DOI: https://doi.org/10.15407/pmach2019.04.041

UDC 621.165.62

# ASSESSMENT OF RESOURCE PARAMETERS OF THE EXTENDED OPERATION HIGH-PRESSURE ROTOR OF THE K-1000-60/3000 TURBINE

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*The reliable operation of nuclear power plants (NPPs) is a prerequisite for the constant development of Ukraine's energy sector. At the current stage of development, a considerable part of the NPP steam turbine equipment is reaching its end-of-design-life value. The continuation of the operation of NPPs beyond original design life requires that the remaining useful life of its main components be verified. A model for the estimation of the resource parameters of the high-pressure (HP) rotor of a K-1000-60/3000 steam turbine has been developed. On the basis of the three-dimensional spatial analogue, the calculation of the thermal and stress-strain states of the HP rotor has been performed for all typical operating modes. It has been established that the stress concentration zones are the fillets and relief holes in the first stages, as well as the axial relief holes in the fourth and fifth stages. The calculation of the rate of cyclic damage accumulation in the base metal has been performed using correlational low-cycle fatigue dependencies, since there are no experimental data on the resistance of steel grade 30KhN3M1FA, from which the rotor is made, in the literature. Permissible values of the number of startup cycles from different thermal states and the permissible operating time under steady-state operating modes have been calculated. The level of the accumulated cyclic and static damage has been estimated for the HP rotor of Rivne NPP (RNPP) Unit 3. The loss of long-term steel strength, as a mechanism of destruction, has been found to have a dominant influence on the resource performance of the rotor under study, compared to low-cycle fatigue. The static component, $D_{st}$, of the accumulated damage of the HP rotor of the K-1000-60/3000 turbine of RNPP Unit 3 is 77%, the cyclic one $D_{cy}$ is 11%. The individual remaining useful life is 26,287 hours, which allows extending the HP rotor life by additional 25 thousand hours.*

***Keywords:*** *nuclear power plant, continued operation, residual life, steam turbine, low-cycle fatigue, long-term strength, design life.*

## Introduction

With taking into account both the exhaustion of the resource of the power equipment of thermal power (TP) and nuclear power (NP) plants and the shortage of organic fuel at TP plants, the reliability of nuclear power creates preconditions for the constant development of the energy sector of Ukraine. Electricity production by domestic NP plants is about 50%.

According to the Program for extending the life of the power equipment of the Ukrainian NPPs, out of fifteen Units, the lives of Units 1 and 2 of the Rivne NPP (RNPP), Zaporizhia NPP (ZNPP), South Ukrainian NPP (SUNPP) has been extended by ten to twenty years. The experience of the work done has shown that the specific financial costs of meeting the requirements of the regulatory documents that provide the opportunity to obtain a license for the operation of power units during additional life, are significantly less than the cost of building new power units.

In 2017–2018, the operational life of Unit 3 of the RNPP, Units 3 and 4 of the ZNPP and Unit 1 of the Khmelnytska NPP (KhNPP) expired. By 2020, the design life of Unit 3 of the SUNPP and Unit 5 of the ZNPP will have expired. Extending the life of NPP units after the design life expiry, subject to compliance with nuclear and radiation safety standards, is one of the most effective ways to partially solve the problem of replacing generating capacities.

A revision of the previously established terms of service of the power equipment of NPP units provides an estimate of the remaining useful life of the power equipment according to regulatory documents [1–5].

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## Purpose and Goal of the Study

The purpose of this paper is a calculated study of the resource parameters of the high-pressure (HP) rotor of the K-1000-60/3000 steam turbine of the 1000 MW unit of the state-owned enterprise NNEGC "Energoatom" during its operation beyond design life in accordance with regulatory documents [2, 5].

To achieve this goal, we performed:

– an estimated study of the HP rotor remaining useful life and allowable number of the K-1000-60/3000 steam turbine startups from different thermal states under cyclic loading ;

– a design study of the remaining useful life of the K-1000-60 / 3000 steam turbine HP rotor under static loading;

– an assessment of the possibility of a further extension of the K-1000-60/3000 steam turbine HP rotor operation beyond design life.

## Object of Study and Numerical Model Peculiarities

The object of this study is the K-1000-60/3000 condensing steam turbine with uncontrolled steam extraction, intermediate separation, and one-stage steam intermediate superheating that is designed for operation in a Unit with a VVER-1000 reactor. The high-pressure cylinder (HPC) is located in the middle section of the turbine, and low pressure cylinders (LPCs) are located symmetrically on both sides of the HPC. A detailed description of the rotor under study is given in [6].

The study of the thermal state of a HPC involves solving the boundary value problem of non-stationary thermal conductivity, for which the boundary conditions of the heat exchange on the rotor surfaces are set according to the software complex developed [7]. Diagrams of steam leaks both in the flow path and in the seals were taken into account, as well as the actual operating schedules for the typical operating modes, namely, the stationary one, as well as a cold, warm, and hot startups. The geometric model for the highly engineered HP rotor is made in a three-dimensional formulation, taking into account the main structural elements. The model is based on the K-1000- 60/3000 production drawings.

The stress-stain state (SSS) was estimated in an elastic-plastic formulation, using the finite element method of computational domain digitalization. The main types of stresses were taken into account, namely, temperature, irregularity of temperature fields, stresses from pressure, and centrifugal forces. The results of the calculation of the thermal and stress-strain states of the HP rotor under typical operating modes are given in [6].

The calculated assessment of the accumulated cyclic damage of the turbine equipment, according to normative documents [2, 4], should be performed according to the admissible numbers of the cycles of startups from different thermal states. For this purpose, experimental low-cycle fatigue curves are used for the particular steel, from which the turbine element under study is made.

A key feature of the calculation model is that there are no experimental curves of low-cycle fatigue for steel grade 30KhN3M1FA, from which the rotor under study is made, so it is proposed to calculate the permissible number of cycles according to the correlational dependencies of small-cycle fatigue [4]

$$N_{\text{adm}} = \left[1 - \left|\frac{1.25\sigma^{c}}{\sigma_{\text{LTS}}}\right|^{q}\right] \min\left\{\frac{N_1}{n_N}; N_2\right\},$$

$$N_{1,2} = \left[\frac{\frac{1}{4}\ln\frac{100}{100-\psi_{\text{LTP}}}}{C\left(n_{1,2}\varepsilon_{\text{amp}} + \frac{1-2\nu}{3E}\sigma_i\right) - \frac{\sigma_N}{E}}\right]^{\frac{1}{0.6}},$$

where $\sigma^c$ is the intensity of stresses in the state of constant creep; $\sigma_{\text{LTS}}$ is the limit of long-term strength; $q$ is the exponent in the long-term strength equation; $n_N$ is the strength reserve by the number of cycles; $\psi_{\text{LTP}}$ is the long-term plasticity determined by the median values for each temperature level $\theta_1$–$\theta_2$; $\theta_1$ and $\theta_2$ are the temperatures corresponding to the maximum and minimum strain rates in the load cycle; $C$ is the coefficient of the current number of cycles $C = \begin{cases} 1, \text{at } N \le 10^4 \\ \dfrac{\overline{K}_T}{K_T}, \text{at } N > 10^4 \end{cases}$; $n_1$=1; $n_2$=$n_\varepsilon$ are the margins of safety; $\varepsilon_{\text{amp}}$ is the amplitude of the strain intensity in the cycle $\varepsilon_{\text{amp}} = \dfrac{1+\nu}{1.5 \cdot E}\left[C \cdot \sigma_{\text{amp}} + \min(\sigma_{-1};\sigma_{\text{LTS}}) - \overline{\sigma}_N\right]$; ν is the Poisson ratio; $E$ is the Young modulus for the maximum temperature in the cycle $t_{\max}$; $\overline{\sigma}_N = \min\{\sigma_N; \sigma_N^c\}$ is the fatigue limit for an asymmetric load cycle; $\sigma_N = \dfrac{\sigma_{-1}}{1 + \dfrac{\sigma_{-1}}{\sigma_{\text{ftq}}} \cdot \dfrac{1+r}{1-r}}$,

$\sigma_N^c = \begin{cases} \min\left\{\dfrac{\sigma_{\text{amp}} \cdot \sigma_{\text{LTS}}(\theta_1)}{|\sigma_{\max}|}; \dfrac{\sigma_{\text{amp}} \cdot \sigma_{\text{LTS}}(\theta_2)}{|\sigma_{\max} - 2 \cdot \sigma_{\text{a}}|}\right\}, \text{at } \sigma_{\text{amp}} < \overline{\sigma}_{0.2}^{\text{cy}} \\ \min\{\sigma_{\text{LTS}}(\theta_1); \sigma_{\text{LTS}}(\theta_2)\}, \text{at } \sigma_{\text{amp}} \ge \overline{\sigma}_{0.2}^{\text{cy}} \end{cases}$; $r$ is the asymmetrical load cycle factor;

$r = \begin{cases} \max\left\{\dfrac{\sigma_{\max} - 2\sigma_{\text{amp}}}{\sigma_{\max}}; -1\right\}, \text{at } \sigma_{\max} > 0 \\ -1, \text{at } \sigma_{\max} \le 0 \end{cases}$; $\sigma_{\text{LTS}}(\theta_1)$, $\sigma_{\text{LTS}}(\theta_2)$ are the long-term strength limits corresponding to the temperatures $\theta_1$ and $\theta_2$; $\sigma_{\max}$ is the maximum tension in the cycle; $\sigma_{\text{amp}}$ is the amplitude of stress intensity; $\overline{\sigma}_{0.2}^{cy}$ is the average value of the reduced theoretical temperature cyclic limits of the material liquidity at the temperatures $\theta_1$ and $\theta_2$.

## Calculated Estimate of the Remaining Useful Life and Permissible Number of Startups for the HP rotor

The estimation of the resource parameters of power equipment is performed on the basis of calculation of static and cyclic damages of metal. For this purpose, it is necessary to have data on the thermal and stress-strain states of the rotor under all typical operating modes.

The thermal and stress-strain states for the stationary operating mode is performed in a quasi-stationary formulation [6]. The temperature level is 270 °C for the first stage and 165–228 °C for the second to fourth stages. The maximum stress intensity $\sigma_i$=158 MPa is observed in the axial relief hole and in the relief holes of the discs of all five stages. In other characteristic HP rotor areas, the stress intensity is 66–105 MPa. The high level of stress intensity in the axial hole region is explained by the large values of the centrifugal forces acting on significant mass concentrations, such as the discs of the pressure stages and their working blades. Under this condition, the highest level of stress is observed closer to the fifth stage, which is most massive and bladed with the heaviest blades (Fig. 1).

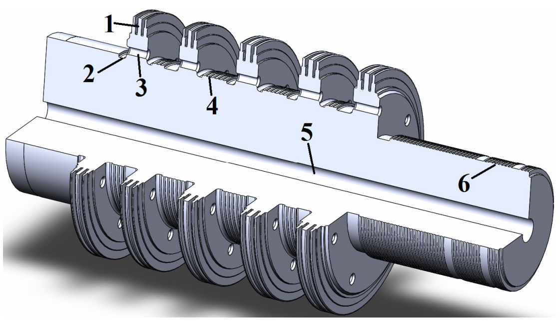

***Fig. 1. Typical study areas of the K-1000-60/3000 turbine HP rotor:***
1 – first stage tail attachment, 2 – first stage fillet from the steam inlet side, 3 – first stage relief hole, 4 – second stage diaphragm seals, 5 – axial hole in the area of the fourth and fifth stages, 6 – second stage of end seals

The startup modes are considered in a non-stationary formulation. Of particular interest in variable operating modes is the information on the irregularity of temperature fields over time, which is represented as the dynamics of the temperature gradient change for the most characteristic regions [6].

Thus, for a cold startup, the temperature gradient reaches its maximum value in the initial startup stages and for certain study areas is equal to 1,200 K/m. In general, the temperature gradient level does not exceed 1,300 K/m during the cold startup, which indicates that the temperature field unevenness is moderate.

Regarding the SSS, it should be noted that the highest modulus values of stress intensity $\sigma_i$=231 MPa are observed in the initial stages of a cold startup for the relief holes of the first stage disk (Fig. 2). These values remain almost unchanged until a point of time of 6,800 s, beginning with which a gradual decrease in the total stress level immediately before the turbine startup phase is completed. Starting from the 6,800 s time point, the turbine speed reaches its nominal value (3,000 rpm), the stage disk fillets and the axial rotor hole becoming zones of high stresses (Fig. 2).

Similar data have been obtained for a hot startup mode (Fig. 3). The calculations performed make it possible to evaluate the long-term strength and resistance to low-cycle fatigue of the rotor base metal. For this purpose, the K-1000-60/3000 turbine HP rotor of RNPP Unit 3 was selected.

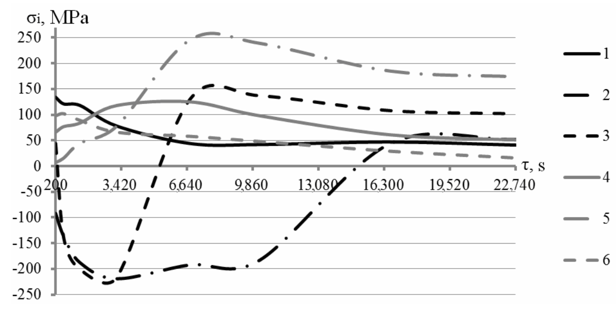

***Fig. 2. Dynamics of the change of stress intensity in the characteristic research areas of the K-1000-60/3000 turbine HP rotor during a cold startup***

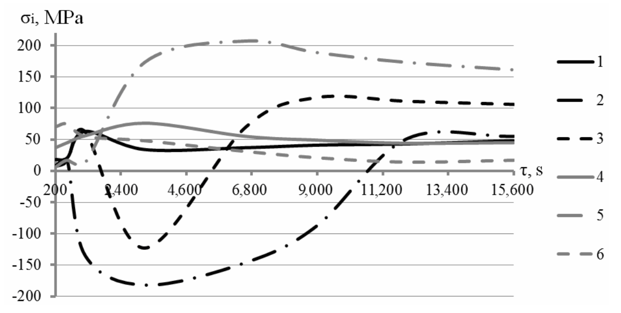

***Fig. 3. Dynamics of the change of stress intensity in the characteristic research areas of the K-1000-60/3000 turbine HP rotor during a hot startup***

The resource design life characteristics of the K-1000-60 / 3000 turbine according to the data of NNEGC "Energoatom" are as follows: service life – at least 30 years, permissible design number of startups – 600, yearly number of startups – 20. The service life is calculated to reach the boundary condition based on the maximum number of cycles per year.

During the scheduled preventive repair works at RNPP Unit 3 in 2014, the operating time parameters for the operating period were (as of 01.07.2014): total number of startups – 230, number of cold startups – 49, number of hot startups – 181, operating time – 177,919 hours. Thus, as a percentage, the number of cold startups is 21.3%, the number of hot startups is 78.7%. Assuming that during the following 5 years the Unit was operated in the same mode, then, as of July 2019, the operating time should be 209,690 h; the total number of startups, 271; the number of cold startups, 58; and the number of hot startups, 213.

According to the data of NNEGC Energoatom, the permissible design life is at least 30 years, and corresponds with 220 thousand operating hours for basic units. In the calculations, the power reserve coefficients of 10 and 1.5 are adopted respectively for the power reserve by the number of cycles and for the power reserve by the strain in accordance with regulatory documents [4].

The results of the calculated study of the resource characteristics of the HP rotor of the K-1000-60/3000 turbine of RNPP Unit 3 are shown below. Low-cycle fatigue was estimated from the permissible values of the numbers of startups from different thermal states, which had been calculated using the correlational dependencies of the fatigue of steel grade 30KhN3M1FA, from which the HP rotor is made [4]. The calculated cyclic damage $D_{cy}$ of the base metal is 11%, with the calculated static damage $D_{st}$ being equal to 95%. This predictively indicates a less significant effect of low cycle fatigue as a rotor damage mechanism compared to long-term strength loss.

The static damage was estimated by the design life of 220 thousand hours in accordance with regulatory documents [5], and is equal to 95%. The total damage of the base metal is 107%, i.e, exceeds 100%. This testifies to the end of the K-1000-60/3000 turbine HP rotor design life of 220 thousand hours.

We conducted experimental studies of the long-term strength of steel grade 25Kh1M1FA at a temperature of 500°C, which is used in the manufacture of HP and MP rotors of K-200-130 turbines [7, 8]. The results of the studies revealed the possibility of increasing the permissible number of operating hours up to 370 thousand hours.

***Resource characteristics of the K-1000-60/3000 turbine HP rotor of RNPP Unit 3***

| Resource characteristics | | Value | |
|---|---|---|---|
| Unit operating time | | 209,690 h | |
| Total number of start-ups | | 271 | |
| Yearly operating time | | 6354 h/year | |
| Year of commissioning year | | 1,986 | |
| Current number of startups from different thermal states | CS | 58 | |
| | HS | 213 | |
| Stress intensity in the nominal mode | | 158.5 MPa | |
| Permissible number of cycle startups from different thermal states | CS | 1,945 | |
| | HS | 2,591 | |
| Cyclic damageability | | 11.20 % | |
| Permissible operating time | | 220,000 h | 270,000 h |
| Static damageability | | 95.4% | 77.66% |
| Total damageability | | 106.6% | 88.86% |
| Residual service life | | <0 h<br>Resource depleted | 26,287 h |

There are no similar literature data regarding steel grade 30KhN3M1FA, from which the K-1000-60/3000 turbine HP rotor is made. It is understandable that due to the differences in the physical and mechanical properties of steel grades 25Kh1M1FA and 30KhN3M1FA, their long-term strength curves will also differ. However, taking into account that the operating temperatures of the metals of the HP rotors of the K-200-130 and K-1000-60/3000 turbines are 540 °C and 270 °C, respectively, it is proposed to evaluate the static damageability of the HP rotor of RAES Unit 3 with using the long-term strength curves of steel grade 25Kh1M1FA at a temperature of 500 °C as a calculation in the margin of safety. Additionally, it should be noted that NPP turbines require higher operational reliability. Therefore, it is proposed to accept the permissible number of operating hours for the steel used in the K-1000-60/3000 turbine HP rotor at the level of 270 thousand hours. Then the calculated static damage $D_{st}$ will be 78%, and the total damage of the base metal $D_{tot}$ will be 89%.

If the expert commission that is composed, in accordance with SOU-N IPE 40.17.401: 2004 [1], of the representatives of the power plant, specialized and other organizations, can accept the permissible operating time of the metal at the level of 270 thousand hours, then the total calculated damage $D_{tot}$=89%, and the remaining useful life of the metal of the K-1000-60/3000 turbine HP rotor of RNPP Unit 3 will be 26,287 hours. This will allow us to extend the K-1000-60/3000 steam turbine HP rotor operating time by 25 thousand hours.

## Conclusions

1. A model for calculating the thermal and stress-strain states of the K-1000-60/3000 steam turbine HP pressure rotor has been developed on the basis of the 3D-space analogue. It is established that the stress concentration zones are the fillets and relief holes in the first stage, as well as the axial hole of the shaft in the zone of the fourth and fifth stages.

2. It is determined that for the HP rotor, the SSS is dominantly influenced by the centrifugal force acting on massive turbine rotating elements. It is established that the maximum stress intensity value occurs in the region of the axial hole of the shaft under the fifth pressure stage, and is 158 MPa.

3. During a cold startup, the maximum stress intensity level ($\sigma_i$=263 MPa) occurs at a time point of 1,400s, and is related with the interaction of temperature stresses and temperature field irregularity. During a hot startup, the maximum stress intensity level ($\sigma_i$=226 MPa) occurs at a time point of 3,200 s in the region of the axial hole of the shaft.

4. According to the results of the numerical studies of the resource parameters of the K-1000-60/3000 turbine HP rotor, the total damage is 107%, including the cyclic and static damages of 11% and 95%, respectively, at design life of 220,000 h. Thus, the further operation of the HP rotor of RNPP Unit 3 is not allowed.

5. If the expert commission that is composed, in accordance with SOU-N IPE 40.17.401: 2004 [1], of the representatives of the power plant, specialized and other organizations, can accept the permissible oprerating time of the metal at the level of 270,000 h, then the remaining useful life of the metal of the

K-1000-60/3000 turbine HP rotor of RNPP Unit 3 will amount to 26,287 hours. This will allow us to extend the K-1000-60/3000 steam turbine HP rotor operating time by 25 thousand hours.

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*Received 06 November 2019*

## Оцінка ресурсних показників ротора високого тиску турбіни К-1000-60/3000 при продовженні експлуатації

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*Надійна робота атомних електростанцій (АЕС) є передумовою сталого розвитку енергетичного сектора України. На поточному етапі напрацювання значної частки паротурбінного устаткування АЕС наближається до свого паркового значення. Продовження експлуатації АЕС понад парковий ресурс потребує проведення перевірного розрахунку залишкового ресурсу його основних елементів. Розроблена модель оцінки ресурсних показників ротора високого тиску парової турбіни К-1000-60/3000. На базі тривимірного просторового аналогу виконано розрахунок теплового та напружено-деформованого стану ротора високого тиску для всіх типових експлуатаційних режимів роботи. Встановлено, що зонами концентрації напружень є галтельні скруглення та розвантажувальні отвори* *перших ступенів, а також осьовий отвір турбіни в області четвертого та п'ятого ступенів. Розрахунок темпів накопичення циклічного пошкодження в основному металі проведено з використанням кореляційних залежностей малоциклової втоми, оскільки експериментальні дані щодо опірності сталі 30ХН3М1ФА, з якої виготовлено ротор, в літературі відсутні. Розраховано допустимі значення чисел циклів пуску з різних теплових станів та допустимого часу роботи за стаціонарних режимів експлуатації. Для ротора високого тиску енергоблока № 3 Рівненської АЕС (РАЕС) оцінено рівень накопиченої циклічної та статичної пошкоджуваності. Встановлено, що вичерпання довготривалої міцності сталі, як механізм руйнування, має домінуючий вплив на ресурсні показники досліджуваного об'єкта порівняно з малоцикловою втомою. Статична складова накопиченої пошкоджуваності ротора високого тиску турбіни К-1000-60/3000 блока № 3 РАЕС* $П_{ст}$*=77%, циклічна* $П_{ц}$*=11%. Індивідуальний залишковий ресурс складає 26287 годин, що дозволяє продовжити термін експлуатації ротора високого тиску на додаткові 25 тисяч годин.*

***Ключові слова:*** *атомна електростанція, продовження експлуатації, залишковий ресурс, парова турбіна, малоциклова втома, довготривала міцність.*

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