Situational Awareness for Reactive Power Management in Large-Scale Electric Grids

Jessica L. Wert, Ju Hee Yeo, Farnaz Safdarian, Thomas J. Overbye
Department of Electrical and Computer Engineering
Texas A&M University
College Station, TX
{jwert; yeochee26; fsafdarian; overbye}@tamu.edu

***Abstract*—Situational awareness is imperative for reactive power management, particularly for interpreting the results of studies evaluating the impact of geomagnetic disturbances or high levels of renewable generation on the grid. This paper introduces a visualization technique, VAR Ready Reserves (VRRs), to provide a novel and useful tool to enhance the situational awareness of users performing and interpreting power system studies. This visualization technique can be adapted to demonstrate the dispatch, injection, and absorption capability of reactive power devices (such as generators, shunts, SVCs) in either a chart view (VRR charts) or with an integrated system view (VRR GDVs) to provide users with the awareness of reactive power capability and dispatch over the duration of a simulation or spatially. This paper reviews industry practices for reactive power management, summarizes existing visualization strategies, and demonstrates the newly-developed VRRs on a 2000-bus case study.**

***Index Terms*—Reactive power, Reactive power management, Situational awareness, Visualization**

I. INTRODUCTION

Reactive power plays a fundamental role in maintaining power system voltage stability. Maintaining voltage levels within acceptable bounds enables the delivery of active power to consumers in the system. Voltage instability issues usually occur when a heavily-loaded system does not have a sufficient amount of reactive power reserves [1]. Thus, power system operators must have an appropriate management strategies for and awareness of reactive power to avoid possible voltage instability concerns and even blackouts.

Generators and devices such as shunts and static var compensators (SVCs) can be used to provide reactive power resources (through injection or absorption) to the grid. Although operators aim to minimize the use of switch shunts, they can be used to improve system voltages for regular or post-contingency scenarios. According to the PJM's operation manual, the response time when tripping or closing automatic shunts ranges from 1 second to 15 minutes [2].

Independent System Operators (ISOs) have established their own reactive power management strategies to maintain and regulate system voltage within acceptable ranges under both normal and contingency conditions. For example, PJM monitors reactive power reserves using real-time unit reactive capability data obtained from each generation owner or operator [3]. This management scheme enables PJM operators and engineers to maintain awareness of individual unit reactive power output and capacity within the interconnection to preserve steady-state operating conditions. The Electric Reliability Council of Texas (ERCOT) relies on an updated reactive capability curve by computing limiting factors such as under/over-excitation limiters and ambient temperature limitations across the MW range of the unit. Currently, the most limiting elements for the leading and lagging reactive output are considered [4]. ERCOT has developed a Reactive Power Coordination (RPC) tool to optimize the use of reactive power control devices such as shunts, generator voltage setpoints, and SVCs, across a multi-hour interval [5]. This tool aids in reducing the number of switching actions and augmenting transfer capability in areas where have voltage instability issues.

The Federal Energy Regulatory Commission (FERC) and ISOs in North America have settled certain reactive power requirements that are needed to be met to manage the power systems properly [2], [6]–[9]. Table I presents the requirements of minimum reactive power capability and voltage range. Generally, generators are required to have 0.95 lag to lead power factor at the Point of Interconnection (POI) and voltage range to be between 0.95 and 1.05 per unit. These limits can differ depending on the type and voltage level of the machines [2], [8].

TABLE I: Reactive Power Requirements

	Power Factor Limit		Voltage Range (p.u.)
	Synchronous	Non-synchronous	
FERC	± 0.95	± 0.95	-
ERCOT	± 0.95	± 0.95	$0.95 \leq V \leq 1.05$
PJM	+0.9/-0.95	± 0.95	$0.90 \leq V \leq 1.10$
CAISO	+0.9/-0.95	± 0.95	$0.95 \leq V \leq 1.05$

A. Motivation for Reactive Power Situational Awareness

The importance of reactive power management situational awareness is highlighted when considering required studies and trends in generation technologies. Geomagnetic disturbances (GMDs) have the potential to increase reactive power demand and can introduce harmonics which may result in the tripping of reactive power resources. This presents a challenge for grid planners and operators anticipating a GMD as the reactive power device availability may suddenly change. In North America, per TPL-007-2, engineers must study the possible effects of GMDs in the planning of the system [10]. Situational awareness of reactive power is an important part in interpreting the results of such studies particularly with the strong impact that GMDs can have on reactive power resources. Power generation trends show an increasing incorporation of renewable resources into large-scale power systems. Because the power electronics for the renewable generators provide reactive power support and voltage regulation, a need for continued awareness of reactive power availability and levels is illuminated.

B. Paper Structure

This paper presents a review of visualization strategies and introduces a novel visualization tool to strengthen reactive power situational awareness by enabling ease of recognizing real-time status of reactive power and capacity. Section II presents a discussion of the role that situational awareness can play in reactive power management and presents a novel visualization tool for enhanced situational awareness of reactive power. Section III presents a case study of reactive power management over time and demonstrates the use of the situational awareness tools introduced and discussed. The paper concludes with a summary of work and discussion of future applications in Section IV.

II. Reactive Power Situational Awareness

Reactive power situational awareness tools are designed for different types of studies and user environments. Some of these tools provide awareness of reactive power for individual generators while others provide situational awareness for wide-area system studies. Generally, approaches for reactive power situational awareness incorporate data from either shunts or generators separately. Situational awareness of voltage has been used as a proxy in some cases for the reactive power needs in different regions of a system.

A. Graphs and Charts

For awareness on a generator-level, the reactive power capability of generators is presented by the use of their reactive capability (or “D”) curves [3], [11], [12]. This approach is useful in smaller systems or for considering generators within a pre-identified region-of-interest within the system. Reference [13] shows the reactive capability aggregated zonally for a small system to integrate individual generator reactive capability curves to a small system view. This technique provides awareness to the reactive generation capability from generators from a wider range of consideration and could be used more generally when confronted with a region of reactive power imbalance. Post-study situational awareness of the reactive power needed from each generator in the system to support SCOPF simulations was managed with the use of bar charts in [12].

B. Integrated System Visualizations

Approaches which integrate reactive power visualizations with the system diagram have been explored as well. This is shown as 3D bars at generator reactive reserves locations in oneline diagrams in [14], [15]. More recently, icons called geographic data views (GDVs) have been integrated into oneline displays or maps to provide additional system information such as shunt status or generators near their limits for generating or absorbing reactive power [16], [17]. The placement of these GDV icons is traditionally geographic, though the layout may also be modified to optimize for use of display space, with examples of shunt relative location and dispatch status depicted in [16].

C. Voltage Visualizations

System voltages are typically represented through the use of a voltage contour to present the bus voltages in the system for cases [18]. This provides visibility to the voltage level in areas of the system and may highlight regions with voltage issues in which reactive power dispatch may provide support to the voltage. Another approach to communicate the need for voltage support with reactive power could be signaled by visualizing the status of buses within the system by their distance from voltage collapse. This is done in [19] using a surface plot of the distance from voltage collapse. An application of voltage awareness in the distribution system is provided by [20].

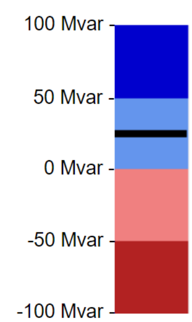


Fig. 1: VAR Ready Reserve GDV

D. VAR Ready Reserves

This paper introduces VAR Ready Reserves (VRRs) to offer a tool to be leveraged either in a chart view (as a VRR chart), or with an integrated system view (as a VRR GDV). VRRs incorporates available reactive power support from both generators and other reactive power devices. In chart form, the reactive power capability and dispatch is represented over a duration of time for a specific region of the system. In GDV form, VRRs are incorporated as GDV icons overlaid over a system diagram and are used to represent a region of the system's available reactive power resources. Depending on the scale of the system and the desired scope of analysis the region of the system may be pre-designated areas or zones or other, user-defined regions. The VRR presents the following levels of information:

- **Level 1:** Online regional reactive power capability
- **Level 2:** Offline regional reactive power capability
- **Level 3:** Present regional reactive power dispatch

For Level 1, the VAR Ready Reserve aggregates the available reactive power absorption and production capabilities for committed reactive power devices including generators, shunts, and SVCs for a region of the system. This is depicted by lighter colors in the middle of the VRR. For Level 2, the VAR Ready Reserve encompasses the reactive power capabilities for offline devices. This is depicted by darker colors in the VRR and form the upper and lower bound for the reactive power capabilities within a region of a system. Level 3 is the regional reactive power dispatch at a present state of the system. This is presented by the black line within the VRR. A blue-red color mapping is used within this paper, but any high-contrast color mapping may be applied.

Figure 1 presents an example of a VAR Ready Reserve GDV icon for a region in the system with 50 Mvar capability for online reactive power generation (indicated by the light blue), 50 Mvar capability for absorbing reactive power using online devices (indicated by the light red). This region also contains an additional 50 Mvar capability for reactive power generation with devices currently offline (indicated by the dark blue), and 50 Mvar capability for reactive power absorption with devices that are currently offline (indicated by the dark red). Thus, the total regional reactive power capability for generation is 100 Mvar and absorption is 100 Mvar. Within the sample region, approximately 25 Mvar is the net reactive power generation being dispatched in a sample case, as presented by the black line in the VRR.

This visualization method is unique as it aggregates all reactive power capabilities including that of generators and other reactive power devices for each region. By presenting this information in an integrated system view, this situational awareness approach may be particularly beneficial for evaluating the possible actions available to mitigate voltage issues in a study case. Using a chart view to demonstrate the VRR information could benefit a post-study analysis considering the commitment of reactive power devices over the course of the simulation for a region of study.

III. Case Study

A. Scenario Description

Since the information of actual electric grids is confidential and protected as Critical Energy Infrastructure Information (CEII), Texas A&M University has created synthetic electric grids that are realistic in structure and function, but do not compromise CEII. These have been developed for various regions of United States' footprint and are available for research and educational purposes [21]. These synthetic grids are created based on publicly available data such as U.S. Census data [22] and generators' information that is available at Energy Information Administration website [23]. Reference [24] outlines fundamental steps for the creation of synthetic power system models including geographic loads, generators, substations, and assignment of transmission lines. The overall approach for building these networks is described more in [24]. The general process includes substation planning, transmission planning and reactive power planning. Also, these synthetic grids are validated based on important characteristics of actual grids named as validation metrics [25], [26] for achieving realistic data sets. One important feature of these synthetic grids is the availability of geographic information of system elements. The geographic information is explicitly used to develop scenarios with various system operating conditions and create load and renewable time series [27]–[29].

ACTIVSg2000 [21] is used for study in this paper. This synthetic grid is sited on the geographic footprint of Texas and includes 2,000 buses, 1,250 substations, 2,345 transmission lines, 1,350 loads, 544 generators, and 8 areas. The total generation capacity is 100 GW. Load and renewable time series are created based on the strategy explained in [27]–[29]. The created time series are also synthetic but validated based on the real data [27]. A high load day in August (the 11th day) is selected for a more detailed study of reactive power changes in this paper. The system load peaks at 3:00 PM in the simulation, with a system load of about 66.3 GW.

Three visualization strategies are demonstrated ranging from graphical representation of reactive power levels to the VRRs introduced in Section II-D. Figure 2 shows a strictly graphical representation of reactive power dispatch, providing insights to regional reactive power levels over time. Figure 3 demonstrates VRR charts for regions of interest within the system to provide insights to the flexibility of reactive power levels over time. Figures 4 and 5 demonstrate the VRR GDVs in a system-integrated visualization technique. These showcase the reactive power level and flexibility for regions within the system at times of interest. The VRR GDVs can be readily integrated with other visualization techniques such as voltage contours to provide additional perspectives or could be animated to show the change in dispatch and flexibility over time. These situational awareness strategies are discussed in the next section.

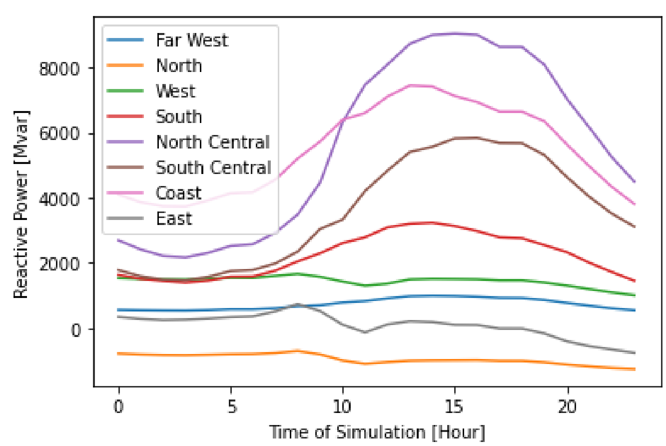


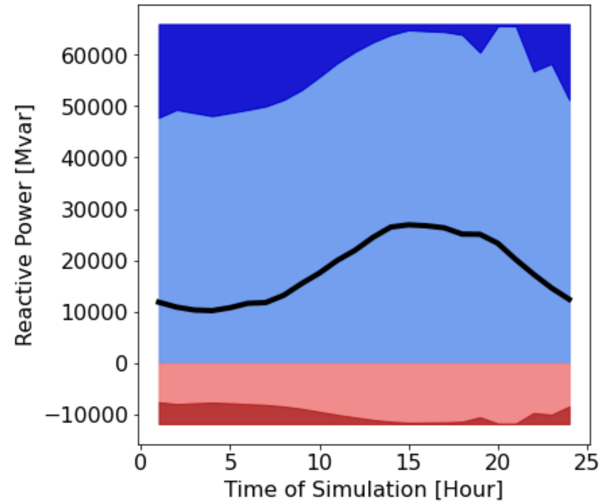
Fig. 2: Reactive power dispatch levels within each area of the case over the 24-hour simulation window.

B. Results and Discussion

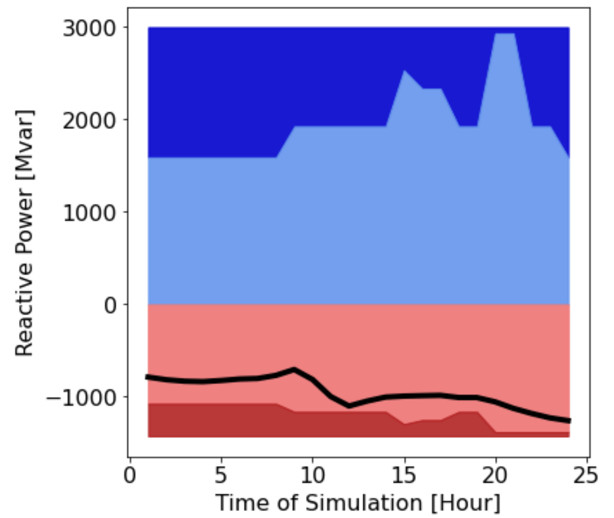
The reactive power dispatch for reactive power devices in each area for the duration of the simulation is shown in Figure 2. Each of the eight system areas are depicted. The system's peak reactive power level is highest in the early afternoon hours to support the delivery of the afternoon peak active power within the system. Each of the system areas experiences different levels of variation over the course of the simulation, with each demonstrating changes to reactive power levels at around 10:00 AM. Although this corresponds with a net increase in reactive power injection for the case as a whole, the North, West, and East areas demonstrate lower levels of reactive power injection (or higher levels of reactive power absorption) during this part of the simulation.

Figure 3 demonstrates reactive power capability and dispatch in VRR charts for different regions of the system, where light blue presents online reactive power injection capability, light red represents online reactive power absorption capability, dark blue shows the total system (online and offline) reactive power injection capability, and dark red shows the total system reactive power absorption capability. The black line denotes the net level of reactive power used within the case over the 24-hour simulation window. Figure 3a shows an aggregation of the lines from from Figure 2 as the black line and provides additional information as to the degree of flexibility of this dispatch level by demonstrating characteristics of the VRR over time for the entirety of the system. Over the course of the simulation, there is great flexibility in the reactive power injection of the system as a whole. Changes in the status of reactive power devices can be seen with the amount of dark red and dark blue shown in the graph. Figures 3b and 3c show the VRR charts for the North and Coast areas, respectively. The North area demonstrates a net absorption of reactive power for the entire duration of the simulation, with nearly all of the online reactive reserve absorption capacity being used during the twelfth hour of simulation. The Coast area has great flexibility in reactive power dispatch for all hours of the simulation.

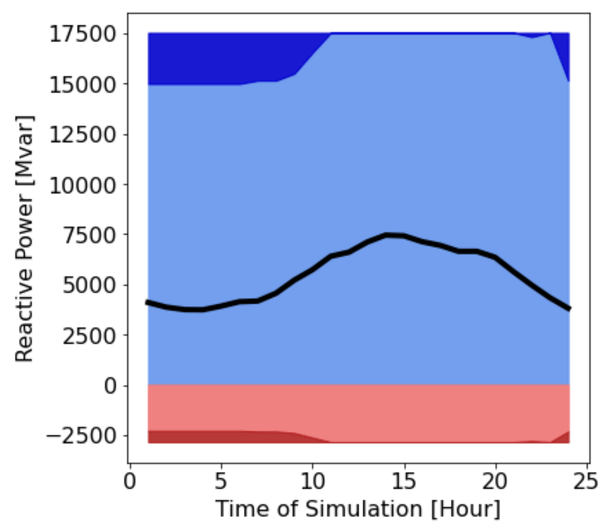
Figures 4 and 5 provide additional insights to the reactive power dispatch and availability for 3:00 AM and 2:00 PM in the system simulation, respectively. These demonstrate the flexibility of reactive power resources for regions of the system at a snapshot in time during the simulation. Figure 4 demonstrates that, at 3:00 AM in the simulation, the East area in the case has the smallest proportion of reactive power reserves online. The other regions at this time in the simulation demonstrate a greater range of flexibility even though there are some reactive power resources offline in each area of the system. The VRR GDVs in Figure 5 show that a majority of reactive power devices are committed within the grid at this point in time which leaves the simulation with highly flexible reactive power support deployment. Between the two figures, one can see that the commitment of generators and the status of reactive power devices has changed, as has the dispatch of these devices, within each area of the system. This



(a) System-wide VRR chart.



(b) North area VRR chart.



(c) Coast area VRR chart.

Fig. 3: VRR charts for various regions of the system over the course of the simulation.

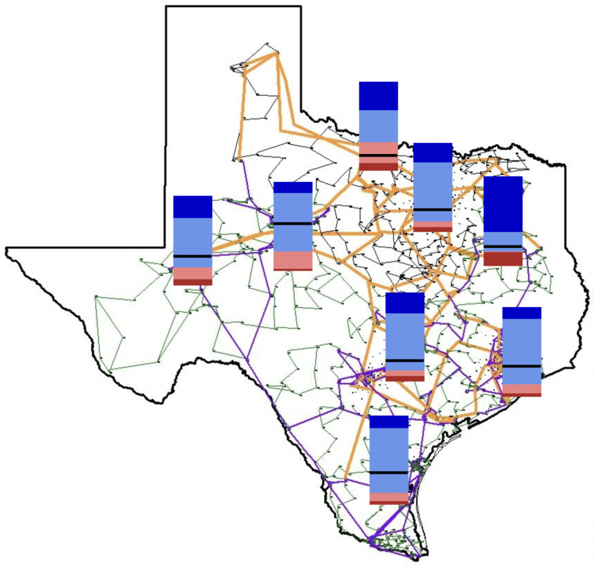


Fig. 4: VRR GDVs at the simulation hour of 3:00 AM.

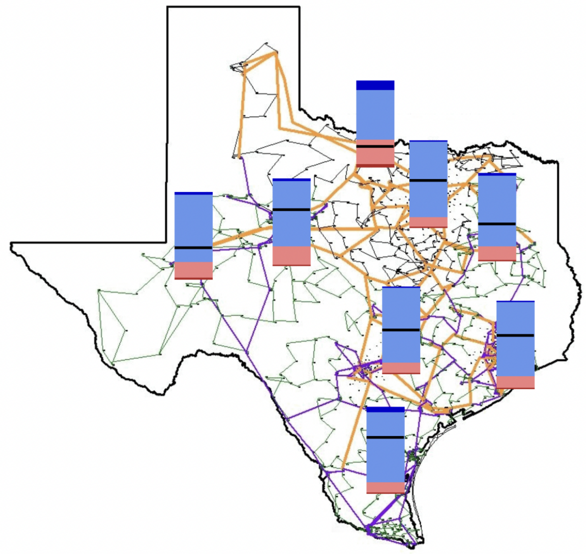


Fig. 5: VRR GDVs at the simulation hour of 2:00 PM.

visualization strategy enables the user to identify the regions of possible adjustments to reactive power levels within the system, which may be particularly useful when working with voltage issues in a more highly constrained system.

Each of these visualization strategies is well-suited for different applications. VRRs as a situational awareness tool provide insight into unit commitment and grid operation within a case. These may also be leveraged for planning future cases, designing power system scenarios, evaluating an aspect of flexibility or resilience, or as a method of validation for synthetic power grid scenarios. Both forms of the VRR offer a view of reactive power reserves and the flexibility of reactive power within a region of the case. The VRR chart could readily benefit post-scenario study of the reactive reserves within a case. The VRR GDV could be used to provide operators of capability of reactive power within a region that could be used to mitigate voltage issues for a given time point. As with any tool, each has applications for which it is better suited and the selection of the situational awareness strategy should be made with the application and user in mind. The unique perspective offered by both forms of the VRR relative to other visualization strategies is a demonstration the flexibility of reactive power dispatch within the case and the incorporation of the reserves from all reactive power devices in a region (including generators, shunts, and SVCs).

IV. Conclusions

This paper introduces VAR Ready Reserves (VRRs) in chart form and GDV form to provide users with situational awareness of the availability and dispatch of reactive power devices within a case. In industry, reactive power management strategies are defined according to power factor and voltage ranges to control reactive power in a reliable manner. Those requirements are maintained by controlling generator set points and reactive power devices such as shunts and SVCs. Industry and academia alike have relied on a variety of visualization strategies to help maintain situational awareness of reactive power levels within cases. Each of the identified visualization techniques has benefits and limitations. Authors introduce a new visualization strategy, VRRs, for reactive power situational awareness to address some of the observed limitations of existing visualizations. VRRs present an aggregate visualization of the availability of reactive power resources (generators, shunts, SVCs) as well as present dispatch levels for a region of the case. These enable users to have an indication of the flexibility of reactive power resources for a region of the system. The VRRs may be leveraged in chart form with VRR charts, or in an integrated system view, with VRR GDVs. The use of VRR GDVs enables easy combination with other visualization tools such as voltage contours. A case study is presented using ACTIVSg2000 to demonstrate the VRRs in both chart form and GDV form. Future applications of this work include synthetic grid scenario realism validation, flexibility of regions within planning cases, or the evaluation of planning cases with increasing integration of renewable generation in the grid.

Acknowledgment

This work is partially supported through funding provided by the U.S. National Science Foundation (NSF) in Award 1916142, the U.S. Department of Energy (DOE) under award DE-OE0000895, the US ARPA-E Grant No. DE-AR0001366, and the Power Systems Engineering Research Center (PSERC).

References

[1] W. Qin, P. Wang, X. Han, and X. Du, "Reactive power aspects in reliability assessment of power systems," *IEEE Transactions on Power Systems*, vol. 26, no. 1, February 2011.

[2] PJM, "PJM manual 03," URL: https://www.pjm.com/~/media/documents/manuals/m03.ashx, 2021.

[3] PJM, "Reactive reserves and generator D-curves," URL: https://www.pjm.com/-/media/training/nerc-certifications/gen-exam-materials-feb-18-2019/training-material/02-generation/6-2-reactive-reserves-and-generatord-curve.ashx, 2018.
[4] ERCOT, "ERCOT nodal operating guides," URL: http://www.ercot.com/content/wcm/libraries/137048/October_1__2017_Nodal_Operating_Guide.pdf, 2017.
[5] ——, "Reactive power coordination workshop," URL: http://www.ercot.com/content/wcm/key_documents_lists/188717/Reactive_Power_Coordination_Workshop_090619.pdf, 2019.
[6] A. Ellis, R. Nelson, E. V. Engeln, R. Walling, J. MacDowell, L. Casey, E. Seymour, W. Peter, C. Barker, B. Kirby, and J. Williams, "Analysis and visualization method for understanding the voltage effect of distributed energy resources on the electric power system," *IEEE Power and Energy Society General Meeting*, July 2012.
[7] T. DeVita, "PJM reactive supply compensation overview," URL: https://www.pjm.com/-/media/committees-groups/committees/mic/2021/20210210/20210210-item-14-reactive-power-in-pjm.ashx#:~, February 2021.
[8] F. Alvarado, B. Borissov, and L. D. Kirsch, "Reactive power as an identifiable ancillary service," Laurits R. Christensen Associates, Inc., Tech. Rep., March 2003.
[9] ERCOT, "Nprr 849: Clarification of the range of voltage set points at a generation resource's POI," *Nodal Protocal Revision*, 2017.
[10] North American Electric Reliability Corporation, "Standard TPL-007-2 – transmission system planned performance for geomagnetic disturbance events," https://www.nerc.com/files/TPL-007-2.pdf, 2021.
[11] Y. Makarov, J. Ma, P. Etingov, and K. Subbarao, "Online analysis of wind and solar part ii: Transmission tool," Pacific Northwest National Laboratory (PNNL), Tech. Rep., 2012.
[12] F. Capitanescu, "Assessing reactive power reserves with respect to operating constraints and voltage stability," *IEEE Transactions on Power Systems*, vol. 26, no. 4, pp. 2224–2234, 2011.
[13] B. Avramovic and L. Fink, "Real-time reactive security monitoring," in *[Proceedings] Conference Papers 1991 Power Industry Computer Application Conference*, 1991, pp. 373–378.
[14] T. Overbye and J. Weber, "Visualization of power system data," in *Proceedings of the 33rd Annual Hawaii International Conference on System Sciences*, 2000, pp. 7 pp.–.
[15] T. Overbye, D. Wiegmann, and R. Thomas, "Visualization of power systems," Power Systems Engineering Research Center (PSERC), Tech. Rep., 2002.
[16] 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.
[17] T. J. Overbye, J. L. Wert, K. S. Shetye, F. Safdarian, and A. B. Birchfield, "The use of geographic data views to help with wide-area electric grid situational awareness," in *2021 IEEE Texas Power and Energy Conference (TPEC)*, 2021, pp. 1–6.
[18] J. Weber and T. Overbye, "Voltage contours for power system visualization," *IEEE Transactions on Power Systems*, vol. 15, no. 1, pp. 404–409, 2000.
[19] C. A. Martinez, J. Dyer, and M. Skowronski, "Real-time voltage monitoring and var management system," CERTS, Tech. Rep., 10/2003 2003.
[20] A. Auld, J. Brouwer, and G. Samuelsen, "Analysis and visualization method for understanding the voltage effect of distributed energy resources on the electric power system," *Electric Power Systems Research*, vol. 82, p. 44–53, 01 2012.
[21] [Online]. Available: https://electricgrids.engr.tamu.edu/
[22] "Census 2019, zip code tabulation areas gazetteer file." 2019. [Online]. Available: https://www.census.gov/geo/maps-data/data/gazetteer2019.html
[23] "Form eia-860," 2019. [Online]. Available: http://www.eia.gov/electricity/data/eia860/index.html.
[24] "A methodology for the creation of geographically realistic synthetic power flow models," in *2016 IEEE Power and Energy Conference at Illinois, PECI 2016*, ser. 2016 IEEE Power and Energy Conference at Illinois, PECI 2016. United States: Institute of Electrical and Electronics Engineers Inc., Apr. 2016.
[25] V. Krishnan, B. Bugbee, T. Elgindy, C. Mateo, P. Duenas, F. Postigo, J.-S. Lacroix, T. G. S. Roman, and B. Palmintier, "Validation of synthetic u.s. electric power distribution system data sets," *IEEE Transactions on Smart Grid*, vol. 11, no. 5, pp. 4477–4489, 2020.
[26] A. B. Birchfield, E. Schweitzer, M. H. Athari, T. Xu, T. J. Overbye, A. Scaglione, and Z. Wang, "A metric-based validation process to assess the realism of synthetic power grids," *Energies*, vol. 10, no. 8, 2017. [Online]. Available: https://www.mdpi.com/1996-1073/10/8/1233
[27] 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, pp. 961–969, 2021.
[28] H. Li, A. L. Bornsheuer, T. Xu, A. B. Birchfield, and T. J. Overbye, "Load modeling in synthetic electric grids," *2018 IEEE Texas Power and Energy Conference (TPEC)*, pp. 1–6, 2018.
[29] H. Li, J. H. Yeo, J. L. Wert, and T. J. Overbye, "Steady-state scenario development for synthetic transmission systems," in *2020 IEEE Texas Power and Energy Conference (TPEC)*, 2020, pp. 1–6.