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AUTOMATED CONDITION MONITORING SYSTEM FOR TURBINE GENERATOR UNIT SHAFTS[1]

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Abstract: *Condition monitoring of the turbine generator unit (TGU) shaft is very important for TGU lifecycle estimation and operational reliability assessment. The lack of effective monitoring systems poses a threat to technogenic disasters. The paper presents an automated system for TGU shaft condition monitoring, its structure and operating algorithms. The main functions of this system are to detect impacts of perturbations from electric power system, to evaluate shaft material damage and to track the history of shaft torsional vibrations. It is also shown how the thermal power station statistics can be used for shaft damage analysis.*

Keywords: *Condition Monitoring, Turbine Generator Unit, Automated System*

INTRODUCTION

The turbine generator unit (TGU) is constantly affected by the power system perturbations such as short circuits, commutations, out-of-phase synchronizations, adjacent turbine generator units and electrical loads switching, etc. As a result of these perturbations, the torsional oscillations of the TGU shaft occur, which cause the accumulation of fatigue damage of the shaft material. This, in turn, leads to a reduction of the TGU lifecycle, its premature decommissioning, and, under certain conditions, to large-scale accidents, including well known equipment failures in 1974 at the Gallatin fossil plant (Kramer and Randolph, 1976) in the United States and in 2002 at Kashirskaya power station in Russia (Zagretdinov at al., 2004).

This problem can be solved by creating favorable conditions for increasing durability, by performing timely repair, reconstruction and decommissioning, as well as by monitoring and clarifying the residual life beyond the calculated one.

Recently, automated subsystems of diagnostics of thermal stress state and residual life of turbine have been integrated into modern automated systems of technological processes of power units, which include a TGU (Zile at al., 2014, Shulgenko at al., 2014). In Ukraine, such systems have only just begun to be developed and implemented in recent years. One such system was developed at the Institute of Problems of Mechanical Engineering n. a. A. M. Podgorny of National Academy of Sciences of Ukraine; it was preliminary tested at the Kharkov TPP-5 unit (Shulgenko at al., 2014).

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One of the functions of the system is to determine and record the damage of individual sections of the shaft on the turbine high pressure rotor. Damage is determined by the rotor speed, temperature and pressure of the hot steam in front of the stop valves and the active power of the generator, which are fixed at intervals of 30 s.

A limitation of the above systems is that their developers take into account only part of the turbine shaft and do not consider the turbine and generator rotors as a single complex object. However, accidents involving shaft damage occur not only in the area of the turbine rotor, but also in the area of the generator rotor, such as cases of damage to the coupling between the exciter and the generator, etc. (Shkhati, 2008).

On the other hand, it can be said that in practice there are no reliable industrial data channels for monitoring non-stationary processes in the TGU shafts. In addition, there is no proven diagnostic factor that determines the impact of these processes on the TGU shaft characteristics.

EXPOSITION

The approach to the solution of the problem described above, which is proposed in this paper, is to design the automated condition monitoring system for TGU shaft (ACMS), that differs, firstly, by a complex approach to the TGU shaft, and, second, by using new sources of data for its functioning. ACMS can be integrated into the automated control system of TGU as a subsystem (Baliuta and Kuievda, 2017).

For the monitoring of TGUs during the action of torsional vibrations, several stage techniques are used. Torsion monitoring provides a detailed analysis of each torsional event. Using the data collected through monitoring, it can be estimated the mechanical forces in each section of the shaft and determined the service life of each of them. The monitoring system continuously monitors the mechanical system of the TGU in presence of torsional vibrations. During high mechanical stress events, the subsystem detects the element with the highest stress and transmits data to a torsional force analyzer that evaluates the system response and analyzes the shaft behavior due to mechanical effort.

Let’s consider the mathematical models and algorithms used in the monitoring system design and operation.

For the purpose of this study, to determine the mechanical stresses and torques in dangerous sections of the shaft, it is appropriate to use, as a part of the mathematical model of TGU, a multi-mass shaft model of the following form (Bovsunovskii at al., 2013)

$$\mathbf{J}\frac{d}{dt}\mathbf{\Omega} = -\mathbf{C\Phi} - \mathbf{Z\Omega} + \mathbf{M}_G - \mathbf{M}_T,$$
$$\frac{d}{dt}\mathbf{\Phi} = \mathbf{\Omega}, \qquad (1)$$

where $\mathbf{\Phi}$ is the vector of the rotation angles of the shaft masses, $\mathbf{\Omega}$ is the vector of the angular velocity deviations of the masses, $\mathbf{M}_G$ is the electromagnetic moment of the generator, $\mathbf{M}_T$ is the torque of the turbine stages, $\mathbf{J}$ is the matrix of moments of inertia of point masses, $\mathbf{C}$ is the matrix of the stiffness coefficients of the shaft elements between the masses, $\mathbf{Z}$ - matrix of damping coefficients of torsional vibrations.

To improve the accuracy of the calculations for model (1), its parameters need to be adjusted using identification procedures. In (Kuievda and Baliuta, 2017) the authors propose a method for identifying mechanical parameters of TGU based on genetic algorithms.

One of the most important indicators of the TGU shaft residual resource used in the monitoring system is the fatigue damage rate of the shaft material. There are various methods for determining fatigue damage to materials, but the simplest and fastest method is to determine the damage to the material of TGU shaft based on the Palmgren-Miner’s rule of linear damage accumulation using the parameter D of the following form (Bovsunovskii, 2012):

$$D = \sum_{i=1}^{s} D_i = \sum_{i=1}^{s} \frac{1}{N_{ip}}, \qquad (2)$$

where D_i is the damage to the material on the i-th oscillation cycle, N_{ip} is the number of cycles to failure with the stress amplitude of the i-th oscillation cycle. Compliance with condition $D \geq 1$ means that the shaft material reaches the fail state.

ACMS promptly performs the following functions: systematic control and evaluation of impacts on the TGU shaft of any disturbances occurring in the electrical network, evaluation of mechanical effects on the couplings of the shaft sections, registration of the complete history of the excitation of the torsional oscillations of the TGU shaft, estimation and prediction of shaft residual resource.

The functional diagram of ACMS is shown in Fig. 1. Measurement information is supplied to the monitoring system from the pressure sensors of individual turbine stages (block 2) to calculate the torsion moments (block 6), which are generated at the individual sections of the turbine and act on the shaft, as well as from the phase voltage sensors at the generator outputs (block 3) and current sensors in the stator phases (block 4) to calculate the electromagnetic torque acting on the turbine generator rotor (block 7). Then, using a signal from the angular velocity sensor of the shaft line (block 1), the mathematical model in the form of observer (block 5) is adjusted to ensure the identity of the actual data and the calculated values of the amplitude and the phase of torques and angular frequencies of the individual elements of the shaft line. With respect to the stochastic nature of these measurements, their statistical processing is performed to ensure data validation (block 8).

The calculation of torques in the individual elements of the TGU shaft line and angular velocities (block 12) is performed using an observer in the form of a Kalman filter (block 9), which is synthesized on the basis of the mathematical model that describes the processes in the TGU (1). On the basis of the obtained torques, the algorithm determines the elements of the shaft line that can be damaged, as well as the damage of the material of the shaft line D_i on particular cycle. In addition, the cumulative damage D (2) of the shaft is determined as a result of the action of torques in transient modes (block 11). Based on the statistics of the transient and abnormal modes of TGU (block 10), the damage of the shaft for the future fixed period of operation is estimated and the residual resource of the shaft (block 11) is determined.

The database (block 14) accumulates information on the modes of operation of the TGU, which cause the occurrence of torsional vibrations of the shaft and swing.

The monitoring system uses the following algorithms to calculate the parameter D (2), which is a measure of the damage of the TGU shaft material. For the above functions of this system, estimation of the initial value of parameter D is required, as well as calculation of current value of D. The current value calculation is presented in 2 options, which differ by presence or absence of additional sensors.

The initial D value is assessed to determine the initial damage level of shaft before the monitoring system is put into operation.

The algorithm for estimating the initial value of D is based only on historical data of power plant and power system, it includes the following steps:

- using the mathematical model of TGU it calculates the values of damage for each of the modes of operation of TGU by digital simulation of each mode;
- on the base of the simulation results a table "operating mode-resulting damage" is filled for all TGU operation modes with different parameters, including emergency ones. An example of such data given in table. 1 (Bovsunovskii and Kuievda, 2015). Simulation was performed on four-mass model of shaft. As we see from this table the most stressed section in given mode is coupling between turbine low pressure stage and medium pressure stage, it will reach fail state after 1889 successful out-of-phase generator switchings with load angle 120°. It should be mentioned that for different operation modes the most stressed sections of the shaft can be different;
- matching data from the table "operating mode-resulting damage" to the statistics of the TGU operating modes of the power plant and statistics of the emergency modes of the power system, the system estimates the initial cumulative value of D before implementation of ACMS.

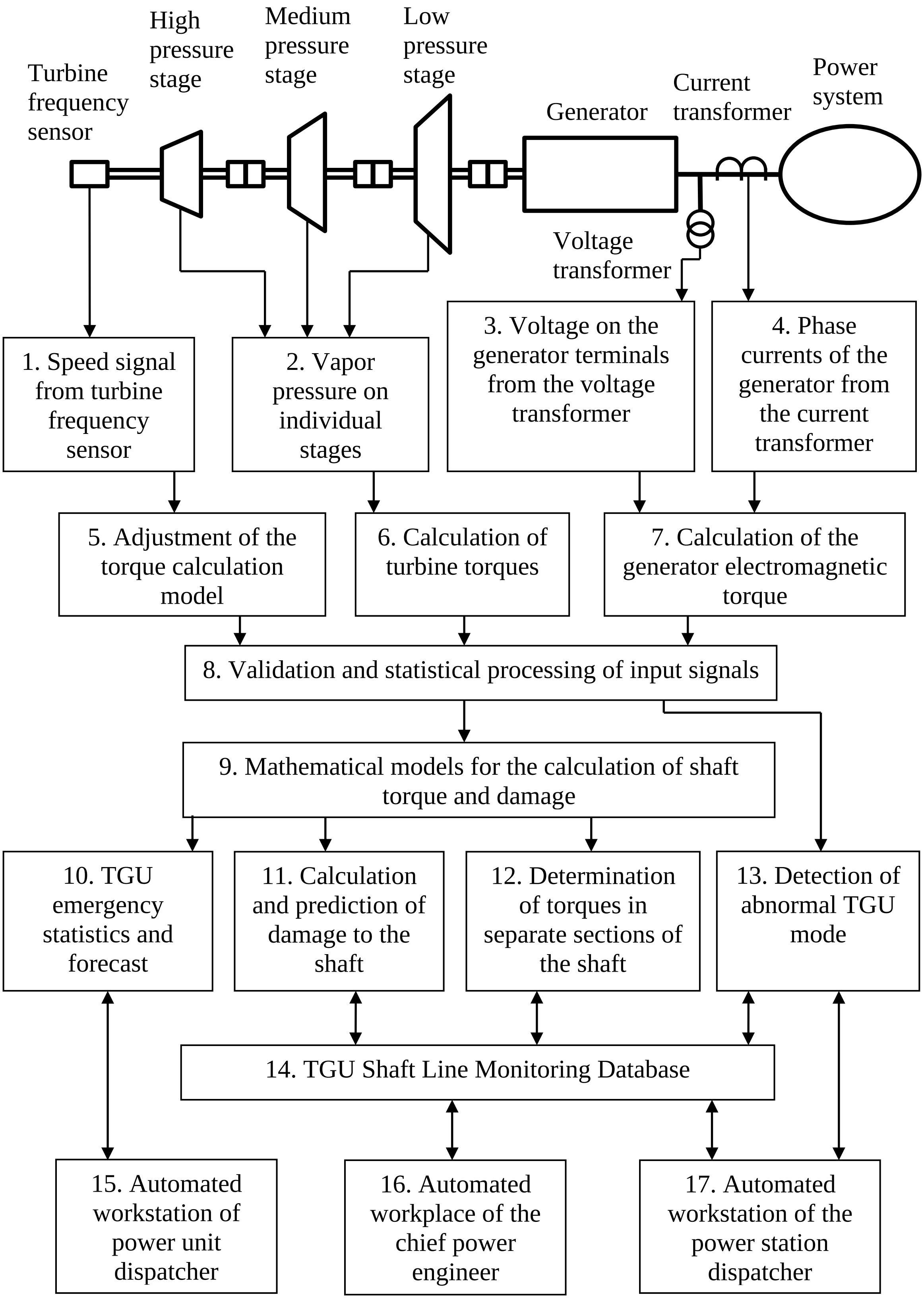

Fig. 1. The functional structure of ACMS

After the implementation of the monitoring system, the D current value calculation algorithm begins to work according to one of the options, depending on the presence of sensors in the system. D current value calculation, option 1 (in the presence of sensors):

- rotation speeds are measured at the outputs of the TGU shaft;

- with the help of the observer the rotation angles of the shaft elements, which are necessary to obtain the torques, are calculated;
- the algorithm of calculation of D from TGU model is applied.

D current value calculation, option 2 (in the absence of sensors):

- evaluation of D according to the algorithm of initial damage assessment and stationary statistics of TGU operation modes continues to be used.

Table 1. Fragment of the table "operating mode-resulting damage"

Operating mode	**Operating mode parameters**	**Shaft element**	***D***
Successful out-of-phase switching	Generator load angle when switched on, 120°	Coupling: generator – turbine low pressure stage	0
Successful out-of-phase switching	Generator load angle when switched on, 120°	Coupling: turbine low pressure stage – medium pressure stage	$5,295 \cdot 10^{-4}$
Successful out-of-phase switching	Generator load angle when switched on, 120°	Coupling: turbine medium pressure stage – high pressure stage	$1,045 \cdot 10^{-4}$

According to the accumulated history of the current values of the turbine damage parameter and statistics of operating modes of TGU as well as transitional and emergency modes of the power system using a separate algorithm, periodic prediction for a certain period of time of the residual life of the TGU shaft is carried out.

The algorithms for the monitoring of the damage of the TGU material shaft are quite complex, branched and multifunctional, which involves both analytical work on the identification of the most difficult modes of operation of turbine units, conducted by technical experts, and work in real time using current data.

The above-mentioned features of the algorithms impose high requirements for its implementation, that is, for the development of appropriate software.

CONCLUSION

The permanent operation of ACMS during torsional vibrations gives possibility to track in every moment all violations of operating modes and evaluate their impact on the damage of the TGU shaft. The monitoring system is designed to be integrated into the TGU automated control system, allowing it to exchange data and use control resources of that upper system.

Different variants of the algorithms of the monitoring system ensure its operation, both with and without the installation of additional equipment. The use of power plant and power system statistics allows it to estimate both the initial fatigue damage of the TGU shaft and predict its residual life for a certain period of time.

Thus, ACMS helps to track strength of TGU shaft, its durability, as well as estimate its residual life and predict the need of periodic maintenance.

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