Influence of disturbances in power network on torsional torques in big power turbines-generator shafts

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The mechanical data of turbines and a generator of 1000 MW reference unit, working at overcritical parameters, were established. Using the modal method, the characteristic frequencies of torsional oscillations in shafts of rotating masses were calculated. The values of torsional torques in shafts which can arise during faults in electrical networks, like close distance short-circuits, the action of automatic reclosing, synchronization, as well influence of electromagnetic torques from the network side causing the resonance oscillations of unit were investigated.

1. Introduction

Planned in nearest future implementation of 1000 MW unit working with overcritical parameters (program 50+) into the National Power System poses new problems in the area of cooperation between the unit and the power system [1].The planned parameters of units are the following: temperature 560÷580°C, and pressure 25.8 MPa.

The issues of the rotating set of turbines and generator masses modeling are presented. The aim of the modeling is to calculate torsional torques in shafts between the individual masses during faults appearing in the power network. Calculations were performed using the EMTP/ATP program.

The elements of the turbine - generator unit are connected with shafts (Fig. 1), with limited mechanical endurance which can be exceeded during some faults.

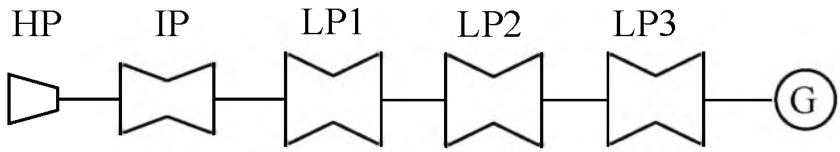


Fig. 1. Structure of 1000 MW reference unit

Due to transport limits, it is not possible to use a single three phase transformer with power over 1000 MVA in the generator-transformer unit. Power station designers and producers of big power transformers take into consideration the use of two three-phase transformers in parallel work or more reliable system of three one-phase transformers (and reserve one) with the summary power adequate to the unit power, Fig. 2.

The EMTP/ATP [2] program enables us to simulate dynamics of the synchronous generator with any number of turbines fixed on the common shaft. The mechanical system is considered as linear, therefore spring-connected rotating masses can be described by the second Newton law:

$$\mathbf{J} \cdot \frac{d^2}{dt^2} \boldsymbol{\delta} + \mathbf{D} \cdot \frac{d}{dt} \boldsymbol{\delta} + \mathbf{K} \cdot \boldsymbol{\delta} = \mathbf{T}_{turb} - \mathbf{T}_{gen} \quad (1)$$

where: $\boldsymbol{\delta}$ - angular positions, $\mathbf{J}$ - moments of inertia, $\mathbf{D}$ - damping coefficients, $\mathbf{K}$ - stiffness coefficients of shafts between rotating masses, $\mathbf{T}_{turb}$ - torques applied to turbines, $\mathbf{T}_{gen}$ - electromagnetic torque of a generator.

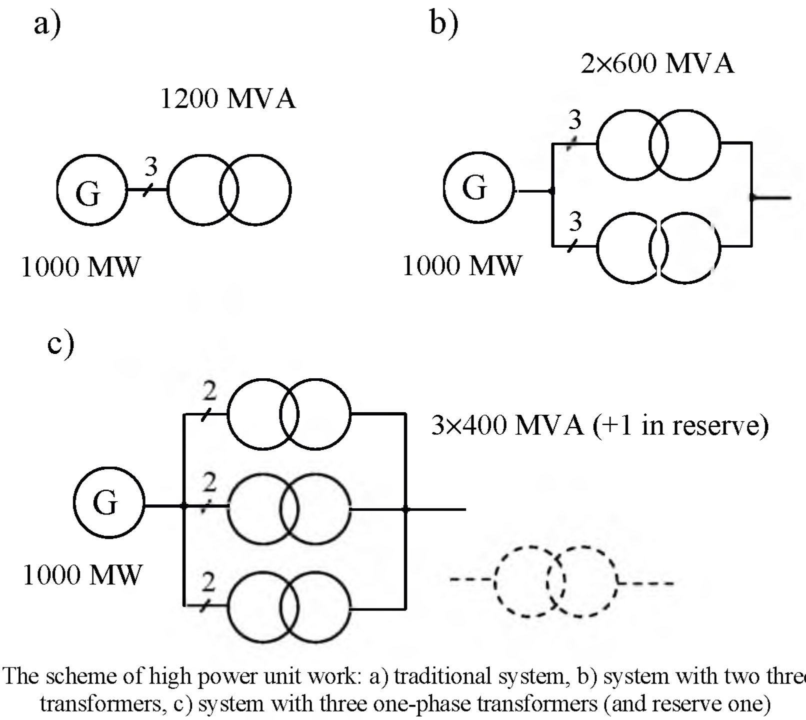


Fig. 2. The scheme of high power unit work: a) traditional system, b) system with two three-phase transformers, c) system with three one-phase transformers (and reserve one)

To determine the expected mechanical data of a similar power unit, the review of literature describing these problems was presented. On the basis of many publications, for example [3÷7], the mechanical parameters of units were compared. Inertia constants of generators H_{gen} in [p.u.*s] units and their mean value H_{gen_mean} (about 0.82 p.u.*s) as well as sums of inertia constants of turbines propelling the generator H_{turb_sum} and the mean value of these sums $H_{turb\_sum\_mean}$ (about 2.96 p.u.*s) for the range of unit power 500÷1100 MVA were shown in Fig. 3.

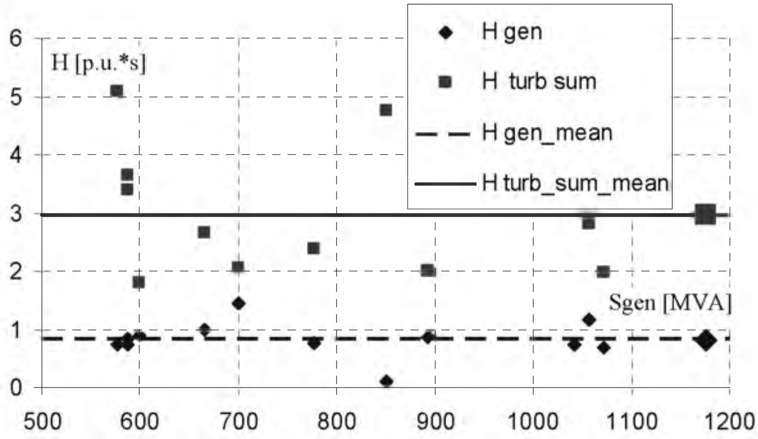


Fig. 3. Inertia constants of generators H_{gen} , sums of inertia constants of turbines H_{turb_sum} and their mean values H_{gen_mean} ,and $H_{turb\_sum\_mean}$ for different powers of units

The similar analysis for establishing stiffness coefficients K and damping coefficients D was performed. Mean values of stiffness coefficients of shafts between rotating masses K_{mean} in [p.u./rad] units for the same range of unit power and their average value $K_{mean\_average}$ (about 83.5 p.u./rad) were presented in Fig. 4.

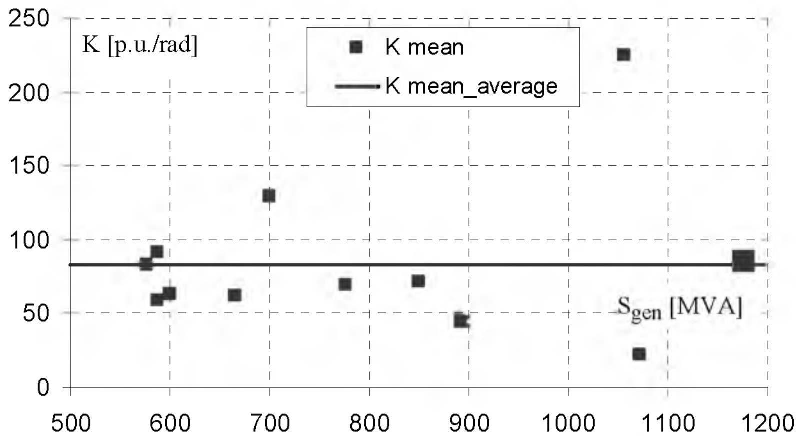


Fig. 4. Mean values of stiffness coefficients K_{mean} of shafts between rotating masses and their average value $K_{mean\_average}$

Parameters of the 1000 MW referent unit were set as: **Inertia constants** (p.u.*s): HP=0.17, IP=0.4, LP1=0.6, LP2=0.6, LP3=0.6, GEN=0.8, **Stiffness**

coefficients (p.u./rad): HP-IP=150, IP-LP1=200, LP1-LP2=250, LP2-LP3=300, LP3-GEN=350.

Using the transformation modal matrix **Q** with columns being eigenvectors of expression $\mathbf{J}^{-1} \cdot \mathbf{K}$, the equation (1) can be transformed to the modal formula. Its solution enables to find the modal frequencies of system oscillations [2, 3, 5]. For the considered unit these frequencies are: **f** = [1.44 13.37 23.77 32.98 38.17 44.9] Hz.

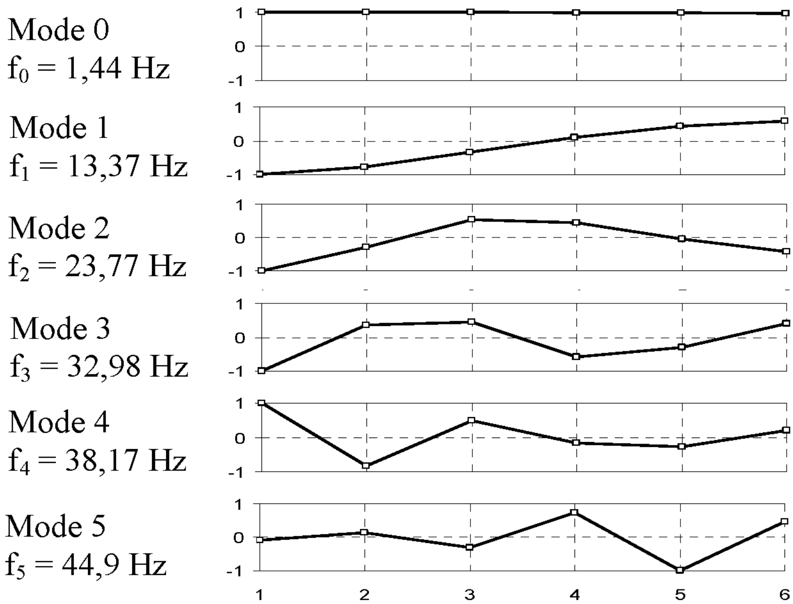


Fig. 5. The shapes of individual modes (normalized values of elements of eigenvectors of transformation modal matrix **Q**)

The shapes of individual modes (i.e. normalized values of elements of eigenvectors of the transformation modal matrix **Q)** are presented in Fig. 5. The mode shape illustrates the maximal relative displacement of rotating masses during the appearance of resonance with the given modal frequency.

Fig. 6 presents the dependence of maximal values of torsional torques T_i (related to nominal torques of shafts) in individual shafts on frequency of the sinusoidal external input torque with amplitude 1% of nominal electromagnetic torque T_{n_gen}, affecting on the generator rotor.

It should be noticed that even this small effect of the network disturbance on the rotor at some resonance frequencies results in the torsional torques exceeding nominal values for these shafts.

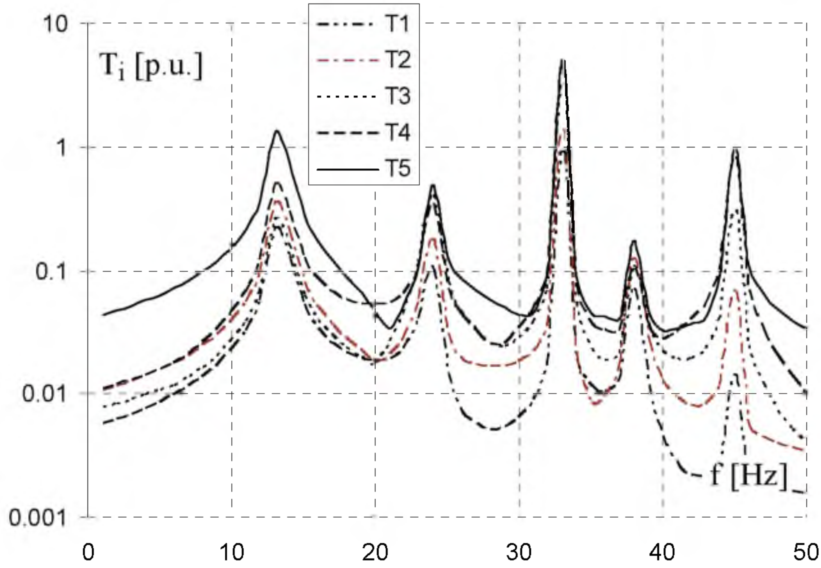


Fig. 6. Dependence of maximal values of torsional torques in individual shafts on frequency of the sinusoidal external input torque with amplitude 1% T_{n_gen}, affecting a generator rotor

2. Calculations of torsional torques

Influence of network on generator rotor. Susceptibility of rotating masses to the influence of a disturbing signal with the close to natural frequency was examined. Such a disturbance can come from the network side as the generator current with this frequency component. More and more power electronic devices in the network encourage to such a situation.

The presence of the disturbing sinusoidal torque with the frequency equal to the resonance frequency and amplitude of 1% of the rated torque was assumed. Using the EMTP/ATP program the simulations were performed for the rated loaded generator as well as for the synchronized one without a load. In the shaft sections significant values of torsional torque appeared and their values were higher in the case of the generator loaded. The modeled generator-transformer-line unit power lead is shown in Fig. 7.

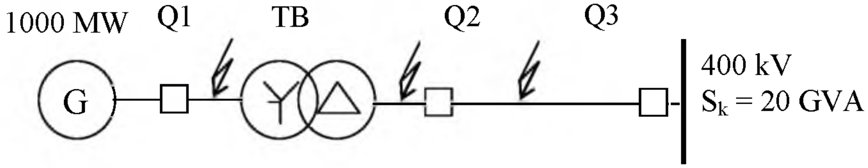


Fig. 7. Scheme of the generator - transformer unit for calculations of mechanical shaft torques during selected faults

The amplitudes of torsional torque, expressed in relative units [p.u.], related to the rated torque of each shaft sections, during the action of the disturbing torque are presented in Fig.8. The generator is rated loaded.

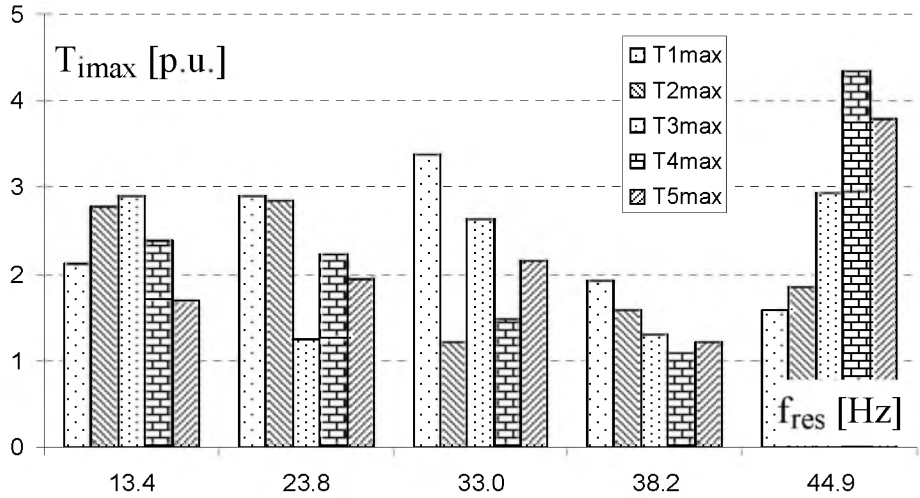


Fig. 8. The amplitudes of torsional torque, during the action of disturbing torque with the value of 1% of the rated rotor torque T_{r_gen}

<u>Short-circuits in power network.</u> Fig. 9 presents the maximal values of torques in shafts of the rotating unit at some faults in the network:

- 3-phase short-circuit on generator voltage bus bars for a rated loaded (A), (Fig. 10) and unloaded generator (B).
- 3-phase short-circuit on HV side of the unit transformer for a rated loaded generator (C) and unloaded generator (D).
- 1-phase short-circuit in 400 kV unit line. 1-phase effective automatic reclosing with time 0.4 s (E).

The calculations show that values of torques significantly exceed permissible limits.

The calculations of torsional torques in the turbines - generator unit while carrying out the generator synchronization using a generator breaker Q1 were made. The analysis was performed for the difference in frequencies of the generator and the network $\Delta f = 0.1$ Hz and for differences $\Delta\varphi$ of voltage phases in the range $0° \div 180°$. Fig.11 presents the differential voltage U_{diff} (on Q1 breaker) and torsional torques T_i in the shaft sections during synchronization with differences $\Delta\varphi = 5°$ of phase voltages.

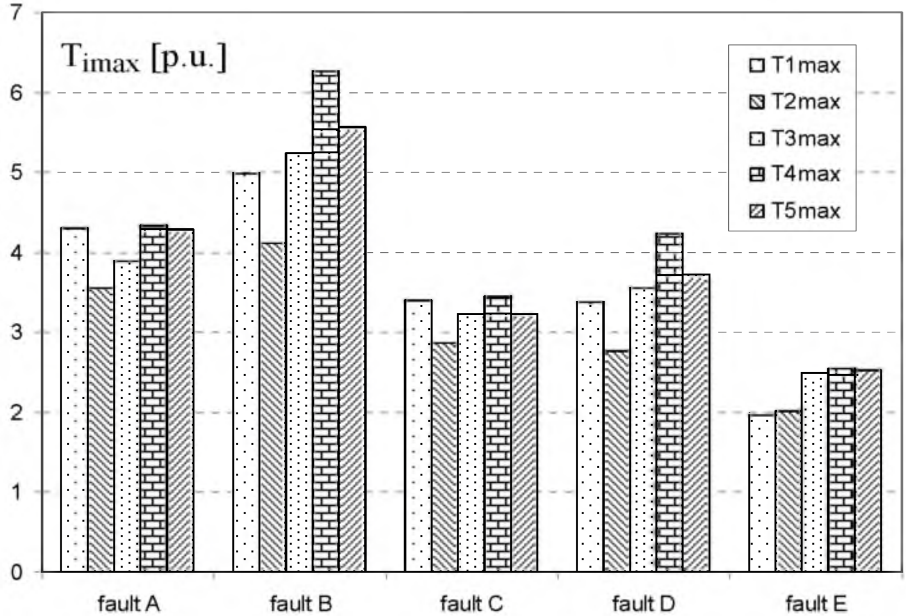


Fig. 9. The maximal values of torques in shafts of the rotating unit at some short-circuits close to generator

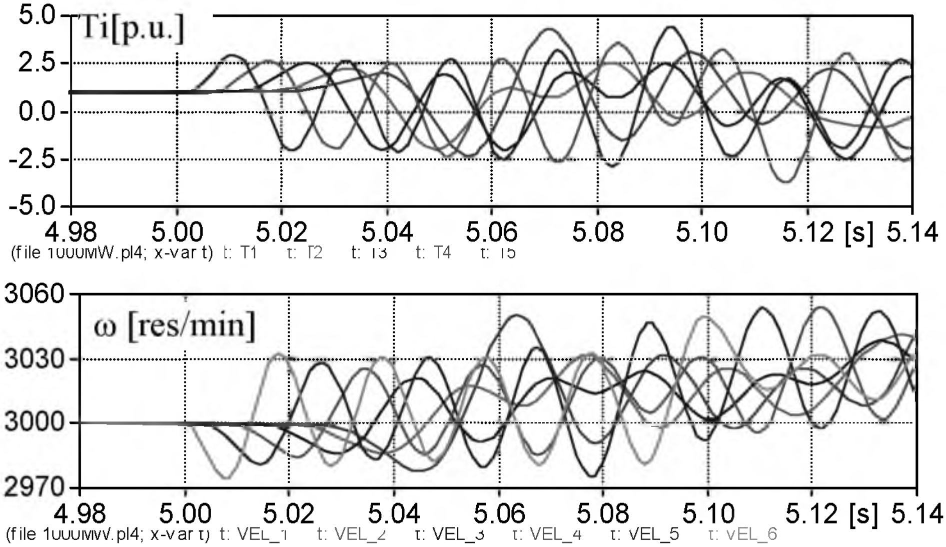


Fig. 10. Mechanical torques T_i and the generator and turbine rotation speed ω_i during 3-phase short-circuit on generator voltage bus-bars for a rated loaded generator (fault A)

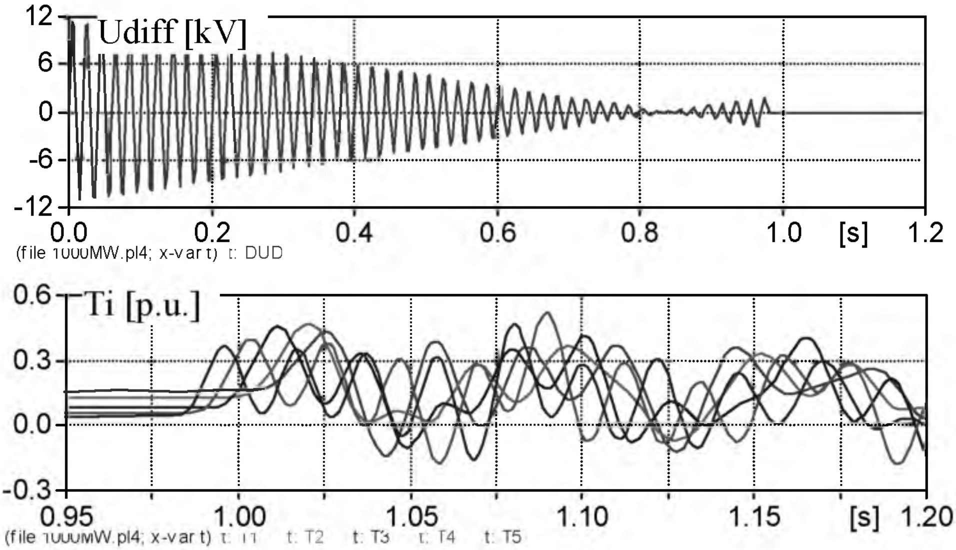


Fig. 11. The differential voltage U_{diff} (on Q1 breaker) and torsional torques T_i during synchronization with differences $\Delta\varphi=5°$ of phase voltages

The dependence of maximal torque values on differences $\Delta\varphi$ of voltage phases during synchronization is presented in Fig. 12.

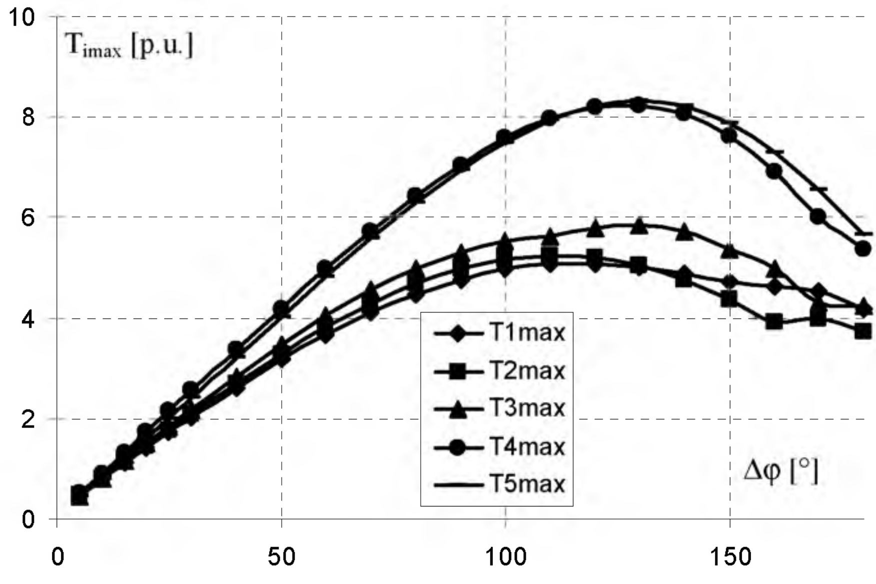


Fig. 12. Dependence of maximal torque values on differences $\Delta\varphi$ of voltage phases during synchronization

The results of the analysis indicate that for the studied unit the maximal values of torques for individual shafts appear at synchronization with the difference $\Delta\varphi$ of voltage phases in the range 110°÷130°.

The phase of voltage at the moment of breaker closing does not influence the value of torsional torques in shafts.

Calculation of shaft fatigue. The degree of the shaft fatigue caused by the torsional oscillations depends on the amplitude of torsional stress and the number of oscillations. The number of oscillations is influenced by the level of oscillations damping. Figure 13 shows an example of the curves for determining the fatigue caused by torsional oscillations [8].

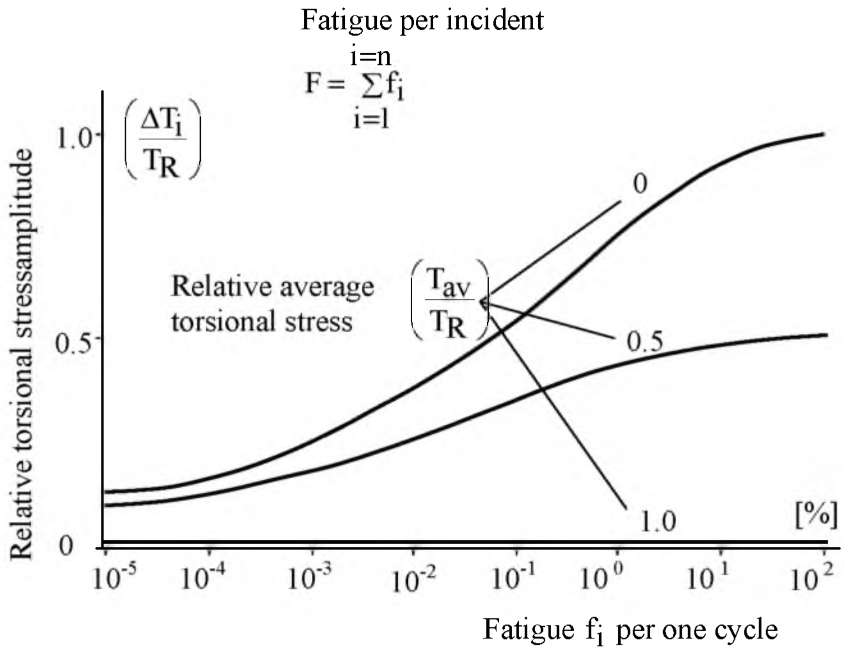


Fig. 13. Example of the curves for determining the fatigue caused by torsional oscillations [8]

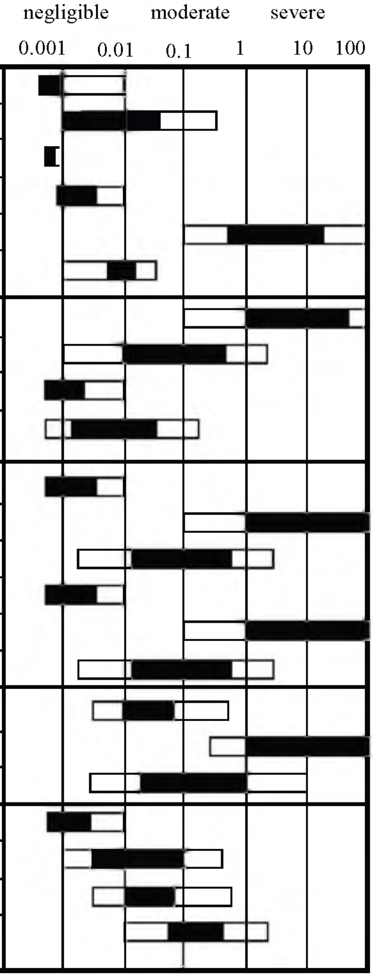
This Figure allows to read the value of fatigue f_i [%] caused by one swing (horizontal axis) in relation to the value of the relative torsional stress amplitude $\Delta T_i / T_R$ (vertical axis). The value f_i can be read on the curve corresponding to the relative average torsional stress T_{av}/T_R. T_R is the rupture stress causing the destruction of the material, T_{av} means average stress (constant component) and ΔT_i means amplitude of an alternating component of torsional stress.

In Table 1 the impact of different system switching operations and fault conditions on the fatigue of turbine-generator unit shafts is presented [8].

Table 1. Impact of different system switching operations and fault conditions on the fatigue of turbine-generator shafts [8]

Fatigue per incident [%]

Normal line switching	$\Delta P \leq 0.5$ p.u.	
	$\Delta P \geq 0.5$ p.u.	
Synchronizing	Automatic	
	Manual ($\Delta\varphi \leq 10°$, s = 0.7%)	
	Faulty ($90° \leq \Delta\varphi \leq 120°$)	
Full load rejection		
Line-to-ground fault	Triple pole reclosing	successful
		unsuccessful
	Single pole reclosing	successful
		unsuccessful
Line-to-line fault	Clearing	
	Reclosing	successful
		unsuccessful
Line-to-line-to-ground fault	Clearing	
	Reclosing	successful
		unsuccessful
Three phase fault	Clearing	
	Reclosing	successful
		unsuccessful
Terminal-to-terminal unit short circuit	HV side(system bus)	
	LV side (gen. leads)	
Three phase unit short circuit	HV side(system bus)	
	LV side (gen. leads)	



3. Conclusions

Calculations of system turbines and generator natural frequencies of oscillation are an important element of the shaft designing process. They allow to avoid working of the unit in conditions of hazard of arising oscillations caused by external influences.

Calculations of torsional torque values can be useful for finding out a reason for shaft damage, applying preventing means and for determining exploitation rules for unit work.

The studied cases of short-circuits, synchronization and the effect of external electromagnetic torque with resonance frequency on a generator rotor were characterized by high values of torsional torques exceeding the permissible values.

Acknowledgment

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