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IDENTIFICATION AND DAMPING OF LOW-FREQUENCY OSCILLATIONS BASED ON WAMS DATA AND THE REVISITED RESIDUE METHOD – PART I

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The results of low-frequency oscillations identification in the Republic of Kazakhstan power grid by using a Wide Area Measurement System are presented and an algorithm for damping low-frequency oscillations is proposed in this paper. Analysis of weakly damped inter-area low-frequency oscillations revealed a constant mode with a frequency range of 0.3–0.4 Hz. It was determined that at these low-frequency oscillations, the amplitude of active power fluctuations along the transmission line was 150 MW with a duration of 9 minutes. The modal analysis calculation of the Republic of Kazakhstan power system model in the «DigSilent Power Factory» software shows the dangerous low-frequency oscillation modes having a damping ratio is 2.2 % and an eigenfrequency 0.328 Hz. These oscillation modes identified by the real data and in the developed model indicate the incorrect tuning of power system stabilizer parameters at power plants. It is necessary to retune the power system stabilizer parameters whenever changing the system's and mode's configurations.

An analysis of existing power system stabilizer tuning methods was performed, and revisited residue method was determined as sufficiently effective. Thus, the developed algorithm for identification and damping of low-frequency oscillation consists of three tasks. The first task is data collection from the Wide Area Measurement System and Supervisory Control and Data Acquisition system and updating the calculation model based on the current status of equipment (generators, transformers, transmission lines, etc.). The second task is the identification of dangerous electromechanical oscillations and modal analysis based on information obtained in real-time. The third task is tuning the power system stabilizer parameters for damping dangerous low-frequency oscillation modes based on the revisited residue method

Keywords: identification of oscillations, WAMS, power system stabilizer, damping, residue method

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1. Introduction

Ensuring the stability of the electric power system is critical. When electrical connections appear between large electric power systems (generation sources), challenges related to non-damped electromechanical low-frequency oscillations (LFOs) appear for the System Operator [1–3]. These oscillations can result from a sudden increase in load, a shutdown of a large generator, or a change of synchronous generator operation or power plant due to an incorrect setting of the generator excitation system [4, 5]. In the case of a short-term disturbance in the system, LFOs in power lines, significantly affecting the regime stability parameters, are present for a long time. In some cases, they increase causing the system to split in the absence of an adequate response from the power plants to damp oscillations. These oscillations not only limit the capacity of long lines but can also lead to major system accidents in post-accident regimes [6]. As is known, synchronous generators are equipped with automatic voltage regulators (AVRs), which regulate the voltage at the generator terminal by controlling the amount of current supplied to the field excitation winding. However, the high gain of the excitation system can also contribute to oscillational instability in the power system.

One of the main directions for maintaining stability is to ensure sufficient damping of LFO. Installing a power system stabilizer (PSS) is an efficient and cost-effective way to improve oscillatory stability and solve this problem. The main function of the PSS is to extend the stability limit by modulating the excitation of the generator to provide positive damping for power fluctuation modes. The PSS generates an additional signal that is added to the generator control loop to create positive damping. The PSS is directly connected to the AVR of synchronous generators and the main purpose of the PSS-AVR excitation control configuration is to provide damping and voltage control. But the installation of AVR and PSS does not fully solve the problem of damping LFO. Because it is critically necessary to correctly tune the parameters for proper damping of oscillations based on the power plant location [7].

At the same time, the identification of dangerous LFO in the process rate is a fundamental task for the correct assessment of power system stability and tuning PSS parameters. Recently, a wide area measurement system (WAMS), which is a system of synchronized phasor measurements, has been used in international practice to study the quasi-dynamic and transient characteristics of the system and LFO [8, 9].

Based on the seriousness of the LFO problem for the power system stability, it is important to correctly identify them using WAMS data, an assessment of dangerous modes impact, and develop an algorithm for tuning PSS parameters. Therefore, research on the development of the method for identification and damping dangerous LFO modes in real time is relevant for power system stability.

2. Literature review and problem statement

The study of low-frequency oscillations is an important research area for the stability of power systems with long transmission lines. The main reasons for LFO are the occurrence of power imbalance in systems interconnected by transmission lines, mechanical mass oscillations, a change in the synchronous operation of the generators in the power system due to incorrect tuning parameters of the excitation systems, AVR, and PSS [10]. The interaction occurs during the transmission of the oscillation initiated by one system through intermediate subsystems into another system causing the development of transient processes in regions remote from the oscillation point.

Analysis of the recorded emergency events in power systems of different countries has shown that the largest number of power system blackouts were caused by oscillations with frequencies from 0.1 to 0.7 Hz. Based on many previous works, these LFOs are considered in international practice as the most dangerous. In research [11] are presented an overview of low-frequency oscillation phenomena in power systems, a case study in a simple system, and dangerous oscillations defined at a frequency of 0.1–2.0 Hz. In [12] researched the nature of the electromechanical oscillations in power systems, and outlined local-area oscillations with frequency from 0.7 to 2 Hz and inter-area oscillations from 0.1 to 0.8 Hz. Also, in work studied the influence the power system structure, modeling of a generator, excitation type, system loads, and DC link. In work [13] a classification of stability is given, with the definition of dangerous inter-area oscillations with a frequency range of 0.2–0.8 Hz, the work still presents several recorded accidental events in Continental Europe with the presence of electromechanical oscillations.

One of the first major accidents caused by LFO was recorded in North America in October 1964, during tests to combine the Northwest Power System with the Southwest [14]. A power oscillation with a frequency of 0.1 Hz was observed along an intersystem power line. Since this emergency event, many incidents involving LFOs in transmission networks have been reported around the world. A few examples of such incidents in large power systems are given below:

1. In the late 1970s and early 1980s, low-frequency power oscillations were discovered in the UK power system along an intersystem power line connecting Scotland and England. Operational experience has shown that these oscillations were due to the relatively long line and its high load in the transmission of electricity from Scotland to England. Many measurements made from 1980 to 1985 showed that oscillations occurred when power flow reached a certain level, and often the oscillation had a frequency of 0.5 Hz [15].
2. In 1984, constantly present LFOs were recorded in Taiwan's power system. These oscillations were usually observed when overloading of extended high-voltage power lines occurred. This phenomenon was discovered when a decrease in the transmission of electric power over extended lines improved the damping of these oscillations. Installation of PSSs in power plants made it possible to successfully damp LFO. Subsequent studies revealed other factors such as AVR gain and the nature of the load, affecting oscillation damping [16].
3. On August 10, 1996, a major accident occurred in the western power system of North America (WSCC), when 9 million customers were left without electricity for 7.5 hours. It was later found that the cause of such a large-scale accident was LFO having the most dominant modes of 0.2~0.3 Hz. These oscillations led to the shutdown of a 500 kV overhead (OHL) line that was overloaded at that time and had low voltage. The accident spread quickly with a shutdown of neighboring lines and some of the generating units, which ultimately led to the separation of the western power system into four isolated areas [17].

Identification of LFOs and detection of dangerous modes of oscillation is the primary task. Accordingly, it is necessary to create an effective system to monitor and identify LFOs in the power system.

The emergence of synchronized phasor measurement technologies makes it possible to create a system for monitoring the power system's steady-state and transient stability, as well as on its basis the possibility of creating a real-time test system [8]. In [18] authors provides an overview of the WAMS system, the ability of monitoring power system stability in real time and the stages of implementation in the power systems of Brazil, India, Continental Europe, North America and other large power systems. The paper [19] presents the history of WAMS development in China, the structure of its construction, as well as the functionality of the system including monitoring of oscillatory stability and transients and the possibilities of expansion. That makes it possible to predict dangerous modes leading to stability failure, including oscillation stability control.

After identification of LFO in the power system it is necessary to correctly tune the PSS parameters for damping dangerous oscillations. Scientists and engineers have proposed many methods for optimal tuning of PSS parameters to improve the power system operation stability. The tuning methods can be divided into two categories – practically used and those of scientific interest.

Methods based on the amplitude-frequency response, gradient descent, and others are used as practical methods by excitation systems and PSS manufacturers, as well as by

R&D institutes. As mentioned in [20, 21] programs, based on frequency methods began to be developed to study oscillation stability in the twentieth century. These programs were used to analyze the effects on the regions of oscillation stability. Further improvement of the algorithms was carried out by rationalizing the initial equations for joint optimization of several station excitation system parameters. This problem was solved by calculating the curves of equal stability degree one by one based on programs with the D-partitioning procedure. By the 1980s, disadvantages of the D-partitioning method began to appear, especially in the search for AVR and PSS parameters settings of complex multi-machine power systems [22]. The above methods have proven their reliability when setting the parameters of AVR and PSS of synchronous generators in power plants that only allow the modeling of simple third-order generator models in the absence of large computing power and industrial calculation programs. Today, with the development of a full-fledged control system and the development of computers and programs for modeling dynamic processes of the power system in the programs – Matlab, PowerFactory, PSS/E, RSCAD, and RTDS, it has become possible to use other methods of finding the optimal parameters for tuning the AVR and PSS.

PSS tuning optimization algorithms have been of scientific interest in recent years. The most popular optimization algorithms for tuning AVR and PSS parameters are Particle Swarm Optimization (PSO) and Genetic Algorithm (GA) [23, 24]. PSO is one such heuristic method based on swarm intelligence. PSO was developed in 1995 [25]. This method is based on the social and cognitive behavior of individuals in a swarm, such as a swarm of fish or locusts. The algorithm used is considered simple and efficient to implement. The optimization heuristic algorithms are not applied in practice when setting the parameters of the AVR and PSS, because there is no guarantee that the parameters found are optimal for the generator in question. For these optimization algorithms, it is necessary to correctly determine the optimization function, select the parameters and set the limits for them. These algorithms are more applicable for distribution networks in the optimization of the power-flow distribution to reduce power losses and to find optimal nodes for the placement of compensation devices [26, 27].

According to the research [28, 29] in recent years scientists and engineers are also actively studied the residue method for tuning PSS parameters. This method is further considered for tuning the PSS parameters as part of the proposed algorithm.

Emergency events [11–17] caused by LFO resulted in significant consumer outages in power systems around the world and reduced power capacity on transmission lines. Outages of consumers and lines capacity limitation always leads to negative social and economic consequences. At the same time, studies of the accidents were carried out in different ways, and were not always accurate, due to the lack of synchronized measurement technology. But definitely state that the frequency of dangerous electromechanical oscillations was always in the range from 0.1 to 4 Hz.

The development of synchronized phasor measurement technology has provided an opportunity to monitor transients in the power system [8, 18, 19] in particularly dangerous electromechanical oscillations. However, it is not specified that for correct monitoring it is necessary to properly install PMU devices at power facilities, how to organize the structure of data transceiving, as well as solutions to create a system for retuning the parameters of control automation devices in real time. With the organization of good communication channels between facilities, it is possible to use WAMS also for emergency automatics. Consequently, this article presents a study of the possibility of using WAMS to create an adaptive system of power system mode control and dangerous LFOs.

A further step after identification is the damping of dangerous oscillations to improve stability, to achieve this, engineers and scientists have indicated the effectiveness of using PSS device [1–4, 10]. But it is not enough just to install the PSS in a power plant, its PSS parameters must be properly configured. If it is tuned incorrectly, the system stability will only decrease due to the wrong assignment for the synchronous generator's excitation system. On this basis, various ways of PSS tuning are studied [20–24, 26–29], each of which has its advantages and disadvantages related to the calculation model formation, the input data of the system, as well as the power system structure. Features of the power system structure are related to the total power consumption and generation, the length and number of transmission lines, the remoteness of power plants, and the types of excitation system with PSS.

The analysis of literature review revealed that at present, power systems with large power transmission schemes between large stations by weak lines encounter several problems due to the features of static and oscillatory stability disturbance. These problems lead to the need to develop algorithms for the transient modes identification and oscillatory stability based on WAMS data and to develop algorithms for damping dangerous oscillations using the adaptive model of the power system in the control loop. In turn, the creation of such a system will increase the power system stability and increase the transmission capacity, which is much more economical than the construction of new power lines.

3. The aim and objectives of the study

The purpose of research is to identification and damping low-frequency oscillations which pose a risk to the power system stability.

To achieve the aim, the following objectives are accomplished:

– to identify LFO which poses a risk to the system stability based on synchronized phasor measurement data from the WAMS system;

– to carry out modal analysis for evaluation of LFO parameters by determining the position of the characteristic equation roots (eigenvalue) on the s-plane;

– to define an optimal method for tuning power system stabilizer parameters to improve the oscillation stability of power system operation;

– to design an algorithm for identification and damping dangerous modes of LFO in real time when changing the parameters of the power system.

4. Materials and methods of research

4. 1. Hardware and software system for identification of low-frequency oscillations in the Republic of Kazakhstan power system

The paper discusses the identification and damping of dangerous oscillations using new methods and technologies with proposing an algorithm for real time operation.

A wide area monitoring system is based on data coming from a synchronized phasor measurement unit (PMU) and is in wide use now. WAMS allows the identification of LFO. For example, the WAMS recorded constant low-frequency oscillations between the North and South of Europe with frequencies of 0.2–0.3 Hz and between the Western and Eastern parts at 0.4–0.5 Hz [30].

Based on the successful experience of using WAMS in many power systems around the world, the System Operator of the Republic of Kazakhstan together with the research center at the Almaty University of Power Engineering and Telecommunications, implemented a WAMS system, based on General Electric equipment, in the 500-kV grid in 2019. The WAMS structure in the Republic of Kazakhstan is established by installing 39 PMU devices at 500 kV substations along the North-South transit with a length of more than 1300 km and which is connected to the power systems of Central Asia, Siberia, and Urals. The transmission network is shown in Fig. 1.

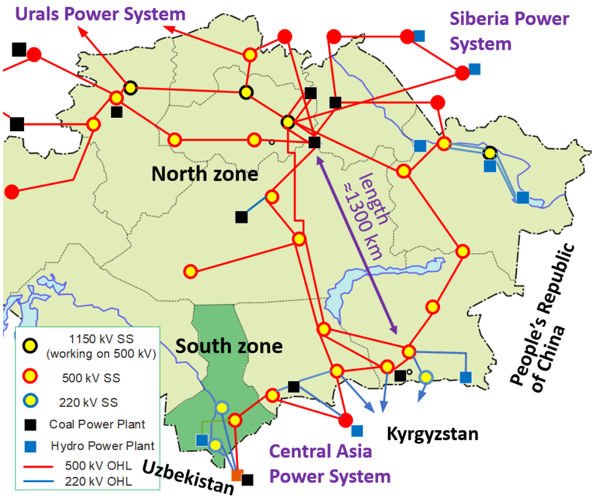


Fig. 1. The «North-South» transit of 500 kV OHL in the Republic of Kazakhstan's grid

Since the WAMS system implementation in the Republic of Kazakhstan's National Electric Networks, analytical work has been carried out on the nature of changes in mode parameters during oscillations in the system, in particular, on LFO identification.

4. 2. Evaluation methods of the low-frequency oscillations parameters

Electric power systems have a complex structure in which the network parameters the state of transmission lines, transformers, generators, and other equipment, and as a consequence, the system parameters voltage, frequency, active, reactive power, etc., are changing constantly. There are various criteria for assessing the stability and reliability of power system operation with the main classification into rotor angle, frequency, and voltage stability as shown in Fig. 2 [1].

The focus of research in this paper is to maintain the oscillatory stability of the power system, which refers to rotor angle stability. Calculations of oscillatory stability need to be performed to clarify the range of acceptable modes and to determine effective measures to prevent oscillatory instabilities using eigenvalue analysis techniques.

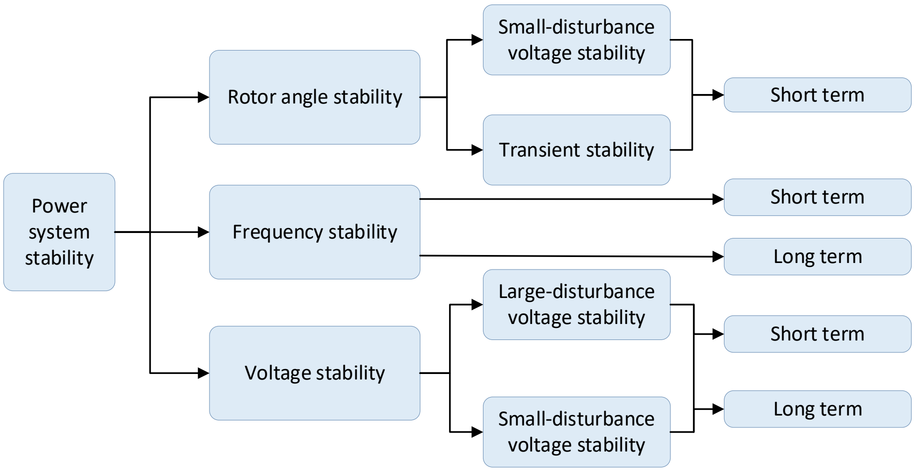


Fig. 2. System stability classification

One of the main indicators of system stability is the position of the roots of the characteristic equation (eigenvalue λ) on the s-plane [1]. An estimate of the impact of the LFO mode on the stability of the power system by eigenvalue analysis can be made by performing modal analysis [31].

Proceeding from the modal analysis, it is accepted that low-frequency modes with a negative value of damping ratio are the source of power system instability and those below 5 % are a threat to system stability. Modes in the range of 5 to 10 % also need to be controlled [5]. Accordingly, these criteria were applied in the analysis of simulation results to identify dangerous LFO modes on the system. Boundaries on the plane for the eigenvalue of LFO modes, which divides them into dangerous or safe for power system stability, and modes that are worth paying attention to are shown in Fig. 3.

The real eigenvalue component shows damping and the imaginary component shows the oscillation frequency. The negative real part represents the damped oscillation and the positive part the increasing oscillation. Accordingly, this eigenvalue pair (λ) is expressed as (1):

$$\lambda_i = \sigma_i \pm j\omega_{di}, \tag{1}$$

where σ is damping coefficient; $j\omega_{di}$ is frequency of oscillation. The frequency of oscillation in Hz: $f=\omega/2\pi$.

This corresponds to the actual or damped frequency. For real-time data analysis, it is important to know the damping ratio (ζ) calculated from the expression (2):

$$\zeta_i = \frac{-\sigma_i}{\sqrt{\sigma_i^2 + \omega_{di}^2}}, \tag{2}$$

The damping ratio (ζ) determines the rate of damping of the oscillation amplitude. An important indicator of the damping ratio of low-frequency oscillations is the damping time (t), which is the time in which the maximum amplitude of the oscillation decreases to 36.7 % ($1/e$) of its initial value.

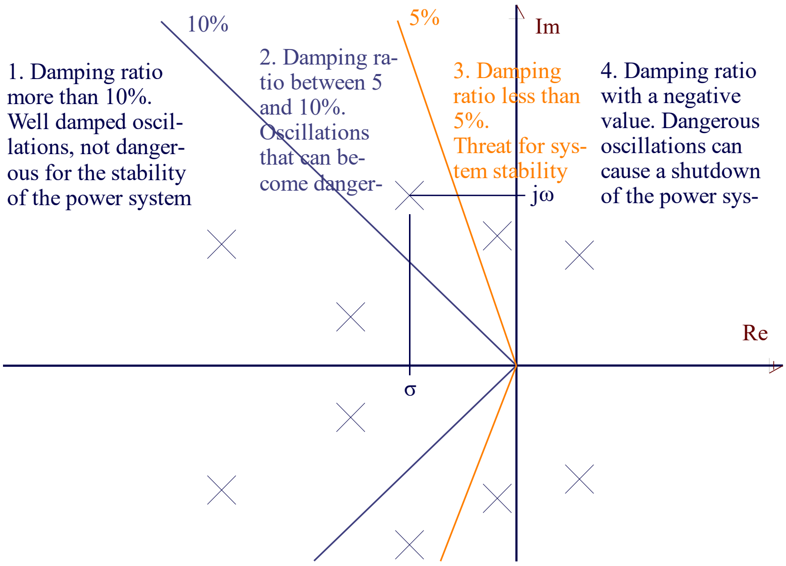


Fig. 3. Eigenvalue location on the s-plane

For identification of dangerous modes with a damping ratio of less than 5 % on the s-plane was developed model of the Republic of Kazakhstan power system on the program DigSilent:PowerFactory.

4. 3. Tuning power system stabilizer parameters using the residue method

PSS is part of the excitation system of a synchronous generator. It is necessary for damping of LFO and accordingly stabilization of the power system. The location of the PSS in the generator control system, as well as its input and output signals, are shown in Fig. 4.

The following is a brief description of this method for tuning the PSS parameters. Let's consider the simplest PSS feedback circuit, shown in Fig. 5. The input signal in the transfer function used to calculate $H(s)$ is the regulator reference voltage and the output signal can be the rotor speed of the generator, the electrical power at the generator output, or eventually, the accelerating power ($P_a=P_m-P_e$). These output variables are chosen because they are associated with high participation factors in the analysis of electromechanical modes.

The main equation for the PSS transfer equation, T_{pss}, is (3):

$$T_{PSS} = K_{PSS}\left|H_{PSS}\right|e^{j\arg(H_{PSS})}. \qquad (3)$$

Provided that the transfer function of the feedback is only a gain of a relatively small value, the shift of the eigenvalue is opposite to the direction of the residual connected as shown in Fig. 6 and described by (4):

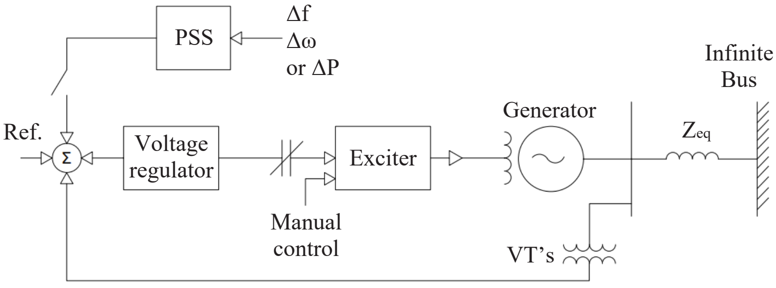


Fig. 4. Generator control structure

$$\frac{\partial\lambda_i}{\partial k} = -r_i \to \partial\lambda_i = -r_i k. \qquad (4)$$

Considering the whole PSS transfer function, (4) changes to (5), (6):

$$\Delta\lambda_i = -r_i K_{PSS} H_{PSS}, \qquad (5)$$

$$\Delta\lambda_i = -K_{PSS}\left|r_i\right|\left|H_{PSS}\right|e^{j(\arg(r_i)+\arg(H_{PSS}))}. \qquad (6)$$

It is usually necessary to increase the damping of the mode without too much change in its frequency, since the PSS is tuned to a specific mode and, therefore, to a specific frequency. One way to proceed is to change the direction of the displacement (initially $\arg(r_i)+180°$) by correctly selecting $\arg(H_{PSS})$ to make this eigenvalue move along the real axis to the negative side (Fig. 7 and (7)):

$$\arg(r_i)+\arg(H_{PSS})=0 \leftrightarrow$$
$$\leftrightarrow \arg(H_{PSS})=-\arg(r_i). \qquad (7)$$

Based on the fact that change the direction of the displacement for 180° may not always be optimal the residue method for tuning PSS continues to be developed [32, 33].

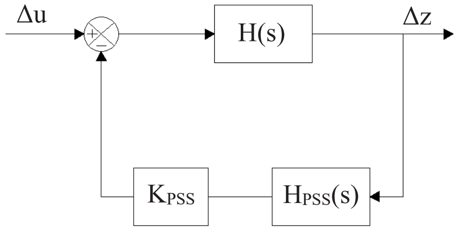


Fig. 5. Power system stabilizer feedback diagram

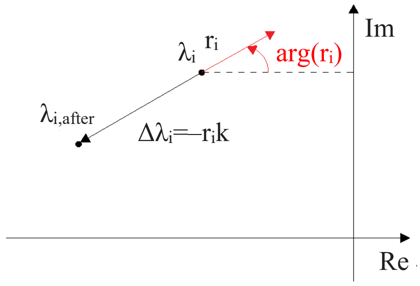


Fig. 6. Eigenvalue displacement due to a feedback transfer function of gain *K*

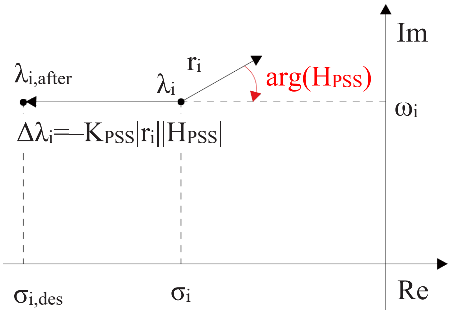


Fig. 7. Eigenvalue displacement with a tuned power system stabilizer

5. The results of the low-frequency oscillations identification and revised algorithm for their damping

5. 1. Identification of low-frequency oscillations in the Republic of Kazakhstan power system by using Wide Area Measurement System

A study of oscillatory stability using the WAMS in the Republic of Kazakhstan's grid showed the presence of non-damped inter-area LFO with frequencies range of 0.3–0.4 Hz and oscillation duration of up to 4–5 minutes. These LFOs not only limit the power flow capacity of the North-South transit but can also lead to major system accidents in the post-fault regime during transit operation in the maximum allowed power flow. Over the monitoring period, the longest and weakly damped LFOs were selected and identified. Recorded events for the period 2020–2021 on transit «North-South» of the Republic of Kazakhstan's grid are shown in Table 1.

Based on the recorded LFOs in the Republic of Kazakhstan's grid specified in Table 1, it can be concluded that a significant part is inter-area oscillations. Further, using the example of events No. 1, 2 mentioned in the table, graphs from the WAMS system on the change in active power, voltage, and frequency for the objects of the 500-kV network are presented.

Event No. 1. Date 2020-11-25, start time 11:52:20, duration of oscillatory process 9 minutes, frequency of LFO – 0.35 Hz.

The maximum amplitude of the power flow oscillations during the LFO event is fixed at OHL-500 kV Shu-Frunze and is about 140 MW, the transmitted active power fluctuates in the range from 640–500 MW as shown in Fig. 8).

The maximum amplitude of system frequency oscillations is fixed on the «Shu» 500 kV substation and the oscillations in the range of 49.96–50.02 Hz are shown in Fig. 9. The nominal frequency of the system is 50 Hz.

Event No. 2. Date 2020-12-14, start time 08:45:55, duration of oscillatory process 4 minutes, frequency of LFO – 0.31Hz.

The maximum amplitude of the power flow oscillations during the LFO event is fixed at 500 kV OHL «Republic of Kazakhstan – Central Asia» and is about 150 MW, the transmitted active power fluctuates in the range from 520 to 740 MW as seen in Fig. 10.

The maximum amplitude of system frequency oscillations is fixed on the «Zhambyl» 500 kV substation and oscillations in the range of 49.98–50.05 Hz in Fig. 11.

Analysis of mode parameters in the power system of the Republic of Kazakhstan and Central Asia by using WAMS shows weak damping of the LFO with a frequency range of 0.3–0.4 Hz along the entire transit «North-South», which indicates the presence of inter-area oscillations.

5. 2. Evaluation results of the low-frequency oscillations parameters

In the developed model of the Republic of Kazakhstan power system on the program DigSilent:PowerFactory, dangerous modes with a damping ratio of less than 5 % are identified on the s-plane. It was determined that the source of these is the Moynak hydropower plant, which is connected to the system by two 220 kV transmission lines with a length of about 220 km. The results of the eigenvalue analysis are shown in Fig. 12.

Table 1

Results of LFO monitoring in 500 kV power grid by using WAMS

No.	Date (day/month/year)	Oscillations start time (hour/min/sec)	Duration of oscillations,	Natural frequency of LFO, Hz	Maximum fixed oscillations amplitude of:		
					Active power, MW	Voltage, kV	Frequency, Hz
1	25.11.2020	11:52:20	9 min.	0.35	±140	±10	±0,06
2	14.12.2020	08:45:55	4 min.	0.31	±150	±20	±0,07
3	18.12.2020	08:43:40	4.5 min.	0.38	±100	±7	±0,05
4	12.032021	21:29:40	3 min.	0.33	±70	±10	±0,04
5	12.03.2021	21:36:30	4 min.	0.34	±80	±15	±0,05
6	16.03.2021	19:56:30	4.5 min.	0.36	±80	±15	±0,05

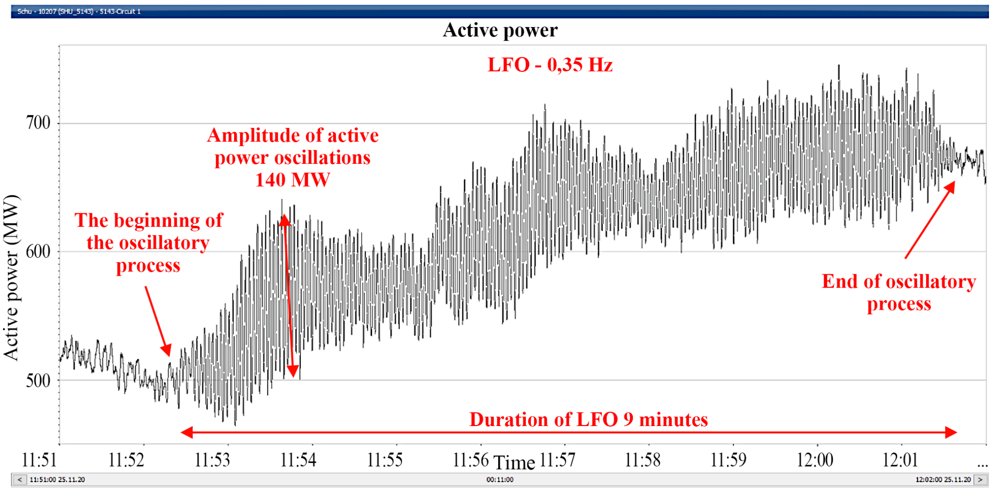


Fig. 8. Graph of active power change on 500 kV line in South zone, MW

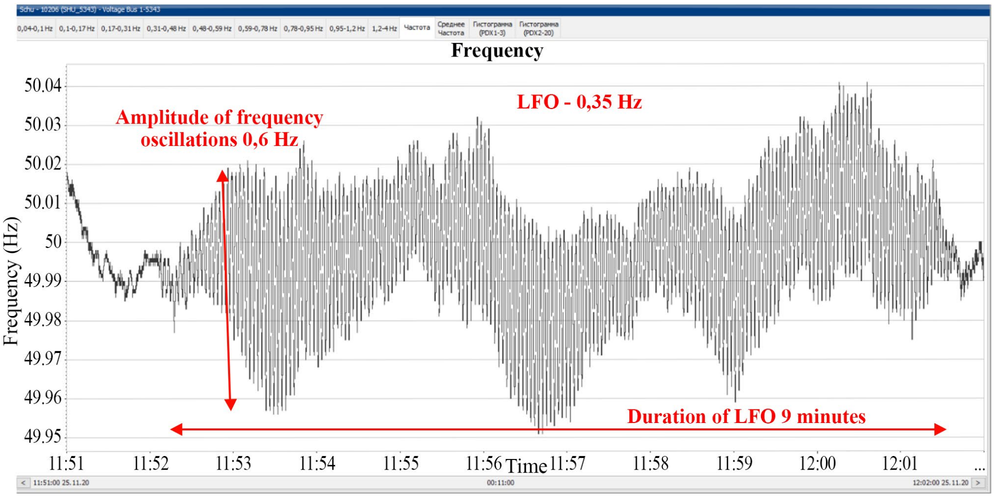


Fig. 9. Graph of frequency change at «Shu» 500 kV substation (South zone), Hz

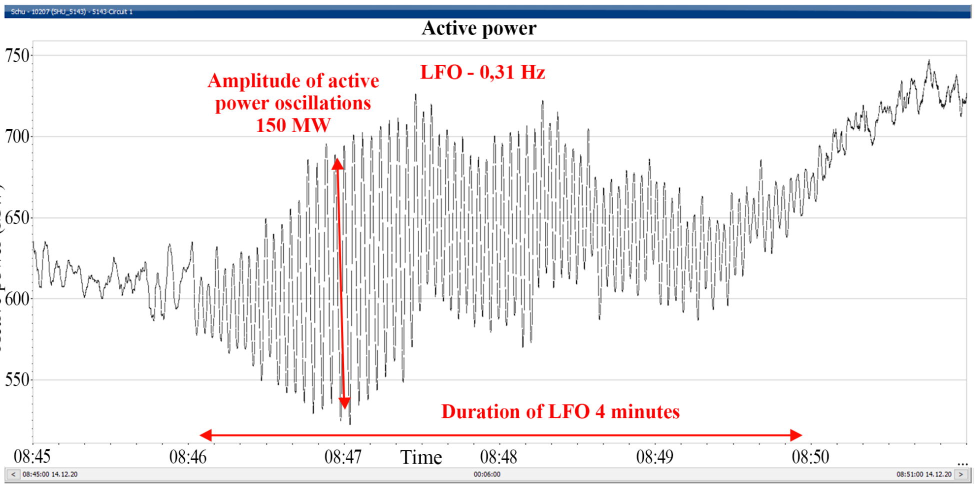


Fig. 10. Graph of active power change on 500 kV OHL «Republic of Kazakhstan – Central Asia», MW

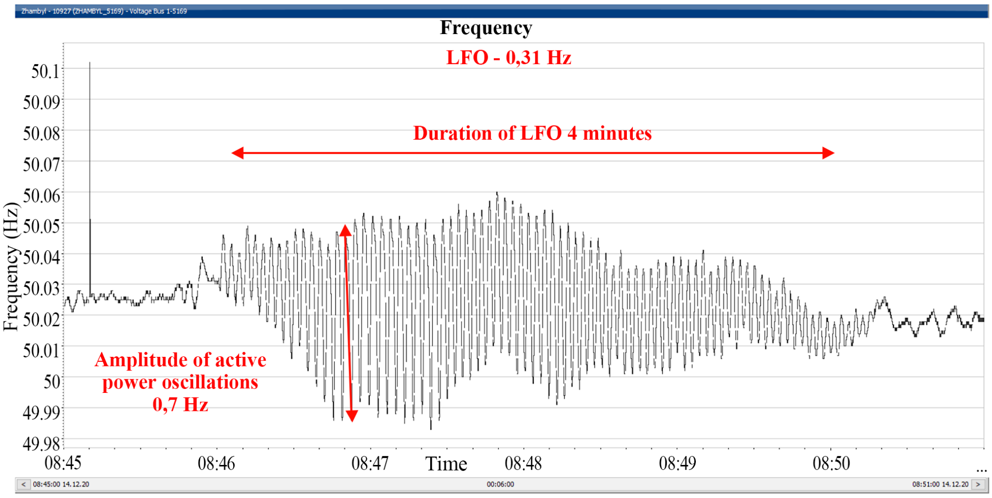
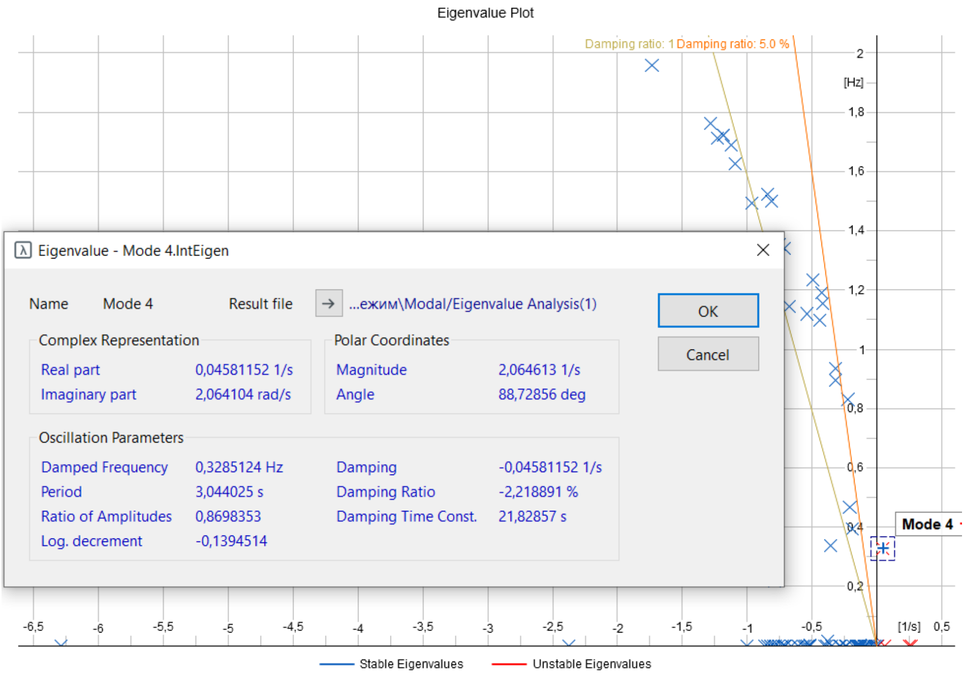


Fig. 11. Graph of frequency change at «Zhambyl» 500 kV substation (South zone), Hz

The eigenvalue plot, Fig. 8, shows the presence of the dangerous LFO mode with a frequency of 0.328 Hz and a damping ratio is 2.2 %. In addition to this mode, there are also LFOs in the frequency range from 0.39 Hz to 1.6 Hz with a damping ratio of less than 10 %.

Therefore, identified electromechanical oscillations with a frequency of 0.3–0.4 Hz in the power system of the Republic of Kazakhstan according to WAMS, were also determined in the developed model by eigenvalue analysis on the plot.



Name Mode 4 Result file ...ежим\Modal/Eigenvalue Analysis(1)

Complex Representation

Real part 0,04581152 1/s
Imaginary part 2,064104 rad/s

Polar Coordinates

Magnitude 2,064613 1/s
Angle 88,72856 deg

Oscillation Parameters

Damped Frequency 0,3285124 Hz
Period 3,044025 s
Ratio of Amplitudes 0,8698353
Log. decrement -0,1394514
Damping -0,04581152 1/s
Damping Ratio -2,218891 %
Damping Time Const. 21,82857 s

Fig. 12. Modal analysis for Moynak HPP in the Republic of Kazakhstan's power system

5. 3. Damping of low-frequency oscillations with tuning power system stabilizer using revisited residue method

New research has determined that phase compensation at 180° is not always optimal when looking for PSS parameters, and a better result may be at a different angle. If the phase compensation is calculated together with the gain coefficients using a consistent optimization problem, better results are achieved [32]. It is thus necessary to consider the change in the phase shift to the optimal angle, as shown in Fig. 13.

Once the displacement λ_i is in the desired direction, the new goal is to obtain the desired degree of damping $\zeta_{i,\,des}$ for that mode (8):

$$\zeta_{i,des} = -\frac{\sigma_{i,des}}{\sqrt{\sigma_{i,des}^2 + \omega_{di}^2}} \leftrightarrow \sigma_{i,des} = -\frac{\zeta_{i,des}\omega_i}{\sqrt{1-\zeta_{i,des}^2}}. \tag{8}$$

For small $K_{PSS}|H_{PSS}|$ values, the following equation holds (9), (10):

$$|\Delta\lambda_i| = |\sigma_i - \sigma_{i,des}| = K_{PSS}|H_{PSS}||r_i|, \tag{9}$$

$$K_{PSS}|H_{PSS}| = \frac{|\Delta\lambda_i|}{|r_i|}. \tag{10}$$

After tuning the PSS parameters by this method and considering the optimal phase shift, it is necessary to perform modal analysis and calculate the system's transient process parameters to obtain positive results for the damping of LFO. At the same time, it is necessary to tuning PSS parameters to increase the damping of the investigated dangerous LFO modes and not to worsen the state of other modes.

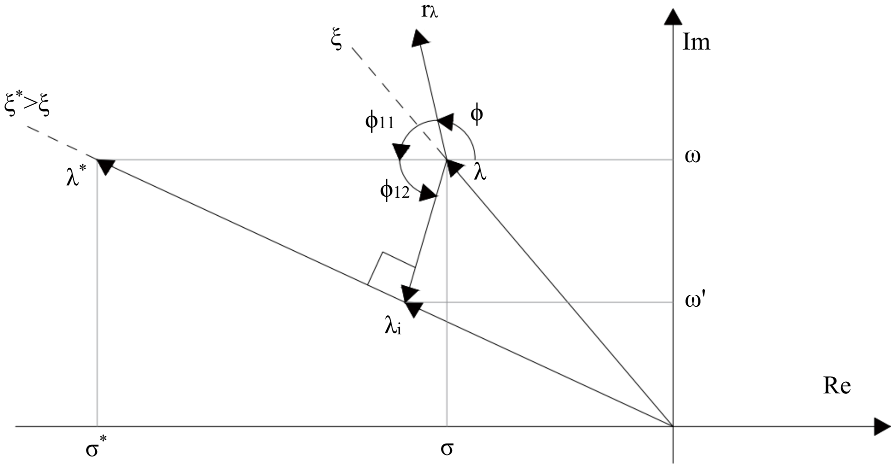


Fig. 13. Eigenvalue displacement with a well-tuned power system stabilizer

5. 4. Results of the developed algorithm for identification and damping low-frequency oscillations

This section presents the algorithm for tuning the PSS parameters for damping dangerous LFO. The novelty is the study of applying the residue possibility method when creating a model of the generator and power system based on data from the WAMS and Supervisory Control and Data Acquisition (SCADA) systems. Application of real-time data from WAMS with the creation of a Wide Area Damping System (WADS) to improve the stability and damping of LFO is actively studied these days [34–37].

Based on the described criteria for assessing the dangerous LFO modes using the eigenvalue analysis methods (eigenvalue analysis), the analysis of PSS tuning methods and the possibility of updating the model according to the WAMS and SCADA systems, a new algorithm, shown in Fig. 14, for damping of LFO oscillations in real time is proposed.

According to the proposed algorithm, the PSS parameters will be tuned based on real-time data from WAMS and SCADA and the residue method for calculation parameters.

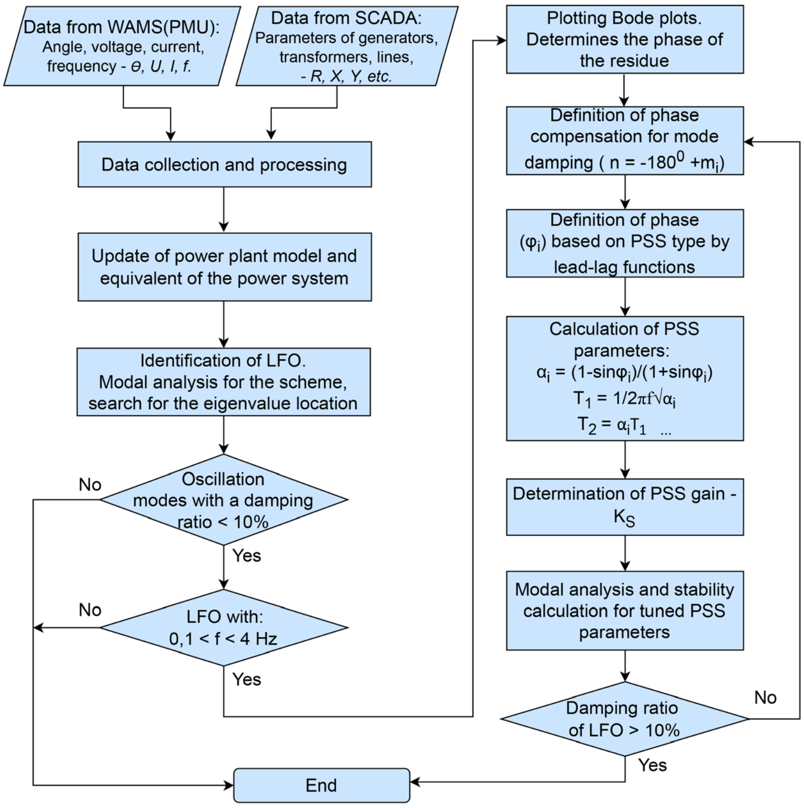


Fig. 14. Proposed algorithm for damping dangerous low-frequency oscillations modes based on residue method

6. Discussion of the results of the proposed algorithm for identification and damping low-frequency oscillations

Identification and analysis of electromechanical oscillations in the Republic of Kazakhstan power system by using WAMS shows weak damping of the LFO. Frequency range of dangerous LFO are 0.3–0.4 Hz along the entire transit «North-South», as presented in Table 1, which indicates the presence of inter-area oscillations. Accordingly, the weak damping of the LFO in the power system of the Republic of Kazakhstan may indicate the need to adjust the operation of the excitation system, in particular, the PSSs at the power plants and the neighboring Central Asia republics for damping inter-area LFOs.

The modal analysis on eigenvalue plane in the developed South zone of the Republic of Kazakhstan power system shows the presence of the dangerous LFO mode. As shown in Fig. 8, this oscillation has a frequency of 0.328 Hz and a damping ratio is 2.2 %. In addition to this mode, there are also LFOs in the frequency range from 0.39 Hz to 1.6 Hz with a damping ratio of less than 10 %.

For damping dangerous modes of low-frequency oscillations by tuning PSS parameters with the revisited residue method. The method is considering the optimal phase shift, it is necessary to perform modal analysis and calculate the system's transient process parameters to obtain positive results for the LFO damping.

As a result, the paper presented an algorithm for the LFO identification, evaluation of their danger and further damping by retuning the PSS parameters. Based on the structure of the proposed algorithm, the current state of the generators, step-up transformers, and power lines come as telemetry information from the SCADA server. Synchrophasor measurements of voltage angle, voltage magnitude, current, and frequency come from the WAMS server. After receiving the information, the following is performed an assessment of the power system state, calculation of the mode, calculation of transient's stability, modal analysis, identification of local and inter-area dangerous LFO modes, and identification of sources of instability. After the identification of dangerous LFO modes (with frequency from 0.1 to 4 Hz) starts the process of calculating the PSS parameters for damping LFO. The process of PSS parameters tuning begins with the formation of the power plant connection diagram to the system. In the PSS parameters tuning algorithm, the first step is the construction of a Bode diagram and the second step is the calculation of parameters with the residue revisited method. After tuning the PSS parameters, the next stage is the verification of the new parameters by modal analysis and transient stability calculation in the power system model. If the damping ratio is insufficient (less than 10 %), the PSS parameters are corrected according to the revisited residue method. Overall, according to the proposed algorithm, PSS parameters will be tuned based on the current state of the power system.

In real operation, the proposed algorithm will have limitations due to the quality of data transmission channels from power facilities to the central WAMS server [38] and quantity and locations of PMUs in power system [39]. Also, method has technical difficulty in identifying the dangerous LFO mode in real time because of data transmission delay [40]. Timely determination of dangerous LFO is necessary for the tuning PSS parameters at specific generator and further damping this LFO. Also, for the reason that in a large power system main frequency is not the same at every area, which makes it difficult to determine the specific generator where the PSS parameters need to be tuned.

Therefore, the development of this study may consist of optimize the WAMS uncertainties and refinement of search the dangerous LFO modes for definition which eigenfrequency of electromechanical oscillation need to damp by tuning PSS at specific generator or group of generators.

7. Conclusions

1. According to the WAMS data, identification of inter-area electromechanical oscillations, and determination of their frequencies and oscillations amplitude were performed. The WAMS system in the Republic of Kazakhstan is implemented by installing 39 PMU devices at 500 kV substations and server equipment in the dispatch center of the System Operator. Over the past 3 years, an analysis of electromechanical oscillations has been conducted, which identified that the LFO frequencies are in the range from 0.3 to 0.4 Hz, with the amplitude of the active power oscillations on the power lines to 150 MW and duration up to 9 minutes. Thus, the presence of prolonged electromechanical power oscillations in the power grid of the Republic of Kazakhstan was determined.

2. The modal analysis in the developed model of the Republic of Kazakhstan power system shows the dangerous LFO modes with a damping ratio is 2.2 % having eigenfrequency of 0.328 Hz and also LFOs with a damping ratio of less than 10 % having eigenfrequency range from 0.39 Hz to 1.6 Hz. These oscillations indicate an insufficient tuning of PSS parameters at power plants when changing the structure of the power system, especially ay Moynak HPP. Accordingly, it is necessary to retune the PSS parameters whenever changing the structure of the system.

3. An analysis of the existing methods of tuning PSS consisting of those used in practice and of scientific interest are presented. The residue method is investigated in detail, and accepted that optimizing the phase compensation for better damping of dangerous LFO modes because the compensation at 180° is not always optimal. An algorithm for tuning PSS parameters based on the WAMS synchrophasor measurements analysis, control of the power system parameters from SCADA data, identification of dangerous LFOs and the revisited residue method for tuning PSS parameters is proposed in this paper.

4. The proposed algorithm consists of three tasks – the first task is data collection from WAMS, and SCADA systems and updating the calculation model based on the current structure of the power system, the second task is the identification of dangerous LFOs and modal analysis, and the third task based on a revisited residue method for determining the tuned PSS parameters and verification of the new parameters by modal analysis and transient stability calculation in the power system model. Consequently, using the proposed algorithm, PSS parameters will be tuned for damping dangerous LFOs modes based on the current structure of the power system.

Simulation results according to the algorithm on the Republic of Kazakhstan's real power system example with the tuning of PSS parameters will be presented in Part II.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The manuscript has no associated data.

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