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Paper title

IMPLEMENTATION OF TOTAL MACHINE CONDITION MONITORING SYSTEM ON PUMP STORAGE GENERATOR IN PSPP AVČE

This paper describes the implementation of a machine condition monitoring system on a 180MW motor-generator at the Avče Pump Storage Power Plant (PSPP). At PSPP Avče a permanent condition monitoring system, specially tailored to suit the particular custom design of the M-G set, is installed and used to detect the vibro dynamic behaviour of the machine and predict possible deviations and variations in its operating condition.

PSPP Avce has a unique design utilizing AC excitation and having a variable rotating speed. This creates an extra challenge in designing the concept for machine condition monitoring. Based on the knowledge acquired through results of data recorded during all phases of commissioning and test run operation, additional monitoring system needs were defined, and existing requirements revised. The standard monitoring system, consisting of vibro dynamics, generator air-gap measurement and the monitoring of unit operating parameters, is supplemented with measurements of thermal impact on vibro dynamics, power quality, transient recording, as well as partial discharge and penstock monitoring.

Most attention was focused on expanding the vibration monitoring capabilities with an additional radial clearance module implemented on the lower guide bearing and the correlation of bearing clearances with temperatures in order to obtain the impact of heating on changes in vibrational behaviour of the machine.

I. INTRODUCTION

In operation since 2010 PSPP Avče is the first pump storage plant in Slovenia. The plant located on the Soča river and is a part of a hydro plant cascade system. Being a pump unit, it is reversible, driven by a Francis turbine with 185 MW of installed power with a nominal rotational speed of 600RPM. It has an AC excitation system, with nominal speed at 600RPM enabling a ±4% variation in rotating speed. The maximum head is 521m, and annual average production is 426GWh. The motor-generator unit has two guide bearings (upper generator and turbine bearing) and one combined thrust and guide bearing at the lower generator bearing position.

The machine is designed to operate in 4 different operation modes (generate, generate - condenser, pump and pump condenser) and usually operates at variable outputs and intermittently. It has 3-4 run ups and coast down daily, generates base power and, peak power, and supports secondary regulation. It is utilized as system prime reserve for urgent requirements of the power system (start or stop of the unit or a significant change of power on demand). Consequently the availability and reliability of the machine is of great importance, which brings the challenge of continuous data tracking, condition monitoring, and diagnostics for early warning of a deteriorating trend.

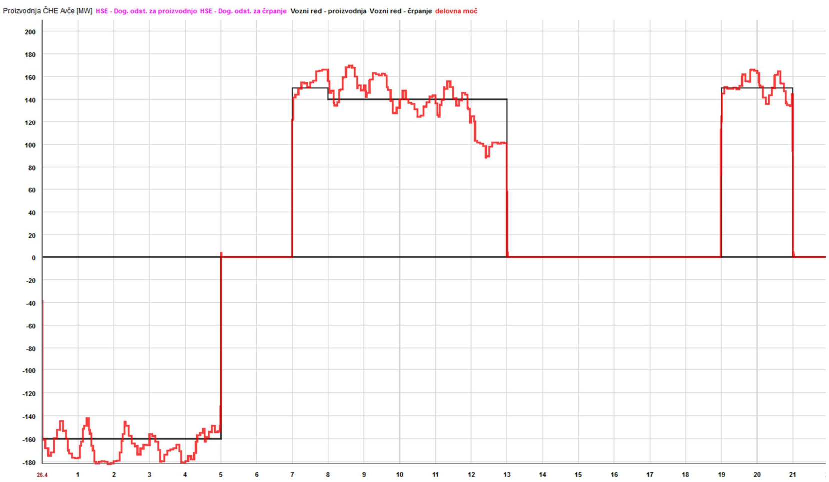

Figure 1 –Typical Daily operation of PSPP Avče (power output shown on diagram)

The basic approach to the implementation of a Computer Diagnostic System (CoDiS) monitoring system is the open software architecture allowing the user to request custom tailored modules. These are integrated into a system with a unique database providing cross-correlation analysis of all recorded values. The display feature of such a module is also programmed according to end user requests.

Continuous Machine Condition Monitoring (MCM) is very important as the plant is unattended and is operated from a remote dispatch centre. The MCM system is available on both the plant and dispatch networks and the CoDiS client software provides all the data to the remote end user PC location.

The system has a protection module for vibration and mechanical values (CoDiS RT), a Diagnostic module with MySQL database (CoDiS DM) and electrical monitoring with power quality (CoDiS TR). The user has a complete overview of machine condition and the quality of generated power with all the data constantly stored to database for historical review and off line analysis. Penstock hydraulic condition monitoring, CoDiS CV, is also integrated into the system.

The system was installed during the motor-generator unit commissioning period, and the full scope was defined after the first measurements were performed and analysed. The initial configuration covered vibration, air gap and magnetic field monitoring, but analysis of data collected during commissioning led to recommendations to expand the system with specific quantities of interest to help identify the condition of such a complex machine.

The current configuration of the system includes the following modules:

- Vibration (Relative shaft vibration, Absolute bearing vibration, Stator core vibration, Turbine head cover vibration)
- Bearing clearance, Axial displacement of rotor
- Air Gap and magnetic flux in the air gap
- Forces in bracket arm beams
- Thermal dilatations of thrust bearing collar
- Power quality with electrical fault recording
- Partial Discharge
- Cavitation
- Penstock hydraulic monitoring
- Process quantities (Integration of 60 process parameters from the plant SCADA system)

Some of the modules were added in the year following commissioning, each completely custom tailored for the purpose of identifying and monitoring the condition of critical areas of the machine.

The system automatically recognizes the unit operation mode and changes the applied analysis procedure and database storage mode accordingly. Automatic reporting is provided to the customer by filtering the data and making their asset management and machine tracking much easier.

The monitoring functionality and analysis used to recognize and define the machine condition are described in the following sections of this paper.

II. DESCRIPTION OF MONITORING SYSTEM

Measurements are distributed on two processing units, one for mechanical and process quantities and other for electrical quantities, both of them communicating with the main server. The system layout is shown on figure 2.

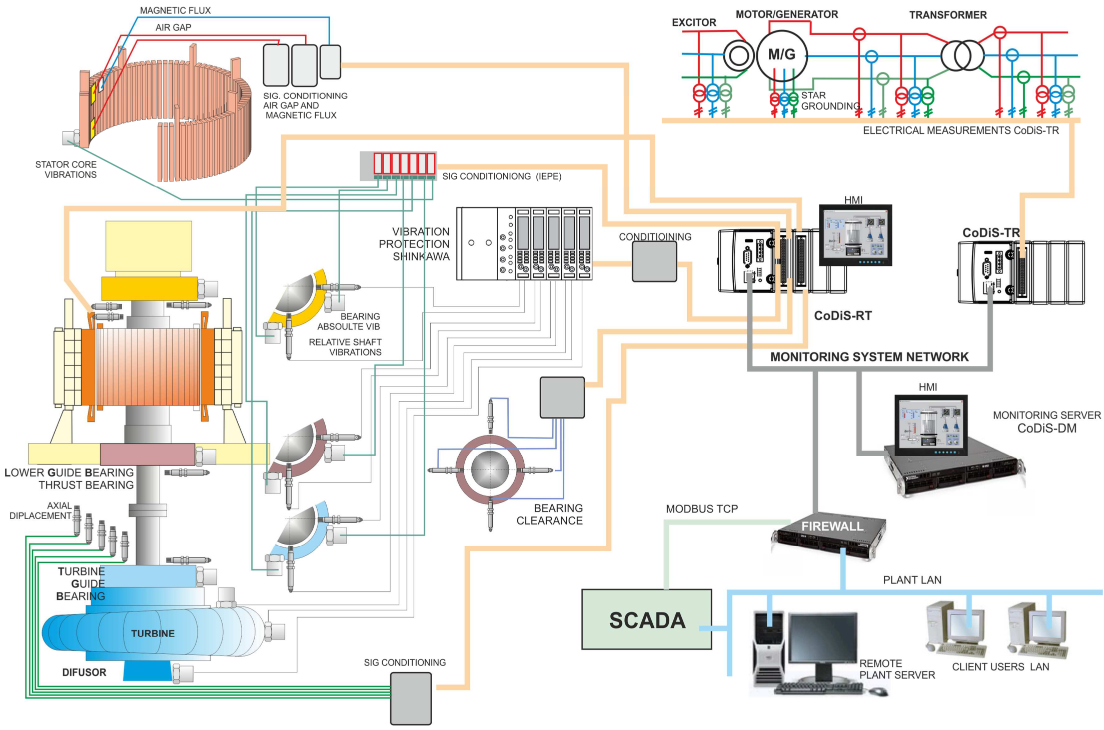

Figure 2 –Schematic block diagram of initial CoDiS system installed in PSPP Avče

II.1. SYSTEM CONFIGURATION

The system has diagnostic and protective functionality in order to predict and prevent the faults. Extensive diagnostic tools provide analysis sufficient to highlight any changes and determine the root cause of detected problems. This is the basis for predictive maintenance planning.

The system consists of:

- Front end components and signal conditioning
- Processing units for acquisition, online analysis and protection, operating in a Real Time Operating System
- Diagnostic server PC

The system is located in two cabinets:

- One on the generator level at -72m, containing processor CoDiS RT for mechanical protection, and
- A main cabinet which is located in control room, level 0m, containing the electrical monitoring processing unit, CoDiS TR, and a server PC.

Both cabinets have a Touch panel for local data display. The client software is installed on remote users' PC's (specialist staff), located 15 km away in the company headquarters.

The protection system has a capability to allow the user to set the trigger conditions on any measured/calculated value, with the possibility of a combination of set triggering conditions to avoid false alarms. The time delays and levels are set for each value individually so the system can trigger on fast occurring events, like a sudden increase of vibration amplitude (time delay in seconds), but also on long term events (trend alarming), such as temperature increase or partial discharge changes.

All measured values are integrated into a single GUI (Graphical user interface) with a hierarchical view of plant/unit/measurements

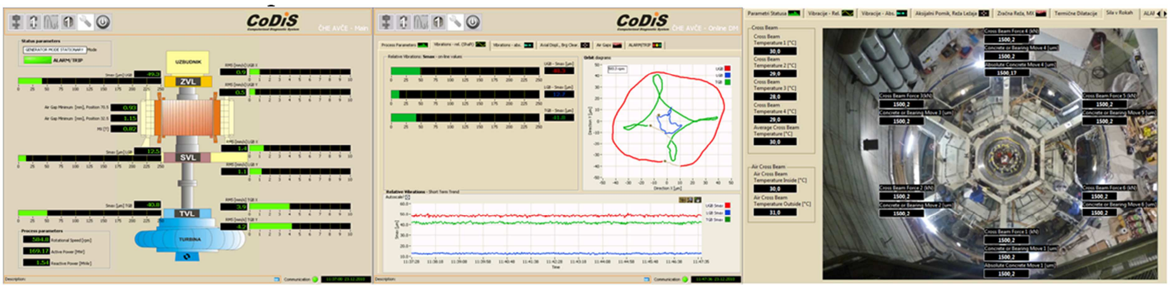

Figure 3 –Real time (online) data displays (Main screen, Vibration, Forces in bracket arm beams shown Left to Right),

Database overview is available on screen button activation having several options:

- Trend database (stored on daily basis)
- Run up/Coast down database
- Event database (alarms and user created – 2 to 60 sec of waveform data)
- Electrical transient events (automatically recorded or user created – 10 sec of waveform data)
- Penstock Hydraulic event quantities (6 min of waveform data)

The system filter the data according to operation mode so data recorded during each pump or generator mode can be displayed separately.
Both time and frequency domain analysis results are available to end user so every event can be analysed in details.

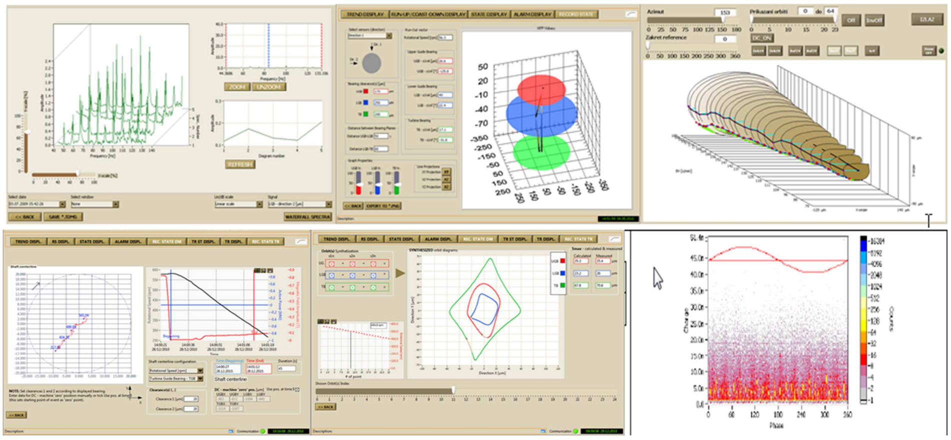

Figure 4 – Screenshots of some of the analysis modules displays
(Waterfall spectrum, 3D shaft Run out, 3D Orbits, 2D shaft centerline, 2D orbit analysis in transient, Partial discharge)

Data are transferable to ASCII code or as an image (custom requested formats can be implemented) to be readable by other analysis software.

The system has a module for automatic statistical report generation on user request, with detailed analysis of operation in each mode (time of operation, start up time, alarm in start up, etc.)

III. ANALYSIS AND IDENTIFICATION OF MACHINE CONDITION

Vibration response of the turbine - generator unit is defined by elastic and inertial properties of the structure and by the forces that are affecting the machine. Forces affecting the machine are hydrodynamic, electrical and mechanical thus the identification of the machine condition has to take into consideration all of them simultaneously as they influence one another significantly. The monitoring system is designed to recognize the possible faults in the early stages of development combining the parameters that will collectively be able to predict and prevent the irregularities.

The examples that will be presented here are focused on obtaining the vibro-dynamic response that changes with the temperature of the bearing. This is one of the critical condition areas that is focused on by the monitoring system. The analysis will show how the vibrational behaviour and dynamic response of the generator is changing with the bearing temperature. This will also include the description of monitoring modules specially designed to monitor the behaviour and it's manifestation on machine parts.

III.1 ANALYSIS OF VIBRATION RESPONSE WITH TEMPERATURE OF THE BEARING

Most of the faults or disturbances occurring on the hydro generator can be detected through vibration response analysis. They usually appear as harmonic frequencies of rotation (Mechanical or electrical unbalance, shaft runout…). Well-designed diagnostic tools for the analysis of vibrational behaviour are basic for machine condition monitoring and they must provide the relevant information such as tracking of the orders and frequencies on which these forces are manifested. Analysing the amplitudes and phases of different frequencies can help one identify the machine behaviour and find the root cause of the problems.

All significant monitoring systems have a feature for tracking harmonic components and for their continuous storage to a trend database (First, second, third and higher harmonics, both amplitude and phase, as well as non-harmonic components). Storage of these components in a long history database, along with other parameters, such as magnetic field, air gap, active and reactive power, temperatures and other process or electrical quantities is essential for obtaining complete information of machine behaviour in different operating conditions.

Another important feature is to track and store the process quantities (bearing and stator core temperatures, water levels etc.) as well as the influence of heating and cooling on mechanical response (bearing clearance, air gap, thermal dilatation and forces in bracket arm beams) while the machine is not in operation as this is shown to be critical information. The changes that occur with thermal dilatations on this machine significantly influence the change in the machines dynamic response during run up. The Machine in PSPP Avče has several start-ups daily with different stand-still durations between them, resulting in different responses. Consequently, alarm and trip settings have to be correlated to operating condition in order to prevent false alarms from occurring.

As described in the paper, the changes in unit condition and response during start-up and coast down bring the challenge of detecting those changes that are correlated to the degradation of machine parts.

In Figure 5 there are two days of operation displayed as recorded by monitoring system.

In the diagrams shown in Figure 5, the following values are displayed:

Lower diagram – RPM, Active power, Generator mode active, Pump mode active

Upper diagram: UGB Smax, LGB Smax, TGB Smx

(Smax =Amplitude of maximum displacement measured from two perpendicular proximity probes)

Figure 5 – Trend diagrams recorded over two days

As shown in the trend diagrams, during every run up there are higher vibration amplitudes on generator bearings, notably on LGB.

The increased vibration amplitudes are not as emphasized when the machine coasts down, as seen on both generator bearings UGB and LGB .

It is obvious that vibration behaviour of this machine differs significantly from start up to run down.

In Figure 6 relative shaft vibrations during run up recorded in maximum vector monitoring resolution (condition vector elements are scalars and vectors calculated out of waveforms in a specific time frame – here every second) are shown.

Figure 6 – Relative shaft vibrations during start-up.

Run up in pump mode last much longer and it is a better indicator for analysis of vibration response than the shorter run up in generator mode.

With rotational speed of about 500 RPM vibrations start to increase remarkably with speed and have their peak at maximum achieved speed (upper diagram on Figure 6.) The gradient of the vibration curves which can be seen in the diagram points to non-linearity of the system. This is a response due to the non-linear bearing stiffness which had to be considered as a very important property of the system in its modelling. Analysing multiple start-ups shown on the daily trend display (Figure 5) we can see that amplitudes are different in every start-up, as they depend on initial conditions which are different for every start-up as well.

The amplitudes decrease as the machine operates at nominal power (see Figure 5, from 0 AM-6AM), and then afterwards, when unit goes to coast down, vibration amplitudes are significantly lower than amplitudes recorded during start up. It is obvious that in order to define, explain and diagnose this behaviour on-line we have to include the influence of temperature in the analysis as well.

Figures 7 and 8 show sensor positions and the temperature of the generator radial guide bearings as well as the temperature of the axial thrust bearing, and bearing clearance on the LGB recorded on the same day.

The segments of thrust bearing and LGB are located very near one to another in the same housing. When the thrust bearing is heated, the thrust collar (shown yellow on figure 7) expands which influences the clearance of lower guide bearing as the segments (red square in Figure 7) are located around the thrust collar and they also heat up in time. This bearing has a large initial clearance influencing the stiffness to be lower in the cold state. When heated the clearance of LGB decreases (Figure 8) and stiffness increases.

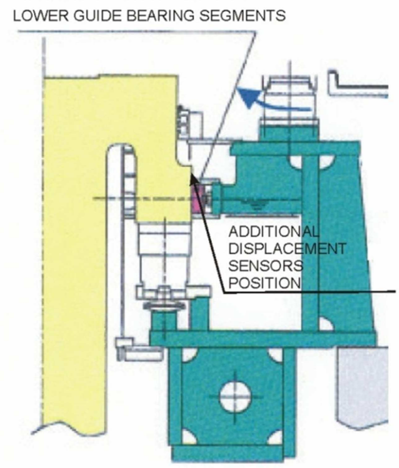

Figure 7 - Positions of the sensors which measure radial clearance of the lower guide bearing.

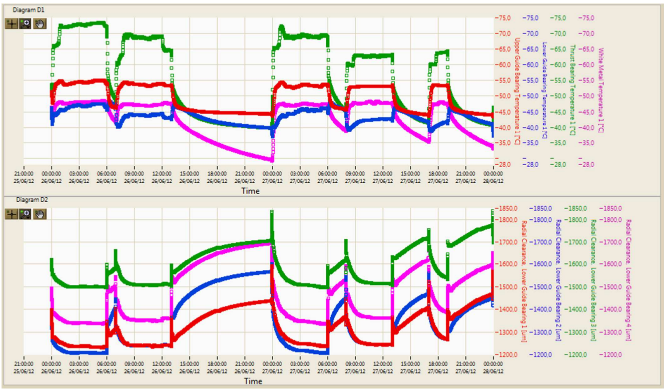

Figure 8 – Temperature of segments of Guide bearing and Thrust bearing (upper diagram), LGB radial clearances in 4 directions /0, 90, 180, 270 ° (lower diagram)

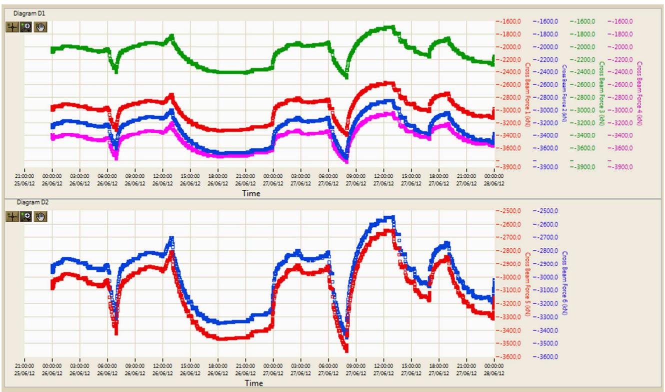

Figure 9 – Forces in bracket arm beams – generator has 6 arm beams

Temperatures of the thrust or axial bearing segments are higher than temperatures of the guide or radial bearing segments and, due to construction of the bearing, this temperature is transferred to the LBG segments. The LGB, as part of the generator thrust and guide assembly, has a cooling system and its initial temperature is lower than the UGB and TGB. In addition, its temperature increase is slower than on other two bearings. It was realized through measurements that the temperature increase on this bearing has an impact on the machine response as it raise due to heating and expansion of thrust collar. The temperature of thrust collar couldn't be measured, but it was assumed that it was higher than the temperatures of LGB segments as the thrust collar was transferring energy to the segments of LGBs.

The process of heating and cooling is recorded during unit's operation, but also during the unit at stand-still, showing the change of clearance in both conditions.

After the unit is at stand-still for a few hours, and after it is completely cooled, the bearing clearance on LGB increases and achieves the initial value. This initial clearance results in lower stiffness of the bearing during start and thus vibrations are at maximum around the nominal operating speed. In operation, when the machine is loaded, the temperatures increase, and the thrust collar expands due to temperature influencing the thermal growth on LGB segments. This results in a reduction of bearing clearance and after few hours at nominal power output the clearance decreases and becomes constant. The difference between the start and end clearance values ends up with an overall increase in the bearing stiffness. This is the cause of a different vibration behaviour when unit goes into coast down after operation. When coasting down, the unit is hot and the dynamic conditions are different compared to start (cold) conditions. These differences in dynamics are due to different bearing stiffness.

The upper bracket has 6 arm beams supports, symmetrically mounted. The forces in these arms change during the operation due to temperature distribution. The concrete foundation resists thermal growth creating the accumulation of forces in every beam. The forces are highest when machine is at stand-still, due to lack of ventilation. The purpose of monitoring these forces is to detect the possibility of failures in the concrete foundation. If a crack in the concrete occurs, the forces would decrease due to the allowance of some thermal expansion of the beam arm.

III.2 MODEL FOR CONTINUOUS ANALISYS

The model used for simulation of the vibration behaviour is defined as a nonlinear dynamic system with 5 independent degrees of freedom. It is used to predict the vibro dynamic behaviour of the system in case of possible developing faults (e.g decrease of bearing clearance or stiffness of foundations). The reliability of the prediction is achieved using measurement results (stiffness, critical speed etc.) as input data and boundary conditions and then used for fine adjustments (updating) of the model.

The model is used to identify the dynamic parameters such as vibrating masses, stiffness and damping and to obtain machine dynamic signatures and simulate its behaviour under different conditions. To be able to obtain those values the model requires input of data obtained through measurements in 5 independent planes in pure mechanical free run, at three different rotating speeds. This is necessary to form the set of differential equations defined in a way that vibrational parameters can be obtained.

Simulation is performed with the assumption that the excitation force, the mechanical unbalance, is strictly described as F= m.r.ω2 .

The rotating speed is programmed as a ramp from 0 up to 1100RPM with 200 seconds of linear sweep.

This approach made possible obtaining system responses for situations which cannot be achieved in reality.

The results of the simulation of initial condition (cold unit) such as one the one that is recorded on Figure 6, are shown in Figure 10. This condition was used to verify the model by comparing the results with the real measured data.

In the upper diagram changes of vibration amplitudes on the LGB and UGB are shown, In the lower diagram, changes of stiffness of the LGB (oil film) is shown.

The non-linearity of the oil film, due to large clearance, is manifested through the continuous increase of vibrations as an effect of clearance itself. The stiffness increases proportionally with vibration amplitudes (see Figure 10, lower diagram).

The simulation shows that dynamic response, after the cold unit’s start, stabilizes in certain conditions, above nominal speed.

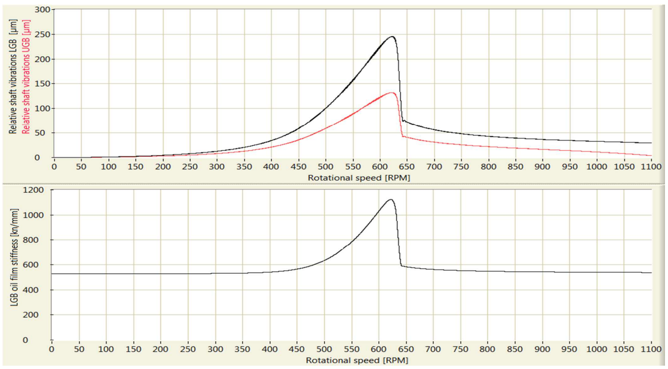

Figure 10**.** Simulation results - under slow start up conditions
Upper diagram: relative shaft vibration UGB (red curve) and LGB (black curve)
Lower diagram: LGB oil film stiffness

As part of the commissioning process, a series of load rejection tests (recorded by the CoDiS monitoring system as well) were performed. Load rejection tests were performed from 25 %, 50%, 75 %, and 100 % of nominal power. The rotating speed increased up to 790 RPM after load rejection from 100 % power.

These tests were used to provide additional verification of the model by comparing the measured and simulated values. The initial values and change of bearing stiffness were taken into consideration to simulate the conditions in load rejection tests. Since the behaviour of the machine changes with operation, the model was used to establish a signature for each of the conditions that will be used further on as a reference for tracking of changes in their early stages.

A series of simulations of the faults possible under different conditions (e.g. change in the bearing stiffness, or change in the stiffness of concrete foundation) were performed, and the system responses to these conditions were filed. If a fault or irregularity should occur we should be able to identify the nature of it based on the response when compared to simulation results.

IV. CONCLUSION

Vibration behaviour of the generator in PSPP Avče is specific and not very common for standard hydro machines. Due to this, the monitoring system in Avče is expanded and custom tailored to track the unusual responses and changes in the behaviour that are in direct correlation with change in the unit stiffness.

The thermal growth or expansion of the LGB are tracked as radial clearance measurements, along with the expansion and forces in bracket arm beams. The latter are added as a special measurement in order to better understand the effect of thermal dilatation of the thrust bearing.

The system has been identified by measurements and a model was established based on the experience gained through a series of measurements. The reference point was that measurements showed a very uncommon result of vibration behaviour measured during machine run up. This behaviour was not recorded during the unit's coast down.

Measurements of bearing clearance changes correlated with bearing temperature measurements and showed that the stiffness of Lower Guide Bearing (LGB) changes under load due to the heating process.

The thrust collar, which is near the LGB segments and operates at a higher temperature, was transferring heat to the LGB segments causing thermal dilatation and reduction of clearances.

To be able to better understand the behaviour and detect the possible risk of an operating situation, based on actual condition monitoring, a simulation model of the system was designed. This model is a part of a monitoring expert module used for the identification of dynamic parameters of the hydro generators and is based on initial measurement results as an input for normal operational conditions.

The model is used to simulate the behaviour and response at unit speeds that are physically not achievable. This response is used as a signature to identify the stiffness and vibrating masses of the system. For Avče a 5 degrees of freedom system was used and its accuracy verified with measurements in cold and hot operational conditions and through load rejection tests during machine commissioning.

After the parameters are identified (e.g stiffness of the bearing or foundation or the change in dilatation and forces of the bracket arm beams), simulated response in cases where those values change due to a fault occurrence can be achieved, which provides the possibility to use the model for continuous condition monitoring and detection of risk situations.

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