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AUTOMATIC REGULATION OF EXCITATION OF A SYNCHRONOUS COMPENSATOR WITH BIAXIAL EXCITATION

A.Y.Bekishev[1], SH.B.Korjovov[1], N.A.Kurbanov[2]

[1]Tashkent State Technical University named after Islam Karimov, 100095, Uzbekistan, Tashkent, University St. 2A.

Gmail: qorjovovsherdor@gmail.com

Abstract: *Articledue to significant achievements of domestic research electric power organizations, engineering centers and research and production enterprises in the development and implementation of the next generations or new microprocessor, especially integrated, devices for automatic control of the normal operation of power plants and electric power systems.*

There was a need for a more detailed presentation of not only the principles of operation, but also the functioning algorithms, functional and structural diagrams and methods of technical implementation of modern domestic microprocessor automation and relay protection of electric power systems.

The purpose of the scientific work is to provide undergraduates and graduate students with educational and scientific material on new domestic microprocessor integrated automatic devices and systems, to promote advanced training of personnel at power plants and electric power systems and to introduce into operation microprocessor-based automation equipment for electric power systems in the process of its modern updating.

Modern high and ultra-high voltage power transmission lines are powerful uncontrolled reactive power generators when the transmitted active power Pr is less than natural Pnat, or consumers - when Rl>Pnag - Therefore, traditional modern reactive power generators - synchronous compensators function as controlled reversible sources, i.e. and as its consumers.

New reactor (consuming) and reactor-capacitor (reversing) static reactive power compensators, designed for connection to the buses of power stations and intermediate node substations of main power transmission lines, have been created and continue to be developed.

Reversible controlled synchronous reactive power compensators provide:

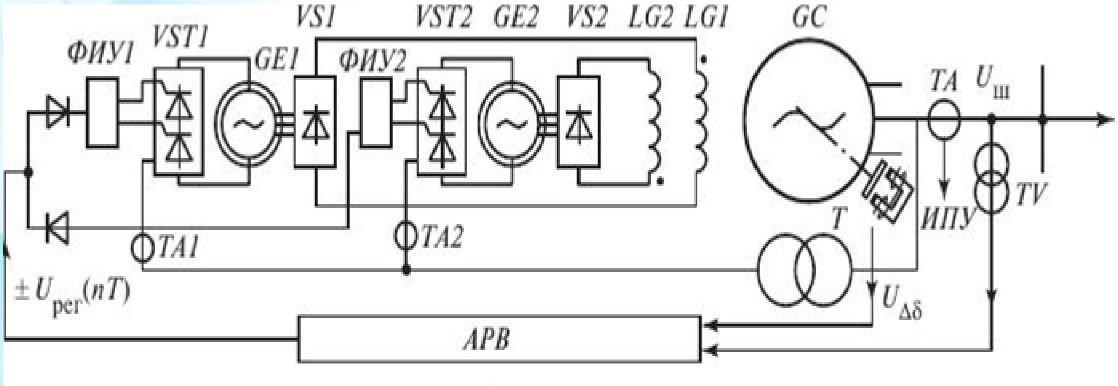
required operating modes of power lines in terms of voltage and reactive power;

effective damping of rotor vibrations (oscillations) of synchronous generators;

high limits of transmitted active power under the conditions of static and dynamic stability of the EPS;

balancing voltages and currents even in open-phase operating modes of power lines;

preventing switching overvoltages on lines and improving the conditions for extinguishing the electric arc of a single-phase short circuit when only one damaged overhead line wire is disconnected.



a)

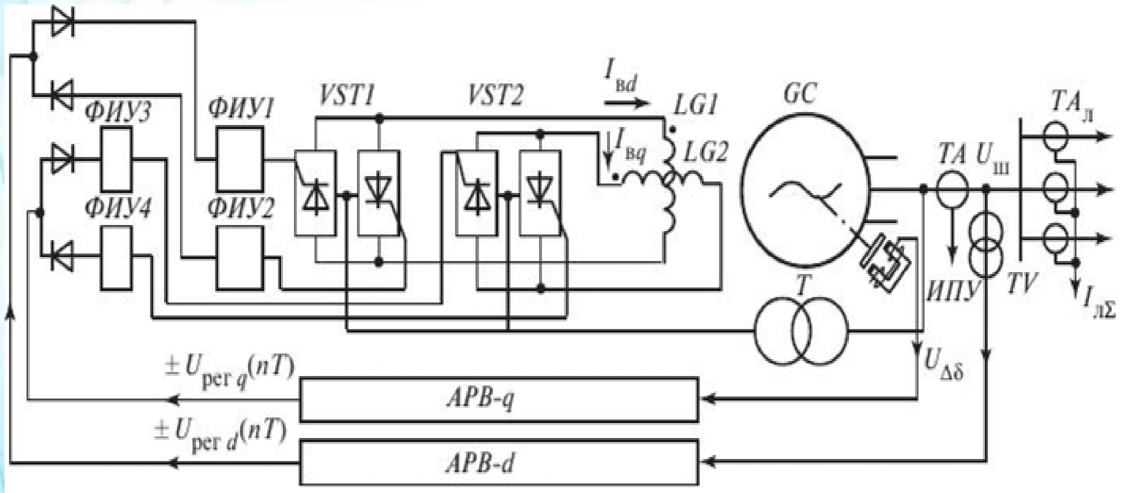


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Fig. 1. Scheme of thyristor brushless excitation (a) and excitation of a synchronous compensator with a transverse rotor winding (b)

A synchronous compensator is used in modern EPS not only as a generator of reactive power, but also as its controlled consumer. The generation (output) or consumption mode is determined by the excitation of the synchronous compensator.

Modern promising synchronous compensators GC have two excitation windings LG1, LG2, located either in parallel (Fig. 1, a) or along the longitudinal and transverse magnetic axes of the rotor (Fig. 1, b). Two parallel windings creating reverse excitation provide artificial stability of the synchronous compensator in the mode of reactive power consumption.

With brushless excitation, the rotor windings LG1, LG2 (Fig. 1, a) are connected to rotating diode rectifiers VS1, VS2, powered by two inverted synchronous generators GEI, GE2. The generators have thyristor excitation - thyristor converters VST1, VST2 are connected via transformer T to the terminals of the synchronous compensator. Thyristor converters in rectification mode through phase-pulse control devices FIU1, FIU2 (pulse shapers of thyristor switching currents) are controlled by the positive and negative influence of ±Ureg(nT) of the reversible automatic regulator and the automatic excitation regulator ARV.

In the reactive power generation mode, the control action Ureg(nT) is positive, excitation is created by the first exciter - GE1, VS1, VST1. It is proportional to the positive deviation of the substation bus voltage Ush from the prescribed value Ushpr: ΔU= Ushpr-Ush.

At voltage Uш>Unp the regulating effect Upcr(nT) is negative. In this case, VST1 closes and the second exciter - GE2, VS2, VST2 - comes into action, creating negative excitation. The synchronous compensator switches to the reactive power consumption mode and tends to fall out of synchronism: its internal angle δ increases, the information signal about the angle δ is generated by a pulse measuring angle converter IPU similar to the one previously discussed. The resulting positive or negative torques slow down or accelerate the rotor, which, vibrating, is kept in a dynamically equilibrium position close to the transverse axis.

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In this case, the field windings of the synchronous compensator only serve to hold the rotor in the specified position. The same role of holding the rotor in position along the longitudinal axis, i.e. at angle δ=0, and negative excitation, the second holding excitation winding LG2, located along the transverse axis of the rotor, performs (see Fig. 1, b). Synchronous compensators with two excitation windings - the main longitudinal and holding transverse - can be loaded with any reactive power consumption limited only by the thermal resistance of the stator windings at the rotor position angle δ=0.

Reversible excitation of a synchronous compensator with an additional rotor winding LG2 located along its transverse axis is also created by two thyristor exciters VST1, VST2 (Fig. 1, b), each consisting of two back-to-back thyristor rectifiers connected through transformer T to the terminals of the stator windings, controlled by two automatic excitation regulators ARV-d and APB-q.

The automatic regulator APB-d of the excitation current ±Iвd in the LG1 winding ensures that the voltage Ush on the buses is maintained by changing the reactive power generated or consumed by the synchronous compensator. Its regulatory effect ±Ureg(nT) is proportional to the voltage deviation on the lines Ush of the substation and the deviation UΔδ of the internal angle δ from the boundary value δgr <π/2.

The automatic regulator of the excitation current ±Iвq in the transverse winding LG2 holds the rotor of the synchronous compensator in position along the longitudinal axis, i.e. at internal angle δ=0, in reactive power consumption mode. Its regulatory effect ±Uregq is proportional to the deviation of the angle δ from the zero value UΔδ.

Automatic regulator of a synchronous compensator with two longitudinal rotor windings. The main feature of the digital automatic controller of reversible (alternating) excitation, due to ensuring artificial stability of the synchronous compensator in the mode of reactive power consumption, is the need for high-speed generation of information signals about the disconnection of the rotor angle δ from a value close to the boundary δgr = π/2. Therefore, its functional diagram (Fig. 2), in addition to the main voltage measuring element ION, contains a measuring element

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of the internal angle of the position of the longitudinal magnetic axis of the rotor of the synchronous compensator IOU.

The IOU angle measuring element uses pulse signals from the IPU angle measuring transducer (see Fig. 1), the same as on an asynchronized generator. It contains an analog memory element of the EAP (Fig. 2), which stores the instantaneous voltage value ia of phase A of the synchronous compensator at the moment of the appearance of the pulse signal u from the IPU, moving along the time axis as the angle δ changes.

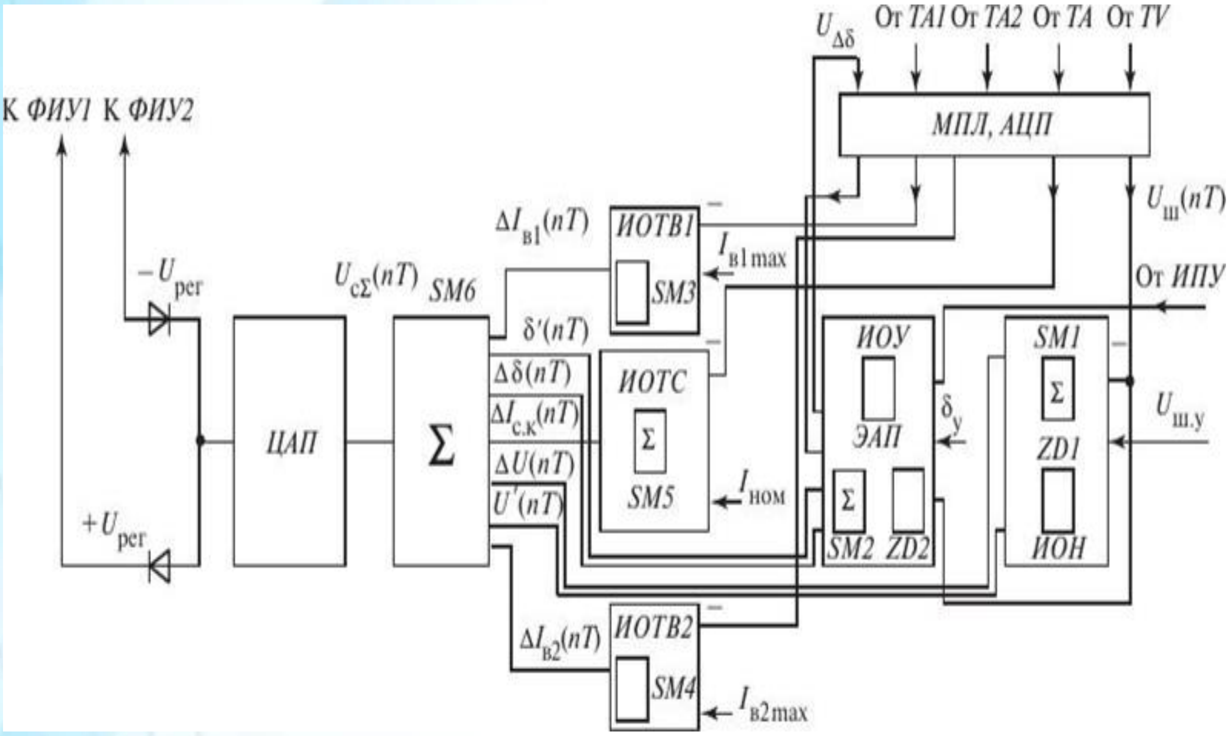

Fig. 2. Functional diagram of a digital automatic controller for reversible brushless excitation of a synchronous compensator (see Fig. 1, a)

The implementation of the main specified feature is facilitated by the measuring elements of positive and negative excitation currents IOTV1, IOTV2. The measuring and converting functional part of the regulator also includes a measuring element for the IOTS stator current.

The measuring elements are implemented by the computational functional part of the regulator, which uses digital ADC signals with a multiplexer MPL of analog signals from the primary measuring voltage transformers TV and current TA of the synchronous compensator, measuring transformers of its excitation currents TA1, TA2 and the signal UΔδ of the analog part of the IOU.

Digital information signals required for the regulator operation algorithm: about voltage deviations on the substation buses Ush from the set value ±ΔU(nT)=Ush-Ush(nT) and the angle Δδ(nT)=δy-δ(nT) of their derivatives, ensuring artificial stability synchronous compensator in the mode of consuming maximum, close to rated, reactive power; signals about the deviation of the excitation currents ΔIв1(nT), ΔIв2(nT) from the set maximum values Iв1max, Iв2max of the stator current ΔIc.к(nT) from the nominal In are generated by software elements for comparing digital signals - operations of algebraic summation SM1-SM5 and digital differentiation ZD1, ZD2.

The output digital signal UcΣ(nT) of the adder SM6 is converted by a digital-to-analog converter DAC into a continuous-discrete regulatory effect ±Upcг on the phase-pulse control elements FIU1, FIU2 (see Fig. 1, a) of the thyristor converters of the exciters of the synchronous compensator.

The functioning algorithm of the microprocessor automatic controller in z-operator form in accordance with the functional diagram is presented in the following form:

$$U_{c\Sigma}(\bar{z}) = \left(k_U + k_U^{'}\frac{1-z^{-1}}{T}\right)\cdot\Delta U(\bar{z}) + \left(k_\delta + k_\delta^{'}\frac{1-z^{-1}}{T}\right)\times$$
$$\times k_{I\text{в}}\,p\left[\Delta I_{\text{в}1}(\bar{z}) + \Delta I_{\text{в}2}(\bar{z})\right] + k_I \Delta I_{c.\text{к}}(\bar{z}) \qquad (1)$$

where ku, kδ, kIв, kI are dimensionless regulator tuning coefficients; $k_U^{'}$, $k_\delta^{'}$ - tuning coefficients with the dimension of time constant.

The corresponding (1) block diagram of the regulator is shown in Fig. 3, a. The algorithm for functioning in real discrete time nT is described by the difference equation:

$$U_{c\Sigma}(nT)=k_U\cdot\Delta U(nT)+\frac{k_U^{'}}{T}[\Delta U(nT)-\Delta U(nT-T)]+k_\delta\Delta\delta(nT)+$$
$$+\frac{k_\delta^{'}}{T}[\Delta\delta(nT)-\Delta\delta(nT-T)]+k_{I\text{в}}[\Delta I_{\text{в}1}(nT)+\Delta I_{\text{в}2}(nT)]+$$
$$+k_I\Delta I_{C.K}(nT) \quad (2)$$

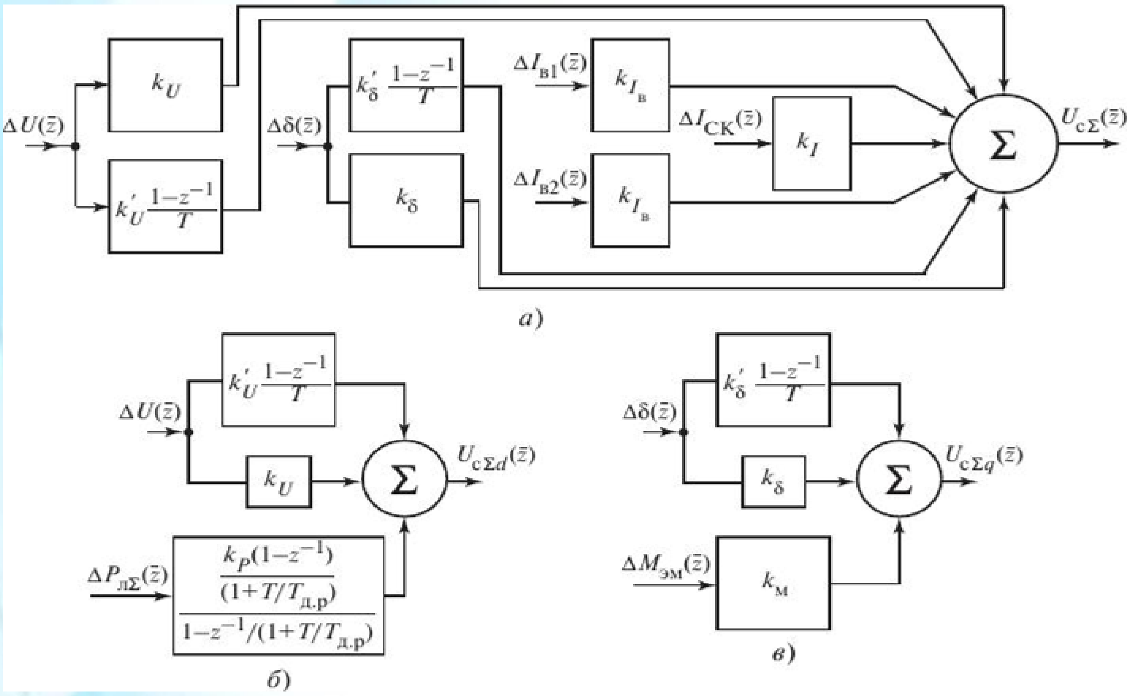

Fig.3. Block diagrams of digital automatic controllers of brushless excitation (a) - see Fig. 1, a, and excitation of a synchronous compensator with an additional transverse rotor winding (b, c) - see Fig. 1, b

Automatic control of the excitation of a synchronous compensator with a transverse rotor winding is carried out by two separate regulators ARV-d and ARV-q (see Fig. 1, b), which, unlike the two ARV channels of an asynchronized generator, do not interact with each other.

The first regulator - ARV-d has only one purpose - maintaining voltage Ush on the buses of a power plant or substation by changing the generated or consumed reactive power by a synchronous compensator. It is a PD regulator that generates a regulatory effect based on the voltage deviation ΔUsh and its derivative. Full use of synchronous compensators is achieved not only in the generation mode, but also in the consumption mode of reactive power.

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The tasks of the second APB-q controller are: maintaining the synchronous compensator in artificial stability mode when the rotor is positioned along the longitudinal axis and the negative excitation current Iвd is not limited by the condition of equality of negative electromagnetic and positive reactive torques; preventing self-oscillation of the rotor and damping its vibrations and maintaining, as indicated, the angle δ≈0. Therefore, the regulatory impact $U_{рег\_q}$ is formed by a PD controller operating based on deviations of the angle Δδ from δ = 0 and on its first and second derivatives.

The functioning algorithms of automatic regulators are determined by their purpose. The APB-d regulator ensures that the voltage Um on the busbars is maintained by changing the reactive power generated or consumed by the synchronous reactive power compensator. It is also entrusted with the task of damping the oscillations of synchronous generators of power plants by creating forced voltage oscillations on the buses with the oscillation frequency of the generator rotors with a phase that ensures effective damping.

This is achieved by using a signal based on changes in active power $\Delta P_{л\Sigma}$ in power lines formed by a real differentiating link. Regulatory Impact $U_{рег\_d}$ determined by the sum of signals indicating voltage deviation $\Delta U = U_{шу} - U_{ш}$ derivative of voltage and specified power change.

In accordance with the functional diagram of automatic regulators (Fig. 4), the indicated signals after analog-to-digital (multiplexer MPL and ADC) conversion of analog input signals of information about voltage on the substation buses - the primary measuring transformer TV (see Fig. 1, b), o the current of the synchronous compensator - the primary measuring transformer TA and the load current of the power transmission lines IlΣ (from TAl) are formed:

software functional elements of measuring elements of voltage ION, internal angle δ of the synchronous compensator IOU and measuring elements of active power of power lines IOAM and electromagnetic torque of the synchronous compensator IOEM (Fig. 4);

active power measuring converters IPAM1 and IPAM2;

elements comparing digital signals of installed (setting elements ZE1, ZE2) power and torque, voltage Ush and angle δy≈0 with their true values (adders SM1-SM4 in subtraction mode);

differentiators ZD1, ZD2, close to ideal;

real differentiator ZD3.

Adders SM5 and SM6 generate signals UcΣd(nT) and UcΣq(nT), converted by DAC1 and DAC2 into analog-discrete control actions Upepd and Uregq on phase-pulse control elements FIU1-FIU4 by thyristor converters of exciters of the synchronous compensator (see Fig. 1, b) .

The signal generated from the voltage derivative stabilizes the automatic excitation control system along the longitudinal axis, i.e. preventing its transition to an unstable self-oscillatory state due to the usually very high values of the signal amplification factor for voltage deviation (kU≈100).

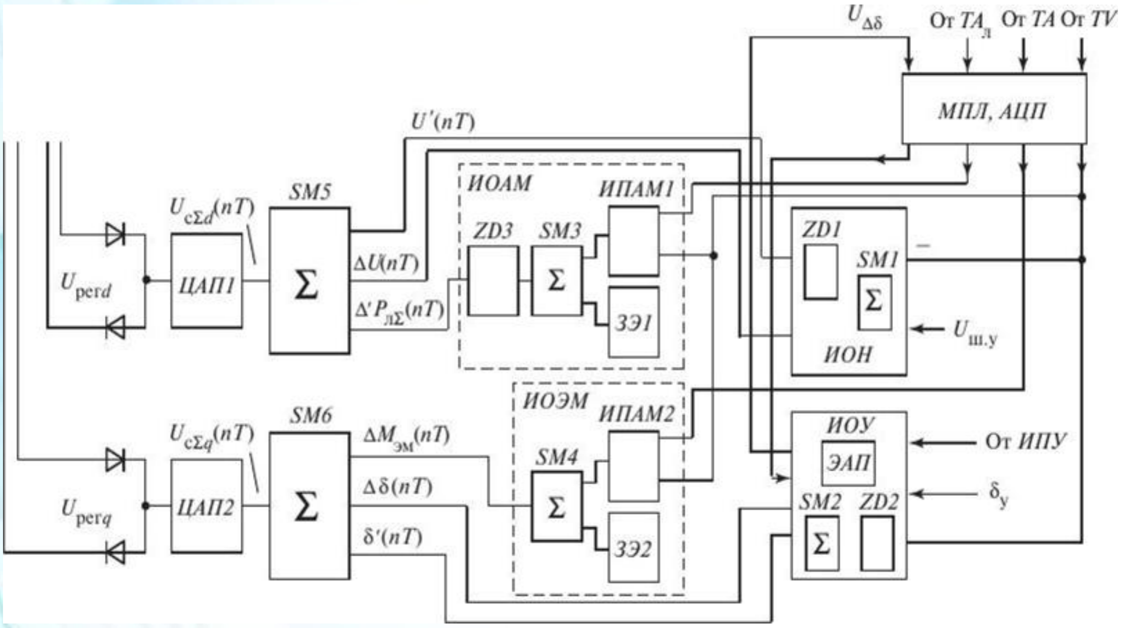

Fig.4. Functional diagram of an automatic excitation controller of a synchronous compensator with a transverse rotor winding

The algorithm for generating the output signal of digital automatic control of excitation along the longitudinal axis in z-operator form is presented as follows:

$$U_{c\Sigma d}(\bar{z})=\left(k_U+k_U^{'}\frac{1-z^{-1}}{T}\right)\cdot\Delta U(\bar{z})+$$

$$+k_p\frac{1-z^{-1}}{\left(1+\frac{T}{T_{\partial.p}}\right)\left[\frac{1-z^{-1}}{1+\frac{T}{T_{\partial.p}}}\right]}\Delta P_{л\Sigma}(\bar{z}) \quad (3)$$

Expression (3) corresponds to the block diagram of digital ARV-d (see Fig. 2, b).

The algorithm for automatic control of excitation along the transverse axis is determined by its purpose, which, as indicated, is to hold the rotor in position along the longitudinal axis, i.e. at angle δ=0, in the mode of reactive power consumption with a negative excitation current IBd of the longitudinal excitation winding LG1 and damping of rotor oscillations in the mode of artificial stability of the synchronous compensator.

Therefore, the APB-q regulator uses signals on the deviation of the angle Δδ from δ=0, its derivative and the deviation (appearance) of the electromagnetic torque - active power on the shaft of the synchronous compensator.

The algorithm for generating the output signal of digital automatic control of excitation along the transverse axis in z-operator form is as follows:

$$U_{c\Sigma q}(\bar{z})=\left(k_\delta+k_\delta^{'}\frac{1-z^{-1}}{T}\right)\cdot\Delta\delta(\bar{z})+k_M\Delta M_{ЭМ}(\bar{z}) \quad (4)$$

Expression (4) corresponds to the block diagram of ARV-q (see Fig. 3, c).

Algorithms for the functioning of microprocessor automatic regulators ARV-d and ARV-q in accordance with (3) and (4) are the following discrete time functions nT:

$$U_{c\Sigma d}(nT) = k_U \cdot \Delta U(nT) + \frac{k_U^{'}}{T}\left[\Delta U(nT) - \Delta U(nT-T)\right] + k_\delta \Delta\delta(nT) +$$
$$+ \frac{k_P}{\left(1+\frac{T}{T_{Д.Р}}\right)}\left[\Delta P_{л\Sigma}(nT) - \Delta P_{л\Sigma}(nT-T)\right] - \frac{k_P}{\left(1+\frac{T}{T_{Д.Р}}\right)}\Delta^{'} P_{л\Sigma}(nT-T) \quad (5)$$

$$U_{c\Sigma q}(nT) = k_\delta \Delta\delta(nT) + k_\delta^{'}\left[\Delta\delta(nT) - \Delta\delta(nT-T)\right] + k_M \Delta M_{ЭМ}(nT) \quad (6)$$

Where $\Delta^{'} P_{л\Sigma}(nT-T)$- discrete value of the output differentiator (power change signal of power lines) in the previous sampling interval T.

CONCLUSION

Microprocessor automatic excitation control provides:

- maintaining the power factor cosφ of the synchronous compensator or the effective voltage value at the terminals of its stator in accordance with the specified setting, with droop changing in the range from 0 to 20%;

- stable operation and effective damping of rotor swings of the synchronous compensator;

- forcing excitation when stator voltage decreases;

- limitation of the minimum excitation current in accordance with the factory characteristics of the synchronous compensator in the mode of reactive power consumption;

- limiting the excitation current according to the time impulse response when the rotor is overloaded with current;

- limitation of the limiting value of the excitation current;

- automatic continuous monitoring of the backup regulator over the setpoint of the regulator in operation, ensuring that when switching from the working to the reserve channel, the deviation of the excitation current of the reserve and operating control channels is no more than 3%.

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