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Adaptive emergency control system with an algorithm for rapid assessment of sustainability united energy system

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Abstract. In the present study described the methodology for determination of sustainable modes of long equivalent of the interconnected power systems of various structures with simplified representation of excitation controllers of generators. According to the results of numerous studies, the criterion of oscillatory disturbance of static stability based on the control of the partial derivative $\partial A_N / \partial \delta$ is formulated. To confirm the formulated criterion of violation of the static vibrational stability performed quantitative mapping of polynomial coefficients of haracteristics equations and additional applications of the matrix equations is redundant points of the equivalent circuit of the Electrical Power Systems (EPS) obtained under the criterion Hurwitz. Quantitative comparison and qualitative analysis of the nature of the change in the roots of the characteristic equation and the Hurwitz determinants confirm that the transition across the boundary of the stability region, found by the formulated criterion on the basis of the control of the partial derivative $\partial A_N / \partial \delta$ taking into account the proposed simplified model of generators at the constant excitation voltage U_f = const, is accompanied by the appearance of reciprocal values of the Hurwitz determinants. Taking into account the generalizations and conclusions obtained, a modified method of studying the static oscillatory stability of the EPS is proposed. The efficiency of the developed algorithm for determining the boundary of the region of potentially stable regimes is estimated. It is shown that the proposed method has the best performance indicators and can reduce the computational cost.

1. Introduction
Maintaining the stability of power systems is presently being done to ensure standardized inventory to specific design image of the limit of the transmit power regimes. Determination of these modes in the course of research can be performed using both static and dynamic models of electric power systems implemented in modern specialized software systems. The desire to improve the accuracy of modeling in the verification of the used models leads to an increase in the order of differential equations, which greatly complicates the use of existing methods of quantitative evaluation of reserves for stability. Subsequent qualitative analysis of electromechanical transients and improvement of damping parameters using a complete system of equations leads to an increase in computational cost and increase the complexity of the calculations performed. Despite this, a quick search for the region of stable modes can be performed using simplified models that reliably reflect the electromechanical motion of the generators. Made in [1-9, 14, 17-26] functional analysis of the vibrational characteristics of violation of static stability of simplified models of the power system in the representation of the excitation regulators of the generators in the constancy of the excitation voltage U_f = const [6-17] allowed to improve the methodology to study the static oscillatory stability of power grids. The use of

this model of automatic excitation regulator allows to determining the area of potentially stable modes of the investigated (real) power system with high-speed excitation regulators at the preliminary stage.

In this article the modified technique of research of static oscillatory stability which allows to carrying out primary, qualitative assessment of the modes of power systems of various structure limiting on the transmitted power is stated. The tool is formulated and proved a criterion of oscillatory violations of static stability $\partial A_N / \partial \delta$.

2. Mathematical model and method research description

Numerical experiments were carried out in relation to the design schemes containing a different number of equivalent power systems (from 2 to 6). For ring and chain schemes of power connections, containing N generators with a simplified model of automatic excitation regulators (U_f = const), without taking into account the equations of damper circuits and when replacing loads with constant resistances, the characteristic equation of free movement of the Electromechanical system takes the form:

$$p^{3N-2} + A_1 \cdot p^{3N-3} + ... + A_{k-2} \cdot p^{3N-k} + ... + A_{3N-3} \cdot p^1 + A_{3N-2} = 0 \qquad (1)$$

Computer studies were carried out in relation to typical structural schemes of chain and ring power transmission with variations in stiffness and installed capacities of equivalent power systems. Equivalent ring schemes are typical for system-forming networks of 330 kV and 500 kV of large megacities and regional energy associations (for example, the North-West Power Pool). Intersystem transmission lines completed 500 kV and 750 kV, chain structure characteristic of the major of power grids of the Power Pools of East and Siberian. When allocating groups of in-phase relative motion of equivalent generators, the Russian Electricals Power Systems can also be represented by an equivalent power system of a chain structure.

It is established that the region of potentially stable regimes, which corresponds to the unregulated (U_f = const) representation of equivalent generators, regardless of the structure and design conditions, is near the maximum angular characteristic (margin from 0.01% to 10%) and characterizes the greatest use of power. The performed computational studies found that the stability region determined by the simplified model U_f = const is always to the left of the minimum of the free term A_N. In all the studied circuit-regime conditions, regardless of the structure (chain or ring) and the stiffness of power transmission, the boundary of the static vibrational stability region is characterized by a minimum of dependence $A_N = f(\delta)$ without changing the sign of the free term. This is explained by the fact [9-17] that the transition across the boundary of root decay with further weighting of the regime is accompanied by a relatively rapid increase in the absolute value of the real parts of two pairs of complex conjugated roots ($+\alpha \pm j\,\omega$ and $-\alpha \pm j\,\omega$).

The required normative reserves of 8 % and 20 % correspond to the regimes located within the area of potentially stable regimes determined using the proposed structural criteria and characterized by the introduction of stabilization by the damping decrement α = -0,3...-0,4 s^{-1} [2-14].

The analysis of the change in the roots of the characteristic equation (column 1 of the table 1) with the variation of its coefficients A_1 ... A_{3N-2} found that near the boundary of the stability region there is a significant increase in the increment of electromechanical oscillations and a decrease in the damping time constant of aperiodic processes in the circuits of automatic excitation regulators.

Comparison of polynomial coefficients of the characteristic equation and additional minors of the matrix of equations of excess moments of the equivalent two-machine circuit of the Electrical Power Systems, obtained using the algebraic Hurwitz criterion, confirms that the transition across the boundary of the stability region (δ_{g21} = 87.36°) of the model at U_f = const is accompanied by the appearance of negative values of Hurwitz determinants. In the course of qualitative studies of the product of the roots of the characteristic equation and the free term in the function of the relative angle, some important results were obtained – in General, with an odd number of equivalent generators, A_{3N-2} is located in the region of negative values of the free term.

Table 1. Coefficients of the characteristic polynomial unregulated model (U_f = const) and Hurwitz determinants.

The angle between the EMF, degree	Roots characteristic equation, s^{-1}	Coefficients of the characteristic polynomial					Hurwitz determinants			
		A_0	A_1	A_2	A_3	A_4	Δ_1	Δ_2	Δ_3	Δ_4
δ_{g21}=58,75°	–0,314; –0,209; –0,074±j0,640	1,0	+0,670	+16,195	+8,409	+1,055	+0,670	+2,447	+20,108	+21,212
δ_{g21}=87,36°	–0,333; –0,333; –0,001±j0,425	1,0	+0,668	+7,260	+4,753	+0,814	+0,668	+0,095	+0,089	+0,073
δ_{g21}=106,50°	–1,743; –0,357; **+0,714±j0,083**	1,0	+0,672	**–1,595**	+0,754	+0,487	+0,672	**–1,826**	**–1,570**	**–0,777**

In the domain of stable modes of the model U_f = const, the product of the dominant components of the relative motion is proportional to the change of the product of all roots of the characteristic equation. The obtained results confirm the competence of the proposed model of excitation regulators for a rapid and reliable analysis of the stable regimes.

3. Results

The results presented in this publication are a generalization of studies [9-26] using the previously proposed criterion of vibrational disturbance of static stability, based on the control of the change of the free term of the characteristic equation.

The computation time of the coefficients of the characteristic polynomial and eigenvalues of the matrix of coefficients of the equivalent system of linearized equations of transients in the unregulated model U_f = const is two orders of magnitude less than the same calculation time in the complete system of differential-algebraic equations, which allows us to talk about the efficiency of the developed algorithm (figure 1, 2).

On the basis of the obtained results was c method reliable determination of the region of stable regimes, based on the control of the partial derivative ∂A_N / $\partial\delta$, which consists of the following sequence of operations:

– formation of a system of algebraic equations of nodal voltages of the electrical network;

– reduction of the order (equivalent) of the subsystem of algebraic equations by means of elimination of variables (node voltages of the electric network) by the Gauss method;

– formation of expressions for electrical power in the nodes;

– the formation of a subsystem of the linearized differential equations of the relative motion of the Electromechanical synchronous machines;

– numerical analysis of the free term, roots of the characteristic equation and determination of the domain of stable regimes;

– calculation of the eigenvalues of the coefficient matrix of the complete system of linearized differential equations of transients in synchronous generators, excitation systems and their automatic regulators;

– calculation of eigenvalues of the coefficient matrix of a system of linearized differential equations in simplified models.

Proposed an improved method for the rapid assessment of steady-state modes of the controlled power systems can be used in the control algorithms of the interconnection with the structure of devices of automatics prevent loss of stability. On the basis of rapid assessment using structural stability criteria can be determined (calculated) and formed the corresponding control effects of automatic unloading equipment (unloading stations and etc.). The problem of rapid assessment can be solved by implementing several options:

1) rigidly defined (known in advance) the structure and parameters of the sections controlled in it, for example, two-(n)-machine circuit of intersystem power transmission;

2) only the structure of the equivalent power system is known, and its parameters and "weak" (controlled) sections must be determined;

3) it is necessary to identify the structure and parameters of the equivalent circuit of the Electrical Power Systems, as well as to determine the "weak" interconnection.

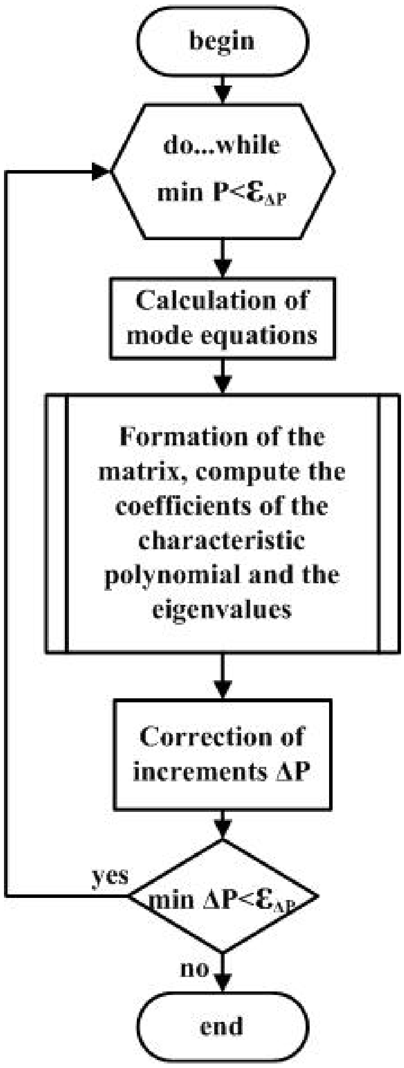

Figure 1. Algorithm of the procedure for determining the boundary of the domain of stable regimes.

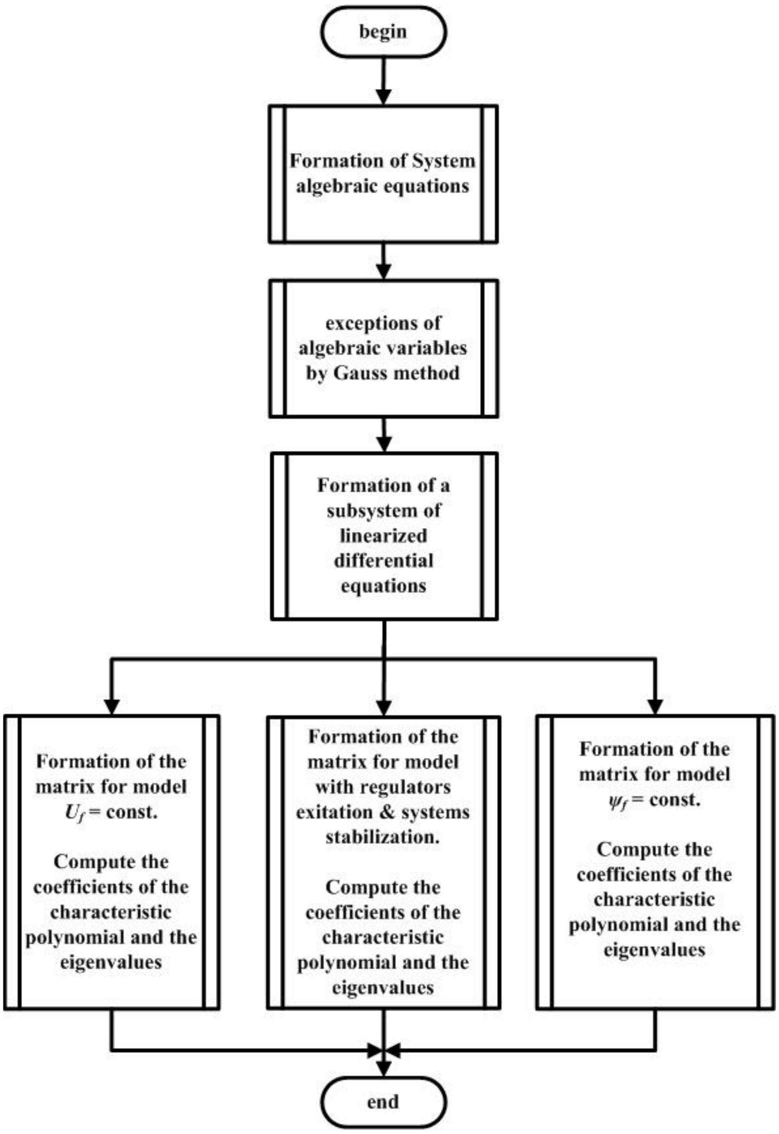

Figure 2. The algorithm of the procedure of formation of the matrix, compute the coefficients of the characteristic polynomial and the eigenvalues of the linearized system of differential equations.

In all three cases, it is necessary to know the equivalent electromechanical parameters of the combined power systems, while the third method is the most time-consuming, in terms of computational costs.

4. Conclusions

The identified characteristic features of the disturbance of stability and associated changes in polynomial coefficients allowed to develop methods for studying the dynamic properties of combined power systems of arbitrary structure and to formulate on this basis new practical criteria for assessing stability.

The proposed improved method of evaluation of static oscillatory stability can be used by design organizations, joint and regional dispatching offices for rapid analysis of the static stability in modern complex power systems. Computational studies using the developed software allow us to formulate requirements for the speed and selectivity of the main and backup protection and emergency automation.

As the results of numerous studies have shown, the application of the developed method for determining the boundary of the region of stable regimes can significantly reduce the computational cost (processor time) even for the Electrical Power Systems schemes characterized by a small order of the system of equations of transients.

The most effective application of the developed algorithm as part of modern microprocessor means of emergency control of power line equipment overload limitation. The implementation of this algorithm in the means of emergency control can improve the efficiency and efficiency of AC power transmission due to a reasonable and safe increase in the load of overhead lines.

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