Investigation the influence of the parameters of the computational scheme on detecting the source of low-frequency oscillations

Kirill Butin[1,2*], *Aleksandr* Popov[1,2], and *Andrey* Rodionov[1]

[1]Engineering Center «Energoservice», Russia
[2]Northern (Arctic) Federal University

Abstract. The dispatching control requires the ability to detect the source of low-frequency oscillations in the power system based on the online processing of synchrophasor measurements data. This is a complex task; therefore, new approaches to its solution and variations of existing ones are constantly emerging. As a rule, a short expression of the criterion of a particular method hides a number of stages of computational data processing. The number of possible implementations of these stages increases during the investigation. The set, settings, implementation of the stages of the computational scheme, and combination of these stages affect the final result. Earlier, the authors developed a high-performance software platform that allows describing computational schemes in a general way, and then performing calculations with specified sets of algorithms. In this paper, a generalized calculation scheme for the dissipating energy method is constructed, and experiments are performed showing the influence of details of the implementation of data processing stages on the result of the online detection of the source of low-frequency oscillations.

Introduction

The monitoring of low-frequency oscillations (LFO) is one of the most relevant areas of data processing of synchrophasor measurements data and is included in the decision-making in most dispatch centers of system operators [1]. An effective solution for the problem of LFO source online localization is particularly in demand. We understand it as identifying as close as possible such a part of the power system that makes the greatest positive contribution to the development of the oscillatory process.

Paper [2] analyzes a number of LFO cases that have occurred in the Russian power system in recent years.

The interest in the problem of LFO has grown today, including in connection with the development of renewable energy sources, the introduction of which leads to the destabilization of the traditional power system, the emergence of new types of oscillations, and the complexity of control [3, 4].

For online processing, it is required to minimize the time from the beginning of oscillations mode to making a stable correct decision about the localization of their source.

The search for the LFO source can include an assessment of the role of generators in the development of the oscillatory process, comparison of the amplitude-phase characteristics of the components of measuring signals, analysis of wave propagation in the power system, comparison of measurement data with simulation results, data accumulation and machine learning, etc. [5, 3] However, none of the existing methods provides a final practical solution for real power systems [6].

Various ways of combining alternative methods are proposed [8, 9], ensembles of methods are being built [10], computing platforms are being created for comparative experiments [10, 1], test data sets are being accumulated [7], typical simulation models of power systems are being formed [12] for testing analysis methods, etc.

1 Calculation templates

In data analysis problems, the calculations often can be represented by generalized schemes or templates. The nodes of templates correspond to subtasks without indicating a specific solution of them. In the LFO analysis, such general tasks are: data pre-processing, mode detection, extraction of informative signal components, calculation of the dynamic parameters of oscillations, and the actual search for the source. On the other hand, as research develops, the variety of processing methods at each stage is constantly increasing. At the same time, the methods have different sets of parameters and software implementations. Therefore, the implementation of the whole problem is combinatorial.

Previously, the authors developed [13] and implemented in the form of a software platform [1] an approach to describe calculations in the form of generalized schemes with the possibility of varying algorithms at the user level. A computational scheme (plan) is a set of interrelated stages of calculations

* Corresponding author: k.butin@narfu.ru

(works). The plan defines the structure of the task, the work corresponds to the subtasks. To launch the plan, each work must be associated with a performer, the implementation of some data processing algorithm.

2 Dissipating energy flow method

The detection of an LFO source based on the estimation of oscillatory energy demonstrated high efficiency [7, 2]. In [14], an integral expression was derived for the energy of oscillations. In this case, the measuring signal is considered as the sum of the trend and the oscillations. In the context of a different signal model (summed modes), in [6] this expression was transformed and the so-called dissipative energy flow (DEF) method was obtained. In the DEF method, for each object, the value of W_{ij}^D is calculated in signal sections of a length of 5 to 20 LFO periods [6]:

$$W_{ij}^D \approx \int 2\pi \Delta P_{ij} \Delta f_i dt + \Delta Q_{ij} \frac{d(\Delta V_i)}{\tilde{V}_i + \Delta V_i} \quad (1)$$

The symbol Δ here denotes the operation of extracting the oscillatory component from the measuring signal. P_{ij} – active power on line $i - j$, Q_{ij} – reactive power, f_i – frequency, V_i – voltage, $\tilde{V}_i$ – average voltage value at point i. The direction of the energy dissipation flow is determined by the slope of the linear regression:

$$W_{ij}^D(t) = DE_{ij} * t + b_{ij} \quad (2)$$

Positive values of DE_{ij} indicate the flow of oscillation energy from the object to the system, and negative values indicate the opposite direction of the flow. Thus, the largest value of DE_{ij} corresponds to the LFO source. After the implementation of DEF in the ISO New England power system [11], a number of refinements (for example, node weights) were required to correct the solution. In addition, for archival records, it is allowed to manually search for the LFO source including the analysis of the power system topology. The criticism of DEF with examples of its incorrect operation is presented in [15]. Variations of the DEF method can be found, for example, in [16, 17, 18]. In other words, the potential for the development of the method has not yet been exhausted.

3 DEF template

Fig. 1 shows one of the possible calculation schemes for the DEF method. First, a set of quantities is prepared that are necessary for (1). Then the signals are packed into a special structure, the trend is removed, the modes are distinguished, the oscillation energy is calculated, and the rate of its change is calculated.

The * symbol means that the work is applied to all elements of the input data. For example, if filtering is used to extract a mode, then the same filter is applied to all values. The line thickness reflects the number of data elements in the stream.

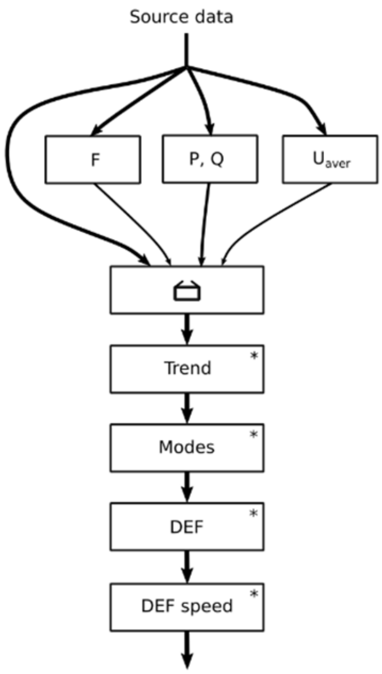

Fig. 1. DEF template.

Table 1 lists the possible performers for the selected jobs and the variable parameters.

Table 1. Calculation steps.

	Work	Workers	Parameters
1	***f*** calculation	From data	
		Left shift	
2	***P*** and ***Q*** calculation	From data	
		Function	
3	$\tilde{V}$ calculation		Number of averaged values
4	Removing a trend (detrending)	No	
		Averaging filter	Window function
			Win length
		Savitzky-Golay filter	Polynomial degree
			Length
5	Mode extraction	No	
		Finite impulse response (FIR) filter	Bandwidth
			Order
			Window function
		Infinite impulse response (IIR) filter	Order
			Bandwidth
6	DEF calculation	With Q	
		Without Q [17]	
7	DEF slope calculation	Linear Regression	Window length

It is supposed to be possible to add any other performers that are compatible in terms of the interaction interface.

4 Objective function

Let there be a data set of syncrophasors obtained during the LFO mode. Also, let the LFO source be known, and the data contain signals from the source.

Taking into account the application of a certain method to determine the source of an LFO, we introduce a function $s(t)$ such that $s(t) = 1$ in those cases where the source is correctly specified at time t, and $s(t) = 0$ in all other cases. Consider also the function $r(t)$ – the time until the moment t, during which $s(t) = 1$ and $s'(t) = 0$, that is, the decision was correct and did not change.

In discrete form:

$$r(n) = \begin{cases} 0, & n = 0 \\ s(n)\big(r(n-1) + s(n)\big), & n > 0 \end{cases}$$

We emphasize that the output of the function $r(t)$ is time. We will compare $r(t)$ with some setting τ_r: if $r(t) > \tau_r$, then we will say that at time t there is a stable correct solution.

The strict requirement 'the solution did not change' can be replaced by a softer 'solution almost did not change' and use, for example, the ratio of the correct answers number to the total one at a level close to 1.

The described is schematically shown in Fig. 2. For convenience of perception, r(t) is shown as a solid line.

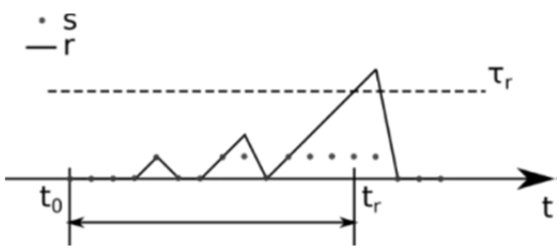

Fig. 2. Determining the time of a stable correct solution.

5 Real LFO case processing

Consider a case that occurred in January 2022 in the western part of Russia. Fig. 3 shows the time interval from the beginning of the LFO. The lines show raw frequency data for the 21 input signals. An LFO is observed in the region of 0.85 Hz.

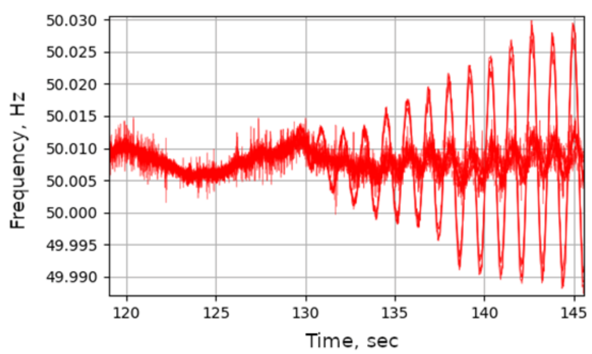

Fig. 3. LFO at frequencies.

The duration of the oscillation is about 14 minutes. Visually, the fluctuations begin at about 129 sec. Let us take the following parameters: $t_0 = 120$ sec, and τ_r=30 sec. Thus, starting from a time point of 120 seconds, the DEF method should consistently produce the same source for 30 seconds. This duration corresponds to about 25 waves of oscillations, which are enough with a margin to speak about the finding of the source [6]. The time when the DEF method began to give the correct answer (it is known to us in advance) will be considered as the moment the source was discovered.

In accordance with Table 1, we define the sets of possible performers and their parameters. The length of filters and windows varies from 5 to 1001 samples. For the IIR filter, we use the Butterworth filter of orders 2 and 3. For the Savitzky-Golay filter, the degrees of the polynomial are 5 and 6. Bandpass filter ranges: from 0.1 to 4.0 Hz, from 0.81 to 0.91 Hz, from 0.76 to 0.96 Hz, from 0.66 to 1.06 Hz, and from 0.56 to 1.16 Hz. Since the number of different combinations exceeds 10^{12}, a complete enumeration of all options is not possible, so the Monte Carlo method is used. At each step, one of the possible configurations is generated with equal probability and the DEF method is run for it. After each launch, the configuration and time of source detection are fixed.

6 Results

The calculations were carried out on the nodes of the computing cluster of the Northern (Arctic) Federal University [19]. Each node has two ten-core Intel Xeon E5-2680 processors with 64 GB of RAM.

All signals were processed in online streaming mode without creating artificial delays. Here are the main characteristics of the calculations: 127706 launches and 29.8 hours of computer time. The average processing time for one variant is 840 ms.

Fig. 4 shows a histogram for the number of correct detections (total 84002) of the LFO source depending on the time. The peak of around 140 seconds corresponds to the most frequent detection of the source. This is primarily due to the total delay of the methods. Each method can introduce a delay. Since the lengths of the filters were selected equally likely, the average total delay of the filters was about 12 seconds, which gives a peak 12 seconds after the start of the LFO.

The worst results in terms of time are given by methods either with the maximum total delay or with a too short search window for the linear regression coefficient. This is due to the fact that the DEF integral fluctuates relative to the trend and the regression coefficient constantly changes sign.

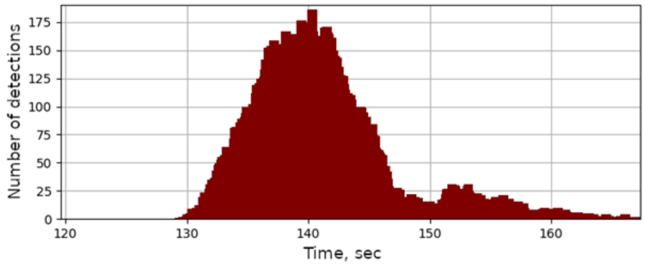

Fig. 4. Source detection frequency diagram.

The best combination of methods identified the source at 128.82 sec. Fig. 5 shows the stages of calculations.

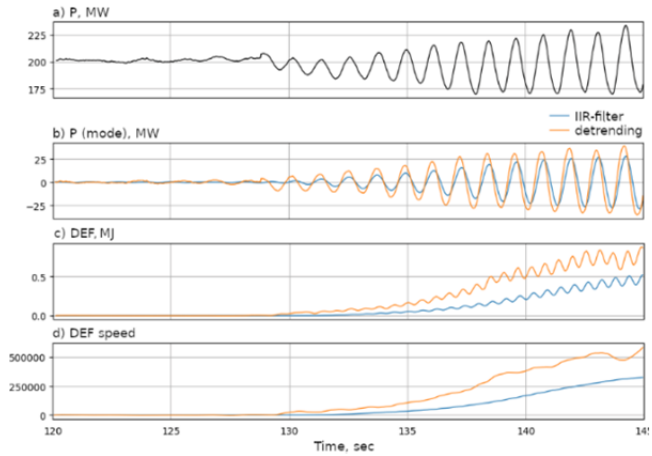

Fig. 5. Step-by-step calculation.

Fig. 5.a shows the original active power over time. Detrending was applied without further filtering using an averaging filter with a length of 35 points (Fig. 5.b). For comparison, the blue line shows the result of applying the second-order IIR filter in the band from 0.76 to 0.96 Hz. It is slightly behind and has a smaller amplitude. Fig. 5.c shows the calculation of DEF in a sliding window of 71 points. The calculation of DEF is executed without the contribution of reactive power. Fig. 5.d shows the linear regression coefficient in a sliding window. The detrending method without filtering in this case produced a positive linear regression coefficient earlier. Visually, this corresponds to the time of the beginning of the LFO.

The detrending subtask is one of the most important. Depending on the removal method, in some cases, opposite in sign values of the regression coefficient are obtained. You can remove the trend using bandpass filtering. This task is handled by an IIR filter. Its disadvantage is the accumulation of calculation errors.

Conclusions

Dispatch centers need timely LFO source detection using synchrophasor measurements. There are a variety of methods for identifying the LFO source. The DEF method is one of the promising ones. Software implementation of DEF involves some steps of calculations with variable performers and parameters. The paper presents a computational experiment on a high-performance cluster in order to select the optimal configuration that reliably determines the LFO source in a short time. The sets of possible step performers and their parameters are determined. The dependences of the final result on the calculation parameters are revealed. The possibility of using the dissipating energy flow method online has been tested. An example with a combination of calculations is given, in which the method detects the LFO source at the beginning of the oscillations. This allows us to know where the LFO source is at the time the oscillatory mode is detected. In the future, we plan to expand the test suite and use machine learning to fit the calculation parameters.

References

1. A. Popov et al. *Framework for synchrophasor measurements data processing and the case studies of the low-frequency oscillations* (https://www.naspi.org/sites/default/files/2021-04/D3S7_01_butin_energoservice_naspi_20210415.pdf)
2. A. Popov et al. *Examples of processing low-frequency oscillations in Russia and ways to improve the analysis*, in Proceedings of the 2022 International Conference on Smart Grid Synchronized Measurements and Analytics (2022)
3. L.G. Meegahapola et al. *Review on Oscillatory Stability in Power Grids with Renewable Energy Sources: Monitoring, Analysis, and Control using Synchrophasor Technology* in IEEE Transactions on Industrial Electronics, **68** (2020)
4. J. Ma et al. *Equipment-level locating of Low Frequency Oscillating Source in Power System with DFIG Integration Based on Dynamic Energy Flow* in IEEE Transactions on Power Systems (2020)
5. B. Wang, K. Sun. *Location methods of oscillation sources in power systems: a survey* in Journal of modern power systems and clean energy **5** (2017)
6. S. Maslennikov et al. *Dissipating energy flow method for locating the source of sustained oscillations* in International Journal of Electrical Power & Energy Systems, **88** (2017)
7. B. Wang, S. Maslennikov. *IEEE-NASPI Oscillation Source Location Contest-Case Development and Results* in Tech. rep. National Renewable Energy Lab (2021)
8. G. Ding et al. *Analysis of ultra-low frequency oscillation in southwest power grid based on measurement data* in Proceedings of 37th Chinese Control Conference, CCC (2018)
9. A. Popov et al. *Combined method for identifying a source of low-frequency oscillations in power system* in AIP Conference Proceedings **2552, 060004** (2023)

10. U.I.H. Banna, Solanki S.Kh., Solanki J. *Data-driven disturbance source identification for power system oscillations using credibility search ensemble learning* in IET Smart Grid 2.2, (2019)
11. S. Maslennikov, E. Litvinov. *ISO New England Experience in Locating the Source of Oscillations Online* in IEEE Transactions on Power Systems (2020)
12. C. Canizares et al. *Benchmark models for the analysis and control of small-signal oscillatory dynamics in power systems* in IEEE Transactions on Power Systems 32.1 (2016).
13. A. Rodionov et al. *Practical Issues of Processing Synchrophasor Measurement Data in the Analysis of Low-Frequency Oscillations in Power System* in Proceedings of 2nd International Youth Scientific and Technical Conference on Relay Protection and Automation, RPA (2019)
14. L. Chen, Y. Min, W. Hu. *An energy-based method for location of power system oscillation source* in IEEE Transactions on Power Systems, **28** (2013)
15. Y. Zhi, V. Venkatasubramanian. *Analysis of Energy Flow Method for Oscillation Source Location* in IEEE Transactions on Power Systems, (2020)
16. W. Hu et al. *Disturbance source location of forced power oscillation in regional power grid* in Proceedings of the 2011 IEEE Power Engineering and Automation Conference, **2** (2011)
17. S. Guo et al. *An Alternative Way to Locate Disturbance Source for Low Frequency Oscillation Considering Control Devices of Generator* in MS&E 740.1 (2020)
18. P.G. Estevez et al. *Complex Dissipating Energy Flow Method for Forced Oscillation Source Location* in IEEE Transactions on Power Systems (2022)
19. HPC NArFU (http://fujitsu-19-02.narfu.ru)