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Development and Introduction of Diagnostic System for Vibroacoustic Monitoring and Technical Condition of Hydropower-Generating Units of Vartsikhe HPP

The Author's Abstract

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General Description of Work

Topicality of research. There is a lot of medium, large and small hydropower plants in Georgia. So far, none of them has the reliable control systems, particularly the modern systems of vibroacoustic monitoring and diagnostics (there is carried out only the temperature control, at best. The reliability and security aspects are reliant only on the intuition of experienced engineers. The introduction of the vibroacoustic and diagnostic systems will enable us to control any process occurring in hydropower plants and to disclose the defect since the moment of its inception.

Problem statement. Vibration monitoring consists in monitoring of changes in the vibration state of the system, as well as in the analysis of the reasons for these changes. The relevance of vibroacoustic problem and its practical application were caused by the need for the existence of operating control on the technical condition of the machine. Obtaining information about the technical condition of the equipment by means of the control facilitiescurrently existing in various engineering fields, is only possible through its internal monitoring, i.e. it becomes necessary to take it out of operational mode, or to take it down partially, and if this is not sufficient, completely, that would give rise to financial implications. The major objective of vibroacoustic diagnostics is precisely to provide the control of the technical condition of the machine without taking it down as well in its operational mode. Such common methods as temperature control, the quality of lubrication and other ones are no longer needed – they are replaced by the vibration analysis. Vibration diagnostics consists in detecting and identifying defects of the diagnostic mechanical system (by identifying the type and the extent of the defects).

Goal of research. Goal of the dissertation is to develop theoretical and practical bases of vibroacoustic diagnostics and create highly effective methods of diagnostics within such universal mathematical program, as a package MathCad, which provides high level of reliability in response to modern development trends of power equipment.

Objectives of research. To achieve this goal, it is necessary to attain the following objectives:

1. Systematizing methods and means in the field of vibroacoustic

diagnostics based on surveys of the world's leading firms, as well as identifying the ways and methodological approaches for improving their quality in developing the technical diagnostics systems.

2. Creating theoretical and methodologicalframeworkfor the automated system of technical diagnostics on the basis of monitoring vibration processes occurring in the hydropower-generating units.

3. Developing theoretical models, which link spectral characteristics of the vibration elements of hydropower-generatingunitsto their design parameters and allow for determining the technical conditions. Selecting and justifying diagnostic signs and spaces of signs, which characterize hydropower-generating units, based on mathematical modeling and real experiments.

4. Finding and defining functional relationships (analytical and statistical) between vibroacoustic signals and the technical conditions of the hydropower-generating units.

5. Developing the methodology of diagnosis of the hydropower-generating units, which provide the reliability of the vibration control results and allow for using the actual operating conditions.

Methods of research. When solving the set problems, there have been used the provisions from the theories of machines and mechanisms, dynamics of machines, image discrimination, probability and mathematical statistics. In the experimental studies, there have been used the modern methods of narrowband, octave and tierce-octave analysis (SpectraLab, MathCad). Mathematical processing of experimental data has been performed in Mathcad package.

When developing the diagnostics algorithms, there have been used the methods of the theory of decision-making and image discrimination theory.

The Provisions Brought to Defense:

1. The principles of building the system of vibroacoustic monitoring and technical diagnostics of the hydropower-generating units, which envisage division of information frequencies and assessment of their results, formation of diagnostic signs of vector, assessment of the technical conditions, which is based on the image discrimination theory.

2. The methods for technical assessment of the main vibroacoustic components of the hydropower-generating units, which are based on the total

levels of vibroacoustic acceleration, narrowband, octave and tierce-octave analysis, as well as on envelope of high-frequency oscillations, methods for detecting the information frequencies in the vibration spectrum of the hydropower-generating units and assessment of their informational contents.

3. The bases for building the models of diagnostics, which allow for classifying the technical conditions of the hydropower-generating units by means of multi-dimensional diagnostic signs.

4. Methodology for diagnosis, in a Mathcad package, of the technical conditions of the hydropower-generating units' electromechanical system, which allows for establishing the technical conditions and forecasting their development trends during operation.

Novelty of Research. The novelty of this research consists in fact that for the first time ever, there were first formulated the principles of constructing the system of vibroacoustic monitoring and technical conditions of the hydropower-generating units, which include assignment of information frequencies and assessment of their values, formation of diagnostic signs of the vector, construction of tables of defects and symptoms, assessment of the technical conditions, based on the image discrimination theory. On the basis of this, a new methodology ofvibroacoustic diagnosis has been created, which is constructed within such universal mathematical program, as a package MathCad (that is practically free, in contrast to the expensive products of the world's leading firms – economic issues are very important here).

Practical bearing. Data of diagnostic signs and diagnostic models for assessing the technical conditions of the hydropower-generating units, are methodological bases for the development of instruments of the technical conditions, as well as an important factor of the organization of the repair and maintenance system. Their practical bearing consists in fact that they allow for:

1. Using the developed diagnostic instruments in the processes of their manufacturing, adjusting and monitoring during operation.

2. Performing computer-based modeling and forming diagnostic signs, creating databases, which are the basis for assessing the technical conditions of the elements of the hydropower-generating units, as well as for a statistical analysis of the quality of the running.

3. Introducing the hydropower-generating units' technical maintenance system "by the actual state", which is based on diagnostic control by the vibration characteristics.

Application and implementation of the results of research. The developed models, methodology and technical means complex should be used in the development and introduction of the computer-based diagnosis system of the hydropower-generating units in all hydropower plants throughout Georgia.

The results of the dissertation work will be used in training process at the energy specialties of AkakiTsereteli State University, in preparing the graduation papers as well as in research works performed by Master and PhD students.

Approbation work. The provisions and results of work of the Thesis topic, have been presented at the international scientific conferences:

1. Energy: Regional Problems and Development Opportunities;
2. Sustainable Energy: Challenges and Development Prospects.

Publications. On the Thesis topic, the author haspublished3 articles in the internationally recognized scientific journals.

Volume and Structure of Dissertation. Dissertation comprises 107 printing pages. It includes Introduction part, 4 chapters, conclusions and list of 47 References.

Brief Content of Dissertation.

Introduction dwells onsubstantiation of the relevance of the topic, goals, objectives and methods of research.Also, novelty of research and its practical bearing are shown.

The first Chapterdeals with a general overview of of the origins of vinroacoustic diagnostics and stages of its development, as well asdescribes the different systems of vinroacoustic diagnostics.

The second Chapter describes theoretical research, according to which there have been studied how to:formulate and attain the objective of vibroacoustic diagnostics.

Mathematical link in the mechanical system between the symptoms and

measurements can be established in the following way:

$$A_1 = f_i(\Delta_{r_1}, \Delta_{r_2}, \dots \dots, \Delta_{r_m}), i = 1, 2, \dots, n.$$

where f_i is a differential or an algebraic operator. This relationship in the deferential form allows us for obtaining the desirable result of vibroacoustic diagnostics only in low-frequency range.

Currently, vibroacoustic diagnostics is carried out by means of the image discrimination theory:

1. It is assumed that the technical object exists in in finite set of technical conditionsსლებბა - S. From this set of technical conditions, there are extracted two subsets $S_1 U S_2$. S_1 is a subset of workable technical conditions andS_2 - a subset of unworkable technical conditions.
2. A subset S_1 implies all those conditions, according to which the object functions correctly, but a subset S_2 implies all all those conditions, according to which some defects come out, which impact on the quality of object operation.The transition from one state to another depends on the defects existing inside the object.
3. The technical object diagnostics is brought to the analysis of S_1 setor$S_1$and S_2 subsets. When determining working ability of the object, it is subject to assessment and after this assessment, it is addressed [illegible] $S_1$and S_2 subsets. This followed by detail assessment of the object and it can be moved from one subset to another.
4. The inception of the defect does not necessarily imply that the object [illegible] not functional at all. The workable object may also have [illegible] defect is a large-scale, the object just moves from one state [illegible] both the workable and unworkable objects may have the defe[illegible] after assessment of the object, it must not move from one subse[illegible]

Description of the algorithm of identification of techni[illegible] the of the energy unit is also possible.

The vibroacoustic diagnostics procedure is divided into three parts:

The first stage is to address the general problem of acceptability of the equipment, and with that in mind, the technical condition pertains to subsetS_1orS_2. Mathematically, this process has the following form:

if$\overline{X} \leq \overline{X^э} + \overline{\delta}$ is acceptable

if$\overline{X} > \overline{X^э} + \overline{\delta}$ is unacceptable,

where$\overline{X}$ is a vector of the output measuring parameter, $\overline{X^э}$- is a vector corresponding with the reference parameter, and $\overline{\delta}$ - is permissible deviation from a reference value. If even only one parameter is obtained from a permissible value, the object is considered unworkable and unacceptable, and the objective technical condition moves into the S_2 subset.

The second stage is to address the analysis of technical condition. At this stage, a new coefficient of performance is introduced. To do so, by means of $\overline{\delta}$ there is determined the zone,where the existing technical condition is at this moment in time. Coefficient of performance is $\overline{C} = 0 \div 1$. The higher is performanceC, the closer it is to 1. Mathematically, this can be expressed in the following form:

$$\overline{C} = 1 - \left|\frac{\overline{x} - \overline{x^{э}}}{\overline{\delta}}\right|,$$

where $\overline{C}$ is a coefficient of performance. If $\overline{C} = 0$, the object is unacceptable, if $\overline{C} = 1$, its state is considred reference. If $0 \leq C \leq 0{,}25$, the object has a very high coefficient of performance, if $0{,}25 < C \leq 0{,}5$, we have a very low pereformance value, and if $0.5 < C \leq 0.75$ – a high performance value, and if $0.75 < C \leq 1$ –a very high performance value.

The third stage is to address to which class of technical condition pertains the object in accordance with the existing defects, as to how far its parameters are from a reference one. This is expressed in the following formula:

$$D_{ik} = \sum_{k=1}^{n} [\overline{A}_{ik} - A_k^{э}]$$,

where, $\overline{A}_{ik}$ are the symptoms, which are obtained as a result of developing signal obtained from measuring. $A_k^{э}$ - is a reference value, which is placed in the algorithm of diagnostics.

Mathematically, the algorithm of identification has the following form:

if $D_{ik} \leq \Delta_{ik}^{n}$ - there is a no defect

if $D_{ik} > \Delta_{ik}^{n}$ –there is a defect.

Here Δ_{ik}^{n} is a limiting value, and these values have been obtained statistically and experimentally. If the vibration level is doubled, this already points to the existence of the defect.

The method for determining and predicting linear trends of changes in the technical conditions of the energy-converting machinery in the objectives of diagnostics.

The trend characteristic (the development trend of characteristic) allows for forecasting the moment of catastrophic changes in the technical conditions. Based on this, it is possible to forecast the remaining resource, as well as to determine the time for repair scheduling.

Mathcad has the functions „detrend" and „predict" for determining trend of changes and

for predicting changes (Burge's function is based on the autoregressive method), which produce good practical results.

This method with high accuracy makes forecast of the expected points based on the process itself. In the real systems, if it contains any pattern, the method displays this pattern and uses it for forecasting the expected points with high accuracy.

We shall use this method for predicting the total vibration level (dB) of turbine bearing and for forecasting the expected changes (Fig. 1).

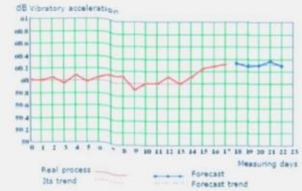

Fig. 1. The example of determining and predicting linear trend of the technical states

Once the degradation processes start in a bearing, the method makes prediction of signal coming from a sensor and establishes the trend that calls the operator to required action. This approach is ideal for the automation of processes, especially as work is currently under way on creating the automated control systems by using the vibration signals.

Also there are considered the reference vibroacoustic characteristics of the hydropower-generating unit during operation and their analysis. Many years experience of operating hydropower plants, by changing noises and vibrations, clearly demonstrates to personnel some changes in operating equipment, but deviation from the reference– the norm of the technical state can be determined only by measuring noise and vibrations. The reference is a system, which is close to perfect.The factory-manufacturer of the hydropower-generating units has the statistically established permissible limiting values of vibrations. Also, the State Standard GOST5616-89 envisages that for hydro-generators, the values of vibrations in all directions (double amplitude and distance of oscillations) in all operating modes should not exceed the permissible limiting values specified in this standard.

For example, for the hydro-generators, whose rated number of revolutions is equal from 100 to 187,5 revolutions per minute, the permissible vibration amplitude is 0,15 mm. This value must be considered the reference. In general, the lower are the reference permissible values, the more sensitive is a diagnostic system towards the defects. In our research, we considered a permissible value relating to the scale – 6 dB, that is, if vibrations were doubled, then the defects were expected.

The third Chapter completely refers to the universal program of special diagnostics developed within a MathCad computer software, which allows for analyzing and comparing the taken vibrating signals, and making conclusions on them.

Mathematical environment of the analyzer allows for computing easily values required for diagnostics. For example, the root-mean-square (RMS) value of signal, which is proportional to vibration capacity, as well as CrestFactor, which represents the ratio of RMS to maximum value of signal

$$RMS = \sqrt{\frac{1}{N-1}\sum_{i=0}^{N-1}(C_i)^2}$$

$$CrestFactor = \frac{max(C)}{RMS}$$

Defect – mechanical balance weight.

Symptom- an increase in total level of the vibrations of the upper and lower guide bearings, as well as an increase in the first harmonic.

Permissible values in decibels are $\Delta 111 < 6$ *and* $\Delta 112 < 6$

$$\overline{A}_1 = [A_1(f_{rev})] f_1 := 53_0 V'_1 := 54.5 V'_2 := 56$$

$$\Delta 111 := V'_2 - V'_1 \Delta 112 := 032_{0,1} - 031_{3,1} \Delta 111 = 1.5 \Delta 112 = 9.158$$

D11:= | There is a defect if Δ111 > 6
There is a defect if Δ112 > 6
There is a no defect otherwise
D11:=There is a defect

The fourth Chapter describes the methodology for conducting the experiment, the forms of the considered vibration signals with radial, vertical and tangential directions within an octave band, and also spectra of signals. Also, this Chapter describes the program of special diagnostics and the results and main conclusions obtained through this program.

Within a Mathcad environment, the special computer program has been created and developed, which, in a few minutes, determines all vibration characteristics and compares them to each other as the results of several measurements, and also, if required, the results of measurements of the different energy-generating units.

Measurements were carried out in all three directions at fourvibro-active points of the units (at Vartsikhe HPP). These points are as follows: turbine, bottom bearing, top bearing and the "combinator".

There have been determined and analyzed the following vibration characteristics of the removed signals:

- Shapes of vibro-acceleration signals;
- The root-mean-squared values of signals (RMS).

In our example, about 400 diagrams have been designed and compared for the units of Vartsikhe HPP. One of the typical diagrams of the vibration fields is given below in Fig. 2.

red color, and the second measurement results – in blue color)

Also, there is described the experimental study of vibroacoustic characteriscs of the hydropower-generating units of Vartsikhe HPP for the purpose of diagnosis of the technical conditions.

An experimental study has been carried out on vibroacoustic characteriscs of the hydropower-generating unitsfor the purpose of diagnosis of the technical conditions. The measurement point has been selected on the mounting pad at the distance of 1m near the turbine rotor shaft.

The root-mean-squared value (RMS) of the acoustic signal, which is proportional to acoustic power and characterizes the source of noise as a whole, and CrestFactor, which is a ratio of a maximum to RMS and points to the possible impacts in an oscillatory system.

$$RMS := \sqrt{\frac{1}{N-1}\cdot\sum_{i=0}^{N-1}\left[(RTS^{\langle 1\rangle})_i\right]^2} \quad RMS = 23.807$$

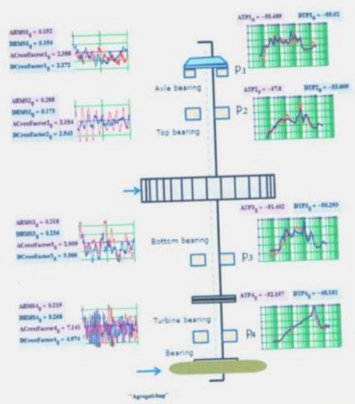

Fig. 2. Comparison of the signals of the old and new vibration fields measured in the radial direction (the first measurement results are marked in

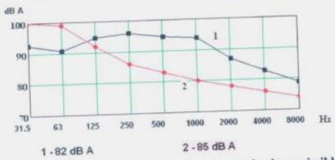

Fig.3.Comparison of the noise levels with the standard permissible values

$$CrestFactor := \frac{\max(RTS^{\langle 1 \rangle})}{RMS} \quad CrestFactor = 2.257$$

The above mentioned characteristics of vibroacoustic signal are the diagnostic signs, and their continuous monitoring allows for monitoring and full-fledged diagnosis of the technical conditions of the hydropower-generating units.

Conclusions

1. The universal computer software has been designed in a Mathcad package for vibroacoustic diagnostics of the hydropower-generating units, which allows for analyzing the taken vibration signals, comparing them with each other and making relevant conclusions.

2. Besides insignificant deviations in the vibration characteristics of the aggregates by the monment of measuring, to judge, as far as possible, by one-time measurements that there are no significant defects in the system, and malfunction and aggregates are in satisfactory technical condition. These technical states, with a certain degree of accuracy, can be considered as the initial (reference) ones, and in the future, we should purposefully search for the possible deviations and defects caused by these states.

3. In order to detect the incepted defects in case of insufficient lubrication, it is necessary to control the appearance of impact pulses in accordance with the value of CrestFactor. Then, the results of measuring this value must be compared with data of the high-frequency envelope spectrum, in order to determine the appearance of non-periodic impact pulses caused by the defects of lubrication.

4. It is necessary to control the low-frequency vibration energy of the bearing and of the whole machine, since the pre-accidenttechnical condition ofthe bearing may randomly impact on the vibration levels of the other components without significant increase in the vibration harmonic constituents. More needed to be measured the vibration acceleration.

5. It is necessary to provide control of the levels of constituents of the separate harmonics at low and high frequencies. During the accumulation of several significant defects simultaneously in the bearing, the vibration may be sharply increased at the previously unknown combination frequencies as what are the particular ratio and the spatial arrangement of defects.

6. The mentioned method of diagnosis can be used not only for the cases with the hydropower-generating units, but in the any field of engineering, with appropriate modifications.

7. The mentioned computer software is ready to be introduced in Vartsikhe HPP, as well as in any other hydropower plant.

On the Thesis topic, the author has published 5 articles:

1. Kopaliani N., Zivzivadze O., Dzadzamia D. Experimental study of the acoustic characteristics of power transformer at high-frequency sub-stations. Third International Scientific Conference "Energy: Regional Problems and development Opportunities" - Kutaisi. 2015, pp.75-78

2. Kopaliani N., Dzadzamia D., Gogisvanidze V. Determining changes trend in technical state of energy-converting machines and forecasting in technical diagnostics problems. International Scientific Conference "Sustainable Energy: Challenges and Development Prospects". Kutaisi. 2015, pp. 32-36

3. Kopaliani N.,Pilia R., Dzadzamia D., Gogisvanidze V.The possibilities of drawing and sound creation through mathematical modeling in a Mathcad package. Periodical scientific journal "Novation", No 15, - Kutaisi. 2015, pp. 56-61

4. Kopaliani N., Zivzivadze O., Dzadzamia D. Implementation of vibroacoustic diagnosing problem of the technical conditions of the hydropower-generating units in a Mathcad package. Periodical scientific journal "Novation", No 15, - Kutaisi. 2015, pp. 232-238.

5. Kopaliani N.,Dzadzamia D., Purtseladze I. Experimental study ofthe acoustic characteristics of the hydropower-generating units for the purpose of diagnosis of technical conditions. Messenger of AkakiTsereteli State University. No 1(7). 2016, pp. 76-86.