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REAL-TIME CONTROL ACTION FORMATION FOR PREDICTING POST-ACCIDENT ELECTRICAL MODES CONSIDERING PERMISSIBLE STABILITY MARGINS

Karmel Tokhtibakiev
Candidate of Technical Sciences, Senior Lecturer*
Alexandr Gunin
PhD Student*
Yerlan Kenessov
Corresponding author
PhD Student*
E-mail: ye.kenessov@aues.kz
Daniil Vassilyev
Master's Student*
Anur Bektimirov
PhD Student*
*Department of Electric Power Systems
Almaty University of Power Engineering and Telecommunications named after Gumarbek Daukeyev
Baytursynuly str., 126/1, Almaty, Republic of Kazakhstan, 050013

The object of the research is an emergency control system for ensuring the stability of electric power systems (EPS) in case of emergency unbalances. The relevance of the problem of ensuring EPS stability is due to the need to improve the efficiency of emergency control to reduce the risk of system accidents with significant damage. To solve this problem, we propose an algorithm for selecting the volume of control actions based on the principles of adaptive control for predicting the post-emergency mode with an acceptable stability margin. The algorithm of forming the volume of control actions is based on the dependence of the value of control actions on the value of stability reserves estimation by the value of the Jacobi determinant. To build this dependence, the algorithm of searching for the limiting mode by the trajectory of change in the equilibrium position of the steady state of the system from the initial to the limiting one is used. In contrast to the existing algorithms, the proposed algorithm establishes a functional dependence of the control value on the current parameters of the regime or the stability margin, which increases the efficiency of calculations for selecting control actions. Realization of the proposed algorithm is carried out on the basis of the functional scheme according to the data of the vector measurement system.

The advantage and novelty of the proposed algorithm is the possibility of eliminating the disadvantages of existing systems of mode automation, the main of which are:

– the necessity to perform numerous variant calculations for selecting the volume of control actions;

– possible excessive volume of control actions in case of a mismatch of the actual mode with the calculated one

Keywords: power system stability, stability margin, emergency control systems, control actions

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1. Introduction

Improvement of reliability and efficiency of control over electric power systems (EPS) functioning is achieved by the successful implementation of modern computer facilities, creation of information-computer systems and operational information complexes for solving the tasks of dispatch and emergency control of power systems. Special attention is paid to electrical mode management in case of emergency disturbances. At the same time, ensuring the stability of the EPS mode under emergency disturbances is achieved by means of emergency control systems (ECS) [1–3]. In case of insufficiency and ineffectiveness of the emergency control system, large system accidents with significant damage to the economy and welfare on the scale of any country occur. The main causes of large-scale stability failures are the occurrence of emergency power imbalances first at individual nodes, which are then transmitted through intersystem links and supply lines throughout the system. In this regard, the main task of ensuring the stability of coordinating ECS systems is to control power flows over intersystem links in order not to exceed their maximum permissible values [3].

To solve this problem, new methods and algorithms are being developed including [4]:

– calculations of limit modes directly in the control loop of power systems and power unions based on information obtained on the rate of mode change;

– selection of the volume of control actions based on forecasting the post-accident mode in the control loop with an estimation of the permissible control area under the condition of ensuring steady-state stability (SSS) or voltage stability;

– creation of scientifically grounded methods of estimation and rationing of stability reserves based on the data of the current system regime parameters.

Currently, the successful resolution of these problems is based on approaches utilizing adaptive emergency control systems, which rely on the development of intelligent systems for steady-state stability monitoring and network capacity management.

Therefore, research on the development of adaptive emergency control systems and intelligent stability monitoring methods is highly relevant for ensuring the reliable and efficient operation of electric power systems.

2. Literature review and problem statement.

The papers [5, 6] present that the efficiency and reliability of emergency automation (EA) systems operation have been largely determined by the success in solving the problems of ECS control using new control principles and technologies since their creation.

Under the normative materials on ECS, the most important task is the selection of the type and volume of control actions to maintain the stability of the parallel operation mode of EPS. Due to complexity and scale, this task is solved in two stages:

– at the design stage, the principles, type, system structure, detection and triggering devices, and technical solutions for ECS realization are determined;

– at the operation stage, calculations of the volume of control actions, storage and control execution are performed. The tasks of selection and volume of control actions are solved from a certain (specified) set of them, based on the known (specified) intensity of the emergency disturbance.

Another study suggested that the most important and significant achievement was the use of an approach that provides the translation of the solution of the second ECS problem into the control loop. In the theory of automatic control, this approach is understood as adaptive control using current process parameters [5].

However, there were unresolved issues related to the use of the adaptive approach for controlling EPS modes based on real process parameters, which differ from the principles of traditional adaptive control in automatic control systems.

In EPS, this approach is based on the principles of control by current system parameters without establishing a feedback law. The purpose of adaptive ECS is to ensure stability in the event of an emergency disturbance by adequately determining the amount of control actions. In this case, the adaptability of ECS is understood as a transition from methods of dosage calculation outside the control loop, as in systems with program control, to calculations directly into the control loop according to the parameters of the actual network mode. The works [4, 7] highlight the advantage of adaptive ECS over software-based principles of EA, specifically noting that calculations are performed solely for the current mode rather than for potential modes of network operation.

This approach requires fundamentally new methods and algorithms providing automation of calculations minimizing and excluding human participation in calculations. For this purpose, new methods, technologies and algorithms have been developed that transform the calculation part of emergency control into an intelligent system, which consists of the following blocks [4]:

– system status evaluation unit;

– block of adaptive model formation using measured regime parameters;

– block for calculating the volume of ECS control actions;

– block for memorizing the volume of ECS control actions in the form of tables.

The algorithm presented in this paper describes the main issues necessary for creating an adaptive emergency control system. However, the issue with the block of determining the volume of ECS control actions is not fully detailed enough.

When creating an intelligent part of the ECS, the problems of selecting the volume of control actions in EA systems to prevent stability violation (stability control schemes – SCS) in EPS were most successfully solved [8].

In SCS, the selection of control actions is carried out on the basis of local information or a centralized information database on the scheme and modes of the entire controlled network – centralized emergency control system (CECS). It is necessary to note the following features of calculating the volume of control actions in SCS, which allow achieving adaptability [5]:

– calculations of the volume of control actions are performed cyclically as the mode parameters change and are output to memory devices, thus achieving the adequacy of dosage to the state of the network mode and fast performance at the moment of a possible emergency disturbance;

– calculations are performed for all calculated accidents, which are formed by the list of starting bodies.

The publications on the creation of the intelligent part of CECS show significant successes in solving the problem of ensuring the EPS stability using adaptive algorithms for balancing the mode by intersystem connections, construction of the stability region in the space of observed parameters of the mode, optimization of the mode with minimum load power constraints [9, 10]. These works are based on the studies on the application of stability theory methods in solving practical problems of ensuring stability in EPS.

However, in the papers for the systems under consideration, the factor of automatic operation is the presence of a starting organ, which is absent in the ECS systems of mode automatics, for example, in the systems functioning at power overloads in the cross-section – automatics against power surge [11].

The principal difference between the mode automation and the automatic control system is that the calculated disturbance is not fixed by the operation of the starting organ and the operation of the automation is carried out upon detecting the conditions of stability violation leading to the system exit from the permissible area of mode reliability. For example, in [12], the parameter of the rate of change in the mutual voltage angle between the substations for detecting the emergency perturbation is considered. This difference leads to a difference in the content and purpose of calculations for tuning the ECS. Two types of calculations are performed to tune the mode automatics:

– evaluation of conditions on stability violation detection to set up a detection device that monitors certain mode parameters;

– determination of the volume of control actions, providing finding or entering the system into the stability region.

Adjustment of the detecting device when using the existing methods of searching for limiting modes is performed without taking into account the current state of the network, which allows performing these calculations at the stage of adjustment for the most severe network mode. This circumstance significantly reduces the efficiency and selectivity of the dosage of automatics from power surge.

To eliminate these drawbacks and improve the efficiency of mode automation, new methods and algorithms are currently proposed to search for conditions of stability violation based on the observed mode parameters [9, 11].

These algorithms are based on the principles of searching for limit modes in the control loop. Currently, for a number of power systems, intelligent systems for monitoring the stability margin have been developed, in which continuous calculations to determine the stability margin are performed on the monitored parameters of the mode in real time [6, 10]. Obviously, the algorithms of these systems will be used in the future when setting up a detection device for power surge automation.

Many studies use various machine learning systems or neural networks to predict power system stability disturbances. Most of them mainly involve two stages [13, 14]: offline training and online application. The stability classifier is learnt in the training phase, where a large-scale stability/instability database from time domain modeling is required. In the online application phase, where post-crash dynamic characteristics such as rotor angles are input to the classifier, the instability state can be determined in advance. For example, the papers [15, 16] propose the use of a machine learning neural network to predict the stability margin of a power system considering voltage stability and small signal stability requirements. It is proposed to train the neural network based on WAMS data. In another work [17], a new unified approach to rotor angle stability prediction for both small signals and transient period is proposed. This work uses deep learning techniques to train an online rotor angle stability prediction model using phase voltage measurements collected throughout the system. The main difficulty in creating such systems is that it is necessary to have a significant amount of data for training neural networks. This can significantly increase the implementation time of such systems, especially in case of incompleteness of such information.

The paper [18] presents algorithms for identifying nodes that are weak in terms of static aperiodic stability based on spectral analysis of the conductivity matrix and decomposition by singular values of the Jacobi matrix. According to the developed methodology, there is a possibility of more efficient mode control and network optimization at the design stage. However, the paper does not consider the application of these algorithms to determine the optimal amount of control actions to maintain stable operation of the power system.

In [19, 20], the methodology is proposed for determining sensor nodes in an electric power system and impact assessment of adjustable parameters (node generation and load power) based on calculations of the union Jacobian matrix elements using marginal modes equations. The methodology has been developed for identifying weak links in terms of the steady-state stability of the electric power system based on calculating the gradients of active and reactive power losses in branches located in the near-limit zone. It is shown that the method application allows one to make reasoned decisions to optimize the structure and measures to increase the static stability of the electric power system. However, the issue of forming control actions at the pace of the process was not addressed in the aforementioned studies. All of this indicates that it is worthwhile to conduct a study on real-time control action formation for predicting post-accident electrical modes considering permissible stability margins.

The literature review has shown the need to use the principles of adaptive tuning of mode automatics. In this regard, this paper proposes the development of methods and an algorithm for adaptive tuning of automatics in the control loop on the network mode model. The proposed algorithm for selecting the volume of control actions is based on the development of methods for searching for limiting modes using algebraic stability assessment criteria and makes it possible to predict the post-emergency mode with an acceptable stability margin.

The principle of predicting the post-emergency regime for expected disturbances consists in performing calculations to determine the amount of control actions to ensure stability in the pre-emergency regime directly for the current regime. These algorithms are based on the use of adaptive principles of emergency control using computational models of EPS [20].

3. The aim and objectives of the study

The aim of this study is to develop an algorithm for selecting the volume of control actions for adaptive systems of mode automation, on the example of automation from a power surge, using the dependence of the stability margins by the value of the Jacobi determinant on the regime parameters of the system. This will reduce the excessive volume of control actions in case of a mismatch of the actual mode with the calculated one, as well as significantly reduce the volume of calculations required for this purpose, since in the proposed algorithm the calculations are performed only for one mode, the current one.

To achieve this aim, the following objectives are accomplished:

– to determine the dependences of the EPS stability margin on the mode parameters for the grid design model based on the development of the stability assessment method using the Jacobi matrix determinant property;

– to provide the formation of the volume of ECS control actions using the above-mentioned dependence between the power and the value of stability margin and the observed parameters of post-accident steady-state modes;

– to make calculation (experimental) substantiation of the proposed method for constructing stability margin dependencies on mode parameters and algorithm of ECS formation, providing preservation of post-accident mode stability with acceptable stability reserve by means of modeling in the DigSilent Power Factory and RastrWin complex for the calculation model of the network with power deficit;

– to develop a functional scheme for implementing the algorithm of forming the volume of ECS control actions using the existing modules of the intelligent part of adaptive ECS systems.

4. Materials and methods

4. 1. Principles of selecting the emergency control system control actions volume to ensure stability of the post-emergency mode

The research object is the emergency control system, algorithms for selecting control actions for stability preservation.

The selection of the volume of ECS control actions is made from the conditions of providing the post-emergency mode with a sufficient power system stability reserve, at which the system does not reach the boundary of the limit of electrical modes or to the exit of the system from the stability region in the coordinates of the observed parameters of the mode [4, 9].

In practice, the stability region of the power system is formed in the coordinates of power flows between large system nodes or voltages in nodes in systems with a predominance of load, and entering the system into the stability region means fulfilling the conditions of finding the observed coordinates in the region of permissible values according to the stability conditions. In this sense, the ECS ensures the entry of systems into the stability region according to the conditions of static stability of post-emergency modes [4].

This task is reduced to ensuring such a power balance in large system nodes, which allows unloading the sections to the maximum permissible power flows along the section and restoring the voltage in the network nodes within permissible limits [21, 22].

From this, the volumes of control actions are formed according to the conditions of static stability of the post-emergency mode with the required reserve, which ensures the elimination of the post-emergency imbalance and the restoration of the power balance in all system nodes.

In order to develop this approach, this paper proposes a new method and algorithm for selecting the control actions of the EA.

The theoretical justification of the proposed algorithm is based on the development of existing methods and approaches to the use of:

– algebraic criteria for assessing stability based on the Jacobi matrix;

– principles of adaptive control of the state of an object using the model formed at the rate of change in the object's operating mode.

The development of the method for assessing stability based on the use of the Jacobi matrix consists in constructing the dependence of the system's stability reserve on the system's operating parameters, which is formed based on the results of calculations when the power system mode is aggravated. This dependence determines the trajectories of changing the equilibrium position of the object from the initial to the limit mode.The development of the adaptive control principle in the proposed algorithm consists in forecasting the dependencies (tabular, graphical or approximating) of control on the controlled parameters. These dependencies are formed at the rate of change in the system state (mode) periodically, in the pre-emergency state for the expected calculated disturbances.

According to this, in the proposed algorithm the volumes of control actions are formed according to the conditions of static stability of the post-emergency mode with the required reserve, which ensures the elimination of post-emergency unbalance and restoration of power balance in all system nodes.

The principle of forecasting the post-emergency mode for expected disturbances consists in performing calculations to determine the volume of control actions to ensure stability in the pre-emergency mode directly for the current mode. These algorithms are based on the use of adaptive principles of ECS using calculation models of the EPS, formed according to the current network parameters.

4. 2. Existing static stability criteria

As mentioned above, the methodology for selecting the volume of ECS control actions in electrical networks with predominant load under the conditions of static stability is to eliminate overload by reducing the power in the receiving part of the system. In this case, the volume of ECS control actions ensuring the system's entry into the stability region for the observed network parameters (cross-sectional flow and voltage in the network nodes) is determined by the static stability reserves for the cross-sectional capacity (power flow) between the sending and receiving parts of the scheme and the stability reserves for voltage in the monitored network nodes.

Following the above approaches, the determination of the volume of control actions is performed according to the normative reserves of static stability, in relation to the maximum permissible overflows along the network sections and critical values of voltage in the nodes, which characterize critical or limit modes of the network [6, 9].

In the power deficit grids we are considering, to bring the system into a critical state, it is necessary to increase the power consumption of the selected load or group of loads. In this case, it is possible to use various indicators of mode stability, which are determined by modeling of electrical modes. In these modes, the critical loads can be calculated in stand-alone mode according to the criterion *dE/dU* or *dQ/dU* (Table 1), taking into account the load distribution [23].

Table 1

Summary table on SSS criteria

No.	Parameter	Formula	Critical value
1	Dynamic characteristic of EMF variationwith voltage	$\frac{\partial E}{\partial U}$	>0
2	Dynamic characteristic of reactive power tovoltage variation	$\frac{\partial Q}{\partial U}$	<0
3	Resilience margin in terms of cross-flow	$\frac{(P_{mar}-P)}{P_{mar}}$	>20 %
4	Voltage stability margin in EA mode, Ku	$\frac{(U-U_{crit})}{U}$	<15 %
5	Stability margin by the sign of the Jacobi determinant	$\det[\partial\psi/\partial X]\neq 0$	>0

Practical criteria (No. 1 and 2) correspond to the requirements of voltage stability preservation arising from the method of small deviations, namely the condition of positivity of the free term of the characteristic equation describing the transient electromechanical process [23, 24].

However, the above criteria do not allow us to search for the limiting modes of the system. These criteria are not related to the definition and stability reserves of the current mode, which does not allow evaluating the stability region, by the value of which the volumes of ECS control actions are selected. These shortcomings of the existing approaches to determining the limit modes for static stability are noted in the reviews [6, 11].

The criteria (No. 3 and 4) determining static stability reserves by network mode parameters are the closest in content and meaning to the ECS objectives.

For network sections connected to a large capacity system, the node voltage stability criterion is used to calculate the static load stability margin. When the voltage drops in the nodes, the criterion is calculated in the form of a voltage safety factor at the load node using the formula:

$$Ksf=\frac{(U-U_{crit})}{U}, \quad (1)$$

where U is the load node voltage in the reference mode; U_{crit} is the critical node voltage, the value of which is assumed to be at least 0.7 U_{nom}.

Stability criteria based on the calculation of its reserve through the coefficients (Z_{sc}) on the observed parameters of the mode are expressed by the following requirements:

a) if Z_{scc} (stability criteria of capacity) determined by the difference between the maximum permissible and initial capacity of the cross-section is less than the normative reserve;

b) if Z_{scv} (stability criteria of voltage) determined by the difference between the initial and critical voltage is less than the normative reserves.

At these data Z_{sc}, the conditions of static stability violation are not observed.

According to conditions A) and B), the task of selecting the volumes of control actions using the normative stability reserves is reduced to calculating the estimate of Z_{sc} for the parameters of the limit modes and plotting the dependence of the stability reserves of the predicted post-emergency mode.

On this basis, this work proposes an algorithm for selecting the amount of control actions based on the prediction of the stability margin estimation (or post-accident unbalance estimation) using algebraic stability criteria based on Hurwitz determinants.

The mathematical formalization of this problem is reduced to finding the roots of the characteristic equation of any order in special extreme points, on the boundaries of the region of admissible solutions [10, 25].

According to the Hurwitz criterion, the stability conditions are determined by the properties of the free term of the characteristic equation (x, y), which corresponds to the determinant of the square matrix of coefficients of equations.

The free term will be positive ($a_0>0$), when the roots (x, y) are negative or when the conditions for solving the differential equation are sufficient.

The use of this property of the Hurwitz criterion in a number of works on stability assessment of static aperiodic stability of EPSs allowed developing methods using the property of the determinant of the matrix of the first derivatives of the right parts of differential equations of transient electromechanical processes (Jacobian matrix). Under certain conditions, the determinant of the (Jacobian) matrix is identical to the free term of the characteristic equation. In the stable regime, the determinant has a positive sign, and at the loss of stability it passes through zero and becomes negative (criterion No. 5) [25, 26].

A brief justification for the use of the Jacobian or mathematical formalization of the problem of finding solutions to the roots of equations when using iterative methods boils down to the following algorithm: when representing the system of nonlinear nodal voltage equations in matrix form:

$$\psi(X)=0, \tag{2}$$

where X is the vector of unknowns, the k-th component of which is equal to X_k and $\psi(X)=0$, is the vector function of unbalances.

System (2) is generally solved by Newton's iterative method.

Denoting by X^i the value of the vector of unknowns at the i-th iteration, we can linearize the vector function $\psi(X)$ in the vicinity of the i-th approximation:

$$\psi\left(X^i+\Delta X^{i+1}\right)=0\approx\psi\left(X^i\right)+\left[\frac{\partial\psi(X)}{\partial X}\right]_{X^i}\Delta X^{i+1}, \tag{3}$$

where $[\partial\psi(X)/\partial X]$ is the matrix of the first derivatives of the vector function $\psi(X)$ on X, called the Jacobi matrix.

Hence, under the assumption of non-degeneracy of the Jacobi matrix, we find:

$$\Delta X^{i+1}=-\left[\frac{\partial\psi(X)}{\partial X}\right]^{-1}_{X=X^i}\psi\left(X^i\right). \tag{4}$$

A necessary condition for the convergence of Newton's method is that its Jacobi determinant is not equal to zero in the solved region of the Jacobi matrix $[\partial\psi/\partial X]$, i.e.:

$$\det\left[\partial\psi/\partial X\right]\neq 0. \tag{5}$$

In the stable regime, the determinant has a positive sign, and at the loss of stability it passes through zero and becomes negative. This property of the Jacobian was used to estimate the limit modes under the conditions of static stability of EPS.

For research in this paper, the determinant of the Jacobi matrix is calculated by calculations in DigSilent Power Factory and RastrWin. Recent research and development of the method are based on the analysis and research of the structure of the components of the Jacobi matrix and the construction of algorithms for determining the limit modes using the properties of the Jacobi matrix when the limit values of the network mode parameters are reached.

In the DigSilent Power Factory and RastrWin complex, the iterative process by Newton's method in accordance with expressions (3), (4) is realized when constructing the active and reactive power matrix, but the complex does not set a separate task to use the Jacobian for steady-state stability assessment. Practically, in many modern complexes of calculation and analysis of electrical mode, the stability assessment is determined by the convergence of the iterative process of obtaining the steady-state mode. But there are some studies where criterion (4) determines the stability assessment of solutions without analyzing the conditions of approaching the boundary of the stability region. The results of studying the value of the determinant of the Jacobi matrix, for assessing static stability on the interconnection of large power systems, where it is substantiated that the value of the determinant of the Jacobi matrix, corresponding to the transition of the system into the «Zone of instability», is a property of the considered power system and does not depend on the trajectory of weighting, are presented in [25].

5. Results of the development of an algorithm for forming the volume of control actions for adaptive systems of mode automation

5. 1. Emergency control system selection according to steady-state stability: Theoretical substantiation using Jacobian determinant prediction

With the purpose of further development of the method of stability estimation by the Jacobian sign, in this paper it is shown that practical interest is aroused by the possibility of using the dependence of the Jacobian determinant on the regime parameters in the conditions of approaching the system to the boundary of the stability region. This allows us to determine a quantitative estimate of the system stability under the regime weighting along the trajectory of change in the position y of the system from stable to unstable state, to determine some stability margin in the numerical value of the Jacobi determinant (J_z):

$$J_{Z_i}(P_i,U_i)=f_i\left(\det\left[\frac{\partial\psi}{\partial X}\right]\right), \tag{6}$$

where

$$\psi(X)=\begin{cases}\Delta P(P,V,\delta)=0;\\ \Delta Q(Q,V,\delta)=0.\end{cases} \tag{7}$$

To construct such a dependence of the determinant J_z on an independent argument, for example, on the load parameter (P_t), the Jacobi matrix is defined at each iteration to express the power balance along the weighting trajectory as:

$$\left[\frac{\partial\psi}{\partial X}\right]=\begin{vmatrix}\frac{\partial\Delta P}{\partial\delta} & \frac{\partial\Delta P}{\partial V}\\ \frac{\partial\Delta Q}{\partial\delta} & \frac{\partial\Delta P}{\partial V}\end{vmatrix}. \tag{8}$$

Let us denote this determinant in the form:

$$J_r=J_z(P_r,U_r), \tag{9}$$

where J_r is the Jacobian value at steady state for the system with some value of P_r load, U_r voltage at the controlled nodes. The determinant in the limit mode is expressed as (10):

$$J_a=J_z(P_a,U_a), \tag{10}$$

where J_a is the value of the Jacobian at the limit state of the system; P_a – system load in limit mode; U_a – system voltage in limit mode.

In calculations, the stability margin of any state of the system in numerical values of the Jacobi determinant with respect to the limit steady state can be defined as follows:

$$J_t=(J_t-J_a)\|J_t, \tag{11}$$

where J_r is the steady-state value of J equal to a positive number; J_a is the value of J in the limit mode, which is taken as zero.

Taking into account (11), the estimation of the stability margin (J_t) in relative units from the value (J_a) of the limit mode reflects a quantitative estimate of the stability margin of the post-emergency mode of the system. To obtain such an estimate of the post-accident mode stability margin, it is necessary to use the Jacobian dependences on the weighted parameter, on the voltage at controlled points of the network or on the cross-sectional flow, which can be constructed in the calculation model when the mode is weighted from the initial to the limit mode.

To confirm the above, numerical calculations are given to determine the nature of the Jacobian change in the electrical network, where the stability limit modes are determined by the critical values of voltage at the nodes.

5. 2. Determination of the volume of control actions using the analytical dependence of power on the value of stability margin

The possibility of predicting one parameter when the second parameter is known allows us to determine the value of the second parameter, which can be the basis for finding the necessary amount of control actions to ensure the stability of post-accident mode. When analyzing the results of calculations, it was noticed that the dependence of the Jacobian value at the mode weighting on an independent parameter has an asymptotic monotonic character of change, which excludes the oscillatory change in the trajectory of motion of steady states of the system to the limiting mode under the conditions of statistical stability. This conclusion makes it possible to construct similar dependences between the power value and the determinant J and the observed regime parameters:

$$P=G(J). \tag{12}$$

$$P=G(V). \tag{13}$$

Using (16), (17), it is possible for any value of J or V to determine the value of P.

For this purpose, the possibility to determine analytical dependences in the form of linear or nonlinear approximation on the data of calculations obtained as a result of modeling by complexes of industrial (certified) programs is considered.

In general, the problem of constructing the dependence of the Jacobin value on the regime parameters (dependent (V) and independent or varying (P) is reduced to the definition of some approximation in the form:

$$J_i=k_0+k_1V_i+k_2P_i. \tag{14}$$

or voltage dependence of power:

$$P_i=k_0+k_1V_i+k_2V_i^2. \tag{15}$$

At known values of J_i, V_i, P_i, which can be obtained by calculations of search for limiting modes by values of the determinant approximation using the least squares method (LSM) algorithm is performed in the following order [26].

Make equations in linear or quadratic form:

$$J_i=k_0+k_1V_i+k_2P_i. \tag{16}$$

The function W of the mismatch is compiled in the form:

$$W=\sum\left(J_i-k_0+k_1V_i+kP_i\right)^2=0. \tag{17}$$

The system of equations of all partial derivatives of this function by parameters, i.e. such values of these parameters, at which the non-convexity is equal to zero, is compiled:

$$\begin{cases}\frac{\partial W}{\partial k_0}=0,\\ \frac{\partial W}{\partial k_1}=0,\\ \frac{\partial W}{\partial k_2}=0.\end{cases} \tag{18}$$

After transformations, we obtain a system of three linear equations with three unknowns:

$$\begin{cases}k_0n+k_1\sum_1^n V_i+k_2\sum_1^n P_i=\sum_1^n J_i,\\ k_0\sum_1^n V_i+k_1\sum_1^n V_i^2+k_2\sum_1^n V_iP_i=\sum_1^n J_iV_i,\\ k_0\sum_1^n P_i+k_1\sum_1^n V_iP_i+k_2\sum_1^n P_i=\sum_1^n J_iP_i.\end{cases} \tag{19}$$

The solution of the system of linear equations in matrix form (19) is determined by the following algorithm:

$$A_k = b, \tag{20}$$

$$k = A^{-1}b, \tag{21}$$

where A^{-1} is the inverse matrix.

Matrix A (3×3) is a matrix formed by V or P values. Vector $b3$ is a vector formed by the values of V and P (Table 2). Unknown coefficients make up vector $k3$ ($k0$, $k1$, $k2$).

Table 2

Values of matrix A and vector b

Matrix A(3×3)			Vector $b3$
$a11$	$a12$	$a13$	$b1=\sum_1^n J_i$
$a21$	$a22$	$a23$	$b2=\sum_1^n J_i V_i$
$a31$	$a32$	$a33$	$b3=\sum_1^n J_i P_i$

To form matrices A and vectors b, k, the values of mode parameters and determinant values, which are determined as a result of limit mode calculations, are used.

The coefficients of the approximating curve obtained in the calculation are equal:

$$k_0=k(1),\ k_1=k(2),\ k_2=k(3). \tag{22}$$

The analytical dependence using the found coefficients is expressed as function (18).

Using the above algorithm in the next section, calculations are performed to obtain formulas for determining the amount of control actions (load shedding) for power surges on the transmission line.

5. 3. Calculations to substantiate the method of building stability reserve dependences on electrical mode parameters and the algorithm of forming the volumes of control actions

To determine the dependence of the value of the Jacobian determinant on the mode parameters along the weighting trajectory, the calculation scheme shown in Fig. 1 was selected.

The scheme contains a small capacity gas piston power plant (GPPP) with a total rated capacity of 30.4 MW, the GPPP includes 9 generators: G1–G4 – capacity 4.3 MW, G5–G7 – capacity 3.4 MW, G8, G9 – with a capacity of 1.5 MW, the consumers include a complex load of rotating machines – asynchronous and synchronous motors, which in certain conditions can lead to a voltage avalanche. The section of the calculation scheme with the power plant is connected to a large-capacity power system and belongs to the typical structure II «Large system – receiving system with small generation».

Such a structure is characterized by problems of static voltage load stability.

For such schemes, as the main factor determining the static load stability, it is necessary to consider a voltage drop on the bus bars of the load node (up to 60 % of the nominal operating voltage), which leads to a disruption of power supply to all consumers of this node. In this case, such a voltage drop in the node is called critical (U_{crit}).

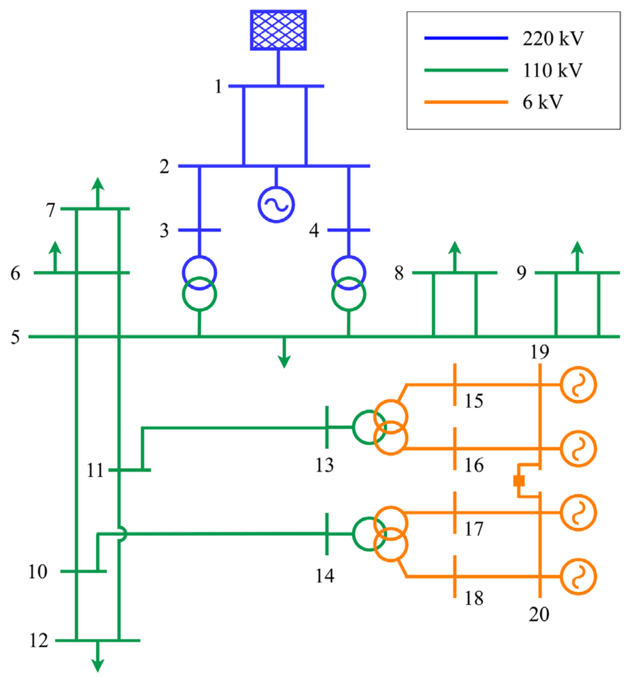

Fig. 1. Calculation scheme of the network

For the design model based on the scheme (Fig. 1), in order to determine the critical voltage and load stability margin, limit mode calculations were performed for the following scheme variants:

1) no generation at the GEGS, two 220 kV lines are switched on;

2) no generation at the GEGS, one 220 kV line is switched on;

3) there is generation at the GEGS, two 220 kV lines are switched on.

Weighting of the initial normal mode was performed by increasing the load power in the receiver system for the scheme under option 1 and 2.

Table 3 shows the results of calculations to determine the parameters of the limiting mode when the voltage is reduced to (U_{cr}). The mode weighting was performed along the trajectory of load increase (P_l) in the network with step dP_i. For this scheme, this weighting led to an increase in the cross-flow capacity of the network connection with the high capacity system, while the power output from the local station remained unchanged:

$$P_{i+1} = P_i + dP_i. \tag{23}$$

Tables 3, 4 are constructed according to the results of calculations of limit modes. Table 3 shows the values of parameters in the initial and limit modes. In all calculations, the moment of transition of the Jacobian J value through zero coincides with the values of (U_{cr}) within the range of (0.7–0.77) U_n, which confirms the normative data on load stability in power systems with power deficit.

Table 4 shows the data of values of mode parameters (voltage and load power) and Jacobi determinant, reflecting the trajectory of change in the position of stable equilibrium in the coordinates of mode parameters. The data values are given in relative units obtained by the formula:

$$X_i = \frac{X_i - X}{X}, \tag{24}$$

where X is the initial value of the variable; X_i is the current value of the variable.

Table 3

Values of initial and limiting regime parameters in weighting different scheme variants

Scheme	P_{gnps}, MW	P_s, MW	P_n, MW	U(SS1), kV	U(SS2), kV	Ug, kV	J_z, p.u.
1. Ex.	–	155	153	112	109	6.3	1
1. Prerequisite	–	180	180	75	69	4.3	0.001
2. Ex.	–	75	73	112	109	6.3	1
2. Prerequisite	–	95	95	75	69	4.5	0.001
3. Ex.	30,4	75	100	108	106	6.3	1
3. Prerequisite	30,4	100	95	73	64	4.1	0.001

Table 4

Values of the determinant of the Jacobian matrix, load power, voltage along the weighting trajectory

Iteration number	P_n, MW	P_n, p.u.	U_n (6 kV)	U_n, p.u.	J_z, relative unit
0	181.4	1.000	5.670	1.000	1.00
1	185.6	1.023	5.624	0.992	0.569
2	189.8	1.046	5.583	0.985	0.311
3	194	1.069	5.538	0.977	0.163
4	198.2	1.093	5.491	0.969	0.08
5	202.4	1.116	5.441	0.960	0.038
6	206.6	1.139	5.387	0.950	0.016
7	210.8	1.162	5.329	0.940	0.006
8	215	1.185	5.265	0.929	0.002
9	219.2	1.208	5.195	0.916	0.000
10	223.4	1.232	5.117	0.903	0.000
11	227.6	1.255	5.029	0.887	0.000
12	231.8	1.278	4.926	0.869	0.000
13	236	1.301	4.799	0.847	0.000
14	240.2	1.324	4.630	0.817	0.000

According to the results of the calculations given in Table 4, the dependence between the values of the Jacobian determinant and the mode parameters (voltage and load power) is determined, reflecting the trajectory of changes in the equilibrium position of stable equilibrium positions. This dependence is theoretically displayed in a three-dimensional space with axes (*J*, *V*, *P*) (Fig. 2):

J – axis on which the determinant values are displayed;

V – axis on which the voltage values are displayed;

P – axis on which the load power values are displayed.

Three-dimensional space is defined by planes:

(*VJ*) – plane with axes of voltage *V* and value *J*;

(*PJ*) – plane with axes of power *P* and value *J*;

(*VJ*) – plane with axes of voltage *V* and power *P*.

The axes indicate characteristic points with the values of the mode parameters in relative units. The basic values for this scheme are taken as:

$P = Rpre = 180$ MW;

$U = Unom = 6.3$ kV;

$J = J_z = 1.$

Fig. 2 shows the characteristic points of the lines determined from the results of the calculations in Table 5.

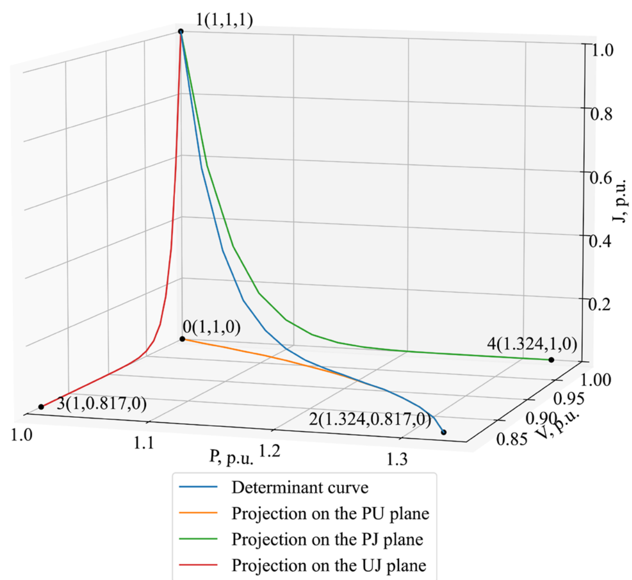

Fig. 2. Graph of the change in the determinant of the Jacobi matrix when changing power and voltage in three-dimensional space

Table 5

Values of the determinant of the Jacobian matrix, load power and voltage at characteristic points of the modes

Point number	Power (*P*), p.u.	Voltage 6 kV (*V*), p.u.	Jacob's number J_z, p.u.	Position in the commonwealth
1	1	1	1.00	Initial mode
2	1.3	0.75	0.0	Limit mode (*VP* plane)
3	1	0.75	0.0	Projection on the *VJ* plane
4	1.3	1.0	0.0	Projection on the *PJ* plane

Given these points, the lines in Fig. 2 mean:

1. Lines 1–2 reflect the trajectory of change in the stable equilibrium position from the initial regime to the limit one in the space of three planes, determined by the expression:

$$J = G(J, V, P). \quad (25)$$

2. Lines 1–3 represent the projection of the trajectory of change in the steady state equilibrium position from the initial regime to the limit regime on the plane (*VJ*):

$$J_z = F_u(V). \quad (26)$$

3. Lines 1–4 represent the projection of the trajectory of change in the steady state equilibrium position from the initial regime to the limit regime on the plane (*PJ*):

$$J_z = F_p(P). \quad (27)$$

4. Lines 1–4 represent the projection of the trajectory of change in the steady state equilibrium position from the initial regime to the limit regime on the plane (*VP*):

$$U_r = G(P_r). \quad (28)$$

The analysis of the curves given in Fig. 2 shows that for the change in the value of the Jacobian determinant J, two sections close to linearity are observed: at the beginning and at the end of the weighting process. This is due to the peculiarities of the voltage stability property. Obviously, in the limit modes, the convergence of the mode establishment process is determined by the nonlinearity of the equations describing the steady-state modes of the network.

Fig. 2 shows the dependence of V on P. The indicated dependence is nonlinear. In the range of the weighting trajectory, the changes of voltage from power obey the equation of quadratic form, which is due to the properties of nonlinear equations. The nonlinearity appears weak, which is further confirmed in comparative calculations with error estimation. When selecting the volume of control actions, it is obviously possible to take advantage of the weak nonlinearity of the considered dependence. Analysis of the character of the curves shows that it is possible to use the linear dependence of the stability margin on the mode parameters, which in practical calculations allows us to apply simple relations and algorithms in the selection of measures to ensure the system stability. When choosing the volume of control actions, it is obviously possible to take advantage of the weak nonlinearity of the dependence of power on voltage in the controlled points of the network.

The construction of analytical dependences of the Jacobian value on the mode parameters: dependent (V) and independent (P) is presented:

1. For curve 1–2 (Fig. 2).

The equations of the approximation line are in the form:

$$J_i = k_0 + k_1 U_i + k_2 P_i. \quad (29)$$

With known values of J_i, V_i, P_i, which can be obtained by calculations of limit mode search, the coefficients of the approximating curve are determined:

k_0=24.639, k_1=–13.449, k_2=–10.284.

Substituting the values of the coefficients into the equation of curve 1–2 we obtain an approximation of the line:

$$J_i = 24.639 - 13.499 U_i - 10.284 P_i. \quad (30)$$

The comparative evaluation of the error of dependence (30) with the results of dependence obtained by modeling is shown in Fig. 3.

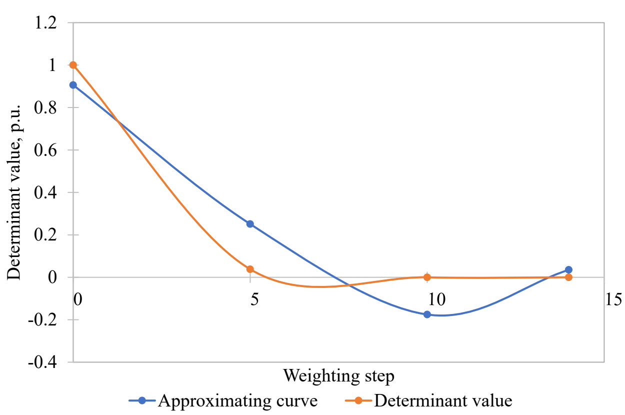

Fig. 3. Comparative evaluation of the error of dependence (30) obtained by modeling

2. Approximating line of power-voltage dependence and stability margin:

$$P_i = 2.51 - 1.43 U_i - 0.124 J_i. \quad (31)$$

The approximation error compared to the original data was 0.037 (3.7 %).

3. Similarly determine the linear approximation equations for the rest of the lines (Table 6):

$$J_i = -3 + 4V_i, \quad (32)$$

$$J_i = -4.33 + 3.33 P_i, \quad (33)$$

$$P_i = 2.2 - 1.2 V_i. \quad (34)$$

The analysis of the dependences shows sufficient approximation accuracy in the first part of the linear part of the graphs, which is more than 80 % of the change in stability reserves. Dependence 5.6 does not coincide with the nonlinear dependence in the middle part of the graph from 5 % to 10 %, which limits its use in the selection of ECS in the refined calculations.

Table 6

Linear approximation equations for the *JV*, *JP* and *PV* lines

Plane	Lines in Fig. 2	Equation	Independent variable	Dependent variable
JV	Line 1–3	(32)	V_i	J_i
JP	Line 1–4	(33)	P_l	J_i
PV	Line 0–4	(34)	V_i	P

Formation of the volume of control actions using the dependence of the determinant on the controlled parameter of the disconnected load power.

When analyzing the results of the calculations shown in Fig. 2, we note the possibility of predicting one parameter when the second parameter is known, which allows us to determine the necessary amount of control actions to ensure the stability of the post-accident mode with a sufficient stability margin. For what, we use the equations given in Table 7:

$$P_i = 2.51 - 1.43 V_i - 0.124 J_i, \quad (35)$$

$$P_i = 2.2 - 1.2 V_i, \quad (36)$$

$$P_i = -7.33 V_i^2 + 11.58 V_i - 3.24. \quad (37)$$

Algorithm for selecting the volume of control actions using formula (37) (Table 7) and graph 2. Fig. 4 shows the graph of ECS formation by two points:

1. At point 1 (Fig. 4), the load power limit ($P_{\max}$) at the point of critical voltage drop (U_{cr}) is determined.

2. Point 2 determines the load power ($P_{\min}$) at the point with voltage ($U_{\min}=U_{cr}/0.85$) in the post-fault mode.

3. The minimum value of the volume of control actions (P_{LS}) is equal to:

$$P_{LS} = P_{\min}(LS) = P_{\text{MAX}} - P_{\text{MIN}}. \quad (38)$$

For dosage values greater than $P_{\min}$, the value increases.

The control volume dosage (R_{on}) is memorized in the dosage setting memorizer.

Table 7

Selection of ECS capacity

Approx.	Equation	Non-dependent variable	Dependent variable	Error
Linear	(35)	V_i=0.97, J_i=0.16	R_m=1.1	3.7 %
Linear	(36)	V_i=0.97	R_m=1.16	6 %
Quadratic	(37)	V_i=0.97	R_m=1.09	1.2 %

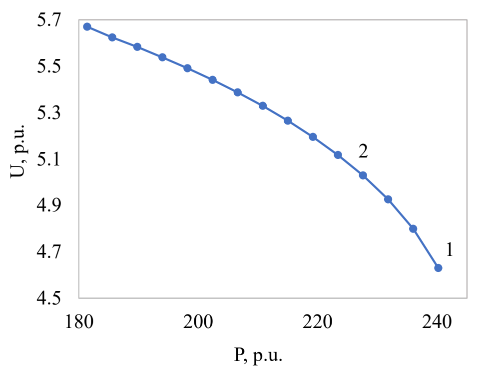

Fig. 4. Formation of emergency control by two points

5. 4. Functional scheme of the algorithm for forming the volume of control actions

According to the proposed approach for adaptive automation, a two-stage algorithm for the operation of the emergency control system is used:

1) formation of the volume of control actions in the control loop in the pre-emergency mode;

2) input of control actions when the detecting device fixes the conditions of stability violation occurrence.

The realization of such an ECS algorithm is carried out on the basis of solving this problem according to the principles of 1-Before and 1-After (Fig. 5).

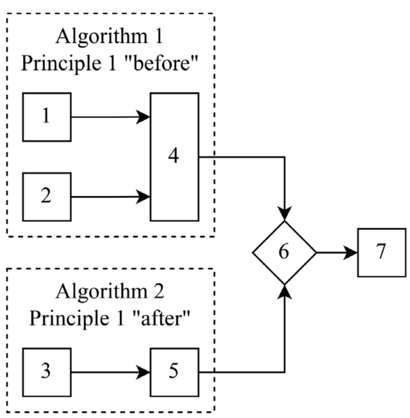

Fig. 5. Algorithm of functioning of adaptive mode automatics: 1, 2 – data by modes (tele-signals, tele-measurements); 3 – data on current control; 4 – block of forming the volume of control actions; 5 – power surge detection unit; 6 – device for memorizing the volume of control actions; 7 – actuator

According to Principle 1, the following steps are performed periodically in the pre-emergency mode to calculate the amount of control actions:

1. Formation of an adaptive model of the steady-state mode of the network based on current data.

2. Search for the limiting regime with weighting along the trajectory of the system motion to the limiting regime. At each iteration of weighting, the mode is calculated, the numerical values of the Jacobi determinant are determined, and the stability reserves in relative terms are determined.

3. According to the results of the mode calculation at each iteration, the dependences of the stability margin on the value of the Jacobian determinant on the weighted parameter $J=f(P_n)$ are formed, as well as the dependences between the observed parameters of the power mode and load voltage $P_n=g(U_n)$.

4. The ECS dosage value is determined from the calculated dependence $Pm=g(V_n)$ (load power on voltage) for the post-emergency mode.

At the second stage, in the «standby» mode, continuous monitoring of the observed parameters of the mode in the control points of the network is performed using the system of vector measurements synchronization. When conditions of stability violation or deterioration of the mode by the controlled parameters are detected, a command to input the appropriate amount of control actions (R_{on}) is formed.

One variant of the implementation of this algorithm is shown in Fig. 6.

The proposed algorithm implements the requirements for the speed and reliability of software automation and selectivity of adaptive automation based on an intelligent system operating in real time.

For the technical implementation of the proposed algorithm, it is possible to use microprocessor module blocks used in digital EA systems with the addition of new blocks for predicting the post-emergency mode with a minimum stability margin and a block for selecting the permissible amount of control actions ensuring the stability of the load voltage.

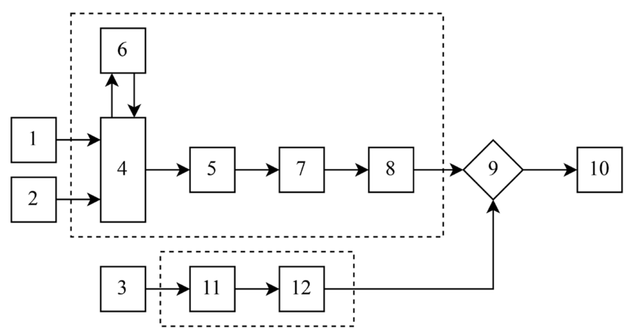

Fig. 6. Functional scheme of the ECS algorithm based on the intelligent system of monitoring and forecasting of stability stocks: 1 – Telemetered data (TI); 2 – Telesignals (TS); 3 – Microprocessor-based data acquisition devices (PMU 1, PMU 2) for synchronization of vector measurements; 4 – SCADA – Supervisory Control and Data Acquisition; 5 – Block of scheme formation and steady state calculation; 6 – Mode evaluation unit; 7 – System for solving the problems of determining the limiting mode and predicting the dependence of stability reserves on the value of the Jacobi determinant when weighting by the network load parameter. Forecasting is performed by the method described in [27]; 8 – System for solving problems on forming the volume of control actions for the post-emergency mode with minimum permissible stability margin; 9 – Device for automatic memorization of the division place; 10 – Control execution device; 11 – WAMS – Wide Area Monitoring System (vector measurement synchronization device) [IEEE Standard C37.118.1™ – 2011]; 12 – Detection device for stability violation fixation

6. Discussion of the results of the study of the proposed algorithm

This paper presents the results of improving and developing algorithms for determining the volume of control actions of the control system in the control loop, which ensure the adaptability of the control system calculations to the actual network mode. To determine the dependence of the EPS stability margin on the mode parameters for the network calculation model shown in Fig. 1, based on the development of a stability assessment method using the property of the Jacobian matrix determinant, calculations were made to determine the parameters of the limit mode when the voltage drops to a critical level. Table 3 shows the parameter values in the initial and limit modes. The data on the mode parameters (voltage and load power) and the Jacobian determinant in relative units were obtained using formula (24) and presented in Table 4.

To ensure the formation of the volume of ECS control actions using the relationship between the power and the value of the stability margin and the observed parameters of post-accident steady-state modes in three-dimensional space, the relationships between the values of the Jacobian determinant and the mode parameters were constructed. The obtained relationships are given in Table 5 and presented in graphic form in Fig. 2. In accordance with formulas (29)–(34), analytical relationships of the Jacobian value on the mode parameters were constructed and the linear approximation equations presented in Table 6 were obtained. To approximate the relationship in the form of an equation, an algorithm using the least squares method was used.

Compared to [5], this paper also uses real-time data to detect instability, but the focus of this work is to calculate the required amount of control actions rather than to develop a transient stability control system. The proposed approach makes it possible to identify unacceptable modes based on the current state of the mode parameters and does not require a large number of calculations.

To substantiate the proposed method for constructing the stability margin dependencies by the operating parameters and the algorithm for generating the volumes of control actions, modeling was performed using the PowerFactory DigSilent and RastrWin complex. When analyzing the calculation results, the possibility of predicting one parameter with a known second was noted, which allows determining the required volume of control actions to ensure the stability of the post-emergency mode. Using equations (35)–(37), a graph of the control action formation by two points was obtained. The results are presented in Table 7 and Fig. 4. The minimum value of the control action volume was determined by (38), which ensured the preservation of the stability of the post-accident mode. To develop a functional diagram for implementing the algorithm for generating the volume of control actions, existing modules of the CECS software were used with the inclusion of algorithms for searching for a limiting mode and generating the dependence of the control action on the stability margin. A description of the functional diagram of the algorithm for generating the volume of control actions is presented in Section 5.3. The algorithm of functioning of adaptive mode automation and the functional diagram of the algorithm based on the intelligent system of monitoring and forecasting of stability margins are presented in Fig. 5, 6.

The main advantages of the proposed algorithm for ECS formation are:

– unlike existing algorithms that select the volume of control actions by enumerating various control volumes to maintain static stability, the proposed algorithm is based on using the dependence of the value of control power on the system stability margin, which is formed periodically at the rate of mode change. The use of this dependence is based on the prerequisites for the development of a method for assessing stability based on the properties of the Jacobian matrix determinant;

– the algorithm for selecting the volume of control actions is implemented in the control loop for the actual network mode, which eliminates the need to perform numerous calculations for a variety of expected modes and estimated emergency disturbances.

At the same time, when performing the necessary research, the authors noted some shortcomings of the proposed algorithms:

– the paper proposes a practical method for constructing the dependence of the Jacobian value on the variable (controlled) weighting parameter. The work does not provide strict theoretical justifications for the proposed approach, which may be the subject of further discussion and can be strictly substantiated by specialists in the mathematical theory of stability;

– in this paper, the search for limiting modes is performed by iterative methods used in algorithms for industrial complexes for calculating stable modes. These algorithms do not allow strictly fixing the transition of the Jacobian determinant from a positive to a negative value, which limits the correctness of the stability assessment.

The results of the study of the proposed algorithm for selecting the control parameters of the automatic control system confirm the possibility of determining sufficient control parameters at power sets leading to line overloads using the dependence of the control power on the stability reserves by the value of the Jacobian determinant.

The future development of this study entails refining algorithms to effectively manage complex network conditions and ensuring scalability to larger systems.

7. Conclusions

1. A distinctive feature and advantage of the proposed algorithm is the ability to select control actions of emergency automation depending on the value of the system stability margin. In the known algorithms, there is no explicit dependence of control actions on the mode parameters and their selection is carried out by enumerating the control value to ensure the stability of the post-emergency mode, which is achieved by searching for the equilibrium position of the system.

2. The principle of selecting control actions in the proposed algorithm allows predicting the post-emergency mode with a standard (sufficient) stability margin. Forecasting the post-emergency mode is reduced to solving two interrelated problems with determining the assessment of the stability margins of steady-state modes: searching for parameters of limit modes with a zero stability margin and constructing the dependence of the stability margin on the value of the Jacobi determinant from the variable parameter of the mode along the trajectory of change in the coordinates of the stable state of the system to the boundary of the unstable state. Using this approach with a simultaneous search for the limit mode

and construction of the stability margin dependence by the Jacobian determinant value allows increasing the accuracy and speed of the algorithm.

3. To confirm the theoretical provisions in the proposed algorithm for selecting control actions of emergency automation, the results of calculations on a model of a system section with a power deficit connected to a high-power system are presented. The stability of the network under consideration is determined by the criteria of static voltage stability. Based on the calculation results, tables and dependences of the stability margin on the mode parameters are constructed, which in three-dimensional space graphically reflect the trajectory of change in the coordinates of the system position from a stable to an unstable state. The volume of control actions for the predicted post-emergency mode is determined on the basis of a graph-analytical algorithm using an approximating dependence of power on the stability margin by the Jacobian value.

4. The possibility of implementing the proposed algorithm is shown in the developed functional diagram using existing software modules in intelligent emergency control automation systems and static stability reserve monitoring systems. For the technical implementation of the proposed algorithm, it is possible to use microprocessor modular units used in digital emergency control automation systems with the addition of new units for predicting the post-emergency mode with a minimum stability reserve and a unit for selecting the permissible volume of control actions ensuring voltage load stability.

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.

Use of artificial intelligence

The authors confirm that they did not use artificial intelligence technology when creating this paper.

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