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HYDRO TURBINE SPEED CONTROL SYSTEM

The article presents a mathematical model of an hydro turbine speed control system. In the world and domestic practice of creating hydraulic turbine equipment, there is a clear tendency to create computer-based rotor speed control systems for hydraulic turbines. Computer systems provide an opportunity to implement the introduction of effective algorithms using software that improve the static and dynamic characteristics of the system. This in turn increases the importance of mathematical modeling both at the design stage and during commissioning. The analysis of the performed works devoted to the mathematical description of the elements of the hydraulic drive of the regulator showed that they are reduced to linearized equations without taking into account a number of important factors that will increase the accuracy of the mathematical model. Improvement of static and dynamic characteristics and the system as a whole can be achieved by solving the scientific problem of studying its dynamics based on the development of a more complete mathematical model. To reduce friction and hysteresis, to prevent obliteration, the electrohydraulic converter plunger in the lower part is equipped with a segner wheel. Improving the dynamic characteristics of hydraulic turbine speed controllers requires the development of nonlinear mathematical models with subsequent analysis of transients in the hydraulic drive of the speed controller. Evaluation of the quality of transient processes and subsequent adjustment of parameters allows to achieve a reduction in the duration of transients, increase the speed and accuracy of positioning at small movements of the servo motor. A number of unaccounted factors during the preparation of the mathematical model of the electro-hydraulic converter makes it possible to increase its adequacy to the real object of study and increase the speed of the control system of the rotor speed of the hydraulic turbine.

Keywords: control system, runner, Kaplan hydro turbine, regulator, mathematical model, positional hydro pneumatic drive, synthesis.

О. І. ГАСЮК

СИСТЕМА КЕРУВАННЯ ОБОРОТАМИ ГІДРОТУРБІНИ

У статті надано математичну модель системи керування оборотами гідротурбіни. В світовій та вітчизняній практиці створення гідротурбінного обладнання визначилася чітка тенденція створення систем управління частотою обертання ротора гідротурбіни на базі комп'ютерів. Комп'ютерні системи відкривають можливість за допомогою програмного забезпечення реалізувати введення ефективних алгоритмів, що покращують статичні і динамічні характеристики системи. Це, в свою чергу, підвищує значимість математичного моделювання як на стадії проектування, так і під час пусконалагоджувальних робіт. Аналіз виконаних робіт, присвячених математичному опису елементів гідроприводу регулятора, показав, що вони зводяться до лінеаризованих рівнянь без урахування ряду важливих факторів, які дозволять підвищити точність математичної моделі. Покращення статичних і динамічних характеристик і системи в цілому можна досягти шляхом вирішення наукової проблеми з дослідження його динаміки на базі розробки більш повної математичної моделі. Для зниження тертя і гістерезису, унеможливлення облітерації плунжер електрогідравлічного перетворювача в нижній частині оснащений сегнеровим колесом. Поліпшення динамічних характеристик регуляторів швидкості гідротурбін вимагає розроблення нелінійних математичних моделей із подальшим аналізом перехідних процесів у гідроприводі регулятора швидкості. Оцінка показників якості перехідних процесів і подальше коригування параметрів дає змогу домогтися зниження тривалості перехідних процесів, підвищення швидкодії та точності позиціонування за малих переміщень сервомотора. Низка неврахованих чинників під час складання математичної моделі електрогідравлічного перетворювача дає змогу підвищити її адекватність реальному об'єкту дослідження і підвищити швидкодію системи керування частотою обертання ротора гідротурбіни.

Ключові слова: система керування, робоче колесо, гідротурбіна каплана, регулятор, математична модель, позиційний гідропневмопривод, синтез.

Abstract. The paper analyzes the existing control systems for hydraulic turbines and provides frequency control schemes for hydraulic turbines from leading manufacturers of hydroturbine equipment. The design features of the construction of circuits with discrete and discrete-analog control methods with an embedded computer system for controlling the speed of a hydraulic turbine, which guarantees trouble-free operation in case of load deviations and power failures, are considered. A fully automatic method for controlling a hydraulic unit is proposed, in which the computer system independently controls the turbine based on the parameters of the operation of the hydraulic unit recorded by devices in accordance with the computer control program. The analysis of the operation of the schemes is carried out, taking into account the specifics of the functioning of the control system. A nonlinear mathematical model of the hydromechanical part of the regulator is considered to assess the quality indicators of transient processes occurring during start-up, shutdown and reverse operation modes of a hydraulic turbine. The use of this mathematical model and control algorithms improves the positioning accuracy and reliability of hydropneumatic systems with the possible simplification of circuit solutions is an effective solution to control problems. A gradual study of the dynamics of the runner hydraulic drive was carried out. The obtained results prove that the use of a positional hydropneumatic drive to build a system for controlling the speed of a hydraulic turbine with discrete and discrete-analog control makes it possible to synthesize a hydropneumatic drive with high positioning accuracy.

1 Introduction. The hydraulic turbine rotor speed control system (RSCS) is designed to perform the following main functions: starting the hydraulic unit (hydro turbine and electric generator), in which the mechanisms are actuated in the desired sequence (turning the runner blades), the unit is turned around, synchronized and connected to the network); work on the power system of high power; work on an isolated (dedicated) load; stable idling; work during load shedding with disconnection of the generator from the power system, etc. A significant place in RSCS is occupied by hydraulic drives (HD), which are a set of hydraulic devices that ensure the coordinated performance of the functions of adjusting the wicket gate (WG) and the runner ® of the Kaplan turbine.

2 Literature Review. A literature review on the topic discussed in the article showed that it is relevant and considered in many works.

The work [1] considers the synthesis of a precision regulator of a hydraulic unit using the method of inverse tasks of dynamics, which makes it possible to provide a transfer function of the general control loop tending to unity, as a result, the maximum values of static and dynamic accuracy are achieved a controller, which, unlike the existing ones, does not contain differentiation contours, is proposed. It implements differential control laws.

In work [2], a mathematical model of a hydro-generator and a control unit of an electro-hydraulic control system for the synthesis of a precision controller is developed. The problem was solved using structural-parametric synthesis and optimization of automated control systems for frequency and rotational power. All is based on the solution of inverse tasks of the dynamics of the hydraulic unit, which allows to register leaks, overflows, as well as the nonlinearity of the characteristics of the servomotor. The proposed automated control system for hydro-generator units provides a two-fold increase in the accuracy of speed and power control, which improves the quality of electricity generated at hydroelectric power plants.

The work [3] is devoted to the study of the operation of controller algorithms for introducing adaptive add-ons, namely gain planning and adaptive control of the reference model, to existing speed controllers to improve network synchronization performance. Experiments show that the proposed add-ons compensate for the negative impact of head loss during network synchronization and operate close to ideal performance at nominal head.

In paper [4] the mathematical model of a hydroelectric power plant is obtained by using physical characteristics of a real-world is proposed. Then by using this model and corresponding real-world data, a set of controller parameters is designed by using tuning methodologies based on heuristic optimization algorithms, and their performances are compared with each other and with a classical tuning methodology. The results also indicate that as long as the desired performance criteria are defined as accurate as possible, the performance of the optimization algorithms is acceptable

In paper [5] mathematical model of a hydropower plant with a surge tank and medium penstock is described. The Massachusetts Institute of Technology (MIT) rule and Lyapunov method were exploited in order to improve the performance of the speed governor for frequency containment control. The active power control with frequency control was enhanced by the aforementioned adaptive control methods. Both methods perform significantly better compared to conventional proportional-integrator control. The performance of the conventional controller improved by 58,8 % using the MIT rule and by 65,9 % using the Lyapunov method. When the two adaptive control approaches were compared with each other, the MIT rule outputted better results than the Lyapunov method when the disturbance frequency was higher.

In paper [6] study of a hydraulic turbine control, considering that the gate opening depends on the velocity of the water. The behavior of the mechanical power of the turbine and speed control of the generator affected by parameter uncertainties have been simulated using the Matlab/Simulink environment.

In article [7] describe the small signal stability of the load-frequency control with hydro-turbine. The effects of parameter variation on the dynamic behavior of the power system have been investigated. Application of compensation in response water turbine with eigenvalues analysis and behavior dynamic simulation of the power system is shown. Also, using transfer function, PID controller for load-frequency control in power system is design and the change of the gains controller is investigated.

In article [8] a solution to the problem of reducing the complexity of operations and the cost of mechanical machining of tempered steels with the provision of quality indicators are of priority value in the modern hydro turbine engineering. Application of modern equipment, materials’ information and software allows increasing of hard steel processing efficiency to receive with necessary characteristics, which is possible due to the introduction of new programming tools and Industry 4.0.

3 Research Methodology.

3.1 The current state of development of the hydraulic turbine rotor speed control system. The further development of computer technology, automation tools, the elementary base of hydraulic equipment and the theory of automatic control made it possible to move on to the development and creation of more advanced control systems of hydro turbines and its components HD_{GV} i HD_R [9].

Fig. 1 shows the functional diagram of the computer RSCS developed by ALSTOM POWER HYDRO (France, Grenoble) [9, 10]. Similar systems were developed by Woodword (USA), VaTech (Austria), Voith Siemens (Germany).

Most hydraulic turbines of hydroelectric power plants (HPP) are operated with hydro mechanical and electro hydraulic speed regulators of the RK and EGRK type, which were developed and manufactured in the 50s and 60s.

These regulators are reliable in operation and maintenance, but today they are inferior to modern digital electronic regulators in terms of such parameters as the speed of the regulator's response to changes in the external load, network power frequency, the ability to diagnose the state of the regulation links and carry out fault finding, to make decisions about the economical use of hydraulic resources.

In order to solve the problem of modernizing the existing system for regulating the rotational speed of hydraulic turbines at HPPs, the "Regulator" consortium (Ukraine, Kharkiv), together with the ALSTOM POWER HYDRO company (France, Grenoble), developed, manufactured and put under load at the Dnipro Cascade

HPP digital regulators and feedback systems that allow the regulation of Francis, Kaplan and Kaplan Bulb turbines [10, 11].

The regulator provides both manual and automatic regulation of the turbine, taking into account regular and non-regular situations. The regulator is equipped with five turbine protection systems against accidents. The regulator consists of an electronic part (on-board computer), electro hydraulic converters, hydraulic actuators and feedback devices for the current and position of actuators of the I / S type.

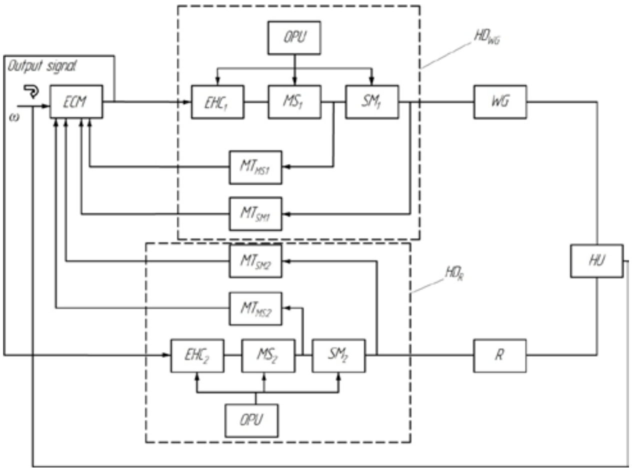

Fig. 1. Functional diagram of the computer RSCS: MT_{MS1}, MT_{MS2}, MT_{SM1}, MT_{SM2} – measuring transducers of the position of the main spool and servomotor, respectively; OPU – oil pressure unit; ECM – electronic computing machine; SM_1, SM_2 – servomotors; EHC_1, EHC_2 – electrohydraulic converters; MS_1, MS_2 – main spools; WG – wicket gate; R – runner; HU – hydraulic unit; HD_R – hydraulic drive for turning the runner blades; HD_{WG} – hydraulic drive for turning the wicket gate vanes

The speed regulator can receive a command from the speed of the turbine shaft, the position of WG or the power of the generator:

1) quick start of the hydraulic unit (hydro turbine + electric generator) and maintenance of stable operation in various operational modes;

2) automatic synchronization of the operation of the hydraulic unit and the electrical network;

3) optimization of the operation of the hydraulic unit is aimed at increasing the efficiency of control by means of collecting and processing information, controlling the amount of load and the characteristics of the hydro turbine in a wide range of heads;

4) autonomous operation of the hydraulic unit under variable and stable loads.

The computer system for regulating the speed of the hydraulic turbine guarantees trouble-free operation in case of load deviation and power failures [12].

A fully automatic way of controlling the hydraulic unit is possible, in which the computer system controls the turbine independently, based on the parameters of the hydraulic unit's operation taken into account by the sensors, in accordance with the program of the control computer. The control system constantly monitors the operation of the hydro turbine, regulates its speed according to the load and performs adequate control operations.

The control system provides communication with the operator: with the help of a personal computer keyboard, the operator can change the points of the set of actions of the system, change the control parameters and test the entire system as a whole.

The system can be equipped with automatic local control and safety devices that check the hydraulic unit, control the temperature, vibrations, register failures, etc.

In general, the computer system for regulating the speed of the hydraulic turbine is more reliable and effective than the previously installed electro hydraulic speed regulators at the Ukrainian HPPs.

3.2 Analysis of regulators. The electro-hydraulic system for controlling the frequency of rotation of the hydro turbine rotor (RSCS) "LMZ" of the EDR-211 type differs from the previous ones in the wider use of means, devices and equipment produced by the electrical, electronic and instrument-making industry [13–15].

Fig. 2 shows the functional diagram of the system and the mechanisms for generating the control signal of this modification. The set value of the adjustable frequency f_3 is applied to the input, with the help of which the necessary changes in the rotation frequency of the shaft of the hydraulic unit operating at idle speed or on an isolated load are made.

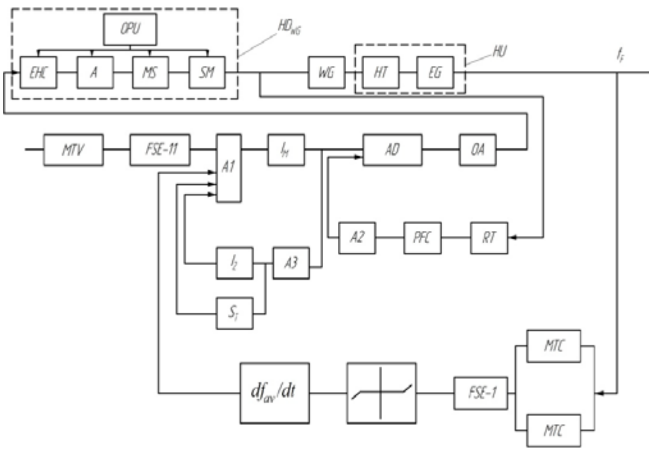

Fig. 2. Functional diagram of the electro-hydraulic RSCS of the new modification: OPU – oil pressure unit; I_M – main integrator; MTC, MTV – current and voltage measuring transformers; FSE-1, FSE-2 – frequency-sensitive elements; A, A1, A2, A3 – amplifiers; OA – output amplifier; EHC – electro-hydraulic converter; Iz – isodromic; S_T – device for changing statics; EG – electric generator; RT – rotating transformer; HT – hydro turbine; AD – adder; WG – wicket gate; HD_R – hydraulic drive for turning the runner blades; HD_{WG} – hydraulic drive for turning the wicket gate vanes; HU – hydraulic unit, PFC – phase-frequency converter; FSE-11 – frequency-sensitive element

This input signal is compared with the actual frequency on the output circuit of the electric generator f_F (measuring voltage and current transformers are used for this purpose). The mismatch signal is sent to the amplifier

A1, the integrator I_M, which are covered by the feedback signal from the electrical isodrome Iz. At the output of I_M, a task signal to change the position of the wicket gate vanes (WG) is formed. At the adder (AD), this task signal is compared with the signal of the actual position of the rod of the servomotor of the wicket gate.

The mismatch signal is sent to EHC, which causes the movement of the main spool (MS), and therefore SM, until the frequency deviation that has appeared has been worked out.

Features of the modification are: another method of measuring the actual frequency of rotation of the hydraulic unit (HU), other devices for converting the signal on the hydraulic drive (HD) and reducing the number of elements included in HD.

The normal functioning of the system is largely determined by the dynamics of its hydro mechanical part. For example, to rotate the vanes of the wicket gate (WG), it includes the oil pressure unit (OPU), the main hydraulic control valve (HV), two servomotors and the wicket gate with the corresponding measuring transducers of their position.

The mathematical model of this part contains the equation of the area of the hydraulic control valve slit

$$A_s = 2R^2\left(\alpha - \sin\alpha\right); \quad \alpha = \arccos\left(1 - \frac{X}{R}\right), \tag{1}$$

the flow equation through the pressure and drain cavities of the hydraulic control valve (HV)

$$Q_p = \mu A_s \sqrt{\frac{2\left|P_{OPU} - P_1\right|}{\rho\left[1 + \left(\dfrac{A_s}{A_c}\right)^2\right]}} \operatorname{sign}\left(P_{OPU} - P\right), \tag{2}$$

$$Q_d = \mu A_s \sqrt{\frac{2\left|P_2 - P_d\right|}{\rho\left[1 + \left(\dfrac{A_s}{A_c}\right)^2\right]}} \operatorname{sign}\left(P_2 - P_d\right); \tag{3}$$

the equation of pressures in the pressure and drain cavities of a generalized (equivalent to two) servo motor (SM)

$$\dot{p}_1 = \frac{\left(Q_p - A_{ar}\dot{x}_z\right)E}{V_{PV} + A_{ar}x_z}, \quad \dot{p}_2 = \frac{\left(A_{ar}\dot{x}_z - Q_d\right)E}{V_{DV} + A_{ar}x_z}; \tag{4}$$

the equation of motion of the servo motor rod, which rotates the vanes of the wicket gate

$$m\ddot{x}_z = A_{ar}\left(P_1 - P_2\right) - F_{fr} - \beta\dot{x}_z - F_c; \tag{5}$$

the expression that determines the movement of the spool of HV caused by the control influence from ECM when the load on the hydro turbine changes

$$x = x(t); \tag{6}$$

here R – radius of the spool of HV; μ, ρ – respectively, the coefficient of flow and density of the working fluid (WF); P_{OPU} – pressure of WF in OPU; A_c – cross-sectional area of the inlet and outlet channels of HV; E – volumetric modulus of elasticity of the working fluid (WF); V_{PV}, V_{DV} – primary volume, respectively, in the pressure and drain cavities of the servomotor; F_{fr} – force of friction of the piston and servo motor rod against the walls; m – total mass of the moving parts of the servo motor; β – coefficient of viscous friction; A_{ar} – effective area of the piston of the servo motor; x_z – movement of the servomotor rod; F_c – resistance force.

When studying the mathematical model (1)–(6) and the linear law of change $x(t)$ in the environment of the simulation package, the transient processes of the movement $x_z(t)$ during the turning the wicket gate vanes were obtained. The research formed the basis for choosing the ratio of the opening of the edges of HV and the speed of movement of the guide vanes to ensure the directive time when starting and stopping the hydraulic turbine. The graphs of transient processes taken during the adjustment of the regulator in the turbine PL20-80Z of the Kremenchug HPP showed that the digital regulator significantly improves the characteristics of the turbine with a wide change in external disturbing factors and can be the basis for further improvement of turbine regulation processes.

4 Results. To confirm the feasibility of using RSCS as a control system for the operation of hydraulic turbines, a study of the dynamics of runner HD was carried out.

The parameters of the EHC are determined, which is the first to perceive the control action from the RSCS, as an internal circuit of the system. Since the dynamic characteristics of this unit affect the operating process of the runner HD, the passage of a harmonic signal through it was investigated. For this, the VisSIM software package was used.

As a result of the research, diagrams of oscillations of the input and two variable signals were obtained (Fig. 3).

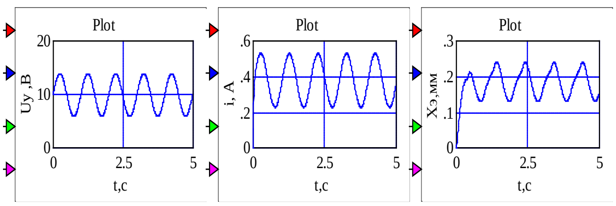

Fig. 3. The passage of the harmonic component of the input signal frequency in ω = 6,283 sec^{-1} (1 Hz)

The current curve i is practically sinusoidal. The oscillations of the spool movement are triangular and are not monoharmonic like the input signal Uy. This is due to the nonlinearities of the EHC. Steady oscillations begin one second after the transient. EHC freely passes vibrations with a frequency of 1 Hz, and is not a filter for this frequency.

With an increase in frequency to 62,83 sec^{-1} (10 Hz), the transient graphs are different (Fig. 4).

At the same amplitude of the input harmonic signal, the oscillation amplitudes have significantly decreased compared to Fig. 3 and practically stop the passage of the oscillatory component of the input signal further to the hydromechanical part of the runner HD. Thus, as the frequency of the input signal increases, the EHC becomes a filter for frequencies above f = 10 Hz.

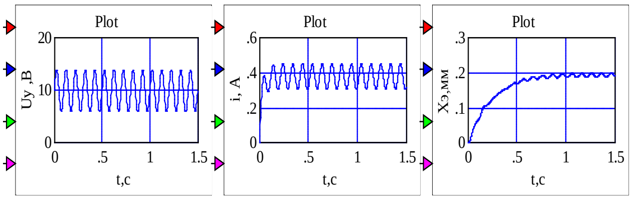

Fig. 4. Diagrams of processes of the EHC unit with the harmonic component of the input signal frequency ω = 62,83 sec^{-1} (f = 10 Hz)

The spool was examined by issuing commands to rise by 10 mm and stay in this position for 1,5 sec and lower by 10 mm. After 4,5 sec a signal is received to return the spool to its initial position. The voltage Uout.k is the input, the output is the displacement Xrz of the spool.

Fig. 5 shows oscillograms of three variables: EHD spool displacement, speed and displacement of the spool.

Thus, the curves on Fig. 5 confirm the efficiency of the input into the control circuit of the PID controller and feedback on the speed of the spool valve.

A study of the dynamics of the computing blocks of the control device, which is part of the runner HD, was also carried out.

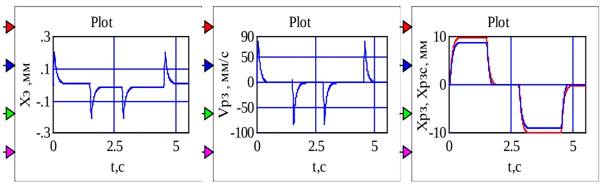

Fig. 5. Transient processes of the unit "EHD – spool valve"

Fig. 6 shows the oscillograms of six variables out of thirteen during the development of the maximum setting action, in which the SM rod traveled a path of 410 mm, and the blades turned at an angle of 37°. Then, after 25 sec there is a return to the starting position.

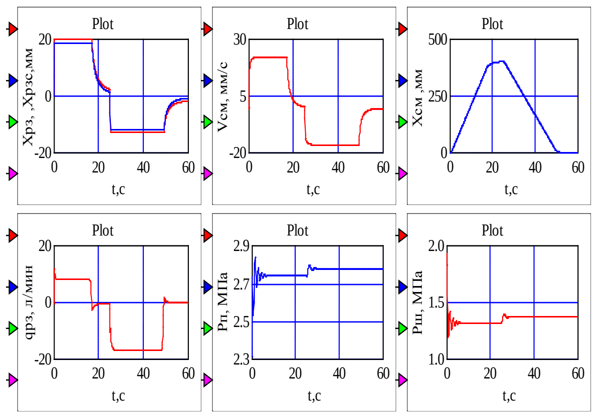

Fig. 6. Transient processes of six variables of the runner hydraulic drive at the maximum setting impact and m_o = 0,025

The analysis of transient processes (Fig. 6) confirms the normal functioning of the hydraulic drive at the maximum setting action (Xz.cm = 410 mm, electrical signal 10 V) and the resistance force on the SM rod (due to the hydrodynamics of the water flow in the runner) equal to 7000 kN.

5 Conclusion. 1. The analysis of RSCS in recent years shows a clear trend of introduction into the system of modern instrumentation and electronic equipment, including computers. This provides: on the one hand, a significant reduction in auxiliary mechanical elements (traction, levers, chains), hydraulic isodromes; on the other hand, the installation of modern measuring transducers (sensors) of rotational speed and the movement of the spools of the hydraulic control valves and servo motor rods.

2. The further development of computer technology, automation tools, the elementary base of hydro pneumatic equipment and the theory of automatic control and synthesis of positional hydro pneumatic aggregates made it possible to move on to the development and creation of more advanced control systems of hydro turbines and its components, the hydraulic drive for turning the wicket gate vanes and the hydraulic drive for turning the blades of the runner, which work according to combinatorial dependence to ensure high efficiency and stable operation of the hydro turbine.

3. A gradual study of the dynamics of the runner HD based on the developed nonlinear MM and the methodology for its implementation, starting with the EHC, then the unit "EHD – spool valve" and the hydraulic drive as a whole, allows to check: the operation and frequency characteristics of the EHC, which is the input electro-hydro device of the runner HD.

Список літератури

1. Русанов А. В., Гнєсін В. І. *Науково-технічні основи моделювання і проектування проточних частин енергетичних турбоустановок*. Харків: ІПмаш, 2019. 386 с.
2. Сокол Є., Черкашенко М., Потетенко О., Дранковський В., Гасюк О., Гриб О. *Гідроенергетика. Том 2. Гідравлічні машини*. Харків: НТУ «ХПІ», 2020. 534 с.
3. Мигущенко Р. П., Черкашенко М. В., Потетенко О. В., Гасюк А. И., Дорошенко А. В., Cherkashenko A. Системы управления гидротурбин. *Bulletin of the National Technical University "KhPI". Series: Hydraulic machines and hydraulic units.* Kharkiv: NTU "KhPI". 2019. No. 1. P. 84–97.
4. Черкашенко М. В., Вурье Б. А., Гасюк А. И., Потетенко О. В. *Синтез комбинационных схем гидропневмоавтоматики.* Germany: GMBH, 2020. 130 с.
5. Канюк Г. И., Мезеря А. Ю., Мельников В. Е. Параметрический синтез астатического регулятора САР частоты вращения гидротурбины на основе решения обратной задачи динамики. *Адаптивні системи автоматичного управління*. 2018. № 1 (32). С. 68–77.
6. Kanjuk G., Mezerya A., Melnykov V., Antonenko N., Chebotarev A. Improving the quality of electric energy at hydrogenerator units by upgrading control systems. *Eastern-European Journal of Enterprise Technologies*. 2018. Vol. 6, no. 2 (96). P. 70–78.
7. *Руководство по эксплуатации регулятора скорости ALSTOM радиально-осевой гидротурбины*. Гренобль, 2011. 206 с.
8. Mahdavian M., Shahgholian Gh., Janghorbani M., Soltani B., Wattanapongsakorn N. Load frequency control in power system with hydro turbine under various conditions. *12th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON)*

(24–27 June 2015, Hua Hin, Thailand). IEEE, 2015. P. 1–5, doi: 10.1109/ECTICon.2015.7206938
9. Qu F., Guo W. Coupling transient behavior of primary frequency regulation of hydropower plant. *Sustainable Energy Technologies and Assessments*. 2022. Vol. 52, part C. Article 102227. doi: 10.1016/j.seta.2022.102227
10. Черкашенко М. В., Потетенко О. В., Гасюк О.І., Пермяков О. А., Панамарьова О. Б., Олексенко Ю. Ю. Пат. 152023, Україна. *Гідропневмопривод*. 2022.
11. Chelabi M. A., Saga M., Kuric I., Basova Y., Dobrotvorskiy S., Ivanov V., Pavlenko I. The effect of blade angle deviation on mixed inflow turbine performances. *Applied Sciences.* 2022. Vol. *12*, issue 8. P. 3781. doi: 10.3390/app12083781
12. Sokol Ye., Cherkashenko M. *Syntesis of control schemes of drives system*. Kharkiv: NTU "KhPI", 2018. 120 p.
13. Черкашенко М. В., Сериков А. Д., Сальга Т. С., Фатеев А. Н., Фатеева Н. Н., Радченко Л. Р. *Позиционные гидропневмоагрегаты.* Харьков: НТУ «ХПИ», 2015. 115 с.
14. Черкашенко М. В., Гасюк О.І., Хавін Г. Л. Пат. 152026, Україна. *Гідропневмопривод*. 2022.
15. Adegbuyi P. Hydraulic and pneumatic cylinder failures, the effect of fluid cleanliness on component life. *Hidraulica*. 2013. No. 1. P. 27–30.

References (transliterated)

1. Rusanov A. V., Hnyesin V. I. *Naukovo-tekhnichni osnovy modelyuvannya i proektuvannya protochnykh chastyn enerhetychnykh turboustanovok* [Scientific and technical bases of modeling and designing of flowing parts of power turbo installations]. Kharkiv, Ipmash Publ., 2019. 386 p.
2. Sokol Ye., Cherkashenko M., Potetenko O., Drankovs'kyy V., Hasyuk O., Hryb O. *Hidroenerhetyka. Tom 2. Hidravlichni mashyny* [Hydropower engineering. Vol. 2. Hydraulic machines]. Kharkiv, NTU "KhPI" Publ., 2020. 534 p.
3. Migushchenko R. P., Cherkashenko M. V., Potetenko O. V., Gasyuk A. I., Doroshenko A. V., Cherkashenko A. Sistemy upravleniya gidroturbin [Hydraulic turbin control systems]. *Bulletin of the National Technical University "KhPI". Series: Hydraulic machines and hydraulic units.* Kharkiv, NTU "KhPI" Publ., 2019, no. 1, pp. 84–97.
4. Cherkashenko M. V., Vur'e B. A., Gasyuk A. I., Potetenko O. V. *Sintez kombinatsionnykh skhem gidropnevmoavtomatiki* [Synthesis of combinatorial schemes of hydropneumoautomatics]. Germany, GMBH Publ., 2020. 130 p.
5. Kanyuk G. I., Mezerya A. Yu., Mel'nikov V. E. Parametricheskiy sintez astaticheskogo regulyatora SAR chastoty vrashcheniya gidroturbiny na osnove resheniya obratnoy zadachi dinamiki [Parametric synthesis of an astatic regulator of the automatic control system of the turbine speed based on the solution of the inverse problem of dynamics]. *Adaptyvni systemy avtomatychnoho upravlinnya*. 2018, no. 1 (32), pp. 68–77.
6. Kanjuk G., Mezerya A., Melnykov V., Antonenko N., Chebotarev A. Improving the quality of electric energy at hydrogenerator units by upgrading control systems. *Eastern-European Journal of Enterprise Technologies.* 2018, vol. 6, no. 2 (96), pp. 70–78.
7. *Rukovodstvo po ekspluatatsii regulyatora skorosti ALSTOM radial'no-osevoy gidroturbiny* [ALSTOM radial-axis hydraulic turbine speed regulator manual]. Grenoble, 2011. 206 p.
8. Mahdavian M., Shahgholian Gh., Janghorbani M., Soltani B., Wattanapongsakorn N. Load frequency control in power system with hydro turbine under various conditions. *12th International Conference on Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology (ECTI-CON) (24–27 June 2015, Hua Hin, Thailand).* IEEE Publ., 2015, pp. 1–5, doi: 10.1109/ECTICon.2015.7206938
9. Qu F., Guo W. Coupling transient behavior of primary frequency regulation of hydropower plant. *Sustainable Energy Technologies and Assessments*. 2022, vol. 52, part C, article 102227. doi: 10.1016/j.seta.2022.102227
10. Cherkashenko M. V., Potetenko O. V., Hasyuk O. I., Permyakov O. A., Panamar'ova O. B., Oleksenko Yu. Yu. *Hidropnevmopryvod* [Hydraulic pneumatic drive]. Patent UA, no. 152023, 2022.
11. Chelabi M. A., Saga M., Kuric I., Basova Y., Dobrotvorskiy S., Ivanov V., Pavlenko I. The effect of blade angle deviation on mixed inflow turbine performances. *Applied Sciences.* 2022, vol. *12*, issue 8, p. 3781. doi: 10.3390/app12083781
12. Sokol Ye., Cherkashenko M. *Syntesis of control schemes of drives system*. Kharkiv, NTU "KhPI" Publ., 2018. 120 p.
13. Cherkashenko M. V., Serikov A. D., Salyga T. S., Fateev A. N., Fateeva N. N., Radchenko L. R. *Pozitsionnye gidropnevmoagregaty* [Positional hydropneumatic units]. Kharkov, NTU "KhPI" Publ., 2015. 115 p.
14. Cherkashenko M. V., Hasyuk O. I., Khavin H. L. *Hidropnevmopryvod* [Hydraulic pneumatic drive]. Patent UA, no. 152026, 2022.
15. Adegbuyi P. Hydraulic and pneumatic cylinder failures, the effect of fluid cleanliness on component life. *Hidraulica*. 2013, no. 1, pp. 27–30.

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