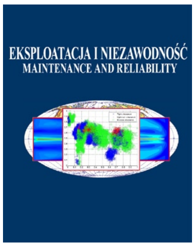

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Steam turbine maintenance planning based on forecasting of life consumption processes and risk analysis

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Highlights

- Flexible operation significantly intensifies the wear of the turbine.
- The forecast of life consumption processes development in turbine rotors is presented.
- The rotor failure probability was estimated for various operating scenarios.
- The optimal interval of preventive actions for turbine rotors is determined.

Abstract

Flexible operation of coal-fired power plants contributes to the intensification of the life consumption processes, which is a serious problem especially in the case of units with a long in-service time. In steam turbine rotors, the crack propagation rate and material wear caused by low-cycle fatigue increase. The aim of the research is an attempt to forecast the development of these processes and to estimate the probability of critical elements damage, such as the high-pressure and intermediate-pressure rotors. In the stress state analyses, the finite element method (FEM) is used, the Monte Carlo method and the second order reliability method (SORM) is apply to calculate the probability of failure. It is proposed to use risk analysis to plan preventive maintenance of the turbine. The optimal intervals for carrying out diagnostic tests and prophylactic repairs is determined for various operating scenarios and various failure scenarios. This enables a reduction of the costs while ensuring the safety of the turbine's operation.

Keywords

steam turbine, risk analysis, preventive maintenance.

1. Introduction

The selection of maintenance methods of technical subjects in power industry is an extremely important procedure due to the need to preserve the continuity of energy supply and limiting the possibility of failure, which would result in serious financial consequences caused by not only the repair costs, but also downtime in the operation of machines and devices. The purpose of developing various maintenance strategies (including, among others, a method based on risk analysis) is therefore the assurance of a good technical condition, avoidance of undesirable incidents, optimally operation management and cost reduction. An example of research in this field can be the analysis carried out for the desulphurization system of the coal-fired plant presented in [15]. In paper [18], a risk calculation for the power plant was performed to assess the potential economic losses related to two scenarios (probable and worst-case). Another example of performing a risk analysis is [4]. In the article, one of the critical elements of the gas block (the oil system used to lubricate the slide bearings of the gas turbine), was taken into consideration. For the power boilers, there is also a chance to conduct research in the maintenance strategy development due to, among others, the phenomena related to erosion and corrosion. A boiler tube protection strategy based on risk calculations is presented in [17]. The characteristics of the maintenance models, as well as the available methods of diagnostic testing used as part of failure prevention, are described in more detail in Section 2 of this article.

Forecasting of the life consumption processes development can be an effective tool that is the basis for decision-making procedure regarding the performance of diagnostic tests or corrective repairs of individual elements within the developed maintenance strategy. For machines and other technical objects, problems related to the crack propagation and material fatigue are often identified. An example of the prediction of crack development in the absorber weld was presented in [16]. Both a simulation and an experimental study were carried out. The calculation of crack propagation performed using the finite element method was described in [6]. Forecasting of the fatigue wear of a steam turbine rotor was presented in [23], where the stress amplitudes for individual cycle come from the online stress monitoring system based on Green's functions. Another example of an attempt to predict the fatigue phenomenon are the results presented in [25]. In this case, the analyzed element was a wind turbine blade.

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Both the selection of maintenance methods and the forecasting of the development of such phenomena as crack propagation or low-cycle fatigue especially relate to the coal-fired plants with a long in-service time, for which a change in operation conditions towards increased flexibility is observed. This mainly applies to the 200 MW units, which in Poland belong to the group of the longest-operating power plants. Plans to increase the degree of diversification of energy sources, as well as the increasingly stronger position of renewable and gas sources, mean that coal units will be slowly phased out, however, the operation of units with the best technical condition is still planned in a longer time horizon, which results directly from the country's energy policy. The aggravating effects of material wear, additionally intensified by the operation of the units in the regulation mode, may lead to damage, including serious failures, the consequence of which are long-term and costly downtime. The reliability of the power unit is also important in the context of participation in the capacity market. It is a support mechanism for units with a low failure rate that are able to provide power in the so-called periods of risk (periods of power shortage in relation to demand) [10]. Lack of energy production may result in the imposition of financial penalties, as well as loss of income related to the fulfillment of the obligation to maintain the declared capacity.

The flexible operation of the conventional power unit is associated with:

- a greater number of start-ups from various thermal states,
- shortening of the start-up time,
- more frequent power changes,
- more frequent work with a partial load,
- lowering of the technical minimum,
- more frequent downtimes.

A particular danger resulting from the regulatory mode of operation is the intensification of the low-cycle fatigue process causing the material damage and the loss of mechanical proprieties. This entails the failure under load lower than those resulting from the strength properties. The process adversely affects the existing cracks in the elements, increasing the rate of their propagation [12]. In the case of steam turbine rotors, the impulse stage central bore is the most vulnerable to fractures. It is associated with the concentration of stresses in this area and with a high probability of material defects caused among others by technological processes at the stage of metallurgical procedures. Fatigue processes can also cause damage in thermal grooves, which results in cracks on the surface or under the surface of the material.

The presented article focuses on the development of a methodology for the prediction of crack propagation and the fatigue process for the identified areas of the steam turbine rotor, which is then used as a part of a maintenance strategy based on risk analysis. Section 3 presents the results of rotor strength calculations performed using the finite element method (FEM). The algorithms for calculating of crack propagation in the central bore and material wear in heat grooves using the Monte Carlo method are presented. The probability of failure caused by these processes is estimated using the SORM method. Section 4 describes a procedure of determining the optimal interval for carrying out diagnostic tests, based on the failure risk analysis. For this purpose, a dedicated NPV index is used, which allows taking into account various failure scenarios and several critical areas of turbine rotors. This leads to the rational maintenance planning of long-operated power units. Section 5 is a short summary of the research with the conclusions.

2. Maintenance strategy for steam turbines

2.1. Available models of steam turbine maintenance

In the managing process for power units, many types of maintenance models are used to ensure the proper technical condition. The basic type is breakdown maintenance (or corrective maintenance), in which an inspection of the machine is carried out at the time of a serious problem that prevents further operation [9]. Based on this approach, no action is taken until a serious damage occurs (run until it breaks) [5]. The downtime associated with a failure may provide an opportunity to inspect the remaining elements, which is called opportunistic maintenance [9]. Due to the high required degree of reliability of the power units, the control of the elements only at the time of failure is not sufficient. For this reason, numerous actions are implemented as part of preventive maintenance [9]. These include, among others, periodic inspections, diagnostic tests, replacement of individual elements or their regeneration or revitalization. Due to budget constraints, preventive maintenance can be performed only for selected components. An example of a method of selecting elements subjected to such activities is presented in [26].

The most basic way to determine the frequency of preventive actions is time-based maintenance [28, 29]. Fixed time intervals are often used in the instructions of manufacturers who recommend routine maintenance [5]. This approach is also useful in the failure finding maintenance (FFM) [28]. The main purpose in this case is to find irregularities in devices that are not in continuous use, but which are significant for the operational safety of the unit and for which, under normal operating conditions, the damage is not visible. An example is turbine shut-off valves. Another type of maintenance is condition-based one (CBM) [27, 30] which also can be classified as a preventive method. It consists in monitoring certain process parameters, which are carefully analyzed. This leads to a decision regarding further operation. The deterioration of parameters may be a symptom of an incoming failure, and the earlier detection of irregularities gives time to react. The development of the CBM method is a predictive maintenance [5]. It uses more advanced techniques such as databases, machine and deep learning. Thanks to it, it is possible to obtain higher accuracy, reduce false alarms and analyze data from various measuring systems at the same time. An example of the use of machine and deep learning to predict failures and plan the maintenance of a turbofan engine is presented in [14]. The predictive method is the basis for prescriptive maintenance [27], in which changes of measured parameters require the initiation of appropriate repair procedures.

As part of preventive actions, it is also possible to implement risk-based maintenance (RBM) [11, 13]. Such a method often focuses on critical parts of the system [15]. In the RBM, activities are planned after prior determination of the level of failure risk, defined as the product of its probability and consequences (e.g. in the form of costs). This approach makes it possible to identify the most dangerous damage and focus on areas where it may occur. Properly conducted calculations, allow planning intervals between subsequent inspections [24] and their scope.

2.2. Diagnostic methods and preventive repairs of steam turbines

During diagnostics of steam turbines, non-destructive tests, which do not deteriorate the properties of the analyzed material, are often used. The basic methods include visual investigation of the object with the use of optical instruments, such as endoscopes, which enable inspection of inaccessible places without the need of disassembly [31]. This solution is often used to test the rotor central bore looking for material fractures. It may be difficult to distinguish common scratches (e.g. caused by cleaning process of the bore) from dangerous cracks. For this purpose, penetrating liquids are used, which will cause coloration only in the presence of a crack due to capillary forces [21]. Penetration liquids are also used to detect low-cycle fatigue cracks in heat grooves.

After locating the defect, more detailed research is applied. For many years, the eddy-current method has been used. It consists in the excitation of a variable electromagnetic field. The changes in the field, the phase shift and the amplitude make it possible to determine the state of the tested surface using special detectors [7]. Another solution used in the tests of central bores is the metal magnetic memory method (MMM). It is based on the control of the metal's normal spontaneous stray field. Devices used to perform this type of research enable the recording and analysis of the obtained measurements. As a result of the steel load, changes in the crystal structure occur, which are the reason for its magnetization. The distribution of the magnetic stray field shows the direction of the stresses. The test does not require prior preparation of the metal surface and allows an early detection of all kinds of discontinuities, material voids or fatigue changes [2].

After disclosure of any irregularities of the material in the tested areas, it is possible to make a correction. In the case of central bores, an effective solution is the rotor turning or top layer grinding [13]. A similar action is carried out in the heat grooves. Elimination of the top layer of metal improves resistance by removing the material with significant fatigue wear.

3. Forecasting of life consumption processes in steam turbine rotor

3.1. Crack propagation in steam turbine rotor

The crack behavior in a material is closely related to the stress intensity coefficient. This coefficient is a characteristic value for the stress distribution and strains located at the very peak of the crack. For fractures subjected to tensile forces, it can be described by the following formula [24]:

$$K_I = M\sigma\sqrt{a} \tag{1}$$

where:

M – nondimensional function of geometrical parameters of the crack and the element,

σ – tensile stress acting on the crack

a – crack dimension.

Crack propagation under variable-load conditions is described by the Paris-Erdogan formula in the form [3]:

$$\frac{da}{dN} = C\left(\Delta K\right)^m \tag{2}$$

where:

C, m - material constants,

$\Delta K = K_{Imax} - K_{Imin}$ – amplitude of stress intensity coefficient,

N - number of fatigue cycles.

Crack propagation in creep conditions during the steady-state is described by the equation [3]:

$$\frac{da}{dt} = AK^n \tag{3}$$

where:

A, n - material constants,

t - steady-state operation time.

During the operation of the steam turbine, the propagation of the existing crack takes place alternately under the variable and constant load. The greatest increase in stress occurs during the start-up. Using the finite element method (FEM), it is possible to determine the stress level in the analyzed area. An exemplary simulation of the heating process is carried out for the rotor high-pressure (HP) and intermediate-pressure (IP) part in accordance with the increase of parameters during two different start-ups (Figs. 1 and 2). The initial values of the temperature of the steam washing the rotor indicate that both start-ups are carried out from the cold state.

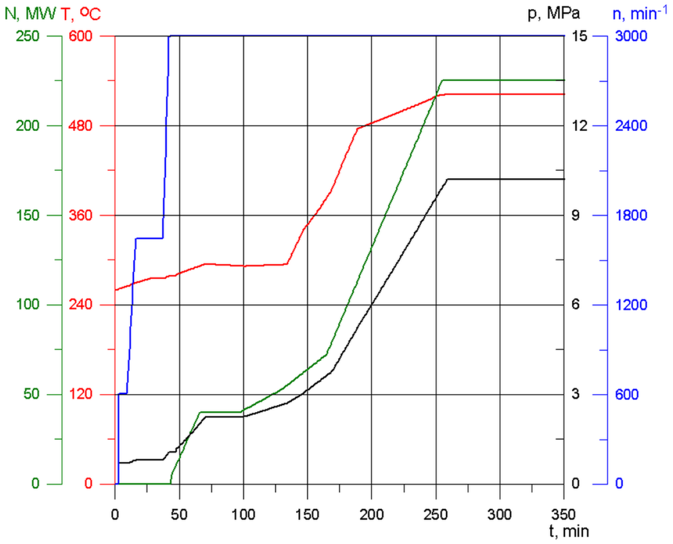

Fig. 1. Change in steam parameters during rotor cold start-up, N—turbine power, T—steam temperature, p—steam pressure, n— rotational speed (data for HP rotor)

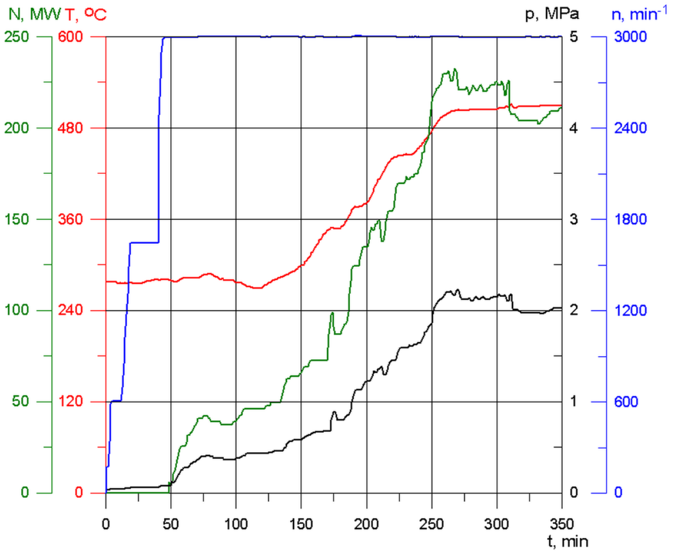

Fig. 2. Change in steam parameters during cold start-up, N—turbine power, T—steam temperature, p—steam pressure, n— rotational speed (data for IP rotor)

The results of the stress distribution for circumferential component, which acts in the direction of crack propagation, are shown in Figs. 3 and 4. The history of changes of these stresses during the cold start-up in the central bores is shown in Fig. 5.

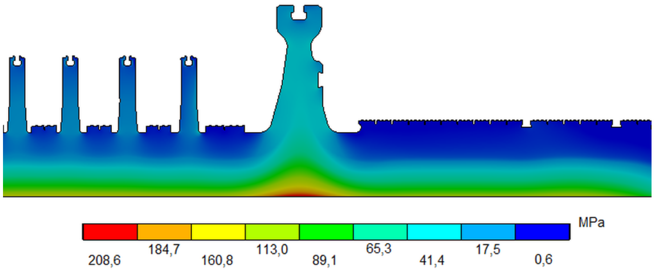

Fig. 3. Distribution of circumferential stress component in HP rotor during cold start-up

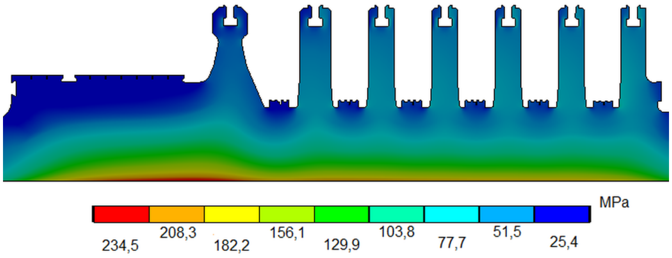

Fig. 4. Distribution of circumferential stress component in IP rotor during cold start-up

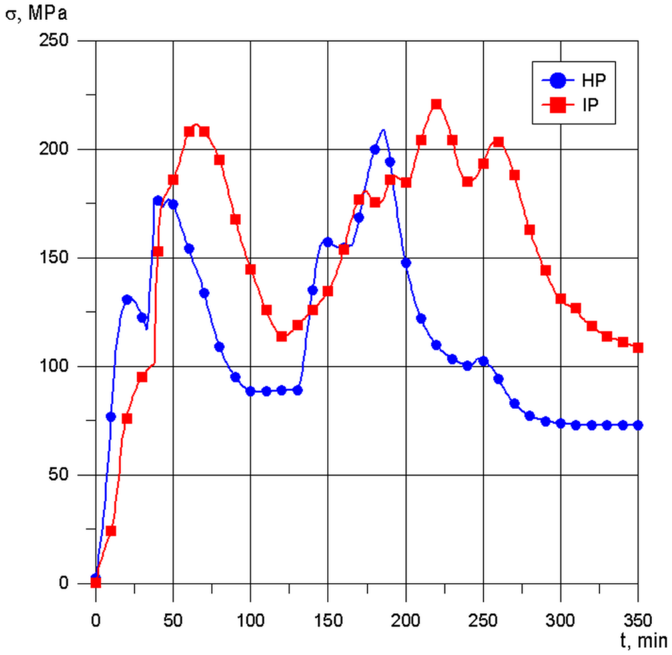

Fig. 5. History of changes in circumferential stress component during rotors cold start-up

Taking into account different types of start-ups, three scenarios are developed (Fig. 6). Each of them assumes that the unit will be started 200 times a year for the next 20 years. In the first scenario (#1), the turbine will be started relatively slowly, which will increase the stresses in the HP and IP central bores each time up to 200 MPa. In scenario #3, each start-up will cause a stress of 300 MPa in both rotors. This means that start-ups will be carried out much faster to meet the demands of the unit's high flexibility. In scenario #2, half of the start-ups will result in stresses at the level of 200 MPa, and the other half at the level of 300 MPa.

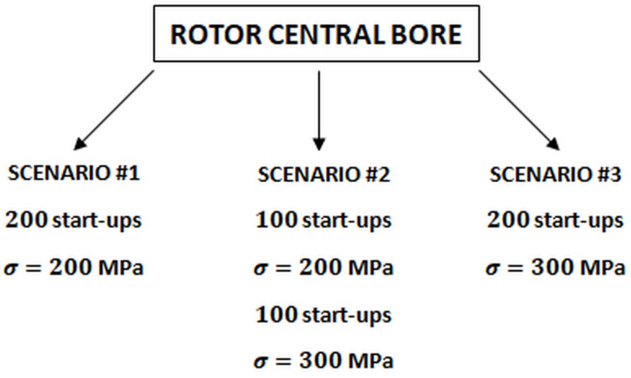

Fig. 6. Stresses in the rotors central bores for different operating scenarios

The period of operation under creep conditions between successive start-ups is 30 hours. The FEM is again used to determine the level of stresses in the steady-state. Figs. 7 and 8 show the distribution of effective stresses in the rotors after the values stabilization due to the relaxation process. The process itself is clearly visible in Fig. 9. In the calculation of stresses in creep conditions, the material model described by Norton's equation [8] is used:

$$\dot{\varepsilon} = B\sigma^n \tag{4}$$

where:

$\dot{\varepsilon}$ - strain change in time,

B, n - material constants, determined during creep testing of rotor steel.

In further calculations, the mean values of stresses under creep conditions are assumed at the level of $\sigma_{creepHP} = 55$ MPa (for the HP rotor) and $\sigma_{creepIP} = 60$ MPa (for the IP rotor)

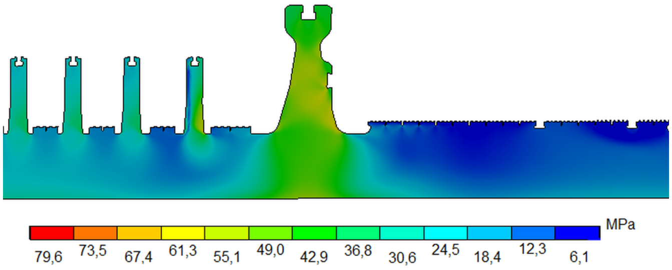

Fig. 7. Distribution of effective stresses after relaxation process in HP rotor

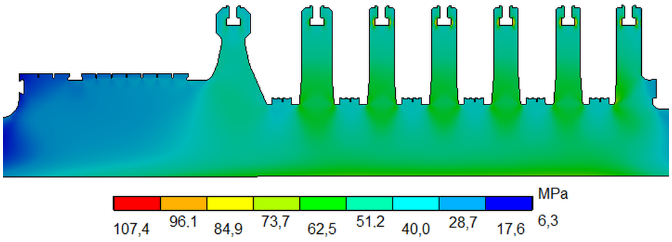

Fig. 8. Distribution of effective stresses after relaxation process in IP rotor

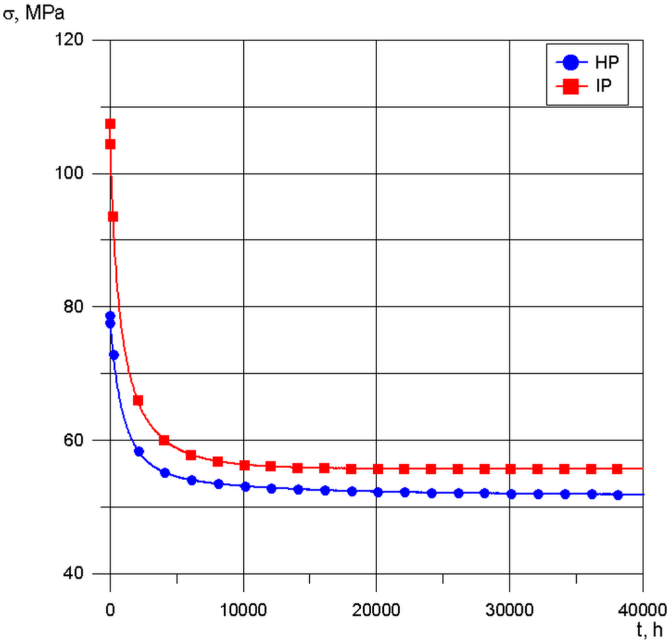

Fig. 9. Stress relaxation process in rotors central bores

The article [24] presents an analysis of the crack propagation in the HP rotor of the steam turbine for the previously mentioned operating scenarios and for selected initial crack dimensions. In this study, the initial dimension is assumed at the level of 2.5 mm and 5 mm. The obtained results are compared with the crack propagation rate in the IP part of the rotor. A crack size of 2.5 mm is problematic to detect due to the specified accuracy of the measurement methods. Therefore, it can be assumed that when during diagnostic tests the discontinuities are not detected, there is a crack of such size that propagates during operation. In order to take into account the possible variability of individual input data during the actual operation of the turbine, the random nature of quantities are assumed, and the Monte Carlo method is used in the calculations. For this purpose, it is assumed that the variables are characterized by normal distributions with a known mean value and a known standard deviation, which are presented in Table 1.

Table 1. Mean values and standard deviations of the quantities affecting the crack propagation

Input data	Mean value	Standard deviation
C	2e-12	1e-13
m	3.4537	0.173
A	3e-14	1.5e-15
n	5.6572	0.283
$\Delta\sigma_1$	200 MPa	10 MPa
$\Delta\sigma_2$	300 MPa	15MPa
$\sigma_{creepHP}$	55MPa	2.75MPa
$\sigma_{creepIP}$	60 MPa	3 MPa
a_0	2.5/5 mm	0.5 mm
t	20 years x 6000 h/year	-
N	200 cycles/year	-

The results of the crack propagation rates are shown in Figs. 10 and 11 respectively for $a_0 = 2.5$ mm and $a_0 = 5\,\text{mm}$. For the initial crack dimension of 2.5 mm, the increment is small and achieves the maximum value of 5.9 mm for scenario #3 over the entire assumed operation time. For a larger initial dimension of 5 mm, the growth is much more rapid. For scenario #1, the value doubles over 20 years of operation, and for scenario #3, it more than triples. Due to the higher stress level during steady-state (under creep condition) in the case of the IP rotor, the achieved dimensions for each subsequent year are also higher than for HP.

3.1. Probability of failure due to crack propagation

Not every crack, even the one that propagates during the operation, will lead to the failure of an object. This happens only when the critical dimension (a_{cr}) is exceeded, which causes the so-called brittle fracture of the material. The failure criterion will therefore take the form of:

$$g_1 = a_{cr} - a \tag{5}$$

The probability of failure is then described as:

$$P_{f1} = P(g_1 \le 0) \tag{6}$$

and can be calculated using the second-order reliability method (SORM).

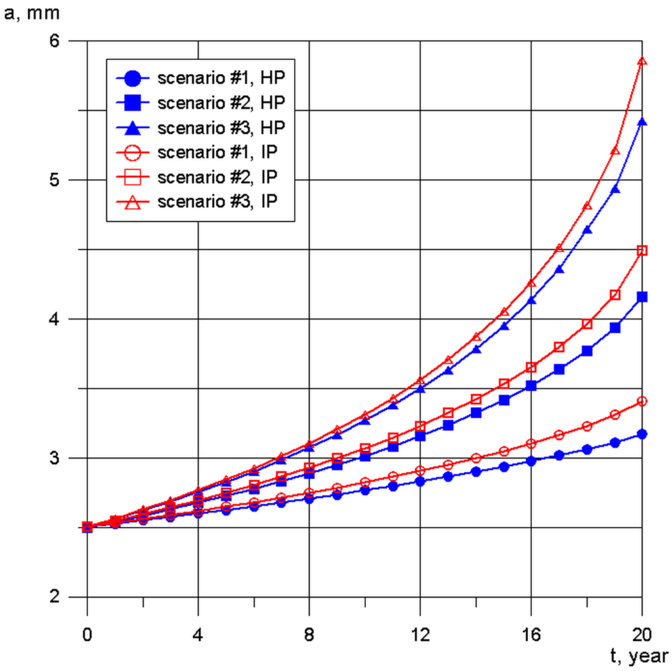

Fig. 10. Crack propagation over time for different operating scenarios ($a_0 = 2.5$ mm)

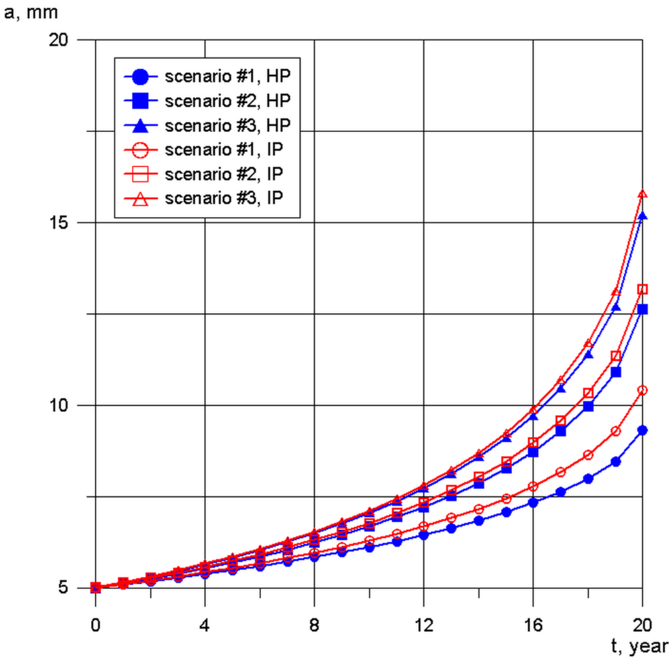

Fig. 11. Crack propagation over time for different operating scenarios ($a_0 = 5\,\text{mm}$)

The critical crack dimension is determined by the relation:

$$a_{cr} = \left(\frac{K_{IC}}{M\sigma}\right)^2 \tag{7}$$

where:

K_{IC} - fracture toughness.

Fracture toughness is a material property that decreases over the years of operation. Its initial value for the analyzed rotor steel is assumed as 100 $\text{MPa}\sqrt{\text{m}}$ and it is possible to determine the decrease using the SPT (small punch testing) method which gives possibility to appoint mechanical properties of the material without the necessity to perform destructive tests [20]. During calculation of the failure probability for long in-service turbines, it is assumed that the fracture toughness dropped to 60% of the initial level and it is a random value with a normal distribution, with a known mean value and a standard deviation of 5%.

Fig. 12 shows the results of the probability (for $a_0 = 2.5\,\text{mm}$) of exceeding the critical dimension, for which the mean value is 21.8 mm in the case of scenario #1 and 10.13 mm for scenarios #2 and #3. The level of 0.001 can be considered as a significant probability value. It will be exceeded in scenarios #2 and #3, which indicates that both the HP and IP rotor should be monitored for crack propagation. For the operation according to scenario #1, the probability is negligible and the critical fracture dimension will not be reached, even for a long assumed time period.

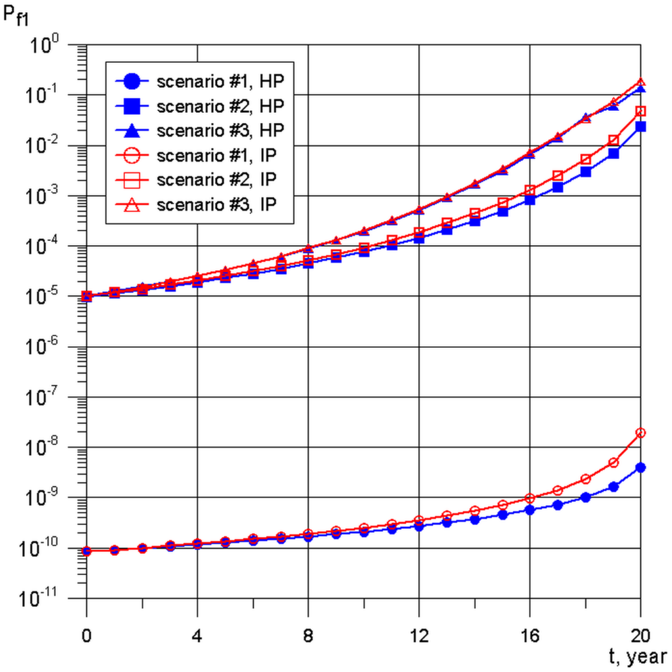

Fig. 12. Failure probability due to crack propagation for different operating scenarios(a_0=2.5 mm*)*

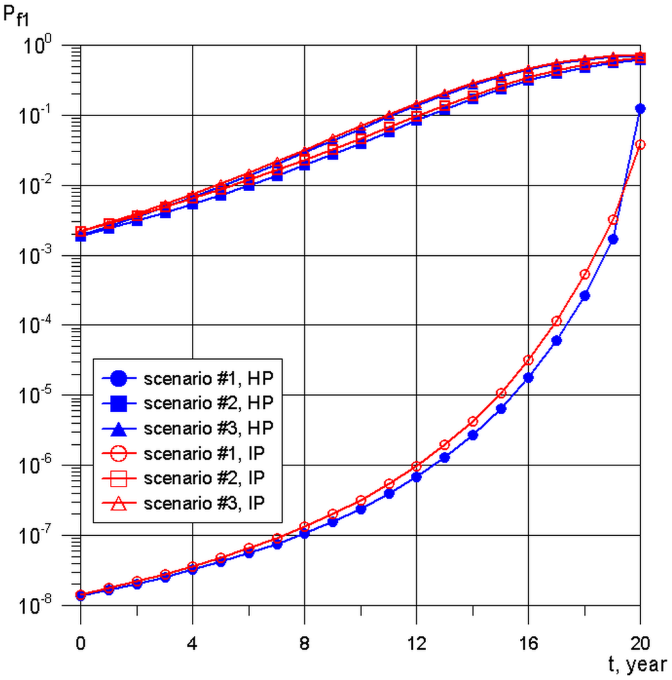

Fig. 13. Failure probability due to crack propagation for different operating scenarios (a_0 = mm*)*

Fig. 13 shows the results of failure probability in the case where the initial crack dimension is found at the level of 5 mm. A similar analysis was performed in [24] for a single element (HP rotor). This paper presents the results for the central bores of both turbine's HP and IP parts. The value of 0.001, indicating a significant risk of failure, is achieved within the assumed operating time for each developed scenario, and in the case of scenarios #2 and #3 even at the beginning of monitored period. This means that diagnosis of a crack should be a signal to consider preventive actions to limit propagation. After 20 years, the probability may even exceed 0.7.

3.3. Life consumption processes in thermal grooves

The highest stresses in the entire turbine rotor occur in transient states in the thermal grooves where they are concentrated [1]. Stress concentration favors the intensification of the low-cycle fatigue process, which in turn contributes to the material consumption in this area. In addition, long-term operation at high temperatures also increases creep wear. To estimate the durability of the rotor material under such conditions, the hypothesis of linear wear accumulation can be used, according to relation [19]:

$$Z = Z_N + Z_t \tag{8}$$

where:

Z - total wear,

Z_N - fatigue wear,

Z_t - creep wear.

Fatigue wear Z_N caused by one cycle is described by the formula:

$$Z_N = \sum_{i=1}^{m} \frac{1}{a\left(\Delta\varepsilon_i\right)^b} \tag{9}$$

where:

a,b - material constants,

$\Delta\varepsilon$ - strain change,

m - number of significant strain changes during one cycle;

The creep wear per one hour of operation in steady-state is described by the formula:

$$Z_t = \frac{1}{c\sigma^d} \tag{10}$$

where:

c,d - material constants,

σ - stress during steady-state;

The total wear after N fatigue cycles and after t hours of operation, according to the linear hypothesis, takes the form:

$$Z = N\sum_{i=1}^{m} \frac{1}{a\left(\Delta\varepsilon_i\right)^b} + t\frac{1}{c\sigma^d} \tag{11}$$

Using the FEM, various types of start-ups, from different thermal states, were analyzed. Examples of the reduced stress distributions occurring during the start-ups carried out in accordance with Figs. 1 and 2 for HP and IP rotor are presented in Figs. 14 and 15. Fig. 16. shows the history of changes for effective stresses in the thermal grooves, where highest values occur.

Based on the analysis, various operating scenarios are developed. The assumptions of operation time and the number of start-ups are the same as described in point 2.1. Scenario #1 again assumes the small-

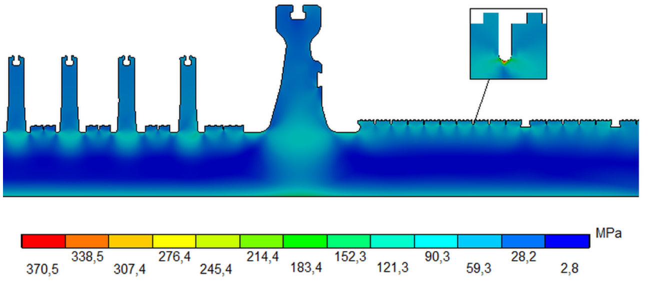

Fig. 14. Distribution of effective stresses in HP rotor during cold start-up

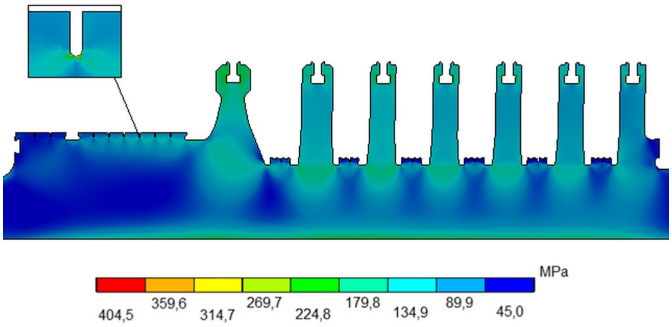

Fig. 15. Distribution of effective stresses in IP rotor during cold start-up

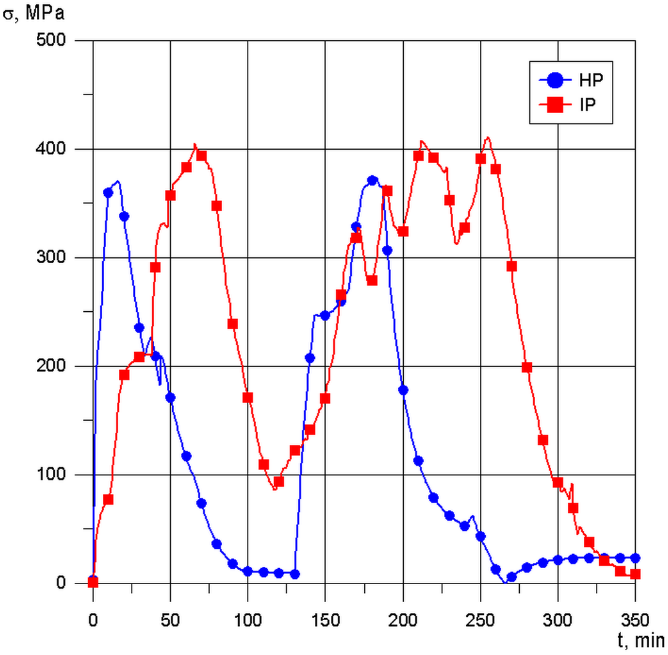

Fig. 16. History of changes in effective stresses during rotors cold start-up

est stress values, and scenario #3 assumes the highest stresses. In the case of the thermal grooves, higher stress values were observed in the IP rotor, therefore the scenarios in this case need to be developed individually for the rotors, as shown in Fig. 17.

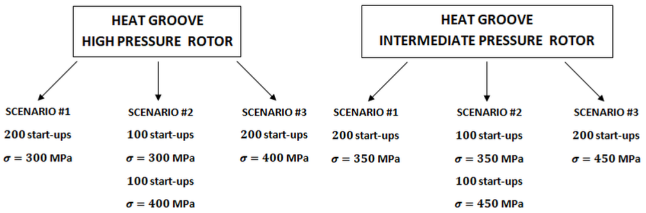

Fig. 17. Stresses in the heat grooves for different operating scenario

The main stress component in the heat groove is thermal one, for which the highest values occur during start-ups and other transient states. After rotor heating process, thermal stresses decrease significantly, which is additionally contributed by the relaxation phenomenon. For this reason, it was assumed that the total creep life of this area is 10^6 h. As in the case of crack propagation, the Monte Carlo method was used to determine the probability of failure caused by the accumulation of fatigue and creep wear. The assumed random variables have a normal distribution with a known mean value and standard deviation (Table 2).

Table 2. Mean values and standard deviations of the quantities affecting life-consumption processes

Input data	Mean value	Standard deviation
a	464	46,4
b	−1,589	−0.079
E	180 GPa	9 GPa
$\Delta\sigma_{1HP}$	300 MPa	15 MPa
$\Delta\sigma_{2HP}$	400 MPa	20 MPa
$\Delta\sigma_{1IP}$	350 MPa	17,5 MPa
$\Delta\sigma_{2IP}$	450 MPa	22,5 MPa
Z_t^{-1}	1 000 000 h	50 000 h
Z_0	0	-
t	20 years x 6000 h/year	-
N	200 cycles/year	-

Fig. 18 shows the results of calculations for total wear, calculated in accordance with the hypothesis of linear accumulation for the first variant, according to which the level of initial wear is assumed as $Z_0 = 0$. In the IP rotor, significantly higher wear levels can be ob-

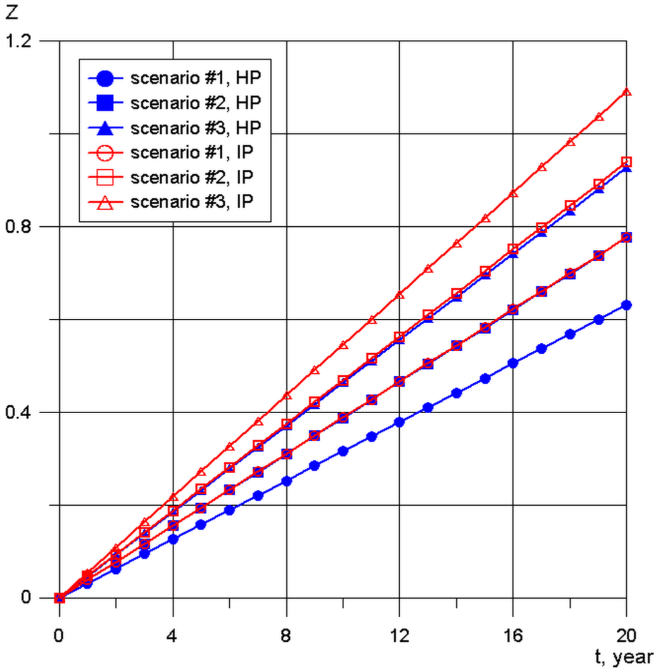

Fig. 18. Material wear over time for different operating scenarios ($Z_0 = 0$)

served for each of the developed scenarios, as well as the exceeding of critical value equal to 1 for scenario #3. The smallest wear occurs in the HP rotor for scenario #1 and it is slightly above 0.5.

Turbine rotors analyzed in the article are the long in-service objects. For this reason, higher initial wear values can be expected. Therefore, the calculations are performed again for the initial rotor wear equal to Z_0=0.5. The results are shown in Fig. 19. In this case, in both rotors and for each scenario, the wear value will exceed the critical limit of 1 between the 8th and 16th years of operation, which indicates the need of material condition monitoring in order to avoid serious failure.

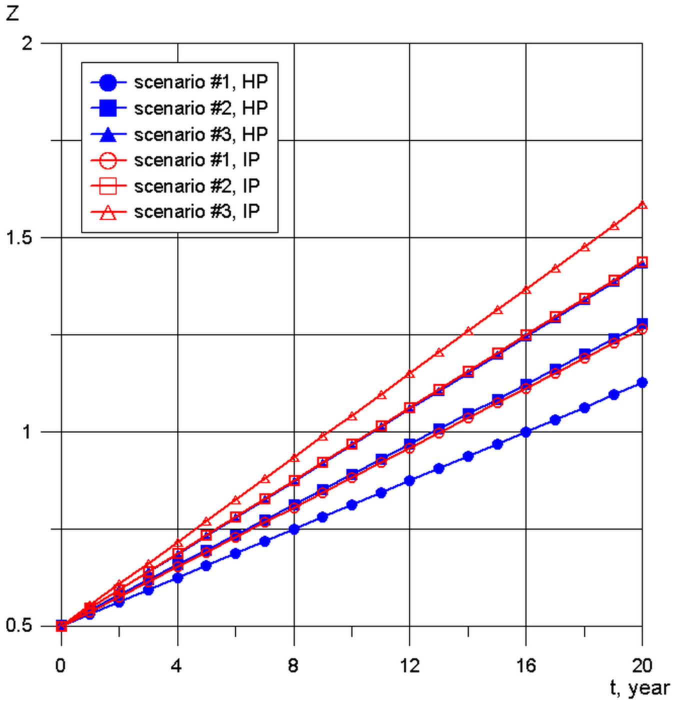

Fig. 19. Material wear over time for different operating scenarios ($Z_0 = 0{,}5$)

3.4. Probability of failure due to material wear in thermal grooves

Rotor failure caused by life consumption processes in the thermal grooves will occur after the limit value Z_g is exceeded which means the material life exhaustion in this area. In such a case, the failure criterion will take the form:

$$g_2 = Z_g - Z \tag{12}$$

As already mentioned, the expected wear limit is equal to 1 (100% wear). Due to the random nature of the fatigue processes, it was assumed in the calculations that this critical value is a random variable with a normal distribution and a standard deviation of 0.03.

The probability of a potential failure is described by the formula:

$$P_{f2} = P(g_2 \le 0) \tag{13}$$

The SORM was again used to calculate the probability of damage. The results for the initial wear $Z_0 = 0$ are shown in Fig. 20. Before the end of the 8th year of operation, for each scenario, the probability of failure is so low that it is not presented in the diagram (below $1 \cdot 10^{-10}$). The highest value is achieved after 20 years for the IP rotor and for the scenario #3 (it is equal to 0.7). The lowest value occurs for the HP rotor and scenario #1 (it does not exceed the value of 0.001, which is considered as significant for operational safety of the turbine). In other cases, the probability is in the range of 0.045-0.34 at the end of the planned operation time.

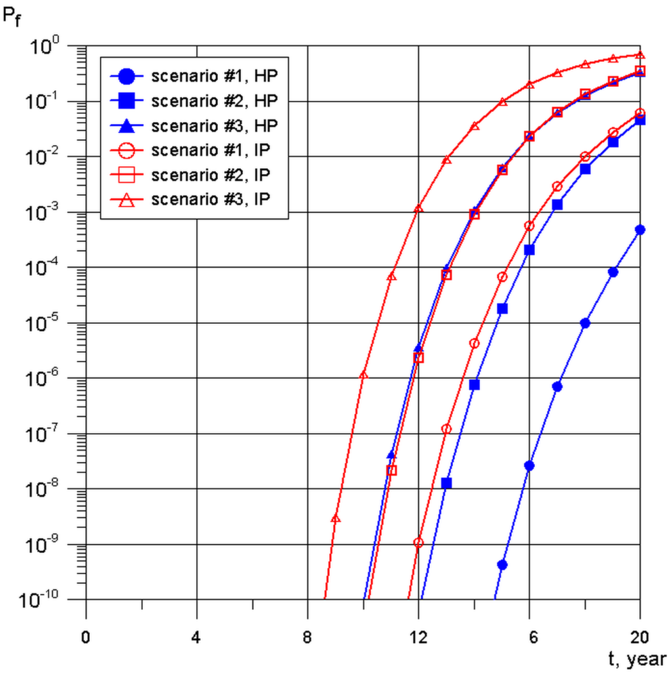

Fig. 20. Failure probability due to material wear for different operating scenarios ($Z_0 = 0$)

Fig. 21 shows the results of the probability of failure due to material consumption in the thermal grooves for the initial wear of this area . In this case, the obtained values are much higher and for each scenario the level of 0.001 will be achieved already in the first decade of the considered operation time. Additionally, after 20 years, the lowest probability value is 0.84 for scenario #1 and the HP rotor, and close to 1 in other cases, which means that the failure is an almost certain event.

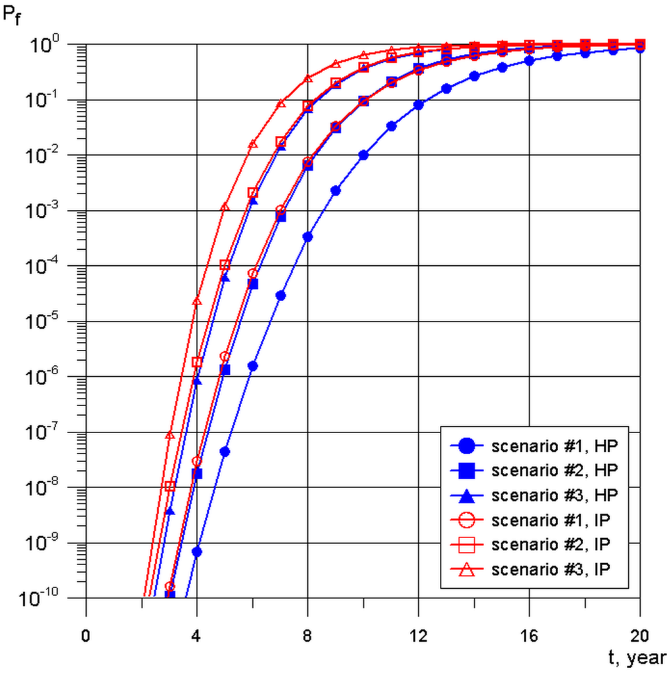

Fig. 21. Failure probability due to material wear for different operating scenarios (Z=0.5)

4. Planning of diagnostic tests and repairs of turbines

4.1. Planning of preventive maintenance intervals

The estimated failure probability P_f of an element or the entire system, as well as the cost value C_t (failure economical consequences), allow determining the level of risk of an undesirable event. The preventive actions carried out contribute to reducing the risk of failure, so that for the assumed time period (*N* years), the so-called avoided risk described by the equation [24] can be determined:

$$R_{Tu} = \sum_{t=0}^{t=n} P_f \cdot C_t \tag{14}$$

Besides the failure costs, rational planning of machine maintenance should also take into account costs related to preventive maintenance. Basic expenses in this area are these allocated to professional diagnostic tests, repairs or element replacement. In order to consider all these aspects, an appropriately formulated NPV index can be used, and due to the long-term planned operation, cash flows should be presented as discounted values. Additionally, it should be taken into account that the failure may concern several elements of a complex system or, within one element, it may be carried out in accordance with several identified scenarios. An index that includes all the described aspects may take the form of equation [22]:

$$NPV = \sum_{j=1}^{l}\sum_{t=0}^{N}\frac{P_{f0j}C_{tj}}{(1+r)^t} - \sum_{j=1}^{l}\sum_{t=n}^{N}\frac{C_{rtj}}{(1+r)^t} - \sum_{j=1}^{l}\sum_{t=0}^{n}\frac{P_{f0j}C_{tj}}{(1+r)^t} - \sum_{j=1}^{l}\sum_{t=n}^{N}\frac{P_{f1j}C_{tj}}{(1+r)^t} \tag{15}$$

where:

P_f - probability of failure in the period prior to diagnostic testing, repairs or replacement,

P_{f1} - probability of failure in the period after diagnostic testing, repairs or replacement,

C_t - cash flows related to a loss of production due to failure and other failure-related costs,

C_{rt} - cash flows related to costs of repairs, diagnostic testing or replacement,

r - discount rate,

N - total planned service life,

n - year in which the element is tested, repaired or replaced,

l - number of risk of failure elements in system or number of failure scenarios.

The first and at the same time the only positive part of equation (15) determines the benefits of the so-called avoided risk of failure. The second part is responsible for the costs related to the inspection and preventive repair or replacement of elements. The third and fourth segment, in turn, illustrate the losses related to forced stoppages and the costs related to the breakdown in the period prior to the inspection (part 3) and after the inspection (part 4).

Determining the value of the NPV index for each year of system operation, allows assessing whether preventive activities is economically justified. The positive values of the index indicate the validity of the preventive maintenance. Performing optimization in order to find the maximum of the NPV(t) function allows determining the best time for the inspection of the object and possible correction of the technical condition.

4.2. Optimization of preventive maintenance intervals

The analyses of crack propagation and the development in material consumption in the HP and IP rotors of the steam turbine, as well as the failure probability determined on this basis, indicate the need to supervise the described critical areas. The supervision is based on carrying out diagnostic tests to verify the condition of the material and its compliance with the forecast condition, as well as preventive repairs to restore the appropriate level of operational safety, which reduces the risk of failure in the long term. In order to determine the best time to carry out the discussed activities, NPV calculations are performed in accordance with the formula (15) for two identified failure scenarios related to exceeding the critical dimension of the crack in the central bore and the exhaustion of material life in the thermal grooves. Fig. 22 shows the whole procedure of maintenance planning.

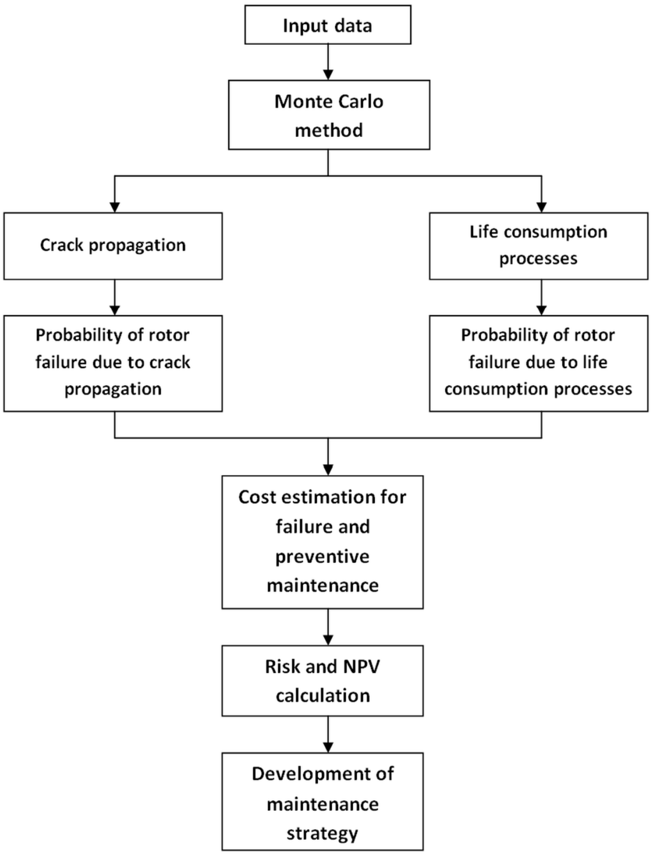

Fig. 22. Maintenance planning procedure for turbine rotors

The article [24] presents the analysis of the NPV index for a single element and one failure scenario (crack propagation in the HP rotor). Fig. 23 presents the change of the NPV index in the assumed operation time for one failure scenario (crack propagation in the central bore), but for both HP and IP rotors. Based on that, it is possible to make decisions related to the operation of a more complex system. The calculations are performed for all three operating scenarios and for following assumptions:

- initial crack dimension a_0 is 2.5 or 5 mm, the fracture toughness K_{IC} is $60\,\mathrm{MPa}\sqrt{\mathrm{m}}$;
- costs related to failure (C_t) due to crack propagation are equal to 100 conventional units (100% of costs), which means that brittle fracture can lead to catastrophic failure of the rotor;
- costs related to preventive inspections and repairs are equal to 15 conventional units (15% of failure costs).

In the case of the initial dimension $a_0 = 2.5\,\mathrm{mm}$, for all operating scenarios the NPV index in the whole analysed time has negative value. This means that the initiation of the period of diagnostic tests and preventive repairs in the central bores is not economically justified. The profit in the form of the avoided risk does not exceed the cost of preventive maintenance. In the case of significant initial crack dimension ($a_0 = 5\,\mathrm{mm}$), the proposed NPV index has a different course, which is visible for scenarios #2 and #3. It is then worth to start the diagnostic period even in the first years of the monitored time, as indicated by a positive NPV value (for scenario #2 from the 4th year, and for scenario #3 from the 1st year). The optimal time for carrying out preventive activities is visible in the point where the extremum of the presented function occurs (for 13th and 12th year of operation, respectively for scenarios #2 and #3).

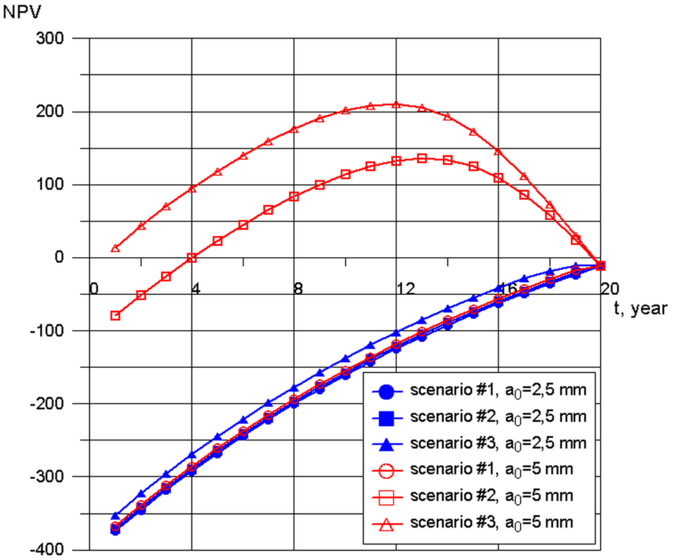

Fig. 23. Change of the NPV index for various operating scenarios and rotor failure due to crack propagation

The NPV index is again calculated, but this time taking into account the second failure scenario (the material consumption in thermal grooves due to fatigue and creep processes). Costs of failure are assumed at a lower level than in the previous case, because this kind of damage is not associated with such serious consequences as a brittle fracture in the rotor central bore. The costs associated with the inspection and preventive repair, however, are the same due to the need to use similar diagnostic and repair methods. Therefore, the following assumptions were made:

- initial wear Z_0 is 0 or 0.5;
- costs related to failure (C_t) due to material consumption are equal to 75 conventional units (75% of failure costs related to brittle fracture);
- costs related to preventive inspections and repairs are equal to 15 conventional units.

Fig. 24 shows the results of the calculations. It can be observed that in the case of $Z_0=0$, the NPV values for all operation scenarios are negative. This again means that it is not worth carring out preventive maintenance. However, such maintenance should be taken in the case of higher level of initial wear (which usually occurs in long in-service turbines). The optimal time to start preventive activities, consisting in the reduction and elimination of the failure risk, is the 12th, 9th and 8th year, respectively, for operating scenarios #1, #2 and #3.

Using the formula (15), all analyzed objects (HP and IP rotors) and all failure scenarios (crack propagation for and material wear for) are combined. All assumptions made so far regarding the costs of failures and preventive maintenance are kept. The results are shown in Fig. 25. The optimal time for starting the period of diagnostic tests or repairs is the 14th, 10th and 9th year of the operation, for subsequent scenarios #1, #2 and #3. In each case, the optimization result occurs earlier than for the crack propagation analysis in the central bore and later than for the material wear analysis in the thermal grooves. The advantage of using a combined NPV index, compared to index calculated individually for each element and for each failure scenario, is the ability to carry out inspection and possible repair for all areas during one stoppage, which reduces the total time in which the turbine does not work.

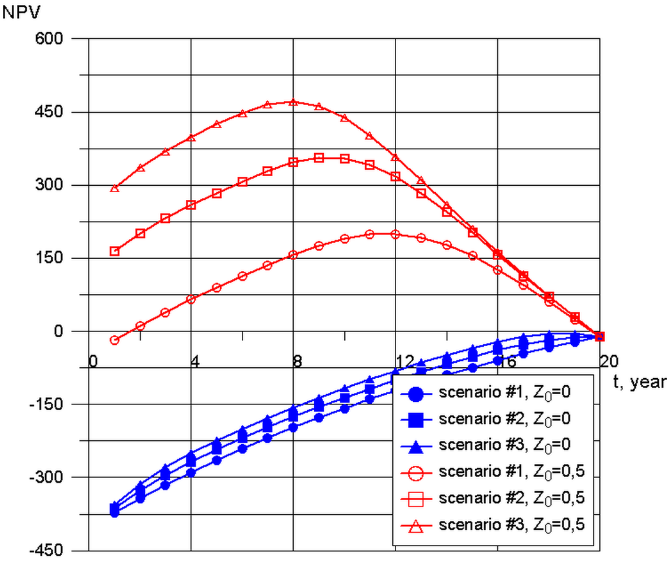

Fig. 24. Change of the NPV index for different operating scenarios and rotor failure due to material wear

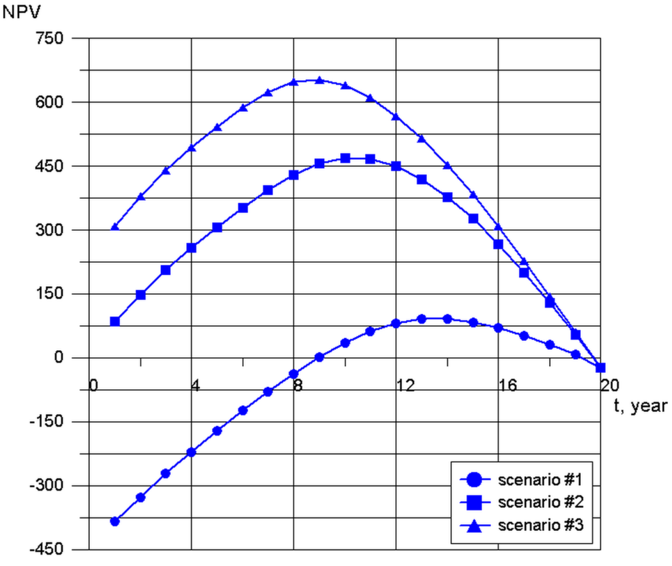

Fig. 25. Change of the NPV index for different operating scenarios and rotors failure scenarios $(a_0 = 5\,\mathrm{mm}, Z_0 = 0{,}5)$

Moreover, the NPV sensitivity analysis are made. Costs related to diagnostic tests and repair of individual areas are assumed on different level (5, 15 and 30 conventional units). The results are presented in Fig. 26. They concern the most dangerous operating scenario (#3). The reduction of costs may occur as a result of, for example, carrying out the diagnostic test alone without preventive repair of the object. Then it is rational to plan the inspection for the entire analyzed period (positive NPV), with the optimal time being achieved in 7th year of operation. Increasing of the preventive activities costs, in turn, makes it justified to use the proposed methodology of maintenance planning based on a risk analysis, because not in the entire monitored period, the profits will exceed the losses. The best time for inspection in this case is 11th year.

5. Conclusions

The aim of the research was to develop a methodology enabling rational planning of steam turbine maintenance based on a risk analysis. The identified critical elements are the high-pressure and intermediate-pressure rotors, and the critical areas are the central bores of the impulsive stages and thermal grooves. In the central bores, the propagating cracks, which can lead to complete destruction of the ro-

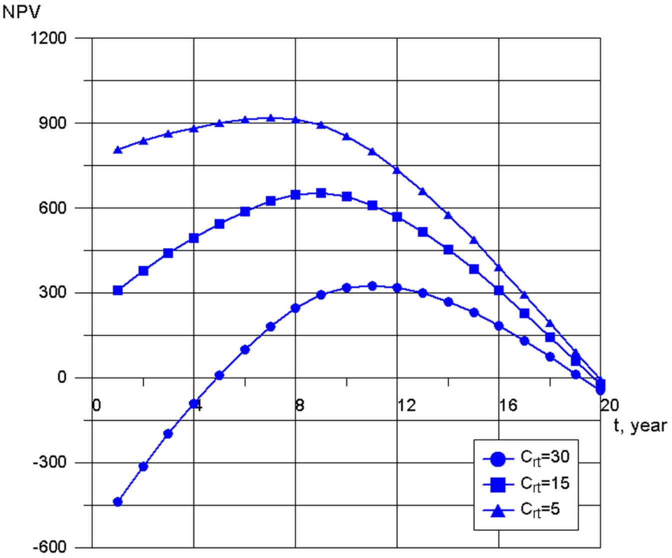

Fig. 26. Analysis of NPV sensitivity to the cost of preventive maintenance Crt (scenario #3, a_0=5 mm, Z_0=0.5)

tor, may appear. In the thermal grooves, the material wear occurs due to low cycle fatigue and creep. The results of calculations showing the development of the life-consumption processes in subsequent years of operation, as well as the probability of failure, have been presented. They have confirmed that the described phenomena constitute a real danger in the operation of steam turbines. During the assumed 20 years, the failure probability at the level of 0.001 may be exceeded, which means that the indicated areas should be supervised.

Limiting or reducing the risk of failure in rotors is achieved through the use of advanced diagnostic testing and repair in order to restore the material's appropriate condition. For this purpose, it is worth using the proposed NPV index, which signals the legitimacy of preventive actions taking into account the economic aspect. Sample courses of the index value for the assumed costs related to the failure and repair of the rotor were analyzed. The influence of possible operating scenarios on the optimal inspection time has been discussed extensively. A similar analysis has been performed for various failure costs and the original material condition. It has been found that the worse the initial condition of the material (greater degree of wear, greater size of the crack), the faster the inspection should be carried out - sometimes it is justified already at the beginning of the monitored period. The optimal time of conducting the tests is transferring towards the beginning of the period, especially when the turbine is operated in worse conditions (flexible regime, faster start-ups, frequent power changes). The developed methodology can be used for real units with known operating parameters and for the exact cost values of the planned tests.

Acknowledgements

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