Design and experimental frequencies for the models type I and II

Frequency №	Object				
	Real onboard equipment	Model I		Model II	
	Frequency, experimental value, Hz	Frequency, design value, Hz	Effective mass, kg	Frequency, design value, Hz	Effective mass, kg
1	183.0	171.1	0.291695	176.0	0.288 266
2	–	320.2	3.90×10^{-04}	324.6	6.96×10^{-04}
3	–	388.8	7.63×10^{-06}	398.0	1.31×10^{-03}
4	482.7	490.9	2.13×10^{-02}	498.2	1.83×10^{-02}
5	–	545.8	3.54×10^{-03}	554.7	2.77×10^{-03}
6	653.0	660.0	1.30×10^{-02}	655.5	2.53×10^{-02}
7	700.0	729.9	2.12×10^{-02}	722.9	1.80×10^{-02}
8	–	740.2	3.98×10^{-03}	745.5	2.00×10^{-03}
9	–	854.6	1.42×10^{-04}	857.2	1.06×10^{-04}
10	–	885.6	1.36×10^{-04}	890.0	7.68×10^{-05}
11	930.9	962.7	9.71×10^{-05}	943.5	2.19×10^{-04}
12	1 043.0	1 018.2	6.74×10^{-03}	1 013.5	6.64×10^{-03}
13	–	1 071.9	2.01×10^{-03}	1 083.9	1.23×10^{-03}
14	–	1 151.1	9.62×10^{-05}	1 121.4	9.41×10^{-04}
15	–	1 152.9	1.06×10^{-03}	1 148.3	1.02×10^{-03}
16	1 237.0	1 258.4	7.21×10^{-05}	1 259.3	6.51×10^{-07}
17	1 276.0	1 276.1	7.74×10^{-05}	1 288.8	2.98×10^{-04}
18	–	1 336.3	3.11×10^{-03}	1 341.6	4.63×10^{-06}
19	1 359.0	1 362.4	1.58×10^{-03}	1 343.1	3.83×10^{-03}
20	1 418.0	1 406.9	7.05×10^{-04}	1 410.4	1.15×10^{-03}
21	1 462.0	1 456.8	1.21×10^{-02}	1 460.1	1.13×10^{-02}

I. V. Ignatyev, A. E. Kovrov
Bratsk State University, Russia, Bratsk

ALGORITHM OF CHOICE FOR AUTOMATIC EXCITATION REGULATOR SETTINGS IN MULTIMACHINE ELECTRIC POWER SYSTEMS

A program-realized coordinated algorithm of choice for automatic excitation regulator settings has been developed. This algorithm is based on the resultant theory and applies a mathematical model which is synthesized by experimental frequency characteristics of an electric power system.

Keywords: automatic excitation regulator, resultant, stability.

The ensuring of stability in electric power systems (EPS) and the damping of fluctuation are realized by automatic excitation regulators (AER) which are placed in power station generators [1].

Today it is matter of current coordinated choices in AER stability coefficients, in conditions of ensuring multimachine EPS with the required intermediary processes quality.

To solve this problem, algorithms have been developed based on the D-dividing method [2–4]. These algorithms assume serial choices for AER settings and for each separate station by a calculated field of stability. In this case, transition from one station to another is realized by increasing the system stability extent. However, in connection with the complexity of using special-purpose functions, these algorithms do not allow us to ensure acceptable EPS property damp with a greater AER number.

Another way to solve this problem is to use algorithms based on the principal matrix calculation values of the Gorev-Park linear differential equation [5–7]. However, these algorithms have a complex operative control in multimachine EPS faults:

1) they are characterized by a high order of differential equation demanding significant calculations;

2) they admit average data value for elements of large EPS units and subsystem during large intervals. The last results in non-conformity mathematic model forming during a current mode situation.

In [8; 9] it has been shown that EPS mathematic models may be obtained through the result of experimental frequency characteristic stability parameters as a characteristic polynom. It allows avoiding of many admission and simulation errors, which are typical for calculated methods; the describing the upper and lower dimension of the AER choice problem settings to coordinate them betimes during the current EPS working conditions.

In this article new coordinated choice algorithms of AER settings for multimachine EPS were obtained. This allowed the consideration of the decision merits offered in works [8; 9] and excluded the mistakes in previously developed algorithms. The realization of the new algorithm program was developed by MATLAB software.

The coordinated choice algorithm of AER setting description. The new algorithm is based on the resultant theory [10]. Resultant is a two polynomial's coefficient function, turning into null; it is essential and satisfies the condition for exciting the common root of these polynomials.

Let's examine the first polynomial characteristic of the studied EPS polynom

$$D(p) = a_0 p^n + a_1 p^{n-1} + a_2 p^{n-2} + \ldots + a_{n-1} p + a_n, \quad (1)$$

in the coefficient where the AES stabilization setting of channels is included. In the final form we can write down:

$$a_i = a_{i0} + \sum_{j=1}^{r} a_{ij} k_j + \sum_{j=1}^{r}\sum_{k=1}^{r} a_{ijk} k_j k_k + \sum_{j=1}^{r}\sum_{k=1}^{r}\sum_{l=1}^{r} a_{ijkl} k_j k_k k_l + \ldots,$$

where r is the amount of generators equipped by AER; k_j, k_k, k_l, ... are stabilizing coefficients.

Polynom's roots with almost no real part modulus determine the static stability degree of analyzing EPS and are called dominate.

The second polynomial is an auxiliary function

$$Q(\lambda) = b_0 \lambda^m + b_1 \lambda^{m-1} + b_2 \lambda^{m-2} + \ldots + b_{m-1}\lambda + b_m, \quad (2)$$

the roots of which are chosen equally for the required meanings of dominate roots.

The issue is to ensure polynom equality of dominate roots (1) with roots of polynom (2) to account the stabilization coefficient's variation and therefore a_i. The acquired AER coefficients should meet this realization in practice settings.

Let us examine the stages of algorithm work in the EPS, for the improvement of damp property; it is necessary to coordinate the AER settings of three equivalent generators. Let us suppose that all these generators are equipped by AER microprocessors.

At the first stage, based on the work procedure offered [8], we shall obtain a mathematic model for studying the EPS as a polynom (1). In the beginning, we shall pick control loops out of the system; these include stabilization channels on a chosen voltage frequency Δf, and its derivative f'. Such an approach is stipulated by placing low-frequency fluctuating damp on the selected AER channels. For the mathematical description of these channels we will use transmission function $F_1(p)$, $F_2(p)$ and $F_3(p)$, the indexes of which correspond to ordinal numbers of the generators.

The remaining part of the EPS, including other AER channels, symmetries about the chosen control loops (fig. 1) through the principal $W_{11}(p)$, $W_{22}(p)$, $W_{33}(p)$ and crosses $W_{12}(p)$, $W_{13}(p)$, $W_{21}(p)$, $W_{23}(p)$, $W_{31}(p)$, $W_{32}(p)$ transmission functions of mode stabilization parameters.

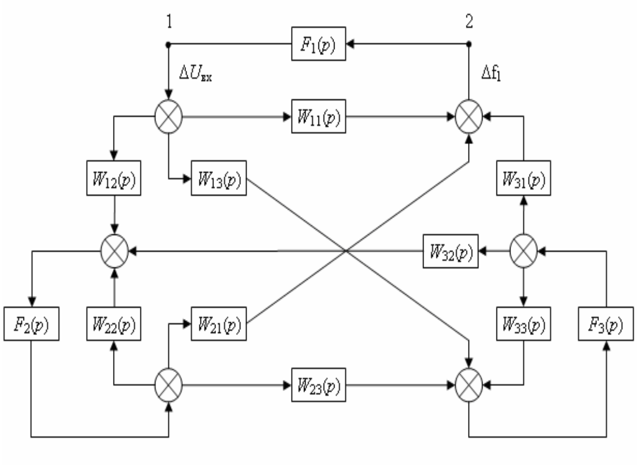

Fig. 1. Three-loop structural representation of EPS

Further, using Mayson's formula we write down the transmission function of regulated EPS from input 1 to output 2 in accordance to fig. 1:

$$W_p = \frac{W_{11}\overline{W}_{12} + \overline{W}_{12}F_2 + \overline{W}_{13}F_3 + \overline{W}_{123}F_2F_3}{1-(W_{11}F_1 + W_{22}F_2 + W_{33}F_3 + \overline{W}_{12}F_1F_2 + \overline{W}_{13}F_1F_3 + \overline{W}_{23}F_2F_3 + \overline{W}_{123}F_1F_2F_3)}, \quad (3)$$

where $\overline{W}_{12}$, $\overline{W}_{13}$, $\overline{W}_{23}$, $\overline{W}_{123}$ are symmetrical cross transmission functions which are accordingly formed to minors and matrix determinants:

$$\overline{W} = \begin{pmatrix} W_{11} & W_{12} & W_{13} \\ W_{21} & W_{22} & W_{23} \\ W_{31} & W_{32} & W_{33} \end{pmatrix}. \quad (4)$$

Note that in expressions (3) and (4) (as it shall be in following complex formulas), we do not use operator "p" for simplification.

The authors of this article have analyzed the dynamic properties of the modern microprocessor AER before. The results of the analysis have produced a transmission function, obtained for choosing stabilizing channels in EPS:

$$F(p) = \frac{2p}{(1+2p)} \cdot \frac{k_{0f}}{(1+0.2p)} + 0.5p\,\frac{k_{1f}}{1+0.5p}, \quad (5)$$

where k_{0f} is the stabilization coefficient of frequency deviation, k_{0f} = 0–15 puU_f/Hz; k_{1f} is the stabilization coefficient of frequency derivative, k_{1f} = 0–5 puU_f/Hz/s.

Reducing the formula (5) to the same denominator, we can write the transmission function of stabilizing channel for AER i-th generator:

$$F_i(p) = \frac{(p^2+2p)\,k_{0fi} + (0.2p^3 + 1.1p^2 + 0.5p)\,k_{1fi}}{0.2p^3 + 1.5p^2 + 2.7p + 1} = \frac{f_i'}{f_i}. \quad (6)$$

Substituting expression (6) to denominator (3) we obtain the characteristic EPS polynom in the general form:

$$D(p) = \Delta_N f_1 f_2 f_3 - W'_{11} f'_1 f_2 f_3 - W'_{22} f_1 f'_2 f_3 - W'_{33} f_1 f_2 f'_3 - \\ - \overline{W}'_{12} f'_1 f'_2 f_3 - \overline{W}'_{13} f'_1 f_2 f'_3 - \overline{W}'_{23} f_1 f'_2 f'_3 - \overline{W}'_{123} f'_1 f'_2 f'_3, \quad (7)$$

where W'_{ij}, $\overline{W}'_{ij}$, $\overline{W}'_{ijk}$ are own numerators and the cross transmission function of mode stabilization parameters; Δ_N is the same denominator for these functions.

For calculating numerical values of zeros and poles for transmitted functions, which are included in formula (7), the authors, according to the method of EPS parametric identification [9] had developed the following procedure:

1) determine the complex sample of principal and cross frequency characteristics for unlocked systems by measuring the EPS time characteristics locked in points 1 and 2 (fig. 1) with help of the fast Fourier transformation;

2) configure the analysis of obtaining frequency characteristics with the purpose of exposing dominating poles and zeros; determine EPS basic dynamic properties in the essential frequency rate;

3) approximate the remainder frequency characteristic by a smooth fractional-rational function with help of the least-square method.

By substituting the (7) zeros and poles obtained previously, we represent a multi-parametric model of EPS analysis as a polynom (1). In result each coefficient of the polynom will include a non-linear combination of AER required settings.

The second stage of the algorithm includes the realization of two procedures: the calculation of characteristic polynom roots and the analysis of their location on the complex plane.

The first procedure making after substituting in expression (1) is the stability value coefficient set in the AER of each generator.

The second procedure can conduct a quantity estimate of the analyzed system's stability degree for the current mode situation. This parameter is determined by the true part modules of the polynom conjugate complex root (1) pair, nearest to the imaginary axis.

The third stage is related to the procedure of auxiliary function calculation. This procedure includes the following steps:

1) from all roots combination of the characteristic polynom, corresponding to electromechanical system traffic component, we select m dominating roots ($m = 6$). The number of m is determined by the amount of coordinated stability coefficients;

2) proceeding onward from the condition of required quality for the transmitted processes in the EPS, we set desirable locations of the chosen dominant roots on the complex plane; meaning their real and imaginary parts;

3) coefficients b_i of function (2) are calculated by preset values of dominant roots.

Thus, in the examined case it is necessary to obtain such stability coefficients, which will ensure the equality of six polynom dominant roots (1) from their total amount n, to roots of auxiliary functions.

On the fourth stage of the solution, we shall compound the resultant matrix by the Silvester rule – the order of which is equal to $m + n$

$$M = \begin{pmatrix} 0 & 0 & \dots & 0 & a_0 & a_1 & \dots & a_{n-2} & a_{n-1} & a_n \\ 0 & 0 & \dots & a_0 & a_1 & a_2 & \dots & a_{n-1} & a_n & 0 \\ \vdots & \iddots & & \vdots & \vdots & & \iddots & & & \\ a_0 & a_1 & \dots & a_{n-2} & a_{n-1} & a_n & \dots & & 0 & 0 \\ b_0 & b_1 & \dots & b_{m-1} & b_m & & \dots & & 0 & 0 \\ 0 & b_0 & \dots & \dots & b_{m-1} & b_m & \dots & & 0 & 0 \\ \vdots & & \ddots & & & \vdots & \ddots & & & \vdots \\ 0 & \dots & & \dots & 0 & b_0 & \dots & \dots & b_m & 0 \\ 0 & & \dots & \dots & 0 & b_0 & \dots & \dots & & b_m \end{pmatrix}, \quad (8)$$

where elements, above a_0, b_m and below b_0 and a_n, are equal to null.

Concordantly, in the resultant theorem [10], for the existence of m common polynom roots (1) and (2), it is quite necessary to perform the following:

$$R(D,Q) = R_1(D,Q) = R_2(D,Q) = \ldots = R_{m-1}(D,Q) = 0, \quad (9)$$

where $R(D, Q)$ is the matrix determinant, which is formed from matrix M by the disposal its m–1 first and last rows, and 2m–2 last columns; $R_1(D, Q)$, $R_2(D, Q)$, ..., $R_{m-1}(D, Q)$ are matrix determinants, which are formed from the previous matrix by serial change in its last column for each of the following columns of matrix M.

Note that the pointed determinant in the theorem is of nonlinear function, containing the AER stability coefficient as a variable.

In conformity with the theorem let us calculate determinants $R(D, Q)$, $R_1(D, Q)$, ..., $R_5(D, Q)$ and then write down a system of nonlinear equations:

$$\begin{cases} R(D,Q) = 0, \\ R_1(D,Q) = 0, \\ R_2(D,Q) = 0, \\ R_3(D,Q) = 0, \\ R_4(D,Q) = 0, \\ R_5(D,Q) = 0. \end{cases} \quad (10)$$

Numerical solutions of the equation system (10), computed by procedures executed at Matlab, allow us to obtain the stability coefficients, provided by polynom dominant roots (1) and required values with a set accuracy.

If in result of calculations the acquired AER settings do not correspond to practice values, then the auxiliary function roots should be changed; the calculation procedure will provide once more, beginning from the third stage. In our case the modification of the function roots (2) is based on the motion of two extreme pair dominant roots directed towards each other.

Thus, the solution of the set problem can have an iterative character; however we can reach the acceptable values of AER settings for some iteration as a rule.

Calculation examples. For the validation of algorithm functionability, a computer experiment was conducted by providing calculations of optimal AER settings for Irkutsk EPS generators.

The realization of given the purpose was reached by solving the following problems:

– data collecting for Irkutsk EPS's elements (parameters of transmit lines, transformers, generators, reactor and control unites);

– forming of EPS model in Simulink;

– checkout of the developed model's adequacy in the real work of the EPS;

– calculating a typical mode which is in the Irkutsk EPS;

– submission of revolt influence in choosing the EPS's points (fig. 1); the recording of obtained time characteristics, reflecting dynamic properties of the system;

– procedure execution of the coordinated choice of AER setting algorithm.

The analysis was provided by SimPowerSystems and Simulink packages of Matlab expansions. SimPowerSystems was used for different EPS device model forming: power systems, systems of automatic regulating, control and measurement systems. The Simulink package was used for AER microprocessor block development and the realization of imitative modeling.

The Irkutsk EPS is a model equivalent to the generators of the Bratsk, Ust-Ilimsk and Krasnoyarsk Hydroelectric Power Plants (HPP). The generating of the Irkutsk HPP is taken into account in load. The fragment of the model realized in Matlab is shown in fig. 2.

During the typical mode data formation for the supervisor lists, the transmit lines (500 kV) of the Irkutsk EPS were used.

To begin the simulation from the set mode, the initialization of synchronic generators and AER for a set load level had been made. Initialization means a setting mode of bidirectional load for a generator equivalent to the Bratsk HPP. For the Ust-Ilimsk and Krasnoyarsk HPP a mode of set active power production supported by a constant stator voltage was chosen.

After the supply revolt influences and executes the procedures of the first two algorithm stages, we get a mathematic description of the EPS as polynom (1); the order of which is n = 28. Results of the dominant root calculation for the polynom of the established settings for generators AER are listed in the tab. 1.

From tab. 1 it can be seen that the analyzed system has low damp properties because the pair of dominant and imaginary roots ω = 7.22 rad/s has low a damping α = 0.23. For such a mode it is necessary to change AER settings to increase the EPS stability. Conforming this are the roots of auxiliary function with set values' real part are $\alpha < -0.6$.

In result of the following calculation procedures, the next stages of algorithm stability coefficients provided polynom dominant roots (1) with set damping. The results of these calculations are listed in tab. 2.

The calculations obtained by us, with the use of such software programs as "Regim", "Sborka", and "Poisk" (developed by the Saint Petersburg State Polytechnic University); completely confirm the results (see tab. 2). This is the correct work of the algorithm and the possibility of its exploitation for the coordinated choice of AER settings in conditions of ensuring the EPS's required level damping transients.

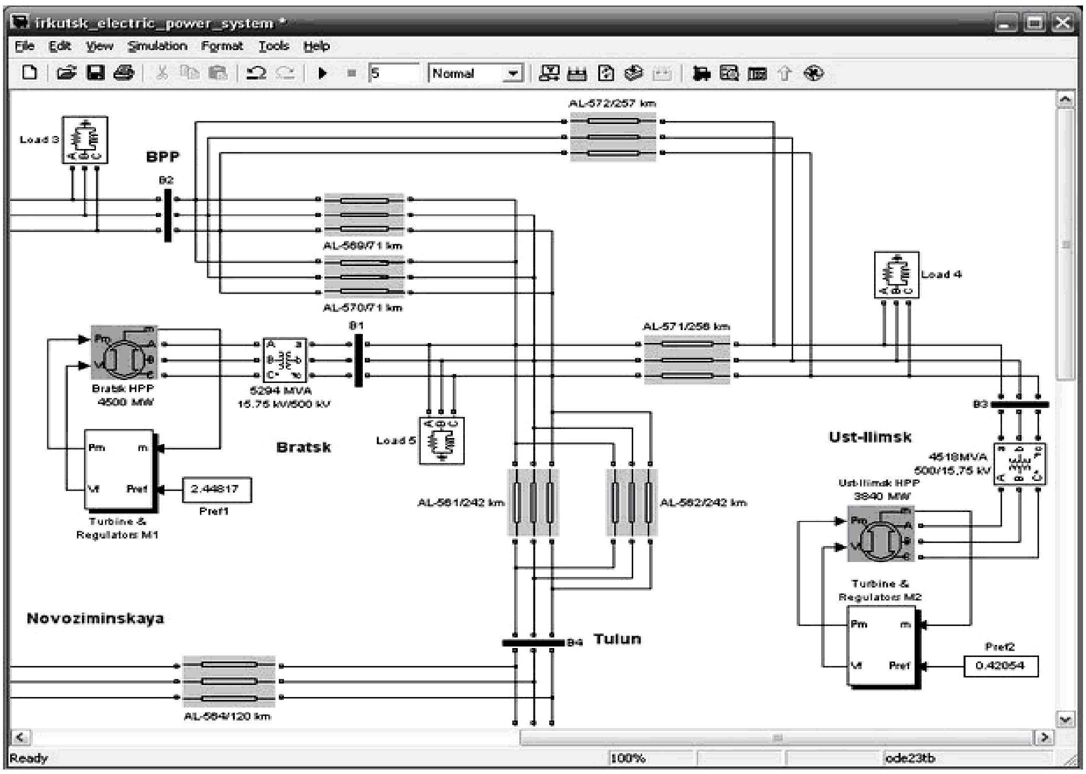

Fig. 2. Fragment of Irkutsk EPS in Simulink

Table 1

Results of dominant root calculations

Dominant roots			AER settings					
Number of root	Real part	Imaginary part	Bratsk HPP		Krasnoyarsk HPP		Ust-Ilimsk HPP	
			k_{0f}	k_{1f}	k_{0f}	k_{1f}	k_{0f}	k_{1f}
1	–0.23	7.22	10	2	15	0	7	5
2	–0.23	–7.22						
3	–0.77	5.35						
4	–0.77	–5.35						
5	–0.97	6.34						
6	–0.97	–6.34						

Table 2

Results of AER setting calculations

Roots of auxiliary function			AER settings					
Number of root	Real part	Imaginary part	Bratsk HPP		Krasnoyarsk HPP		Ust-Ilimsk HPP	
			k_{0f}	k_{1f}	k_{0f}	k_{1f}	k_{0f}	k_{1f}
1	–0.65	7.22	7	2	10	5	5	2
2	–0.65	–7.22						
3	–0.77	5.35						
4	–0.77	–5.35						
5	–0.8	6.34						
6	–0.8	–6.34						

These are the final results:

– a concept resultant was proposed and a new algorithm of AER settings coordinated choice in multimachine EPSs had been developed;

– the new algorithms include mathematic models, synthesized by experimental data;

– a computer experiment has shown that the algorithm allows efficient solving of the ensured quality problem in the EPS transition process;

– the obtained algorithm allows dimension reduction of the choice AER settings' problem essentially; it can be used in real operating condition for the EPS, increasing its stability.

References

1. Ovcharenko N. I. Automation of Electric Station and Electric Power system : Tutorial for High Schools / Under ed. of A. F. Dyakov. M. : Publishing house SC ENAS, 2003.

2. Litkens I. V., Filinskaya N. G. Choice of AER settings in multimachine EPS // Electricity. 1986. P. 15–19.

3. Zekkel A. S. Estimation of regulating quality and method of stability adjustment of AER generators // Electricity. 1988. Vol. 5. P. 15–21.

4. Abdul-Zade V. M, Aliev D. G., Guseynov A. M. Choice of AER generators settings by results of statistical stability analyze // Electricity. 1990. Vol. 3. P. 54–58.

5. Simeonova K. Zh., Stroev V. A. Problems of AER parameters choice in complex electric power system // News of AS SSSR. Power engineering and transport. 1987. Vol. 5. P. 6–71.

6. Maslennikov V. A. Software for calculation of oscillating static stability of electric power system // News of high schools : Power engineering. 1995. Vol. 3–4. P. 33–38.

7. Maslennikov V. A., Ustinov S. M. Software "POISK" – Advanced Information Technology for Power Systems Stability Control // Proc. of International Conference on Informatics and Control (ICI&C'97). St.-Petersburg, 1997. Vol. 2. P. 696–703.

8. Doynikov A. N. Construction of mathematic model for centralize regulating of generators excitation in complex EPS by samples of real signals / Electrification of Siberian metallurgical enterprises / Compose and common ed. B. I. Kudrin. Iss.8. Tomsk : Publishing house Tomsk Univers., 1999. P. 198–202.

9. Doynikov A. N., Grigorieva T. A. Analyze of dynamic properties and model synthesis of electric power system by mode frequency characteristics // Information technology and problems of mathematic simulation of complex systems. Irkutsk : ISURE Institute "Modern Technologies. System Analysis. Modeling", 2005. P. 91–102.

10. Kalinina E. A., Uteshev A. U., Theory of exception: The manual. St. Petersburg. : Publishing house SPb. SU SRI of chemistry, 2002.