Methods for ensuring stability of operating conditions of an electric power system with distributed generation plants

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Article Info

Article history:

Received Mar 2, 2024
Revised Sep 16, 2024
Accepted Oct 23, 2024

Keywords:

Areas of static aperiodic stability
Distributed generation plants
Electric power systems
Equations of limit conditions
Fuzzy control system

ABSTRACT

Modern electric power systems (EPSs) experience an increase in the number of distributed generation plants. These plants can be located far from the center of consumption, which "narrows" the areas of static aperiodic stability, determining the possibility of the existence of the operating mode of the electric power system. Since there can be variations in the operating conditions of distributed generation plants and changes in the areas of static aperiodic stability, it is necessary to use adaptive control algorithms. The presented methods are based on the equations of limit conditions. Reliable convergence of iterative processes is ensured by specifying initial approximations based on the proposed starting algorithms. Modeling of transient processes in the studied EPS was performed for various points in the space of controlled operating parameters in the MATLAB system. It showed the effectiveness of the fuzzy control system when used to adjust the settings of automatic regulators of distributed generation plants. The greatest effect is observed for generator voltage: the transition process time for the first distributed generation installation is reduced by four times, and for the second installation – by 2.3 times; there are no generator voltage fluctuations in transient mode.

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1. INTRODUCTION

Calculations of limit conditions in terms of static aperiodic stability (SAS) [1] are essential for designing and operating electric power systems (EPSs). They are of independent significance and are an integral part of other electric power tasks aimed to ensure the required level of reliability and economic efficiency of the systems [2], [3]. Static stability determines the ability of an electrical power system to return to its original or close to it mode after minor disturbances under current operating conditions. Classical approaches to determining static stability margins are given in [4], [5]. The works [1], [2], [6] present the development of methods for assessing stability based on the equations of limiting modes proposed in [3]. For example, in article [1], the authors propose a non-iterative method for determining the boundaries of static aperiodic stability.

In research [7], power series are used to define the regions of existence of the EPS mode. Article [8] presents the results of an analysis of the state of the EPS based on the tropical geometry of power balance equations over complex multipoles. This circumstance is very important when studying such systems. The study [9] presents the results of studies of static stability margins in systems with DC transmission lines.

The solution to the presented problems is especially relevant in modern power systems with distributed generation (DG) installations [10], [11], which are located in close proximity to consumers. Article [12] proposes a method for assessing the stability of EPS with distributed generation under conditions of rapidly changing loads. In particular, DG plants can be implemented on the basis of non-traditional renewable energy sources (RES) [13]-[15] using electricity storage devices [16], [17]. The renewable energy sources employed can be located far from consumption centers, which “narrows” the SAS regions and has a significant impact on emergency control that ensures stability in post-emergency conditions of the EPS [18]. The study presented in [19] examines the problems of the stability margin of electrical networks with distributed generation plants. Chen *et al.* [20] focus on predicting the stability of electric power systems with a large share of wind generating plants.

Changing the power of the DG plant generators to enable the EPS operating conditions to meet the stability requirements should be carried out with an acceptable quality of dynamic processes. This can be achieved through the use of automatic regulators of excitation (AER) and speed (ASR) of the synchronous generator rotors of the DG plants. It is also worth noting that optimal control requires adjusting the settings of the AER and ASR of the DG plants in the event of significant changes in operating conditions. These requirements can be met by using intelligent control algorithms, for example using genetic algorithms [21] or fuzzy inference systems [22], [23]. Similar studies [24]-[27] consider the issues of analyzing static stability and assessing the stability margin of EPS within the framework of the use of intelligent control algorithms and active network elements. For example, in article [24] it is proposed to ensure the stability of a multi-machine EPS using a static synchronous compensator controlled based on the ant colony algorithm. In [25], the sustainability of the EPS is increased by creating an intelligent hybrid wind-solar power plant as a static compensator. In article [26], the authors consider the problems of increasing the static aperiodic stability in a two-machine EPS by using a fuel cell as a STATCOM. Real-time assessment of voltage stability in a large-scale EPS based on spectrum assessment of vector measurement unit data is given in [27]. Article [28] presents a hybrid method for calculating the voltage stability margin in the power supply system, taking into account the uncertainty of load changes and possible unforeseen modes. To assess the voltage stability of an electrical network, article [29] proposes to use the Euclidean distance between bus voltage vectors.

To improve the stability of the power system under random disturbances [30], strategies based on adaptive control [31], frequency domain approach [32], and particle swarm optimization methods [33] are used. Assessing stability in the transient process for EPS with DG installations is an important task in connection with possible fluctuations in the power of sources. Previous studies [34]-[36], the authors propose a method for estimating the stability margin during transient processes online. The proposed method uses a neural network to depict the relationship between steady-state power flow and generator stability indices under an expected set of unexpected conditions. In article [37], a method for analyzing the transient stability of EPS is proposed, which allows illustrating the structural characteristics of the dynamic stability region. The work also presents results that allow displaying the boundary on the global phase plane. It is very important that the stability boundary and phase portraits are studied in three-dimensional space [38].

Paper [39] presents a hybrid analytical approach combining the direct Lyapunov stability method and time domain modeling for rapid analysis of power system transients. Paper [40] presents a predictive control model based on sensitivity analysis that aims to improve transient stability by reconfiguring the transmission system. Methods for determining limiting modes can be divided into three groups [3]-[5]: discrete weighting, continuous weighting, and those based on limiting mode equations. The results of their comparison based on tabular analysis are given below.

The presented research aims to develop effective methods for enabling the operating conditions of EPS with DG plants to meet the requirements of static aperiodic stability and to test the effectiveness of the fuzzy control system used to adjust the settings of automatic regulators of DG plants to ensure appropriate dynamic behavior of the EPS. This efficiency lies in improving the quality of regulation of EPS mode parameters. Thus, the main result of this work is the application of methods for introducing the operating mode of EPS with DG plants into the region of static aperiodic stability based on the calculation of limiting modes, as well as the use of a fuzzy logic inference system to control the regulators of generators of DG plants and ensuring high-quality dynamic transition at shutdowns of loaded network elements. The paper presents the formulation of the problem in detail, describes algorithms for entering the EPS mode into the stability region, as well as methods for solving the “far boundary” problem when entering the mode into the stability region. In addition, the results of modeling emergency control of DG plants with ensuring high-quality dynamic transition are presented. The structure of the article consists of the statement of the problem, methods for ensuring the stability of EPS, methods for solving the problem of the far boundary when introducing the EPS mode into the stability area, modeling results of the proposed emergency control system for distributed generation installations with ensuring a high-quality dynamic transition and a conclusion where the main conclusions are presented.

2. PROBLEM STATEMENT

Equilibrium state of an autonomous system of differential equations is asymptotically stable. This statement is based on the Lyapunov stability theorem if the linear system of the first approximation. Where $\Delta x_k = x_k - x_{k0}$; x_{k0} – coordinates corresponding to the equations $w_i(x_{10}, x_{20}, \ldots, x_{n0}) = 0$; $i = \overline{1 \ldots n}$. Linearization can be done using function expansion $w_i(x_1, x_2, \ldots, x_n), i = \overline{1 \ldots n}$; $w_i(x_1, x_2, \ldots, x_n) = w_i(x_{10}, x_{20}, \ldots, x_{n0}) + \sum_{k=1}^{n} \left(\frac{\partial w_i}{\partial x_k}\right)_{|X=X_0} \Delta x_k + \frac{1}{2!}\sum_{k=1}^{n}\sum_{j=1}^{n}\left(\frac{\partial^2 w_i}{\partial x_k \partial x_j}\right)\Delta x_k \Delta x_j + \ldots$ and equating nonlinear terms to zero, i.e. $\frac{1}{2!}\sum_{k=1}^{n}\sum_{j=1}^{n}\left(\frac{\partial^2 w_i}{\partial x_k \partial x_j}\right)\Delta x_k \Delta x_j + \ldots \approx 0$. The solution to (1) and (2) is stable if the real parts of all roots of the characteristic equation are negative, as in (3).

$$\frac{dx_i}{dt} = w_i(x_1, x_2, \ldots, x_n);\ i = \overline{1 \ldots n} \tag{1}$$

$$\frac{dx_i}{dt} = \sum_{k=1}^{n} \left(\frac{\partial w_i}{\partial x_k}\right)_{|x_k = x_{k0}} \Delta x_k;\ i = \overline{1 \ldots n} \tag{2}$$

$$D(p) = det\left(\frac{\partial W}{\partial X} - pE\right) = 0 \tag{3}$$

Where $\frac{\partial \boldsymbol{W}}{\partial \boldsymbol{X}}$ is the Jacobian matrix of $W(X)$: $\frac{\partial W}{\partial X} = \begin{bmatrix} \frac{\partial w_1}{\partial x_1} \cdots \frac{\partial w_1}{\partial x_n} \\ \cdots \\ \frac{\partial w_n}{\partial x_1} \cdots \frac{\partial w_n}{\partial x_n} \end{bmatrix}$.

When analyzing steady-state EPS modes, Lyapunov stability is called static. In this case, two types of instability are distinguished: aperiodic and oscillatory. The first type arises in the presence of real positive roots $p_k > 0$, the second - when complex roots $p_k = \alpha_k + j\beta_k$ with a positive real part appear, i.e. $\beta_k > 0$. The methods and algorithms presented below are applicable to the analysis of only static aperiodic stability. Characteristic (3) can be presented in expanded form as in (4).

$$D(p) = p^n + a_{n-1}p^{n-1} + \ldots + a_0 = 0 \tag{4}$$

In order for this equation not to have positive real roots p_k, it is necessary and sufficient that all its coefficients be greater than 0. In practice, the points corresponding to the boundary of aperiodic stability in the parameter space are determined by weighting the initial stable mode. In this case, you do not need to monitor the signs of all coefficients. This is due to the fact that the free term will be the first a_0 to change sign. This conclusion follows $p_k = 0$ from relations (3) and (4) at (5).

$$a_0 = (-1)^n\, det\frac{\partial W}{\partial X} = 0 \tag{5}$$

Thus, if the sign of a real root changes from negative to positive, a sign change occurs a_0. This property forms the basis for methods used in practice for determining the limiting modes of static aperiodic stability, i.e., modes that meet the condition $p_k = 0$. The steady-state conditions of the EPS are defined by nonlinear equations of the form as in (6).

$$F(X, Y) = 0 \tag{6}$$

Where $F = [f_1 f_2 \ldots f_n]^T$ – vector function of power or current balance equations in electrical network nodes. $Y = [y_1 y_2 \ldots y_m]^T$ – vector of adjustable parameters, which are used as active and reactive powers of generators and loads, as well as voltage modules fixed in individual network nodes. $X = [x_1 x_2 \ldots x_n]^T$ – vector of unregulated parameters, which are taken as real and imaginary components or modules and phases of nodal voltages.

The limiting modes of EPS in terms of static aperiodic stability are the modes that correspond to the points X_L, Y_L of the parameter space $Z = X \cup Y$ in which (6) and condition in (5) are satisfied. The expression for a_0 can be obtained directly from the steady state equations as in (7).

$$W(X, Y) = 0 \tag{7}$$

Which are written taking into account the characteristics of EPS elements under small disturbances. It should be noted that to solve practical problems when determining a_0, you can use (6). In this case, parameter a_0 can be defined as in (8).

$$a_0 = (-1)^n \, det \frac{\partial \boldsymbol{F}}{\partial \boldsymbol{X}} \tag{8}$$

In Y space, points Y_L form a hypersurface L_F, as seen in Figure 1, limiting the region of static stability. In the process of managing modes, it is necessary to ensure that the points of the current modes Y_k are located within the stability region. Approaching the L_F boundary is possible at a distance determined by the standard value of the stability margin.

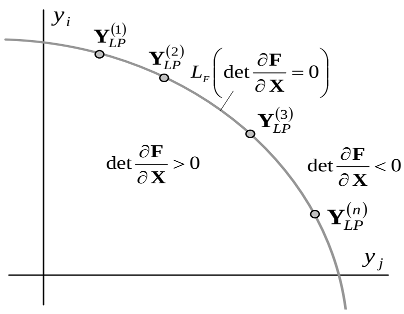

Figure 1. Projections of the regions of stability and existence of operating conditions onto the coordinate plane

3. METHODS FOR ENSURING THE STABILITY OF THE EPS OPERATING CONDITIONS

Ensuring static stability of post-emergency conditions (PAC) is one of the main tasks of emergency control of EPS. The input of the PAC into the stability region is carried out along a certain trajectory in the space of adjustable parameters Y [3], which is chosen to be linear. This trajectory can be set based on preliminary calculations; correspond to the shortest distance to the L_F boundary or be selected by minimizing the damage associated with disconnecting electricity consumers. To determine limiting modes without using multi-step computational procedures, and also to avoid difficulties associated with solving poorly-conditioned systems of linear equations, one can use limiting mode in [3], based on replacing condition (2) with an equivalent relationship, which can be written in two forms as in (9) and (10).

$$V = \frac{\partial F}{\partial X} S = 0 \tag{9}$$

$$V = \frac{\partial F}{\partial X} S = 0 \tag{10}$$

Where V is an n-dimensional vector function; $S = [s_1 \quad s_2 \quad \cdots \quad s_n]^{T[r_1 \quad r_2 \quad \cdots \quad r_n]^T}$ are eigenvectors of matrices $\frac{\partial \boldsymbol{F}}{\partial \boldsymbol{X}}, \left(\frac{\partial \boldsymbol{F}}{\partial \boldsymbol{X}}\right)^T$ that correspond to zero eigenvalue.

Under the emergency operating conditions of the EPS, for example, when, as a result of a power line shutdown, the stability region "narrows" and it is necessary to ensure that the operating conditions are within the stability region, as shown in Figure 2, such a procedure can be performed along the given paths. In this case, the equations of limit conditions are used, as in (11).

$$\left.\begin{array}{l} F[X, Y(T)] = 0; \\ V[X, R, Y(T)] = \left(\frac{\partial F}{\partial X}\right)^T \\ U(R) = R^T\} \end{array}\right\} \tag{11}$$

Where $Y = Y_0 + T\Delta Y$ is a vector of controlled parameters.

The modeling results and calculations of the stability margin for a three-node scheme, as shown in Figure 3, are presented in Table 1 and Figure 4. When setting the unloading direction, which differs significantly from the shortest one to the limit surface, it becomes impossible to reach the stability region parameters. In this case, the unloading point in space Y can be calculated in two stages, as displayed in Figure 5. They are, in the first stage, the limit hypersurface is reached in the direction ΔY and in the second stage, unloading is performed in the direction of vector R, which coincides with the direction of normal to the limit hypersurface.

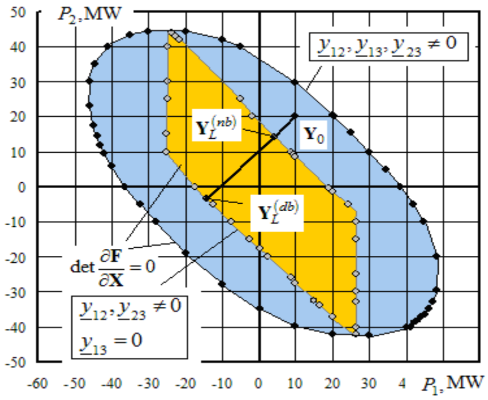

Figure 2. “Narrowing” of the stability region when the line is disconnected

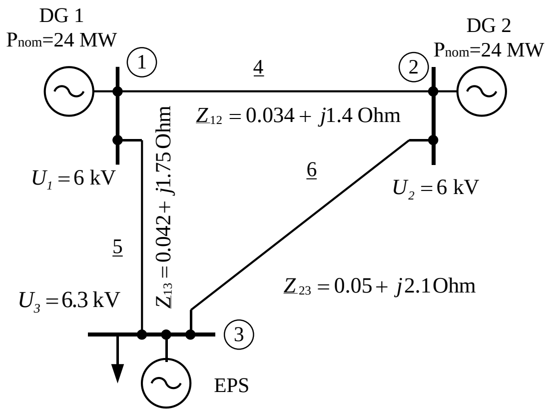

Figure 3. Network scheme

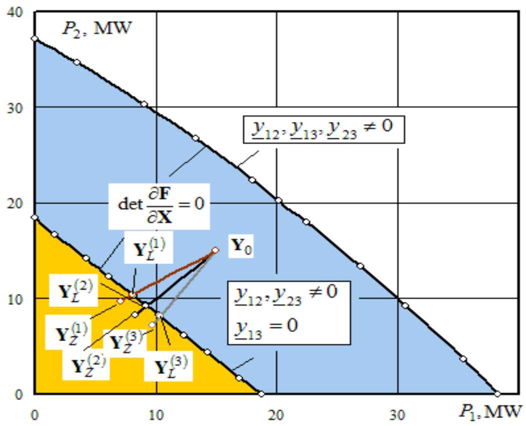

Figure 4. Ensuring the operating conditions within the stability region along the given paths

Table 1. DG power and stability margins

No	P10, MW	P20, MW	PL1, MW	PL2, MW	PZ1, MW	PZ2, MW	$\Im$, MW	$\Im^*$, %
1	15	15	9.23	9.23	8.35	8.35	1.24	15
2	15	15	10.40	8.10	9.75	7.13	1.17	15
3	15	15	8.10	10.40	7.13	9.75	1.17	15

Note: $\Im = \sqrt{\sum_{k=1}^{2}(P_{Lk} - P_{Zk})^2}$; $\Im^* = 100\sqrt{\sum_{k=1}^{2}\left(\frac{P_{Lk}-P_{Zk}}{P_{Zk}}\right)^2}$ is stability margin

Vector R is calculated when solving the equations of limit conditions (10). An example of such unloading is illustrated in Figure 5. It is convenient to determine the margin of static aperiodic stability through the norm of the vector K, corresponding to the distance from the point of the analyzed mode to the boundary L_F (12):

$$\Im = (K^T K)^{\frac{1}{2}} = (\sum_{i=1}^{m} k_i^2)^{\frac{1}{2}} = (\sum_{i=1}^{m} \mu_i^2 \, (y_{iL} - y_{i0})^2)^{\frac{1}{2}}, \; \mu_i = \frac{1}{k_{iN} y_{iNOM}} \quad (12)$$

Each direction of the load increase $\Delta \boldsymbol{Y}_i$ will correspond to its value $\Im_i$ and for a reliable assessment of the stability margin, it is necessary to search for the critical direction of load increase $Y^*(T) = Y_0 + T\Delta Y^*$ corresponding to the least length $\Im_{min}$ of vector K. Stability can be provided along the shortest path by modifying the equations of limit conditions. This modification aims to search for the limit conditions in the critical direction of load increase (13).

$$\left. \begin{array}{l} F\left(X, Y_0 - M^{-2}\left(\frac{\partial F}{\partial DY}\right)^T ()\right) \\ \left(\frac{\partial F}{\partial X}\right)^T \} \end{array} \right\} \tag{13}$$

Where Y_0 is the value of the vector of controlled parameters in the operating conditions; $DY = [dy_1 dy_2 \dots dy_n]^T$ is the variable increment vector Y_0 enabling the operating conditions to reach the limit hypersurface; $M = diag\, \mu_i$. The modeling shows that using (13), it is possible to ensure the EPS operating conditions reaching the stability region boundary along the shortest path. The required margin can be achieved by additional unloading, as displayed in Figure 6.

An algorithm that provides direct input of a mode to the boundary of an admissible region corresponding to a given stability margin can be implemented based on a modification of the limit mode equations as in (14) using the summation of the direct and transposed Jacobian matrices of (6).

$$\left. \begin{array}{l} F(X, Y_0 + T\Delta Y) = 0; \\ \left(\frac{\partial F}{\partial X} + \frac{\partial F}{\partial X}^T\right) S_\rho = \rho\rho_{min} \\ S_\rho^T S\rho - 1 = 0, \end{array} \right\} \tag{14}$$

Where ρ_{min} is the minimum eigenvalue of matrix $A = \frac{\partial W}{\partial X} + \frac{\partial W}{\partial X}^T$; S_ρ is the eigenvector corresponding to the eigenvalue ρ_{min} of matrix A. After simple transformations, we can write (15).

$$\left. \begin{array}{l} F(X, Y_0 + T\Delta Y) = 0; \\ \frac{\partial F}{\partial X} S_\rho + \frac{\partial F}{\partial X}^T S_\rho = \rho\rho_{min} \\ S_\rho^T S\rho - 1 = 0. \end{array} \right\} \tag{15}$$

The calculation results that demonstrate an example of ensuring stability of the operating conditions using (14) are presented in Figure 7 and Table 2.

Table 2. DG power

No	P10, MW	P20, MW	PZ1, MW	PZ2, MW
1	18	18	4	10.5
2	18	18	7.3	7.3
3	18	18	10.5	4

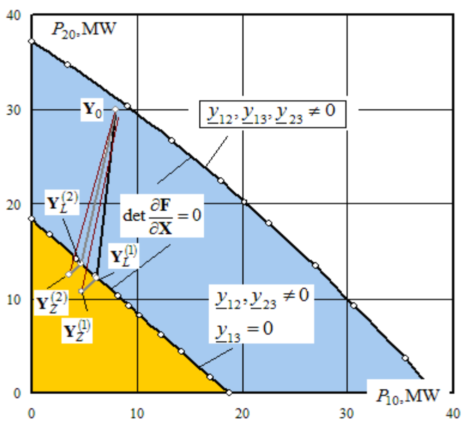

Figure 5. Use of vector R to ensure the operating conditions are within the stability region along given paths

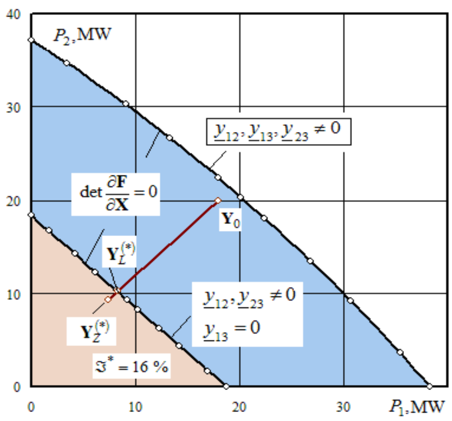

Figure 6. Ensuring the operating conditions are within the stability region along the shortest path

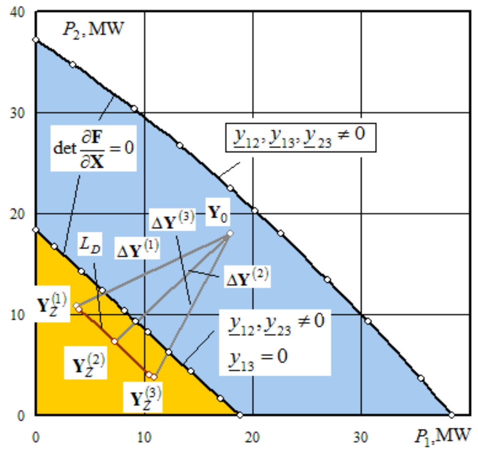

Figure 7. Ensuring the operating conditions are within the stability region using (14): ρ_{min}

4. METHODS OF SOLVING THE FAR BOUNDARY PROBLEM WHEN ENSURING THAT THE OPERATING CONDITIONS LIE WITHIN THE STABILITY REGION

To obtain a reliable solution using the above-described algorithms, the initial approximations must be specified near the limit hypersurface that bounds the SAS area. Initial approximations that ensure reliable convergence of iterative processes can be obtained based on the starting algorithms described in [3]. In addition, there is a problem with reaching the "far boundary" of the stability region: the point $Y_L^{(db)}$ in Figures 8(a) and 8(b). In this case, the resulting solution, which differs in the reverse of the signs of power injections, cannot be used in practice. This problem is solved by the method proposed in [2], which is applicable only in special cases.

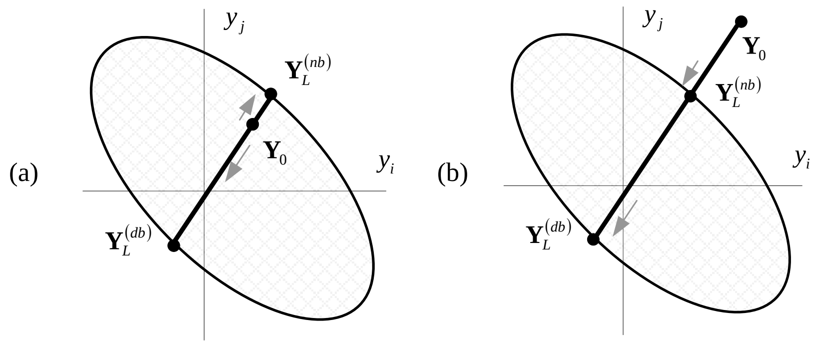

Figure 8. To the "far boundary" problem: (a) when determining the limit conditions and (b) when ensuring that operating conditions are within the stability region

To prevent the computational process from reaching the "far boundary", starting algorithms can be used that take into account the nonlinear terms of the Taylor series expansion of the residual vector function or are based on minimizing the following functional as in (16) [41].

$$\aleph(X) = F^{T(X,Y_0)(X,Y_0)} \quad (16)$$

In this case, Y_0 should be set so that the corresponding point in the space of controlled parameters lies outside the stability region. This condition is met initially when the control actions of emergency control systems are chosen, as seen in Figure 8(b). In the case shown in Figure 8(a), such a point $Y_0^{(*)}$ is determined based on the following relation as in (17).

$$Y_0^{(*)} = Y_0 + tY_0 \quad (17)$$

The use of parameters X calculated by minimizing the functional (16) as initial approximations to solve the equations of limit conditions and their modifications ensures reliable convergence to the desired points $Y_L^{(nb)}$ lying on the "near" boundaries of the stability region, as seen in Figure 2. Point $Y_L^{(db)}$ in the Figure is obtained using a "flat start" (nominal voltages and zero angles). Desired point $Y_L^{(nb)}$ is found by solving the (18).

$$F\left[X, Y_0 - M^{-2}\left(\frac{\partial F}{\partial DY}\right)^{T(1+\alpha)} [];\right] V(X,R) = \left(\frac{\partial F}{\partial X}\right)^{T;} U(R) = R^{T\left(\frac{\partial F}{\partial DY}\right)^{-2}\left(\frac{\partial F}{\partial DY}\right)^{T_1{}^2}} \quad (18)$$

When using initial approximations based on the minimization of the functional (16). For the starting algorithm, you can use the algorithm of V. A. Matveev, which implements the following iterative procedure (19).

$$X^{(k+1)} = X^{(k)} - \lambda^{(k)}\left[\frac{\partial F}{\partial X}\left(X^{(k)}\right)\right]^{-1} F\left(X^{(k)}\right) \quad (19)$$

Where $\lambda^{(k)}$ is calculated like this (20).

$$\lambda^{(k)} = \begin{cases} \frac{1}{B_k}, if\ B_k > 1 \\ 1, if\ B_k \leq 1 \end{cases}; B_k = \frac{1}{2\,max\left|F(X^{(k)})\right|} max\left|\sum_{(i)}\sum_{(j)} \frac{\partial^2 f_i(X^{(k)})}{\partial x_i \partial x_j} \Delta x_j^{(k)} \Delta x_i^{(k)}\right| \quad (20)$$

Procedure (19) ensures the calculation of any existing modes that meet the condition $det\frac{\partial F}{\partial X} > 0$. When trying to determine unstable modes (at $det\frac{\partial F}{\partial X} < 0$), the computational process "gets stuck" at the boundary point L_F, corresponding to the given weighting trajectory and condition $det\frac{\partial F}{\partial X} = 0$. For the starting algorithm, you can use an iterative process that uses nonlinear terms in the Taylor series expansion of the vector function $X = \Phi(Y)$ inverse to $F(X)$; in this case, the vector of the required parameters is represented in the form $X = X_0 + \Delta X_1(\Delta F) + \Delta X_2(\Delta F^2) + \ldots + \Delta X_k(\Delta F^k) + \ldots$, where $\Delta X_k(\Delta F^r)$ – corrections that are calculated like this $\Delta X_1^{(k)} = -\left[\frac{\partial F}{\partial X}\left(X^{(k)}\right)\right]^{-1} F\left(X^{(k)}\right)$; $\Delta X_2^{(k)} = \left[\frac{\partial F}{\partial X}\left(X^{(k)}\right)\right]^{-1} B_2^{(k)}$; $\Delta X_3^{(k)} = \left[\frac{\partial F}{\partial X}\left(X^{(k)}\right)\right]^{-1} B_3^{(k)}$,... where *k* is iteration number; $\Delta X_r^{(k)}$ is vector of the *r*-th corrections; *r*=1...3....

Components of vectors $B_r^{(k)} = \left[b_{r1}^{(k)} \quad b_{r2}^{(k)} \quad \ldots \quad b_{ri}^{(k)} \quad \ldots \quad b_{rn}^{(k)}\right]^T$, calculated using expressions $b_{2i}^{(k)} = \left[\Delta X_1^{(k)}\right]^{T_i^{(k)(k)}{}_1}$; $b_{3i}^{(k)} = \left[\Delta X_1^{(k)}\right]^{T_i^{(k)(k)}{}_2}$, where $\Gamma G_i^{(k)}$ is Hessian matrix of the function $f_i(X)$ calculated at point $X^{(k)}$. If the initial approximations are specified "far" from the L_F boundary, then the convergence of the series $X^{(k)} = X_0 + \sum_r \Delta X_r$ may not be provided. To improve it, a correction factor should be introduced; in this case the series is transformed to the form $X^* = X_0 + \sum_r \alpha^r \Delta X_r$. By selecting the coefficient α, you can ensure reliable convergence of the series and determine the intermediate point X^*, and then proceed to search for a solution X_P. The computational experiments carried out showed that the parameter α should be calculated as (21):

$$\alpha = \sqrt{\beta\frac{\left\|\Delta X_1^{(k)}\right\|}{\left\|\Delta X_p^{(k)}\right\|}} \quad (21)$$

where $0 < \beta < 1$; $\left\|\Delta X_1^{(k)}\right\| = \left\{\sum_{i=1}^{n}\left[\Delta X_{1i}^{(k)}\right]^2\right\}^{\frac{1}{2}}$; $\left\|\Delta X_p^{(k)}\right\| = \left\{\sum_{i=1}^{n}\left[\Delta X_{pi}^{(k)}\right]^2\right\}^{\frac{1}{2}}$ are vector norms of the first-order and higher-order corrections. Next, the following approximation of the vector of dependent variables should be carried out. In this case, it is calculated as shown in Figure 9 (22).

$$X^{(k)} = X^{(k)} + \sum_{r=1}^{p} \frac{1}{r!}\alpha^r \Delta X_r^{(k)} \quad (22)$$

To compare the proposed approach with discrete and continuous weighting methods [3]–[5]. Table 3 shows the results of their comparison according to three main criteria. They are: i) The presence of multi-step computational procedures that significantly increase the calculation time and limit their applicability in emergency control problems; ii) The need to solve systems of equations with ill-conditioned matrices; and iii) The difficulty of taking into account restrictions in the form of inequalities in the process of increasing the severity of the regime. From the Table 3 it is clear that the proposed approach does not require multi-step computational procedures and ensures the reliability of obtaining the result due to the non-degeneracy of the

Jacobian matrix of systems (11), (13) and (15) at the solution point. However, according to criterion 3, it is inferior to the discrete weighting method. This is due to the fact that taking into account restrictions - inequalities at iterations of solving nonlinear equations (11), (13), (15) can lead to an increase in the number of iterations and calculation time. To eliminate this drawback, a post-iteration approach can be used to take into account the restrictions of inequalities on the Y parameters that change in the process of increasing the severity of the regime. To do this, the limit mode is calculated without taking into account restrictions. Parameters that are outside the ranges set (23) are fixed and the calculation of the limit mode is repeated. The use of this procedure slightly reduces the performance of the algorithm, and it can be effectively used in this problem.

$$Y^{(\min)} \leq Y \leq Y^{(\max)}. \tag{23}$$

Table 3. Results of comparative analysis

Method	Criteria 1	2	3
Discrete weighting	Yes	Yes	No
Continuous weighting	No	Yes	Yes
Based on limiting mode equations	No	No	Yes

5. MODELING RESULTS FOR EMERGENCY CONTROL SYSTEM OF A DISTRIBUTED GENERATION PLANT IN POST-EMERGENCY CONDITIONS WITH APPROPRIATE DYNAMIC CONDITIONS ENSURED

Numerous computational experiments indicate that based on the equations of limit conditions, the operating conditions of EPS with DG plants can reach the boundary of the stability region. To achieve the required stability margin, additional unloading is required. Unloading in the selected direction $\Delta Y^{(k)}$ should be performed under acceptable quality of dynamic processes, which can be achieved with AER and ASR of synchronous generators of the DG plants. Emergency control systems of DG plant must ensure stable operation of generators in the post-emergency conditions. At the same time, for the operating conditions to be within the stability region, the generators are unloaded and the settings of AER and ASR are adjusted. The two-step procedure using the vector R is intended only to find the point $Y_Z^{(R)}$. The dynamic transition is made directly to this point, as revealed in Figure 9. To ensure high quality of this transition, you can use optimization of the AER and ASR settings [23].

The modeling was performed for the network scheme shown in Figure 3. The shutdown of line 1–3 was considered as emergency conditions. Ensuring the stability of post-emergency operating conditions along a given path is illustrated in Figures 10(a) and 10(b). The point with coordinates $Y_0 = [20 \quad 20]^T$ is considered as initial loading conditions of DG plant generators. Ensuring that the operating conditions reach the boundary of the stability region along a given path is represented by point $Y_{Z2} = [15.8 \quad 13.6]^T$.

Dynamic processes in the scheme under study, as seen in Figure 3 are modelled in the MATLAB system, considering the AER and ASR, which are described in [23]. Using the method of coordinated adjustment of the AER and ASR settings [23], their parameters were determined for three kinds of operating conditions of the generator (minimum, average, and maximum load). Based on the obtained settings of the regulators for the considered operating conditions, the rule base of the fuzzy control system was created [23]. In the event that one of the connections is disconnected during the operation of DG plants, the system loses stability. To ensure the PEOC stability, it is necessary to unload the generators. In this case the coordinated adjustment of the AER and ASR settings and their change by fuzzy control system can improve the quality indicators of transients. The greatest effect is observed for the voltage of the generators, and for the parameters of the generator having a direct connection with the disconnected line. Corresponding oscillograms of voltage, deviations of rotor speed, and power of the DG plant generators in case of a short circuit and disconnection of line 1-3 by the relay protection are shown in Figures 11(a) and 11(b).

For the voltage of the generator of the DG1 plant, the use of a fuzzy system for controlling the settings of the regulators made it possible to reduce the time of the transient process by 4 times, as in Figure 11(a), and for the DG2 plant - by 2.3 times, as in Figure 11(b). This also made it possible to eliminate voltage fluctuations of DG plants in transient mode. For DG1, the maximum deviation of the generator rotor speed from the steady value is reduced due to the use of fuzzy control of the controller settings. For the power of the generator of the DG1 plant, a decrease in the amount of overregulation by 30% is also observed (Figure 11(a)) when using this system. The results obtained determine the effectiveness of using a fuzzy system control and automatic control systems of generators of DG plants, which provides a better dynamic transition when the regime enters the stability region.

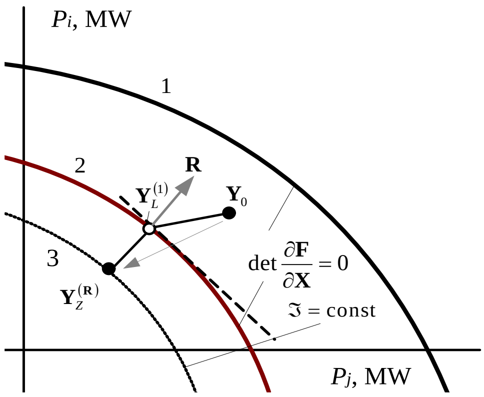

Figure 9. Additional unloading in the direction of vector R

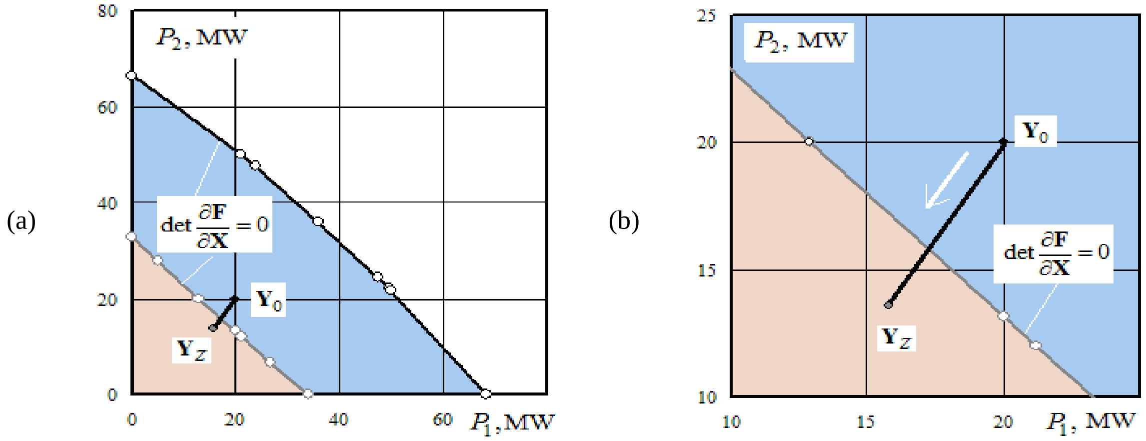

Figure 10. Ensuring that operating conditions are within the stability region: (a) boundaries of the stability region and (b) increased scale of transition to the area of sustainability

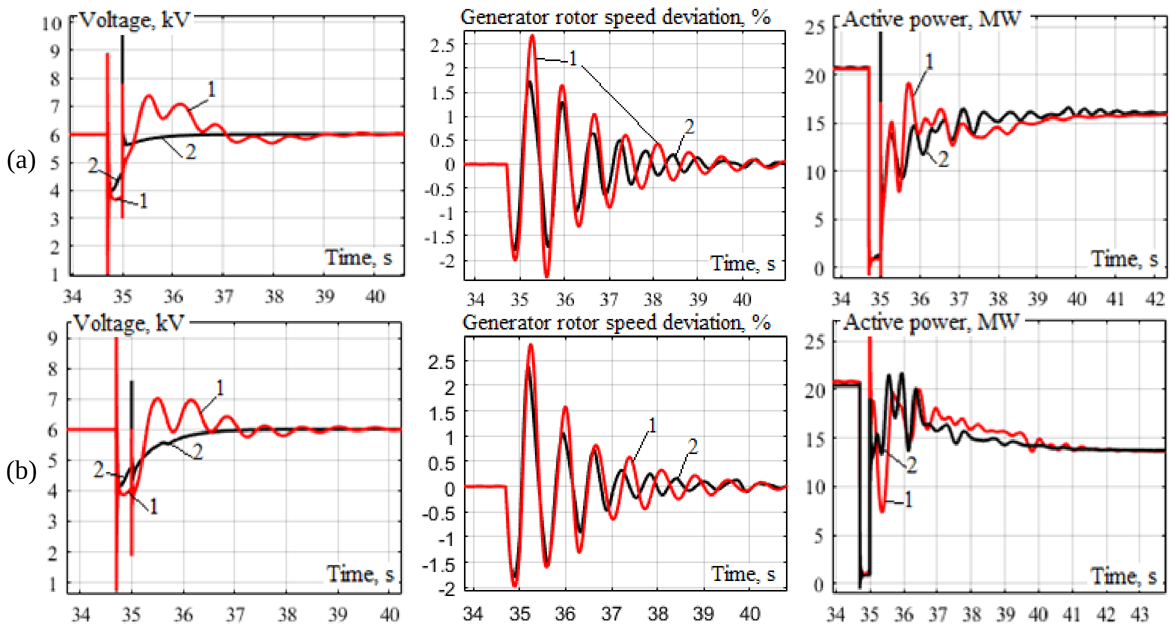

Figure 11. Oscillograms of voltage, rotor speed generator, and power of DG plants in case of a short circuit and disconnection of line 1-3: (a) with no changes in the AER and ASR settings (for DG1) and (b) fuzzy control of AER and ASR settings (for DG2)

6. CONCLUSION

The paper presents the studies on the development of effective methods for ensuring static aperiodic stability of operating conditions of EPS with DG plants. The performance of the fuzzy control system when used for the adjustment of the generator excitation and speed regulators settings was tested to ensure an appropriate dynamic behavior in the post-emergency conditions. To effectively enter the post-emergency mode into the stability region along a given trajectory of its change, you can use the equations of limiting modes; at the first stage, the limit hypersurface is reached in the selected direction □Y; on the second, unloading is performed in the direction of the vector R, which coincides with the direction of the normal to the limiting hypersurface.

The task of introducing the PAC into the stability region along the shortest trajectory can be performed on the basis of a modification of the limit mode equations, designed to search for the limit mode in the critical direction of weighting. The algorithm for entering the PAC into the admissible region corresponding to a given value of the stability margin can be implemented on the basis of relations using the summation of the direct and transposed Jacobian matrices of the steady-state equations. To obtain a reliable solution using the described algorithms, the initial approximations must be specified near the limit hypersurface that delineates the static aperiodic stability region. Initial approximations that ensure reliable convergence of iterative processes can be obtained based on the proposed starting algorithms.

The coordinated adjustment of settings of the AER and ASR of generators of the DG plants provides an appropriate dynamic behavior during unloading in the post-emergency conditions. The use of fuzzy algorithms to control the settings of AER and ASR of generators produces an additional effect on the improvement of the quality of transients for voltage, rotor speed, and power in the post-emergency conditions. The greatest impact on the dynamic conditions is observed for the voltage and for the parameters of the generator directly connected to the disconnected line.

In order to achieve visibility of the results and the possibility of their graphical interpretation on a plane, the article presents simulation results for relatively simple electrical network circuits. It should be noted that the dimension of the simulated circuits is limited only by the characteristics of the computing tools used, the capabilities of which are constantly growing. Development of the proposed methods is possible in terms using non-coinciding matrices for calculating modes $\frac{\partial F}{\partial X}$ and analyzing stability $\frac{\partial W}{\partial X}$.

ACKNOWLEDGEMENTS

This study is financed by the European Union-Next Generation EU, through the National Recovery and Resilience Plan of the Republic of Bulgaria, project № BG-RRP-2.013-0001-C01. The research was conducted within the framework of the state assignment “Conducting applied scientific research” on the topic “Development of methods, algorithms, and software for modeling the operation of traction power systems for DC railways”.

REFERENCES

[1] Yu. V. Makarov, J. Ma and Zh. Y. Dong, “Determining Static Stability Boundaries Using a Non-Iterative Method,” in *2007 IEEE Power Engineering Society General Meeting*, 2007, pp. 1-9, doi: 10.1109/PES.2007.385897.

[2] B. I Ayuev, V. V Davydov and P. M. Erokhin, “Fast and reliable method of searching power system marginal states,” *IEEE Transactions Power Systems*, vol. 31, no. 6, pp. 4525-4533, 2016, doi.org/10.1109/TPWRS.2016.2538299.

[3] A. V. Kryukov, *Limiting regimes of electric power systems* (in Russian), Irkutsk: IrGUPS, 2012.

[4] V. V. Bushuev, A. D. Polyak and V.I. Pustovitov, “The use of dominant roots to assess static stability margins,” *Izvestiya of SB AS USSR. Series: Engineering Sciences*, no. 6, pp. 98-104, 1973.

[5] V. A. Venikov, V. A. Stroyev, V. I. Idelchik and A. A. Vinogradov, “Calculation of the static stability margin of the electrical system,” *Izvestiya of AS USSR. Energy and Transport,* no. 3, pp. 56-65, 1984.

[6] B. I. Ayuev, V. V. Davydov and P. M. Erokhin, “Models of Closest Marginal States of Power Systems in p-Norms,” *IEEE Transactions on Power Systems*, vol. 33, no. 2, pp. 1195-1208, 2018**,** doi: 10.1109/TPWRS.2017.2719125.

[7] V. P. Vasin and V. G. Kondakova, “Investigation of the regions of existence of the regime of electric power systems using power series,” *Izvestiya of RAS. Energy*, no. 1, pp. 47-57, 1995.

[8] B. Kh.Kirshtein and G. L. Litvinov, “Analysis of steady-state modes of electric power systems and tropical geometry of the equations of power balances over complex multipoles,” *Automation and Telemechanics*, no. 10, pp. 110-124, 2014.

[9] L. Sizhuo, Z. Chao, S. Xinfu and L. Pan, “Study on the Influence of VSC-HVDC on Receiving Power Grid Voltage Stability Margin and Improvement Measures,” in *2018 International Conference on Power System Technology (POWERCON)*, 2018, pp. 2503-2508, doi: 10.1109/POWERCON.2018.8601614.

[10] N. Rugthaicharoencheep and S. Auchariyamet, “Technical and Economic Impacts of Distributed Generation on Distribution System,” *International Journal of Electrical, Computer, Energetic, Electronic and Communication Engineering*, vol. 6, pp.385-389, 2012, doi: 10.5281/zenodo.1327636.

[11] T. Ackermann, G. Anderson and L. Söder, “Distributed generation: a definition,” *Electric Power Systems Research*, vol. 57, no. 3, pp.195-204, 2001, doi: 10.1016/S0378-7796(01)00101-8.

[12] R. Kuiava, R. A. Ramos, H. R. Pota and L.F.C. Alberto, “Practical stability assessment of distributed synchronous generators under variations in the system equilibrium conditions,” *International Journal of Electrical Power & Energy Systems*,” vol. 55, pp. 275-284, 2014, doi: 10.1016/j.ijepes.2013.09.013.

[13] N. I. Voropai, K. V. Suslov, T. V. Sokolnikova, Z A. Styczynski and P. Lombardi, "Development of power supply to isolated territories in Russia on the bases of microgrid concept," in *2012 IEEE Power and Energy Society General Meeting*, USA, 2012, doi: 10.1109/PESGM.2012.6344612.

[14] O. Ellabban, H. Abu-Rub and F. Blaabjerg, "Renewable energy resources: Current status, future prospects and their enabling technology," *Renewable and Sustainable Energy Reviews*, vol. 39, pp. 748-764, 2014, doi: 10.1016/J.RSER.2014.07.113.

[15] N. Voropai, E. Ukolova, D. Gerasimov, K. Suslov, P. Lombardi and P. Komarnicki, "A Study on Cost-Effectiveness of Energy Supply Based on the Energy Hub Concept," in *2019 IEEE PES Innovative Smart Grid Technologies Europe, ISGT-Europe*, 2019, 8905736, doi: 10.1109/ISGTEurope.2019.8905736.

[16] X. Shen, S. Zhu, J. Zheng, Y. Han, Q. Li and J. Nong and M. Shahidehpour "Active distribution network expansion planning integrated with centralized and distributed Energy Storage System," in 2015 *IEEE Power & Energy Society General Meeting*, 2015, doi: 10.1109/PESGM.2015.7286069.

[17] W. Xie and X. Xia, "Distributed Energy Dispatch of Electrical Energy Storage Systems Using Consensus Control Approach," *IFAC-PapersOnLine*, vol. 51, no. 13, pp. 229-234, 2018, doi: 10.1016/j.ifacol.2018.07.283.

[18] A. N. Belyaev and S. V. Smolovik, "Designing of adaptive automatic excitation controllers using neuro-fuzzy modeling (in Russian)," *Elektrichestvo*, no. 3, pp. 2-9, 2002.

[19] A. K.Bharati and V. Ajjarapu, "Investigation of Relevant Distribution System Representation With DG for Voltage Stability Margin Assessment," *IEEE Transactions on Power Systems* vol. 35, no. 3, pp. 2072-2081, 2020, doi: 10.1109/TPWRS.2019.2950132.

[20] Y. Chen, S. M. Mazhari, C. Y.Chung, S. O. Faried and B. C. Pal, "Rotor Angle Stability Prediction of Power Systems With High Wind Power Penetration Using a Stability Index Vector," *IEEE Transactions on Power Systems*, vol. 35, no. 6, pp. 4632-4643, 2020, doi: 10.1109/TPWRS.2020.2989725.

[21] Y. Chen, Y. Ma and W. Yun, "Application of Improved Genetic Algorithm in PID Controller Parameters Optimization," *Telkomnika*, vol. 11, no. 3, pp. 1524-1530, 2013, doi: 10.11591/telkomnika.v11i3.2301.

[22] N. I. Voropai and P. V. Etingov, "Two-Stage Adaptive Fuzzy PSS Application to Power Systems," in *Proceeding International Conference on Electrical Engineering ICEE'2001*, Xi'an, China, vol. 1, 2001, pp. 314-318.

[23] A. V. Kryukov, S. K. Kargapol'cev, Yu. N. Bulatov, O. N. Skrypnik, and B. F. Kuznetsov, "Intelligent control of the regulators adjustment of the distributed generation installation," *Far East Journal of Electronics and Communications*, vol. 17, no. 5, 2017.

[24] R. Kumar, R.Singh and H. Ashfaq, "Stability enhancement of multi-machine power systems using Ant colony optimization-based static Synchronous Compensator," *Computers & Electrical Engineering*, vol. 83, 2020, doi: 10.1016/j.compeleceng.2020.106589.

[25] R. Kumar, S. Diwania, R. Singh, H. Ashfaq, P. Khetrapal and S. Singh, "An intelligent Hybrid Wind-PV farm as a static compensator for overall stability and control of multi-machine power system," *ISA Transactions*, vol. 123, pp. 286–302, 2021, doi: 10.1016/j.isatra.2021.05.014.

[26] D. Sarathkumar, V. Kavithamani, S. Velmurugan, C. Santhakumar, M. Srinivasan and R. Samikannu, "Power system stability enhancement in two machine system by using fuel cell as STATCOM (static synchronous compensator)," *Materials Today: Proceedings*, vol. 45, Part 2, pp. 2130-2138, 2021, doi: 10.1016/j.matpr.2020.09.730.

[27] F. Yang, Z. Ling, M. Wei, T. Mi, H. Yang, R. C. Qiu, "Real-time static voltage stability assessment in large-scale power systems based on spectrum estimation of phasor measurement unit data," *International Journal of Electrical Power & Energy Systems*, vol. 124, 2021, doi: 10.1016/j.ijepes.2020.106196.

[28] M. R. Nascimento, F. A. Ramos, L. C. Almeida, N. V. C. Gonçalves, A. P. Grilo-Pavani and R. A. Ramos, "Computation of the Minimum Voltage Stability Margin Considering Loading Uncertainties and Contingency Analysis," in *2023 IEEE Power & Energy Society General Meeting (PESGM)*, Orlando, FL, USA, 2023, pp. 1-5, doi: 10.1109/PESGM52003.2023.10252463.

[29] A. Pourdaryaei, A. Shahriari, M. Mohammadi, M. R. Aghamohammadi, M. Karimi and K. Kauhaniemi, "A New Approach for Long-Term Stability Estimation Based on Voltage Profile Assessment for a Power Grid," *Energies*, vol. 16, no, 5, 2023, doi: 10.3390/en16052508.

[30] Y. Xu, F. Wen, H. Zhao, M. Chen, Z. Yang and H. Shang, "Stochastic Small Signal Stability of a Power System with Uncertainties," *Energies*, vol. 11, no. 11, 2018, doi: 10.3390/en11112980.

[31] G. Kenne, J. Ndongmo, R. Kuate and H. Fotsin, "An online simplified nonlinear controller for transient stabilization enhancement of DFIG in multi-machine power systems," *IEEE Transactions on Automatic Control*, vol. 60, no. 9, pp. 2464–2469, 2015, doi: 10.1109/TAC.2015.2427591.

[32] S. Chandra, D. Gayme and A. Chakrabortty, "Coordinating wind farms and battery management systems for inter-area oscillation damping: A frequency-domain approach," *IEEE Transactions on Power Systems*, vol. 29, no. 3, pp.1454–1462, 2014, doi: 10.1109/TPWRS.2013.2282367.

[33] M.Mokhtari and F. Aminifar, "Toward wide-area oscillation control through doubly-fed induction generator wind farms," *IEEE Transactions on Power Systems*, vol. 29, no. 6, pp. 2985–2992, 2014. doi: 10.1109/TPWRS.2014.2309012.

[34] J. An, J. Yu, Z. Li, Y. Zhou; G. Mu, "A Data-driven Method for Transient Stability Margin Prediction Based on Security Region," *Journal of Modern Power Systems and Clean Energy*, vol. 8, no. 6, pp. 1060-1069, November 2020, doi: 10.35833/MPCE.2020.000457.

[35] J. An, G. Mu, Z. Li; D. Liu, "Power system transient stability margin assessment using steady-state information," in *2019 IEEE Innovative Smart Grid Technologies - Asia (ISGT Asia)*, Chengdu, China, 2019, pp. 642-647, doi: 10.1109/ISGT-Asia.2019.8881332.

[36] Y. N. Bulatov, A. V. Kryukov, K. V.Suslov, "Multi-agent technologies for control of distributed generation plants in the isolated power systems," *Far East Journal of Electronics and Communications*, vol. 17, no. 5, pp. 1197–1212, 2017, doi: 10.17654/EC017051197.

[37] M. Ma, J. Wang, Z. Wang; M. W. Khan, "Global Geometric Structure of the Transient Stability Regions of Power Systems," *IEEE Transactions on Power Systems*, vol. 34, no. 6, pp. 4595-4605, Nov. 2019, doi: 10.1109/TPWRS.2019.2919442.

[38] Monakov, Y., Tarasov, A., Ivannikov, A., Murzintsev, A., Shutenko, N. "Optimization of Equipment Operation in Power Systems Based on the Use in the Design of Frequency-Dependent Models," *Energies*, vol. 16, no. 18, Sep. 2023, doi: 10.3390/en16186756.

[39] M. Kyesswa, H. K. Cakmak, L. Gröll, U. Kühnapfel, V. Hagenmeyer, "A Hybrid Analysis Approach for Transient Stability Assessment in Power Systems," in *2019 IEEE Milan PowerTech*, Milan, Italy, 2019, pp. 1-6, doi: 10.1109/PTC.2019.8810745.

[40] Silva, R.V., Isoda, T., Tonelli-Neto, L.Y.S., Alves, M.A., Minussi, C. R., "Transient stability improvement for electrical power systems based on the impedance change of a transmission system," *International Transactions on Electrical Energy Systems*, pp.1-19, 2020, doi:10.1002/2050-7038.12385.

[41] Girshin, S.S., Shepelev, A.O., "Development of Improved Methods for Calculating Steady States of Power Systems Taking Into Account the Temperature Dependence of the Resistances of the Overhead Transmission Lines," *Power Technol Engineering*, vol. 54, 232–241, 2020, doi: 10.1007/s10749-020-01196-w.

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