Development of methods for visual representation of low-frequency oscillation parameters in power systems

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Abstract. The development of wide area measurement system (WAMS) expands the analysis capabilities of the Unified power system based on computational processing of synchronized phasor measurements (SPM). The analysis of low-frequency oscillations (LFO) in the power system is one of the most relevant applications of WAMS data. The task of locating the source of forced LFO in real-time is highlighted. Due to the increasing complexity and heterogeneity of real power systems, a definitive solution to this problem does not currently exist. However, there are SPM data analysis methods that provide a high probability of identifying the source of oscillations. Informative representation of measurement signals, intermediate, and final LFO analysis results can serve as the basis for decision support tools for operational dispatch personnel. Direct visualization of raw data and computed parameters, such as a set of time function graphs, is inefficient due to the large volume. Therefore, compact high-level representations are in demand. This paper proposes some approaches to visualizing SPM data, computed LFO parameters, and the results of applying various oscillation source detection methods. The presented data visualization methods have been implemented by the authors in a LFO analysis software system.

1 Introduction

In Russia, the development of the Wide Area Measurement System (WAMS) [1] continues. The number of devices supporting Synchronized Phasor Measurement (SPM) technology installed in the components of the Unified Power System is increasing. As of now, approximately 1000 SPM data streams from phasor measurement units (PMUs) are available for online processing, with a data transmission frequency of 50 frames per second.

System Operator [1] outlined the current challenges associated with utilizing WAMS data. One of the top priorities is to enhance the awareness of the operational dispatch personnel regarding the power system's condition. Specifically, there is a demand for the development of tools that provide timely information about the presence of poorly damped low-frequency oscillations (LFO) [2] in the power system, their current and forecasted parameters, as well as potential sources of these oscillations. Effective data visualization tools play a crucial role here.

The analysis of LFO in a centralized setup involves a large number of input measurement signals. Even more signals are generated as a result of data processing. Therefore, compact and informative methods of representation are required for effective perception of LFO analysis data.

A simple set of time function graphs is not suitable for these purposes. Let's consider an example. Suppose there are 1000 sources of SPM data. The following dynamic parameters of oscillations are calculated: amplitude, phase angle, frequency, rate of change of mode magnitude, a measure of oscillation damping, and oscillation energy. Oscillatory components (modes) are extracted from frequency, current, voltage, active and reactive power signals. Monitoring is performed across 20 spectral bands. As a result, we have 600,000 signals. There is a trend towards increasing this number, particularly due to the deployment of more PMU devices.

This paper discusses some approaches to visually representing the results of SPM data processing that are applicable for LFO analysis at the power system level.

Researchers from Engineering center «Energoservice» are developing software for LFO analysis - ES Phasor [3, 4]. One of the main tasks of ES Phasor is to support decision-making in identifying the sources of forced LFO in the power system. The high-level data visualization methods discussed in this report are implemented in ES Phasor. During the development of visualization tools, the authors analyzed the experience of projects such as Phasor Point [5], Oscillation Source Locating [6], Monitoring Software for Synchronous Swing of Active Power [7], as well as joint research experience with the System Operator.

The structure of the paper is as follows. Firstly, methods of compactly representing arrays of raw signals in the time and frequency domains are discussed, along with additional visualizations to express common oscillation parameters and the system's involvement in the process. Then, an approach to visualize the dynamics of oscillation parameters using phase spaces is presented. Methods of interpreting the resulting images are discussed.

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Subsequently, the peculiarities of displaying time-varying amplitude-phase characteristics of the mode array are examined. Finally, a system of symbolic notations for visualizing the flow of oscillation energy on the power system's schematic is proposed. Screenshots of ES Phasor forms obtained during the analysis of real cases of LFO in the Unified Power System were used in the preparation of figures.

2 Visualization of arrays of initial data

Fig. 1 demonstrates one of the methods for visualizing an array of signals in the time domain, using the example of recording network frequency from approximately 100 PMUs during the start of LFO. The original signals are depicted as thin, semi-transparent lines of the same color. This creates a "statistical background" of the process. Additional plots include the mean signal value at each moment in time and the deviation from the mean by the standard deviation. This helps to understand the "commonality" of the oscillatory process.

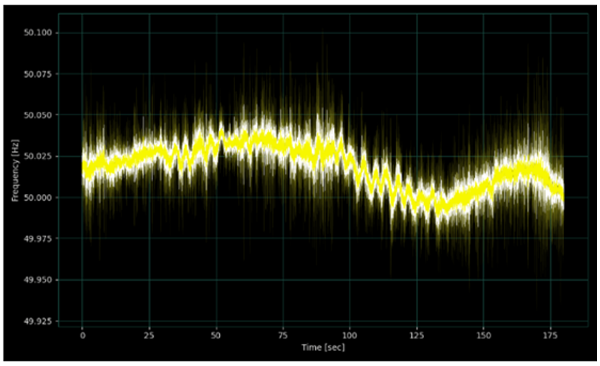

Fig. 1. Raw data in the time domain.

In the provided example, on the interval from 100 to 130 seconds, LFOs are observed in the average values. However, the range of values here is smaller than, for instance, on the interval from 60 to 100 seconds, where the LFO has a smaller amplitude.

It is also useful to examine the original signals in the frequency domain. In Fig. 2, amplitude spectra of active power measured on approximately 100 transmission lines during the LFO mode are shown as thin lines of the same color.

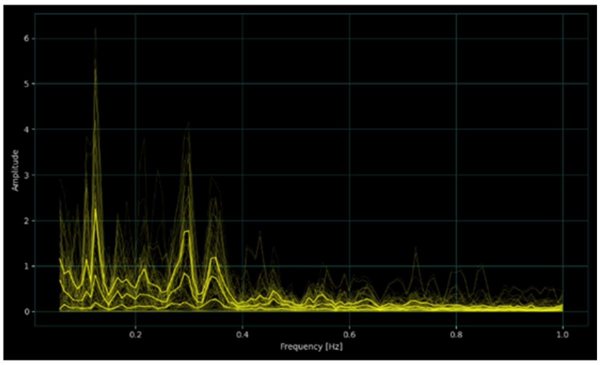

Fig. 2. Raw data in the frequency domain.

For each frequency value, the first, second (median), and third quartiles are calculated. They are represented as bold lines in the figure. Around 0.2 Hz, some signals exhibit an increase in their corresponding harmonic components. However, an analysis of the quartiles (especially the third quartile) indicates that the system's involvement in the oscillatory process as a whole in this case is less than, for example, around 0.1 Hz or 0.3 Hz.

It is also valuable to consider the aggregated spectrum (mean, median) over time. Fig. 3 displays the average amplitude spectrum of frequency at a certain moment in time and a spectrogram.

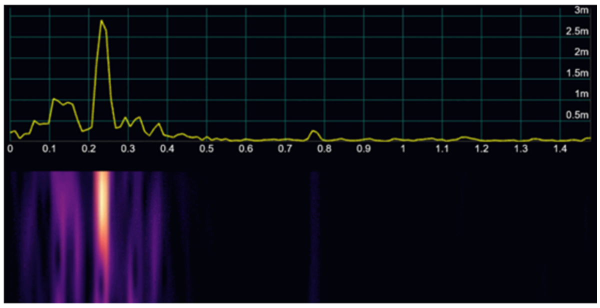

Fig. 3. The average spectrum over time.

In the spectrogram, the most recent values are located at the top. Stable oscillations are observed around 0.25 Hz and 0.8 Hz.

3 Visualization of oscillation dynamics

To represent the dynamic parameters of LFOs in the power system, it is proposed to use a set of moving points on the phase plane. Fig. 4 illustrates the schematic of the phase plane.

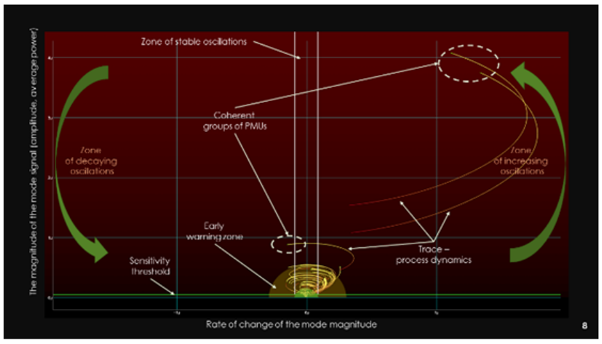

Fig. 4. Interpretation of the representation of LFOs on the phase plane.

The x-axis corresponds to the rate of change of the mode magnitude, while the y-axis represents the mode magnitude itself. Each point describes the evolution of the oscillation state over time. The movement of points to the right signifies the system's oscillatory growth, while movement to the left corresponds to damping of the oscillations. An important element of this representation is the "trace" left by the points. It reflects the recent history of changes in the mode magnitude and the velocity of point movement, allowing the observation of dynamic changes even on a static image.

Different regions on the phase plane correspond to different characteristics of LFO. The right half-plane represents the amplification of oscillations, while the left half-plane corresponds to damping. The upper-middle part is the zone of low-damping, high-amplitude oscillations. A threshold value for the mode magnitude is also set, below which data is not displayed.The proposed representation of data on the phase plane provides feedback on the power system's state under control actions and is a valuable tool for monitoring LFOs.

The magnitude of the oscillations can be estimated in various ways. One approach involves using the amplitude (envelope of the signal), calculated with a Hilbert digital filter. Another approach is based on computing the average power of the signal over a sliding window. This integral value provides an averaged measure of the mode magnitude over a specific time interval and offers greater stability in noisy conditions. Additionally, average power can be calculated for the entire low-frequency range without isolating a specific mode. This approach provides a more general picture of the signal's energy distribution across frequencies and can be useful in situations where it is necessary to analyze the entire low-frequency range rather than individual modes.

Fig. 5 presents an example of phase space for a real case of LFOs.

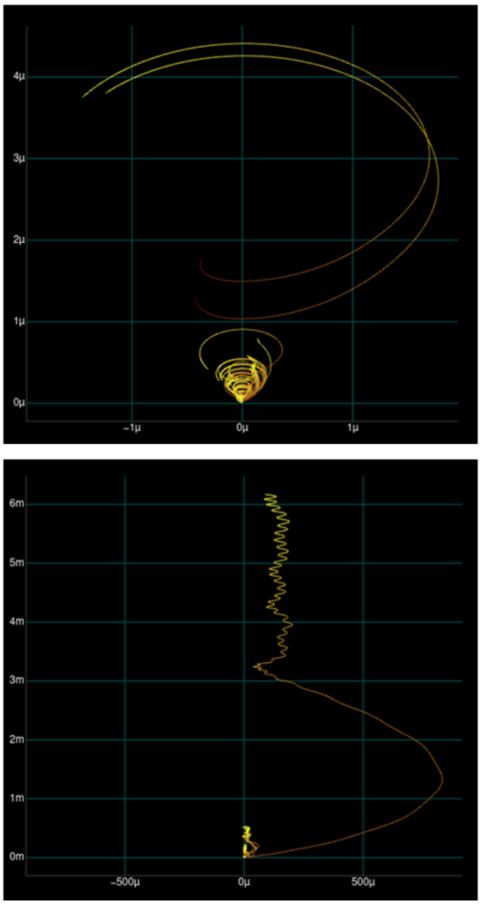

Fig. 5. An example of visualizing modes on the phase plane.

Two frames are depicted, describing the onset of oscillations (top) and their subsequent development (bottom). The mode is extracted from the frequency signal, and data from 80 sources are analyzed.

The process of increasing the magnitude of oscillations is evident. The values have changed by several orders of magnitude. The source of LFO is highlighted, which in this case is characterized by the maximum mode magnitude. On the bottom frame, there is also an attempt to dampen the oscillations when their growth accelerates significantly.

4 Visualization of amplitude-phase characteristics of modes

As another way to visualize the dataset on the scale of the power system, an amplitude-phase diagram is proposed. Fig. 6 presents an example of such representation for one of the cases of LFO. In this form, each mode is depicted as a point at a given moment in time. The distance from the point to the center of the diagram corresponds to the current amplitude, and the angle represents the full phase of the mode. A decaying trace is displayed behind each point.

This representation is associated with one of the common methods for identifying the source of LFO - Mode Shape Estimation (MSE) [8]. The idea behind MSE is that a mode with sufficient amplitude and leading phase belongs to the source of the oscillations. Modes can also group into clusters. In this case, you can talk about leading mode groups and leaders within those groups. Understanding the cluster's structure allows for determining the part of the system involved in the oscillations.

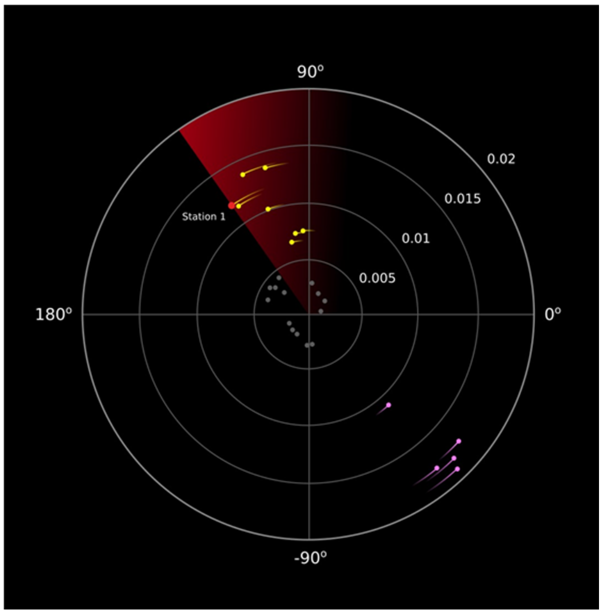

Fig. 6. The amplitudes and full phases of the mode set.

In the example shown in Fig. 6, three clusters of modes are identified: leading, lagging, and a group of modes with low amplitude. The presumed source of the LFOs is highlighted. It's worth noting that in this case, the amplitude of the oscillations from the source is not the highest.

5 Visualization of Oscillation Energy

For visualizing the high-level information about the state of measurements and the development of the oscillatory process, a visualization on the power system scheme is proposed. The cartographic representation includes three levels: the structure of the power system, the state of the WAMS, and the results of the LFO source identification. The visualization at the third level depends on the analysis methods used.

Let's take a closer look at the visualization of LFO energy flows. The assessment of the quantity, direction, and velocity of LFO energy movement is based on the Dissipating Energy Flow (DEF) method [9]. DEF provides an expression for calculating the amount of energy dissipated as a result of oscillations based on filtered synchrophasor data. The sign before the dissipated energy value provides information about the direction of LFO propagation.

The proposed notations are shown in Fig. 7. The power system is represented as a graph, where nodes correspond to power stations and substations, and edges represent power transmission lines. Nodes are tied to the geographical coordinates of power system objects, while the geography of the lines is not considered. Different line thicknesses are used to represent different voltage classes. Power transmission lines with voltage classes of 110 kV and higher are displayed.

Depending on the availability of reliable data in the WAMS, lines are considered as active or inactive. This, in turn, determines the presence of observable and unobservable objects in the power system, such as lines, power stations, and substations. For example, if at least one active PMU is missing on a line, the line is considered unobservable. Similarly, a substation is considered observable if it is connected to at least one observable line. Inactive PMUs and unobservable parts of the system are shown in gray.

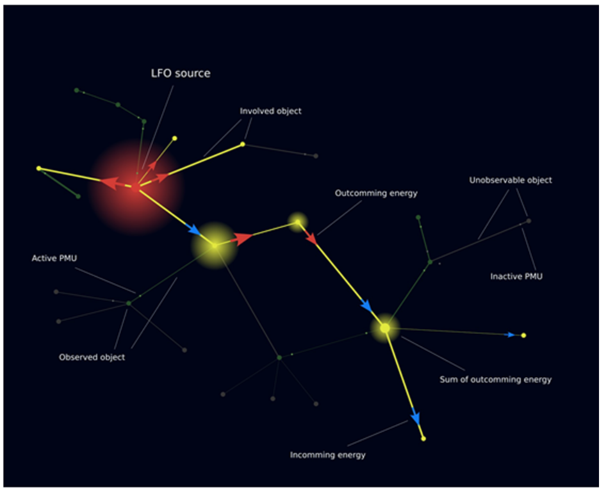

Fig. 7. Legend for DEF visualization on the map.

Dissipative energy is visualized by the brightness of the lights, the thickness of the lines, and the arrows indicating the flow direction of energy. The thickness of the arrows is proportional to the amount of energy from oscillations registered at the corresponding connections, and the total outgoing energy is represented by the glowing around the stations and substations.

Positive values of dissipative energy for PMUs are shown with red arrows pointing away from the stations. Negative values are represented by blue arrows pointing towards the stations. If PMUs are correctly installed on the same line, there should not be two arrows of the same color. The glowing indicates the total outgoing energy.

In Fig. 8, a frame for one of the real cases of large-scale LFOs is shown when the source was located in the power system of a neighboring country.

Fig. 8. Dissipative energy of large-scale LFOs.

The part of the power system involved in LFOs, the most disturbed part of it, and the source of LFOs are visible. Arrows at this scale have become dots, but thanks to the colors, the direction of the flow is visible. Similarly, the results of the modified MSE method [3], in which the frequency is calculated from the current and the leading mode is sought not in the entire power system, but at each station, are superimposed on the power system and WAMS, allowing the selection of an edge leading to the source of LFOs at each observed vertex of the graph.

6 Conclusion

The report discusses various approaches to compact and informative visualization of large volumes of data resulting from the analysis of LFOs in the power system. The proposed approaches have been implemented by the authors in the ES Phasor software. The images presented in the work are obtained from the analysis of real cases of LFOs in the Unified Power System.

The report highlights the challenges of high-level representation of datasets, dynamically calculated oscillation parameters, and data from various LFO source detection methods.

The proposed visualizations are designed to provide additional support for decision-making by operational and dispatch personnel and to assist in further research into LFO analysis methodologies.

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