RIGA TECHNICAL UNIVERSITY
Faculty of Transport and Mechanical Engineering
Institute of Mechanics

Marina GRIŠČENKO
Doctoral student of the doctoral study programme "Engineering, Mechanics and Mechanical Engineering. Applied Mechanics"

AIR GAP MONITORING OF HYDROPOWER UNIT GENERATOR TO ADVANCE VIBRATION DIAGNOSTIC PROCEDURE

Summary of the Doctoral Thesis

Scientific supervisors
Dr. habil. sc. ing., prof.
J. VĪBA
Dr. sc. ing., prof.
J. AUZIŅŠ

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THE DOCTORAL THESIS

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To be granted the scientific degree of Doctor of Engineering Sciences, the present Doctoral Thesis has been submitted for the defence at the open meeting on ………………………..at… …..……… , at the Faculty of Transport and Mechanical Engineering, Riga Technical University, 6 Ezermalas Str., Room 310.

OFFICIAL REVIEWERS

Professor, *Dr. sc. ing*. Rihards Indriksons
Latvian Maritime Academy

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Riga Technical University

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DECLARATION OF ACADEMIC INTEGRITY

I hereby declare that the Doctoral Thesis submitted for the review to Riga Technical University for the promotion to the scientific degree of Doctor of Economics, is my own and does not contain any unacknowledged material from any source. I confirm that this Thesis has not been submitted to any other university for the promotion to other scientific degree.

Marina Griscenko …………………………….(Signature)

Date: ………………………

The Doctoral Thesis has been written in Latvian. It contains an introduction, 7 chapters, conclusions and bibliography with 132 reference sources. It has been illustrated by 63 figures and 49 tables. The volume of the Doctoral Thesis is 145 pages.

CONTENTS

GENERAL DESCRIPTION OF THE THESIS

The Doctoral Thesis is devoted to the research of rotating industrial machinery vibration and possible improvements of vibration monitoring procedure for hydropower generation units, which are located on the River of Daugava in Latvia.

Research Topicality

The qualitative condition diagnostics of hydropower unit allows one to carry out the safe operation of the equipment, to avoid unnecessary repair costs, to reduce outage hours, to forecast the scope of refurbishment and to upgrade projects. The improvement of the measurement procedure requires developing the methodology for the evaluation of results, because the qualitative analysis of the results and storing the data about every hydropower unit help to upgrade equipment monitoring procedure to sophisticated technical diagnostics.

Research Aim

The aim of the research is to develop the methodology for measuring and evaluating the air gap of hydropower units located on the River of Daugava. Since nearly every detail of hydropower unit construction affects the generator air gap, monitoring the air gap is supposed to improve the quality of vibration diagnostics.

Research Tasks

To achieve the aim set and to develop the methodology for air gap monitoring the following tasks are defined:

1) To review the existing significant investigations in the field of air gap monitoring;
2) To develop the mathematical model of the hydropower unit, including description of mechanical forces that affect the unit and taking into account design specifics of units located on the River of Daugava;
3) To calculate self-excitation frequencies and critical speed of the units;
4) To develop the air gap mathematical model and to describe possible faults;
5) To supplement the mathematical model with magnetic forces, which are calculated for synchronous generators, taking into account design specifics of units located on the River of Daugava after the upgrade projects;
6) To carry out experimental air gap measurements on site for hydropower generation units with different turbines (Francis, Kaplan);
7) To develop the methodology for evaluation of experimental results.

The Object and Subject of the Research

The research object is a vertical hydropower generation unit and the slow-speed salient poles synchronous hydropower generator, but the subject of the research is the hydropower generator air gap.

The Scientific Novelty and Main Results

1) In the given Doctoral Thesis the mathematical model is developed, where both mechanical vibration of hydropower unit and generator air gap behaviour depending on vibration are described. The data could be further used for finite element method modelling.
2) The evidence is collected to show in which cases air gap measurements are strongly recommended, when the measurements are advised, and when the measurement is not critical.
3) The set of data about possible air gap faults for different hydropower generation units is collected and systematised.
4) The novel methodology for presenting air gap results is suggested, where the air gap is plotted with reference to rotor spider.
5) The novel methodology to evaluate air gap measurement results, using spectrum analysis, is suggested.

Scientific Conferences and Practical Value of the Research

The main research results concerning the air gap evaluation method using spectrum have been published in the Latvian Journal of Physics and Technical Sciences. A set of other results mentioned in the Thesis have been published in 11 conference proceedings; 7 proceedings out of 11 are quoted by the IEEE and Scopus databases. The research results have been presented during international conferences in Latvia, Estonia, Sweden and Russia.

The evaluation methodology has been used four times to accomplish air gap measurements for two hydropower units (as a part of regular condition monitoring procedure). Some sections of the chapters of the Thesis listed below are of particularly practical value:

1) In the first chapter, many case studies about the possible air gap faults are analysed. Thus, the main symptoms of uneven air gap and the main problems arising from uneven air gap are described. This information would be useful for condition monitoring and diagnostics in the future.

2) In the second chapter, the detailed description of hydropower unit parts is given, which could be used for further finite element method modelling.
3) The computer code is developed which is used for experiments and to obtain measurement data;
4) In the eighth chapter the evaluation methodology is used for the processing of the obtained data.

Research Importance and Research Specifics

The technical condition monitoring and vibration measurement procedures are regulated by standards and normative documents; still, the common theory of hydropower unit vibration is hard to develop due to a number of factors typical of the research object. These factors are as follows:

1) Slow speed of the rotating unit;
2) A great number of factors and subsystems, which affect the unit;
3) Different unit design depending on a manufacturer (size and construction).

In the given Doctoral Thesis, the ideas about the common theory about the hydropower unit vibration are developed and enhanced. Those ideas are found in scientific papers of Canadian, Estonian and Japanese authors, as well as Russian authors' theses. Ideas are reworked so that they could be used effectively for units located on the River of Daugava.

Limitations of the Research

Some phenomena common to hydropower units have not been covered by the Thesis due to the volume limitations and are suggested for the author's further research. Namely, cavitation, resulting high-frequency vibration and hydropower plant foundation quality are not in the scope of the research.

Theoretical and Practical Foundation of the Research

The theoretical and practical foundation is based on foreign authors' ideas about air gap monitoring of hydropower units and vibration monitoring, and Latvian authors' ideas in the theoretical mechanics field. The informative basis of the Thesis comprises the documentation from hydropower plant technical archive, upgrade project documentation, normative documents (ISO, CEA, STO standards).

The Structure of the Doctoral Thesis

The Doctoral Thesis consists of four main sections: literature review, development of mathematical model, experiment and development of evaluation methodology for experimental results.

Research Methods

As the main quantitative method for the research, a series of experiments performed in 2014 were used. During the experiments the air gap of two units with different turbines was measured under different modes and working conditions. For the experiment the “Case Study” method was chosen. Case study has a great advantage for hydropower unit research, compared to other methods, because it does not eliminate any factors (minor at first sight but sometimes the most important ones) within the scope of the research.

For data processing quantitative and statistical methods were used. For literature review also the qualitative methods were used, including interviews with open-ended questions, analysis and comparison. The comparison method was used to structure the information about possible air gap fault symptoms and causes, based on other authors’ case studies. The interviews were used to understand other authors’ ideas and research conclusions about modelling the air gap for synchronous generators. The analysis method was used to evaluate existing normative documents and standards about air gap evaluation criteria.

Main Research Hypotheses

The study puts forward the following research hypotheses:

1) The dynamic air gap monitoring is a contemporary diagnostic tool, and it is more efficient than static air gap monitoring. Dynamic monitoring ensures better evaluation of technical condition and allows for better investigation of possible faults.

2) To evaluate the uneven air gap it is suggested to use a spectrum analysis. The developed method allows discovering the most common faults, such as rotor eccentricity, oval shape, or rotor spider to rim connection defects.

3) The developed evaluation methodology is a useful tool for hydropower unit technical condition assessment in the long run or for evaluating the condition before and after the refurbishment.

The Volume of the Doctoral Thesis

The Doctoral Thesis consists of an introduction, seven chapters, conclusions, and bibliography with 132 reference sources. It comprises 145 pages, including 63 figures and 49 tables.

1. VIBRATION DIAGNOSTICS OF HYDROPOWER UNITS

The following section provides the theoretical background about air gap monitoring, its history and development. It is shown in the introduction that due to the great dimensions it is hard to ensure perfect alignment of the hydropower unit; meanwhile, forces which occur due to uneven air gap could seriously impact the performance of the generator. Research suggests that regular measurement of the generator air gap is recommended both in the hydropower unit maintenance "best practice" catalogue and in the general documentation of hydropower unit upgrade; therefore, the air gap is a subject of the given Thesis.

The air gap is a nominal or measured value between the hydrogenerator rotor and stator, or literally speaking it is the "heart" of a hydrogenerator, because in the air gap the mechanical energy is transformed into the electric energy. Hydropower generator is large, and its dimension could change during operation, so the air gap changes as well. The generator is subjected to different forces, including centrifugal and thermal forces, vibration, magnetic and electric field, geotechnical forces. All the listed factors could have a great impact on the generator and the air gap in the long run. The possible reasons for the uneven air gap could be generator design, eccentricity, unbalance, shaft deformation, mechanical wear of some details, faults in the exciting or cooling system, forces (hydraulic, mechanic, magnetic) and temperature fluctuations. In the long run, even the quality of hydropower plant foundation could lead to a large air gap variation. In the Doctoral Thesis, the special attention is devoted to eccentricity fault and oval shape fault.

In the Doctoral Thesis, the diagnostic symptoms of uneven air gap are described. The most common symptoms in other authors' case studies are shaft misalignment, stator frame vibration, stator core second vibration harmonic, increased amplitude of bearings spectrum first harmonic, uneven magnetic field, wear or cracks in construction elements, winding insulation faults, cracks in rotor poles to rim connection, rotor or stator core corrosion, uneven warm-up or bearing faults.

2. SYSTEM MATHEMATICAL MODEL

The second chapter shows that a hydropower generation unit can be described as an oscillation system with two excitation sources: turbine and generator. The general mathematical model consists of two independent elements as shown in Table 2.1.

Table 2.1

Basic Equations for Mathematical Model

Element	DOF	Direction	Equation in a basic matrix form
Generator as a mass No. 2	Z2	Axial	$[m_2]\{\ddot{x_{z2}}\} + [c_{aks}]\{x_{z2}\} = \{F_{z;gen}\}$
	X2	Radial	$[m_2]\{\ddot{x_{x2}}\} + [c_{rad2}]\{x_{x2}\} = \{F_{x;gen}\}$
	Y2	Radial	$[m_2]\{\ddot{x_{y2}}\} + [c_{rad2}]\{x_{y2}\} = \{F_{y;gen}\}$
	Φ2	Rotation	$[I_2]\{\ddot{\omega}\} + [c_{rad2}](\omega) = \{M_2\}$
Turbine as a mass No. 1	X1	Radial	$[m_1]\{\ddot{x_{x1}}\} + [c_{rad1}]\{x_{x2}\} = \{F_{x;dr}\}$
	Y1	Radial	$[m_1]\{\ddot{x_{y1}}\} + [c_{rad1}]\{x_{y2}\} = \{F_{y;dr}\}$
	Φ1	Rotation	$[I_1]\{\ddot{\omega}\} + [c_{rad1}](\omega) = \{M_1\}$

The general mathematical modelling of hydropower generation unit is accomplished, taking into account design specifics of units located on the River of Daugava; general equations are provided and ready FEM from other authors' Doctoral Theses are discussed.

It is shown that a hydropower generation unit can be modelled as a system with two masses, but it cannot be modelled as a system with "rigid supports". Modelling bearings as a rigid support is inappropriate for vibration diagnostics, because such assumption makes calculation of shaft self-excitation frequency from bending incorrect. It is shown that during modelling stiffness should be calculated both in radial and axial directions.

It is concluded that neither the turbine, nor the generator can be modelled with only one degree of freedom — rotation about the z axis, because hydraulic and electric unbalance creates also transition forces in three directions.

3. SYSTEM CRITICAL ROTATION FREQUENCIES

In the chapter it has been concluded that resonance of hydropower unit can appear due to the design and unsuccessful choice of operation modes. The system self-excitation frequencies have been calculated. It is shown that modelling of hydropower unit shaft includes the following specifics — a slow speed of the rotating masses, shaft vertical alignment and bearings, which are modelled as supports with reduced stiffness. Summarising the calculation done in the chapter, critical rotational speed frequencies from bending and torsion p1—p7 can be described with the zero-determinant (3.1) as a homogenous linear system with seven degrees of freedom and amplitudes a1–a7:

$$0 = \left\| \begin{bmatrix} a_1(-m_2p^2+C_{aks}) & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & a_2(-m_2p^2+C_{rad2}) & a_3C_{rad2} & 0 & 0 & 0 & 0 \\ 0 & -a_2C_{rad2} & a_3(-m_2\cdot^2+C_{rad2}) & a_4C_{rad1} & 0 & 0 & 0 \\ 0 & 0 & -a_3C_{rad2} & a_4\cdot(-m_1p^2+C_{rad1}) & a_5C_{rad1} & 0 & 0 \\ 0 & 0 & 0 & -a_4C_{rad1} & a_5(-m_1p^2+C_{rad1}) & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & a_6(-J_2p^2+C_{rad2}) & a_6C_{rad1} \\ 0 & 0 & 0 & 0 & 0 & -a_6C_{rad2} & a_7(-J_1p^2+C_{rad1}) \end{bmatrix} \right\| \qquad (3.1)$$

As a result, the amplitudes A1(ω) — A7(ω) can be found from the non-homogenous linear equation system for each degree of freedom of harmonic oscillations with excitation and with frequency ω. The example of amplitude calculation from bending and torsion is shown in Fig. 3.1.

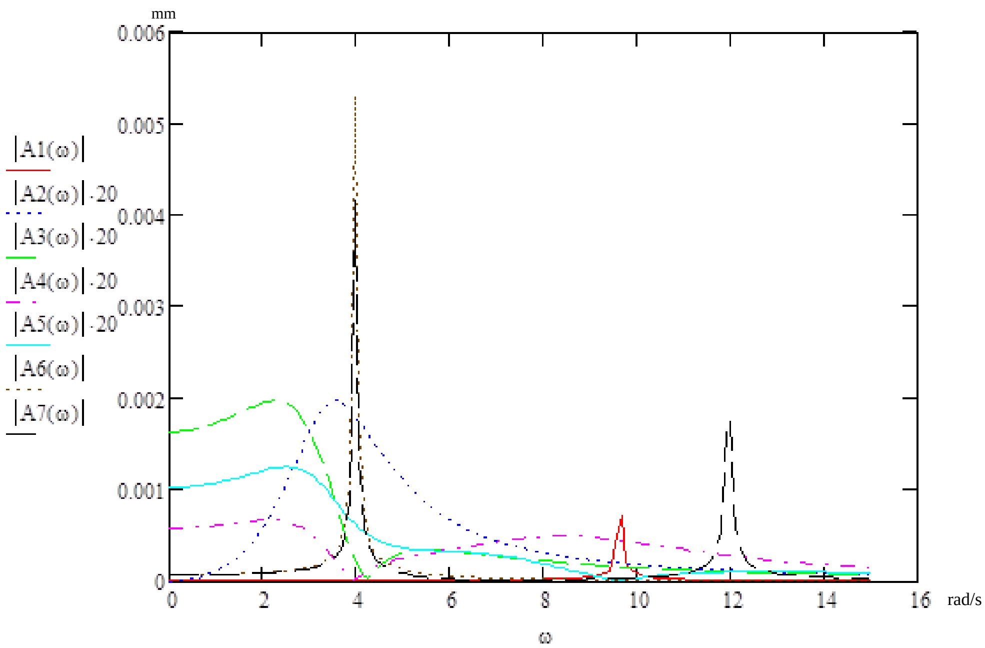

Fig. 3.1. Example for calculation of excited oscillation amplitudes and system critical rotational frequency zones from bending and torsion in MathCAD.

In Fig. 3.1, both the areas of oscillation with large amplitudes and oscillation dynamic damping zones are shown. The graphs explain the specifics of experimentally obtained spectrum results. In the chapter it has been shown, how the critical torsional rotational speed varies when different shear moduli are chosen. It has been concluded that a critical torsional rotational speed cannot be observed during experiments, because hydropower unit shaft initially has quite large reserve for torsional rotation speed.

It has been shown that critical speeds from bending should be calculated only using computer modelling and taking into account stiffness of the bearings, because neglecting this information increases the reserve coefficient for bending critical speed 2÷3 times.

4. UNEVEN AIR GAP

In the chapter, the mathematical model of an air gap has been developed and the most common rotor and stator defects have been described. It has been concluded that hydropower generator stator should not be modelled as a homogenous ring; instead, the number of stator segments should be taken into account. When the rotor and stator shape is measured, and the spectrum diagrams are obtained, one can compose the functions (4.1), which describe rotor and stator roundness:

$$\begin{cases} \phi_{st}(\varphi) = \frac{R_{st}(\varphi) - r_{st,1-6}}{g_0} = \sum_{k=1}^{12} \delta_{st,k} \cos(k\varphi - \gamma_{st,k}) \\ \phi_{rot}(\varphi') = \frac{R_{rot}(\varphi') - r_{rot,0}}{g_0} = \sum_{l=1}^{68} \delta_{rot,l} \cos(l\varphi' - \gamma_{rot,l}) \end{cases} \quad (4.1)$$

where $R_{st}(\varphi)$ — an actual stator radius in some point;

$r_{st,1-6}$ — a designed stator radius;

g_0 — an average air gap;

$\delta_{st,k} = \frac{r_{st,k}}{g_0}$; $\delta_{rot,l} = \frac{r_{rot,l}}{g_0}$; $g_0 = r_{st,0} - r_{rot,0}$;

Then uneven air gap can be described with the functions (4.2):

$$\Delta(\varphi, t) = \phi_{st}(\varphi) - \phi_{rot}(\varphi') =$$
$$\sum_{k=1}^{12} \delta_{st,k} \cos\left(k\varphi - \gamma_{st,k}\right) - \sum_{l=1}^{68} \delta_{rot,l} \cos(l\varphi' - \gamma_{rot,l}) \quad (4.2)$$

Thus, theorethical uneven air gap equation is defined, when the values $\delta_{st,k}$ and $\delta_{rot,l}$ are known (a design value divided with the average).

When both static and dynamic eccentricity is applied to the rotor, which is the common case for hydropower units, the air gap can be described with equation (4.3):

$$g(t) = r_{st,0} - \delta_m g \cdot \cos(\beta_{din}) - \sqrt{{r_{rot}}^2 - (\delta_m\, g \cdot \sin(\beta_{din}))^2} \quad (4.3)$$

where δ_m — a resulting vector from static and dynamic eccentricity;

β_{din} — a variable angle;

g — a designed air gap;

When rotor has elliptic shape, the air gap could be described with equation (4.4):

$$g_0 = r_{st,0} - \sqrt{\left[(r_{rot,0} + e)\cos(\frac{\omega t}{P} - \beta_{el})\right]^2 + \left[(r_{rot,0} - e)\cos(\frac{\omega t}{P} - \beta_{el})\right]^2} \quad (4.4)$$

where e — an elliptic shape coefficient compared to the round shape;

β_{el} — a variable angle;

ω — a rotation speed;

P — a number of poles, in the Thesis 68 and 108.

Rotor radius is obtained from the equation system (4.5):

$$R_{rot}(\varphi') = \begin{cases} r_{rot,0} + \sum_{l=1}^{68} r_{rot,AB}\ \cos(l\varphi' - \gamma_{rot,l}) \\ r_{rot,0} + \sum_{l=1}^{68} r_{rot,KK}\ \cos(l\varphi' - \gamma_{rot,l}) \end{cases} \quad (4.5)$$

Stator radius is obtained from the equation system (4.6):

$$R_{st}(\varphi) = \begin{cases} r_{st,1} + \sum_{k=1}^{12} r_{st,1}\cos(k\varphi - \gamma_{st,1}) \\ r_{st,2} + \sum_{k=1}^{12} r_{st,2}\cos(k\varphi - \gamma_{st,2}) \\ r_{st,3} + \sum_{k=1}^{12} r_{st,3}\cos(k\varphi - \gamma_{st,3}) \\ r_{st,4} + \sum_{k=1}^{12} r_{st,4}\cos(k\varphi - \gamma_{st,4}) \\ r_{st,5} + \sum_{k=1}^{12} r_{st,5}\cos(k\varphi - \gamma_{st,5}) \\ r_{st,6} + \sum_{k=1}^{12} r_{st,6}\cos(k\varphi - \gamma_{st,6}) \end{cases} \quad (4.6)$$

where $r_{st,1} \div r_{st,6}$ — a radius of the stator, which also changes under different operational modes.

Each of six equations $r_{st,1} \div r_{st,6}$ can be different during one operation mode, because the stator can warm up differently in each segment, for example, one segment can expand less that other five segments.

The calculated stator self-excitation frequencies are summarised for the case when stator core sheets are pressed as required, and for the case when pressure is less than required. Table Table 4.1 summarises calculated values for stator core self-excitation frequencies for case without defects.

Table 4.1

Stator Core Self-excitation Frequencies under Force with Different Wave Order

j	1	2	3	4	5	6	68
ω_j (4.21), Hz	6.36	25.43	57.21	101.71	158.92	228.85	29 393.89
ω_{stat} (4.22), Hz	0.00	17.06	48.24	92.51	149.60	219.46	29 384.35

From Table Table 4.1 one can conclude that stator core self-excitation frequency is closer to 100 Hz frequency when the force wave order is equal to $j = 4$.

When the pressure forces are not as great as required, or connections between the stator core segments expand more than designed, the material properties become different, E decreases up to $0.3 \cdot 10^{11} N/m^2$, but J decreases to 0.25, and the stator core self-excitation frequency changes accordingly, as shown in Table Table 4.2.

Table 4.2

Stator Core Self-excitation Frequencies for Construction with Defect

j	*1*	*2*	*3*	*4*	*5*	*6*	*68*
ω_j (4.21), Hz	3.18	12.71	28.61	50.85	79.46	114.42	14 696.94
ω_{stat} (4.22), Hz	0.00	17.06	48.24	92.51	149.60	219.46	29 384.35

From Table Table 4.2 one can conclude that stator core self-excitation frequency with defect is closer to 100 Hz frequency when the force wave order is equal to $j = 4 \div 6$.

It has been shown that elliptic shapes of the core, bearing wear and rotor unbalance are the most common reasons for hydropower unit eccentricity.

From the calculation of stator core self-excitation frequencies, it has been concluded that self-excitation frequency can be quite close to 100 Hz vibration frequency and can cause a resonance effect, because, when the stator core sheets are not pressed well enough, the self-excitation frequency is closer to 100 Hz frequency when the force wave order is equal to $j = 4 \div 6$, while the number of stator segments is 6, and the particular wave order will be definitely present.

5. UNEVEN MAGNETIC FLUX

In the chapter, it has been shown that hydrogenerator uneven rotor shape, uneven air gap and uneven magnetic flux affect the unit and stator core vibration. The magnetic forces acting on a hydropower unit have been described and it has been concluded that uneven magnetic flux can occur due to winding faults or uneven rotor shape.

It has been shown that one of the main tasks for hydropower unit condition monitoring is to check that the rotor is in the centrum of the stator to ensure that magnetic flux in the air gap is as evenly distributed as possible. In the magnetic force model it has been shown that sometimes to eliminate 100 Hz vibration it will not be enough to press the stator core sheets and to change the resonance frequency. Sometimes balancing of the rotor or insulation change between stator core sheets will be required.

Calculations performed in the chapter have shown that vibration velocity, which occurs due to generator design (an uneven number of slots for pole and phase), is greater than the one, which occurs from the main magnetic flux, but the total value of vibration velocity occurring from generator design is quite small, comparing to the allowed value and experimentally measured vibration value.

6. AIR GAP MEASUREMENTS

In the seventh chapter, the experiment performed on two different hydropower units is described. During the experiment, the rotor shape, electromagnetic force, vibration and temperature have been measured, and the rotational speed of the unit has been registered. Measurements on the first unit were made twice — in the spring and in the autumn of 2014, and during that period the unit was under normal operation. Measurements of the second unit were also made in the spring and in the autumn of 2014, but during that period some refurbishment works were performed for the generator. Thus, the first unit measurement has ensured double-checking the results, while measurements on the second unit have ensured the data for evaluation of technical condition before and after refurbishment.

7. EVALUATION OF AIR GAP MEASUREMENTS

In the eighth chapter, it has been concluded that historically the acceptable values for air gap uniformity have changed from 20 % to 3 %. Different methods for evaluating the air gap are described, namely, the evaluation in accordance with standards, polar diagram, vibration and spectrum analysis. The evaluation in accordance with STO and CEA standards and publication materials are summarised in 7.1 Table.

Table 7.1

Evaluation of the Uneven Rotor Shape

STO	CEA	Evaluation
< 3 %	6 %	Acceptable
3–8 %	6 %–8 %	Unacceptable
> 8 %	> 10 %	Critical

In the Doctoral Thesis, it has been discovered that evaluation differs significantly when the rotor roundness is evaluated separately for lower and upper end, or when the average mathematical value obtained from upper and lower end is calculated. The average value provides better evaluation results, for example, the calculated average roundness can be acceptable while roundness for lower and upper end can be unacceptable. It has been concluded that for condition monitoring the average value can be used, but for diagnostics it is suggested to evaluate upper and lower end of the rotor separately. It has also been concluded that the operational modes of the generator have no great effect on the air gap evaluation percentage; therefore, any operational mode can be used for general condition monitoring.

It has been shown how the guaranteed air gap value can be calculated from the polar diagram, and it has also been shown how the information about eccentricity can be obtained from the vibration spectrum diagram first harmonic.

The new methodology of evaluating air gap using spectrum has been described, where the 1st harmonic stands for eccentricity; the 2nd harmonic stands for elliptic shape; the 3rd harmonic stands for triangle shape; the 4th harmonic stands for square shape.

The spectrum results for the first unit in the spring and autumn of 2014 are pretty similar. The 2nd harmonic of the spectrum in Fig. Fig. 7.1. , obtained during the operational mode with 90MW 0 MVAr, shows that rotor lower end has a little bit (~3 %) elliptic shape.

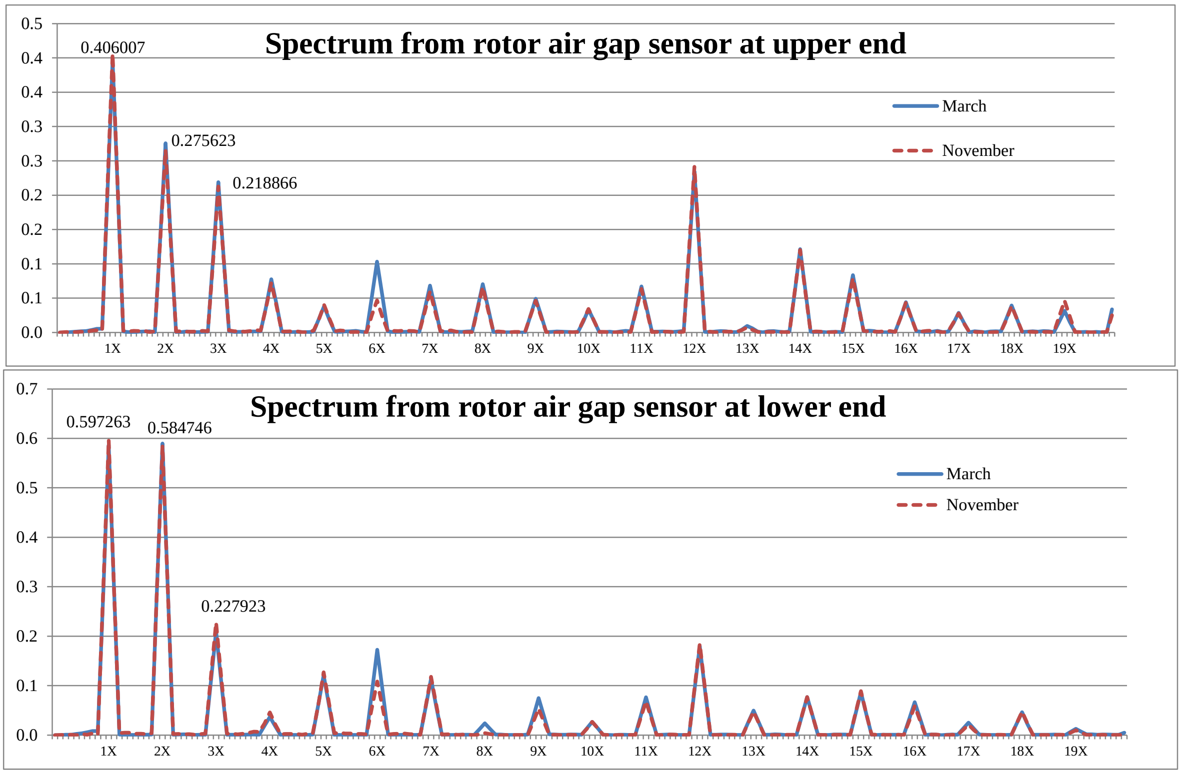

Fig. 7.1. The spectrum of the air gap for the first unit.

The second unit spectrum results are provided in Fig. Fig. 7.2. Result before and after refurbishment differs by approximately 0.2 mm.

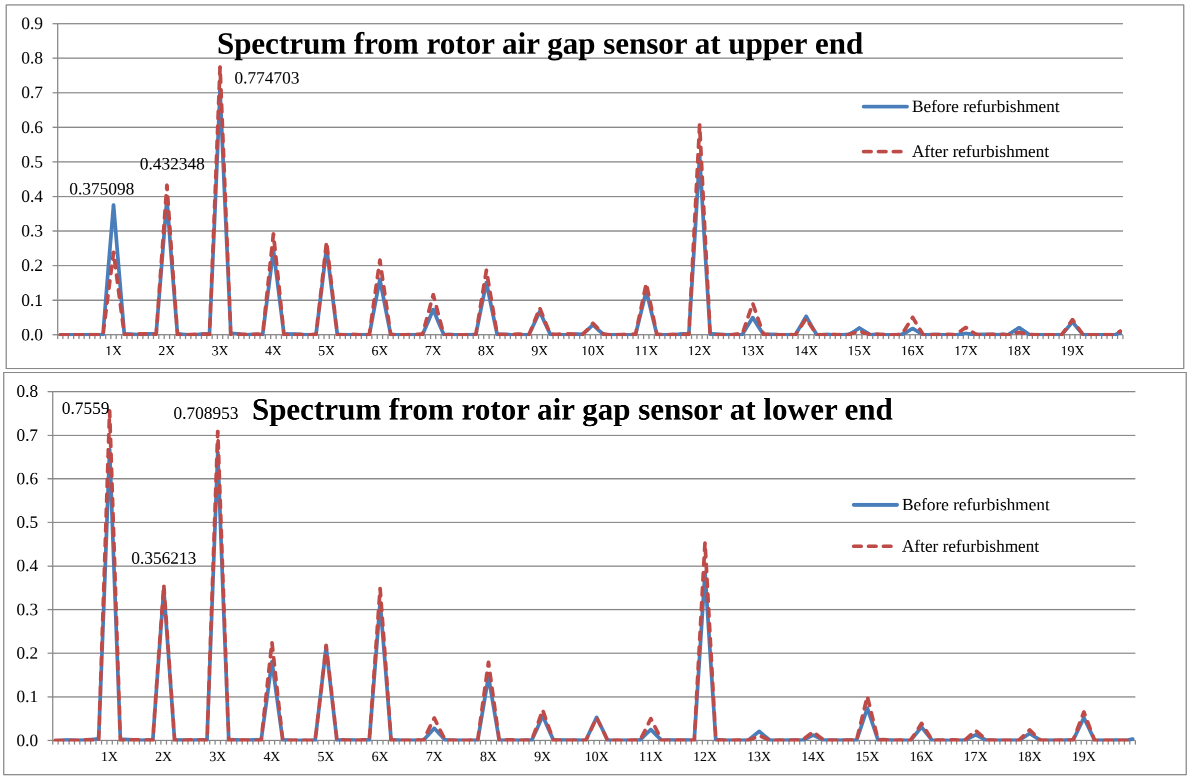

Fig. 7.2. The spectrum of the air gap for the second unit.

CONCLUSIONS

The Doctoral Thesis contains the results about the tasks formulated to advance the hydropower unit vibration diagnostics with the air gap monitoring procedure. To solve the tasks, mathematical models for hydropower unit and the air gap have been developed and calculations based on theoretical and experimental data have been performed. The main conclusions, which are highlighted in the Doctoral Thesis, are as follows:

1) The measurements of air gap are strongly recommended for the units which experience at least one symptom listed in the first chapter (increased vibration, corrosion on the stator core etc.), which suggest that rotor or stator has some eccentricity or uneven shape.

2) Taking into account design specifics, in the mathematical model each rotating mass should be described with four degrees of freedom.

3) Bearings should not be modelled as “rigid supports” or the elements with single stiffness. They should be modelled as elements with reduced stiffness.

4) During the oscillation modelling the stiffness both in radial and axial directions should be taken into account.

5) Critical torsional rotational speed varies significantly when different shear moduli are chosen; therefore, before the modelling the information about the shaft material should be obtained.

6) Critical rotation speeds from bending should be calculated only using computer modelling and taking into account stiffness of the bearings, because ignoring the stiffness increases the reserve coefficient for bending critical speed 2 ÷ 3 times.

7) The elliptic shape of the stator core and bearing wear are the most common reasons for the static eccentricity; therefore, it is not correct to perform mathematical modelling of the stator core as for the homogenous ring.

8) When the stator core sheets are not pressed well enough, the self-excitation frequency is quite close to 100 Hz frequency, which can cause a resonance effect.

9) During the upgrade project, the number of hydropower generator slots has increased, but the vibration velocity, resulting from the uneven number of slots for pole and phase, is quite small, and is not the main cause of increased stator core vibration.

10) Measuring both rotor shape and electromagnetic force helps to find out, if there are any short circuits on the windings.

11) To obtain correct results during the data analysis, the average value of eight measurements of rotor shape and air gap should be calculated, and the upper and lower filter settings should be calculated based on unit rotational frequency.

12) It is recommended to use four sensors for air gap measurements in the future.

13) There is no particular generation mode that should be used for the air gap monitoring. For the diagnostic purposes, different operational modes should be used, including speed-no-load, overspeed etc.

14) For condition monitoring, the average air gap value can be used for evaluation in accordance with the standards, but for technical diagnostics it is suggested to evaluate upper and lower end of the rotor separately.

15) It is highly recommended to perform measurements of the stator shape in addition to the rotor shape in the future.

16) The rotor shape polar diagram should be better plotted on the rotor spider.

17) The novel evaluation methodology, using the air gap spectrum analysis, is a useful tool for technical condition evaluation before and after refurbishment works.

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