Fatigue damage of steam turbine shaft at asynchronous connections of turbine generator to electrical network

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Abstract. The investigations of cracks growth in the fractured turbine rotors point out at theirs fatigue nature. The main reason of turbine shafts fatigue damage is theirs periodical startups which are typical for steam turbines. Each startup of a turbine is accompanied by the connection of turbine generator to electrical network. During the connection because of the phase shift between the vector of electromotive force of turbine generator and the vector of supply-line voltage the short-term but powerful reactive shaft torque arises. This torque causes torsional vibrations and fatigue damage of turbine shafts of different intensity. Based on the 3D finite element model of turbine shaft of the steam turbine K-200-130 and the mechanical properties of rotor steel there was estimated the fatigue damage of the shaft at its torsional vibrations arising as a result of connection of turbine generator to electric network.

1. Introduction.
The analysis of vibration of steam turbine shaft usually focuses upon their transverse vibrations, the intensity of which is especially significant when passing through the critical speeds of shaft rotation. At the same time, in certain cases namely torsional vibrations of turbine shafts are much more dangerous. The evidences of the latter are the catastrophic failure of the rotor of medium pressure steam turbine at the power plant in Gallatin (USA) in 1974, caused by the growth of a crack for several years under the cyclic torsion [1], as well as the destruction of the steam turbine in Kashirskaya thermal station (Russian Federation) in 2002 [2].

The main reasons of the turbine shaft torsional vibrations are the short circuit of turbine generator, the connection of turbine generator to electric network, and the dynamic instability of the system turbine generator – electric network [1-4].

Short circuits of turbine generators happen several times during the operation time. Under certain conditions a short circuit can cause the instant destruction of turbine [2], but the accumulation of fatigue damage of a turbine shaft as a result of short circuit is unlikely. At the same time, the analysis of crack propagation in the destroyed or decommissioned turbine shafts makes it possible to conclude that cracks developed over a long period of time [1, 5]. The reasons of accumulation of fatigue damage of turbine shafts should be sought in theirs multiple startups, which are typical for steam turbine units operating in a flexible manner. The predetermined number of such startups during the operation time is 2000, but in some cases it can be prolonged to 2500 and more. At each startup at least one connection of turbine generator to electric network occurs. At this because of the difference of the phase shift angle between the vector of electromotive force of turbine generator and the vector of electric network voltage the short-term reactive electromagnetic shaft torque arises, resulting in the
turbine shaft torsional vibrations of various intensity. The intensity of torsional vibrations may be so high that they cause the fatigue damage of the shaft.

According to the established practice, the evaluation of residual life of steam turbines is mainly based on the analysis of thermal stress state of rotors and on the study of degradation of mechanical properties of materials of turbine structural elements. Thus the fatigue damage of turbine shaft due to the torsional vibrations is not taken into account, which may be the reason of significant errors of estimation of actual damage of turbines structural elements. The importance of the problem of torsional vibrations of turbine shafts is emphasized in ref. [6].

The aim of the present research was to investigate the factors which affect the fatigue damage of turbine shaft, as well as to assess the level of this damage caused by torsional vibrations arising at the connections of turbine generator to electrical network.

2. Model of steam turbine shaft.

The steam turbine K-200-130 is a complex mechanical system consisting of a high pressure rotor (HPR), middle pressure rotor (MPR), low pressure rotor (LPR) and turbine generator (figure 1; the generator is not shown in this figure). The numbers 1, 2 and 3 in figure 1 point out the most stressed areas of turbine shaft the fatigue damage of which has been the subject of research.

![Figure 1. Steam turbine K-200-130.](image)

The study on forced vibrations of such a mechanical system was performed numerically with a 3-D finite element model (figure 2). As an object for the research was selected the shaft of turbine K-200-130 (200 MW). The model was a mesh of 50000 eight-node elements. The detailed description of the model and the numerical methods used for the solution of the problem can be found in ref. [7].

The scheme of the shaft loading is presented in figure 2, namely the torques arising in HPR \(M_{hp}\), MPR \(M_{mp}\), LPR \(M_{lp}\) and the reactive torque \(M_r\) which arises at connection of turbine generator (TG) to electrical network. Total operating shaft torque is determined as follows

\[
M_{oper} = M_{hp} + M_{mp} + M_{lp}.
\]  

(1)

Calculations of the electromagnetic torque at the connection of the turbine generator TGV-200 to the electric network of voltage 110 KV showed that the reactive torque strongly depends on the phase shift angle \(\theta\) (the so called synchronizing angle) between the vector of electromotive force of the turbine generator and the vector of electrical network voltage [8]. The results of calculation of time dependence of the relative value of reactive shaft torque at different values of synchronizing angle are shown in figure 3. As can be seen, the reactive shaft torque increases in direct proportion to the value of the synchronizing angle and may exceed up to 16 times the operating shaft torque. Since these functions are damped, the almost complete attenuation of the electromagnetic processes in turbine generator occurs in about 4 seconds.
3. Torsional vibrations of turbine shaft at asynchronous connection of turbine generator to electrical network.

Calculations of forced torsional vibrations of turbine shaft were performed for the synchronizing angles $\theta=30, 60, 90$ and $120^\circ$. The level of damping of the mechanical system was estimated by the logarithmic decrement of vibration $\delta$. As far as its actual value is unknown it was accepted in calculations that $\delta=0.3$. Such a high level of damping was justified by the presence of at least four mechanisms of energy dissipation, namely the energy dissipation in the material, structural energy dissipation, the resistance of the air-steam medium and the resistance of turbo generator itself.

The connection of a turbine generator to electrical network can be successful and unsuccessful. In the case of successful connection the turbine generator is not disconnected from the electrical network and the reactive shaft torque gradually vanishes. But if in the process of the connection the intense vibrations of a turbine arise, the turbine generator is disconnected from electrical network, the result of which is the almost immediate disappearance of the reactive torque and of the vibration of the turbine as well. The latter is the case of the so-called unsuccessful connection. The attempt of connection is repeated for as long as it would be successful one.

Torsional vibrations of the turbine shaft at successful and unsuccessful connection of turbine generator to electrical network have some specific features.

Thus at successful connection of turbine generator torsional vibrations of the shaft are maintained at relatively high level for almost the entire duration of the reactive torque action (figure 4). The most intense vibrations are excited in the case of the angle $\theta=120^\circ$, as far as the reactive torque reaches maximum value. With the decrease of the synchronizing angle from $120^\circ$ to $30^\circ$ the amplitude of torsional vibrations of the shaft drops in half.

The most intense stresses are observed in areas 2 and 3. The fatigue limit of R2MA rotor steel at normal temperature is $\tau_{-1}=230$ MPa (it is shown in figure 4, c and d by a horizontal line). As can be seen, at certain conditions the stress level may exceed the fatigue limit of rotor steel, that is the reason of fatigue damage of the shaft. It is evident that the higher is the synchronizing angle the more intense is the fatigue damage of the shaft.

As the reactive electromagnetic torque attenuates the torsional vibrations of the shaft gradually reduce. At high level of damping in the mechanical system fatigue damage occurs only at first few cycles of vibration as far as the intensity of stress quickly drops to the safe level.

In the case of unsuccessful connection of a turbine generator to electrical network the intensity of torsional vibrations of the shaft depends not only on the synchronizing angle, but also on the duration of the reactive shaft torque $t_r$.
Figure 4. Time dependences of the reactive torsional moment \((a, b)\) and shear stresses \((c, d)\) in areas 1, 2 and 3 of the shaft at successful connection of turbine generator.

The development of torsional vibrations of the shaft when trying to connect the turbine generator to electrical network and subsequent its emergency disconnection at different duration of the reactive shaft torque is demonstrated in figure 5. As can be seen, the intensity of forced vibrations in both cases \((t_r=0.271\) and \(0.291\) sec) is almost the same. However, the difference between the intensity of free vibrations reaches several times. So the duration of the reactive torque strongly affects free vibrations of the shaft.

4. Calculations of fatigue damage of turbine shaft.

The fatigue damage of turbine shaft as a result of torsional vibrations was evaluated based on the hypothesis of Palmgren-Miner [9]

\[
D = \sum_{i=1}^{n} \frac{1}{N_{id}},
\]

where \(n\) is the number of damaging cycles of vibration, in which shear stresses exceed the fatigue limit of rotor steel \(\tau_{\text{r};}\); \(N_{id}\) is the number of cycles till the fracture under the stress \(\tau_{\text{max}}\). In 2000 connections of a turbine generator the total fatigue damage was determined as \(D_{\text{total}}=2000D\). The limiting state of the rotor steel is attained in condition \(D_{\text{total}}=1\).

Calculations of cyclic damage of the shaft were performed with the fatigue curve for the rotor steel R2MA, which was obtained at symmetric cycle of loading and for normal temperature [10]. The influence of scale effect, temperature and asymmetry of cyclic deformation on the fatigue properties of the steel was taken into account by means of correction factors

\[
\tau_{\max} = K_s K_d K_t \left[ \eta_0 + \eta_v (N)^c + \eta_d (N)^b \right],
\]

where \(\eta_0=208.3;\ \eta_v=3176.2;\ \eta_d=1.86\cdot10^5;\ c=-0.3114;\ b=-0.8348;\ N\) is the number of loading cycles;
$K_s$ is the scale factor; $K_a$ is the asymmetry factor; $K_t$ is the temperature factor. Based on the experimental research [11] the values of scale and temperature factors were excepted to be $K_s=0.58$ and $K_t=0.78$. The asymmetry factor was determined by the formula

$$K_a = \frac{\sqrt{\tau_2^2 - \xi^2\psi \tau_2^2}}{\tau_1^2},$$  \hspace{1cm} (4)$$

where $\tau_1$=230 MPa; $\xi=0.922$; $\psi=0.505$ [10]; $\tau_m$ is the mean stress.

The results of calculation of the shaft’s fatigue damage as a result of torsional vibrations for 2000 successful connections of turbine generator to electrical network are shown in the table 1. As can be seen, in the case of synchronizing angle $\theta=30^\circ$ the total fatigue damage of the shaft does not exceed 16%, so there is a significant reserve of residual durability. The increase of synchronizing angle causes the growth of damaging cycles and, consequently, the spread of fatigue damage. Most dangerous situation is observed in the case $\theta=120^\circ$ when even high level of damping is not able to prevent the rotor steel to attain the limiting state. In all cases being considered the area 1 of the shaft practically is not subjected to the fatigue damage.

At unsuccessful connection of turbine generator to electrical network it is necessary to take into account the duration of the reactive shaft torque. In this case the vibrations consist of forced vibration under the action of reactive torque and of free vibration arising after the disconnection of turbine generator from electrical network.

The dependencies of total damage, as well as damage due to forced and free vibrations of the shaft on the duration of the reactive torque are shown in figure 6. As can be seen, the curves are quasi-periodic with the trend of gradual reduction of the maximal damage. At small damping ($\delta=0.02$) the damage of area 2 is higher than of area 3, but at high damping ($\delta=0.3$) the damage of area 3 exceeds that one of area 2. The data on damage of area 1 is not shown because it does not exceed 15%.

It is also evident from figure 6 that if the level of damping would be low, the damage accumulated mainly at free vibrations (figure 6, a, b). High damping rapidly reduces theirs intensity to
the safe level and damage accumulates mainly at forced vibrations (figure 6, c, d). It is necessary to note that each point of the curves in figure 6 was obtained under the assumption that the duration of reactive torque at every of 2000 connection was the same. Obviously, in practice this value is different at each connection.

| $\theta$, ° | Areas of the shaft | $n$ | $D_{total}$ |
|------------|-------------------|----|------------|
| 30         | 2                 | 2  | 0.113      |
|            | 3                 | 3  | 0.167      |
| 60         | 2                 | 3  | 0.414      |
|            | 3                 | 4  | 0.669      |
| 90         | 2                 | 3  | 0.762      |
|            | 3                 | 4  | 1.343      |
| 120        | 2                 | 3  | 0.969      |
|            | 3                 | 10 | 1.776      |

Therefore, a more realistic assessment of damage should be performed based on the assumption that the duration $t_r$ is distributed equiprobably in a certain range $\Delta t_r = t_{r,K} - t_{r,1}$ ($t_{r,1}$ and $t_{r,K}$ are the initial and end value of the range, respectively). The initial value of the range was taken to be $t_{r,1}$=$0.25$ sec. The step of change of duration $t_r$ was 0.001 sec. The averaged over the range damage was determined by the formula

$$
D_{av} = \frac{\sum_{i=1}^{K} D_{total,i}(t_{r,i})}{\Delta t_r},
$$

where $D_{total,i}$ is the total damage at the duration of the reactive torque $t_{r,i}$.

Figure 6. Dependences of total fatigue damage of turbine shaft in area 2 (a, c) and 3 (b, d) on the duration of the reactive torque at unsuccessful connection of turbine generator ($\theta$=30°): free vibration (dash dot line); forced vibration (dot line); sum (solid line).
As can be seen from figure 7, the averaged damage over the lifetime of the turbine is quite smooth characteristic and depends weakly on the averaging range. This characteristic can be used to assess the fatigue damage of the shaft as a result of torsional vibrations through the turbine lifetime.

![Figure 7](image)

**Figure 7.** Dependences of averaged fatigue damage of turbine shaft in area 2 on the range of duration of the reactive torque at unsuccessful connection of a turbine generator: free vibration (dash dot line); forced vibration (dot line); sum (solid line).

It is practically unlikely that all 2000 connections of turbine generator to electrical network would be successful. The more realistic scenario should count for possibility of certain number of unsuccessful connections which is different for various steam turbines. Figure 8 presents the results of averaged damage assessment for two hypothetical cases: first case considers 2000 successful connections and second one – 2000 unsuccessful connections. It should be noted that the attempts to connect the turbine generator to electrical network continues until it will be successful. Therefore, in the calculations there was taken into account that 2000 unsuccessful connections were accompanied by the same amount of successful ones.

In all cases presented in figure 8 the averaged damage is strongly dependent on the synchronizing angle and on the number of unsuccessful connections. The scenario of damage accumulation presented in figure 8 by solid line is optimistic in term of the number of unsuccessful connections. The actual number could be much higher than 2000.

![Figure 8](image)

**Figure 8.** Dependences of averaged fatigue damage of turbine shaft in area 2 (a) and 3 (b) on the angle $\theta$. 2000 successful connections (dash line); 2000 unsuccessful and 2000 successful connections (solid line).

Comparison of figure 8, a and b demonstrates that the fatigue damage of area 3 is more intense than of area 2 of the shaft. Therefore, the conclusion about the possibility of safe operation of the turbine should be done based on the analysis of fatigue damage accumulated in area 3. In such a way
the limiting state of the rotor steel can be achieved in condition $\theta \geq 75^\circ$ if all connections would be successful and in condition $\theta \geq 50^\circ$ if the number of unsuccessful connections would be 2000 (vertical dash lines in figure 8, b). It is evident that the higher is the number of unsuccessful connections the lower is the synchronizing angle.

Consequently the safety of steam turbines in operation to a great extent is affected by the number of unsuccessful connections and by the synchronizing angle. The value of synchronizing angle should be controlled at every connection of the turbine generator to electrical network.

5. Conclusions.
The results of research have shown that the evaluation of fatigue damage of turbine shaft should be based on the account not only of the transverse but also of the torsional vibrations occurring at the connection of turbine generator to electrical network. The intensity of the latter depends essentially on the synchronizing angle, duration of the reactive shaft torque and damping level.

The torsional vibrations of turbine shaft are the reason of turbine shaft fatigue damage. In general case the fatigue damage is a function of three parameters: the synchronizing angle, the number of unsuccessful connections and the duration of the reactive shaft torque at unsuccessful connections.

The assessment of fatigue damage of turbine shaft at torsional vibrations for 2000 successful connections of turbine generator to power network showed that at high level of damping in the mechanical system the limiting state of the rotor steel can be achieved in condition $\theta \geq 75^\circ$. Each unsuccessful connection decreases this value by about 0.013°.

The efficient way to control the extent of fatigue damage of turbine shaft is the on-line measurement of the shaft vibrations and the use this information to assess the damage based on the model proposed in the present work.

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