Visualization of the Oscillatory Dynamics of an Island Power System

Preprint

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National Renewable Energy Laboratory

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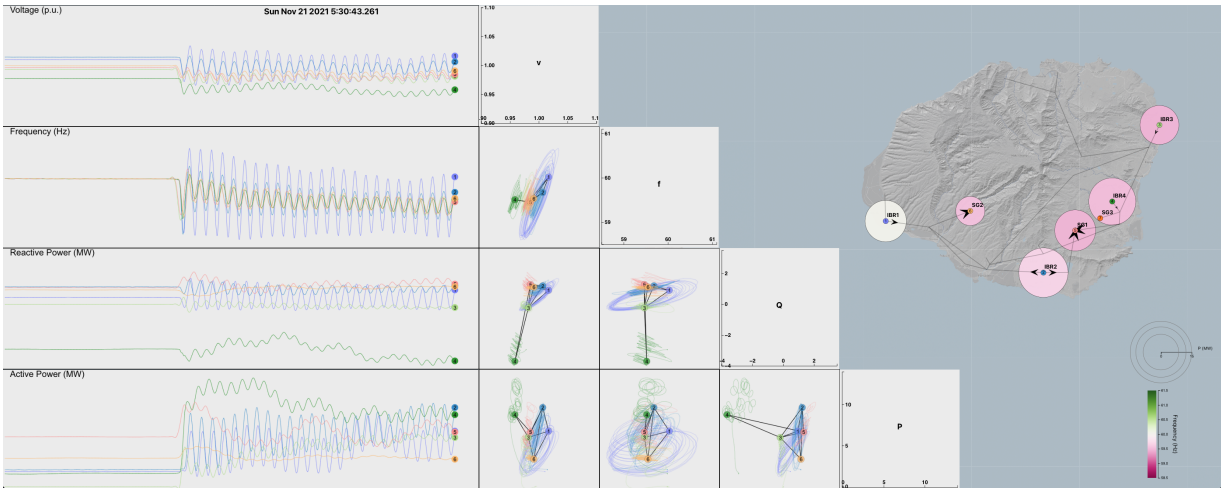

Figure 1: The figure visualizes the Kaua'i transmission system during an oscillation event after a generator trip. Left: time-series plots showcase the behavior of per unit voltage (v), frequency (f), reactive power (Q), and real power (P) of the generators over time. Middle: oscillatory-trajectory curves illustrate the relationships among the time-series waveforms. Each generator plots in a unique color, and the black lines represent the network connections between generators. Right: a geographical plot emphasizes the spatial distribution of generators within the system. The generators are sized proportionally based on their real power output and colored by their frequencies. The comprehensive view of the Kaua'i transmission system during an oscillation event, combining time-series plots, oscillatory-trajectory curves, and a geographical representation, help understand and illustrate the forces driving the oscillation.

Abstract

In this work, we discuss the design of visualizations for understanding the complex oscillatory dynamics of an island power system with renewable generation sources after the loss of a large oil power plant. As more renewable generation sources are added to power systems, the oscillatory dynamics will change, which requires new visualization techniques to determine causes and strategies to avoid unwanted behaviors in the future. Our approach integrates geographic views, time-series plots, and novel oscillatory-trajectory curves, providing unique insights into the interdependent oscillatory behaviors of multiple state variables and generators over time. By enabling multi-node and multivariate comparisons over time, users can qualitatively determine drivers of oscillations and differences in generator dynamics, which is not possible with other commonly used visualization techniques.

Index Terms: Visualization—Power Systems—Oscillations—;

1 Introduction

Inverter-based generation technologies, such as wind or solar farms, introduce new dynamics into power systems that need to be understood to maintain system reliability. An example of one type of oscillatory instability arising from inverter-based resources occurred on November 21, 2021, when an oil power plant on the Hawaiian island of Kaua'i disconnected, resulting in large oscillations in the rest of the system. Researchers studied the event and learned that inverter-based resources were the cause of the oscillations [4]. In this work, we discuss our efforts to help researchers visualize, understand, and communicate this event using novel techniques to illustrate how the inverters drove the system oscillations. In particular, we present a technique to compare multiple time-series variables for multiple generators at a time, which better highlights the role of the inverters in the instabilities.

2 Background and Related Work

To maintain the reliability of a power system, the amount of power generated must match the amount of power consumed every instant. When nodes like generators become disconnected, this causes the rest of the power system to react, typically in an oscillatory fashion (e.g., periodic), as the system moves to a new operating state. This motion and the new state of the power system are not guaranteed to be stable. For example, without appropriate control mechanisms to damp these reactions, oscillations can grow and spread, further destabilizing the power system. When such events occur, it can be difficult to determine why or which system components are the cause of oscillations and destabilization, which is important for operators to know so that they can take appropriate actions to prevent the oscillations from spreading. Inverters, which have their own controllers, interface renewable generation sources to a power system and can further complicate this situation. Inverters differ from traditional generation sources like natural gas or coal power plants in several

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ways. For example, they have independent, heterogeneous controllers and tunable parameters, which change their damping effect on the system. These new controls present additional complexity when trying to maintain the stability of a power system.

Oscillatory behavior is not a new phenomenon in power systems, and there is past work on visualizing such events. One method utilizes heatmaps (sometimes called contour maps in the literature) to show how a single dynamic variable of the system changes through a system over time and space [13, 17]. However, recent work has shown that heatmaps can be misleading when used networked power systems data, because it trims extrema and assumes the heatmapped variable has spatial continuity, which is often not the case for power systems [6]. Furthermore, heatmaps are limited to showing one variable at a time, which makes it difficult to understand the interplay between multiple state variables. In the case of inverters, understanding the relationship between multiple state variables can be crucial for diagnosing issues in control parameters. Therefore, a key goal of this work is to determine ways to facilitate comparisons among multiple state variables across many generators.

Visualization of time series of a networked dynamical system is an understudied area in the visualization community. Although there is significant work that considers how to visualize networks [5], understanding the time-varying dynamics occurring on networks is still a challenge. There is also work studying visualization systems for discrete event dynamics on networks, such as in cybersecurity contexts [11], or power flow across a power system [10], but continuous time multivariate dynamics on networks, such as the oscillation event studied here, is under explored [12].

To visualize the oscillatory dynamics of the Kaua'i transmission network, we developed a visualization with multiple coordinated views [14], including a novel adaption of Lissajous curves to represent multivariate network dynamics. Lissajous curves are generated by graphing sinusoidal data in orthogonal axes, named after French mathematician Jules-Antoine Lissajous who studied these curves in relation to the dynamics of compound pendulums [2]. These curves have found diverse applications in various fields, including analyzing electrocardiogram data, examining oxygen saturation using photoplethysmogram signals [8], identifying faults in power transformers [1] and distribution systems [7] through voltage and current signals, representing DNA molecule configurations, and used in electrical engineering to compare complex electric signals (e.g., real and imaginary axes) [3]. Our oscillatory-trajectory curves differ from traditional Lissajous curves as we simultaneously incorporate signals from multiple generators while depicting the underlying topology between the generators. This topological reference illustrates how specific generators drive the system dynamics during oscillatory events as the amplitudes, phases, and wavelengths on individual generators evolve.

3 Design

Working with power system engineers, we devised three goals for our visualization system: communicate the time evolution of four state variables for six generators, highlight the relationship between the dynamic variables and the network structure and geographic locations of the generators, and illustrate how a subset of the inverter-based generators forced the rest of the system to oscillate. To achieve these goals, we visualized the geographic network, with time-series plots and oscillatory-trajectory curves of the voltage, frequency, and reactive and real power time series of the power system. Figure 1 shows the visualization system we built, and an animation of the visualization can be found in the Supplementary Material.

3.1 Geographic View

Our geographic view plots the generator locations and network structure of the power system on a map, which provides important context for power system engineers. We use circular glyphs at the generator locations to indicate the real power of the generator at the current time step. We additionally color the nodes according to the generator frequency, which helps users compare the relationship between real power and frequency for multiple generators across the system. Finally, we incorporate the energy dissipation metric [4] along the edges of the power system. The *sign* (e.g., positive or negative) of the dissipating energy is represented by arrows on the edges, which indicate whether the generator is adding or absorbing energy from the system, and the size of the arrows indicate the magnitude of energy dissipation. The geographic view allows users to see how oscillations progress in space and it provides important spatial context for the system.

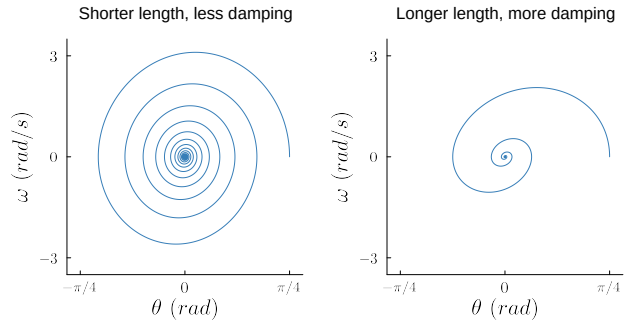

Figure 2: A visualization of state-space diagrams of pendulums with different lengths and damping constants. The differences in the system dynamics is immediately apparent from the diagrams, we see that the left pendulum oscillates longer than the right pendulum, as evidenced by the number of spirals in the trajectory.

Although the geographic view highlights where oscillations are occurring and where energy is being injected or absorbed into the system, it can only indicate a single time step. This places more cognitive load on users to remember how the system has already behaved and then analyze that behavior. We address this shortcoming by showing time-series views of the state variables next to the geographic view.

3.2 Time-Series Views

For every generator, we show the time evolution of each state variable in two ways, as shown in the left and center panels of Figure 1. The left panel shows the state variable of every generator together on the same plot, which provides a general sense of how the system state changes over time. Specifically, each state variable is shown in a row of the time-series views.

The time-series views for each generator allows users to see the individual oscillations in each state variable, and it becomes immediately apparent that generators 1 and 2 oscillate with larger amplitudes than the rest of the generators. However, it is difficult to understand the interdependence of the oscillations among state variables and across the system. Furthermore, it is not obvious that a subset of the generators are driving the oscillations from the standard time-series views or geographic views. To address this gap, we discuss a new way of viewing this behavior that is especially suited for networked oscillatory systems, such as power grids.

3.2.1 Oscillatory-Trajectory Curves

To better capture interdependent oscillatory dynamics of multiple variables and generators, we display *oscillatory-trajectory curves*, which draw inspiration from state-space diagrams and Lissajous curves. Animated state-space diagrams illustrate how a dynamical system progresses through time, and important properties of the system are immediately apparent from such diagrams [16]. As a simple example, consider a damped pendulum with the following

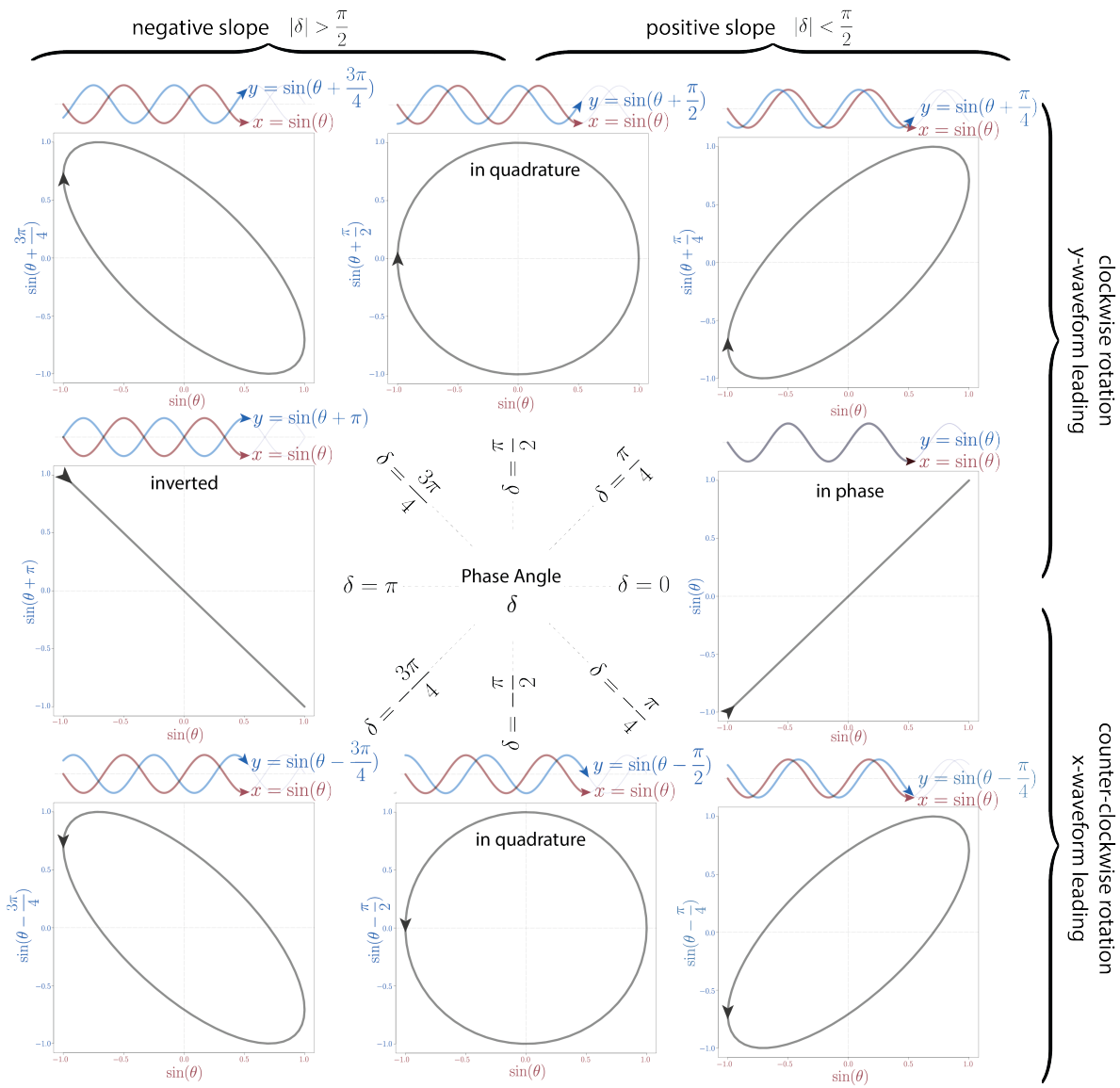

Figure 3: Example Lissajous plots for two oscillatory signals with different phases. Plotting the leading waveform on the y-axis, results in a clockwise rotation. Plotting the leading waveform on the x-axis, results in counter-clockwise rotation. The width and height of the ellipse indicates the magnitude of the phase shift.

equations of motion

$$ml^2\dot{\omega} - b\omega + mgl\sin\theta = 0, \qquad \omega = -\dot{\theta} \tag{1}$$

where m is the mass of the pendulum, l is the length, b is the damping constant, g is the gravitational constant, θ is the pendulum angle (with respect to the vertical axis), and ω is the frequency of oscillation (how often it crosses the vertical axis). The state-space diagram of this dynamical system plots the pendulum angle versus the pendulum frequency (i.e., its position and momentum variables). An example of two state-space diagrams for two different pendulums is shown in Figure 2: the left plot shows a pendulum with a shorter length and smaller damping constant, while the right shows a pendulum with a longer length and a larger damping constant.

The differences in the pendulum oscillations due to the different lengths and damping constants are immediately apparent in the state-space diagrams, as the left diagram shows larger and more spirals around the center as compared to the right diagram. This is because the pendulum represented in the left diagram oscillates faster and more than the pendulum represented in the right diagram. This kind of information is also important to know about generators in a power system, as it indicates which generators are participating more in an oscillation and could have damping issues.

Along with state-space diagrams, the oscillatory-trajectory curves also share similarities with Lissajous curves. Lissajous curves are well suited for comparing oscillatory variables because they highlight the variable that is leading the oscillation versus following, depending on the direction and slope of the curve (see Figure 3). For traditional generators and inverters, the phase difference between state variables can be a crucial indicator of controller issues.

Our oscillatory-trajectory curves share similarities with state-space diagrams and Lissajous curves, but there are a few key differences. First, our power system has more than two state variables and so our curves will not guarantee the same properties as state-space

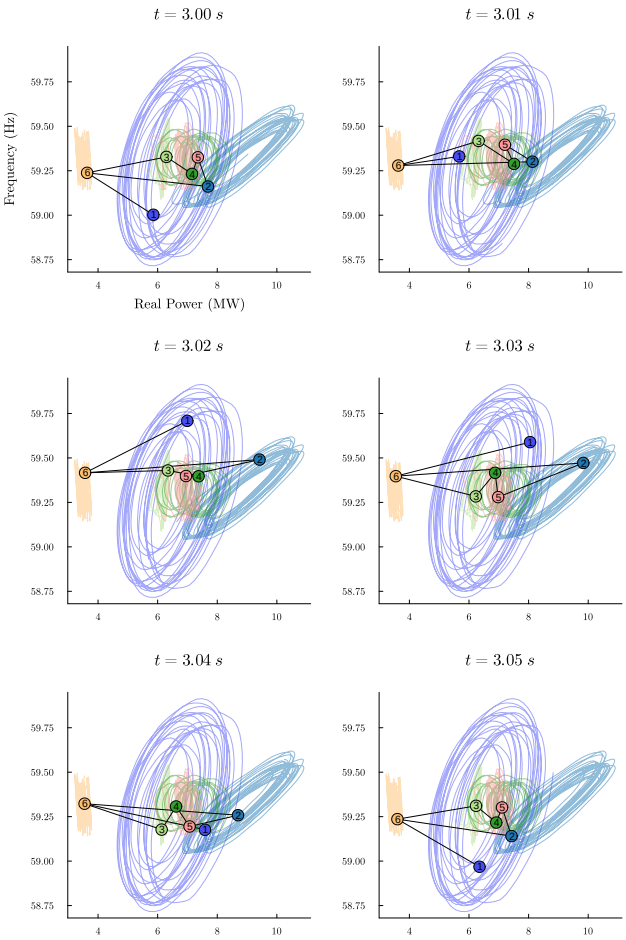

Figure 4: Snapshots of one of the oscillatory-trajectory curves. Generators 1 and 2 have larger ellipses and rotate clockwise, while all other generators have smaller ellipses and rotate counter-clockwise. For clarity, the entire time period is not represented in these curves as is the case for those in Figure 1. See the Supplementary Material for an animation of these oscillatory-trajectory curves.

diagrams. Namely, each point in our plot will not uniquely define a state of the system, as is the case for state-space diagrams of 2D dynamical systems [15]. Additionally, only some of our curves are analogous to position and momentum variables, which are the typical axes for state-space diagrams. Lissajous curves are typically used for signals with fixed frequencies and phases, which is not guaranteed in power systems because of control equipment. Finally, we only explore our oscillatory-trajectory curves in the context of power grid dynamics—the properties and features we observe here might not hold or be useful for other types of motion or time-evolving behaviors.

4 Analysis of Oscillatory-Trajectory Curves

Our oscillatory-trajectory curves incorporate multiple generators, track the evolution of signal properties, and explicitly represent the topological connections between the generators within the plot (see Figure 4). We visually link the current position of each generator to its topological neighbors, providing a direct and intuitive representation of the underlying network structure in the visualization. By showcasing these topological connections alongside the oscillatory dynamics, our approach enables a comprehensive understanding of how the generators interact and influence one another during the oscillation event.

A few key features are apparent from the oscillatory-trajectory curves in Figure 4. First, it is still immediately apparent that the oscillation amplitudes of the frequency and real power of generators 1 and 2 are larger than the other generators because the ellipses have larger radii. Furthermore, as time progresses, generators 1 and 2 rotate clockwise, which indicates that the frequency oscillations reach peaks and valleys *before* peaks and valleys occur in the real power oscillations. On the other hand, all other generators rotate counter-clockwise, which indicates that frequency oscillations reach peaks and valleys *after* peaks and valleys occur in the real power oscillations. This highlights a key dynamical difference between generators 1 and 2 and the rest of the system: generators 1 and 2 use frequency to respond to fluctuations in real power, while other generators, like generator 4, use real power to respond to fluctuations in the frequency. Specifically, this illuminates that generators 1 and 2 are grid-following inverters, while the other inverters are grid-forming or traditional generators [9].

In our system in Figure 1, the oscillatory-trajectory curves are shown in the middle panel. We arrange the oscillatory-trajectory plots in a bivariate lower triangular matrix. Each row in the left panel corresponds to one state variable of the generators, and each column in the middle panel corresponds to another state variable. These indicate which state variables will be plotted as an oscillatory-trajectory curve. For example, the plot under the column labeled "v" and the row labeled "f" plots voltage and frequency as an oscillatory-trajectory curve.

In addition to the observations about the inverters for the specific oscillatory-trajectory curves discussed above, the other oscillatory-trajectory curves in Figure 1 highlight other key features of the system and the generator dynamics that was observed by our collaborators. First, generator 4 is notably distant from the rest of the generators in every oscillatory-trajectory curve, which highlights how it is trying to control and mitigate the instability by counteracting the motion of the rest of the system. Second, the slopes of the frequency-voltage oscillatory-trajectory curves are consistent across all generators. This indicates a consistent phase difference between frequency and voltage across the entire system.

The power system engineers also observed interesting features in these curves. Specifically, they found that comparing the various state variables together for every generator can also highlight which inverter control parameters might be causing issues during this event. For example, the voltage-reactive power oscillatory-trajectory curves show fewer differences between generators 1 and 2 and many of the other generators in the system, while the frequency-real power curves show a lot more variation across the generators. This suggests that control parameters in inverters 1 and 2 related to the real power and frequency might need adjustment, while the ones related to voltage and reactive power are likely not an issue.

5 Conclusion

In this work, we presented a visualization system designed to illustrate the complex dynamics of an island power system during an oscillation event. We introduced oscillatory-trajectory curves, which show how state variables of generators in the power system change over time together and superimpose the network structure to indicate the relationship between the dynamics and network structure. This highlighted the dynamical differences of a subset of generators that were not immediately apparent in the standard time-series or geographic views.

Future work will further explore how to use oscillatory-trajectory curves in analysis contexts and for comparison of events. We will study users' interpretations of oscillatory-trajectory curves in more detail, as it is not a presentation that people tend to be familiar with. We expect that these curves are best used during deep analyses of

power system events, rather than during real-time operations, because of their complexity and richness of information. Additionally, we will explore how to apply oscillatory-trajectory curves to larger power systems where visualizing the network structure alone can be challenging. It is common for power systems to have different balancing areas, and it is possible using these areas to divide the network into groups and present small multiples of oscillatory-trajectory curves is one approach that could solve the scaling issue. For events that last longer than a few seconds, overplotting may become an issue in the oscillatory-trajectory curves. To address this, we intend to explore ways to simplify and determine representative glyphs of oscillatory-trajectory curves.

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