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OPTIMIZATION OF DIRECT QUALITY INDEXES OF AUTOMATIC CONTROL SYSTEMS OF STEAM GENERATOR PRODUCTIVITY

The system of automatic control of the productivity of the PGV-1000 steam generator of the power unit of the nuclear power plant with the WWER-1000 reactor is considered. This control system includes a system for automatically controlling the water level in the steam generator. The error signal, which is fed to the input of the productivity controller, is generated by the signal of the specified speed of the drive turbine, as well as pulses from the thermal power sensor and from the water and vapor pressure sensors. Based on the model of the water level control system in the steam generator, mathematical models of performance control systems have been developed under various control laws. To formulate optimization tasks for performance management systems, vectors from variable parameters of performance controllers are formed, constraints on these parameters are imposed, constraints are created for the areas of system stability, direct indexes of system quality are introduced, and a vector objective function is created that takes into account all imposed restrictions and quality criteria. Computational experiments on optimizing the controllers of productivity control systems were performed on the basis of direct quality indexes of systems by modified methods of step adaptation and Nelder – Mead. Analysis of the results of optimization of performance control systems allows us to conclude that, in comparison with the minimization of integral quadratic estimates, the optimization of direct quality indexes has made it possible to substantially improve the speed of the systems. The greatest value of the control time takes place for the differential controller, and the smallest identical values – for the proportional-integral and proportional-integral-differential regulators. Theoretically, the expediency of using a more simple proportional-integral controller in the steam generator productivity control system is justified. Additional analysis of the state variables in the productivity control system and comparison of transients before and after optimization allows us to conclude that the maximum deviation of the water level in the steam generator has decreased and its oscillations have disappeared. Also, fluctuations in water flow disappeared, the maximum deviation and oscillation of the control error decreased substantially, the overshoot and oscillations of other state variables practically disappeared. Thus, the optimization of the quality indexes of the automatic control system of the steam generator’s productivity has made it possible to significantly improve the main processes in it.

Keywords: the steam generator of the nuclear power plant, the regulator of steam generator productivity, the automatic control system, the mathematical model, the direct quality indexes, the vector objective function, the optimization method.

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ОПТИМИЗАЦІЯ ПРЯМИХ ПОКАЗНИКІВ ЯКОСТІ СИСТЕМ АВТОМАТИЧНОГО КЕРУВАННЯ ПРОДУКТИВНОСТЮ ПАРОГЕНЕРАТОРА

Розглянуто систему автоматичного управління продуктивністю парогенератора ПГВ-1000 енергоблока атомної електричної станції з реактором ВВЕР-1000. Ця система управління включає систему автоматичного управління рівнем води в парогенераторі. Сигнал помилки, який надходиться на вход редуктора продуктивності, формується сигналом заданої частоти обертання приводної турбіни, а також імпульсами з датчика теплової потужності та з датчиків тиску води і пари. На підставі моделі системи управління рівнем води в парогенераторі розроблені математичні моделі систем управління продуктивністю при різних законах регулювання. Для постановки задач оптимізації систем управління продуктивністю сформовані вектори змінних параметрів регуляторів продуктивності, накладені обмеження на ці параметри, сформовані обмеження для областей стійкості систем, введені прямі показники якості систем і сформована векторна цільова функція, яка враховує всі введені обмеження і критерії якості. Проведено обчислювальні експерименти з оптимізації регуляторів систем управління продуктивностю на підставі прямих показників якості систем модифікованими методами адаптації кроку і Нелдера – Міда. Аналіз результатів оптимізації систем управління продуктивністю дозволяє зробити висновок, що в порівнянні з мінімізацією інтегральних квадратичних оцінок оптимізація прямих показників дозволила значно підвищити швидкодію систем. На основі проведеного додаткового аналізу змінних стану в системі управління продуктивністю парогенератора більш простого пропорційно-інтегрального регулятора. Теоретично обґрунтовано доцільність застосування в системі управління продуктивністю парогенератора більш простого пропорційно-інтегрального регулятора. Додатковий аналіз змінних стану в системі управління продуктивністю і порівняння переходних процесів до і після оптимізації дозволяє зробити висновок, що зменшилося максимальне відхилення рівня води в парогенераторі та знижено його коливання. Також зникли коливання витрати води, істотно знизились максимальне відхилення і коливання інших змінних стану. Таким чином, оптимізація показників якості систем автоматичного управління продуктивністю парогенератора дозволила істотно поліпшити основні процеси, котрі в ній протікають.

Ключові слова: парогенератор атомної електростанції, регулятор продуктивності парогенератора, система автоматичного управління, математична модель, прямі показники якості, векторна цільова функція, метод оптимізації.

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ОПТИМИЗАЦІЯ ПРЯМИХ ПОКАЗАТЕЛІВ КАЧЕСТВА СИСТЕМ АВТОМАТИЧНОГО УПРАВЛІННЯ ПРОДУКТИВНОСТЬЮ ПАРОГЕНЕРАТОРА

Розглянуто систему автоматичного управління продуктивністю парогенератора ПГВ-1000 енергоблока атомної електричної станції з реактором ВВЕР-1000. Ця система управління включає систему автоматичного управління рівнем води в парогенераторі. Сигнал помилки, який надходиться на вход регулятора продуктивності, формується сигналом заданої частоти обертання приводної турбіни, а також імпульсами з датчика теплової мощності та з датчиків тиску води і пари. На основі моделі системи управління рівнем води в парогенераторі розроблені математичні моделі систем управління продуктивністю при різних законах регулювання. Для постановки задач оптимізації систем управління продуктивністю сформовані вектори змінних параметрів регуляторів продуктивності, накладені обмеження на ці параметри, сформовані обмеження для областей стійкості систем, введені прямі показники якості систем і сформована векторна цільова функція, яка враховує всі введені обмеження і критерії якості. Проведено обчислювальні експерименти з оптимізації регуляторів систем управління продуктивностю на підставі прямих показників якості систем на основі різних законів регулювання.

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proportionally-integral and proportionally-integral-differential regulators. Theoretically based was a comprehensive approach to the system of steam generator productivity. The developed generator was an integral part of the power unit. Additionally, the design was optimized with the aim to improve system efficiency and reliability.

Introduction. Water feeding department of the steam generator (SG) of the power-generating unit of the nuclear power plant equipped with a WWER reactor, is a critical element of heat schedule [1–5]. Its reliable and efficient work provides reliability and efficiency of work of a power-generating unit [2, 3, 6]. The steam generator control is performed by two main automatic control systems (ACS): ACS of the water level in the SG (LACS), and ACS of the feeding department productivity (PACS), including LACS [6]. Synthesis of optimal control schedules of the steam generator PGV-1000, which is included in the composition of WWER-1000 equipped NPP power-generating units, is a non-resolved task relevant with modernization of running power-generating units of the energy system of Ukraine.

The optimal PACS synthesis task for SG PGV-1000 is a task of multi-criteria optimization and includes setting of varying variables, forming of the ACS quality parameters and restriction of varying parameters [7–9]. The varying parameters are the parameters of the ACS regulators, the quality criteria are the direct quality indexes (DQI) of the ACS. The conditions of technical workability of the systems in a form of two-sided inequalities and the ACS stability condition are superimposed on the varying parameters.

Publications review. In the present time, a general methodic is developed for ACS many-criteria synthesis of the NPP power-generating unit based on models and techniques of the ACS quality criteria optimization [10]. For the ACS quality criteria optimization, the OPTLAB laboratory is used, including variety of one-dimensional and many-dimensional optimization techniques [10, 11].

The NPP power-generating unit ACS mathematical models are represented in the form of the differential equations systems (DESs). Those systems are stiff and for their solution, the matrix integrating techniques are developed [11].

The controlled value transition process quality is estimated by the quality numerical indexes, direct and indirect. By the DES integrating, a transition process graph is plotted, where the DQI are determined: over-regulation, oscillations factors, regulation time [11]. The indirect quality ACS factors are calculated simpler than DQI, without the DES integrating. They include integral quadratic estimates (IQEs), that are expressed by an integral from the regulation mistake function square and gives uniform numerical quality indicator characterizing the over-regulation and damping rate of the transition process in aggregate [10, 11].

During the ACS quality indexes optimization, it is necessary to consider variety of restrictions of varying parameters, including the technical feasibility restrictions and the ACS stability conditions. For a consistent accounting of all the restrictions, a step-by-step approach is proposed for the IQE and DQI optimization tasks [10, 11]. Such approach realization is based on the optimization of vector objective functions [11].

The mathematic models of the LACS and PACS of the SG are developed [10]. An identifying of the NPP power-generating unit SG PACS parameters is performed by the experimental characteristics [12]. Multi-criteria synthesis of the SG PACS is performed through the minimization of the IQE [10]. The SG PACS synthesis by the DQI isn’t described in any of the analyzed sources.

Research models and techniques. SG PACS is designed to regulate the feeding water consumption in the steam generator, maintain a balance between the feeding water pressure and pressure of the steam supplied into the turbine. The PACS basic diagram is presented at the Fig. 1. The PACS is three-impulse: error signal fed at the productivity regulator (PR) enter is formed by the signal of the driving turbine rotation frequency master \( \omega_d \) and impulses from the heat capacity \( Q_e \) and from the gauges of water pressure \( P_w \) and steam pressure \( P_s \). The productivity regulator signal influences the actuating device (PAD) changing the variable \( m_d \) of the steam feeding regulating valve (SFRV) with discharge flow \( G_d \) for the driving turbine. By the rotation frequency change \( \omega_d \) of the driving turbine, the feeding turbo pump (FTP) productivity changes, where the feeding water with discharge \( G_p \) is applied. From the FTP, the feeding water through tubes passes the high pressure heater (HPH) and is supplied at the feeding valve regulator (FVR). The FVR is driven by the level regulator (LR). The error signal fed at the LR enter, is formed by the level master signal \( H_{LR} \), level master impulses \( H \) and from the water discharge \( G_w \) and steam discharge \( G_s \) gauges. The feeding regulator signal influences the level actuating device (LAC) changing the \( m_w \) variable of the FVR. The ACS input actions are the heat carrier heat capacity \( Q_c \), variable \( \omega_d \) of the turbine regulating valve (TRV), the driving turbine rotation frequency \( \omega_d \), steam discharge \( G_d \) to the driving turbine and the feeding water discharge \( G_p \).

Basing on the steam generator level ACS model with PI regulating law, the mathematic models of the SG PACS are developed with various regulating laws, and the model parameters identifying with PI regulators is performed [10, 12]. Let’s calculate parameter values of the SG PACS by the steam generator ACS DQI optimization with objective of choice of most efficient productivity regulator of minimal complexity.
To set the problem of the PACS parameters optimization, form the vector $x \in R^p$ of the PR varying parameters $K_p$, $\lambda_i$ and $\lambda_D$. Depending of the productivity regulator type $p \in \{1, 2, 3\}$: for a proportional (P), integral (I) and differential (D) regulators $p = 1$, for PI, ID and PID regulators $p = 2$, for a PID regulator $p = 3$. For a PR parametric synthesis under a disturbing action $u_s$ and outgoing variable of the feeding water flow $g_w$ let’s represent a PR PACS model in the form:

$$\frac{dX}{dt} = AX + B_u\varphi_s + B_d q + B_u u_s, \ g_w = C_g X. \quad (1)$$

The matrix and model vectors parameters (1) are obtained on the basis of experimental processes and corresponds to the different regulators types [10, 12].

Apply the restrictions on the varying parameters: $a_i \leq x_i \leq b_i, i = 1, p$. Using the cut-off operation $[y] = \text{max}(y, 0)$ form the penalty function

$$S(x) = \sum_{i=1}^{p} \left[|a_i - x_i| + |x_i - b_i|\right].$$

To account the PACS stability by its model stage matrix $A(x)$ form the characteristic polynomial $\sigma(x, s) = \sum_{i=0}^{n} a_i(x) s^{n-i}$ and calculate the Routh table first column factor $\rho_k(x), k = 0, n$. Determine the PACS stability region:

$$a_i(x) > 0, i = 0, n, \ \rho_k(x) > 0, k = 2, n - 1. \quad (3)$$

The first inequalities group violation stage (3) represent by a penalty function

$$P(x) = \sum_{i=0}^{n} [-a_i(x)]. \quad (4)$$

DQI are the over-regulation $\sigma(x)$, oscillations range $\zeta(x)$, regulation time $t_c(x)$ and its relative value $\tau(x) = t_c(x)/T_c$. Regulation time must be minimal under the system stability and the factors restrictions:

$$\sigma(x) \leq \sigma_m, \ \zeta(x) \leq \zeta_m, \ \tau(x) \rightarrow \min. \quad (5)$$

All the inequalities correspond with the restrictions fulfillment regions:

$$G_1 = \{x|a_i \leq x_i \leq b_i, i = 1, p\},$$
$$G_2 = \{x|a_i(x) > 0, i = 0, n\},$$
$$G_k = \{x|\rho_k(x) > 0\}, k = 0, n,$$
$$G_{n+1} = \{x|\sigma(x) \leq \sigma_m\}, G_{n+2} = \{x|\zeta(x) \leq \zeta_m\}.$$

Form a system of quasi-allowable regions from them:

$$D_1 = G_1, \ D_k = D_{k-1} \cap G_k, k = 2, n + 2.$$

Build the non-intersecting regions of the restrictions levels:

$$H_0 = R^p \setminus D_1,$$
$$H_k = D_k \setminus D_{k+1}, k = 1, n + 1,$$
$$H_{n+2} = D_{n+2}.$$

Introduce the factors deviations $\Delta\sigma(x) = \sigma(x) - \sigma_m$, $\Delta\zeta(x) = \zeta(x) - \zeta_m$. Basing on the functions (2)–(5) we form the two-dimension multilevel objective function

Fig. 1. Steam regulator ACS basic diagram
This vector function in the form of \( F(x) = (F_1(x); F_2(x)) \) considers two-sided restrictions of varying parameters, necessary and sufficient conditions of the ACS steadiness and the demands for its DQI. For the optimization task solution of the SG PACS regulator parameters the function (6) will be optimized considering the priority of its components: the first component \( F_1(x) \) is a level function, with maximizing priority, and the second \( F_2(x) \) – the penalty function – is minimizing \[10, 11\]. For the function (6) optimization, modify the methods of unconditional minimization by introduction of the “better” operation \(<\) for two values of the function (6) \( U = (U_1, U_2) \) and \( V = (V_1, V_2) \) \[10, 11\]:

\[
U < V = \begin{cases} 
1, & U_1 > V_1 \lor U_1 = V_1 \land U_2 < V_2, \\
0, & U_1 > V_1 \lor U_1 = V_1 \land U_2 \geq V_2.
\end{cases}
\]

The methods of unconditional optimization, solving the optimization task for multilevel function (6) are modified, where the usual scalar comparison \(<\) is replaced for the “better” operation \(<\) by the formula (7). For the research, the one-dimension search step adaptation method and multi-dimension optimization Nelder – Mead method are chosen \[11\].

**Calculation experiments of the control systems synthesis methods.** Perform SG PACS analysis with productivity regulators various types by model (1) under disturbing action \( u_s = 1(t) \). Form function (6), impose two-sided restrictions on varying parameters values: \( a_i \leq x_i \leq b_i, a_1 = 0, b_1 = 100, i = 1, p \). For obtaining of the optimum processes with minimal regulation time, set the DQI restrictions: the maximum deviation value of the water flow variable \( \sigma_m = 1 \), permissible value of the system’s variability \( \xi_m = 0.65 \), DES (1) integrating by matrix method \[11\] with input parameters values – integration time \( T_{mf} = 500s \), integration steps quantity \( L = 200 \), process established value \( \gamma_w = 1 \), regulation time interval parameter \( \delta_x = 0.05 \), calculate the DQI value, form the function (6) and optimize it by the modified numerical method.

The function (6) optimization graphs for PACS with PI regulator modified by the Nelder – Mead method are represented at the Fig. 2 and 3. The varying parameters are \( x_1 = K_p \) and \( x_2 = \lambda_0 \). All the search points are shown by the thin line, the better points – by thick line, the initial point is marked by a circle, the final – by a rhombus. Fig. 2 reflects the level function \( F_1(x) \) optimization process and permits to conclude that in the final point all the restrictions of the optimization task are fulfilled. Fig. 3 reflects the penalty function \( F_2(x) \) minimization process and shows that the regulation time minimum point is obtained.

**The control systems synthesis results.** The PACS synthesis results by the function (6) optimization with different varying regulators parameters P, I, D, PI, PD, ID and PID are presented in the table 1, where the PR types are represented, the function \( N_f \), calculations quantity, regulators optimal parameters \( K_p^*, \lambda_1^*, \lambda_2^* \), and also corresponding function values (6) \( F_1^* \) and \( F_2^* \), index of oscillation \( \zeta^* \), regulation time \( t_r^* \). Those results show that all restrictions of the optimization task of the regulators parameters and DQI restrictions are fulfilled at the optimal points, maximum regulation time values \( t_r^* \) are obtained, which will permit to comparison the regulators efficiency.
Table 1 – DQI SG PACS optimization results

| PR | Np | \( K_p \) | \( \lambda^*_f \) | \( \lambda^*_p \) | \( F^*_f \) | \( F^*_p \) | \( \zeta^* \) | \( t^*_f \) |
|----|----|--------|----------------|----------------|-----------|-----------|----------|--------|
| P  | 62 | 61,143 | –               | –              | 16        | 0.3708    | 0.54     | 185    |
| I  | 62 | –     | 0.8356         | –              | 17        | 0.3151    | 0.65     | 157    |
| D  | 76 | –     | –              | 100            | 17        | 1.3071    | 0.26     | 653    |
| PI | 377| 16,0178| 0.3741         | –              | 17        | 0.2635    | 0.65     | 131    |
| PD | 345| 63,6232| 0.0047         | 22,0041        | 17        | 0.3691    | 0.54     | 185    |
| ID | 308| –     | 0.6714         | –              | 18        | 0.2788    | 0.65     | 140    |
| PID| 606| 15,6927| 0.3886         | –              | 18        | 0.2625    | 0.65     | 131    |

Fig. 4. The feeding water flow change

The function (6) optimization modified methods permit to solve all the synthesis tasks of the optimum SG PACS with various PR types. To optimize PRs with one variable parameter, a modified method is used of step adaptation, and for the PR optimization with several varying parameters – the Nelder – Mead modified method. Authenticity of obtained results of the optimal SG PACS synthesis is confirmed by successful solution of a number of analogous synthesis tasks for another ACS of a NPP power-generating units by different optimization techniques [10, 11].

The optimum SG PACS synthesis results, presented in the table 1, permits to make the following conclusions. Comparing to the IQE minimization, the DQI optimization permits to increase significantly the SG PACS performance speed. The maximum regulation time \( t^*_f \) happens for the D regulator, and the minimal similar values – for PI and PID regulators. The practicability of the PI regulator in the SG PACS is theoretically grounded, because the PI regulator is simpler than PID regulator.

The stage variables change additional analysis in the SG PACS and comparison of the transients before and after the optimization permits to conclude that the maximum deviation of the SG water level variable decreased and its oscillations vanished. Also, the water flow variables oscillations, FTP and HPH pressures vanished, maximum deviation and error oscillations significantly decreased, over-regulation and the FVR and PAD variables oscillations virtually vanished. Thus, the PACS quality indexes optimization permits significant enhancement of the main regulating processes happening inside it [10]. The considered methodic for the optimum ACS synthesis can be recommended also for synthesis of the other complicated control systems.

**Conclusions.** The PGV-1000 SG of an NPP power-generation unit with a WWER-1000 reactor productivity optimal automatic control systems synthesis task is solved. Basing on the ACS of the SG level, a SG productivity ACS general mathematical model is considered in the state space with relative variables and various regulators, intended for a PACS parametric synthesis. The further development is achieved by the models and methods of parametric synthesis of the SG control systems basing on the ACS models with utilization of optimization methods, which permit to increase quality of the main processes in the productivity control system. The PACS quality indexes system permit to enhance significantly the main control processes emerging inside it. At the first time, basing on comparison of the various PRs inside the SG PACS, the practicability of the PI regulator utilization is theoretically justified. The practical significance of the obtained results lies in the fact that to enhance the quality of the NPP steam generator control processes in normal operation modes, the mathematical models of the automatic control systems in the stages space of the PGV-1000 steam generator productivity. The multi-criteria parametric synthesis of control systems methods based on the modification of the one-dimension and multi-dimension optimization methods are considered. Further research is recommended to perform into the direction of the mathematical models enhancement for the control systems of the steam generator feeding department and optimal systems synthesis. Further research is recommended to perform in the direction.

**References**

1. Иванов В. А. Регулирование энергоблоков. Ленинград: Машиностроение, 1982. 311 с.
2. Иванов В. А. Эксплуатация АЭС: учебник для вузов. Санкт-Петербург: Энергоатомиздат, 1994. 384 с.
3. Демченко В. А. Автоматизация и моделирование технологических процессов АЭС и ТЭС. Одесса: Астроинпринт, 2001. 305 с.
4. Денисов В. П., Драгунов Ю. Г. Рекуперативные установки ВВЭР для атомных электростанций. Москва: ИздАТ, 2002. 480 с.
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