DOI: https://doi.org/10.15407/pmach2024.01.015

UDC 621.165.62

PROLONGATION OF SAFE OPERATION OF THE K-1000-60/3000 TURBINE POWER UNIT AFTER DAMAGE TO THE HPC ROTOR

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Currently, when large-scale military actions are taking place on the territory of Ukraine, the inclusion of the domestic energy system in the European one is a reliable component of providing electricity to the country's energy market. However, according to experts, uninterrupted and safe operation of nuclear power plants is still considered a prerequisite for the stable operation of the energy sector of Ukraine. The purpose of the paper is to assess the damageability and individual resource of the rotor of high-pressure cylinder (HPC) of the K-1000-60/3000 turbine power unit of the LMZ after damage to the blades in order to prolong the operation of the power unit in the conditions of a stressed state of the power system. One of the most effective ways to partially solve the problem of replacement of generating capacities is to extend the operating periods of NPP power units after the end of the project operating period, provided that nuclear and radiation safety standards are met. The review of the previously established service life of the energy equipment of NPP power units involves the assessment of the residual resource of the energy equipment in accordance with the regulatory documents. After the accidental damage of the blades of the last stage of the HPC rotor of the K-1000-60/3000 turbine power unit of the LMZ, there was a need to study the cyclic and static damage, the individual residual resource of the HPC rotor. In the process of achieving the goal, studies were carried out for three design options: the original option (five stages of the HPC rotor), the option without the blades of the last stage and the option without the fifth stage (with four first stages). The calculation of the resource indicators of the rotor in the execution of the HPC without blades of the 5th stage shows that the static damage accumulated in the main metal is 52%, the cyclic damage is 5% when applying the standard strength reserves for the number of cycles and for deformations at the level of n_N=10 and n_ε=1.5 according to the recommendations of SOU-N MEV 40.1-21677681-52:2011. Thus, the total damage to the base metal is 57%, which sets the residual resource of the HPC rotor at the level of 88.4 thousand hours. The calculation of the resource indicators of the rotor in the execution of the HPC without entire 5th stage shows that the static damage accumulated in the base metal is 52%, the cyclic damage is 6% when applying the standard strength reserves for the number of cycles and deformations at the above-mentioned level. The total damage to the base metal is 58%, which determines the residual resource of the HPC rotor at the level of 85.6 thousand hours.

Keywords: *nuclear power plant, steam turbine, K-1000-60/3000, high-pressure cylinder, rotor of high-pressure cylinder, power, pressure, temperature, loss, equipment resource, unsteady thermal conductivity, thermal state, stress-strain state, low-cycle fatigue, long-term strength, residual resource, permissible number of starts.*

Introduction

In today's conditions, when large-scale military actions are taking place on the territory of our country, the inclusion of Ukraine's energy system in the European one is a reliable component of providing electricity to the country's energy market. However, it is worth remembering that the generation of electricity by domestic nuclear power plants in the total balance of consumption was about 50% before the start of the full-scale invasion, and therefore, the uninterrupted and safe operation of NPPs is a prerequisite for the stable operation of the energy sector of Ukraine. In addition, the reliability of the operation of the nuclear power industry against the background of the significant depletion of energy equipment resources and the shortage of organic fuel at thermal power plants has a positive effect on the socio-economic development of Ukraine. At the current stage, operating time of a significant part of the steam turbine equipment of the NPP is approaching its equipment value. The continuation of their operation beyond the equipment resource requires a verifying calculation of the residual resource of its main elements.

According to the Program for Extending the Service Life of Energy Equipment of NPPs of Ukraine, the service life of twelve power units out of fifteen operating power units has been extended for 10–20 years. The experience of the carried work has shown that the specific financial costs required for meeting the requirements of regulatory documents, which ensure the possibility of obtaining a license for the operation of power units during the additional service period, are significantly lower than the costs required for building new power units [1].

One of the most effective ways to partially solve the problem of replacement of generating capacities is to extend the terms of operation of NPP power units after the end of the project period, provided that nuclear and radiation safety standards are met. The review of the previously established service life of the energy equipment of NPP power units involves the assessment of the residual resource of the energy equipment in accordance with regulatory documents [2–5]. In the event of emergency situations, a verifying calculation of damaged power equipment is carried out in accordance with regulatory documents [3, 4], which determine the order and frequency of control, as well as the admissibility of extending the service life of the power equipment.

The experience gained in the operation of equipment of the same type at different power plants allows to extend the allowable period of operation of the turbine equipment beyond the equipment resource.

The calculation of the individual resource of the rotor of high-pressure cylinder (HPC) of the K-1000-60/3000 turbine is carried out using a comprehensive approach, which involves taking into account the results of non-destructive metal testing with verifying calculations for strength and durability, as well as a detailed study of the individual history of the unit's operation. At the stage of monitoring the condition of the metal of the power equipment, which has worked additionally for a long time, the possibility of choosing rational coefficients of the reserve strength of the metal, which is possible when conducting special experimental studies, should be studied.

As international experience shows, extension of the operating periods of NPP power units after the end of the project operating period is potentially possible, and provided that nuclear and radiation safety standards are met, it is one of the most effective ways to partially solve the problem of replacing generating capacities [6–8].

Research purpose

The purpose of the research is to assess the damageability and individual resource of the HPC rotor of the K-1000-60/3000 turbine power unit of the LMZ after damage to the blades in order to prolong the operation of the power unit in the conditions of the power system's stressed state. To achieve this goal, an appropriate technique was developed, a mathematical model of the thermal and stress-strain state of the high-pressure rotor of a powerful steam turbine was improved, and relevant research was conducted.

Study of the individual resource of the HPC rotors of steam turbines of NPPs

When studying the individual resource of the HPC rotors of steam turbines of NPPs, a comprehensive approach was applied to establish the individual resource of steam turbines and the possibility of continuing the operation of power equipment, which includes a calculation study of both the individual operating time and the permissible number of starts from different thermal states under cyclic loading of the HPC rotor of the K-1000-60/3000 steam turbine, as well as the individual working time at a static load of the HPC rotor of the K-1000-60/3000 steam turbine; assessment of the possibility of further continuation of operation beyond the equipment resource of the HPC rotor of the K-1000-60/3000 steam turbine. The calculated study of the resource indicators of the HPC rotor of the K-1000-60/3000 steam turbine of the 1000 MW unit during operation was carried out in accordance with regulatory documents [3–5].

The purpose of the analysis of the technical (operational, design and repair) documentation of the inspected equipment is to identify the elements of its structures and areas that work in the most stressful conditions and/or those that are affected by negative factors, the action of which can lead to accidents or operation failures; detection of modes under which changes in the structure and properties of materials are possible; determination of the defects development dynamics; development of an expert examination program.

Power unit equipment aging management is carried out at all stages of the service cycle and involves the following: development of station programs for the aging management of power unit elements and structures; formation of a list of elements and structures of the power unit that are subject to aging management; detection and study of aging processes of elements and structures of the power unit (understanding of aging); taking measures to monitor aging processes of elements and structures of the power unit (metal control); assessment of the current technical condition of energy equipment elements and forecasting its replacement due to aging; implementation of measures to mitigate degradation; optimization of programs for maintenance, control and repair of energy equipment of the power unit of the power plant; introduction of additional means of control and diagnosis of the current technical condition of elements and systems of the power unit of the power plant; analysis of resource and reliability indicators of structures, systems and elements, performance of work on resource reassignment of elements, replacement of those that have reached the limit technical condition; the development of technical and organizational measures for the modernization and reconstruction of the energy equipment of the power plant unit, as well as the minimization of the elements degradation and their aging management; continuous improvement of the aging management program based on feedback between operational experience and research, as well as the results of self-assessment and expert assessments (development and implementation of additional measures for monitoring and degradation mitigating); documenting activities, creating and maintaining a database of the technical condition of energy equipment elements and detected defects based on the generalization of information about manufacturing, operation, maintenance, repairs, etc.

When evaluating the residual resource of elements of high-power steam turbines that have exhausted their equipment resource, it is necessary to perform a verifying strength calculation for energy equipment elements in which the structure and properties of the metal change, and damage from creep and short-cycle fatigue accumulates [4].

When assessing the residual life of the rotors of NPP steam turbines, a calculation study of the thermal, stress-strain state, short-cycle fatigue, static damage and individual resource is performed, taking into account both the actual data on the operating modes of the high-power steam turbine of the NPP, and the metal properties of its main elements, repair and restoration measures regarding the main elements of the equipment [8–10].

The HPC rotor considered in the paper was installed on the NPP power unit by the manufacturer of the turbine in 1995. The K-1000-60/3000 turbine plant is operated at the NPP power unit in accordance with the technical requirements of the manufacturer. The resource according to the technical conditions of the manufacturing plant is 30 years.

The operating time of the NPP power unit was 122,000 hours with a total number of starts of 52. At the same time, similar equipment indicators are equal to 30 years and 600 starts. Over the entire period of operation of the power unit, the number of starts from cold and close to it thermal states is 27, from hot – 25, that is, the power unit was operated in basic mode.

Study of resource indicators of the HPC rotor of the K-1000-60/3000 turbine

After the accidental damage to the blades of the last stage HPC rotor of the K-1000-60/3000 turbine power unit of the LMZ, there was a need to study the cyclic and static damage, the individual residual resource of the high-pressure rotor. In the process of achieving the goal, a study was conducted for three design options: the initial option (five stages of the HPC rotor), the option without the last stage blades and the option without the fifth stage (with the four first stages).

Mathematical model for calculating the residual resource of the HPC rotor of the K-1000-60/3000 turbine power unit of the NPP

The studies of the thermal and stress-strain states of the HPC rotor of the NPP power unit presented above showed that the most heavily loaded areas of the HPC rotor are the axial channel in the region of the fourth stage, the welding fillet roundings of the pressure stages and their unloading holes.

The calculation of the accumulated low-cycle fatigue in the high-pressure rotor was performed in accordance with regulatory documents [4].

The amplitude of the intensity of the deformation was set according to the values of the intensity of the deformation during the loading cycle

$$\varepsilon_a = \frac{1}{2}\left(\varepsilon_i^{\max} - \varepsilon_i^{\min}\right),$$

where $\varepsilon_i^{\max}$, $\varepsilon_i^{\min}$ are maximum and minimum value of the strain intensity in the load cycle.

The number of load cycles before the appearance of a crack was determined by the experimental curves of low-cycle fatigue, obtained from the results of tensile-compression tests of samples at a rigid symmetrical cycle and constant temperature. The permissible number of start cycles was taken from the experimental curves as the smallest of the two values

$$N^{\text{perm}} = \min\left\{\frac{N_1}{n_N}; N_2\right\},$$

where N_1, N_2 is the number of load cycles corresponding to the deformation intensity amplitudes on the short-cycle fatigue curves ε_a and $n_\varepsilon \cdot \varepsilon_a$ respectively; n_N, n_ε is the safety margin factor for the number of cycles and deformation.

The key feature of this calculation model is that in the regulatory documents there are no experimental short-cycle fatigue curves for 30HN3M1FA steel, from which the HPC rotor of the K-1000-60/3000 turbine is made. Therefore, according to the recommendations of RTM 108.021.103-85, it is proposed to calculate the permissible number of cycles based on the correlation dependence of low-cycle fatigue [8, 9]:

$$N_{1,2} = \left[\frac{\frac{1}{4}\ln\frac{100}{100-\psi_{\text{ls}}}}{C\cdot\left(n_{1,2}\cdot\varepsilon_a^{\text{r}} + \frac{1-2\cdot\nu}{\varepsilon\cdot E}\cdot\sigma_i\right)}\right]^{\frac{1}{0.6}}; \quad N^{\text{perm}} = \left[1 - \left|\frac{1.25\cdot\sigma^c}{\sigma_{\text{ls}}}\right|^q\right]\cdot\min\left\{\frac{N_1}{n_N}; N_2\right\},$$

where σ^c is the stress intensity in the state of constant creep; σ_{ls} is the limit of long-term strength; q is the exponent in the long-term strength equation; ψ_{ls} is the long-term plasticity determined by the median values for each temperature level $\theta_1 \ldots \theta_2$; θ_1 i θ_2 are temperatures that correspond to the maximum $\varepsilon_i^{\max}$ and minimum $\varepsilon_i^{\min}$ deformation intensity during the cycle, respectively; C is the coefficient of the current number of cycles

$$C = \begin{cases} 1, \text{ at } N \le 10^4 \\ \dfrac{\overline{K}_T}{K_T}, \text{ at } N > 10^4 \end{cases};$$

$\overline{K}_T$ is the effective coefficient of stress intensity

$$\overline{K}_T = 1 + p(K_T - 1);$$

p is the coefficient of sensitivity of the material to stress concentration; $n_1=1$; $n_2=n_\varepsilon$ are safety margin factors; ε_a^{r} is the amplitude of strain intensity, reduced to a symmetrical load cycle

$$\varepsilon_a^{\text{r}} = \frac{1+\nu}{1.5\cdot E}\left(C\cdot\sigma_a + \min(\sigma_{-1};\sigma_{\text{ls}}) - \overline{\sigma}_N\right);$$

ν is the Poisson's ratio; E is the temperature-dependent Young's modulus; $\overline{\sigma}_N$ is the fatigue limit at an asymmetric load cycle

$$\overline{\sigma}_N = \min\left\{\sigma_N; \sigma_N^c\right\};$$

σ_N is the fatigue limit of steel under a certain asymmetry of the load, characteristic to this starting mode

$$\sigma_N = \frac{\sigma_{-1}}{1 + \frac{\sigma_{-1}}{\sigma_{\text{tens}}}\cdot\frac{1+r}{1-r}};$$

σ_N^c is the fatigue limit of steel under asymmetric loading and constant creep

$$\sigma_N^c=\begin{cases}\min\left\{\dfrac{\sigma_a\cdot\sigma_{\text{ls}}(T_1)}{|\sigma_{\max}|};\dfrac{\sigma_a\cdot\sigma_{\text{ls}}(T_2)}{|\sigma_{\max}-2\cdot\sigma_a|}\right\},\ \text{at}\ \sigma_a<\overline{\sigma}_{0.2}^{\text{cycl}}\\ \min\{\sigma_{\text{ls}}(T_1);\sigma_{\text{ls}}(T_2)\},\ \text{at}\ \sigma_a\ge\overline{\sigma}_{0.2}^{\text{cycl}}\end{cases};$$

r is the coefficient of asymmetry of the load cycle

$$r=\begin{cases}\max\left\{\dfrac{\sigma^{\max}-2\cdot\sigma_a}{\sigma^{\max}};-1\right\},\ \text{at}\ \sigma^{\max}>0\\ -1,\ \text{at}\ \sigma^{\max}\le 0\end{cases};$$

$\sigma_{\text{ls}}(\theta_1)$, $\sigma_{\text{ls}}(\theta_2)$ are long-term strength limits corresponding to temperatures θ_1 and θ_2; $\sigma^{\max}$ is the maximum stress in the cycle; σ_{-1} is the fatigue limit of steel under symmetrical loading; σ_{tens} is the tensile strength of steel; σ_a is the stress intensity amplitude

$$\sigma_a=\frac{\sigma^{\max}-\sigma^{\min}}{2};$$

$\overline{\sigma}_{0,2}^{\text{cycl}}$ is the average value of the cyclic yield strength of the material at the temperature reduced to the calculated temperature θ_1 and θ_2.

The total damage accumulated in the metal of the rotor from the combined action of static loads at q' different types of stable modes and cyclic loads at k' different types of alternating modes is determined using the Palmgren-Miner hypothesis with an equation of the form:

$$\Pi'=\Pi'_{\text{stat}}+\Pi'_{\text{cycl}}=\sum_{j=1}^{q'}\frac{t'_j}{t'_{pj}}+\sum_{l=1}^{k'}\frac{n'_l}{N'_{pl}},$$

where Π'_{stat}, Π'_{cycl} are static and cyclic damage accumulated in the studied area of the rotor at the time of calculation of resource indicators; t'_j is the working time on j-th steady mode at the temperature of the metal T'_j and equivalent local creep stresses $(\sigma'_{ej})^{\max}$; t'_{pj} is the time before the limit state under the action of equivalent local creep stresses $(\sigma'_{ej})^{\max}$ at the temperature of the metal T'_j; n'_l is the number of l-th type cycles; $N'_{pl}=N^{\text{perm}}$ is the number of cycles before the appearance of fatigue cracks under the action of cyclic loads of l-th type only; q' is the number of different types of stable modes during assessment, at the temperature of the metal T'_j and constant equivalent local creep stresses $(\sigma'_{ej})^{\max}$; k' is the number of different types of cycles during assessment, with different amplitudes of reduced stress intensities $\Delta\sigma'_l$, or amplitude of deformations ε'_{al}.

All values related to the previous period of operation before the calculation of the residual resource are marked with a dash.

If, according to the data of the power plant, the distribution of starts by type is unknown, but only their total number n is known for the time up to the moment of assessment, then the accumulated cyclic damage Π'_{cycl} is determined in reserve according to a simplified formula

$$\Pi'_{\text{cycl}}=\frac{n}{N_{\partial}},$$

where N_p is the the number of cycles before the appearance of a fatigue crack, which corresponds to the most rigid mode (the mode with the maximum deformation amplitude ε_a).

Residual operating time before the appearance of a crack $[G]^{\text{res}}$ is determined by the formula

$$[G]^{\text{res}}=\frac{1-\Pi'}{\Pi''_{\text{pr}}},$$

where Π''_{pr} is the averaged hourly damage (resource depletion rate) predicted for the next estimated period of operation, which will accumulate in the studied area of the rotor during rotation of q''-types of stable modes and k''-types of cycles with different cyclic loads. All values related to the period of operation after calculation and extension of the resource are marked with two strokes.

Calculation of the accumulated damage and residual resource of the HPC rotor of the K-1000-60/3000 turbine power unit of the NPP

Using the data on the dynamics of changes in stress intensity in the high-pressure rotor of the NPP power unit during start from different thermal states (Fig. 1), the values of stress intensity amplitudes σ_a, load asymmetry coefficient *r*, etc., were determined for all characteristic areas. In addition, other indicators of low-cycle fatigue, necessary for calculating the permissible number of start cycles from different thermal states for all structural versions of the HPC, are also determined.

In the high-pressure rotor, 12 characteristic areas of research are chosen in the calculations of damageability, low-cycle fatigue, long-term strength and individual resource. They are shown in Fig. 1, namely:

1 – axial hole of the rotor in the region of the 4th pressure stage;
2 – tail fastening of the blades of the 1st stage;
3 – 2nd-stage welding fillet from the exhaust side;
4 – 3rd-stage exhaust welding fillet;
5 – unloading hole of the 3rd stage disc;
6 – diaphragm sealing of the 4th degree;
7 – unloading hole of the 4th stage disc;
8 – diaphragm seal of the 5th degree;
9 – unloading hole of the 5th stage disc;
10 – 5th-stage exhaust welding fillet;
11 – ridges of final seals on the side of chamber *A*;
12 – rotor shaft in the area of chamber *B* of end seals.

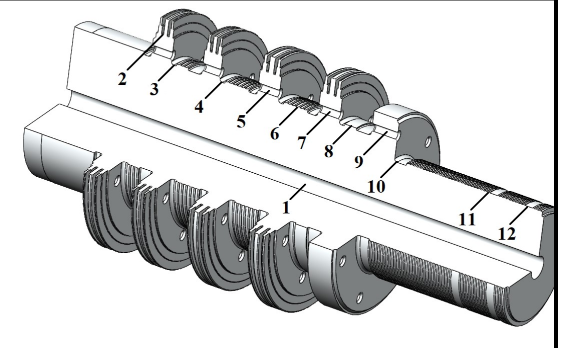

Fig. 1. Characteristic areas of HPC rotor research with repair restorations

The most critical points from the point of view of stress intensity and resource indicators are: 1 – axial hole of the rotor in the region of the 4th pressure stage; 3 – 2nd-stage welding fillet from the exhaust side; 7 – unloading hole of the 4th stage disc; 8 – diaphragm seal of the 5th stage; 10 – 5th-stage welding fillet from the exhaust side. Calculation studies were carried out for all types of starts in the indicated zones of the HPC rotor.

Concerning the given data, it should be noted that all presented limits of strength, fatigue and yield strength σ_j are temperature dependent t_j. They are obtained due to the analytical processing of experimental data on the study of physical and mechanical properties of 30HN3M1FA steel at different operating temperatures, given in [4]. The basic equation of the exponential association of the following form was used to approximate the experimental data

$$\sigma_j = a \cdot (b - e^{-c \cdot t_j}),$$

where *a*, *b* i *c* are constants determined by mathematical processing of experimental data.

Analyzing the given data on the resource indicators of low-cycle fatigue of the rotor of different structural designs of the HPC, it can be noted that most of the studied areas are subjected to symmetrical loading during the start cycles. Such areas are: 3 – 2nd-stage welding fillet from the exhaust side; 4 – 3rd-stage welding fillet from the exhaust side, 8 – diaphragm seal of the 5th stage and 10 – 5th-stage welding fillet from the exhaust side. For them the asymmetry coefficient is $r = -1$. Characteristic regions 1 – axial hole of the rotor in the region of the 4th pressure stage and 7 – unloading hole of the 4th stage disc are subjected to asymmetric loading, for them the asymmetry coefficient is different for all types of the HPC start and design.

For the constructive performance of the HPC without blades of the 5th stage with a standard nozzle device when starting from a hot state (HS), the highest tensile stress that the HPC rotor undergoes is $\sigma_{\text{HS}}^{\max}$ =267.0 MPa, and the largest compressive one is $\sigma_{\text{HS}}^{\min}$ = -196.0 MPa. Similarly, when starting from a cold state (CS) $\sigma_{\text{CS}}^{\max}$ =257.0 MPa, $\sigma_{\text{CS}}^{\min}$ = -178 MPa.

For the constructive performance of the HPC without the entire 5th stage when starting from a hot state, the largest tensile stress that the high-pressure rotor undergoes is $\sigma_{\text{HS}}^{\max}$ =299.0 MPa, and the largest compressive one is $\sigma_{\mathrm{HS}}^{\min}$ = -206.0 MPa Similarly, when starting from a cold state: $\sigma_{\mathrm{CS}}^{\max}$ =296.0 MPa, $\sigma_{\mathrm{CS}}^{\min}$ = -190.0 MPa.

Due to the rather high level of stress intensity amplitudes and the asymmetry of the load cycles, areas 1 and 7 are the zones that most significantly limit the permissible number of start cycles from different thermal states for all three HPC structures. Moreover, when starting from a hot state of metal, the area subject to the most intensive accumulation of cyclic damage is 7 - the zone of unloading holes in the disc of the 4th stage. The permissible number of start cycles from the hot state of the $N_{\mathrm{HS}}^{\mathrm{p}}$ for HPC without blades of the 5th stage is 1061, for HPC without the 5th stage - 891.

At the same time, when starting from a cold state of the metal, the area subject to the most intensive accumulation of cyclic damage is 1 – the zone of axial boring of the shaft in the area under the 4th pressure stage. The permissible number of start cycles from the cold state of the $N_{\mathrm{CS}}^{\mathrm{p}}$ for HPC rotor without 5th-stage blades is 1219, for HPC without entire 5th stage – 1050. The results of all calculation studies are summarized in the form of resource indicators of the high-pressure rotor of the K-1000-60/3000 turbine power unit of the NPP for various constructive execution of the HPC and are given in the Table 1.

Table 1. Resource indicators of the rotor for various structural designs of the HPC of the K-1000-60/3000 turbine power unit

The studied parameter	Notation, dimension	HPC without blades of 5th stage	HPC without the entire 5$^{\mathrm{th}}$ stage
Current operating time of the power unit	T, hours	122000	
The current total number of starts	n	52	
The number of starts from the HS	N_{HS}	25	
The number of starts from the CS	N_{CS}	27	
Coefficients of safety margin	n_N / n_ε	10 / 1.5	
Intensity of stress on nominal mode	σ_i^{nom}, MPa	185.0	194.0
Amplitude of the stress intensity at HS	$\sigma_{a\,\mathrm{HS}}$, MPa	155.0	167.0
Amplitude of the stress intensity at CS	$\sigma_{a\,\mathrm{CS}}$, MPa	146.0	164.0
Allowable operating time	T^{allow}, hours	220000	220000
Permissible number of starts from HS	$N^{\mathrm{p}}_{\mathrm{HS}}$	1061	891
Permissible number of starts from CS	$N^{\mathrm{p}}_{\mathrm{CS}}$	1219	1050
Static damage	Π'_{stat}, %	52.0	52.0
Cyclic damage	Π'_{cycl}, %	5.0	6.0
Total damage	Π'_{Σ}, %	57.0	58.0
Residual resource	G^{res}, hours	88400	85600

Discussion of results

The calculation of the resource indicators of the rotor in the execution of the HPC without blades of the 5th stage shows that the static and cyclic damage accumulated in the main metal is Π'_{stat}=52%, Π'_{cycl}=5% when applying the standard strength reserves for the number of cycles and deformations at n_N=10 and n_ε=1.5 according to the recommendations of SOU-N MEV 40.1-21677681-52:2011. Thus, the total damage to the base metal is Π'_{Σ}=57%, which sets the residual resource of the high-pressure rotor at the level of 88.4 thousand hours (Table 1).

The calculation of the resource indicators of the rotor in the execution of the HPC without the entire 5th stage shows that the static and cyclic damage accumulated in the base metal is Π'_{stat}=52%, Π'_{cycl}=6% when applying the standard strength reserves for the number of cycles and deformations at the level of n_N=10 and n_ε=1.5 according to the recommendations of SOU-N MEV 40.1-21677681-52:2011. Thus, the total damage to the base metal is Π'_{Σ}=58%, which sets the residual resource of the high-pressure rotor at the level of 85.6 thousand hours (Table 1).

The maximum stress intensity for the option without the entire 5th stage increased by 12% compared to the HPC option without the blades of the 5th stage.

According to the results of the calculations of the individual resource indicators of the HPS rotor of the K-1000-60/3000 turbine for various designs of the HPC, it was established that the operation of the HPC without the entire 5th stage leads to an increase in the rate of accumulation of damage in the main metal of the rotor and, as a result, to a decrease of its individual resource.

Due to the changes made to the design of the rotor, it is recommended to carry out detailed calculations of critical rotation frequencies to ensure a safe set of frequencies during start modes, to perform balancing of the HPC rotor. In addition, taking into account the damage to the HPC housing, it is necessary to carry out a verifying calculation and determine the remaining resource of the HPC housing, taking into account the existing damage in the form of cracks in the diaphragm fastening zones, etc. [1].

If the expert commission, which, in accordance with [3], consists of representatives of the power plant, specialized and other organizations, can accept the permissible working time of the metal at the level of 220 thousand hours, then for the option **without blades of the 5th stage** the static and cyclic damage accumulated in the main metal is Π'_{stat}=52%, Π'_{cycl}=5% when applying the standard safety margins for the number of cycles and deformations at the level of n_N=10 and n_ε=1.5 according to recommendations [4]. Thus, the total damage to the base metal is Π'_Σ=57%, which sets the residual resource of the high-pressure rotor at the level of 88.4 thousand hours. This will allow to continue operation of the K-1000-60/3000 steam turbine HPC rotor for 50,000 hours.

The results of the calculated study of the resource characteristics of the high-pressure turbine rotors of NPP power units operating in Ukraine indicate that short-cycle fatigue due to low temperature values in NPP steam turbines is quite small, i.e. the calculated cyclic damage of the base metal was 5–7%. The main influence on total damage and individual resource is given by static damage that occurs during the operation of the power unit in the basic mode.

If the expert commission, which, in accordance with [3], consists of representatives of the power plant, specialized and other organizations, can accept the permissible working time of the metal at the level of 220 thousand hours, then for the option **without the entire 5th stage** the static and cyclic damage accumulated in the main metal is Π'_{stat}=52%, Π'_{cycl}=6% when applying standard safety margins for the number of cycles and deformations at the level of n_N=10 and n_ε=1.5 according to recommendations [4]. Thus, the total damage to the base metal is Π'_Σ=58%, which sets the residual resource of the high-pressure rotor at the level of 85.6 thousand hours. This will allow to continue operation of the K-1000-60/3000 steam turbine HPC rotor for 50,000 hours.

So, from the point of view of resource indicators, the operation of a power unit with a capacity of 1000 MW without blades of the 5th stage of HPC and without the entire 5th stage of HPC is practically the same. The technical and economic performance of the equipment comes to the fore. However, due to the changes made to the design of the rotor, it is recommended to carry out detailed calculations of the critical rotation frequencies to ensure a safe set of frequencies during start modes, to perform balancing of the HPC rotor. In addition, taking into account the damage to the HPC housing, it is necessary to carry out a verifying calculation and determine the remaining resource of the HPC housing, taking into account the existing damage in the form of cracks in the diaphragm fastening zones, etc.

Conclusions

1. The maximum stress intensity for the option without the entire 5th stage increased by 12% compared to the option of the HPC without the blades of the 5th stage.

2. According to the results of the calculations of the individual resource indicators of the HPC rotor of the K-1000-60/3000 turbine for various designs of the HPC, it was established that the operation of the HPC without the entire 5th stage leads to an increase in the rate of accumulation of damage in the main metal of the rotor and, as a consequence, to the reduction of its individual resource.

3. A conclusion on the possibility of applying the results of the report for different power levels of the reactor unit can be made after the calculation of the flow part of the K-1000-60/3000 steam turbine power unit of the NPP, which must be carried out with the drawing up of the technical task and the mandatory determination of the operating mode in which steam turbine K-1000-60/3000 of the NPP power unit will work most of the time during the year.

4. If the expert commission, which, in accordance with SOU-N MPE 40.17.401:2021, consists of the representatives of the power plant, specialized and other organizations, can accept the permissible working time of the metal at the level of 220 thousand hours, then for the option **without the entire 5-th stage**, the total damage of the base metal is Π'_{Σ}=58%, which sets the residual resource of the HPC rotor at the level of 85.6 thousand hours, for the option **without blades of the 5th stage**, the total damage of the base metal accumulated in the base metal is Π'_{Σ}=57%, which sets the residual resource of the high-pressure rotor at the level of 88.4 thousand hours. This will allow to continue the operation of the K-1000-60/3000 steam turbine HPC rotor for 50 thousand hours.

Recommendations

1. Due to the changes made to the design of the rotor, it is recommended to carry out detailed calculations of critical rotation frequencies to ensure a safe set of frequencies during start modes, to perform balancing of the HPC rotor. In addition, taking into account the damage to the HPC housing, it is necessary to carry out a verifying calculation and determine the remaining resource of the HPC housing, taking into account the existing damage in the form of cracks in the diaphragm fastening zones, etc.

2. To increase the reliability of turbine elements, reduce heat loads and improve operating conditions, it is recommended to implement the following measures:

– modernize the control system of the main parameters of the turbine with the registration of parameters affecting the turbine reliability and resource;

– implement systems for monitoring the vibration activity of the turbine unit with diagnostics of the condition of the elements of the shaft pipeline, including the presence of cracks in the rotors;

– adhere to the task schedules developed by the manufacturing plant and try to minimize significant deviations;

– implement systems of control and technical diagnostics of the thermal and stress-strain state of HPC rotors, as well as HPC housings, stop and control valves, based on real-time modeling of the thermal and stress-strain state of the equipment.

3. At each subsequent planned extension of operation for equipment that has exhausted the equipment resource (SOU-N MPE 40.17.401:2021), it is needed to perform an additional calculation refinement of the individual resource of the HPC rotor of the K-1000-60/3000 steam turbine:

– experimental studies during planned and preventive repairs in accordance with regulatory documents (non-destructive control of metal to detect defects and experimental assessment of the resulting damage, study of the structure and properties of metal of high-temperature elements of a steam turbine);

– experimental studies of the effect of aging on changes in the physical and mechanical properties of structural alloyed steels at operating temperatures for elements that have exceeded the equipment operating time;

– verifying calculation of the individual resource of the power unit taking into account the actual data on the properties of the metal and operating modes, changes in the project design during repairs and restorations, features of start and variable modes of operation, etc., as well as the results of an experimental study of the metal, for elements that have exceeded the equipment operating time;

– technical audit of the current state of the equipment;

– expert assessment of the condition of the steam turbine's energy equipment with an indication of the possibility of continuing operation beyond the equipment resource in accordance with regulatory documents.

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Received 14 August 2023

Продовження безпечної експлуатації турбоустановки К-1000-60/3000 після пошкодження ротора ЦВТ

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Нині, коли на території України ведуться широкомасштабні бойові дії, включення вітчизняної енергосистеми до європейської є надійною складовою забезпечення електричною енергією енергетичного ринку країни. Проте передумовою сталої роботи енергетичного сектору України, на переконання фахівців, все-таки вважається безперебійна й безпечна робота атомних електростанцій. Мета публікації полягає в оцінці пошкоджуваності, індивідуального ресурсу ротора циліндра високого тиску (ЦВТ) турбіни К-1000-60/3000 енергоблоку ЛМЗ після пошкодження лопаток для подовження експлуатації енергоблоку в умовах напруженого стану роботи енергосистеми. Одним із найбільш ефективних шляхів часткового вирішення проблеми заміщення генеруючих потужностей є продовження строків експлуатації енергоблоків АЕС після завершення проєктного строку експлуатації за умови виконання норм ядерної та радіаційної безпеки. Перегляд раніше встановлених строків служби енергетичного обладнання енергоблоків АЕС передбачає оцінку залишкового ресурсу енергетичного обладнання згідно з нормативними документами. Після аварійного пошкодження робочих лопаток *останнього ступеня ротора ЦВТ турбіни К-1000-60/3000 енергоблоку ЛМЗ виникла необхідність у вивченні циклічної та статичної пошкоджуваності, індивідуального залишкового ресурсу ротора ЦВТ. У процесі досягнення поставленої мети були проведені дослідження для трьох варіантів конструкцій: вихідний варіант (п'ять ступенів ротора ЦВТ), варіант без робочих лопаток останнього ступеня і варіант без п'ятого ступеня (з чотирма першими ступенями). Проведений розрахунок ресурсних показників ротора у виконанні ЦВТ без робочих лопаток 5-го ступеня показує, що накопичене в основному металі статичне пошкодження складає 52%, циклічне пошкодження – це 5% при застосуванні нормативних запасів міцності по числу циклів і по деформаціях на рівні* $n_N=10$ *і* $n_\varepsilon=1{,}5$ *згідно з рекомендаціями СОУ-Н МЕВ 40.1-21677681-52:2011. Таким чином, сумарне пошкодження основного металу складає 57%, що встановлює залишковий ресурс ротора ЦВТ на рівні 88,4 тисяч годин. Проведений розрахунок ресурсних показників ротора у виконанні ЦВТ без всього 5-го ступеня показує, що накопичене в основному металі статичне пошкодження становить 52%, циклічне пошкодження – 6% при застосуванні нормативних запасів міцності по числу циклів та по деформаціях на вищезазначеному рівні. Сумарне пошкодження основного металу складає 58%, що визначає залишковий ресурс ротора ЦВТ на рівні 85,6 тисяч годин.*

***Ключові слова**: атомна електростанція, парова турбіна, К-1000-60/3000, циліндр високого тиску, ротор циліндра високого тиску, потужність, тиск, температура, втрата, парковий ресурс, нестаціонарна теплопровідність, тепловий стан, напружено-деформований стан, малоциклова втома, довготривала міцність, залишковий ресурс, допустиме число пусків.*

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