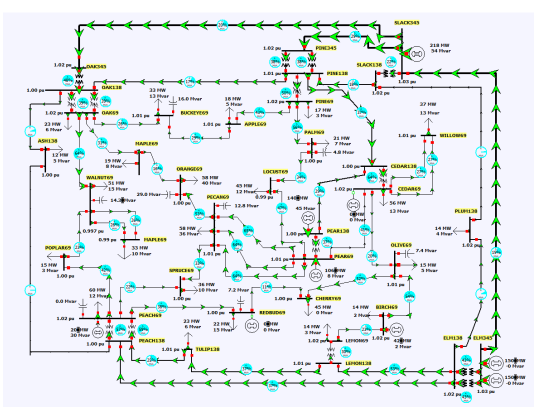

Fig. 1: 37-Bus System Oneline

The third issue is the story synthesis, which involves first creating story slices, defined generally as an information construction obtained from the original data, and then arranging the slices into the full story [4]. For example, if the desired story is to show the operation of the 37-bus grid over the course of a day sampled at 15-minute intervals, story slices might include some text-based images summarizing the operation of the grid over the day, some traditional graphs with time on the x-axis such as shown in Figure 4, and then perhaps some time sequence animations visualizing the grid using some of the techniques described shortly.

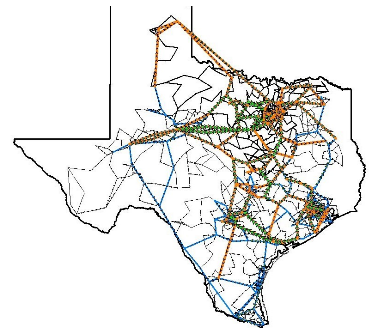

Fig. 2: 2000-Bus (2K) System Oneline

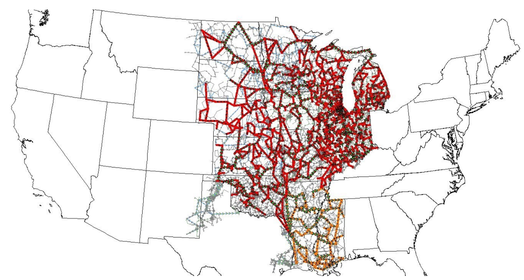

Fig. 3: 24,000-Bus (24K) System Oneline

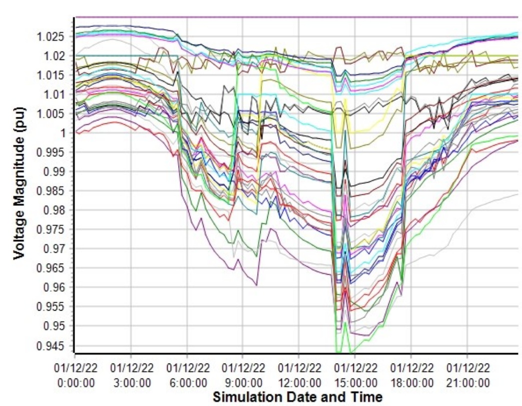

Fig. 4: 24 Hour, 37-Bus Case Voltage Variation

How the animation story slices are presented depends upon the application. One approach is to use the traditional uniform time, constant camera angle such as used in [15]. However, in many applications it is better to use the importance-driven approach of [25], [26]. As is common in many domains, with electric grid operations how the data changes temporally and spatially can vary dramatically. This is evident in Figure 4, in which during some time periods the voltage variation is minor, whereas during others (corresponding to generator outages here) the variation is substantial. Hence, when animating this data, a non-linear time scale may be preferred.

TABLE I: 37-Bus 24 Hour Operation Story Narrative

Story Slice	Story Element Block	Purpose	Approach	Duration (s)
1	Introduction to the 37-bus 24 hour operation	Provide education on this narrative technique	Text description	5
2	Introduction to the 37-bus grid	Show system element information	System diagrams and tables are presented	5
3	Scenario description	Introduce scenario and key events	Charts and text are used to provide a scenario overview	10
4	Animation of voltage contour (linear time)	Show system behavior through a voltage lens	Voltage contour on system diagram, jpeg snapshots are presented linearly	12
5	Animation of voltage contour (non-linear time)	Show system behavior through a voltage lens, emphasizing the peak load period	Voltage contour on system diagram, jpeg snapshots are presented non-linearly	20
6	Pseudogeographic mosaic display (PGMD) animation	Show system with a line loading lens	PGMD jpeg snapshots presented linearly	12

What information is shown, and how it is shown is also an important consideration. With the focus here on wide-area transmission grid operations, over the years a number of different approaches have been developed that build on the tradition oneline. Early approaches include the use of dynamic sizing of grid elements, transmission line flow animation, the use of zooming and panning, contouring of electric grid information, and the use of alpha-blending to emphasize portions of the electric grid [27]–[30]. More recently these approaches have been supplemented with newer ones such as the use of geographic data views to leverage the geographic information now included in many grids [31]–[34]. The next section demonstrates how some of these techniques can be used in storytelling on grids ranging in size from 37 buses to 24,000 buses.

III. Example Grid Case Studies

A. Information Sources

The grids used in these case studies rely on synthetic time series to create a story of realistic fiction. The load time series are generated according to [35], in which the time series are created on a bus-level based on the geographic location and the load bus composition ratio (the ratio of the load which are residential, commercial, and industrial demands). The renewable generation time series is developed by leveraging the generators' geographic locations and the solar and wind resource data made available by the National Renewable Energy Laboratory (NREL) [36], [37].

B. Intended Audience

The intended audience of the 37-bus and 2,000-bus grid stories are people with a power systems background. That is, the audience will have an understanding of power system concepts such as how to read a oneline diagram, power flows, voltages, and the various elements of power systems (i.e., loads, generators, shunts, etc.). We are assuming that the audience is not yet familiar with the grids presented in the 37-bus case study. The audience of the 2,000-bus case study is assumed to be somewhat familiar with the case. The intended audience of the 24,000-bus grid story is people with a very basic knowledge of power systems. The story told with the 24,000-bus grid example is designed to be understood by members of the public with limited knowledge of power system elements.

Thus, in telling the story of each grid, it is important to introduce the electric grid, its components and typical operation, a timeline of key events, and the impact of these events. The following sections provide the additional details to the storytelling of each case and the corresponding videos are available at [20].

C. 37-Bus Grid Story Synthesis

Each story is comprised of various chapters, or "slices," that present the narrative blocks of the story. These story slices may be stitched together using video editing software. A variety of techniques can be used to organize these slices in the preparation of a narrative such as yarn diagrams [38], charts, or tables. Table I presents the organization of the narrative blocks for the 37-bus example, their purpose within the complete narrative, the approach used to create the visuals in the movie, and the display duration.

The first slice of the story is an introduction to the narrative. This block provides big-picture motivation for the case study and a high-level overview of what the story will show. The 37-bus grid case provides a small grid as a demonstration of this narrative technique.

The next story element introduces the audience to the 37-bus grid. As the audience is assumed to have no experience with this case, background information on grid elements and topology are provided. Given the audience is assumed to be people in the field of power systems, it is reasonable to present this information without defining typical field-specific vernacular. This slice presents the composition of this grid.

The third story element sets the scene by providing an overview of the scenario. This story presents "37-Bus 24 Hour Operation," in which the grid is operated over 24 consecutive hours on a late-summer day with no major events. During this simulation, grid operation on a normal day is presented; the loads and generation dispatch change on an hourly basis.

When analyzing the results of operation or study, there are a variety of possible lenses of interest including voltage levels, generation dispatch, and line loading. In order to effectively communicate the story of each perspective, various story element blocks may be used. This narrative highlights the voltage level and line loading over the 24-hour period of study. The fourth story slice shows a time lapse of the voltage contour over the duration of the study in which each hour of simulated operation is depicted as a 0.5-second frame within the video. The next story slice depicts the voltage contour over the same period of study, but presents it in non-linear time. This demonstrates another narrative technique in which uneventful time periods are glossed over such that more emphasis can be

TABLE II: 2,000-Bus Line Switching Story Narrative

Story Slice	Story Element Block	Purpose	Approach	Duration (s)
1	Introduction slide	Provide education on this narrative technique	System diagrams and tables are presented	4
2	Introduction to the 2,000-bus case	Show high-level view of system and its geographic site	Oneline diagram emphasizing 115-kV and 161-kV networks, indication of region of study	5
3	Scenario description	Introduce contingency and resulting overload	Charts and text are used to provide a scenario overview	5
4	Beginning of day	Show system behavior during an uneventful start of the day	Zoomed view of oneline with power flow and line loading shown	13
5	Post-contingency with "do nothing" approach	Show line overloads with no corrective actions	Zoomed view of oneline with power flow and line loading shown	13
6	Post-contingency with corrective line switching	Demonstrate alleviation of overload with line switching	Zoomed view of oneline with power flow and line loading shown	13
7	Impact of corrective actions	Quantify the impact of corrective actions in this scenario	Text and tables showing a comparison of costs for each scenario	5

placed on periods of interest. In this example, the contour from the hours of 12:00 AM to 2:00 PM are shown for 0.25 seconds each. The peak hours (2:00 PM to 6:00 PM) are depicted with more granular time steps of 15 minutes, each shown for a duration of 0.5 seconds. Once the period of interest has passed, the view of the case returns to showing the frames for 0.25 seconds each.

The sixth story slice within this narrative showcases the line loading over the course of the system operation simulation. The visualization technique of pseudo-geographic mosaic displays (PGMDs) [39], in which mosaic tiles represent branches within the system, is used. These tiles are colored according to the line loading and are placed in a pseudo-geographic manner which allows them to be displayed with approximate positions to maximize the use of display space. The PGMDs are used to show the congestion pattern of the grid over the course of the simulation and to demonstrate another storytelling technique.

D. 2,000-Bus Grid Story Synthesis

The story elements in the 2,000-bus grid are summarized in Table II. This story's purpose is to demonstrate the use of line switching as a corrective action. The story compares two possible story lines to demonstrate two possible responses to the branch overload. The first response involves a "do nothing" scenario in which no corrective action is taken and the second is the use of corrective line switching to mitigate branch overloads which occur as a result of the outage.

The first three slices introduce the story, case, and scenario, respectively, as in the previous example. The 2,000-bus case is presented using a oneline diagram with emphasis on the branches of the voltage levels central to the plot in this story (115 kV and 161 kV). As the movie itself focuses on a narrow subregion of the system, this is indicated on the system oneline diagram with a red box. The scenario information notes that this study was performed during a mid-summer day. A chart is included to illustrate the relatively high system loading as well as the pattern that the system loading follows over the course of the simulation. The contingency is presented via text and an annotated diagram and the resulting line overload is noted. The two paths followed in the story are presented: a do-nothing scenario, and a scenario in which line switching is used as a corrective action to alleviate congestion in the case.

The fourth story slice depicts the events of the day preceding the line outage using a close-up view of the oneline diagram to show the line status, line loading, and flow of power in the subregion of the system. As the portion depicted in this story slice is uneventful, a time step of 5 minutes is employed and

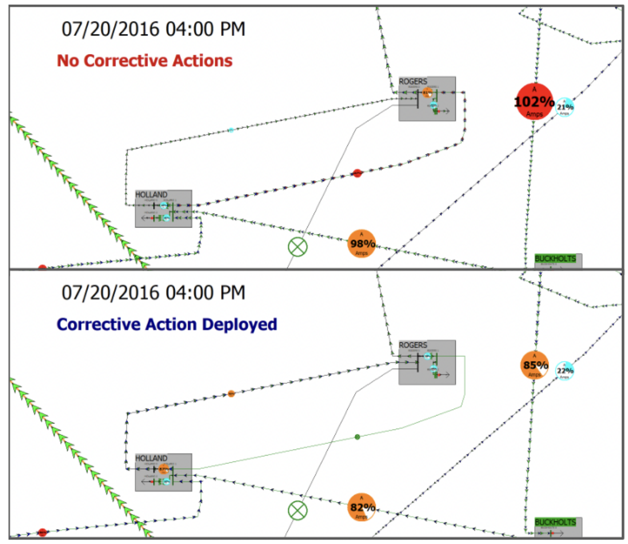

Fig. 5: Frames from the 2000-bus line switching narrative slice 5 (top) and slice 6 (bottom).

a frame rate of 12 frames per second (fps) was selected for this slice in the movie. The line outage occurs at 1:15 PM in the simulation and a resulting overload of a 115-kV line is promptly observed.

The fifth slice picks up the story from the time of the contingency. Text is shown on the display to indicate which of the alternative scenarios is being shown. No corrective action is applied and overloads are indicated on the line loading pie charts. The simulation plays out for the remainder of the day. The sixth slice returns the story to the time of the contingency. Text is shown on the display to indicate which of the alternative scenarios is being shown. The line switching corrective action is applied 5 minutes later (1:20 PM). The action is shown to have eliminated the overload. The simulation plays out for the remainder of the day. Figure 5 shows frames from narrative slices 5 and 6.

The seventh story slice presents the impact of the results of the corrective actions by presenting a cost comparison of the operational costs associated with grid operation over the course of the day in the do nothing scenario and the line switching scenario. The line switching corrective action is shown to reduce operational costs.

E. 24,000-Bus Grid Story Synthesis

The story elements in the 24,000-bus grid are summarized in Table III. This story's purpose is to demonstrate the impact of

TABLE III: 24,000-Bus Contingency Story Narrative

Story Slice	Story Element Block	Purpose	Approach	Duration (s)
1	Introduction slide	Provide education on this narrative technique	System diagrams and tables are presented	5
2	Introduction to the 24,000-bus case	Show system element information	Voltage levels and generation charts, description of grid	5
3	Scenario description	Introduce contingency and resulting overload	Charts and text are used to provide a scenario overview	5
4	Beginning of day	Show system behavior through line loading and voltage lens	Substation GDVs colored by primary fuel type, sized by MW dispatch and voltage contour	24
5	A high load day normal operation	Show system behavior in a normal situation	Zoomed view of line loading and voltage contour in Michigan	11
6	A high load day and stormy weather	Show system behavior in an important line outage situation	Zoomed view of line loading and voltage contour in the impacted area	11
7	Impact of outage	Quantify the impact of outages	Text and tables showing a comparison of each scenario	5

an event such as lighting that causes a transmission line outage in a high-load day. The story compares two possible story lines to demonstrate two possible scenarios with and without the outage. The first slice of the story is an introduction to the narrative. This block provides big-picture motivation for the case study and a high-level overview of what the story will show. The 24,000-bus grid case provides a very large grid as a demonstration of this narrative technique. The next story element introduces the audience to the 24,000 bus grid. The story is intended to be understandable for people with basic knowledge of power systems.

The first three slices introduce the story, case, and scenario, respectively, as in the previous examples. The 24,000-bus case is presented using a oneline diagram with emphasis on the high branches with zooming on Michigan state and emphasizing on 345-kV transmission lines to show overload due to the 345-kV line outage at 4:16 PM in Michigan. As the movie itself focuses on a narrow subregion of the system, this is indicated on the system oneline diagram with a box. The scenario information notes that this study was performed during a high-load mid-summer day. A chart is included to illustrate the relatively high system loading as well as the pattern that the system loading follows over the course of the simulation. The outage is presented via text and an annotated diagram and the resulting line overload is noted. The two paths followed in the story are presented: a scenario of normal system operation and a scenario in which line outage happens.

The fourth story slice depicts the operation of the grid at the beginning of the day preceding the line outage using a close-up view of the oneline diagram of Michigan to show the line status, line loading, and flow of power in the subregion of the system. As the simulation depicted in this story slice is uneventful, a time step of 8 minutes is employed and a frame rate of 5 fps was selected for this slice in the movie.

The fifth slice continues the story, depicting a timeline in which no outage occurs. Text is shown on the display to indicate which of the alternative scenarios is being shown. The sixth slice returns the story to the mid-afternoon. The 345-kV line outage occurs at 4:24 PM in the simulation and a resulting several overloads in the system, indicated on the line loading pie charts. Text is shown on the display to indicate which of the alternative scenarios is being shown. The simulation plays out for the remainder of the day. Figure 6 shows frames the scenarios presented slices 5 and 6.

The seventh story slice presents the impact of the outage by presenting a cost comparison of the operational costs associated with grid operation over the course of the day in the normal scenario and the line outage scenario.

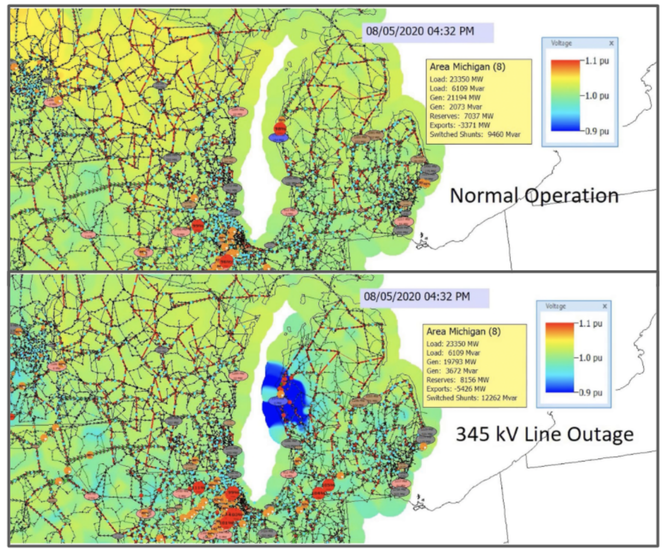

Fig. 6: Frames from the 24,000-bus contingency story narrative slice 5 (top) and slice 6 (bottom).

IV. Summary and Future Work

The use of storytelling as a means of communicating data from electric grids is motivated by the need to communicate the results of studies involving lots of data to various audiences in a compelling manner. By framing the issue of communicating the vast amounts of data associated with wide-area transmission grid operation as a story to tell, those tasked with presenting this data are encouraged to consider what makes an effective story and, in turn, create compelling and understandable stand-alone narratives.

Storytelling approaches are demonstrated on 37-bus, 2000-bus, and 24,000-bus grids. These videos are available at [20]. The 37-bus grid story presents a small test case demonstrating a day of uneventful operation with the intention of demonstrating visualization techniques including the use of onelines, contours, and mosaic displays to an audience with basic power system knowledge, but no system-specific knowledge. The 37-bus story featured a technique of storytelling in linear and non-linear time.

The 2,000-bus story presents a larger case to demonstrate the impact of line switching as a corrective action. This story highlights the storytelling technique of alternate path storytelling by setting up two alternative story paths to show the grid's behavior with different operator approaches. This shows "what would have happened if" the operator performs or does not perform corrective actions.

The 24,000-bus story shows the impact of a high voltage 345-kV line outage on a very large grid. This story compares two operational scenarios: a normal high-load day without any outages, and a scenario with a line outage, to highlight the impact of a line outage on the other line loadings in the system.

This work introduces the concept of storytelling to the domain of power systems. Future work includes additional automation in the story creation process.

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REFERENCES

[1] E. National Academies of Sciences and Medicine, *Analytic Research Foundations for the Next-Generation Electric Grid*. Washington, DC: The National Academies Press, 2016.

[2] M. T. Fischer, "Towards a survey of visualization methods for power grids," 2021. [Online]. Available: 2106.04661

[3] R. Kosara and J. Mackinlay, "Storytelling: The next step for visualization," *Computer*, vol. 46, no. 5, pp. 44–50, 2013.

[4] S. Chen, J. Li, G. Andrienko, N. Andrienko, Y. Wang, P. H. Nguyen, and C. Turkay, "Supporting story synthesis: Bridging the gap between visual analytics and storytelling," *IEEE Transactions on Visualization and Computer Graphics*, vol. 26, no. 7, pp. 2499–2516, 2020.

[5] E. Segel and J. Heer, "Narrative visualization: Telling stories with data," *IEEE Transactions on Visualization and Computer Graphics*, vol. 16, no. 6, pp. 1139–1148, 2010.

[6] K.-L. Ma, I. Liao, J. Frazier, H. Hauser, and H.-N. Kostis, "Scientific storytelling using visualization," *IEEE Computer Graphics and Applications*, vol. 32, no. 1, pp. 12–19, 2012.

[7] A. Figueiras, "How to tell stories using visualization," in *2014 18th International Conference on Information Visualisation*, 2014, pp. 18–18.

[8] C. Tong, R. Roberts, R. Borgo, S. Walton, R. S. Laramee, K. Wegba, A. Lu, Y. Wang, H. Qu, Q. Luo, and X. Ma, "Storytelling and visualization: An extended survey," *Information*, vol. 9, no. 3, 2018. [Online]. Available: https://www.mdpi.com/2078-2489/9/3/65

[9] E. M. Lidal, H. Hauser, and I. Viola, "Geological storytelling – graphically exploring and communicating geological sketches," *EUROGRAPHICS Symposium on Sketch-Based Interfaces and Modeling*, p. 11–20, 2012.

[10] M. Brehmer, B. Lee, B. Bach, N. H. Riche, and T. Munzner, "Timelines revisited: A design space and considerations for expressive storytelling," *IEEE Transactions on Visualization and Computer Graphics*, vol. 23, no. 9, pp. 2151–2164, 2017.

[11] D. Kouřil, O. Strnad, P. Mindek, S. Halladjian, T. Isenberg, M. E. Gröller, and I. Viola, "Molecumentary: Adaptable Narrated Documentaries Using Molecular Visualization," *IEEE Transactions on Visualization and Computer Graphics*, 2022, to appear. [Online]. Available: https://hal.inria.fr/hal-03451509

[12] Y. Zhao, X. Luo, X. Lin, H. Wang, X. Kui, F. Zhou, J. Wang, Y. Chen, and W. Chen, "Visual analytics for electromagnetic situation awareness in radio monitoring and management," *IEEE Transactions on Visualization and Computer Graphics*, vol. 26, no. 1, pp. 590–600, 2020.

[13] 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," https://www.energy.gov/oe/downloads/blackout-2003-final-report-august-14-2003-blackout-united-states-and-canada-causes-and, 2004.

[14] J. Cohn, "When the grid was the grid: the history of North America's brief coast-to-coast interconnected machine [scanning our past]," *Proceedings of the IEEE*, vol. 107, no. 1, pp. 232–243, 2019.

[15] Z. Zhong, C. Xu, B. Billian, L. Zhang, S.-J. Tsai, R. Conners, V. Centeno, A. Phadke, and Y. Liu, "Power system frequency monitoring network (FNET) implementation," *IEEE Transactions on Power Systems*, vol. 20, no. 4, pp. 1914–1921, 2005.

[16] "FNET/GridEye web display." [Online]. Available: http://fnetpublic.utk.edu/

[17] R. Klump and J. Weber, "Real-time data retrieval and new visualization technqiues for the energy industry," *Proc. 25 Hawaii International Conference on System Sciences*, 01 2002.

[18] T. Overbye, "Power system simulation: understanding small- and large-system operations," *IEEE Power and Energy Magazine*, vol. 2, no. 1, pp. 20–30, 2004.

[19] National Renewable Energy Laboratory (NREL), "North american renewable integration study," https://www.nrel.gov/analysis/naris.html.

[20] "Electric grid test case repository." [Online]. Available: https://electricgrids.engr.tamu.edu/

[21] A. B. Birchfield, T. Xu, K. M. Gegner, K. S. Shetye, and T. J. Overbye, "Grid structural characteristics as validation criteria for synthetic networks," *IEEE Transactions on Power Systems*, vol. 32, no. 4, pp. 3258–3265, 2017.

[22] J. D. Glover, T. J. Overbye, and M. S. Sarma, *Power System Analysis and Design*, 6th ed. Cengage Learning, 2017.

[23] A. B. Birchfield, T. J. Overbye, and K. R. Davis, "Educational applications of large synthetic power grids," *IEEE Transactions on Power Systems*, vol. 34, no. 1, pp. 765–772, 2019.

[24] F. Safdarian, A. B. Birchfield, K. S. Shetye, and T. J. Overbye, "Additional insights in creating large-scale, high quality synthetic grids: A case study," in *2021 IEEE Kansas Power and Energy Conference (KPEC)*, 2021, pp. 1–6.

[25] J. Lu, J. Wang, H. Ye, Y. Gu, Z. Ding, M. Xu, and W. Chen, "Illustrating changes in time-series data with data video," *IEEE Computer Graphics and Applications*, vol. 40, no. 2, pp. 18–31, 2020.

[26] X. Tong, T. Lee, and H. Shen, "Salient time steps selection from large scale time-varying data sets with dynamics time warping," in *IEEE Symposium on Large Data Analysis and Visualization*, Seattle, WA, October 2012.

[27] K. M. Gegner, T. J. Overbye, K. S. Shetye, and J. D. Weber, "Visualization of power system wide-area, time varying information," in *2016 IEEE Power and Energy Conference at Illinois (PECI)*, 2016, pp. 1–4.

[28] C. Wang, H. Yu, and K.-L. Ma, "Importance-driven time-varying data visualization," *IEEE Transactions on Visualization and Computer Graphics*, vol. 14, no. 6, pp. 1547–1554, 2008.

[29] T. J. Overbye, E. M. Rantanen, and S. Judd, "Electric power control center visualization using geographic data views," in *2007 iREP Symposium - Bulk Power System Dynamics and Control - VII. Revitalizing Operational Reliability*, 2007, pp. 1–8.

[30] T. J. Overbye, A. Meliopoulos, D. Wiegmann, and G. Cokkinides, "Visualization of power systems and components," *PSERC Publication*, no. 05–65, 2005.

[31] T. J. Overbye, E. M. Rantanen, and S. Judd, "Electric power control center visualization using geographic data views," in *2007 iREP Symposium-Bulk Power System Dynamics and Control-VII. Revitalizing Operational Reliability*. IEEE, 2007, pp. 1–8.

[32] T. J. Overbye, K. S. Shetye, J. Wert, W. Trinh, A. Birchfield, T. Rolstad, and J. D. Weber, "Techniques for maintaining situational awareness during large-scale electric grid simulations," in *2021 IEEE Power and Energy Conference at Illinois (PECI)*, 2021, pp. 1–8.

[33] T. J. Overbye, J. Wert, K. S. Shetye, F. Safdarian, and A. B. Birchfield, "Delaunay triangulation based wide-area visualization of electric transmission grids," in *2021 IEEE Kansas Power and Energy Conference (KPEC)*, 2021, pp. 1–6.

[34] J. L. Wert, J. H. Yeo, F. Safdarian, and T. J. Overbye, "Situational awareness for reactive power management in large-scale electric grids," in *2022 IEEE Texas Power and Energy Conference (TPEC)*, 2022, pp. 1–6.

[35] H. Li, J. H. Yeo, A. L. Bornsheuer, and T. J. Overbye, "The creation and validation of load time series for synthetic electric power systems," *IEEE Transactions on Power Systems*, vol. 36, no. 2, pp. 961–969, 2021.

[36] "Wind resource data, tools, and maps." [Online]. Available: https://www.nrel.gov/gis/wind.html

[37] "Solar resource data, tools, and maps." [Online]. Available: https://www.nrel.gov/gis/solar.html

[38] K. Padia, K. H. Bandara, and C. G. Healey, “A system for generating storyline visualizations using hierarchical task network planning,” *Computers & Graphics*, vol. 78, pp. 64–75, 2019.

[39] T. J. Overbye, J. Wert, A. Birchfield, and J. D. Weber, “Wide-area electric grid visualization using pseudo-geographic mosaic displays,” in *2019 North American Power Symposium (NAPS)*, 2019, pp. 1–6.