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IMPROVING THE EFFICIENCY OF MODE AUTOMATION USING SYNCHROPHASOR MEASUREMENTS TO IDENTIFY STABILITY DISTURBANCE

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The paper presents new approaches and principles for identifying the conditions of stability disturbance based on detecting dangerous disturbances in the early stages using information about changes in regime parameters and their Rate of Change. As a mode parameter, the mutual voltage angle between the controlled 500 kV substation and its Rate of Change was selected in the study. It is suggested to take the values of the mentioned parameters from the Wide Area Measurements System (WAMS). The relevance of the research is due to the need to improve the efficiency and eliminate the drawbacks of existing revealing devices of regime automatics, which will reduce the number of accidents due to disturbances of the power system stability. The proposed principle of predicting stability violation is based on using the provision of Lyapunov's stability theory, according to which the assessment of stability is carried out by the total system energy consisting of kinetic and potential. In contrast to the existing principles of detecting stability violation, where the exit from the stability area is determined by the main parameter (potential energy), the prediction principle allows evaluating stability by its rate of change (kinetic energy), which provides the early detection of stability disturbance.

Calculations were performed on modeling power surges in the North-South interconnection of the Kazakhstan Unified Energy System in the «DigSILENT Power Factory» software on the model, which was verified by real perturbations in the power system according to the WAMS data. The calculations confirmed the effectiveness of the proposed principles and the possibility of using WAMS data for detecting emergency power surges on transit power networks in the initial stage

Keywords: mutual voltage angle, emergency control system, synchrophasor measurements, electric power systems stability, WAMS

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1. Introduction

The reliable and uninterrupted operation of electric power systems is an important aspect of energy security. Ensuring this parameter is achieved by using a number of systems and devices aimed at preventing emergency situations. The purpose of many works and studies is to improve the reliability of power systems, including in the event of abnormal situations in them.

Improving the reliability of the Republic of Kazakhstan Unified Energy System (UES) in keeping with the concept of an Intelligent Electric Grid (Smart Grid) [1] is achieved by creating systems for the management of Electric Power Systems (EPS) in real-time based on digital systems for monitoring the state of the EPS. Also, as required by Electric Grid Rules [2], it is necessary to ensure the reliability of the Republic of Kazakhstan UES under regulatory perturbations. On the way to the implementation of this concept [1], at the moment in the Republic of Kazakhstan UES, in the «KEGOC» JSC company (system operator of the Republic of Kazakhstan), a Wide Area Measurement System (WAMS) is installed [3, 4], which includes a server processing and monitoring measurements and 16 measuring devices PMU (Phasor Measurement Unit), installed at 14 substations (SS) of the 500 kV «North-South» interconnection [5]. This system allows visualization, display, and observation of information about regime parameters and solves many other dispatcher tasks in real-time, and also can be used in protection and control systems [6, 7].

But the most important issue in the introduction of this system is the development of an emergency control system to ensure stable parallel operation of the Republic of Kazakhstan UES and the Central Asia UES on the North-South transit. To solve this problem and increase the emergency control system efficiency and, first of all, devices of automatics against power surges, the authors of this paper investigate the creation of an adaptive emergency control system WAMS information to increase the stable operation of the power system. Therefore, research on improving the efficiency of mode automation is relevant for power system stability.

2. Literature review and problem statement

The paper [8] gives a detailed review of the principles, methods, classification of the issues of forecasting the stability of electric networks. In the work, one of the classes of studies considered is those in which WAMS is used for predicting transient stability. This indicates significant prospects for the application of WAMS systems in the identification and prediction of stability disturbance conditions.

Many of the studied papers consider the issue of stability locally, directly on the busbars of generators. For example, in [9], a model-free approach for online rotor angle stability assessment was proposed based on the maximal Lyapunov exponent (MLE). By using the proposed MLE estimation algorithm, parameter setting rules, and stability criteria, the approach can identify the system stability condition online by using phasor measurement unit (PMU) data. The approach does not need a predetermined observing window to identify the sign of the MLE and can provide reliable and timely assessment results by analyzing the features of the estimated MLE curve.

Another paper [10] presents a new algorithm for out-of-step prediction by using generator acceleration power and rotor speed deviation. In this online method, the trajectory of acceleration power according to rotor speed deviation is drawn in a Cartesian coordinate system. After fault clearance, the trend of this curve will be predicted using the ellipse function curve fitting.

The work [11] presents a method that enables quick real-time predictions of transient instability and the number of generators that must be tripped. The proposed method uses only local measurements and is based on the quick prediction of the magnitude of the power-angle characteristic.

The practical application of such studies on the assessment and prediction of stability locally directly on the busbars of generators is not appropriate for the 500 kV interconnection on the example of the Republic of Kazakhstan, taking into account the current structure of WAMS and due to the large number of power plants in the power systems operating in parallel.

Also, many studies use various machine learning systems or neural networks to predict stability disruptions in the power system. Most of them mainly include two stages [12]: offline training and online application. The stability classifier is learned during the training stage where a large-scale stability/instability database from time-domain simulations is required. For the online application stage, with post-fault dynamic features, e.g., rotor angles entered into the classifier, the instability status can be detected in advance.

For example, the paper [12], using PMU measurements, proposed a model-free method to predict post-fault transient instability and develop emergency generator-shedding control. In [13], a continuous Online Monitoring System (OMS) for power system stability based on Phasor Measurements (PMU measurements) at all the generator buses is proposed. According to the architecture of the WAMS system in the Republic of Kazakhstan and the lack of PMU devices on the generators of many plants, this method is not feasible to implement in the Republic of Kazakhstan UES.

Another paper [14] proposes a novel unified prediction approach for both small-signal and transient rotor angle stability. Deep learning techniques are employed in this paper to train an online prediction model for rotor angle stability (RAS) using the voltage phasor measurements, which are collected across the entire system.

In [15], some trajectory features are selected, which are independent of the size and type of the power system. For stability prediction, the convolutional neural network (CNN) with a novel companion objective function, called twin convolutional support vector machine (TWCSVM), is used. The most noteworthy performance of the proposed approach is 86.27 %, with ten cycles of features length.

To apply these techniques on the example of the Republic of Kazakhstan power system, significant research, collection of a sufficiently large amount of data for training neural networks, and investment for the deployment of such a system are required. The magnitude and complexity of the solution to these problems make it difficult to use them on the «North-South» transit because it has a considerable length and power withdrawal of up to 500 MW in the supplying substations of Central Kazakhstan, as well as the location of a branched group of generators at the ends of the transit.

At present, the following complexes of emergency control systems are in operation in the Republic of Kazakhstan UES:

– centralized emergency control system. The dosage of control actions is performed in the control loop. Triggering is performed upon the fact of identifying the disconnection of the 220–500 kV overhead line (OL);

– local systems. Control actions are introduced upon identifying the conditions of reaching the stability disturbance using revealing bodies, and the condition for triggering is the exit of the observed parameters (voltages or active power overflows) beyond the setpoints.

In both cases, the efficiency of the systems is achieved by using raw data obtained from the systems that monitor the current state of the system and algorithms that provide accurate dosage control, by the general requirements of emergency control systems in terms of speed, reliability, and selectivity.

Existing emergency control systems have numerous other functional and hardware limitations:

1. Tuning is calculated in advance, according to the worst-case scenario of possible circuit-mode situations, while the actual network capacity changes continuously, both in terms of season and time of day and the limit on static stability.

2. Scheduled updating (revision) of the settings of emergency control systems requires a large number of calculations, and further coordination with related power systems, which requires a significant amount of time (several months).

3. It should also be noted that to simplify the existing structure of the emergency control system, as a rule, control over the disconnection of network elements only in the normal scheme and during single repairs is laid in the configuration of automatics. In some cases, this leads to a reduction of permissible overflows in repair circuits.

As an example of the «North-South» interconnection, one of the local systems of the emergency control system is the automation from a power surge, installed on the «YUKGRES» SS and «Taldykorgan» SS. This system was installed on the «YUKGRES» SS before the third line in the 500 kV «Semey – Aktogay – Taldykorgan – Alma» network in 2019 and works only with the control of power flow over two 500 kV «Agadyr – YUKGRES» overhead lines. This system has control impacts on 500 kV shunt reactors on the «YKGRES» SS and load shedding in the Southern zone of the Republic of Kazakhstan UES (Almaty, Zhambyl, Turkestan regions) and the Central Asia UES (as agreed with the power systems). The present settings are designed for operation in the maximum mode of the network on the North-South emergency permissible interconnection overflow with a margin of less than 8 % in terms of static stability.

After the commissioning of the 500 kV «Ekibastuz – Semey – Aktogay – Taldykorgan – Alma» overhead line with the formation of the 500 kV «Ekibastuz – Almaty – Ekibastuz» ring, the principles of mode control became much more complicated. This is because the natural flux distribution along individual «shoulders» of the interconnection varies in a wide range during the day. In this regard, it is impossible to provide the adjustment of both devices of automatics from power surges, which would simultaneously meet the requirements of ensuring reliability and minimizing the volume of control actions.

The experience in using the above-mentioned devices shows that local systems in several cases do not provide the desired efficiency and often, as a result, there are conditions for the development of major system accidents, as an example of a blackout that occurred in the Central Asia UES on January 25, 2022. Under such conditions, the creation of new principles of emergency control systems is required to identify and prevent disturbance of stability.

3. The aim and objectives of the study

The aim of this work is to improve the effectiveness of mode automatics when using new principles of identifying the conditions of stability disturbance according to WAMS data. This research will make it possible to predict the condition of stability disturbance ahead of time before the system leaves the stability area.

To achieve this aim, the following objectives were set:

– to evaluate the possibility of applying the WAMS data to obtain the necessary information for identifying the conditions of stability disturbance in the pace of the process;

– to develop and verify the model of the 500–220 kV network of the Republic of Kazakhstan UES with adjacent power systems to conduct computer simulation of the proposed method;

– to simulate and analyze the effectiveness of detecting power surges by the proposed principle of detecting stability disturbance using the parameters of changes in the mutual angle and its rate.

4. Materials and methods

4. 1. Prospects of application of emergency control using mutual angle (δ) in the interconnection

At present, the Republic of Kazakhstan UES operates in parallel with the russia UES and the Central Asia UES. Communication between the Northern and Southern zones of the Republic of Kazakhstan UES is carried out by 500 kV triple-circuit overhead lines with a length of about 1,200 km. The same 500 kV overhead lines cover the power deficit in the Republic of Kazakhstan UES Southern zone in the amount of about 2,000 MW, which loads the «North-South» interconnection to the maximum permissible values of power overflows. An urgent issue today in terms of maintaining stable parallel operation is the frequent power surges on the «North-South» interconnection of the Republic of Kazakhstan UES in connection with the emergency events in the Central Asia UES. The existing automatics from power surges installed on this link operates with insufficient efficiency.

Studies to assess the stability of 500 kV power networks were performed on the example of the «North-South» interconnection and its 3 500 kV overhead lines. The schematic map of the Republic of Kazakhstan UES is shown in Fig. 1.

Fig. 1. Schematic map of 500 kV power grids of the Republic of Kazakhstan Unified Energy System included in the «North-South» interconnection

The main limitation of the transmitted power along the interconnection is the static stability limit [16, 17], which is calculated in advance, according to the worst-case scenario of possible circuit-mode situations, while the actual network capacity changes continuously, both in terms of season and time of day.

The solution to this limitation can be successfully served by using the data of the synchrophasor system, which allows controlling the network stability areas by the most informative parameters of the mutual angle (δ) in real-time. The use of the mutual angle (δ) between the ends of the «North-South» interconnection became possible with the introduction of the WAMS (Wide Area Measurement System) by KEGOC in 2019, which allows for revising the reliability standards of the «North-South» interconnection and switching from monitoring active power and voltage flows to monitoring the mutual voltage angle (δ).

In the works of the authors [18–20], the results of studies on the justification and use of the mutual angle (δ) between the «Ekibastuz» SS and «Almaty» SS as a measured indicator of static stability disturbance are given.

4. 2. Theoretical foundations for predicting instability in the power system

The advantages of stability control by the mutual angle (δ) are most indicative when controlling and predicting the system condition going beyond the stability area upon the occurrence of emergency unbalances at power surges [18–20].

The theoretical basis of stability disturbance in the power system is given further. In the proposed method, stability violation is predicted by the deviation of the observed parameters and the Rate of their Change. The theoretical basis of this method for predicting the disturbance of dynamic stability is based on the use of stability estimation by the second Lyapunov method. In the electric power industry, this method is presented as the «area method».

According to the second Lyapunov's method [16, 17] concerning the stability of EPS, the total energy of the system generators motion in the transition process should not be greater than the potential energy at the critical point, defined by the mutual angle between the accelerating and braking parts of the system (between the generators on different sides of the section):

$$V_{fi} = V_K\left(T_y W_i\right) + V_\delta\left(\delta_i\right), \qquad (1)$$

where V_K – kinetic energy of motion of generators; V_δ – potential energy in the post-emergency mode; V_{fi} – total energy of the system at the boundary point at the mutual angle.

Condition (1) defines the region of the steady state of the system at any time in the transient process after perturbation. According to the second Lyapunov method, the steady state of the system defined by (1) must not be greater than the potential state at the critical point, defined by the mutual angle between the accelerating and braking parts of the system (between the generators on different sides of the section):

$$V_S \le V_{S_{fi}}, \qquad (2)$$

where $V_{S\,fi}$ – total energy of the system at the boundary point at the mutual angle.

Condition (6) can be fulfilled at:

$$V_K \le V_{S_{fi}} \text{ if } V_\delta = 0, \qquad (3)$$

or

$$V_\delta \le V_{S_{fi}} \text{ if } V_K = 0. \qquad (4)$$

Conditions (2)–(4) make it possible to predict the location of the system in the stability region by the value of total energy, or separately by the value of kinetic energy at equal kinetic energy.

For power surges with a considerable increase in the kinetic energy of the system, conditions (2), (3) come much earlier than condition (4), which allows us to predict the stability disturbance by the Rate of Change of the mutual angle before the system reaches the boundary of the stability region. Condition (3) occurs when the system moves monotonically to the stability boundary in cases of small power surges on the coupling at a small Rate of Change in the mutual angle.

5. Results of research on improving the efficiency of mode automatics

5. 1. Using synchrophasor measurements to predict conditions of stability disruption

To study this issue, we used the physical data obtained from the WAMS system during the power surge from the Central Asia UES in the volume of 700 MW and the recorded transient process on one of the 500 kV «Agadyr – YKGRES» overhead lines of the «North-South» interconnection (Fig. 2).

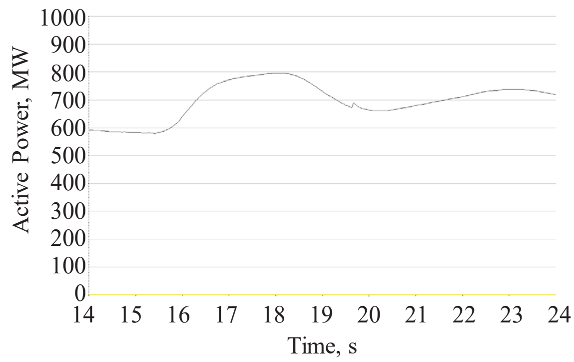

Fig. 2. Plot of change in the active power flow along the «North-South» interconnection from the Wide Area Measurements System with a power surge from the Central Asia Unified Energy System of about 700 MW

Using the WAMS data on this disturbance, the graphs of monitored parameters were constructed:

1) The graph of change of the mutual angle (δ) between the «Ekibastuz» SS and «Almaty» SS. The mutual angle is calculated as the difference of voltage angles between the monitored SS:

$$\delta = \left(\varphi_1 - \varphi_2\right), \qquad (5)$$

where φ_1 – voltage angle at the «Ekibastuz» substation; φ_2 – voltage angle at the «Almaty» substation.

Change of the mutual angle (Δδ) – the difference between the current and previously measured value of mutual angle (δ):

$$\Delta\delta = \left(\delta_t - \delta_{t-1}\right), \qquad (6)$$

where φ_t – current mutual angle measurement; φ_{t-1} – previous measurement of the mutual angle 20 ms ago.

2) Mutual Angle Rate of Change (S) graph – the ratio of mutual angle change (Δδ) to the measurement period equal to 0.02 s:

$$S = \frac{d\delta}{dt} = \frac{\Delta\delta}{0.02} = \frac{\left(\delta_t - \delta_{t-1}\right)}{0.02}. \qquad (7)$$

From the graphs in Fig. 2, 3, it can be seen that the change in the size of power overflow and mutual angle (δ) up to the maximum value is reached for 1.5–2 s and the maximum values of Rate of Change less than for 1 s. According to the presented dependences (Fig. 3) obtained from the data of real measurements, it can be seen that curve S shows the appearance of a power surge at earlier periods of change in the regime parameters. The change in regime parameters on the mutual angle (δ) and its Rate of Change (S) are more informative compared to the values of power overflow on a section (Fig. 2, 3). This information allows us to predict the character of the process of change in the system state at the initial moment of perturbation occurrence.

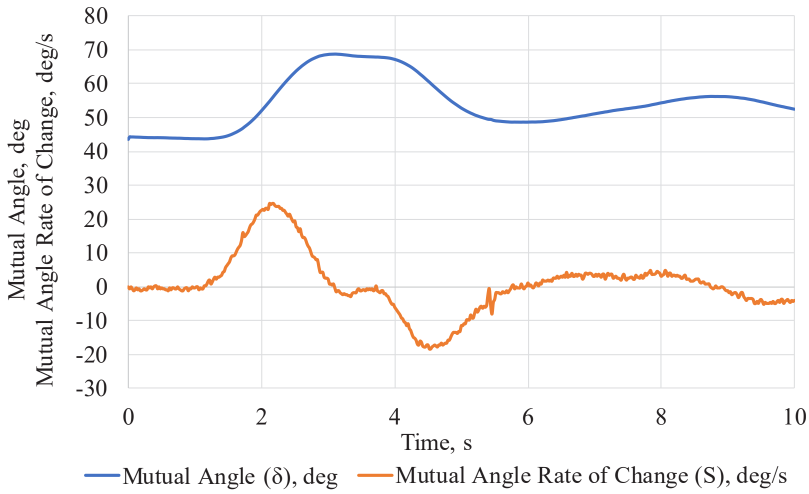

Fig. 3. Plots of the mutual angle (δ, deg) and its Rate of Change (*S*, deg/s) between the «Ekibastuz» substation and «Almaty» substation at the power surge from the Central Asia Unified Energy System in the amount of about 700 MW

Thus, anticipatory detection of conditions of approaching instability is achieved by using the advantage of assessing the system state by two parameters: the magnitude of change of the monitored parameter and the Rate of its Change. This became possible by using the synchrophasor measurements, which provide collection and transmission of mode information at the rate of mode change, synchronized by a single time stamp.

5. 2. Verification of the Republic of Kazakhstan UES model developed in the «PowerFactory DigSILENT» software

The computational model of the Republic of Kazakhstan UES was developed and verified using real data from the WAMS system under various characteristic perturbations in the «PowerFactory DigSILENT» software. The model includes 500–220–110 kV system-forming grids and main power plants of more than 10 MW, for each of which a corresponding dynamic excitation system model is added, including voltage and speed regulators and PSS. Also, nearby 500–220 kV networks of adjacent power systems are added to the model as an equivalent. The model consists of 594 nodes, 743 branches, and 305 PP generators with corresponding dynamic models, the balancing node is in the equivalent network of the adjacent power system.

Verification of the computational model was performed according to the monitored parameters of real perturbations in the electric network, which occurred during the observed period. Several perturbations that occurred in the 500 kV network were selected. The archives of data from the WAMS and SCADA systems were formed. Using these data, for each of the perturbations, the initial pre-fault mode was established and a similar perturbation was simulated using the developed model. According to the results of several calculations, the discrepancies in the monitored parameters according to the WAMS data and modeling results did not exceed 5 %, which confirms the correctness of the developed model of the Republic of Kazakhstan UES in the «PowerFactory DigSILENT» software.

Below (Fig. 4) is one of the verification parameters – the plot of the mutual angle (δ) from the WAMS of one of the perturbations, which was used to verify the model. This perturbation was mentioned above – the 700 MW surge from the Central Asia UES to the «North-South» interconnection.

In this graph, we can see that before the disturbance, the value of the mutual angle (δ) was slightly below 45 degrees, at the peak, it was about 69 degrees. After setting the pre-fault mode according to WAMS and SCADA data, the power surge was simulated by switching off the generation in the amount of 700 MW in the equivalent network of the Central Asia UES. Below (Fig. 5) is a graph of the mutual angle (δ) between the «Ekibastuz» SS and «Almaty» SS based on the results of the simulation.

The resulting graph shows that the mutual angle (δ) was 45.9 degrees in pre-accident mode and 69.9 degrees in peak mode, which is not significantly different from the WAMS data. Also, the character of change of mutual angle curves (δ) under perturbation according to the data from the WAMS system and simulation results is identical.

Comparison of several other controlled parameters such as voltage (*U*) and frequency (*F*) according to the data from the WAMS system and simulation results showed that the discrepancy did not exceed 5 % and is acceptable for further research.

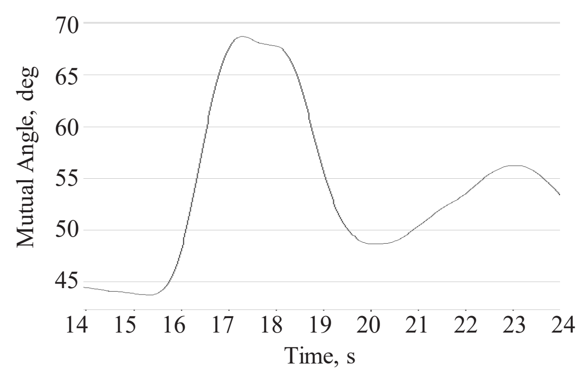

Fig. 4. Plot of the mutual angle (δ) between the «Ekibastuz» substation and «Almaty» substation according to data from the Wide Area Measurements System

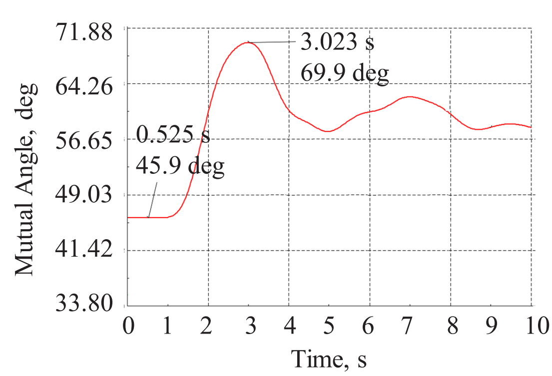

Fig. 5. Plot of the mutual angle (δ) between the «Ekibastuz» substation and «Almaty» substation based on simulation results in PowerFactory DigSILENT

5. 3. Simulation results

Further, a simulation was carried out to determine the characteristic curves of the Rate of Change (S) of the mutual angle (δ) when the static stability is broken as a result of various emergency events.

As emergency events, power surges on the «North-South» interconnection at its maximum allowable load on static stability – 2,100 MW, and at the «working» flow of 1,700 MW were accepted. Capacity surges were determined by the loss of generation in the southern zone of the Republic of Kazakhstan UES and the Central Asia UES in the amount of 200–1,600 MW (in steps of 200 MW). Below (Fig. 6) are the results of calculations in the form of graphs of the mutual angle (δ) and its Rate of Change (S) under these perturbations.

As can be seen from the above graphs, the power overshoot directly affects the change in the mutual angle (δ). The steepness of the rise of the mutual angle (δ) after perturbation in the power system increases with an increase in the power surge value. At the same time, the loss of stability occurs at the surge of 1,200 MW and higher when the interconnection is loaded up to the maximum permissible value – 2,100 MW. The mutual angle (δ) curves for the two versions of interconnection loading show that they reach their first peak approximately 2 seconds after the beginning of perturbation. From the criterion of the worst-case mode introduction scenario, further calculations are performed at an interconnection load of 2,100 MW. Fig. 7 shows the mutual angle Rate of Change plots from the results of the simulation.

The curves Rate of Change (S) of mutual angle depending on power surge (P) show more pronounced differences 0.5–0.6 seconds after the occurrence of emergency perturbation in the system. The simulation proves the effectiveness of using such a criterion as the mutual angle Rate of Change (S) to identify the emergency power imbalance, which will allow for predicting a possible disturbance of stability. Using this parameter (S) in the future will make it possible to identify the emergency power imbalance more quickly and generate the exact amount of control actions on the emergency control system. Table 1 summarizes the data on the maximum values of the Rate of Change (S) at the initial moment of perturbation (Interconnection active power flow – 2,100 MW).

Using the table, we plotted the dependences of the Mutual Angle Rate of Change (S) peak values on the magnitude of the power surge on the interconnection, shown in Fig. 8.

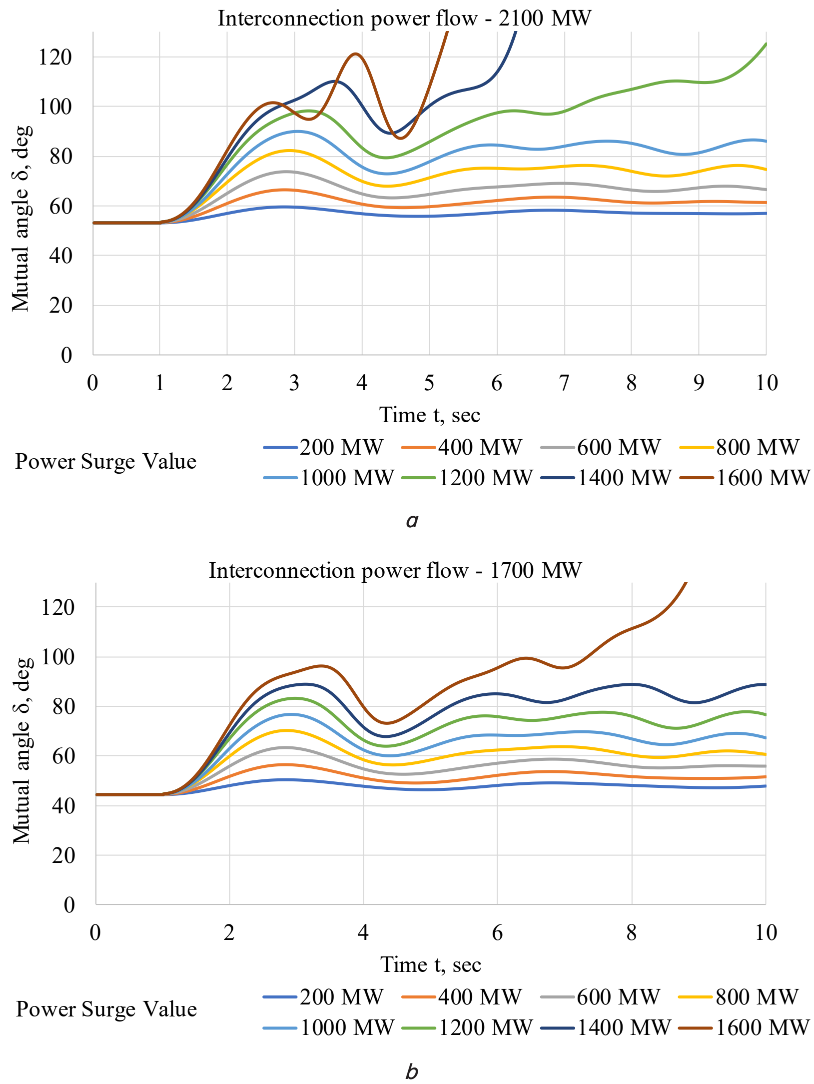

Fig. 6. Plots of the mutual angle (δ) at power surges of different magnitudes and at different loads of the «North-South» interconnection: *a* – power flow of 2,100 MW; *b* – power flow of 1,700 MW

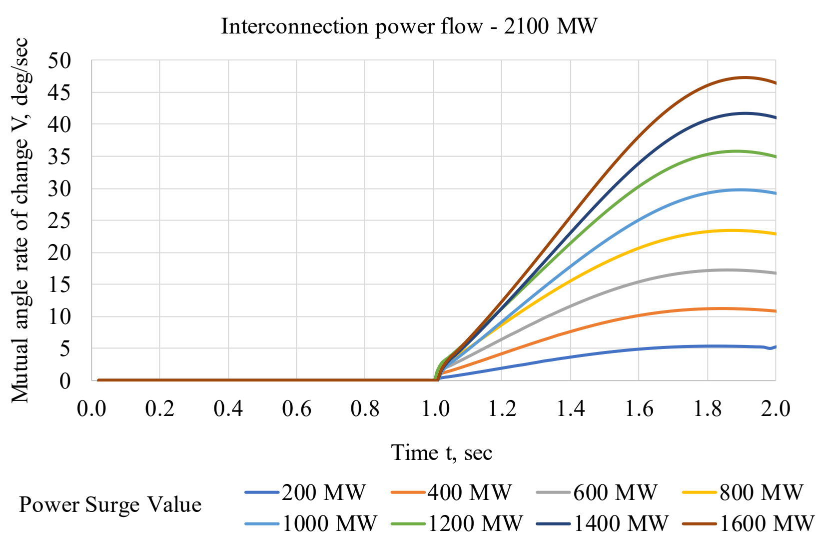

Fig. 7. Plots of the mutual angle Rate of Change (S) during power surges of different magnitudes

Table 1

Maximum mutual angle Rate of Change (S) values at the initial moment of perturbation

Magnitude of power surge, MW	Maximum Mutual Angle Rate of Change for the first 2 seconds after perturbation, deg/s
200	5.45
400	11.18
600	17.20
800	23.48
1,000	29.84
1,200	35.86
1,400	41.69
1,600	47.22

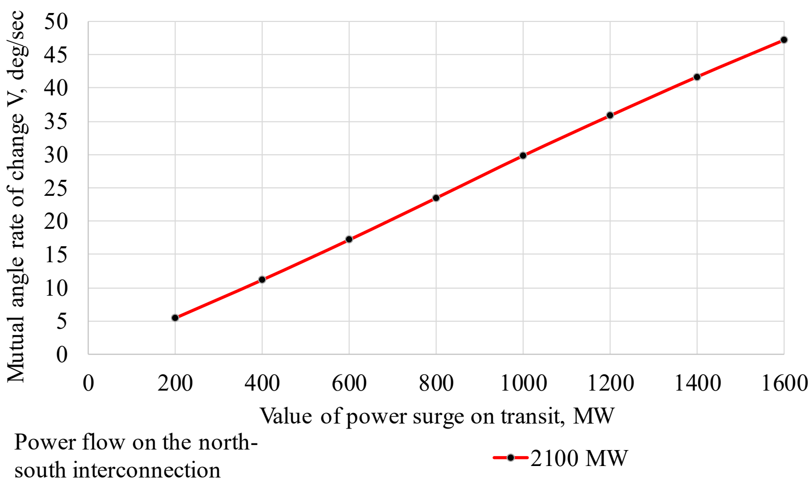

Fig. 8. Plots of dependences of the Mutual Angle Rate of Change (S) peak values on the magnitude of the power surge on the interconnection

According to the above graphs, we can see that the Mutual Angle Rate of Change (S) value changes almost linearly, which in theory once again damages the application of this approach to accurately determine the magnitude of the occurred power imbalance in the process ramp. This will make it possible to dose the control actions and correctly adjust the emergency control system.

6. Discussion of the results of the study on improving the efficiency of mode automation using synchrophasor measurements

Existing principles for detecting power surges based on voltage and active power flow monitoring with worst-case scenarios can detect power surges, but in some cases, the detection rate is insufficient, which can lead to instability in the power system. The study proposed new principles for detecting power surges on transit power grids using information about changes in regime parameters and their Rate of Change. As a mode parameter, the mutual voltage angle (δ) between the controlled 500 kV substation on the «North-South» interconnection and its Rate of Change (S) was selected in the study.

To make the proposed method of detecting power surges work, it is proposed to use WAMS data. The data rate of 20 ms allows the transient process to be monitored in real-time, and therefore a possible stability disturbance can be detected quickly. The graphs shown in Fig. 2, 3 confirm the possibility of using WAMS data for power surge detection. However, their use is also associated with possible limitations of this system. In real operation, the proposed method will have limitations due to the quality of data transmission channels from power facilities to the central WAMS server [21] and quantity and locations of PMUs in the power system [22]. Also, a technical limitation may be the need for uninterrupted communication between the two monitored nodes to transmit the measured values of the mutual angle.

In order to verify the proposed method, calculations were performed on the verified model of the Republic of Kazakhstan UES. The verification of the model was carried out by simulating the perturbations and comparing the graphs of the monitored parameters with the archived WAMS data. Fig. 4, 5 show one of the monitored parameters, changes of the mutual angle between the «Ekibastuz» substation and the «Almaty» substation. Comparison of several other controlled parameters such as voltage (U), and frequency (F) according to the data from the WAMS system and simulation results showed that the discrepancy did not exceed 5 % and is acceptable for further research.

By the calculations presented in Fig. 6, 7, it was determined that the stability of the «North-South» interconnection is violated when the power surge exceeds 1,200 MW. Based on this, we can assume that the Mutual Angle Rate of Change (S) should be used in the emergency control system on the section of the surge below 1,200 MW. The presented numerical values of the mutual angle rate of change (S) before the 1,200 MW surge show clear differences of 6 deg/s, which will allow further more effective adjustment of the corresponding emergency control system.

The main disadvantage of the proposed method of power surge detection may be the difficulty in filtering out the fluctuations of the mutual angle at irregular power fluctuations, as well as disturbances with short circuits in the 500 kV network, which also affect the mutual angle. The solution to this issue will be considered in subsequent studies.

The results of the study obtained from the modeling and presented in Fig. 6, 7 have shown that the use of the mutual voltage angle and its rate (S) allows us to identify the power surge at the initial stage of perturbation (less than 1 second) and perform an estimation of the perturbation energy and adequate control for adaptive emergency automatics. To determine the volume of control actions, it is necessary to develop algorithms for their dosage to unload the interconnection by switching off the load and reducing the power surge effect.

7. Conclusions

1. The analysis showed the effectiveness of using the WAMS data in the proposed method of detecting power surges on the transient power networks, which allows us to eliminate the above drawbacks of the existing detectors of mode automatics. The data arrival frequency of 20 ms allows the transient process to be monitored in real-time, and, accordingly, at the rate of the process by the value of the mutual angle (δ) and its Rate of Change (S) to detect a possible stability disturbance.

2. To test the proposed method, the computational model of the Republic of Kazakhstan UES was developed and verified in the «PowerFactory DigSILENT» software. The model was verified by simulating the perturbations and comparing the graphs of the monitored parameters with the archived WAMS data. Comparison of several controlled parameters such as voltage (*U*), frequency (*F*) and other according to the WAMS data and simulation results showed that the discrepancy did not exceed 5 % and is acceptable for further research.

3. On the verified model of the Republic of Kazakhstan UES in the «PowerFactory DigSILENT» software by the results of calculations on the example of the «North-South» transit, it was determined that the use of the voltage mutual angle (δ) and its Rate of Change (*S*) allows us to identify the power surge at the initial stage of perturbation and predict the moment of stability violation for the correct operation of adaptive emergency automatics. Detection of power surges by the mutual angle Rate of Change is performed when it shows more pronounced differences, which according to the simulation appear 0.5–0.6 seconds after the occurrence of emergency perturbation in the system. Practically, the forecasting of stability violation reduces the risk of development of system accidents and reduces the amount of damage from disconnections of consumers.

Conflict of interest

The authors declare that they have no conflict of interest about 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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