Algirdas DAMBRAUSKAS
Bronius KARALIUNAS
Dinas SHULSKIS

SYNTHESIS OF THE ADAPTIVE EXCITATION CONTROL SYSTEM OF HIGH POWER SYNCHRONOUS GENERATORS

ABSTRACT *New promising excitation systems of high power synchronous generators, which are operating in the interconnected power system, are considered. Based on general assumptions, a system of differential equations, transfer functions and a block diagram of the excitation system, as the automatic control object, were obtained. Mathematical description of electromechanical transient processes for emergency situations in the power system is very complicated and limited. In these cases, the efficiency of the excitation current regulator can be increased by using combined algorithms of the simplex search, when, in the optimization process, the local efficiency function is approximated by a separable equation. Based on the expressions obtained, the synthesis of generator adaptive excitation control system and optimization blocks has been developed.*

The proposed scheme of adaptive system synthesis allows us to eliminate search errors. The results of synthesis show that the transitional process of generator voltage is similar to the optimal.

Keywords: *Powerful synchronous generator, excitation system, adaptive control, optimisation, variable structure, simplex search, software package*

Prof. Algirdas DAMBRAUSKAS, Ass. Prof. Bronius KARALIUNAS, Dinas SHULSKIS M. Sc. Eng.

Vilnius Gediminas Technical University

PROCEEDINGS OF ELECTROTECHNICAL INSTITUTE, Issue 226, 2006

1. INTRODUCTION

Automatic excitation control (AEC) of high power synchronous generators as part of the interconnected power system is one of the most effective means to ensure stability and reliability as well as high quality of power generation. The expected expansion of the national power system and its integration into the power grid of Eastern and Western countries raise new requirements for the system control, its reliability, speed and transient processes. Quantitative and qualitative changes taking place in modern power supply networks determine the search for novel upgraded AEC systems which could be adapted for constantly changing environment and parameters of the system operation modes.

Recently, some papers [1]-[5] considering the problem of automatic control of excitation current of synchronous generators, with the aim to apply the new generation regulators and adaptation principles, have appeared. Algorithms and techniques for microprocessor control of synchronous generator speed and frequency are analyzed in [6]-[8]. Modern control and regulating systems of synchronous generators based on logic control devices are described in [9].

Currently used AEC systems cannot provide the required quality of power system performance, especially when rather complicated electromechanical and electromagnetic transient processes are taking place not only in the system itself but in the excitation system of a synchronous generator as well. Mathematical description of the above processes is rather sophisticated or limited, while there are hardly any works analyzing the emergency situations from this perspective. In this case, it is expedient to apply the adaptation principles based on the regulators of variable parameters and structure to control the excitation current of AEC systems [10]-[13].

The present investigation is aimed to provide a synthesis of the adaptive control system of the excitation current of high power synchronous generators operating in power systems which is based on the application of regulators of variable structure and parameters.

2. BASIC EQUATIONS AND THE BLOCK DIAGRAM

Deriving differential equations for a synchronous generator as an object of automatic control, the following general assumptions are made: the magnetic circuit of the generator is not saturated; magnetic field in the air gap varies in accordance with the sine law; the windings of the stator make a three-phase symmetric system; there are no suppressing contours in the rotor; the hysteresis is neglected. Then, the following system of linear differential equations for small variations can be written [13]:

$$\begin{cases} T_m \dfrac{d^2 \Delta\delta}{dt^2} + \Delta P = 0 \\ T_{d0} \dfrac{d\,\Delta E_{q1}}{dt} + \Delta E_q = \Delta E_{q2} \\ \Delta E_{q2} = \dfrac{k_u}{\left(T_2 \dfrac{d\,\Delta U_G}{dt} + 1 \right)} \Delta U_G \\ \Delta U_r = k_r \Delta\delta + k_d \Delta\omega + \dfrac{k_I}{\Delta\omega} \\ \Delta\omega = \dfrac{d\,\Delta\delta}{dt} \end{cases} \tag{1}$$

where:

- T_m – electromagnetic constant of rotor;
- T_{d0} – electromagnetic time constant of generator excitation winding;
- T_2 – time constant of the excitation device;
- $\Delta\delta$ – angular displacement of rotor axis;
- ΔE_q – rotor's e.m.f. change;
- ΔE_{q1} – change in e.m.f. free component;
- ΔE_{q2} – change in e.m.f. forced component;
- k_u – control factor according to voltage direction;
- k_r, k_d and k_e – coefficients of proportional, differential and integral amplification of regulator;
- $\Delta\omega$ – change in rotor angular velocity.

The change in generator voltage may be expressed by the following equation:

$$\Delta U_G = \frac{\partial U_G}{\partial E_q} \Delta E_q + \frac{\partial U_G}{\partial \delta} \Delta\delta \tag{2}$$

Partial derivatives (2) of the equation depend on generator operational mode which determines major characteristics of a considered non-linear system.

In solving the equation system (1), it is expedient to express the changes of all variables via the changes in angles and the electromotive force E_q. The power of the generator and the turbine power are non-linear functions of two variables $(\delta,\, E_q)$, therefore, their difference may be expressed by partial derivatives:

$$\Delta P = \frac{\partial P}{\partial \delta}\Delta P + \frac{\partial P}{\partial E_q}\Delta E_q \tag{3}$$

The change of the e.m.f. free component will then be:

$$\Delta E_{q1} = \frac{\partial E_{q1}}{\partial \delta}\Delta \delta + \frac{\partial E_{q1}}{\partial E_q}\Delta E_q \tag{4}$$

Taking into account transient processes in the excitation winding, ΔE_q may be expressed in the following way:

$$\Delta E_q = \frac{\Delta E_{q2} - p\Delta\delta T_{d1}\dfrac{x_{d1}}{x_{d2}}\dfrac{\partial \Delta E_{q1}}{\partial \delta}}{1 + pT_{d1}} \tag{5}$$

where:

$$T_{d1} = T_{d0}\frac{\partial E_{q1}}{\partial E_q}$$

x_{d1} and x_{d2} – induction resistances of contours.

Substituting the obtained change expressions into the system of equations (1) and writing them with an operator, we will get:

$$\left(T_m p^2 + \frac{\partial P}{\partial \delta}\right)\Delta \delta + \frac{\partial P}{\partial E_q}\Delta E_q = 0 \tag{6}$$

$$\left[pT_{d1}\frac{x_{d1}}{x_{d2}}\frac{\partial E_{q1}}{\partial\delta}\frac{\partial U_G}{\partial\delta}\frac{k_r k_d k_I}{(pT_2+1)}\right]\Delta\delta+\left[1+pT_{d1}-\frac{\partial U_G}{\partial E_q}\frac{k_r k_d k_I}{(pT_2+1)}\right]\Delta E_q=0 \qquad (7)$$

In equation (6) representing power balance, the change in total power consists of the changes in the turbine power ΔP_t, and generator electromagnetic power ΔP_{el}. Then, having solved equation (6) with respect to $\Delta\delta$, we obtain:

$$\Delta\delta=\frac{\Delta P_t-\partial P_{el}/\partial E_q}{T_m p^2+\partial P_{el}/\partial\delta}\Delta E_q \qquad (8)$$

A block-diagram of the AEC system based on (3)-(8) equations is given in Fig. 1. One can see, that the performance of the synchronous generator, operating in the power system without external feedback loops, is unstable.

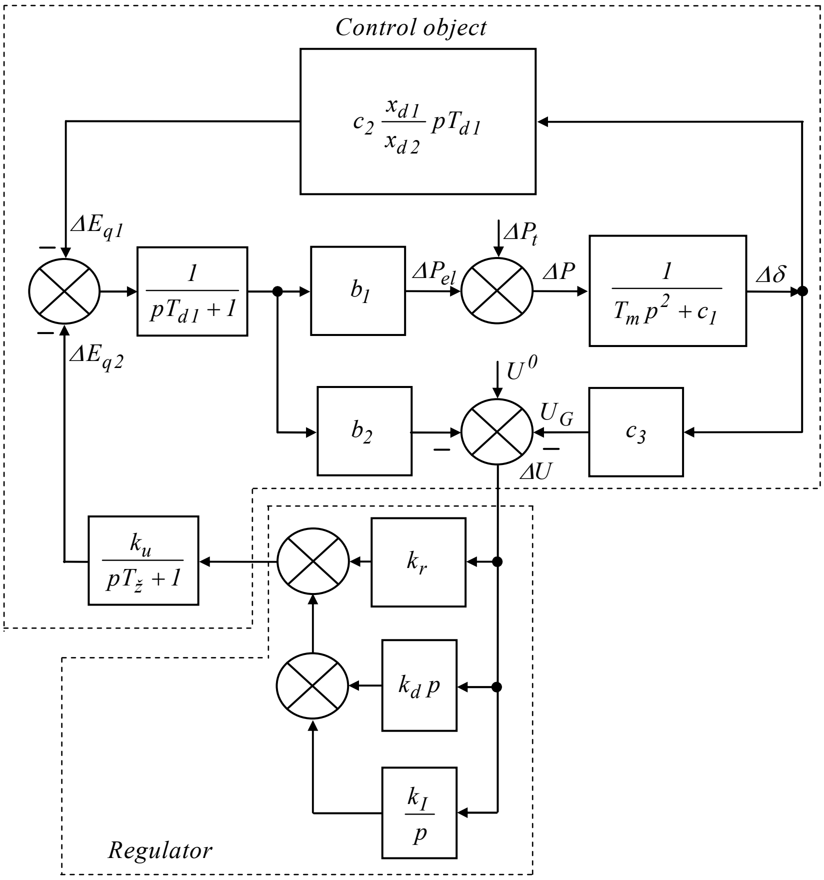

Fig. 1. Block diagram of the AEC system of a synchronous generator

Using the software package Kvazio-1 [14], computer-aided calculation based on the equations obtained above was made of the system transient process (Fig. 2), stabilizing load angle δ.

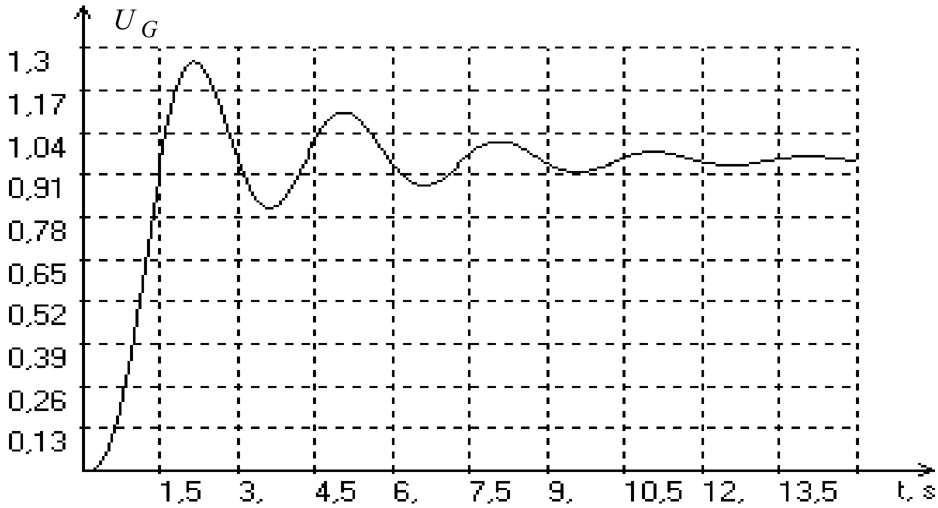

Fig. 2. Transient process of the AEC system of a synchronous generator

3. SYNTHESIS OF A VARIABLE SYSTEM'S REGULATOR

The following condition should be satisfied to provide asymptotic stability of the system using a powerful synchronous generator with the AEC system [13]:

$$\lim_{t \to \infty} \left| \Delta U_G \right| = 0 \quad (9)$$

In this case, the objective of synthesis should be stated as follows: to determine the type of structure, principle of control of the excitation system and the regulator parameters, in compliance with the requirements of system stability and quality of transient processes of the controlled object. By maintaining the required generator voltage and aperiodic stability in compliance with its static angular characteristic, the coefficients of control, taking into account the deviation, have been established. In solving the synthesis problem, special attention was paid to damping the proper oscillations of the generator and power system.

As mentioned above, to control the excitation current, an adaptive stabilizing system with a variable structure regulator can be employed. In this case, the problem formulation of the synthesis of variable structure control system will include determination of transformation laws of the parameters β_i on which the regulator structure depends [14], [15]. For this purpose, a k-dimensional vector is introduced, using discrete values of the vector β components $\beta_i,\ i = 1,...,m$ in the control interval $t_0 \le t \le t_f$, when $t_0 = 0$:

$$x = \{x_1 = \beta_1[0],\ x_2 = \beta_1[1T],...,x_{k-1} = \beta_m[(r-2)T], x_k = \beta_m[(r-1)T]\} \quad (10)$$

where:

$T = t_f / r$ – quantization time; $k = mr$.

Since vector x makes the transformation law $\beta(x, t)$ of parameters β_i in the interval $t_0 \le t \le t_f$, the problem of the system variable structure may be formulated in terms of search optimization.

The aim is to find such vector x^* which would ensure the minimum of the functional:

$$J(x) = J[y, \beta(x, t)]; \qquad t_0 \le t \le t_f \quad (11)$$

with the constraints:

$$h_i[y, \beta(x, t)] = 0; \qquad i = 1,..., p < k \quad (12)$$

$$g_j[y, \beta(x, t)] \le 0; \qquad j = 1,..., p \quad (13)$$

$$x \in \Omega_x \quad (14)$$

where:

J, h, g – characteristics of control (control time t_r, maximum dynamic deviation σ, control error Δy, etc.).

By using penalty functions the problem of search optimization (10)-(14) may be reduced to the following expression:

$$I_1[x] = I(x) + \sum_{i=1}^{p} \Psi_i h_i^2[y, \beta(x,t)] - \sum_{j=1}^{q} \varphi_j g_j[y, \beta(x,t)]\{1 - sign\ g_j[y, \beta(x,t)]\} \quad (15)$$

$$x \in \Omega_x ; \qquad y \in \Omega_y \tag{16}$$

where:

Ψ_i – weight coefficients.

When a control object which experiences controlled disturbances, or its parameters (e.g. $\partial P / \partial \delta$, $\partial U_G / \partial \delta$, etc.) determining the output signal are changing, the efficiency of the regulator synthesis can be improved by applying the active-passive (combined) simplex search algorithm [14], [15].

In this case, optimization search is aimed at local approximation of the efficiency functions by using a separable equation:

$$\hat{J}(x,z) = \sum_{i=1}^{k} A_{in} f_i(x) + \sum_{i=1}^{e} B_{in} \varphi_i(z) \tag{17}$$

where:

$A_{in,}\ B_{in}$ – coefficients depending on the search step;

$f_i(x), \varphi(z)$ – given functions.

To make a search step, the corrected efficiency functions values of the last simplex vertices are used:

$$E_j = J_j - \sum_{i=1}^{e} B_{in} \varphi(z_j) \qquad j = 1,...,k+1 \tag{18}$$

Thus, basing on the data on the controlled disturbances and variation of the parameters, the search error caused by the change in z_i may be eliminated. An adaptive algorithm of combined simplex search, i.e. prediction of the parameters z_i, calculation of the parameters A_{in}, B_{in}, etc. is realized by using the current data on the system state and parameters. All problems concerning synthesis of the systems, written in the form of equations (10)-(18) and based on the information about the controlled parameters z_i, are solved by using the software package Kvazio -1 [16], [17]. Figure 3 gives a schematic view of the adaptive excitation control system synthesis realizing the programs of Kvazio - 1 software package.

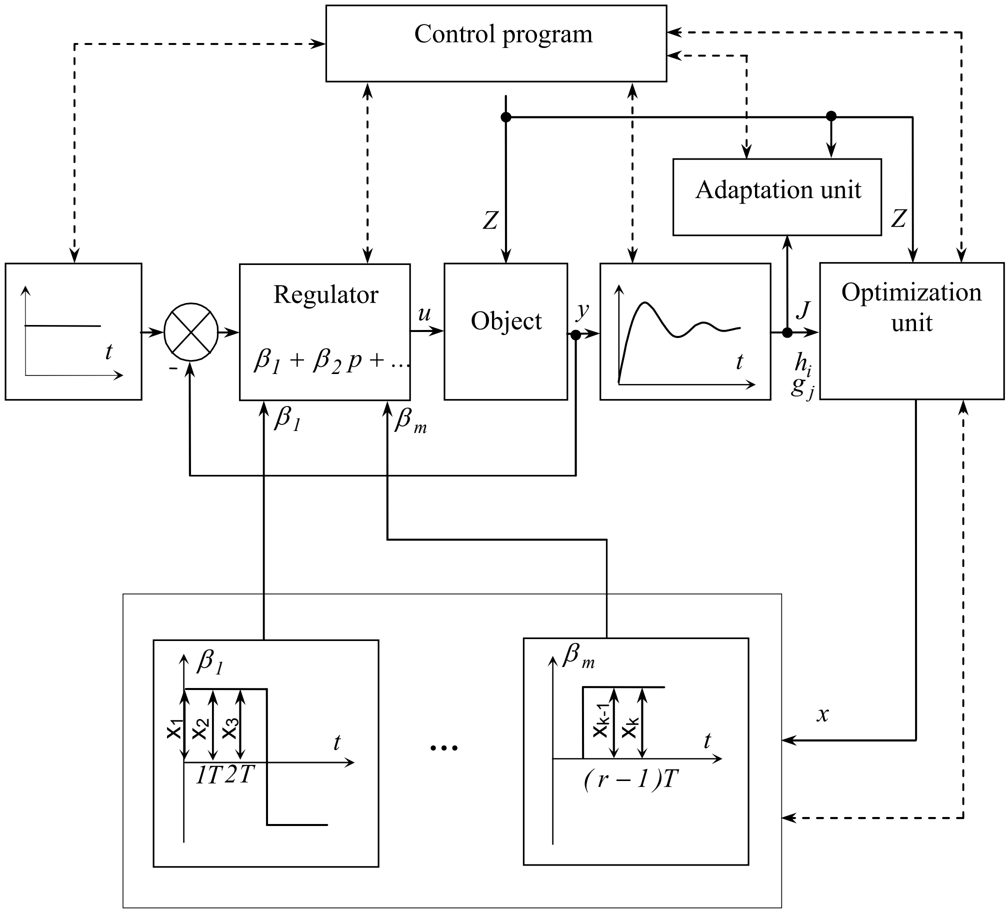

Fig. 3. Synthesis of the adaptive excitation control system of a synchronous generator

The software includes simplex algorithmic search programs (optimization) as well as the programs of the formation of system parameters, control effect, object simulation, control characteristics and adaptation. Based on the suggested method, the variation transformation laws of amplifying the circuit coefficient $k_r(t)$ and differentiating circuit coefficient $k_d(t)$ were stated by using Kvazio - 1 software package. They are given in Fig. 4 and Fig. 5, respectively, while, in Fig. 6, a transient process of the adaptive AEC system of a synchronous generator is shown.

It is obvious, that variation laws of the regulator coefficients $\beta_i(t)$ depend on the system coefficients c_1, c_2, c_3, b_1, b_2. If one or several of them changes during the optimization process, additional contour of adaptation of variation laws of regulator coefficients can be added to the control system. In this case, the variation laws of coefficients $\beta_i\lfloor t, \lfloor c_j(t)\rfloor\rfloor$ are adjusted by the the control system according to the change in the value of the coefficient $c_j(t)$.

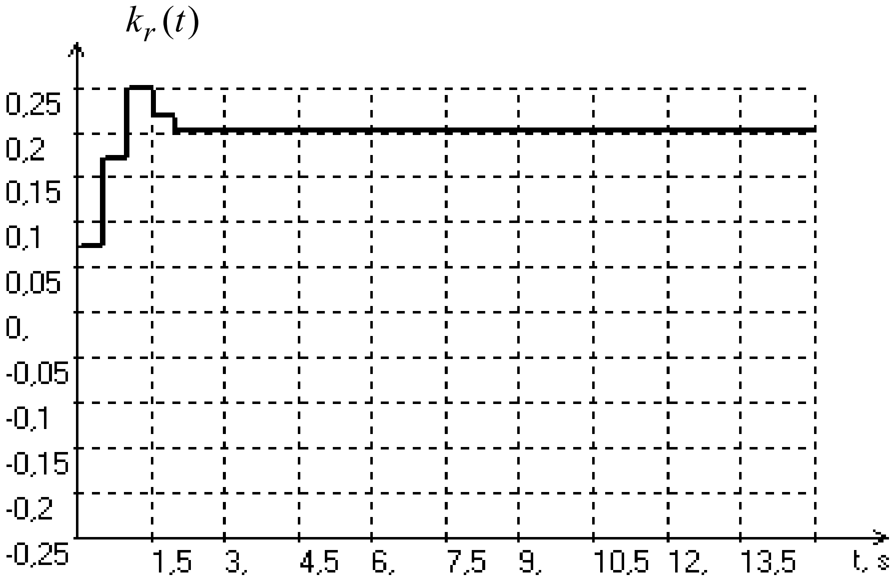

Fig. 4. Transformation law of the proportional circuit amplifying coefficient

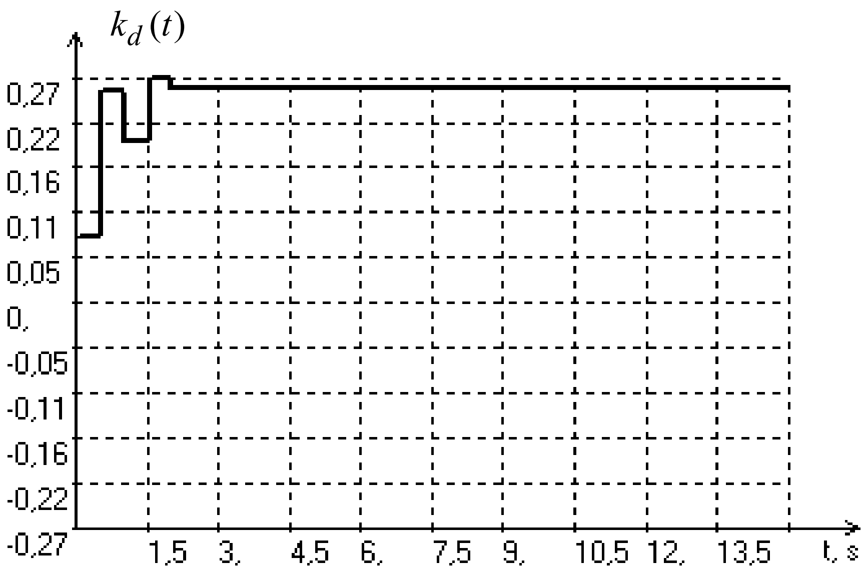

Fig. 5. Transformation law of the differentiating circuit amplifying coefficient

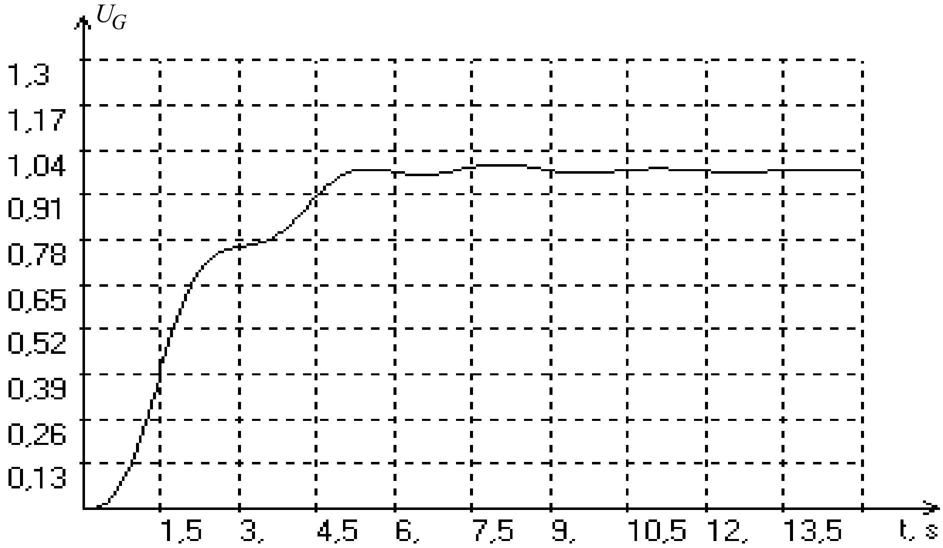

Fig. 6. Transient process in the AEC system of variable parameters

4. CONCLUSIONS

The excitation control of a powerful synchronous generator has been investigated. Algorithmic synthesis methods of systems with variable structure have been suggested to form the AEC generator system.

The research data have shown that algorithmic synthesis methods can help to state nearly optimal transformation laws for the regulator structure even in cases when a mathematical model is either too sophisticated or inaccurate, i.e. when classical synthesis methods of variable structure and optimal control systems can hardly be used.

LITERATURE

1. Chown G. A., Hartman R. C.: Design and Experience with a Fuzzy Logic Controller for Automatic Generation Control. IEEE Trans. on Power Systems, Vol. 13, No. 3, 1998, pp. 202-208.
2. Loc H. D.: Adaptive fuzzy logic control of nonlinear dynamic systems. Budapest, Preprints EURASIP Hungary, 2001, pp. 1-11.

3. Narendra K. S.: Advances in adaptive control. New York IEEE Press, 1991.
4. Kolomeiceva M. B., Loc H. D.: Synthesis a an adaptive system of automatic regulation of a synchronous generator excitation using a fuzzy regulator (in Russian). Electrichestvo, No. 6, 2002, pp. 13-15.
5. Lee C. C.: Fuzzy Logic in control system: Fuzzy logic controller. Part I, II. IEEE Transaction on systems, man and cybernetics, Vol. 20, No. 2, March/April 1990.
6. Hiyama T., Kugimiya M., Satoh H.: Advanced PID type fuzzy logic power system stabilizer. IEEE Transaction on energy conversion, Vol. 9, No. 3, September 1994.
7. Dorf R. C.: Modern control systems. London, Addison-Wesley, 1990.
8. Dorf R.C.: Bishop R. H.: Modern control systems. California, Addison- Wesley, 1998.
9. Ogate K.: Modern Control Engineering. New Jersey, Prentice Hall, International, Inc., 1997.
10. Momoh J. A., Ma X. W., Tomsovic K. O.: Overview and literature survey of fuzzy set theory in power systems. IEEE Transactions on power systems, Vol. 10, No. 3, August 1995.
11. Kitauchu Y., Taniguchi H.: Experimental verification of fuzzy excitation control systems for multi-machine power systems. IEEE Transaction on energy conversion, Vol. 12, No. 1, March 1997.
12. Lown M., Swidenbank E., Hogg B. W.: Adaptive fuzzy logic control of a turbine generator system. IEEE Transaction on energy conversion, Vol. 12, No. 4, December 1997.
13. Dambrauskas A., Karaliunas B., Shulskis D.: Synthesis of adaptive excitation system of synchronous generator (in Lithuanian). Electronics and Electrical Engineering. Kaunas, Technologija , No. 5(47), 2003, pp. 31-37.
14. Dambrauskas A.: Methods of simplex search (in Lithuanian). Vilnius, Technika, 1995.
15. Dambrauskas A.: Problems of automatic control systems optimization (in Lithuanian). Electronics and Electrical Engineering. Kaunas, Technologija, No. 5(34), 2001, pp. 59-66.
16. Dambrauskas A., Schulskis D.: Computer programming equipment of synthesis of the quasioptimal and variable structure control systems (in Lithuanian). Vilnius, Technika, 2002.
17. Dambrauskas A.: Optimization of automatic control systems (in Lithuanian). Vilnius, Technika, 2003.

Manuscript submitted 16.11.2004

SYNTEZA ADAPTACYJNYCH SYSTEMÓW STEROWANIA WZBUDZENIA DO GENERATORÓW SYNCHRONICZNYCH DUŻEJ MOCY

Algirdas DAMBRAUSKAS, Bronius KARALIUNAS
Dinas SHULSKIS

STRESZCZENIE *W artykule omówiono nowe obiecujące systemy wzbudzenia generatorów synchronicznych dużej mocy, pracujących we wspólnym systemie mocy. W oparciu o ogólne założenia otrzymano układ równań różniczkowych, funkcji przejścia oraz wykres blokowy układu wzbudzenia jako obiektu sterowania automatycznego. Matematyczne opisy elektromechanicznych procesów przejściowych są bardzo złożone i ograniczone. W takich przypadkach sprawność działania regulatora prądu wzbudzenia można zwiększyć stosując złożone algorytmy poszukiwań simpleksowych, gdy w procesie optymalizacji, lokalna funkcja sprawności jest aproksymowana równaniem separowalnym. W oparciu o uzyskane wyrażenia opracowano syntezę, adaptacyjny układ sterowania wzbudzenia generatora oraz bloki optymalizacji.*

Proponowany schemat syntezy układu adaptacyjnego pozwala eliminować błędy poszukiwania. Wyniki syntezy wskazują na to, że proces przejściowy napięcia generatora jest zbliżony do optymalnego.

Algirdas Dambrauskas is currently professor of the Automatics Department of the Vilnius Gediminas Technical University (Lithuania). Electrical Engineer (1964), Doctor (1970), Habil. Doctor (1983). Author of 152 publications. Basic research areas: search optimisation, adaptive, extreme and optimal control systems.

Bronius Karaliunas is associated professor of the Automatics Department of the Vilnius Gediminas Technical University (Lithuania). Electrical Engineer (1974), Doctor (1983), Author of 76 scientific articles, Inventor, holds some 27 patents. Basic research areas: problems of non stationary processes in electromechanical power converters, calculations of magnetic fields and development of new braking systems.

Dinas Shulskis is doctoral student at Vilnius Gediminas technical University. He received a B. Sc. degree and the M. Sc. degree in electrical engineering from Vilnius Gediminas Technical University in 1996 and 1998, respectively. Author of 6 scientific articles, basic research areas: optimisation, adaptive and optimal control systems. He is student member of IEEE since 2002.