SAND2019-6545C

Visualization Methods for Quasi-Static Time-Series (QSTS) Simulations with High PV Penetration

Joseph A. Azzolini, Matthew J. Reno, Matthew Lave

Sandia National Laboratories, Albuquerque, NM, 87185, USA

***Abstract* — Distribution system analysis requires yearlong quasi-static time-series (QSTS) simulations o accurately capture the variability introduced by high penetrations of distributed energy resources (DER) such as residential and commercial-scale photovoltaic (PV) installations. Numerous methods are available that significantly reduce the computational time needed for QSTS simulations while maintaining accuracy. However, analyzing the results remains a challenge: a typical QSTS simulation generates millions of data points that contain critical information about the circuit and its components. This paper provides examples of visualization methods to facilitate the analysis of QSTS results and to highlight various characteristics of circuits with high variability.**

I. Introduction

Modern distribution circuits require analysis for understanding the impact of new smart grid technologies and increasingly high penetrations of distributed and renewable resources. Quasi-static time-series (QSTS) simulations solve a series of sequential steady-state power-flow solutions, in which the converged state of each iteration is used as the beginning state of the next. QSTS is used to study equipment control operation, voltage regulation, and reactive power management for distributed energy resources (DER) like solar photovoltaic (PV) systems [1]. Rather than providing a snapshot analysis of worst-case scenarios, QSTS simulations model the discrete, temporally dependent controls that are present in many modern distribution circuits, allowing the time-dependent states of the system to be captured over any given time horizon. Among other practical uses, QSTS simulations can record the time duration of extreme conditions like under-voltage or over-voltage, calculate the effects of daily changes in load and PV output, and enable the study of interactions between control equipment like advanced PV inverters and step voltage regulators or advanced distribution management systems (ADMS) [2].

Conventional QSTS simulations can be prohibitively burdensome and computationally intensive. To accurately capture all distribution system metrics, a yearlong QSTS simulation with a 5-second time step resolution or less is recommended [2]. Using this recommended time step for a yearlong QSTS simulation requires 6,307,200 sequential power flow solutions. Many methods have since been proposed to perform rapid QSTS simulations. The computational time for each power flow can be improved by circuit reduction [3] or by Diakoptics [4]. The total number of required power flows can be reduced using various algorithms [5]–[8]. The QSTS time horizon can also be divided up and solved on multiple CPUs in parallel [9], [10]. Each of these methods preserves the benefits of QSTS simulations while reducing the computational requirement, making QSTS analysis much more practical.

Once a QSTS simulation has finished, there remains the task of analyzing the results to understand the impacts of different DER or control strategies. After each power-flow solution, a new system state is reached with potentially tens of thousands of data points depending on the size of the circuit being solved, and *millions* of steady-state power-flows are solved during a single yearlong QSTS simulation. Figure 1 shows an overview of how a QSTS simulation is run.

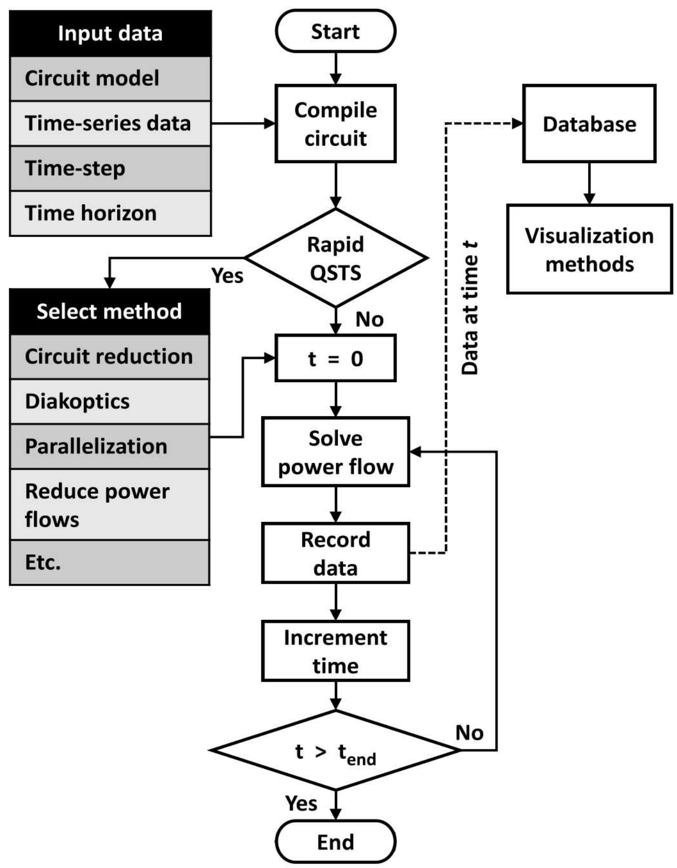

Figure 1. Flowchart for running QSTS simulations and analyzing data with visualization methods.

The available rapid QSTS methods can be applied to quickly simulate large and complex distribution circuits with thousands of buses and multiple controllable elements. For every time step of the simulation, copious amounts of data can be probed from the simulation. This data includes voltages at every bus and

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

node, loading information from power delivery elements (e.g. lines and transformers), active and reactive power injections from distributed generators or energy storage devices, controller states and time delays (e.g. regulator tap position or time until a switching capacitor changes state), and active and reactive power losses. Therefore, the ability to organize and visualize the results of QSTS simulations is critical for analytical purposes.

While there are various visual techniques used in many aspects of power systems, overall there is a lack of techniques for time-series simulations of distribution circuits. This paper presents various visualization methods (implemented in MATLAB) for the efficient analysis of QSTS results, particularly for circuits with high penetrations of PV.

The paper is organized as follows: the next two subsections provide a background of visualization methods for power systems and highlight the specific contributions of the paper, Section II describes the test feeder used for QSTS simulations, Sections III through VII discuss various visualization methods (circuit plots, voltage profiles along a feeder, time-series data, statistical distributions, and controller states, respectively), and Section VIII concludes the paper.

A. Background

Data visualization is a critical aspect of power system analysis in both real-time applications and offline studies. The use of color contouring on one-line diagrams to visualize bus voltage magnitudes has been shown to improve acknowledgment speed of violations compared to a numeric display [11]. Color contouring has also been used to visualize other bus information, like locational marginal prices (LMPs) and line flow information [12]. Three-dimensional visualization methods have been proposed to simplify the results of contingency analyses [13]. For distribution system planning, visualization concepts can be combined with forecasting and financial data, as in [14], to help make informed decisions about circuit upgrades. Visualization is a key component of monitoring and control systems, such as in state estimation platforms [15]. One visualization approach for time series data used a kernel estimation of electrical variables to detect conditions of interest [16].

B. Contributions

While the motivation for QSTS simulations is clear, there is a lack of literature on analyzing or visualizing the results. The objective of this paper is to present a number of visualization methods that leverage the detailed time-series data unique to QSTS simulations in a way that facilitates the analysis of modern distribution circuits. In later sections, various examples will be given that characterize the extreme conditions on the circuit and the various effects of DER. However, it should be noted that these methods and examples are not meant to be exhaustive, but rather were selected to highlight the advantages of QSTS simulations over snapshot methods. Additionally, the plotting functions used to generate the figures in this paper, as well as the test circuit used for the QSTS simulation, are open source and publicly available to be downloaded along with other resources like additional QSTS test circuits and functions for rapid QSTS simulations [17].

II. Large Utility Test Feeder

The results in this paper are from an example QSTS simulation performed on a large test system, based on an actual distribution feeder [18] with 2,969 buses (5,469 nodes), 4 step voltage regulators, and 5 switching capacitors. A total of 144 PV systems (~20% of peak load) are installed on the feeder, including distributed PV systems modeled on the low-voltage networks adjacent to the loads and two centralized utility-scale installations (PV_C1 and PV_C2) with their own interconnection transformers. Each PV system is grouped into one of four categories based on its geographic location and assigned a unique 1-second power injection profile based on solar irradiance data. See [5] for more details on the circuit. The yearlong QSTS simulation was performed in OpenDSS, via the GridPV toolbox in MATLAB [19].

In another QSTS simulation of this same circuit, the two centralized PV systems were modeled with Volt-Var functionality according to IEEE 1547 [1]. The QSTS visualizations methods presented in this paper can be used to highlight the effect of the added advanced inverters.

III. Circuit Plots

Conventional circuit plots based on GPS coordinates of devices show the geometry and orientation of a distribution circuit. These plots are useful for understanding where certain components are located with respect to one another and are typically used to show voltages or power flows at an instant in time, commonly referred to as snapshot analyses. While these methods are useful in certain cases, they cannot provide any insights into the time-dependent nature of the system.

With QSTS, circuit plots can be infused with additional data from simulation results, making them more powerful. Each circuit element in Figure 2 is assigned a unique symbol, making them easy see. For example, in Figure 2, clicking on the voltage regulator symbol shows the total number of tap position changes that occurred throughout the year or clicking on a PV system shows the total amount of energy produced. Other information that can be accessed includes number of capacitor state changes, feeder minimum and maximum active and reactive powers, line loading, etc.

The lines in the circuit plot can also be colored according to QSTS results. In Figure 2, the lines are colored by maximum voltage. This figure reveals that the highest voltages were not recorded near the substation, but near the middle of the feeder, due to the high penetration of PV systems in that area. Line colors can also be assigned by other QSTS results like loading.

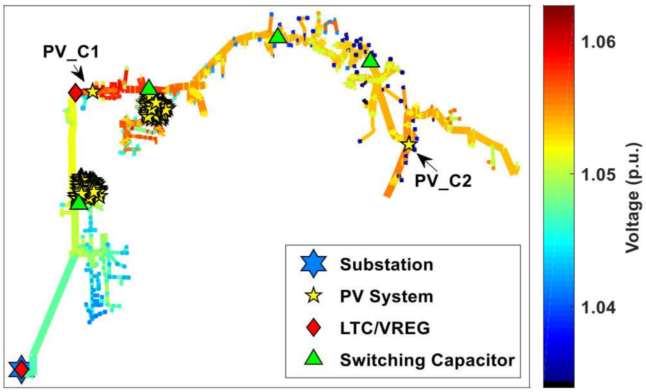

Figure 2. Circuit plot with coloring based on the maximum voltage each node reached throughout the year.

Figure 3. Circuit plotted in Google Earth with coloring based on maximum voltage each node reached throughout the year.

If the model contains real coordinates, the circuit can be plotted in Google Earth using color schemes based on QSTS results. The advantage of Google Earth is that the circuits can be plotted exactly where they are located, giving a better representation of the circuit. In many areas, the "street view" feature in Google Earth is available, making it possible to see actual photos of the circuit components, such as the pole-mounted transformers, voltage regulators, or capacitor banks. Figure 3 shows the same type of circuit plot as Figure 2, but in Google Earth.

IV. Voltage Profiles Along a Feeder

Maintaining voltage levels between acceptable thresholds is crucial for distribution circuits. Typically, the voltage along a feeder drops as the distance from the substation is increased. In modern distribution circuits, there can be multiple devices that contribute to voltage regulation on a single circuit. Voltage profile plots show the feeder voltages as a function of distance from the substation at specific points in time. Symbols representing DER or voltage regulating equipment can be plotted on top of the voltage profile to explain what may be contributing to sudden changes.

Many of the visualization methods presented in this paper make it easy to recognize which parts of the year the circuit experiences high variability or extreme conditions. With that information known, it is possible to take a closer look during those time periods, e.g. when the heaviest overloading occurred or when the feeder experienced its maximum and minimum voltages during the year. Since all the system states throughout the year are known, it is easy to "rewind" to any specific time, *t*. First, the regulator tap positions and switching capacitor states are set to where they were at time *t*, and held constant in those positions. Then, the loads and generators are assigned their injections according to their profiles at time *t*. Lastly, the power-flow is solved.

The procedure described above was implemented to generate the voltage profiles in Figure 4 for two distinct time points. The top subplot represents the time point when the maximum voltage occurred anywhere on the feeder throughout the simulation, i.e. the yearly global maximum node voltage, and the bottom subplot represents the time point when the minimum voltage occurred anywhere on the feeder throughout the simulation, i.e. the yearly global minimum node voltage. The voltage magnitudes at each node are plotted as a function of the distance from the substation. The vertical dashed lines represent the service transformer and low-voltage secondary network that often has a large per unit voltage drop over a short distance. In Figure 4, the profile at maximum voltage shows that the voltage increased steadily from the substation and reached a maximum near a cluster of PV systems' points of common coupling (PCC).

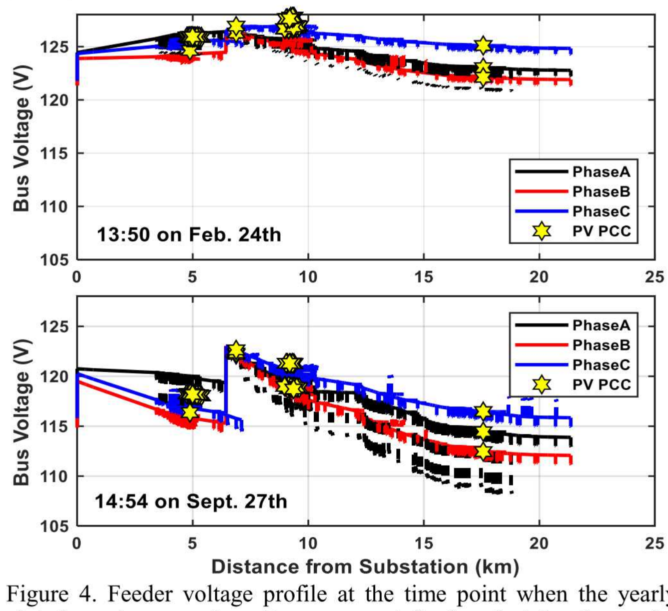

Figure 4. Feeder voltage profile at the time point when the yearly global maximum node voltage occurred (top) and at the time point when the yearly global minimum node voltage occurred (bottom).

V. Time-Series Data

In QSTS simulations, the converged state of a power-flow solution serves as the initial state of the next sequential power-flow. After each solution, data on the state of any circuit element can be collected. Plotting this data against the time point it was taken from gives a very detailed, time-series representation of the system states. Figure 5 shows an example of this, where the tap position of the substation transformer's load tap changer (LTC) and tap position of three voltage regulators along the feeder are plotted against time. These types of plots are helpful in determining minimum and maximum values and understanding the relationships of various circuit elements, e.g. interactions between two voltage regulators or between a voltage regulator and a smart inverter with reactive power control. However, underlying trends may still be difficult to identify.

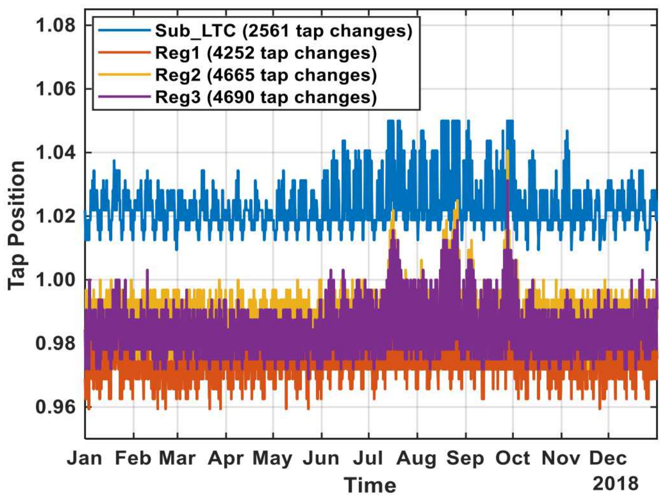

Figure 5. Regulator tap position time-series.

A. Aggregated Time-Series Data

Data aggregation is one method for extracting useful information from time-series datasets and may help to identify the underlying trends in the data. The length of the aggregation window can be adjusted to any size based on the variability of the element being analyzed or the desired resolution. For QSTS simulations with a constant time-step, data aggregation is straightforward. First, the time-series data is reshaped into a matrix, then a function is applied along one dimension, e.g. taking the sum or finding the average value. For QSTS simulations with a variable time-step, the data must either be interpolated down to a constant time-step and reshaped or aggregated by looping through each window individually, which can be computationally intensive when using small window sizes.

By aggregating the regulator tap position time-series data (Figure 5) into monthly totals (Figure 6), it is easier to see how each regulator operates over time with respect to the others. For example, in January, "Reg1" had the most tap changes, but steadily declined until June when it had the least.

Another example of data aggregation can be seen in Figure 7. This figure shows the monthly energy production of the two centralized PV systems. In terms of analyzing distributed generation, this type of plot could give insight into the various PV systems on the circuit, such as their sizes or relative tilt and azimuth angles.

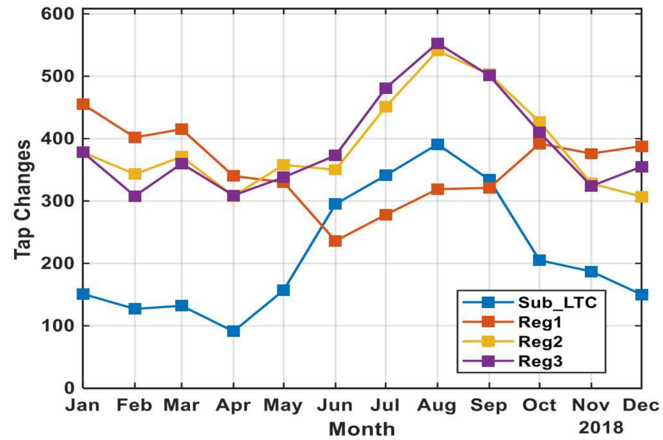

Figure 6. Monthly totals of tap position changes.

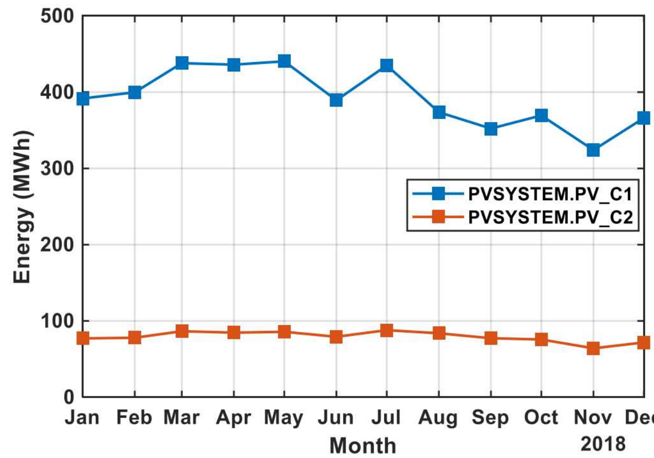

Figure 7. Monthly energy production of the two centralized PV systems.

B. Temporal Raster

Time-series data can also be characterized in a temporal raster plot where the data is organized into a matrix and the color of each pixel represents its value for that point (or aggregated points) in time. By adding this extra dimension, the diurnal trends in the data manifest themselves through color. These plots could also be represented on three-dimensions axes, where the variable's magnitude is plotted on the third axis. Figure 8 shows an example temporal raster plot, using a one-hour aggregation window, of the energy production of the centralized PV systems with Volt/Var function turned on. While PV_C1 is roughly five times larger, the advanced inverter on PV_C2 consumed a greater amount of reactive power and did so more often. The specific impact of the Volt/Var function can be explored by looking at the feeder's time-series data and aggregated data. The addition of advanced inverters on the two largest PV systems helped to reduce the feeder's yearly maximum voltage by 0.0031 per unit, increase the feeder's yearly minimum voltage by 0.0048 per unit, and decrease the number of operations of every voltage regulator and switching capacitor in the circuit.

Another benefit of QSTS analysis is the ability to quantify losses in a distribution circuit. Figure 9 shows a raster plot, using a 10-minute aggregation window, of the line losses in the circuit. Thus, each pixel represents the maximum line losses (in kW) that occurred over the aggregation window. This figure shows that the line losses were mostly less than 100 kW throughout the year, with the exception of a few days. Since a 10-minute aggregation window was used in Figure 9, the pixels appear much smaller and capture more detail than the 60-minute aggregation window used in Figure 8.

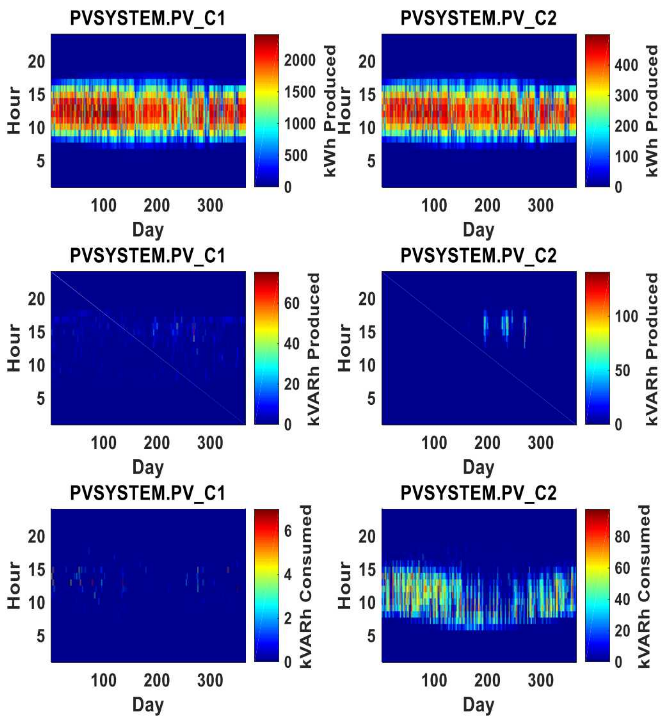

Figure 8. Temporal raster plot with one-hour aggregation of energy production real power produced (top), reactive power produced (middle), and reactive power consumed (bottom) of the two centralized PV systems.

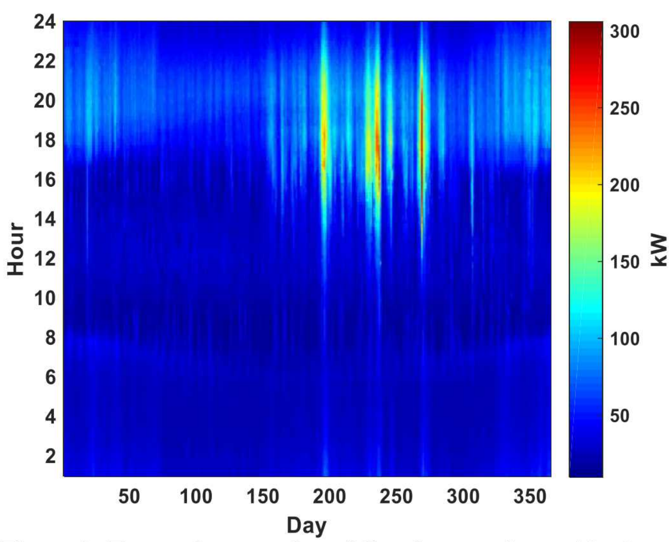

Figure 9. Temporal raster plot of line losses using a 10-minute aggregation window.

VI. Statistical Distributions

Statistical analysis is great tool for dissecting large amounts of data. The following subsections give several examples of how this can be accomplished for QSTS data.

A. *Box Plots*

In QSTS simulations, time-varying circuit components like load and PV generation each have profiles associated with them, consisting of a series of multiplier values. These time-series profiles, or loadshapes, are typically created from actual measured data and dictate how the components change through time.

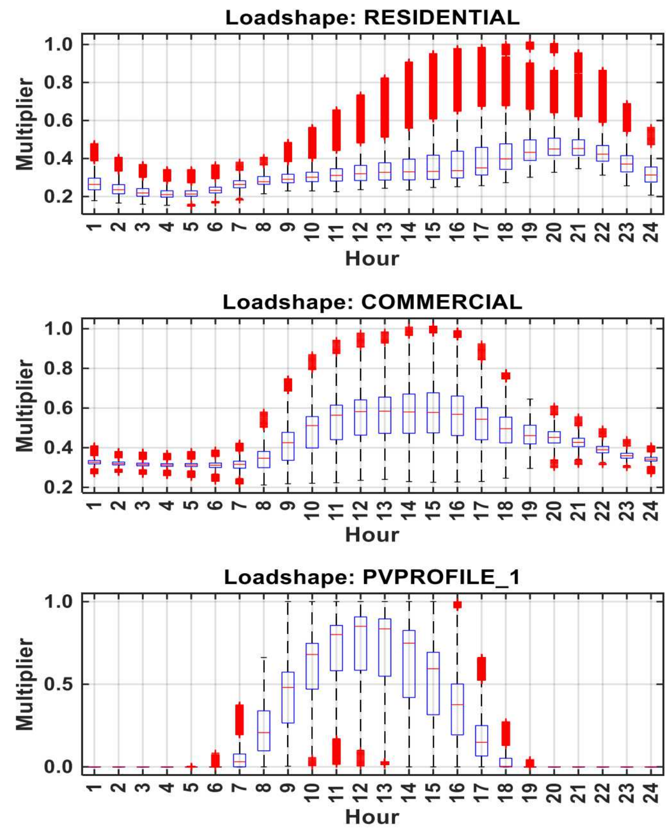

Figure 10. Box plot of 1-second resolution time-series profiles (1,314,000 data points per box).

Figure 10 shows the distribution of multipliers at each hour of the day for three different loadshapes: one for residential loads, commercial loads, and one of the PV profiles. The bottom and top edges of the boxes represent the 25th and 75th percentiles, respectively. The red line inside the box is the median value, while the whiskers extend to the most extreme data points not considered outliers (red crosses). All loadshapes used in these QSTS simulations represent yearly time-series data at a 1-second resolution for a total of 31,536,000 data points per loadshape. This data must first be reshaped before the box plots can be generated. Each hour of the day contains 3600 data points and the time horizon of these loadshapes was 365 days, so each individual box represents 1,314,000 data points. The time-series data can be reshaped in several different ways, depending on what information is important to the user. This would result in days or months being on the x-axis instead of hours. Each loadshape could also be represented in a single box, such that all loadshapes would appear side by side in a single figure.

B. Shaded Percentile Plots

Shaded percentile plots can show how statistical distributions change over time. In these plots, the denser areas of the distribution appear as darker colors and the red line represents the median value. In Figure 11, each vertical slice represents the distribution of the daily minimum voltage each node recorded. These daily minimum values are then sorted to find the values of the various percentiles. For example, in Figure 11, the 75th percentile voltage on the first day of the year was 1.0126 per unit. So on January 1st, 75% of the nodes in the circuit had a minimum voltage less than 1.0126 per unit. This figure also shows that the distribution of percentiles stays relatively constant throughout the year, except for a few periods of time in late summer. The benefit of this type of plot is that it gives insight into the severity of certain extreme circuit conditions. For instance, the lowest node voltage throughout the year, which occurred on Sept. 27th, was 0.9013 per unit—well below the predetermined threshold for this simulation of 0.95 per unit. However, on that same day, 90% of the nodes on the feeder remained above 0.9408 per unit.

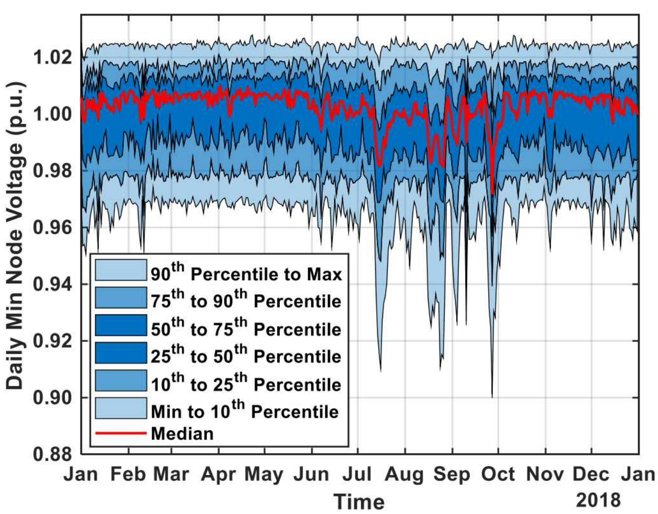

Figure 11. Distribution of daily minimum node voltages (5,469 nodes).

Shaded percentile plots are particularly useful when analyzing a large number of elements at once, such as the 5,469 nodes in Figure 11. Circuits with thousands of nodes would also have a large number of power delivery elements (lines and transformers) to connect those nodes. Thus, we can use shaded percentile plots to analyze the loading characteristics of power delivery elements as well. Figure 12 shows the daily maximum loading of all 2,970 power delivery elements in the test feeder. In this case, overloading is not an issue. In fact, 90% of the power deliver elements experienced a maximum loading of less than 40%, which indicates (from a capacity standpoint) there is room for load and PV growth.

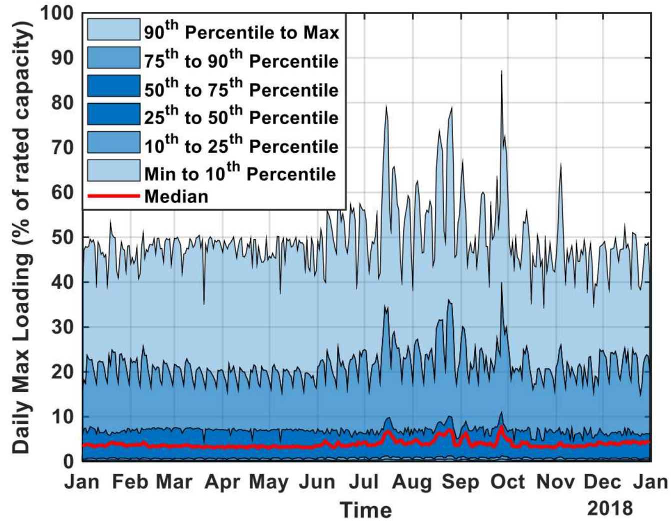

Figure 12. Distribution of daily maximum loading of every transformer and line in the test feeder (2,970 elements).

C. Cumulative Distribution Functions

Cumulative distribution functions, or duration curves, show the proportion of time for which a variable exceeds a certain level. For example, Figure 13 shows a duration curve for the real and reactive power of the feeder. For over 80% of the time, the feeder had more than 5 MW of power flowing through it, and it only had more than 15 MW of feeder power consumption for 0.1% of time (less than 9 hours).

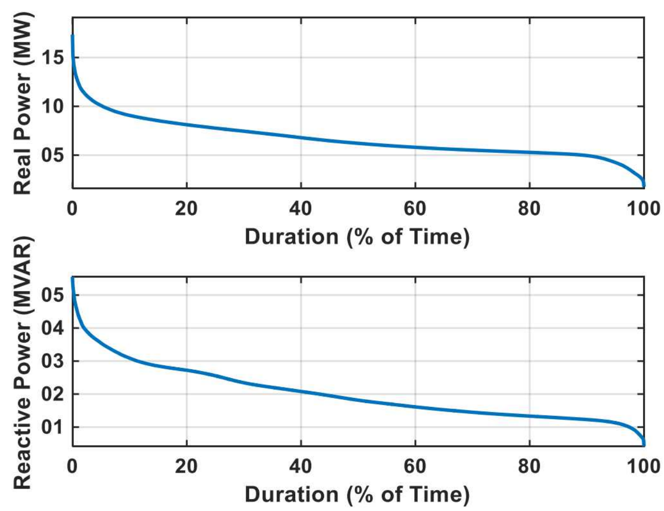

Figure 13. Duration curves of feeder real and reactive power into the feeder.

Duration curves of maximum and minimum voltages can show how much time the feeder spent outside its predetermined operating limits, for example ANSI C84.1. In Figure 14, the x-axis of the duration curve is shown in terms of hours instead of as a percentage of total time. From this figure, it is clear that the maximum and minimum feeder voltages had very different characteristics. The feeder's minimum voltage reached violations of nearly 0.050 per unit, while the feeder's maximum voltage reached violations of only 0.015 per unit. However, the minimum voltage spent only 130 hours outside its threshold, while the maximum voltage spent 195 hours outside its threshold.

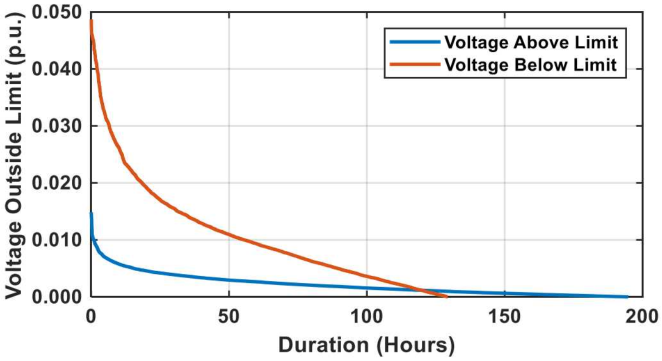

Figure 14. Duration curve of feeder voltage violations anywhere on the feeder.

VII. Controller States

One major benefit of QSTS simulations is the ability to model discrete controls and capture the time-dependent states of controllable elements like switching capacitors and voltage regulators. These expensive devices tend to operate more frequently in the presence of increased variability, such as in circuits with a high penetration of PV. Therefore, understanding their activity is a critical component of distribution system analysis. In Figure 15, the percent of time each capacitor spent switched on is represented as a stacked bar graph. This figure shows that "Cap2" was switched on for more than 95% of the time. Analysis of the data also shows that this capacitor switched states 146 times throughout the year. These results suggest that investing in a static capacitor bank near that location could be beneficial to reduce the number of operations of "Cap2."

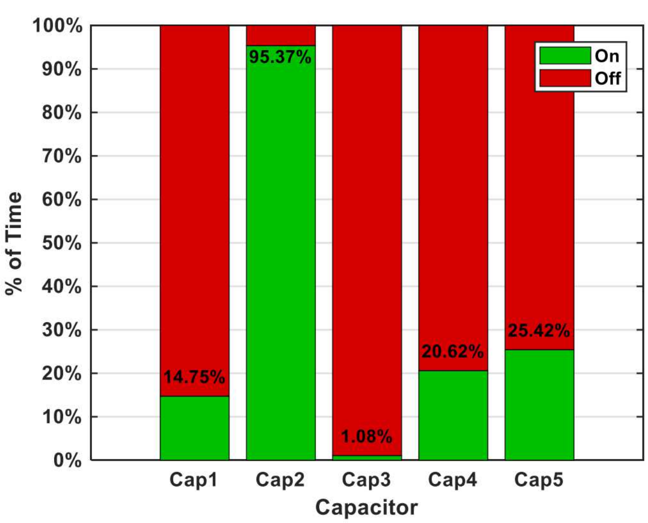

Figure 15. Stacked bar graph of capacitor states

Voltage regulators adjust their tap positions over time to help maintain line voltages within predetermined limits. Understanding how they operate throughout the year can help distribution system engineers find ways to minimize maintenance costs or prolong the lifetimes of the devices. In Figure 16, the x-axis of the subplots shows the available tap positions of each regulator, and the y-axis shows the total amount of time spent in those positions. One interesting thing to note is that only the substation transformer's on-load tap changer (Sub_LTC) spent the majority of its time boosting the voltage.

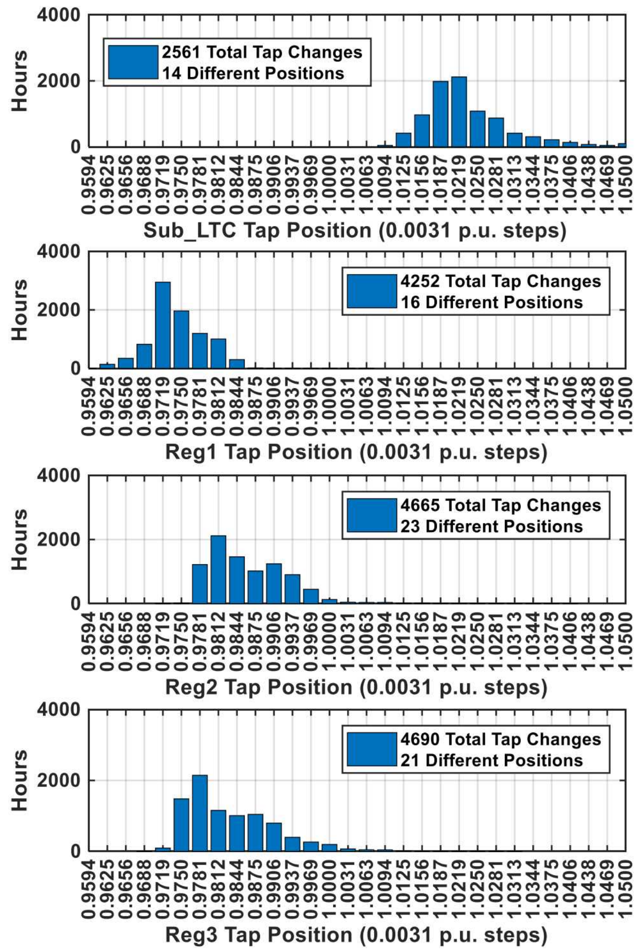

Figure 16. Total time spent at each tap position.

VIII. Conclusion

QSTS simulations are a powerful study tool for the analysis of modern distribution circuits, especially those with high penetrations of DER. Rapid QSTS algorithms have made it practical to simulate large distribution feeders with thousands of buses and multiple controllable elements, but there remains the task of analyzing the tens of millions of data points after the simulation has finished.

One advantage of QSTS simulations is the amount of detailed data available for analyzing extreme circuit conditions. With QSTS circuit plots, the yearly maximum bus voltages were shown as colored lines, making it easy to identify problematic areas. Furthermore, since the states of all controllable devices were recorded, a voltage profile plot at the circuit's yearly maximum could then be generated after "rewinding" to that point in time.

Data aggregation and statistical analysis provide another set of tools for analyzing QSTS results. Monthly totals of tap positions changes were plotted for each voltage regulator, which revealed how their operations changed over the seasons. Three of the different loadshapes used in the test feeder were represented in box plots that showed their variability at each hour of the day over the year.

These visualization methods also help to highlight the benefits of QSTS simulations by showcasing the impacts that various smart grid technologies and increased levels of DER have on the distribution system. In one QSTS simulation, the two large centralized PV systems were equipped with Volt-Var functionality. The temporal raster plot generated from the results of this simulation revealed that that smaller of the two systems consumed much more reactive power than the other. After further investigation of the time-series and aggregated data, it was found that adding the two advanced inverters resulted in a reduction of operations of every single controllable device on the feeder.

The visualization methods proposed in this paper can be used to facilitate the process of analyzing tens of millions of data points and allow for the extraction of underlying trends in the data to help distribution system engineers and planners make informed decisions about circuit upgrades and maintenance.

REFERENCES

[1] IEEE P1547.7/D11, "IEEE Guide for Conducting Distribution Impact Studies for Distributed Resource Interconnection," 2013.

[2] M. J. Reno, J. Deboever, and B. Mather, "Motivation and requirements for quasi-static time series (QSTS) for distribution system analysis," in *IEEE Power and Energy Society General Meeting*, 2017, pp. 1–5.

[3] Z. K. Pecenak, V. R. Disfani, M. J. Reno, and J. Kleissl, "Multiphase Distribution Feeder Reduction," *IEEE Trans. Power Syst.*, vol. 33, no. 2, pp. 1320–1328, 2018.

[4] D. Montenegro, G. A. Ramos, and S. Bacha, "A-Diakoptics for the Multicore Sequential-Time Simulation of Microgrids Within Large Distribution Systems," *IEEE Trans. Smart Grid*, vol. 8, no. 3, pp. 1211–1219, 2017.

[5] M. U. Qureshi, S. Grijalva, M. J. Reno, J. Deboever, X. Zhang, and R. Broderick, "A Fast Scalable Quasi-Static Time Series Analysis Method for PV Impact Studies using Linear Sensitivity Model," *IEEE Trans. Sustain. Energy*, vol. 10, no. 1, pp. 301–310, 2018.

[6] J. Deboever, S. Grijalva, M. J. Reno, and R. J. Broderick, "Fast Quasi-Static Time-Series (QSTS) for yearlong PV impact studies using vector quantization," *Sol. Energy*, vol. 159, no. June 2017, pp. 538–547, 2018.

[7] M. J. Reno and R. J. Broderick, "Predetermined Time-Step Solver for Rapid Quasi-Static Time Series (QSTS) of Distribution Systems," in *2017 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, 2017, pp. 1–5.

[8] M. J. Reno, J. A. Azzolini, and B. Mather, "Variable Time-Step Implementation for Rapid Quasi-Static Time-Series (QSTS) Simulations of Distributed PV," in *2018 IEEE 7th World Conference on Photovoltaic Energy Conversion (WCPEC)*, 2018, pp. 1626–1631.

[9] J. A. Azzolini, M. J. Reno, and D. Montenegro, "Implementation of Temporal Parallelization for Rapid Quasi-Static Time-Series (QSTS) Simulations," in *IEEE Photovoltaic Specialists Conference (PVSC)*, 2019.

[10] R. Hunsberger and B. Mather, "Temporal Decomposition of a Distribution System Quasi-Static Time-Series Simulation," in *2017 IEEE Power & Energy Society General Meeting*, 2017, pp. 5–9.

[11] T. J. Overbye, S. Member, D. A. Wiegmann, and A. M. Rich, "Human Factors Aspects of Power System Voltage Contour Visualizations," *IEEE Trans. Power Syst.*, vol. 18, no. 1, pp. 76–82, 2003.

[12] T. J. Overbye, J. D. Weber, and M. Laufenberg, "Visualization of Flows and Transfer Capability in Electric Networks," in *Proc. 13th Power Syst. Comput. Conf*, 1999, pp. 420–426.

[13] Y. Sun and T. J. Overbye, "Visualizations for Power System Contingency Analysis Data," *IEEE Trans. Power Syst.*, vol. 19, no. 4, pp. 1859–1866, 2004.

[14] I. Kuzle, T. Capuder, and H. P. Zi, "Visualization of distribution system planning for engineers and decision-makers," *Turk J Elec Eng Comp Sci*, vol. 25, pp. 2871–2884, 2017.

[15] B. Lundstrom *et al.*, "A High-Speed , Real-Time Visualization and State Estimation Platform for Monitoring and Control of Electric Distribution Systems : Implementation and Field Results," in *2015 IEEE Power & Energy Society General Meeting*, 2015, pp. 1–5.

[16] M. Hernandez, G. Ramos, H. V. Padullaparti, and S. Santoso, "Visualization of Time-Sequential Simulation for Large Power Distribution Systems," in *2017 IEEE Manchester PowerTech*, 2017, pp. 1–6.

[17] "Quasi-Static Time-Series (QSTS)," *PVPerformance Modeling Collaborative*, 2019. [Online]. Available: https://pvpmc.sandia.gov/pv-research/quasi-static-time-series-qsts/.

[18] M. J. Reno, K. Coogan, J. Seuss, and R. J. Broderick, "Novel Methods to Determine Feeder Locational PV Hosting Capacity and PV Impact Signatures," *Sandia National Laboratories*, vol. SAND2017-4, 2016.

[19] M. J. Reno and K. Coogan, "Grid Integrated Distributed PV (GridPV)," *Sandia National Laboratories*, vol. SAND20 13, no. August, pp. 1–134, 2013.

This research was supported by the DOE SunShot Initiative, under agreement 30691. Sandia National Laboratories is a multimission laboratory managed and operated by National Technology and Engineering Solutions of Sandia, LLC., a wholly owned subsidiary of Honeywell International, Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.