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THE SEMICONDUCTOR SELF-EXCITATION SYSTEM OF SYNCHRONOUS GENERATOR WITH FUZZY VOLTAGE CONTROLLER

The synchronous generator voltage control system with a synthesized fuzzy voltage controller has been described. The controller has been synthesized with the use of mathematical model taking into account the nonlinearity of synchronous machines and semiconductor converters in the excitation system. This distinguishes it from the traditional excitation controllers whose synthesis is based on the use of simplified linearized models. The mathematical modeling results allow the researchers to compare the control characteristics in the system with the proposed fuzzy voltage controller and in the system with traditional voltage controller.

Key words: synchronous generator, excitation system, and fuzzy controller.

Electricity is produced mainly by synchronous generators. The generator is controlled by regulating the excitation current through the excitation system that performs various functions, among which there are as follows:

- To maintain voltage at the control point with given accuracy in different modes;
- To intensively damp small oscillations and significant post-accident fluctuations occurring in the electric power system;
- To ensure a high level of dynamic stability by forcing the excitation to a maximum value during short circuits and load rise in the external electric circuit; and
- To protect the generator.

Raising requirements for power quality imply the improvement of quality of output voltage control, the enhancement of stability of its operation in the electric circuit and damping of oscillations at the generator output, which are induced by the processes in power grid. Among the factors that complicate addressing this urgent problem, there are the permanent variations in the terms of operation of electricity generation system caused by changing the size and the nature of generator load, as well as the presence of nonlinearities in actuating paths.

ANALYSIS OF RECENT RESEARCH

Today, for controlling the excitation of PES powerful synchronous generators, there are used the voltage controllers operating on the basis of proportional-integral (PI) or proportional-integral-differential (PID) law. These controllers are complemented with circuits for control by other coordinates and their derivatives. Their task is to damp oscillations at the generator output and within the power grid [1]. In order to synthesize such excitation control systems the simplified models linearized in a certain point are used. They do not ensure reliable operation of the system in different modes with wide range of coordinate variations.

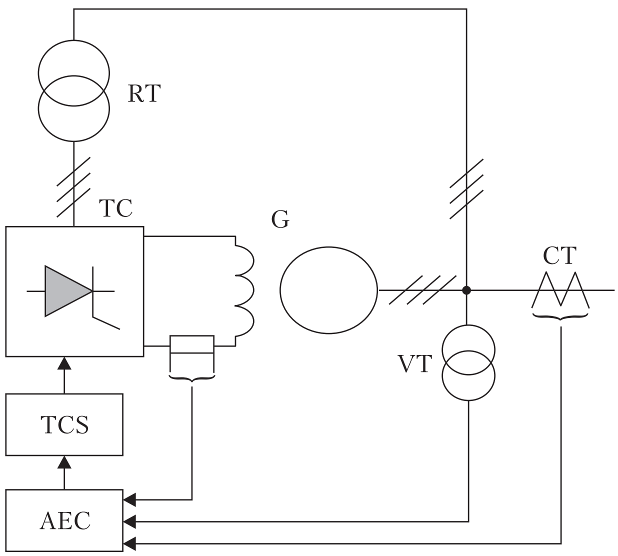


Fig. 1. The static system of self-excitation of synchronous generator: RT is rectifier transformer; TC is thyristor converter; G is generator; CT is current transformer; VT is voltage transformer; AEC is automatic excitation controller; and TCS is thyristor control system

The results of previous research have proved the effectiveness of the use of intelligent controllers in excitation control systems. The controllers are built proceeding from the theory of artificial neural networks and fuzzy set theory. Among the advantages of fuzzy controllers, there are the option of nonuse of system model for the synthesis of controller and the robustness to parametric perturbations [2], which give rise to the controller application in the synchronous generator excitation control systems [3, 4].

To synthesize the controllers of electromechanical and electric systems it is necessary to have information about the system behavior in different (including emergency) operation modes. Obtaining such information is possible with the use of appropriate mathematical and computer models. Using the simplified linearized models of electric machines and semiconductor converters leads to significant errors of results and does not make it possible to adequately reflect the processes in all modes of operation of electrical facilities, which significantly affects the quality of intelligent controllers designed. In this regard, it is appropriate to use the refined models that take into account the nonlinearity of electric machines and semiconductor converters.

The objective of this study is to verify, by means of simulation, the effectiveness of using the fuzzy voltage controller in static synchronous generator excitation control systems.

STATIC SYSTEM OF SELF-EXCITATION OF SYNCHRONOUS GENERATOR

To adjust the excitation of small- and medium-capacity synchronous generators the most widely used system is static self-excitation system. Its block diagram is showed in Fig. 1. The use of these systems in semiconductor converters provides high-speed operation of generator excitation control. However, this system has a disadvantage, a limited possibility of forcing the excitation in emergency operation in the case of significant voltage slump at the generator output and a consequent fall in the input voltage of thyristor converter.

In post-Soviet countries, as a rule, the so-called *adaptive stabilizers* are used to control the PES generator excitation. They use a PID voltage controller and numerous feedbacks by spatial derivatives. The operation of such automatic excitation controller (AEC) (of ARV-SDP type) is described by the following equation:

$$U_f = U_{f0} - K_{0U}(\Delta U_Г - K_{cm} I_r + K_{комп} I_{\Sigma r})\left(1 + \frac{1}{T_i}\right) - -K_{1U} U'_Г - K_{1If} W_{1If} I'_f + K_{0f}\Delta f + K_{1f} W_{1f} f'$$

where ΔU_G is deviation of generator voltage from target value; I_r is reactive current of generator; $I_{\Sigma r}$ is reactive current of group of generators operating on common buses; C_{st} is stabilization factor; C_{comp} is compensation factor of step-up transformer reactance; U'_G is first derivative of generator voltage by time; I'_f is first derivative of generator excitation current; Δf is frequency deviation from nominal value at the output of generator; f' is first derivative of frequency at the output of genera-

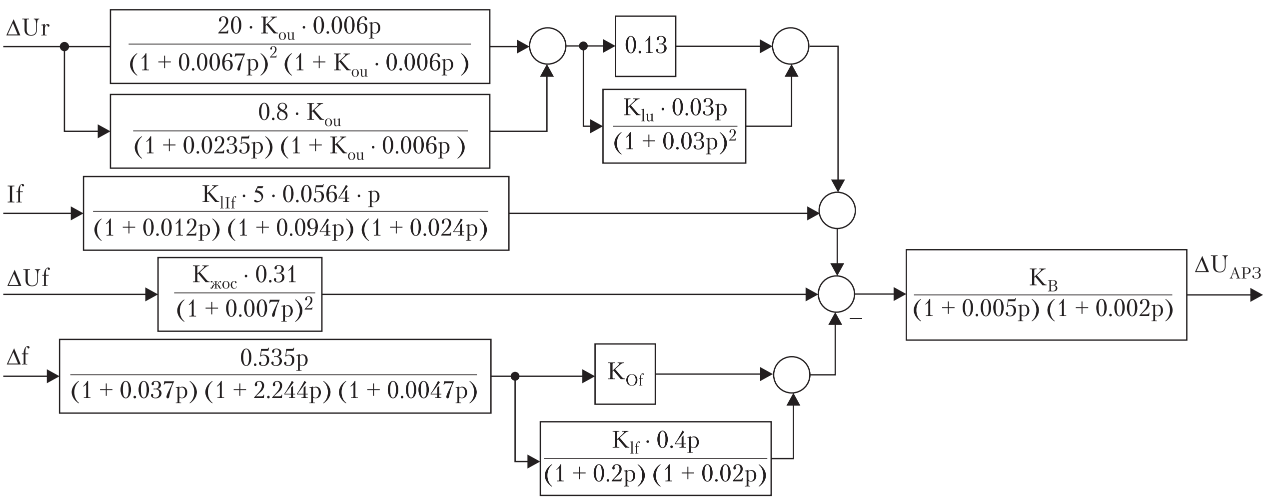


Fig. 2. Block schematic diagram of AEC (ARV-SD, ARV-SDP1)

tor; U_f is voltage of generator excitation; T_i is time constant of integral component.

Given the transmitting functions of the sensor system and transmitting tract, the mentioned AEC can be represented by block diagram showed in Fig. 2 [1]. This block diagram does not contain paths for regulation by reactive current of generator group and compensation of step-up transformer reactance, which are ignored in many cases.

It should be noted that two components are often distinguished in the AEC structure, namely, the *automatic voltage controller (AVC)* whose function is to stabilize voltage on generator buses and *the system stabilizer*, whose purpose is to influence excitement current in such a way as to damp the fluctuations at the output of generator. In the structure of ARV-SD controller type (ARV SDP1) the AVC function is played by voltage actuating paths, with excitation current and frequency actuating paths acting as system stabilizer.

Synthesis of such AEC requires the selection of amplification factors for each path, which determine the characteristics of control in different modes of operation that, given a quite large number of these factors, greatly complicates the problem of synthesis and configuration of the controller. The controller parameters calculated using the simplified models of generator unit linearized in the vicinity of a working point do not provide adequate quality of control indicators in all operation modes. They require changing the controller parameters depending on the mode, which is a difficult task.

In this regard, it is interesting to use intelligent excitation controllers based on fuzzy logic theory for controlling the generator excitation. Such controller will be synthesized using refined mathematical models taking into account the non-linearity of magnetic conductor of synchronous generator, effect of its damper system, nonlinearity of thyristor converter, and discreteness of its valves.

MATHEMATICAL MODEL OF POWER GENERATING UNIT

The object-oriented analysis of valve-engine systems was used to build a mathematical model of static excitation system [5]. An advantage of this method is a possibility to create mathematical and computer models that can operate in real-time mode while interacting with physical objects. The given method uses the theory of object-oriented design and programming, according to which the model is represented as a set of objects interacting with each other.

The development of a computer model is reduced to combination of objects representing the models of typical elements of valve-engine systems (VES). They are transformers, DC and AC machines, valve groups (the cathode and the anode ones), power grid (three-phase, single-phase ones), *RL*-links with EMF, and capacitors.

Using the object-oriented method for developing a model of complex system, the user deals with ready models of system components represented by multipoles and shaped as objects instead of a set of equations and algorithms. A detailed procedure for the synthesis of mathematical model using the common multipole element models implemented in the object-oriented form is described in [5]. In this case, according to the design scheme showed in Fig. 3, the object models of structural elements are the objects implementing the model:

- synchronous machine (SM);
- three-phase transformer (Tr);
- cathode (KVG1) and anode (AVG1) valve groups (from which the model of thyristor converter is formed);
- Grid (MER).

The design diagram of the power section of generating unit with a static system of self-excitation is showed in Fig. 3.

The design model of synchronous machine as eight-terminal circuit, which is based on the approach implemented in the theory of simulation of valve-engine systems [6] is showed in Fig. 4. The damping system of synchronous machine is modeled in the *dq* coordinates and represented by two short-circuited inductances oriented along the *d* and *q* axes of synchronous machine.

The equation system to describe explicitly the poled synchronous machine (Fig. 3) is as follows:

$$\vec{\varphi}_1 - \vec{\varphi}_2 - p\vec{\psi}_{\mathbf{e}} - \breve{R}_{\mathbf{e}} \cdot \vec{i}_{\mathbf{e}} = 0,$$
$$p\vec{\psi}_{\mathbf{i}} - \breve{R}_{\mathrm{i}} \cdot \vec{i}_{\mathrm{i}} = 0, \qquad (1)$$

where $\vec{\varphi}_1 = (\varphi_{A1}, \varphi_{B1}, \varphi_{B1}, \varphi_{f1})$, $\vec{\varphi}_2 = (\varphi_{A2}, \varphi_{B2}, \varphi_{B2}, \varphi_{f2})$ are vectors of potentials in connection points; $\Psi_{ee} = (\psi_A, \psi_B, \psi_C, \psi_f)_{te}$ and $\Psi_{ii} = (\psi_D, \psi_Q)_t$ are vectors of flux linkage; $R_{ee} = diag(r_A, r_B, r_C, r_f)$ is matrix of stator winding reactance and excitement; $R_{ii} = diag(r_D, r_Q)$ is matrix of reactance of damper winding.

The derivatives of flux linkage are determined as follows:

$$p\vec{\psi}_{\mathbf{e}} = \frac{\partial\vec{\psi}_{\mathbf{e}}}{\partial\vec{i}_{\mathbf{e}}} \cdot p\vec{i}_{\mathbf{e}} + \frac{\partial\vec{\psi}_{\mathbf{e}}}{\partial\vec{i}_{\mathrm{i}}} \cdot p\vec{i}_{\mathrm{i}} + \frac{\partial\vec{\psi}_{\mathbf{e}}}{\partial\gamma} \cdot p\gamma = = \breve{L}_{\mathbf{e}} \cdot p\vec{i}_{\mathbf{e}} + \vec{L}_{\mathbf{ei}} \cdot p\vec{i}_{\mathrm{i}} + \vec{\psi}_{\mathbf{e}}^{\Gamma} \cdot p\gamma \qquad (2)$$

$$p\vec{\psi}_{\mathbf{i}} = \frac{\partial\vec{\psi}_{\mathrm{i}}}{\partial\vec{i}_{\mathbf{e}}} \cdot p\vec{i}_{\mathbf{e}} + \frac{\partial\vec{\psi}_{\mathrm{i}}}{\partial\vec{i}_{\mathrm{i}}} \cdot p\vec{i}_{\mathrm{i}} + \frac{\partial\vec{\psi}_{\mathrm{i}}}{\partial\gamma} \cdot p\gamma = = \breve{L}_{\mathbf{ie}} \cdot p\vec{i}_{\mathbf{e}} + \vec{L}_{\mathrm{i}} \cdot p\vec{i}_{\mathrm{i}} + \vec{\psi}_{\mathrm{i}}^{\Gamma} \cdot p\gamma.$$

The coefficients in equations (2) are determined as follows:

$$\vec{\psi}_{ee}^{\Gamma} = \breve{L}_{ee}^{\Gamma} \cdot \vec{i}_{ee} + \breve{L}_{ei}^{\Gamma} \cdot \vec{i}_{ii}, \quad \vec{\psi}_{ii}^{\Gamma} = \breve{L}_{ie}^{\Gamma} \cdot \vec{i}_{ee}, \qquad (3)$$

where $L_{ee}{}^{G}$, $L_{ei}{}^{G}$, $L_{ie}{}^{G}$ are derivatives of matrixes L_{ee}, L_{ei}, L_{ie} by rotor angular displacement;

$$\breve{L}_{ee} = \begin{bmatrix} L_{AA} & L_{AB} & L_{AC} & L_{Af} \\ L_{BA} & L_{BB} & L_{BC} & L_{Bf} \\ L_{CA} & L_{CB} & L_{CC} & L_{Cf} \\ L_{fA} & L_{fB} & L_{fC} & L_{ff} \end{bmatrix} \quad \breve{L}_{ei} = \begin{bmatrix} L_{AD} & L_{AQ} \\ L_{BD} & L_{BQ} \\ L_{CD} & L_{CQ} \\ L_{fD} & L_{fQ} \end{bmatrix}$$

$$\breve{L}_{ie} = \begin{bmatrix} L_{DA} L_{DB} L_{DC} L_{Df} \\ L_{QA} L_{QB} L_{QC} L_{Qf} \end{bmatrix}.$$

Here, L_{ee} is (4 × 4) matrix of mutual inductance and self-inductance of stator phase winding and excitation winding, where the diagonal elements L_{AA}, L_{BB}, L_{CC}, L_{ff} are self-inductances of phase winding and excitation winding, with the others being mutual inductances of the respective windings; L_{ei}, and L_{ie} are matrixes of mutual inductances of damper windings, stator phase winding and excitement winding; $L_{ii} = (L_{DD}, L_{QQ})$ is damper winding self-inductance matrix. These inductances are calculated on the basis of CM electromagnetic parameters: L_d, L_{ad}, L_q, L_{aq}, L_{sf}, L_{sD}, $_{LsQ}$, and L_0.

To take into account the nonlinear characteristics of magnetic conductor the inductance of armature reaction of salient-pole synchronous machine on the *d* axis (L_{ad}) is assumed to be a function of magnetization current (tabulated by magnetization curve) that is determined by the following formula:

$$i_{\mu} = \frac{2}{3}\left[i_A \cos(\gamma) + i_B \cos(\gamma - \rho) + i_C \cos(\gamma - 2\rho)\right] + \frac{i_f}{k_i} + i_D.$$

The equation system (1) after the insertion of expressions from (2) is written as follows:

$$\vec{\varphi}_1 - \vec{\varphi}_2 - \breve{L}_{\mathbf{e}} \cdot p\vec{i}_{ee} - \breve{L}_{ei} \cdot p\vec{i}_{ii} - \vec{\psi}^{\,r}_{ee} \cdot p\gamma - \breve{R}_{ee} \cdot \vec{i}_{ee} = 0,$$
$$\breve{L}_{ie} \cdot p\vec{i}_{ee} + \breve{L}_{ii} \cdot p\vec{i}_{ii} + \vec{\psi}^{\,r}_{ii} \cdot p\gamma + \breve{R}_{ii} \cdot \vec{i}_{ii} = 0. \qquad (4)$$

Having found the expression for pi_{ii} from the second equation of the system and inserted it into the first equation, we obtain:

$$\vec{\varphi}_1 - \vec{\varphi}_2 - (\breve{L}_{ee} - \breve{L}_{ei} \cdot \breve{L}_{ii}^{-1} \cdot \breve{L}_{ie}) \cdot p\vec{i}_{ee} -$$
$$-(\vec{\psi}^{\,r}_{ee} \cdot p\gamma + \breve{R}_{ee} \cdot \vec{i}_{ee} - \breve{L}_{ei} \cdot \breve{L}_{ii}^{-1} \cdot (\vec{\psi}^{\,r}_{ii} \cdot p\gamma + \breve{R}_{ii} \cdot \vec{i}_{ii})) = 0 \cdot \qquad (5)$$

Having taken into consideration that $p\gamma = p_0\omega$, where γ is rotor angular displacement in electrical degrees, p_0 is number ofpole pairs, ω is rotor angular displacement and having denoted that

$$\breve{L} = \breve{L}_{ee} - \breve{L}_{ei} \cdot \breve{L}_{ii}^{-1} \cdot \breve{L}_{ie},$$
$$\vec{E} = \vec{\psi}^{\,r}_{ee} \cdot p\gamma + \breve{R}_{ee} \cdot \vec{i}_{ee} - \breve{L}_{ei} \cdot \breve{L}_{ii}^{-1} \cdot (\vec{\psi}^{\,r}_{ii} \cdot p\gamma + \breve{R}_{ii} \cdot \vec{i}_{ii}),$$

let us write the equation system (4) as follows:

$$\vec{\varphi}_1 - \vec{\varphi}_2 - \breve{L} \cdot p\vec{i}_{ee} - \vec{E} = 0,$$
$$p\vec{i}_{ii} = -\breve{L}_{ii}^{-1} \cdot (\breve{L}_{ie} \cdot p\vec{i}_{ee} + \vec{\psi}_{ii} \cdot p_0\omega + \breve{R}_{ii} \cdot \vec{i}_{ii}). \qquad (6)$$

The obtained SM mathematical model (equation (6)) should be complemented with mechanical condition equation:

$$M + M_{n} = Jp\omega, \qquad (7)$$

where M is electromagnetic torque of machine, M_n is torque attached to the rotor shaft, and J is rotor moment of inertia.

The mathematical models of semiconductor converters are based on the following assumptions:

- Power circuits of semiconductor converters are considered to be electrical circuits with constant structure and variable parameters;
- Convector valves are presented as circuit branches consisting of series-connected reactance r and inductance L which are small in the open position of the valve and large in the closed position. The L/r ratios in both states of thyristor are assumed to be equal to approximately 10—

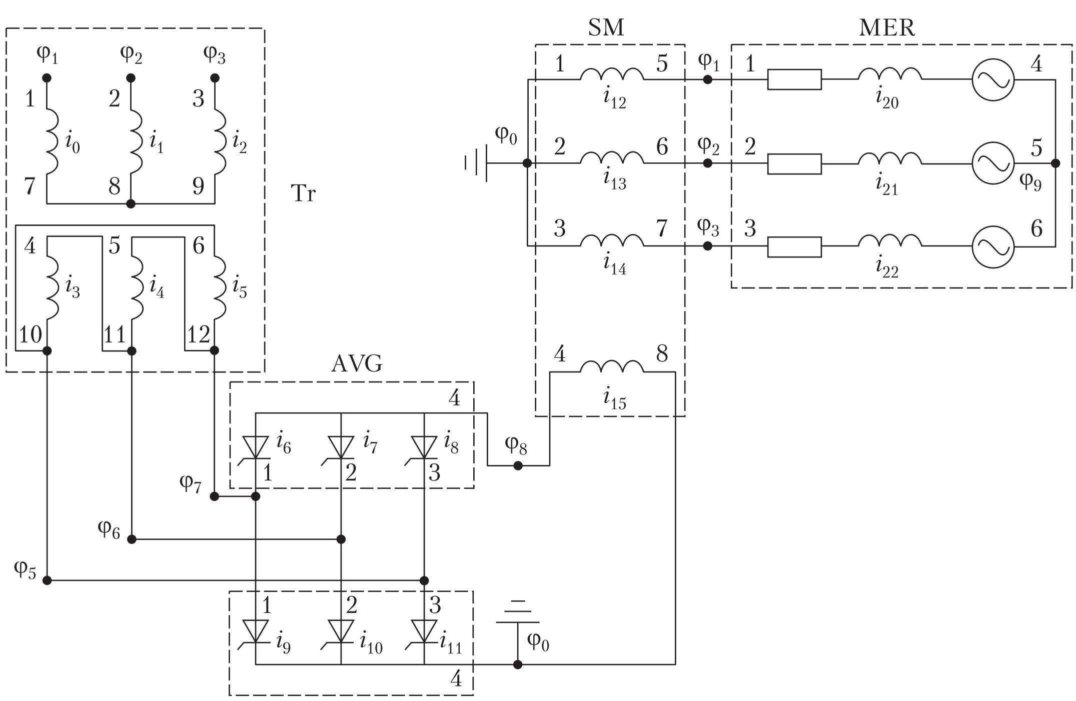


Fig. 3. Design diagram of the power section of SM self-excitation system: $i_0 \dots i_{22}$ are currents of structural element electric branches, $\varphi_1 \dots \varphi_9$ are potentials of independent units of valve-engine system

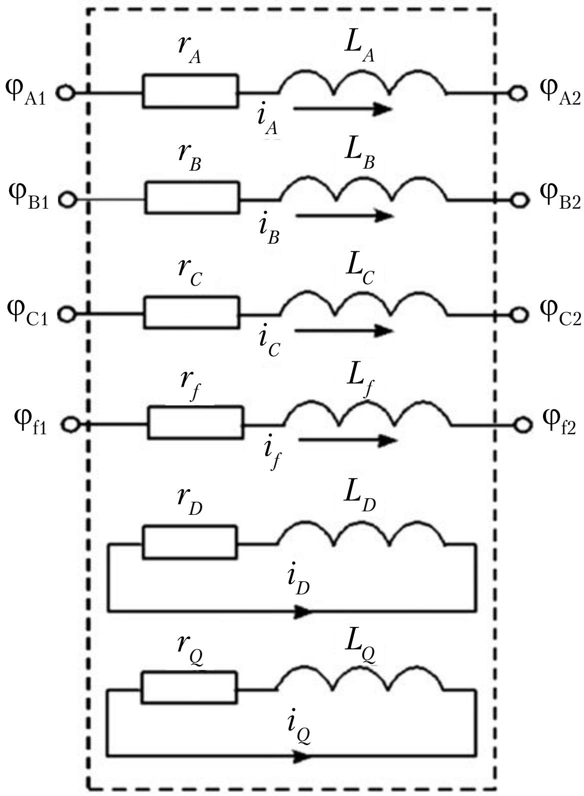


Fig. 4. SM design diagram

50 times greater than the expected average step of numerical integration of differential equations that describe the electromagnetic and electromechanical processes;

- Valves shut at the moment when time dependence of their currents passes through zero changing the sign from positive to negative value. This assumption implies that time of recovery of valve turnoff properties is equal to zero;
- The valve opening point is found by solving the logic equations describing the valve control system (the valves open instantly).

Models of semiconductor converters were presented as a set of the objects implementing the power section models and the object implementing the control system model.

The model of semiconductor converter power section is formed of object models of anode and cathode valve groups (Fig. 5). The power section of cathode or anode valve group is presented as two-port terminal device and is described by equations based on the nodal potential method:

$$\varphi_1\frac{1}{L_1}-\varphi_4\frac{1}{L_1}+\dot{p}_1=-\frac{R_1 i_1}{L_1},$$
$$\varphi_2\frac{1}{L_2}-\varphi_4\frac{1}{L_2}+\dot{p}_2=-\frac{R_2 i_2}{L_2},$$
$$\varphi_3\frac{1}{L_3}-\varphi_4\frac{1}{L_3}+\dot{p}_3=-\frac{R_3 i_3}{L_3},$$
$$\varphi_4\left(\frac{1}{L_1}+\frac{1}{L_2}+\frac{1}{L_3}\right)-\varphi_1\frac{1}{L_1}-\varphi_2\frac{1}{L_2}-\varphi_3\frac{1}{L_3}+\dot{p}_4=$$
$$=\frac{R_1 i_1}{L_1}+\frac{R_2 i_2}{L_2}+\frac{R_3 i_3}{L_3}, \quad (8)$$

where i_1, i_2, i_3, and i_4 are exterior branch currents; φ_1, φ_2, φ_3, and φ_4 are potentials of exterior poles.

The opening pulses are fed to the thyristors of the converter controlling SM excitation current synchronously with the rotor angular displacement (in its turn, it determines phase output voltage quite precisely). Respectively, the conditions for opening of thyristor converter valves are written as follows:

$$(TM(\mathrm{i})>\alpha)\cap(TM(\mathrm{i})<\alpha+\Delta\alpha)\cap$$
$$(VT(\mathrm{i})>0)\cap(IT(\mathrm{i})=0)=\text{true}, \quad (9)$$

where TM is 6-dimension array whose elements are equal to: $TM(1)=\gamma_R$; $TM(2)=\gamma_R+4\pi/3$; $TM(3)=$ $=\gamma_R+2\pi/3$; $TM(4)=TM(1)+\pi$; $TM(5)=TM(2)+$ $+\pi$; $TM(6)=TM(3)+\pi$; γ_R is rotor angular displacement; VT is array whose elements are the valve voltages; IT is array whose elements are functions of the state of the valves (taking on a value of 1 when the valve is open and 0 when the valve is closed); and $\Delta\alpha$ is width of the opening pulse.

While studying the modes of no-load initial excitation of synchronous turbo-generator the turbine is assumed to rotate with a constant velocity. The excitation system parameters used in the calculations of processes in the system are as follows: for synchronous turbine generators (type TGV-200-2MU3): P_{nom} = 210 MW; nominal voltage and current U_{nom} = 15 750 V, I_{nom} = 9 060 A; no-load excitation current $i_{fn.l.}$ = 715 A; nominal excitation current i_{fn} = 1 945 A; active resistance of the stator and excitation windings r_{st} = 0.0024 ohms, r_f = 0.174 ohms;

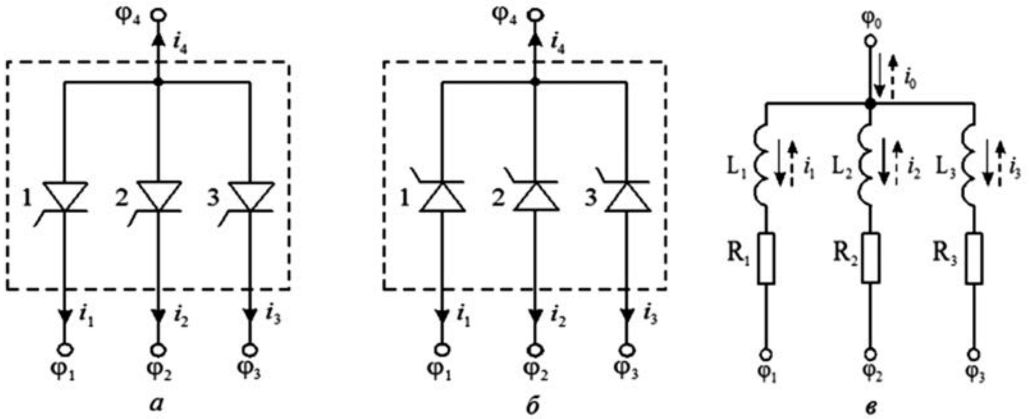


Fig. 5. Diagram of anode (*a*) and cathode (*b*) valve groups and their design diagram (*c*)

inductive reactance H_d = 1.997 p.u., H_{ad} = 1.723 p.u., H'_d = 0.34 p.u., and X''_d = 0.223 p.u.

For rectifier transformer (RTr, type TSZP-3000/20 VU3): S_{nom} = 2540 kVA; nominal voltage of primary and secondary windings U_{1n} = 15750 V and U_{2n} = 855 V; no-load current I_{nl} = 0.9%; short circuit voltage U_{sc} = 6.5%; and active loss power ΔR*sc* = 22 kW.

The AEC parameters: K_{OU} = 20; K_{1U} = 0.5; K_{1If} = = 1.0; K_{0f} = 0.3; and K_{1f} = 0.8.

STRUCTURE OF FUZZY EXCITEMENT CONTROLLER

To ensure synchronous generator voltage control the structure of fuzzy controller is proposed (see Fig. 6).

The fuzzy voltage controller (FVC) exercises output voltage control and ensures duty initial excitement. To its input there are fed: Δe_u difference between the given and the actual output voltage (error of voltage control) and e_u is an increase (first derivative) in voltage control error. The use of control circuits by voltage and its first and, sometimes, second derivative is typical for the majority of present-day AEC.

In addition, flexible feedback by generator excitation current ($-\Delta i_f$) is included into the fuzzy controller. The inclusion of this feedback makes it possible to raise damping properties of the controller, which improves the quality of control of excitation current and generator voltage.

The Takagi-Sugeno controller with constant outputs is used as basis. The rules of voltage controller are based on the standard MacVicar–Whelan rules as revised.

It is known that the signal at the output of the fuzzy controller depends on the generated membership functions, including their overlapping and type, as well as on the chosen method of defuzzification. Selected membership functions for the input variables of fuzzy voltage controller are showed in Figs. 7 and 8. The formed framework of rules for fuzzy controllers is given in Table below. To eliminate fuzziness the gravitational method is used.

According to the selected principle of defuzzification, increase in output signal of fuzzy voltage controller is defined as:

$$\Delta u_{pu} = \frac{\mu_1\mu_2 y_{11} + \mu_1(1-\mu_2)y_{21} + (1-\mu_1)\mu_2 y_{12} + (1-\mu_1)(1-\mu_2)y_{22}}{\mu_1\mu_2 + \mu_1(1-\mu_2) + (1-\mu_1)\mu_2 + (1-\mu_1)(1-\mu_2)} = \mu_1\mu_2 y_{11} + \mu_1(1-\mu_2)y_{21} + (1-\mu_1)\mu_2 y_{12} + (1-\mu_1)(1-\mu_2)y_{22}, \quad (10)$$

where μ_1 is membership function for voltage control error e_u; μ_2 is membership function for increase in voltage control Δe_u.

Increase in output signal of fuzzy voltage controller is complemented with a signal proportional to derivative (increase) in excitation current Δi_f

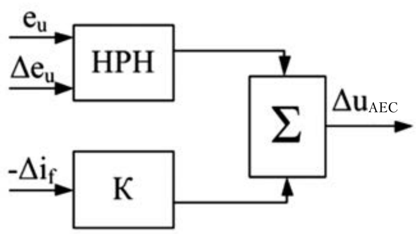


Fig. 6. Structure of fuzzy voltage controller

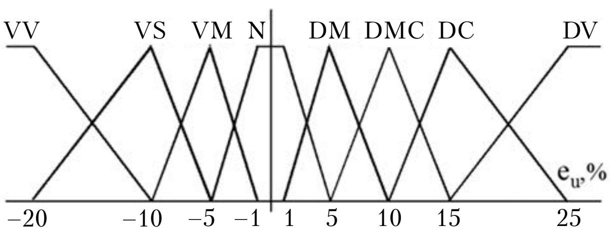


Fig. 7. Membership function for voltage control error

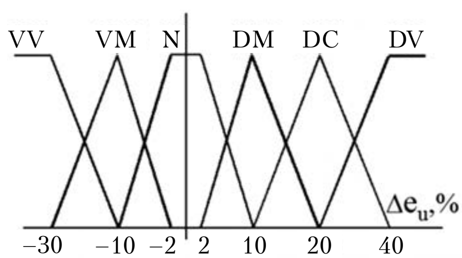


Fig. 8. Membership function for increase in voltage control error

taken with opposite sign. As a result, increase in total output signal of FVC is calculated as

$$\Delta u_{\text{HP3}} = \kappa_1 \cdot \Delta u_{\text{pu}} - \kappa_2 \cdot \Delta i_{\text{f}}, \qquad (11)$$

where κ_1, κ_2 are weights, either constant or variable, depending on the operation mode of generator (for example, at the initial no-load excitation of generator $\kappa_1 = \kappa_2 = 1$, while in the case of networked generator κ_2 grows (as need in feedback by excitation current increases), whereas κ_1 decreases, as the generator output voltage varies insignificantly.

The FEC configuration settings mentioned above were selected on the basis of experimental data using mathematical model of SM self-excitation system described above.

RESULTS OF RESEARCH

The results of research of electromagnetic processes in the system with fuzzy voltage controller have been compared with those with traditional stabilizer ARV-SDP1 structured as described above.

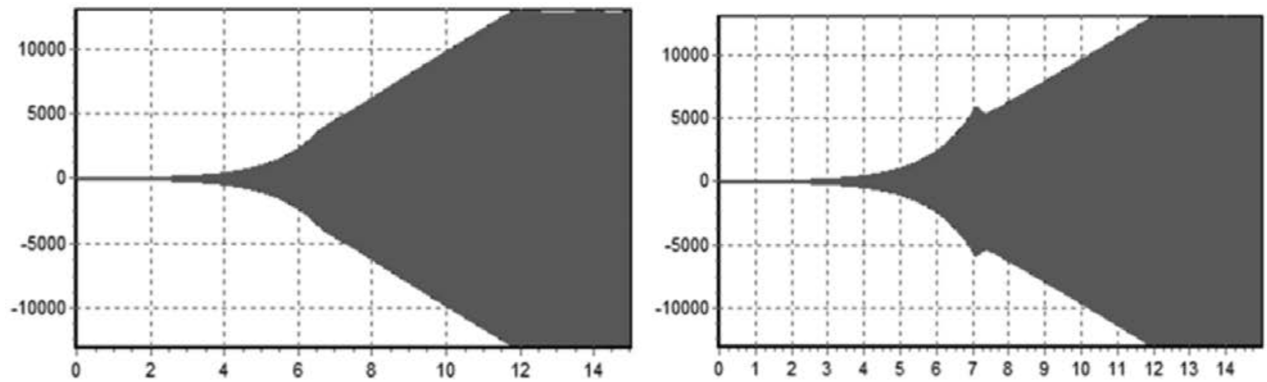
Figs. 9 and 10 feature the research results for processes in SM self-excitation system in initial no-load excitation mode. The research results are given for: *a)* stabilizer, *b)* fuzzy voltage controller.

In this case, the excitation is of duty nature: firstly the signal for SM voltage setting at a value of 0.333 U_v is fed in a stepwise manner; as soon as SM voltage reaches this value (in about 6.5 s) the SM voltage setting signal increases linearly to the nominal value; and so does the output voltage (Fig. 9).

As showed in Fig. 9, the SM stator phase voltages are slightly different within the range where they approach a preset value: in the case of traditional controller one can observe oscillating process with little readjustment of 1.44% which lasts 1.5 sec. In the case of FEC the SM voltage reaches the preset value without readjustment and

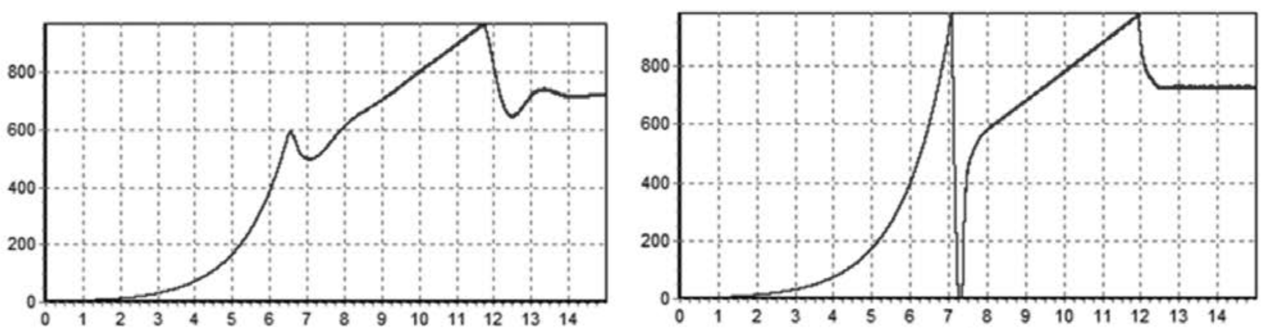
Framework of Rules for Voltage Controllers

Δe_u	e_u							
	VV	VC	VM	N	DM	DMS	DS	DV
DV	−1.2	1.6	5	8	15	15	15	15
DS	−1.2	−0.05	0.5	8	8	15	15	15
DM	−6	−1.2	0	5	8	8	8	15
N	−15	−6	−6	0	5	5	8	8
VM	−15	−6	−6	−1.2	0	0	1	8
VV	−15	−15	−15	−15	−1.2	−0.05	0.5	5



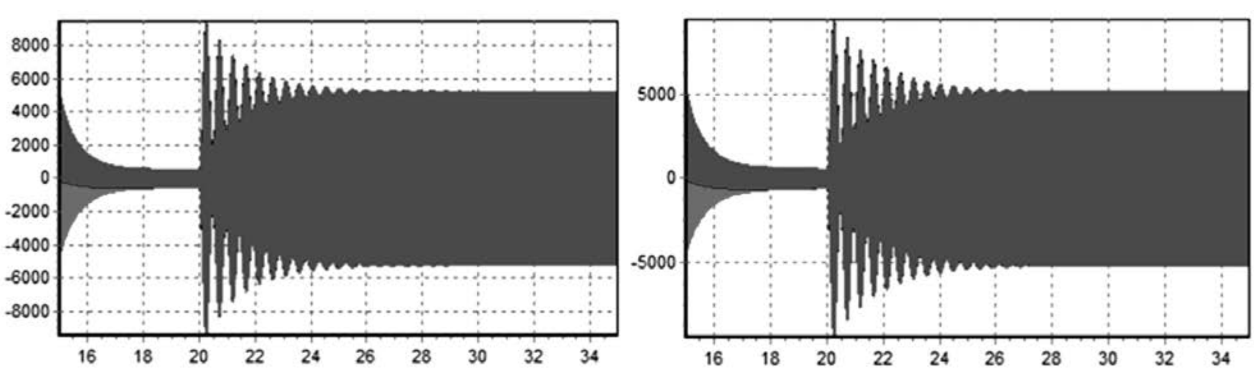
a *b*

Fig. 9. SM stator voltage (phase-to-neutral instantaneous values, B) in initial excitation mode: *a*) stabilizer, *b*) fuzzy voltage controller



a *b*

Fig.10. SM excitation current (A) in initial excitation mode: *a*) stabilizer, *b*) fuzzy voltage controller

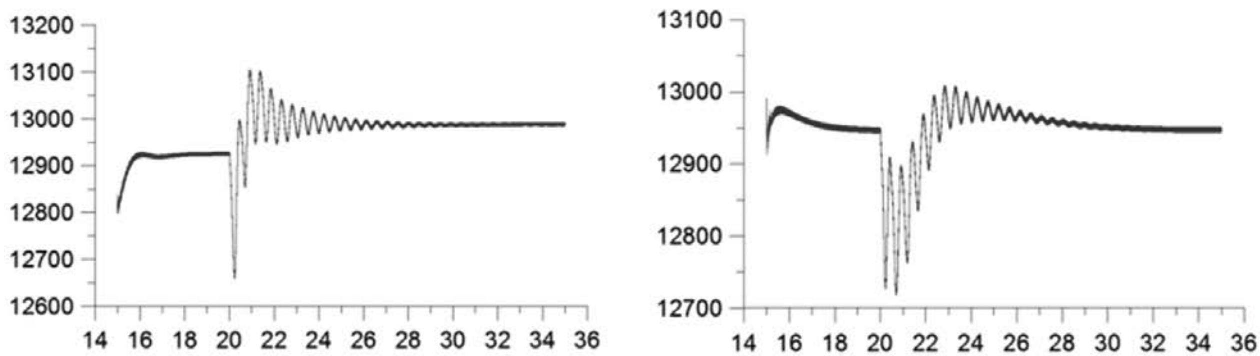


a *b*

Fig. 11. SM stator current (instantaneous value, A) when the generator is networked for 15 s with further load rise (20 s): *a*) stabilizer, *b*) fuzzy voltage controller

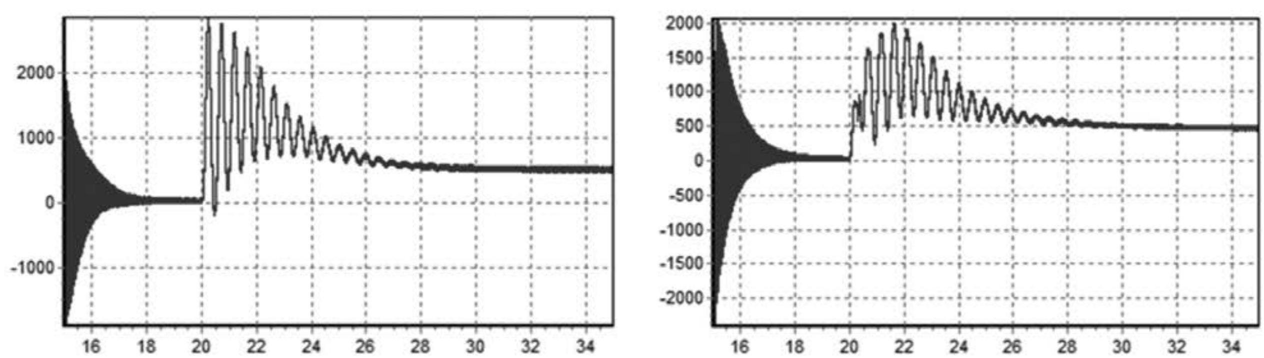
fluctuations. The absence of voltage fluctuations in the presence of fluctuating excitation current (Fig. 10) is explained by influence of generator's damping system.

Figs. 11—14 show the results of research in the mode when the generator is turned on for 15 s, with further rise in load (during 20 seconds) by 50% of nominal voltage. To evaluate the damping proper-



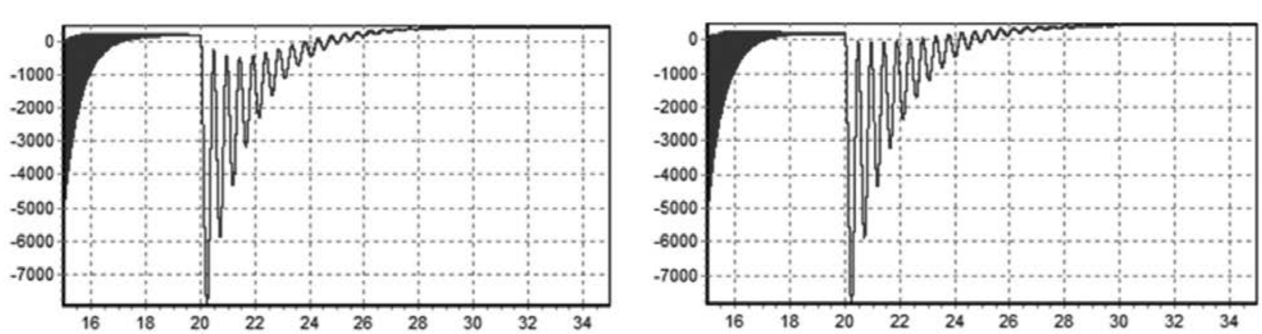
a *b*

Fig. 12. SM phase voltage envelope (B) when the generator is networked for 15 s with further load rise (20 s): *a*) stabilizer, *b*) fuzzy voltage controller



a *b*

Fig. 13. Damping winding current on *d* axis (A): *a*) stabilizer, *b*) fuzzy voltage controller



a *b*

Fig. 14. Damping winding current on *q* axis (A): *a*) stabilizer, *b*) fuzzy voltage controller

ties of excitation control system the SM operation mode under the most unfavorable conditions, a stepwise rise in load has been studied (practically, the generator operating in parallel with the network is smoothly loaded with active power due to gradual increase in power generated by turbine).

In fact, having compared the system behavior when using different types of excitement controllers, we can state that in given modes the voltage control system with fuzzy excitement controller matches the stabilizer in controlling capability. In the case of abrupt load the system with FEC provides lower maximum dynamic error of voltage control (2.2% vs. 3%) and lower static error. It should be noted that the introduction of flexible feedback by generator's excitation current in the structure of system with FEC (and in the system with stabilizer as well) is appropriate, inasmuch as it prevents deterioration of damping properties and growth of oscillability and time of transition.

CONCLUSIONS

1. To design the excitement control systems of synchronous machines it is advisable to use refined mathematic models that take into consideration a nonlinear character of synchronous machines and semiconductor converters of the excitement system.

2. A fuzzy voltage controller for the modes of initial SM excitement, networking, and stepwise changes in voltage has been designed. It matches the traditional stabilizer (ARV-SDP1) and ensures improved quality of voltage control in the above modes (lesser dynamic and static errors, no readjustment in initial excitement mode).

3. To improve quality of transition processes it is advisable to introduce a reverse feedback by excitement current derivative into the structure of voltage control system with FVC.

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СТАТИЧЕСКАЯ СИСТЕМА САМОВОЗБУЖДЕНИЯ СИНХРОННОГО ГЕНЕРАТОРА С НЕЧЕТКИМ РЕГУЛЯТОРОМ НАПРЯЖЕНИЯ

Рассмотрена система регулирования выходного напряжения генератора с синтезированным нечетким регулятором напряжения. Синтез такого регулятора проведен с использованием уточненных математических моделей, учитывающих нелинейность синхронной машины и полупроводниковых преобразователей системы возбуждения. Это отличает его от традиционных регуляторов возбуждения, синтез которых основывается на использовании упрощенных линеаризованных моделей. Представленные результаты математического моделирования позволяют сравнить регулировочные характеристики в системе с предложенным нечетким регулятором напряжения и в системе с традиционным регулятором.

Ключевые слова: синхронный генератор, система возбуждения, нечеткий регулятор.

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СТАТИЧНА СИСТЕМА САМОЗБУДЖЕННЯ СИНХРОННОГО ГЕНЕРАТОРА З НЕЧІТКИМ РЕГУЛЯТОРОМ НАПРУГИ

Розглянуто систему регулювання вихідної напруги генератора з синтезованим нечітким регулятором напруги.

Синтез такого регулятора проведено з використанням уточнених математичних моделей, які враховують нелінійність синхронної машини та напівпровідникових перетворювачів системи збудження. Це відрізняє його від традиційних регуляторів збудження, синтез яких ґрунтується на використанні спрощених лінеаризованих моделей. Наведені результати математичного моделювання дають можливість порівняти регулювальні характеристики в системі з запропонованим нечітким регулятором напруги і в системі з традиційним регулятором.

Ключові слова: синхронний генератор, система збудження, нечіткий регулятор.

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