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BASIC BASES OF CALCULATIONS AND OPTIMIZATION OF NPP POWER UNIT EQUIPMENT PARAMETERS METHODS OF MATHEMATICAL MODELLING

The materials of the article consider the optimization of certain parameters and characteristics of the equipment of NPP power units, which are closely related to the processes of their design and construction. Modern NPP power units are complex technical systems. They include a set of interconnected equipment for different technological purposes, which ensures the performance of power units of a complex function of electricity production and heat of the specified quality and according to a given load schedule. Complete mathematical models of the functional state of steam turbine power units are characterized by a large number of nonlinear connections and contain implicit functions. This complicates their widespread use to solve problems of systematic analysis of the quality of operation of power units. The aim of the work is to analyze the basic theoretical foundations, methods and approaches to the calculation and optimization of the parameters of the equipment of NPP power units by methods of mathematical modeling. The solution of the problem of optimization of NPP power unit parameters includes the following stages: selection of optimality criteria (objective functions); development of a system of interconnected mathematical models in accordance with the required hierarchical level of optimization research; selection of computational methods and optimization algorithms. Taking into account the above methodological provisions and approaches increases the efficiency of mathematical modeling to solve problems of calculations and optimization of NPP power unit parameters.

Key words: NPP power unit equipment, mathematical modeling, parameter optimization.

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БАЗОВІ ОСНОВИ РОЗРАХУНКІВ ТА ОПТИМІЗАЦІЇ ПАРАМЕТРІВ УСТАТКУВАННЯ ЕНЕРГОБЛОКІВ АЕС МЕТОДАМИ МАТЕМАТИЧНОГО МОДЕЛЮВАННЯ

У матеріалах статті розглянуті базові основи розрахунків та оптимізація окремих параметрів і характеристик устаткування енергоблоків АЕС, які тісно пов’язані з процесами їх проектування і конструювання. Сучасні енергоблоки АЕС є складними технічними системами. Вони включають до себе безліч взаємопов'язаного між собою устаткування різного технологічного призначення, що забезпечує виконання енергоблоками складної функції виробництва електричної енергії та теплоти встановленої якості і за заданим графіком навантаження. Повні математичні моделі функціонального стану паротурбінних енергоблоків АЕС характеризуються великою кількістю нелінійних зв’язків і містять неявні функції. Це ускладнює методи та принципи їх математичного моделювання і обумовлює застосування спеціальних принципів та підходів.

Ключові слова: устаткування енергоблоків АЕС, математичне моделювання, оптимізація параметрів.

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БАЗОВЫЕ ОСНОВЫ РАСЧЕТОВ И ОПТИМИЗАЦИИ ПАРАМЕТРОВ ОБОРУДОВАНИЯ ЭНЕРГОБЛОКОВ АЭС МЕТОДАМИ МАТЕМАТИЧЕСКОГО МОДЕЛИРОВАНИЯ

В материалах статьи рассмотрены базовые основы расчетов и оптимизации отдельных параметров и характеристик оборудования энергоблоков АЭС, которые тесно связаны с процессами их проектирования и конструирования. Современные энергоблоки АЭС являются сложными техническими системами. Они включают в себя множество взаимосвязанного между собою оборудования разного технологического назначения, которое обеспечивает выполнения энергоблоками сложной функции производства электрической энергии и теплоты, установленного качества и за заданным графиком нагрузки. Полные математические модели функционального состояния паротурбинных энергоблоков АЭС, характеризуются большим количеством нелинейных связей и содержат неявные функции. Это усложняет методы и принципы их математического моделирования и обусловливает применение специальных принципов и подходов.

Ключевые слова: оборудования энергоблоков АЭС, математическое моделирование, оптимизация параметров.

Introduction

Modern NPP power units are complex technical systems. They include a set of interconnected equipment for different technological purposes, which ensures that power units perform a complex function of electricity production and heat of the specified quality and according to a given load schedule. Such systems are characterized by multiparametricity, complex structural and functional relationship of parameters, the presence of restrictions on the change of parameters and relationships, functioning under the influence of random factors, a variety of physicochemical processes occurring in them. In this regard, complete mathematical models of the functional state of steam turbine power units are characterized by a large number of nonlinear (in many cases transcendental) connections and contain implicit functions [1, 2]. This complicates their widespread use to solve problems of system analysis of the quality of operation of power units.

The goal of the work

Optimization of individual parameters and characteristics of NPP power unit equipment is closely related to the processes of their design and construction. The initial data for the first preliminary optimiza-

tion calculations in the design process are structural developments of the equipment. The results of preliminary optimization, taking into account the change of the initial data in the allowable range of values, serve as a basis for new optimization calculations of parameters and designs of equipment, taking into account the specific conditions of its operation. Thus, the optimization of parameters and characteristics of the equipment of NPP power units is a complex iterative process, and each stage of optimization research during the creation and improvement of equipment is characterized by its methods and means.

The aim of the work is to analyze the basic theoretical foundations, methods and approaches to the calculation and optimization of the parameters of the equipment of NPP power units by methods of mathematical modeling.

The general part

In the first stage of optimization, the amount of information about the object being optimized is minimal, and the original data have a significant error. Therefore, it is often impossible to describe quite accurately how the parameters are interrelated and how they determine the type of objective function. In this regard, at the first stage of optimization calculations, the most effective analytical methods of optimization.

They allow you to clearly identify the impact of the relationship between the original data, to obtain with minimal time the general dependences to determine the optimal parameters for various combinations of technical and economic factors.

In the following stages, the amount of information about the object of optimization increases significantly. New thermodynamic, constructive, regime factors and necessary technical limitations are revealed. Since these stages are directly related to the creation of equipment, it is necessary to more accurately and fully take into account all the factors that determine the criterion of optimality, and this significantly increases the number of parameters that are optimized. At the same time, the relationship between the parameters becomes more complex, and to obtain an analytical solution is possible only with a significant simplification (idealization) of real dependencies.

The following idealization methods are used in the mathematical modeling of NPP power units: division into simpler technological subsystems (decomposition method); selection of the most significant properties and influences on them in parametric form (macromodeling method); linearization of nonlinear models in some area of variable change (linearization method); bringing the system with distributed parameters to the system with concentrated parameters; neglect of the properties of the dynamics of technological processes.

At the stages of final optimization research, the most effective optimization method is the method of simulation modeling, which allows to achieve the required degree of accuracy in the description of the object being optimized and use special mathematical methods to find the optimum in solving multifactorial and multicriteria problems [3–5].

For the effective implementation of tasks related to the determination of optimal parameters and designs of NPP power units with the help of mathematical modeling and well-developed methods of multifactor optimization, it is necessary to meet a number of requirements in their formulation. Practice shows that it is impractical to optimize with one mathematical (simulation) model the whole set of parameters that characterize this power unit, because in this formulation optimization problems are often mutually incorrect due to significant inconsistencies in the accuracy of different source information, inequality of parameters on the objective function, specific differences in the mathematical description of different components and elements of the power unit. To effectively optimize the parameters of NPP power units, it is necessary to create a system of interconnected mathematical models, which include: a group of detailed mathematical models of individual units and equipment elements of power units; more generalized mathematical models for the main equipment of power units are built on their basis; complete mathematical model of power units.

In accordance with the above, it is advisable to optimize the parameters of NPP power units using a system of mathematical models of the main equipment: reactor, steam generator, turbine. The main equipment, in turn, should be divided into characteristic units. This partition allows rationally, taking into account the specific features of the functional relationships between the parameters of each node, to create their mathematical models and optimize both individual nodes and the main equipment of NPP units by sequential refinement.

The parameters of each node can be divided into two groups: external parameters that determine the relationship between nodes, and internal parameters that characterize only this node, the values of which depend mainly on external binding parameters.

If the number of external parameters for this node is small, then the optimization of its internal parameters can be performed in the area of their expected optimum separately from other nodes with fixed external parameters, and then taking into account the optimal values of internal parameters to optimize external parameters. Thus, the NPP steam generator is connected to the turbine installation by the following parameters: thermal power, pressures, costs and temperatures of generated steam and feed water. Since the number of these connecting parameters is relatively small, the internal parameters

of the steam generator, such as water velocity in the tubes of the heat exchange surface, the length of the tubes, their outer and inner diameters, etc., can be optimized separately from the turbine. and feed water, presented in the form of restrictions. At the same value, separately from the steam generator, the internal parameters of the turbine are optimized. Then the parameters of the generated steam and feed water connecting the steam generator and the turbine are optimized using appropriate mathematical methods.

If the number of connecting parameters between nodes is large, it is advisable to optimize these nodes together in a single model. For example, it is necessary together with the main thermal and hydraulic parameters of the thermal scheme of NPP power units with WWER reactors to optimize the internal parameters of their systems of external separation and intermediate superheating of steam, because they are related to the separation pressure of heated steam, flow rates, pressures and temperatures. heating, and heated steam at the inlet and outlet of the stages of the superheater, the loss of pressure of the heated steam in the stages of the superheater and others.

Thus, the solution of the problem of optimization of NPP power unit parameters includes the following stages: selection of optimality criteria (objective functions); development of a system of interconnected mathematical models in accordance with the required hierarchical level of optimization research; selection of computational methods and optimization algorithms.

When optimizing the parameters of NPP power units, it is very important to determine under which given constraints it is advisable to optimize: at constant electric power of the NPP unit or at constant thermal capacity of the reactor of the NPP unit. If the optimization is carried out at a given constant electric power of the NPP, it is necessary to create a mathematical model that describes the operation of all equipment of the NPP, and take into account the continuous change in thermal power of the reactor.

In nuclear energy, for reasons of reliability and economy, reactors are usually designed on the basis of designs of standard fuel elements (fuel rods), which have fixed geometric characteristics and a certain thermal capacity. The total thermal capacity of the reactor varies discretely by changing the number of operating fuel rods, and, importantly, is not proportional to their number. This unevenness is due to the fact that the energy release in the core of the reactor also depends on the geometric dimensions of the zone itself. In this regard, it is very difficult to take into account the continuous change of the thermal power of the reactor in the process of optimizing the parameters under the conditions of a given constant electric power of the NPP power unit.

Therefore, it is advisable to optimize the parameters of NPP units at a constant thermal capacity of the reactor, and to bring the options to the same energy effect by taking into account changes in the electric capacity of the unit, i.e. the introduction of so-called replacement electric power in the power system. In this formulation, mathematical models of the following equipment are required to solve the problems of optimization of the main thermal and hydraulic parameters of NPP power units with water-cooled reactors: reactor, steam generator, turbine, external separation and intermediate steam superheating system, regeneration system and condenser system “water cooler”.

The depth of detail of the mathematical modeling of this equipment should be based on the principle of equal accuracy, i.e. in each model it is necessary to take into account the parameters that have one order of influence on the objective function.

Conclusions

Taking into account the above methodological provisions and approaches increases the efficiency of mathematical modeling to solve problems of calculations and optimization of NPP power unit parameters.

References (transliterated)

1. Yefimov O. V., Goncharenko L. V., Potanina T. V. (2013), *Sovershenstvovanie i optimizacija modelej, processov, konstrukcij i rezhimov raboty jenergeticheskogo oborudovanija AjeS, TjeS i otopitel'nyh kotel'nyh : monografija* [Improvement and optimization of models, processes, designs and operating modes of power equipment of nuclear power plants, thermal power plants and heating boilers], monograph, Pidruchnik NTU “KhPI”, Kharkov, 268 p.
2. Yefimov O. V, Pilipenko M. M., Potanina T. V., Kavertsev V. L., Garkusha T. A. (2017), *Reaktory i parogeneratory energoblokiv AES: shemy, procesy, materialy, konstrukcii', modeli : monografija* [Reactors and steam generators of NPP power units: schemes, processes, materials, constructions, models], LLC “In the case”, Kharkov, 420 p.
3. Yefimov O. V. et al. (2018), “Avtomatyzovana systema pidtrymky pryjnjattja rishen' ekspluatacijnym personalom energoblokiv AES po kryteriju tehniko-ekonomichnoi' efektyvnosti z urahuvannjam pokaznykiv nadijnosti [Automated decision support system by operational personnel of NPP power units according to the criterion of technical and economic efficiency taking into account reliability indicators]”, *Jaderna ta radiacijna bezpeka* [Nuclear and radiation safety], no. 2(78), pp. 11–19. https://www.scopus.com/authid/detail.uri?authorld-7202040387.
4. Yefimov O. V., Potanina T. V., Yesypenko T. O., Kavertsev V. L., Harkusha T. A., Tiutiunyk L. I. (2021), *Systems supporting decisions at the stage of operation and equipment diagnostics nuclear power units with pressurised water reactors. Scientific research of the XXI century. Volume 1 : collective monograph*, Compiled by V. Shpak ; Chairman of the Editorial Board S. Tabachnikov. Sherman Oaks, GS publishing service, Los Angeles, 430 p.
5. Yefimov O. V. et al. (2018), “Vykorystannja metodiv interval'nogo analiza dlja ocinky bezpeky ta nadijnosti energoblokiv AES [Use of interval analysis methods to assess the safety and reliability of NPP power units]”, *Jaderna ta radiacijna bezpeka*

[Nuclear and radiation safety], no. 3(79), pp. 15–21. https://www.scopus.com/authid/detail.uri?authorld-72020403.

Список літератури

1. Єфімов О. В., Гончаренко Л. В., Потаніна Т. В. *Совершенствование и оптимизация моделей, процессов, конструкций и режимов работы энергетического оборудования АЭС, ТЭС и отопительных котельных : монографія*. Харків: Підручник НТУ «ХПІ», 2013, 268 с.
2. Єфімов О. В., Пилипенко М. М., Потаніна Т. В., Каверцев В. Л., Гаркуша Т. А. *Реактори і парогенератори енергоблоків АЕС: схеми, процеси, матеріали, конструкції, моделі : монографія*. Харків: В справі, 2017. 420 с.
3. Єфімов О. В. та ін. Автоматизована система підтримки прийняття рішень експлуатаційним персоналом енергоблоків АЕС по критерію техніко-економічної ефективності з урахуванням показників надійності. *Ядерна та радіаційна безпека.* 2018. № 2(78). С. 11–19. https://www.scopus.com/authid/detail.uri?authorld-7202040387.
4. Yefimov O. V., Potanina T. V., Yesypenko T. O., Kavertsev V. L., Harkusha T. A., Tiutiunyk L. I. *Systems supporting decisions at the stage of operation and equipment diagnostics nuclear power units with pressurised water reactors. Scientific research of the XXI century. Volume 1 : collective monograph*. Compiled by V. Shpak ; Chairman of the Editorial Board S. Tabachnikov. Sherman Oaks, Los Angeles : GS publishing service, 2021. 430 p.
5. Єфімов О. В. та ін. Використання методів інтервального аналіза для оцінки безпеки та надійності енергоблоків АЕС. *Ядерна та радіаційна безпека*. 2018. № 3(79). С. 15–21. https://www.scopus.com/authid/detail.uri?authorld-72020403.

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