Damage to Steam Turbine Rotors Due to Asynchronous Connections of Electric Generators to the Unified Power System

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Abstract. The article aims to contribute to the ongoing study of damage to steam turbine rotors resulting from asynchronous connection of electric generators to the unified power system. At the present time, the assessment of the residual life of steam turbine equipment is based on the study of the degradation of the mechanical properties of steels and the analysis of the thermal stress state. The aim of this work was to determine the impact of such vibrations on the mechanical properties of rotors and their damage. This goal was achieved by solving the following tasks: developing a 3D model of the K-1000-60/3000 LMZ turbine unit shaft based on design documentation; calculating the stress-strain state of the shaft resulting from asynchronous connections using finite element analysis; and evaluating the level of metal damage in the rotors due to torsional vibrations. The developed mathematical model used a classical approach, replacing the working blades and bandage fastenings with concentrated masses and moments of inertia. The most important results are the calculated rotor damages that occur due to asynchronous connection of the turbogenerator to the unified power system with a synchronization angle of 30°. The greatest damage to the rotor metal was found in the shaft section between the steam turbine and the electric generator. The significance of the results obtained is that the use of this data will improve methods for assessing the remaining life of turbogenerators. This, in turn, will improve the reliability and safety of power plant operations.

Keywords: steam turbine, rotor, asynchronous connection, torsional vibrations, stress-strain state, damage.

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Deteriorarea rotoarelor turbinelor cu abur ca urmare a conectării asincrone a generatoarelor electrice la sistemul energetic unificat

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Rezumat. Articolul își propune să contribuie la studiul în curs de desfășurare a deteriorării rotoarelor turbinelor cu abur rezultate din conectarea asincronă a generatoarelor electrice la sistemul de alimentare unificat. În prezent, evaluarea duratei reziduale a echipamentelor cu turbine cu abur se bazează pe studiul degradării proprietăților mecanice ale oțelurilor și pe analiza stării de solicitare termică. Scopul lucrării a fost de a determina impactul unor astfel de vibrații asupra proprietăților mecanice ale rotoarelor și deteriorarea acestora. Acest obiectiv a fost atins prin rezolvarea următoarelor sarcini: dezvoltarea unui model 3D al arborelui turbinei K-1000-60/3000 LMZ pe baza documentației de proiectare; calcularea stării de tensiune-deformare a arborelui rezultată din conexiuni asincrone utilizând analiza cu elemente finite; și evaluarea nivelului de deteriorare a metalelor în rotoare din cauza vibrațiilor de torsiune. Modelul matematic dezvoltat a folosit o abordare clasică, înlocuind lamele de lucru și prinderile de bandaj cu mase concentrate și momente de inerție. Cele mai importante rezultate sunt avariile calculate ale rotorului care apar din cauza conexiunii asincrone a turbogeneratorului la sistemul de alimentare unificat cu un unghi de sincronizare de 30°. Cea mai mare deteriorare a metalului rotorului a fost găsită în secțiunea arborelui dintre turbina cu abur și generatorul electric. Semnificația rezultatelor obținute este că utilizarea acestor date va îmbunătăți metodele de evaluare a duratei de viață rămase a turbogeneratoarelor. Acest lucru, la rândul său, va îmbunătăți fiabilitatea și siguranța operațiunilor centralei electrice.

Cuvinte-cheie: turbină cu abur, rotor, conexiune asincronă, vibrații de torsiune, stare de tensiune-deformare, deteriorare.

Повреждаемость роторов паровых турбин в результате асинхронных подключений электрогенераторов к объединенной энергосистеме

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Аннотация. Статья посвящена исследованию повреждаемости роторов паровых турбин, возникающей вследствие асинхронных подключений электрогенератора к объединенной энергосистеме. Продолжительная эксплуатация паровых турбин в сложных технологических условиях приводит к образованию усталостных трещин в конструктивных элементах турбоагрегатов, что может стать причиной аварийных ситуаций и катастрофических разрушений. Пока оценка остаточного ресурса паротурбинного оборудования выполняется на основе исследования деградации механических свойств сталей и анализе термонапряженного состояния ротора и корпуса турбоагрегата. При этом не учитывают усталостных повреждений роторов, возникающих из-за крутящих колебаний вала во время асинхронных подключений. Цель этой работы заключалась в определении влияния таких колебаний на механические свойства роторов и их повреждаемость. Поставленная цель достигалась путем решения следующих задач: разработка 3D модели вала турбоагрегата К-1000-60/3000 ЛМЗ на основе конструкторской документации; расчет методом конечно-элементного анализа напряженно-деформированного состояния вала вследствие асинхронного подключения; оценка уровня повреждения металла роторов в результате крутильных колебаний. В разработанной математической модели использовался классический подход с заменой рабочих лопаток и бандажных креплений на сосредоточенные массы и моменты инерции. Наиболее важными результатами являются рассчитанные повреждения роторов, возникающие в результате асинхронного подключения турбогенератора к объединенной энергосистеме с углом синхронизации 30°. Наибольшее повреждение металла роторов было обнаружено на участке вала между паровой турбиной и электрогенератором. В частности, после 156 асинхронных подключений уровень повреждения металла составил 10,686%. Значимость полученных результатов заключается в том, что использование этих данных позволит усовершенствовать методы оценки остаточного ресурса турбоагрегатов, что, в свою очередь, повысит надежность и безопасность эксплуатации энергетических установок.

Ключевые слова: паровая турбина, ротор, асинхронное подключение, крутильные колебания, напряженно-деформированное состояние, повреждение.

INTRODUCTION

Steam turbine power plants are among the primary energy-generating facilities. They are designed to reliably supply electricity and heat to industrial and domestic consumers.

Steam turbines operate under challenging conditions, including high temperatures, intense static and dynamic loads, and corrosive environments. As a result, fatigue cracks inevitably initiate and develop in the structural elements of the turbine [1-3].

The process of crack initiation and propagation is mainly studied empirically, based on the principles of fracture mechanics. [5] - [7]. Accelerated ageing of metal specimens is performed on specialised equipment to determine the time to failure. From the data obtained, low cycle fatigue or long term strength curves are constructed. In addition, empirical relationships are derived to describe the mechanisms of damage accumulation under specific types of loading.

One of the most critical components of a steam turbine is the rotors, on which the working blades are mounted. Together with the guide vanes located in the steam cylinder casing, they form the flow section of the turbine, where the force of the steam flow on the working blades is converted into torque.

Several serious accidents related to the fatigue failure of rotors and working blades in large turbine units (TU's) have prompted extensive research into the torsional vibrations of shaft lines resulting from the interaction between the turbogenerator and the unified power system [[8] - [9]]. In addition, the issue of ensuring the safe operation of steam turbine equipment in power plants is becoming more critical every year as the individual lifetimes of energy generating equipment are being exhausted.

Typically, operating turbine units are monitored only for transverse vibrations, particularly as they pass through critical rotational speeds [[10] - [12]]. However, numerous theoretical and experimental studies have shown that torsional vibrations of the turbine shaft line can also be intense enough to cause fatigue damage, potentially leading to catastrophic failure of the turbine unit [13] - [15].

Years of experience in operating steam turbines have identified several primary causes of rotor torsional vibration [13] [16] - [17]. The most dangerous of these are short-circuits, although these may occur only a few times during the lifetime of a turbine unit, potentially leading to its failure. Therefore, such emergency situations are unlikely to cause significant long-term accumulation of fatigue damage. Other causes of torsional vibrations include the connection of the turbogenerator to the power system with rough synchronization [13] [16] - [17] and the dynamic instability of the turbogenerator-power system [17] - [18].

The primary source of torsional fatigue accumulation in steam turbine rotors throughout the operating life of a unit is the connection of the turbogenerator to the power system.

The process of connecting a turbogenerator to the power system is called synchronization. For successful synchronization, the rotational speed of the turbine unit must match the frequency of the power system, the voltage at the generator terminals must equal the system voltage, and the phases in both systems must align. Even if the first two parameters are perfectly matched, a phase angle difference (synchronization angle) can cause balancing currents to flow in the generator windings, leading to an increase in braking torque on the rotor. As a result, torsional vibrations occur along the entire length of the turbine unit's rotor [19]. The magnitude of the reactive torque during asynchronous connection is proportional to the phase angle difference – the larger the angle, the greater the reactive surge [13].

The intensity of tangential stresses during torsional vibrations can be sufficient to accumulate fatigue damage [16] - [20]. This fatigue damage typically manifests itself as a fatigue crack, which can reach critical dimensions within a relatively short period of time and lead to failure of the turbine unit [9].

Following each disconnection of the turbogenerator from the power system, whether due to an emergency or for scheduled maintenance, the unit is restarted, synchronized with the unified power system, and reconnected. It is not always the case that a successful connection is achieved on the first attempt. Consequently, the total number of generator connections to the grid is significantly in excess of the number of turbine startups. Given that each connection of the turbogenerator to the power system generates a reactive torque that induces torsional vibrations of varying intensity in the shaft, it is of particular importance to consider the torsional fatigue of turbine rotors.

The current methodology for assessing the residual life of steam turbines involves the calculation of thermal stress states for rotors during startup and transient operating modes, as well as the degradation of steel due to prolonged operation at high temperatures [2], [21] - [22]. However, this approach does not account for the metal damage caused by torsional and bending vibrations of the rotors. Consequently, significant errors can arise in the assessment of the individual residual life of the turbine unit.

The objective of this work is to evaluate the metal damage in steam turbine rotors caused by the asynchronous connection of the turbogenerator to the power system.

STRESS-STRAIN STATE OF TURBINE UNIT ROTORS

The assembly of turbine rotors, interconnected by various types of couplings, is referred to as the shaft line of a steam turbine. The overall torque on the rotor is the sum of the torques from each working cylinder. This combined torque is transmitted to the turbogenerator, where the mechanical energy of the rotating rotors is converted into electrical energy [23] - [24].

Thus, the maximum static torque acts on the section of the shaft line between the steam turbine and the turbogenerator. It can be determined using the following equation:

$$M_s = M_1 + M_2 + M_n, \tag{1}$$

where: M_1, M_2, M_n is the nominal torque of each working cylinder.

In the case of asynchronous connection of the turbogenerator to the power system, a reactive braking torque arises on the generator rotor. This torque has the potential to exceed the nominal torque by a factor of several. Its amplitude significantly depends on the synchronization angle (phase shift) between the voltage vectors of the power system and the electromotive force vectors of the generator [13].

The magnitude of the reactive torque on the generator rotor during its asynchronous connection to the grid is determined by the following equation:

$$M_r = M_{TG} + M_\theta, \tag{2}$$

where: M_{TG} is the nominal torque of the electric generator, which is determined by its electromagnetic resistance; M_θ is the reactive torque, on the rotor of the generator, due to its connection with imprecise synchronization.

After the cessation of the reactive torque that arises from the generator's rough synchronization with the power grid, the free vibrations of the shaft line gradually decay. The energy dissipation of these forced vibrations is primarily due to the damping properties of the turbine unit's material.

Damping can be defined as the system's capacity to absorb and dissipate vibrational energy. There are three principal types of damping: material damping, friction damping and viscous damping.

Material damping occurs due to intermolecular interactions within the body, where the external energy is absorbed by the material, transformed, and released as heat. In the case of friction damping, the system's energy is reduced due to the friction generated between the moving parts. This energy is transformed and released as heat and noise. Viscous damping occurs when the system in question moves through a gaseous, steam-gas, or liquid medium.

The collection of rotors in the turbogenerator, along with the attached rotating masses, represents a classical multi-resonance torsional pendulum system. In this system, free and forced rotational vibrations occur around the rotor's axis of rotation.

The torsional vibrations of the mechanical system that arise from the reactive surge on the generator rotor during its asynchronous connection to the power system are described by a system of four differential equations in matrix form:

$$[I]\left\{\ddot{\varphi}\right\}+[D]\left\{\dot{\varphi}\right\}+[K]\left\{\varphi\right\}=\{M\}F(t), \tag{3}$$

where: $[I]$ is the inertia matrix of the disk masses; $[D]$ is the damping matrix; $[K]$ – stiffness matrix; $\{M\}$ is the vector of moments; $F(t)$ is the function describing the torque; $\{\varphi\}$ vector of the angular displacement of the disks.

In this study, the damage calculation due to asynchronous connections was performed for the K-1000-60/3000 turbine unit manufactured by LMZ (Leningrad Metal Plant). At the time of data collection from the power plant, the nuclear power plant unit had been in operation for 18 years. The total operating time amounted to 121978 hours, with a total of 52 start-ups.

The steam turbine consists of five cylinders: one high-pressure cylinder (HPC) and four low-pressure cylinders (LPC). All cylinders have a symmetrical two-flow design.

The HPC rotor is solidly forged, and all working stages have the same root diameter. Each flow contains five working stages.

All LPC rotors have the same design and are two-flow, with five working stages in each flow. The root diameter of all stages is identical. The LPC rotors are solidly forged from rotor steel grade P2A (30KhN3M1FA) and are connected by rigid couplings. The shaft ends contain the bearing necks, grooves for the final labyrinth seals, and the fins of the relative expansion sensor.

Figure 1 shows the geometric model of the K-1000-60/3000 LMZ turbine unit's shaft line with concentrated masses and moments of inertia, replacing the working blade apparatus.

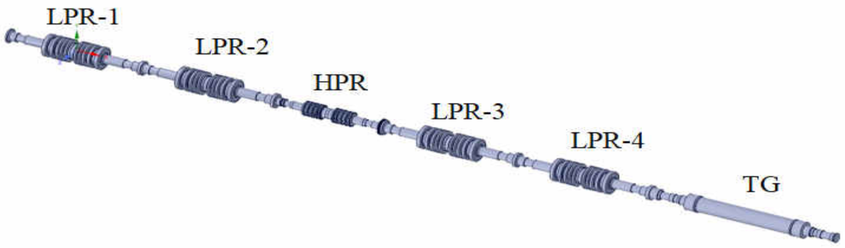

Fig. 1. Geometric model of the shaft line of the K-1000-60/3000 LMZ turbine unit.

The calculation of the stress-strain state of the shaft line of the K-1000-60/3000 LMZ turbine unit during asynchronous connection to the power grid was calculated using the "Transient Analysis" module of the ANSYS software package.

In the initial phase of the modelling process, the physico-mechanical properties of the rotor steel were established. In accordance with the technical documentation of the K-1000-60/3000 turbo unit, the shaft line of the installation is composed of a chromium-nickel alloyed steel grade 30KhN3M1FA. The material in question exhibits the following physico-mechanical properties: density γ=7900kg/m^3, fatigue limit σ_{-1}=284MPa, yield strength $\sigma_{0.2}$=582MPa, modulus of elasticity E=184.62GPa, and a logarithmic decrement of torsional vibrations δ=2% (damping capacity of the rotor steel).

The next important step was determining the torques on each working disk and the rotor of the electric generator.

The torsional moments on the working disks of each stage were considered stationary, with their magnitudes taken from the thermal calculation of the turbine's flow path.

The determination of reactive torque values at various synchronization angles of the turbogenerator with the power system is a complex and time-consuming task. In the analyzed sources, reactive torque values were found only for the case of asynchronous connection with a synchronization angle of 30° [13]. Consequently, the calculation of tangential stresses was performed for this synchronization angle only.

The finite element analysis of the stress-strain state of the turbine shaft line allowed for the determination of the distribution of shear stresses along the entire length of the turbine shaft line.

Figure 2-6 illustrates the fluctuations in maximum shear stresses at different sections of the turbine shaft line during the asynchronous connection of the K-1000-60/3000 LMZ turbine unit to the power system with a synchronization angle of 30°.

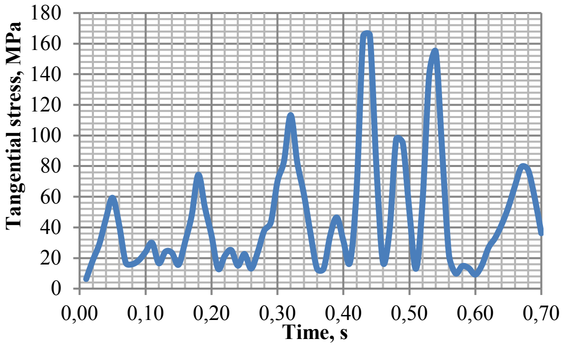

Fig. 2. Maximum shear stress between LPC-1 and LPC-2.

Tangential stress exceeding the endurance limit of rotor steel during torsion were observed in all sections of the rotors between the steam cylinders, particularly in the bearing areas. Therefore, it can be concluded that torsional vibrations caused damage to the rotor metal.

The most stressed section was the one between the steam turbine and the generator. This section experienced five damage cycles.

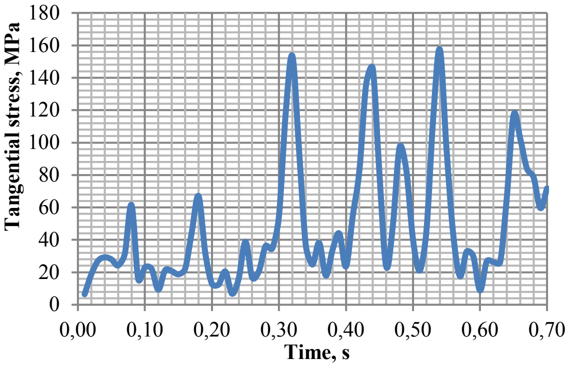

Fig. 3. Maximum shear stress between LPC-2 and HPC.

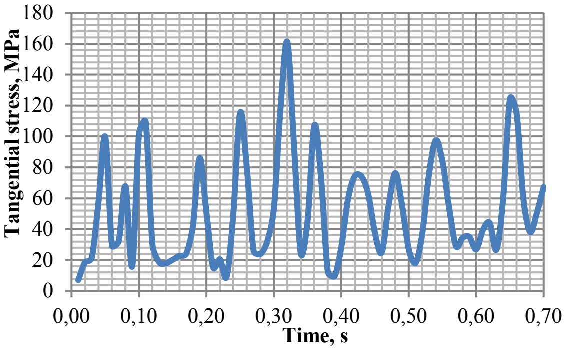

Fig. 4. Maximum shear stress between HPC and LPC-3.

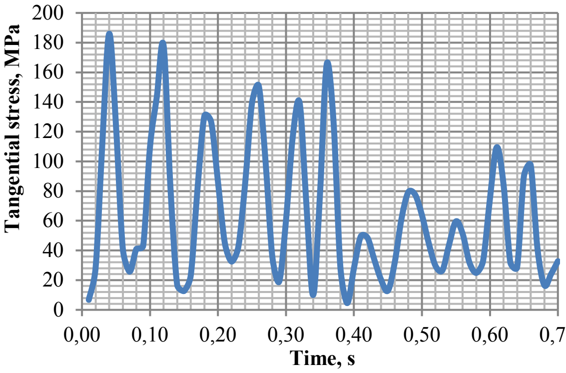

Fig. 5. Maximum shear stress between LPC-3 and LPC-4.

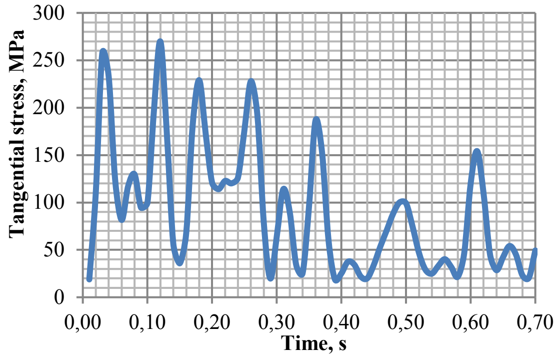

Fig. 6. Maximum shear stress between LPC-4 and TG.

Figure 2-6 show that connecting the generator with a synchronization angle of 30° caused torsional vibrations in all rotors of the turbo unit.

DAMAGE TO TURBINE ROTORS DUE TO TORSIONAL VIBRATIONS

In calculating the cyclic strength of the rotors, the linear damage accumulation theory (Palmgren-Miner hypothesis) was employed. The failure condition according to this hypothesis under block loading is expressed as follows:

$$\sum_{i=1}^{s}\left(n_i/N_{ip}\right)=1, \qquad (4)$$

where: n_i is the number of load blocks with a stress amplitude $\tau_{i\max}$; N_{ip} – is the number of cycles to failure under cyclic loading with a stress amplitude $\tau_{i\max}$; s – is the total number of load blocks.

In order to calculate the cyclic damage to the rotors resulting from torsional vibrations, it is necessary to determine the number of load blocks s, which is equal to the number of deformation cycles. Consequently, the cyclic damage to the metal was evaluated using the following equation:

$$D=\sum_{i=1}^{s}D_i, \qquad (5)$$

where: D_i – damage to the rotor metal at the *i*-th oscillation cycle.

When calculating the damage to the rotor metal, the following algorithm was applied: first, based on the finite element model, the oscillation amplitudes that arose due to asynchronous connection to the power grid were determined. The variation of tangential stresses in the most heavily loaded sections of the rotors is shown in Figure 2-6. Next, using the fatigue curve under torsion, the number of cycles to failure was determined for each oscillation. The damage to the rotor metal at the *i*-th oscillation cycle was calculated using the following equation:

$$D=\frac{1}{N_{ip}}, \qquad (6)$$

The calculation of damage was performed for load cycles in which tangential stress exceeded the endurance limit of the rotor steel $\tau_{-1}=100$ MPa.

The number of damage cycles and the magnitude of cyclic damage for the most heavily loaded sections of the rotors are presented in Table 1.

Table 1. Cyclic damage of the rotors of the K-1000-60/3000 turbo unit due to asynchronous connection

Shaft section	s	D
LPR-1 – LPR-2	3	$7{,}17\cdot10^{-5}$
LPR-2 – HPR	4	$7{,}57\cdot10^{-5}$
HPR – LPR-3	5	$4{,}26\cdot10^{-5}$
LPR-3 – LPR-4	7	$2{,}15\cdot10^{-4}$
LPR-1 – TG	7	$6{,}85\cdot10^{-4}$

According to the calculations, the greatest damage to the metal due to asynchronous connection of the turbogenerator to the power grid with a synchronization angle of 30° occurred in the shaft section between the steam turbine and the electric generator. This is caused by the action of the maximum torque in this section of the shaft. Therefore, this particular section of the metal will experience the maximum damage under torsional vibrations, especially if they are caused by intense changes in the torque on the electric generator rotor.

According to the information provided by the nuclear power plant maintenance personnel, after shutting down the K-1000-60/3000 turbo unit, it is not always possible to successfully synchronize the turbogenerator with the power grid on the first attempt. The maintenance personnel perform several repeated disconnections and reconnections of the turbogenerator until synchronization is successful. Each such reconnection results in a reactive torque spike on the electric generator rotor, which causes torsional vibrations across all the rotors of the turbo unit.

Assuming that during each startup of the K-1000-60/3000 LMZ turbo unit, there were 2-3 connections of the electric generator to the unified power grid with rough synchronization, then throughout the entire operation of the nuclear power plant, which was started 52 times, there were 104-156 connections with rough synchronization, during which torsional vibrations of the shaft occurred. Thus, the metal damage due to torsional fatigue during 104 connections with a synchronization angle of 30°

is $104\cdot 6.85\cdot 10^{-2}=7.124\%$, and during 156 connections, it is $156\cdot 6.85\cdot 10^{-2}=10.686\%$.

CONCLUSIONS

The considerable mass and dimensions of the high-speed K-1000-60/3000 LMZ turbo units render synchronization a challenging endeavour. In the event of unsuccessful synchronization and connection of the turbogenerator to the power grid, it is disconnected and the synchronization and connection are repeated until a successful outcome is achieved. Each connection attempt to the power grid is accompanied by a reactive torque spike on the turbogenerator rotor.

The conducted study demonstrated that during the process of rough synchronisation of the turbogenerator, torsional vibrations with sufficient amplitude to potentially induce torsional fatigue in the rotor metals arise on the shaft.

The study confirmed that the highest tangential stress intensity and, accordingly, the greatest metal damage due to rough synchronization of the turbogenerator with the power grid occur in the shaft section between the steam turbine and the electric generator. This can be explained by the fact that the maximum mechanical torque generated by the steam flow in the turbine is concentrated in this section.

The exact number of asynchronous connections of the turbogenerator to the power grid depends on many factors, including the type of equipment and the qualifications of the personnel. Assuming that 156 asynchronous connections occurred over the entire period of turbo unit operation, the metal of the electric generator rotor was damaged by $156\cdot 6.85\cdot 10^{-2}=10.686\%$. Thus, the cumulative damage due to torsional vibrations over the entire operational period of the power unit is substantial and must be considered when assessing the residual service life of steam turbine equipment.

Unfortunately, torsional vibrations of rotors are not monitored in operating power units. This significantly complicates the prediction of the permissible number of incorrect synchronizations and the time until fatigue cracks form in the metal. The results of this study demonstrate that failed synchronizations can cause serious damage to the metal, thereby reducing the safe operating life of the turbo unit.

For a more accurate assessment of the remaining life of turbo unit shafts, it is necessary to implement continuous monitoring tools for torsional vibrations and conduct additional experimental studies of the mechanical properties of rotor steels.

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