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Decision support from monitoring of hydro power stations
An approach to the vision of monitoring systems giving decision support in operation of hydro power stations

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Master of Science in Energy and Environment
Submission date: June 2009
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Problem Description

The task is to study how the use of modern computer software can be used in advanced monitoring of hydro power plants. Advanced monitoring that will provide guidance to operational staff about how to handle faults. Today the monitoring usually reacts on single information given on a binary level. To get better grounds for decision making modern computer software can be used to automatically compare different information making it possible to detect unwanted operating conditions and faults that are developing at an early stage. This will make it easier to make correct decisions on how to react on events in the hydro power station. Intervene at an earlier time when serious errors are under development, avoiding unnecessary stops of the plant and avoid major breakdowns.

Assignment given: 22. January 2009
Supervisor: Lars Einar Norum, ELKRAFT

Preface

This project is a part of the fourth semester in the two year master program in electric engineering at NTNU. It is weighted with 30 credits meaning that it shall cover all the workload of this semester. The project is a cooperation between Voith Siemens, Volve, SKF and NTNU, where Voith Siemens is the company who came up with the problem description. The companies SKF and Volve are involved since they deliver software that is investigated during the project.

This report can be divided into four different parts. In the first part it is described how information is important for the monitoring systems to be able of detecting faults. The most important measuring equipment of hydro power stations today is presented and vibration analysis is described. The next part gives a presentation of how the Volve system presents its results to the user and the basic behind how the system "understands" the real time operation. In addition an evaluation of the advantages and disadvantages of this software is given. In the third part the software from SKF is described. This part gives an explanation of how this system operates and how it helps the user in detecting faults. It is also described and shown how the results are presented to the user and an evaluation of the advantages and disadvantages of the software is given. In the last part two additional sensors capable of increasing the information flow to the monitoring systems is investigated and discussed.

I will by this give thanks to Professor Lars Norum at NTNU, and Øyvind Holm, Oddbjørn Hansen, Steinar Maalen and Pål Glimen at Voith Siemens for valuable help and guidance. I will thank Frode Sørmo at Volve for giving me an introduction to the Volve system. I will thank Per-Magnus Karlsson and Tor Morten Øverby Olsen at SKF for valuable help and guidance concerning the @ptitude Observer and vibration analysis.

Summary

This report is the results of the work on a master thesis concerning monitoring of hydro power stations giving user support to the operational staff of the hydro power station. In the report two different types of computer software is investigated to find out whether they are suitable to make out a monitoring system capable of giving the user information about faults and unwanted operating conditions at an early stage. It is also investigated whether the software has proven the capability to detect faults and unwanted operating conditions. The different advantages and disadvantages of the two software products are commented and the two software products are compared.

This report shows that the two software products are quite different. The software from Volve is software meant to construct an expert system capable of recognising faults from previous cases of faults. The software from SKF is software that gives intelligent machine diagnostics from analysis of vibration measurements in addition to measuring and trending of other variables. It also gives the user tools for analysing the root cause of faults influencing the bearing system of different industry machinery. This means that the software from SKF demands some involvement from the user to produce the best and most precise results. The expert system developed from the Volve software on the other hand is meant to present only results and advice to the user.

The results from tests and simulations of the expert system developed by the Volve software are very limited. It is not possible to conclude which of the two software products is better before more tests of the Volve system is performed.

In addition to the investigation of these two monitoring software products two different types of sensors are investigated. The sensors that are investigated are smoke sensors and sensors for detection of ultrasonic sound. Both types are commonly used in monitoring of industry processes similar to those in hydro power stations. These two sensors are capable of giving additional information to the monitoring system making it possible to detect faults that it is difficult to detect today. This is because the two sensor types perform measurements that the normal measuring equipment of today is incapable of. This will increase the information flow to the monitoring systems of hydro power stations making it possible to perform better and more precise monitoring.

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1 Introduction

1.1 Background and work done

Today most hydro power stations are operated by remote control. The machine expert that in the old days used to keep attention with the hydro power station is too expensive today. The vision is therefore to create a monitoring system that replaces this machine expert entirely. This means that the control and surveillance system must have the ability to "understand" the operation of the hydro power station and give information about faults and unwanted operating conditions to the user. From this information it must be possible to predict what is going to happen in the future, not only to say something about the current situation. The system must be able to see relations between different monitored values and know what these relations mean. The conclusion from Erlend Timberlid's master thesis from 2008 was that the expert system developed by the company Volve has the abilities required to form such a system [2]. In this report software developed by the company SKF is investigated and the goal is to be able to compare the software and comment upon the ability and method of the two different software products to detect faults and unwanted operating conditions.

The background for this project is the motivation to develop better monitoring systems for the hydro power industry. The work done in this report is a continuation of the work done by Erlend Timberlid and Øystein Fjellheim in their master theses. Øystein Fjellheim did his master thesis back in 2007 where he focused on expert systems in hydro power stations [1]. Erlend Timberlid continued on Fjellheim's work on his master thesis in 2008. He concluded that the software developed by Volve called Volve Knowledge Tools has the capabilities to construct an expert system that can be used to monitor a hydro power station [2]. However expert systems is very time consuming to develop and in the work done by Øystein Fjellheim and Erlend Timberlid no alternatives to the expert system developed from the Volve Knowledge Tools where investigated. Therefore is the goal of this report to investigate a system that will be easier to implement and to compare this system with the system developed from the Volve software.

In addition to investigate the two different software products for monitoring purposes this report will focus on the information available for monitoring of the hydro power station. In

hydro power stations today the information available for a monitoring system is limited. To make better and more precise monitoring systems the information available from the measuring equipment of the hydro power station must be increased. In this report two types of measuring sensors that is not used in hydro power stations today is presented. These sensors can in the future contribute with important information to the monitoring system of the hydro power station.

1.2 Limitations and scope

Because the hydro power station is a large and complex operating unit it would be difficult with the time available in this project to focus on the whole hydro power station. To limit the scope of this project it is decided to focus on the bearing system of the hydro power station and faults influencing on the bearing system. The bearing system is a natural choice because it is one of the most vital parts of the hydro power machine and several faults that can arise in the hydro power station will influence on the bearing system. A fault in the bearing system leading to a bearing breakdown always means large repair cost for the owner of the hydro power station. The faults in a bearing system can be difficult to detect, even though several operating conditions of the bearing system is being monitored. A fault is often not discovered before the bearing temperature is rising rapidly. At this point it is often too late to avoid severe damage to the machine. A fault leading to a bearing breakdown like this could be the result of a minor fault evolving over time. If this minor fault could have been discovered then the bearing breakdown could have been avoided. This is the background for choosing the bearing system as the area to focus on in this report. If a monitoring system could have discovered the fault at an early stage and given the user information about the fault and advice on how to avoid the fault in evolving, then the bearing failure and the bearing breakdown could have been avoided. This would have saved the owner company the money needed for the repair caused by the bearing breakdown.

2 Information about the operation is the key to detect problems

To be able to detect a problem in the bearing before the bearing is damaged or destroyed it is important to be able to analyse earlier cases of bearing problems. If earlier cases of problems can be analysed it will be possible to draw a conclusion of why the problem occurred and in the future be able to detect the problem at an early stage. To be able to analyse the bearing it is necessary to have data on the operation of the bearing [5]. The operation is monitored by an extensive instrumentation that gives a lot of data on the operation of the bearing. The instrumentation is the main source of information about the real time operating conditions of the bearing. In table 7.1 the parameters that it is normal to monitor are listed with information of where it is normal to monitor this parameter.

Table 2.1: Parameters it is normal to monitor [7]

Operational parameter	Where it is monitored
Temperature	Bearing segments, bearing shell, hot and cold lubrication oil, hot and cold cooling water
Circulation	Lubrication oil, cooling water
Fluid volume	Lubrication oil, cooling water
Levels	Lubrication oil in bearing housing/oil tank
Pressure	Oil lifting system pressure, operating pressure in lubrication oil, differential pressure in oil filter, operating pressure of cooling water, differential pressure in water filter
Bearing voltage	Voltage over the bearing isolation
Shaft current	Circulating current in shaft/bearing system
Vibrations	Bearing pedestals, spiders
Bearing load	Pressure pad

All of these parameters say something about the operating condition of the bearing. However three of them are much more important than the rest. These three are temperature, bearing

voltage/shaft current and vibrations. Temperature is very important since all critical faults that can arise in the bearing system will lead to increasing temperature in the bearing. The monitoring of the bearing voltage is important since shaft currents quickly will damage the babbitt metal and lead to a rapid breakdown of the bearing. Vibrations are very important since it is possible to perform vibration analysis. Vibration analysis can give a lot of information about the operating condition of the bearing and several faults influencing on the bearing system can be detected from the information given by vibration analysis. Vibration analysis will be described closer in chapter 2.1.

In addition to the information given by the instrumentation of the hydro power station it is possible to collect information about rotational speed, load, water flow and similar operating conditions of the hydro power station.

The information sources mentioned over is the sources of information available for the intelligent monitoring systems. It is from this information the systems must build their conclusions. It is then evident that measuring devices giving valuable and good information is very important to be able to perform monitoring that will detect faults at an early stage and give the user advice about how the fault should be handled.

2.1 Vibration analysis

One of the most important information sources to detect problems influencing the bearing system to day is vibration measurements. From vibration measurements it is possible to perform vibration analysis. Vibration analysis is a method where vibrations in the hydro power machine and machine parts are measured at several different places. The results from these measurements is then analysed to find out which problems that causes the vibrations. Trough these analyses several problems influencing the bearing can be detected. Information about them can be given to the user so that necessary action can be taken and bearing breakdown with stop in production as a result avoided.

Today it is normal to measure vibrations on a machine for the purpose of troubleshooting and for maintenance planning. By measuring vibrations it is possible to get objective numbers on the behaviour of the machine during operation. This makes it possible to conclude on the machines status without dismounting it, which would have lead to long periods of shutdown.

In vibration monitoring it is normal to differ between a continuous measurement strategy and a periodic measurement strategy. This report has its main focus on the continuous measurement strategy. These systems are traditionally proximity sensor based systems which presents the behaviour and movement of the shaft to the user. By seeing how the shaft behaves and moves it is possible to perform some simple diagnoses telling the user about the overall condition of the machine [7]. This type of continuous monitoring system is already installed in some Norwegian hydro power machines and this system is shown in figure 2.1.
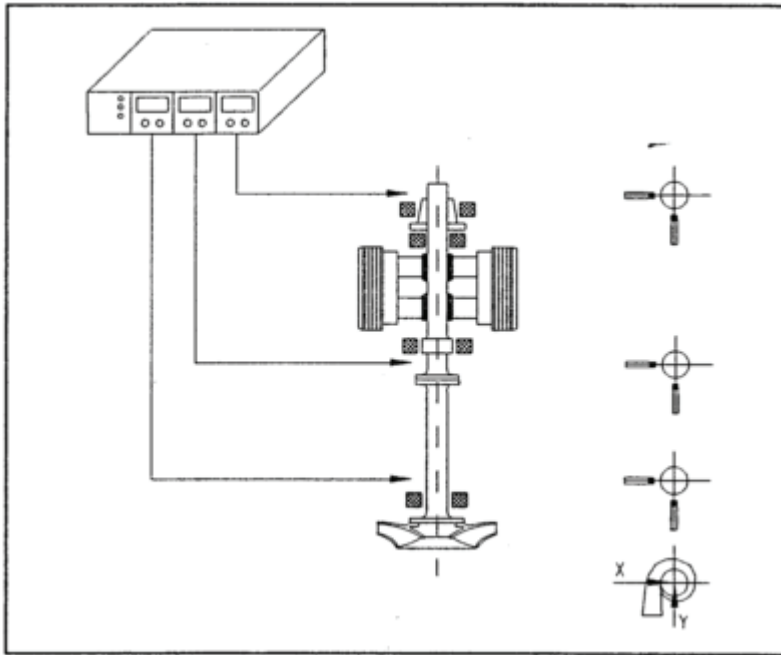
Figure 2.1: Proximity sensor based continuous surveillance system

This system is simple and it does not need a lot of processor power. Today it is possible to make more complex systems than pure proximity sensor based systems, systems that in addition to proximity sensors also use accelerometers to detect more high frequent vibrations. These processor based systems can measure several parameters, present development over time and be programmed to look for special patterns in the measured parameters [7]. With this type of more advanced vibration monitoring systems it is possible to perform more advanced vibration analysis that can give the user more information about why vibrations are developing.

2.1.1 Reference measurement – a "picture" of the normal operation

To make it easier to separate characteristic vibrations of the machine from vibrations caused by unwanted development in the machine and faults it is necessary to do a reference measurement. In practice this is just a normal measurement of all the parameters that are measured in the machine done at a time where the machine is supposed to function correctly. By taking reference measurements like this you get important information about how the normal operating "picture" of the machine should look like [7].

2.1.2 Measuring equipment

To measure vibrations there are two types of sensors that are used. One is to measure the movement and position of the shaft, the other type is to measure vibrations in parts of the machine. The position and movement of the shaft is measured by a proximity sensor. The proximity sensor creates an electric field between the sensor and the surface of the shaft. The strength of this electric field is proportional with the distance between the sensor and the surface of the shaft and therefore this gives a description of the position and movement of the shaft. The vibrations are measured by accelerometers which measure both speed and acceleration.

The proximity sensors are best adapted for measuring low frequent vibrations up to 5 times the rotational speed of the machine while the accelerometers are best adapted for more high frequent vibrations [7]. Normally it is sufficient to measure vibrations with frequency under 2000 Hz.

2.1.3 Typical bearing problems detectable with vibration analysis

There are several different bearing problems that can be detected by vibration analysis. In the following it is described how some of the most frequent problems influencing on the bearing system are detected. By studying how these problems are detected by vibration analysis it is possible to get an overview of how vibration analysis are used to detect faults and in which way it can give the user information about the fault.

2.1.3.1 *Unbalance*

It is normal to differ between to types of unbalance in shafts. One type is the so called static unbalance, the other type is coupled unbalance. Both types will look the same in the vibration spectrum. Unbalance will create a peak in the vibration spectrum at 1x the rotational speed of the shaft. There will always be a peak in the spectrum at 1x the rotational speed, but the amplitude of the peak created by unbalance will increase with the square of the rotational speed [16]. To be able to separate static unbalance from coupled unbalance it is necessary to measure the phase of the vibration. If the vibration in both ends of the shaft is in the same phase it proves that it is static vibration present. In the case of coupled unbalance there will be 180º phase difference between the two ends of the shaft [16].

If the shaft has an overhung rotor with unbalance it gives high vibrations both in axial and in radial direction. It is only this case of unbalance that gives vibrations in the axial direction [16].

2.1.3.2 *Eccentric rotor*

Eccentric rotor is when the rotational centre of a rotor differs from the geometric centre of the rotor. This problem will give a peak in the spectrum at 1x the rotational speed and with direction trough the centre of the two shafts. The phase angel between horizontal and vertical direction can be either 180º or they can be in phase [16].

2.1.3.3 *Bent shaft*

Problems with bent shaft give high axial vibrations with phase difference of 180º between the two ends of the shaft. If the peak at 1x the rotational speed of the shaft is the largest the shaft is bent in the middle. If the peak at 2x the rotational speed of the shaft is the largest it proves that the shaft is bent closer to the bearing [16].

2.1.3.4 *Misalignment*

There are three different types of misalignment. These three types are angular misalignment, parallel misalignment and misaligned bearing cocked on shaft.

Angular misalignment gives high axial vibrations with 180º phase shift from one side of the coupling to the other. Vibration peaks at 1x, 2x and 3x the rotational speed of the shaft. None of these peaks will be dominant [16].

Parallel misalignment gives similar pattern as angular misalignment, but parallel misalignment also gives high levels of radial vibration. These radial vibrations will be 180º phase shifted over the coupling. The peak at 2x the rotational speed is often larger than the one at 1x the rotational speed, but the relationship is dependent on the type of coupling and the construction. In the case of large parallel misalignment faults there can be large values at 4x – 8x the rotational speed or several harmonics can appear. This is similar to the vibration pattern of mechanical looseness. The spectrums appearance is to a large extent dependent on the construction of the coupling [16].

Misaligned bearing cocked on shaft gives high axial vibrations. There will be a 180º phase shift between top and bottom of the bearing. An attempt to balance or to align the coupling gives no result [16].

2.1.3.5 *Resonance*

Resonance appears if vibration corresponds with a natural frequency. This can give extremely high vibrations, in theory infinite. Resonance can lead to rapid and severe damages. To detect resonance problems the natural frequency of the different monitored equipments has to be known. When the natural frequency is known it is easy to detect resonance problems as vibrations with a frequency equal to the natural frequency of the equipment.

2.1.3.6 *Mechanical looseness*

Mechanical looseness gives vibration spectrums with unstable patterns that change from one measurement to another. It is normal to distinguish between two different types of mechanical looseness. These two types give spectrums with slightly different appearance. The first type which is shown in figure 2.2 is typically made by loose securing screws, cracks in engine frames or bearing housing.

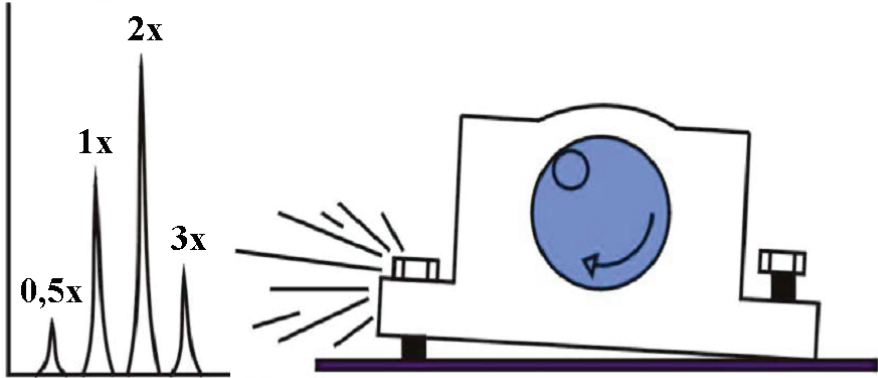**Figure 2.2: Vibration spectrum of loose securing screws, cracks in engine frames or bearing housing [16]**

The second type is made by incorrect adjustments between machine parts and is shown in figure 2.3. These faults give in the time domain sinuses that are chopped off which leads to several overtones in the frequency spectrum. These faults often occur in gear wheels, bearing rings and rotor fittings.
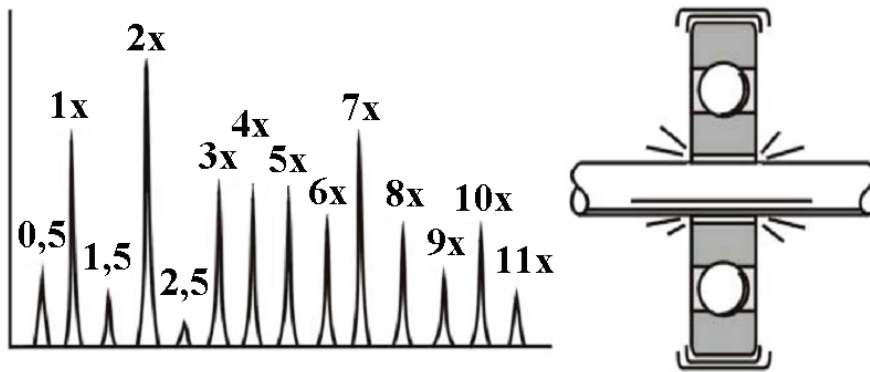
Figure 2.3: Vibration spectrum of incorrect adjustments between machine parts [16]

The vibrations of mechanical looseness are generally most powerful in only one direction and it also gives sub harmonic peaks at exactly 1/2x and 1/3x the rotational speed.

2.1.3.7 *Metallic contact between rotating and stationary parts*

The spectrums given by metallic contact between rotating and stationary parts are similar to the spectrums given by mechanical looseness. The contact can be in just a little part of the rotation to almost continuous contact. This contact will create several peaks in the spectrum at different frequencies. These peaks can also often hit natural frequencies and create resonance. Peaks at sub harmonic frequencies are also common. The typical vibration spectrum created by a metallic contact is shown in figure 2.4.
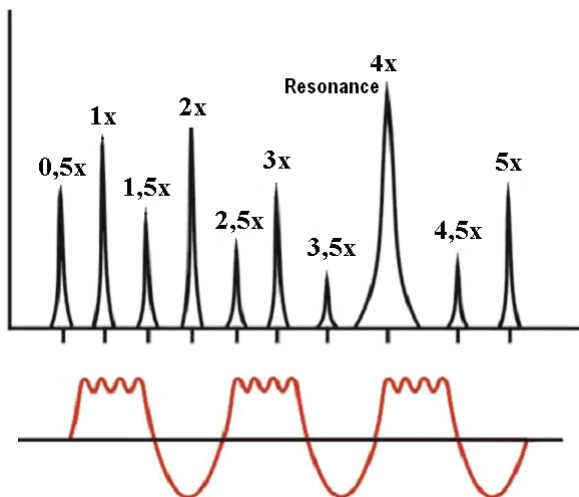
Figure 2.4: Vibration spectrum of metallic contact between rotating and stationary machine parts [16]

Metallic contact can also give high frequency noise which can be detected by ultrasonic detection probes [16]. Ultrasonic detection will be further explained in the section "new sensors" of this report.

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2.1.3.8   *Vibrations caused by electric machines*

There are several problems with electric machines that can be detected by the vibrations these faults cause. Faults in electric machines will often create vibrations with frequency equal to n times the mains frequency. Vibration peaks at these frequencies will therefore be a clear indication of a problem with an electric machine [16].

Stator eccentricity gives a stationary fluctuating air gap between stator and rotor. This leads to powerful radial vibrations in only one direction. The largest peak in the vibration spectrum will be at 2x the mains frequency. This is shown in figure 2.5.
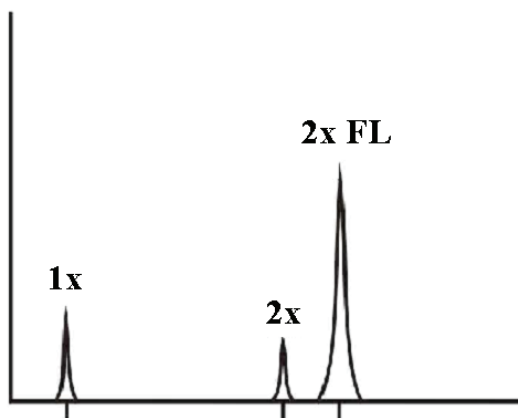
Figure 2.5: Vibration spectrum caused by stator eccentricity [16]

Rotor eccentricity gives a rotating fluctuating air gap between stator and rotor. This leads to pulsating vibrations with frequency equal to 2x the mains frequency and the closest rotational frequency. In radial direction the peak at 2x the mains frequency will have side bands at 2x the slip frequency and the peak at the rotational speed will have side bands at 2x the slip frequency. This is shown in figure 2.6.
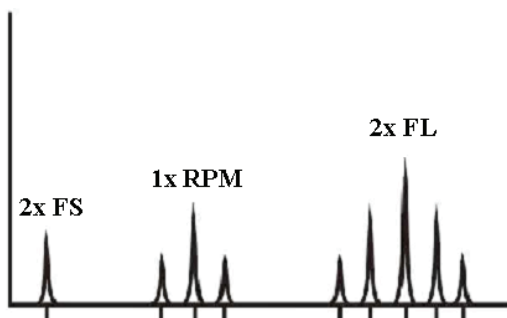
Figure 2.6: Vibration spectrum from radial direction measurements caused by rotor eccentricity [16]

Short circuits in rotor or damages in rotor windings or rotor bars results in high vibrations at 1x the rotational speed. In radial direction the peak at 1x the rotational speed will have side bands at 2x the slip frequency. This is shown in figure 2.7.
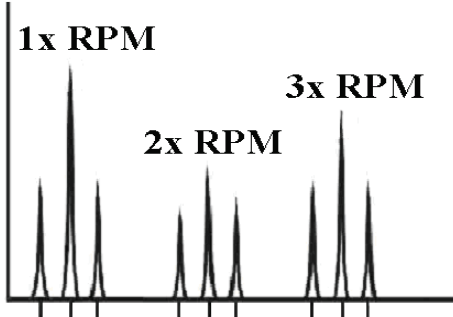
Figure 2.7: Vibration spectrum caused by short circuits in rotor or damaged rotor windings [16]

Loose stator windings in synchronous generators gives high vibrations at the coil pass frequency (number of coils times the rotational speed). This peak at the coil pass frequency will have sidebands at 1x the rotational speed. This is shown in figure 2.8.
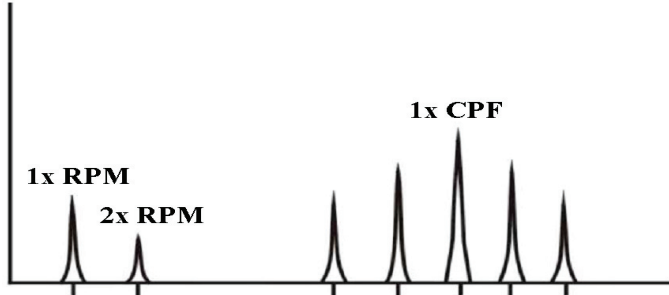
Figure 2.8: Vibration spectrum created by loose stator windings in a synchronous generator [16]

Phase problems because of loose or damaged contactors can result in very high vibrations. These vibrations have a frequency equal to 2x the mains frequency with sidebands at 1/3x the mains frequency. This is shown in figure 2.9.
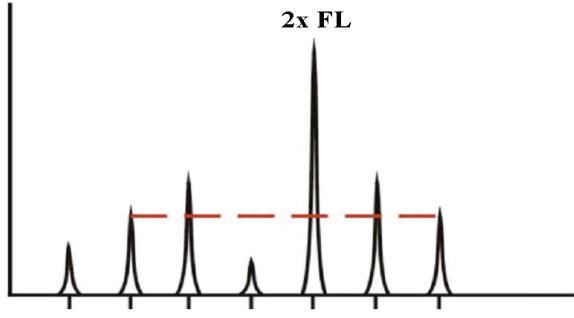
Figure 2.9: Vibration spectrum created by phase problems because of loose or damaged contactors [16]

3 Volve Knowledge Tools

Volve Knowledge Tools is a system which interprets continuous monitored data and uses cased based reasoning to predict if unwanted happenings are likely to occur. It is developed from the program CREEK which stands for "cased based reasoning trough extensive explicit knowledge" [2]. The system is developed to give decision support in oil well drilling, but the developers are eager to find new areas of application. In Erlend Timberlid's master thesis from 2008 he concludes that the Volve system is suitable for developing an expert system for hydro power stations [2].

3.1 Functionality and presentation to the user

The Volve system is developed to give the user decision support [11]. This means that the system is not supposed to make actions on its own. The output from the system is an advice to the user. Typically the advice tells the user what kind of problem that is under development and which actions that has to be performed to avoid that the problem is developing further. A typical screenshot of how the information is presented to the user is showed in figure 3.1.
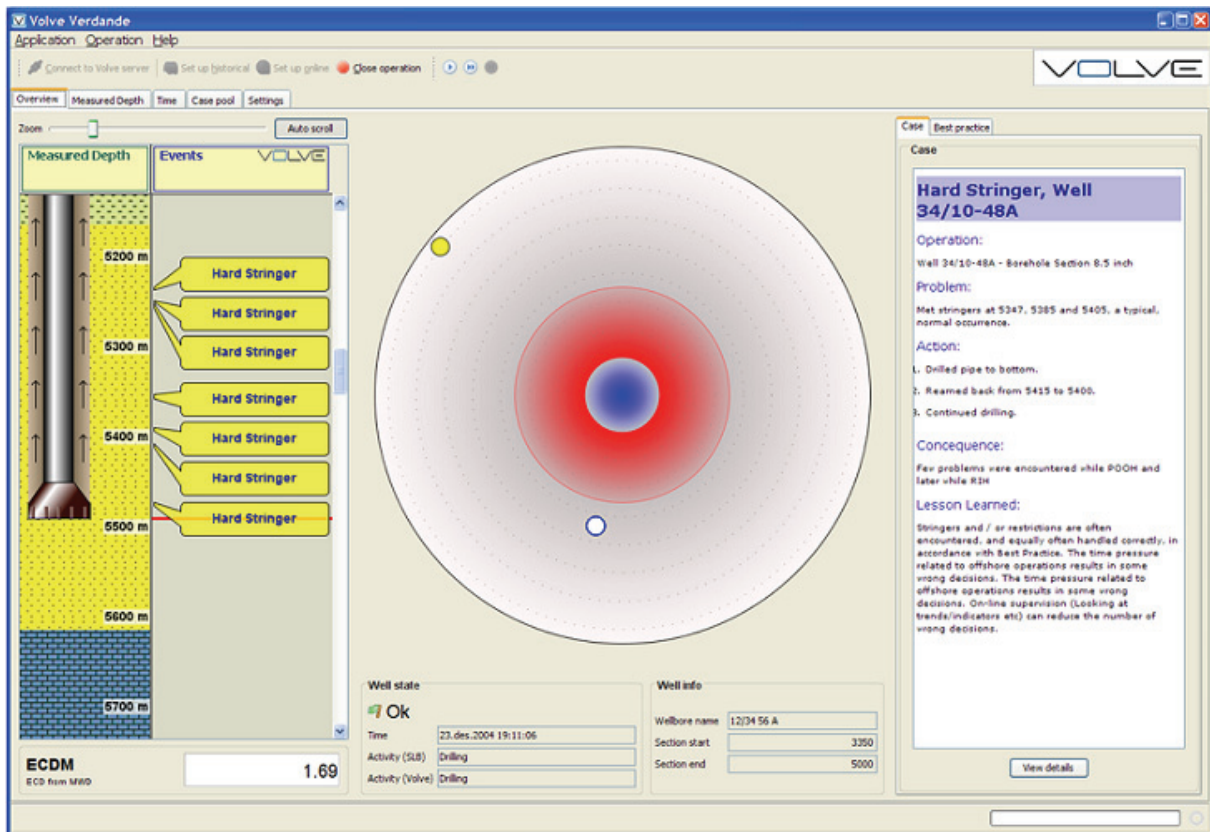
Figure 3.1: Screenshot of the Volve system [11]

In the large circle cases that are under development is indicated trough the smaller circles. The distance from the centre of the big circle to the small circle indicates the match between the case and the current operating conditions. The colour of the small circle indicates how important the case is. A red circle indicates that it is a case that can develop into a sever problem, a yellow case is not as important, and a white case is the least important cases. By clicking on the small circle information and advice concerning the case is presented to the user in a frame at the right side of the screen. It is also possible to get a graphical representation of the different variables concerning the case. This is done by clicking the details button in the information frame. In this graphical representation text boxes explain the different interpretations the system makes and the point where the interpretation was made is shown. In this way it is possible to go in and investigate the reasoning process to better understand why the system came up with the advices it did. By giving the user the opportunity to go in and investigate why the system came up with the solution it did the credibility of the system is increased.

As mentioned earlier the Volve system is based on cased based reasoning. The reasoning process of the Volve system is best described trough figure 3.2, which is shown under.
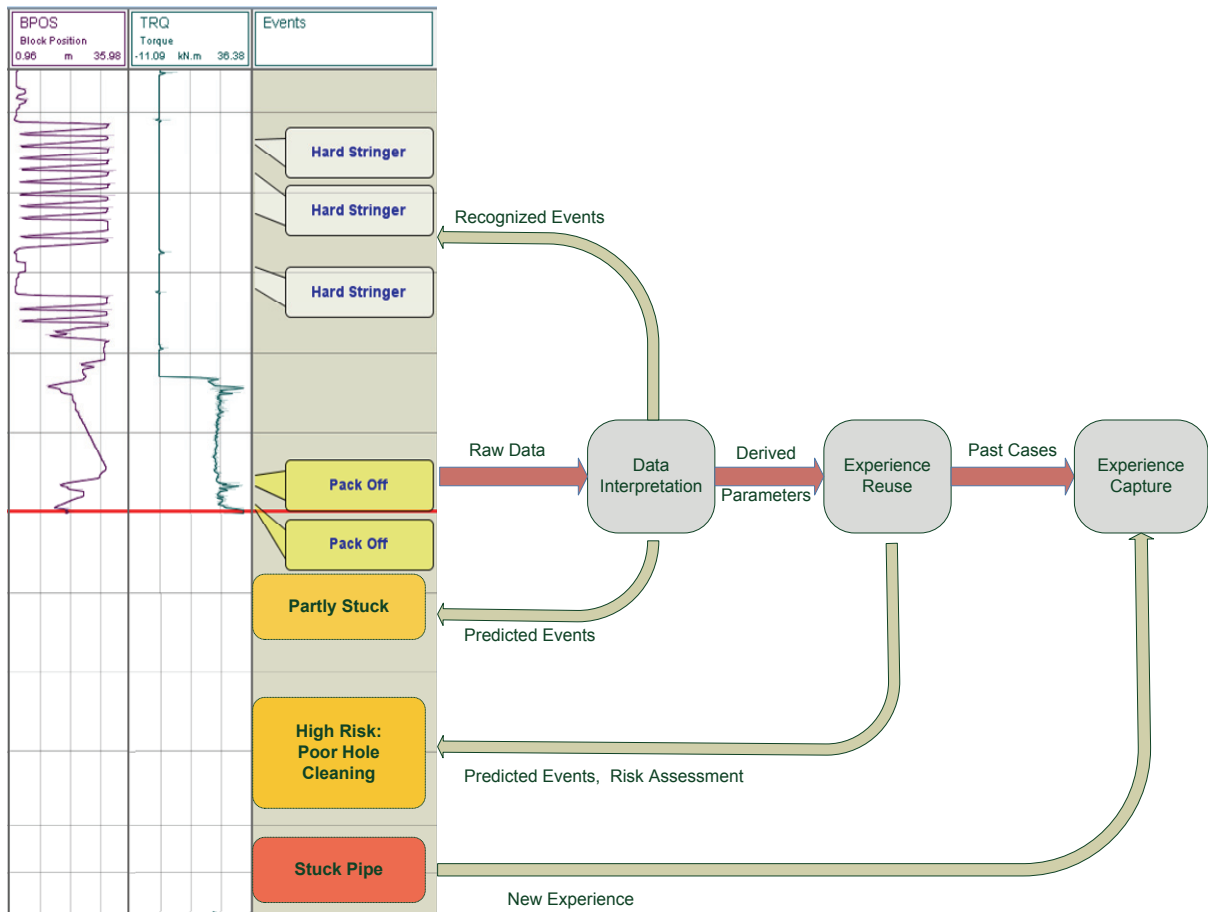
Figure 3.2: Reasoning process in the Volve system [9]

Figure 3.2 show that the system collects the raw data and interprets it. Then it predicts what kind of events that can develop on a short base [9]. It uses the old data that is saved in the data base and compares it with the derived parameters. From the experience reuse it gives a risk assessment telling how severe the problem that is developing can be and what kind of problem it is. It also gives advice on preventive actions. This prediction is on a longer timescale. If the problem that develops is a new experience to the system then this new case is captured and stored in the database.

Information about how the measured parameters develop can in many applications be just as interesting as the instant value of the parameter. Therefore it is possible to make the system plot functions of the parameters that are measured [11]. For example a derivative of a measured parameter will give information about how fast the parameter is changing. In addition to this the system is also available to recognize special patterns in the development of the different parameters.

3.2 Evaluation

Erlend Timberlid concluded in his master thesis from 2008 that the Volve system was suitable for developing an expert system for hydro power stations [2]. He draws this conclusion after having developed a simple expert system in Volve Knowledge Tools and used this system in simulations. From these simulations he gathered information about how the system operates and its functions. From this information it is possible to evaluate the advantages versus disadvantages and the suitability of the program for developing an expert system.

3.2.1 Advantages

The Volve Knowledge Tools can handle real time data which is a very important criterion for a monitoring system meant to monitor hydro power stations [2]. The amount of sensor data processed is only limited by the memory capacity of the computer that the system runs on. This means that Volve Knowledge Tools can handle huge amount of data.

The program has the ability to learn by itself. This means that if the program detects an operating condition it has never seen before it has the capability to store information about this operation condition in the database. When information about the new operation condition is stored the program will recognise it if the same operation condition arise again. If this operation condition needs special care the user saves a case description which will be presented to the user when the program detects this case in the future. In the case description all necessary information to handle the fault or difficult operation condition can be described. This makes it possible for an inexperienced operator to handle the situation. He gets expert advice from the system.

The agents in Volve Knowledge Tools are custom made for each measurement [2]. This makes the program very flexible. The agents can be constructed to interpret the raw data in any way to suit the user [2]. This means that it is possible to construct agents capable of handle any measurements or any measurement type, making it possible to develop a system that covers the whole hydro power station and not only a special part of it.

3.2.2 Disadvantages and uncertainties

Volve Knowledge Tools are in principle developed for the purpose of developing expert systems for monitoring oil well drilling. In oil well drilling the problem in monitoring is that it is so many different measurements performed that it is difficult to get the overview needed to be able to recognise faults and difficult operating conditions. In hydro power stations the problem is the opposite. There are few measurements taken of each process and it is difficult detect different faults and unwanted operating conditions from the limited information given by the measurements. This means that the Volve Knowledge Tools where developed to solve a type of problem quite different from the problem existing in hydro power stations. In simulations Erlend Timberlid has shown that an expert system developed in Volve Knowledge Tools is capable of recognising a problem that can exist in a hydro power station. However this does not show that the expert system will be capable of separating the cases when several cases of problems from hydro power stations is saved in the case base.

The ability of an expert system developed by the Volve software to interpret vibration measurements has not been tested. The information given by vibration measurements and vibration analysis is the single most important source of information to detect faults in the bearing system of a hydro power station. Because of this it is important to find out whether the expert system developed from the Volve software is capable of interpreting vibration measurements and performing vibration analysis.

Volve Knowledge Tools are a software for developing an expert system [2]. An actual expert system capable of monitoring a whole processes in a hydro power station do not exist and has to be developed from scratch. This is a time consuming process and has to be done before reliable tests of the finished expert systems ability to predict different types of faults and difficult operating conditions can be carried out.

4 SKF - @ptitude Observer

@ptitude Observer is an expert guided software and intelligent machine diagnostics for assessment of machines and processes [15]. It is developed for the purpose of giving expert advice about machines and processes without talking to an expert. By connecting the SKF @ptitude Observer monitor to the internet trough a firewall and a modem it can be remote controlled. This makes it possible to access the observer monitor and control it from anywhere in the world where a windows based computer with @aptitude observer installed is present [15]. This means that if something has to be changed or modified in the system you can easily do this from a system control centre or any other remote location. To access only the monitoring features of the @ptitude Observer it is only necessary to have a windows internet browser installed on the computer. This is possible trough the WebCon which is a web page based monitoring centre for viewing the units which is monitored by the @ptitude Observer.

The SKF @ptitude Observer is developed and owned by the Swedish company SKF. SKF has long tradition in making different types of bearings and different applications for bearings [16]. Because of the SKF expertise in bearings and bearing systems this software is developed and specialised in monitoring of bearing systems.

The ability of the @ptitude Observer to detect faults in a bearing system is based on the vibration analysis technology. Hence is the main source of information to the system collected from vibration measurements.

4.1 Machine information database

The @ptitude observer has a machine information database where mechanical data for each machine is stored. This database contains all relevant information about the machine components. The machine information database defines each machine part and how it interacts with other machine parts. Based on this information and information about the shafts rotational speed, the system calculates all defect frequencies automatically [15]. The information stored in this machine information database shall make it possible for the system to recognise the different machine parts and "understand" how they work together.

4.2 Measurement points

Different types of measurement points can be configured to give inputs to the system. The type of measurement point selected defines what type of signal the input is [14]. By defining the type of measurement point the program knows which type of input that is given in the particular measurement point. The input in a measurement point does not need to be a value measured by a measuring device or sensor. It can also be inputs from an external system trough an OPC server, or it can be a derived measurement point which means that it is a result of a calculation from measurements at other measurement points [14]. The different measurement points make it possible to take in measured values from all of the measuring equipment in the hydro power station. The different types of measurement points available in @ptitude Observer is presented in appendix I. The list of different measuring points available show that the @ptitude Observer can take in all types of measuring signals.

4.3 Data storage and trends

Storage of data is necessary for the purpose of later troubleshooting and trend analysis. The @ptitude Observer stores data in a Microsoft SQL server or in an Oracle database. @ptitude Observer can also be connected to other systems through an OPC server using the standard OPC communication protocol. If this is done it is possible to transfer trend data and alarm information, as well as process data to a connected system. This makes the storage capacity of the @ptitude Observer unlimited [15].

From the storage data the @ptitude Observer generates different types of trends. These trends are important for the purpose of evaluating the long term development of different machine parts and the operating conditions of these. Trend data consists of different trend buffers storing data from once every second to once every week. In addition a value from the first trend buffer is stored in the archive buffer every tenth minute [15]. When the user is creating a trend at a measurement point this storage interval can be adjusted to a preferable level. It is also possible to adjust which trend value that should be stored. It is possible to store the maximum value captured, the minimum value captured or the instant value captured in the storage interval. It is also possible to smoothen out the trend with an averaging formula. This smoothening formula makes the trend smooth and prevents the system from giving trend alarms at intermittent disturbances [14].

It is possible to create trends from all kinds of measurement data that the @ptitude Observer handles [16]. This means that it is possible to trend how operating conditions like load, vibrations and temperatures varies over time. It is also possible to trend information of the operation of the hydro power station like operational time and start stop sequences of different equipment of the hydro power station [16]. An example can be a trend showing the development of operational time of a drainage pump. These trends can give important information to the user. If the trend for the operational time of the drainage pump is increasing this can be a sign of a situation where a leakage is developing.

In addition to store data for trending of different measurement points it is possible to store entire vibration spectrums. It can be valuable to store vibration spectrums for later inspection and troubleshooting. Vibration spectrums can be stored automatically at a user defined interval and upon an event. An event in this case is an alarm or a change in process data. This event related storage is triggered by an event in one of several measuring points that is grouped together. By grouping the measurement points together the data from all the grouped measurement points is stored upon an event in one of the measurement points in the group [15].

4.4 Alarms

To make the user of the @ptitude Observer aware of important changes in the measured values different alarms are applied to the system. In @ptitude Observer there are two kinds of alarms, primary and secondary alarm.

The primary alarm is triggered by measured values of the process that excides the alarm limits determined by the user. These alarm limits can be controlled in such a way that they adapt to the current rotational speed or the current load of the machine. These primary alarms are checked typically every second and if a primary alarm is triggered a secondary alarm diagnostics are automatically performed [15].

Secondary alarms are performed by advanced machine diagnostics with sophisticated alarm conditions chosen from an alarm condition library or created by the user. These secondary alarms make prognostics about the condition of the machine three months ahead [15]. This gives the user valuable information about how the machine will develop in the coming

months. These secondary alarms are checked at every event and at an interval selected by the user, typically once a day.

4.5 Diagnosis

The machine diagnostics of the @ptitude Observer uses a ruled based diagnostic system for automatic frequency analysis [14]. Diagnosis rules in the @ptitude Observer is formulas that link together frequencies and harmonics with the correct machine part and cause of error. In @ptitude Observer there are several diagnoses for the most usual faults like misalignment, cavitations, mechanical looseness, and similar that are constructed by vibration experts. In addition to these pre made diagnoses it is possible for the user to define own diagnoses. It is possible to construct diagnoses for all the typical types of faults that it is possible to discover from vibration analysis. This means faults that have a known and recognizable vibration "image". It is this "image" that the diagnosis is programmed to recognise.

In addition to these diagnoses that are constructed to find special vibration patterns it is possible to construct a series of other diagnoses. It is possible to construct diagnoses that include all the different types of measurements the @ptitude Observer handles. This means that diagnoses that compare and combine different types of measurements can be constructed [16]. This makes it possible to construct diagnoses that use information given from other measurements than the vibration measurements. It is then possible to construct diagnoses that find special vibration patterns at a special load situation, diagnoses that compares vibration patterns with temperature, diagnoses that compares load situations with temperatures and so forth.

The diagnoses in @ptitude Observer is a very important feature since it makes it possible for a person without any expert knowledge about the machine or vibration analysis to detect faults in the machinery that is being monitored. When a diagnose is defined it is possible to attach an alarm to the diagnose so that the alarm will be released when the diagnose has a certain possibility of being true [14]. An alarm like this one is called a diagnosis alarm and in the alarm list it will be specified which diagnose that caused the alarm. The user can also follow the development of the diagnosis since the diagnosis is presented graphically to the user as a trend in a diagram.

4.6 Root cause analysis

In addition to the advanced automated diagnostics of the software the software also contains a great variety of tools for advanced root cause analysis [15]:

- Defect frequency display – in spectrum live mode the defect frequencies are continuously updated based on the instant shaft speed
- Digital Peak Enveloping analysis
- RMS-value – this is automatically displayed for each spectrum
- Orbit diagram – displays the orbital movement of the shaft
- Trend/Bode – trending as a function of time, speed or any process parameter recorded is possible
- Machine diagnostics – standard rules for the most common faults in addition user defined diagnosis rules can easily be designed
- Historical comparison of data – spectrums taken at different times can be displayed and individually compared
- Harmonics analysis – the system automatically calculates the best fit for the harmonics, making harmonics effects much more visible
- Sideband analysis – sideband frequencies can be displayed making sideband effects much more visible

Even though this is features that demand a person to operate them they are interesting to comment on. This is because if an alarm or warning is presented to the user it can be important for the user to seek deeper information about the problem causing the alarm. This information can help the user to improve or expand the diagnosis given by the system, and therefore be very important in the maintenance planning. It is also reasonable to think that the possibility for the user to analyse and study the measured values deeper will increase the integrity of the automated diagnostics in the system.

4.7 WebCon

In the daily monitoring of the hydro power station the user of the @ptitude Observer will watch a web page presenting all necessary information [16]. This web page can be accessed from any location where an internet connected computer with a windows web browser

installed is stationed. This web page is called WebCon and from WebCon it is possible to study all monitoring information given by the @ptitude Observer.

4.7.1 Main page and sub menus

When logging in to WebCon the user is presented with the main page which presents a summary of all important status information. This means that the user is presented with the number of warnings, alarms and system alarms currently active in the systems that are being monitored. In addition to alarms and warnings also new messages and upcoming events are presented. In a column to the right of the main window in WebCon the different sub menus of WebCon is listed with icons, these icons links to the different sub menus. By clicking on an icon called view data a map will appear. In this map all the units that are monitored will appear as small icons. These icons are coded which means that if the icon is octagonal and red there is an alarm present in this unit. If the icon is triangular and yellow there is a warning present in this unit and if the icon is octagonal and green the unit is running flawless. The black icons are units that are not currently active. This overview page is shown in figure 4.1. This figure is from a demonstration version of the WebCon and the map does not need to be this map. It is possible to use any map desired when configuring the WebCon.

Figure 4.1: The overview page of the monitored units in the WebCon [16]

In figure 4.1 the different sub menus of the WebCon page are shown in the column to the left of the map in the main window of WebCon. These sub menus are different features available in the WebCon. These features will be commented on only briefly in this report [23]:

- The "view my reports" icon provides the user with a tabular overview of the reports. This feature enables the user to share and store the reports of the monitoring.
- "Upcoming events" give the possibility to mark upcoming scheduled events in a calendar making it easy for the users of the system to keep track of the scheduled events for the different units.
- "Personal messages" are a message system making it possible for all the users of the system to send personal messages to the other users of the system.
- "Company news" is a link to for example the news page of the users company. By default settings this link shows the news page of SKF.

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- "Goto my aptitude" are a link to the SKF @ptitude portal.

4.7.2 Unit overview

In figure 4.1 the Aapua 7 icon has the colour red and an octagonal form. This means that there is an alarm present at this unit. To get to the overview picture of this unit the user just clicks on the icon and the overview picture will appear. This overview picture is shown in figure 4.2. Figure 4.2 shows that Aapua 7 is a wind turbine. This is because the figures in this report are collected from a demo version of the WebCon, as mentioned earlier, and there are no hydro power stations available in this demo version. The overview picture from a hydro power station would have been similar so it is possible to explain the functionality of the system from this figure even though it is a wind turbine [16].

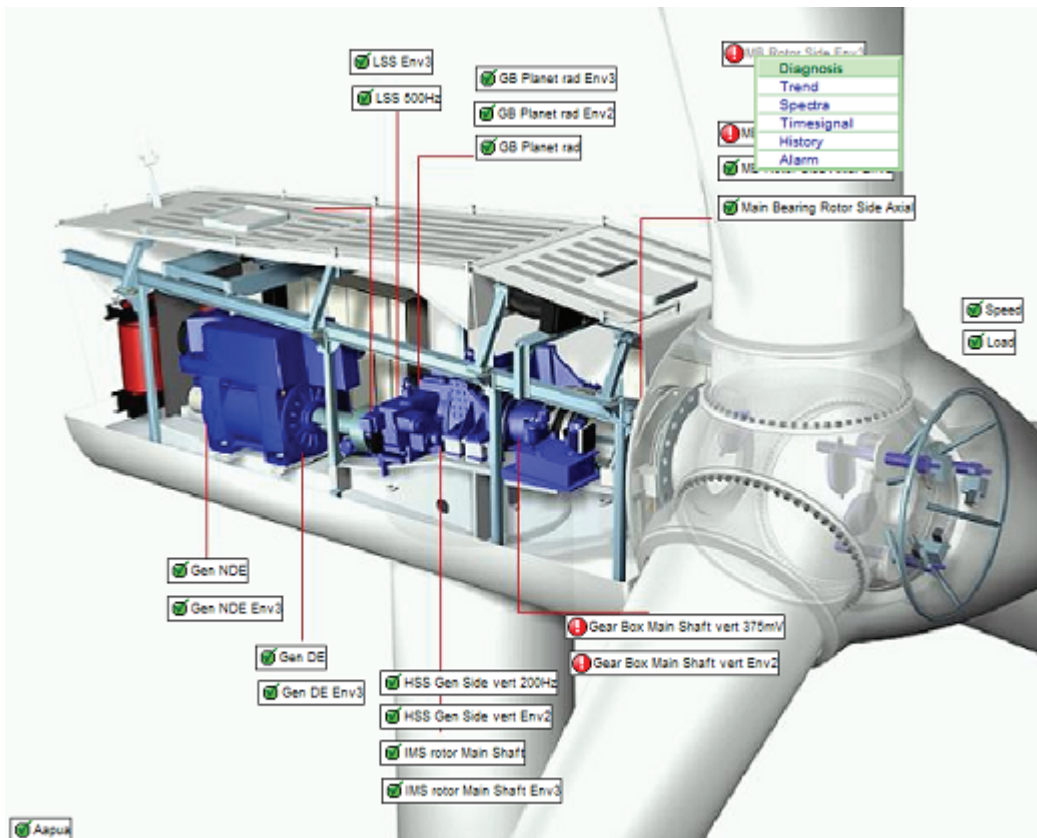**Figure 4.2: Overview picture of a monitored unit in the WebCon [16]**

In the overview picture of the monitored unit in figure 4.2 the different measuring points are indicated with red lines and in the text boxes it is explained what is being measured there. The icons has the same coding here as for the main overview page. This means that it in this case is alarms present at four different measurements.

4.7.3 Presentation of alarms

To view the alarms and inspect it simply right click on the icons that are marked red. When the user has right clicked on an icon a drop down list of all possible options available at that point will appear [23]. This drop down list is also shown in figure 4.2. By clicking on the line where it says alarm, a window with a list of all alarms and warnings at this measurement point will appear. In this list the date for the alarm, the alarm title and the place of the measurement leading to the alarm is given. By clicking on the spectra button the spectrum corresponding to the alarm will appear. On top of the alarm list it is possible to choose between three different categories of alarms to be shown. The "show new alarm" choice will only show new alarms and warnings that have not been acknowledged yet. The show "old alarms" choice will only show alarms and warnings that have been acknowledged, and the "show all alarms" choice will show all alarms and warnings at this point. By acknowledging an alarm the alarm is removed from the active alarms list and can only be found in historical views [23]. An example of such an alarm list is shown in figure 4.3.

Figure 4.3: This figure shows an alarm list from the WebCon [16]

4.7.4 Investigation of alarms

When an alarm or warning is given it is possible to investigate the alarm or warning situation further by clicking on the other options in the drop down list.

4.7.4.1 *History*

By clicking on history a window with the last ten spectrums from this measurement point is presented below one and other. This gives the user an overview of the history of this measurement point.

4.7.4.2 *Timesignal*

By clicking on timesignal it is possible to inspect the timesignal of the measurement in the measurement point.

4.7.4.3 *Spectrum*

By clicking on spectrum a window with the vibration spectrum of the measurements taken in the measurement point will appear. In this window it is possible to select different cursors and markers for diagnostic purposes. These cursors and markers help the user to easily find defect frequencies, harmonics and sidebands [23].

4.7.4.4 *Trend*

By clicking on trend a window with the different types of trends available for this measurement point will appear. It is possible to choose between the different types of trends by clicking on the different legends to enable and disable them. These trends give the user the possibility to investigate the development over time of the measured values at the measurement point.

4.7.4.5 *Diagnosis*

By clicking on diagnosis a window with graphical representations of the diagnostic evaluations of the specific part of the asset will appear. The diagnosis is shown with a statistical weighting of each diagnose in use and is represented as a trend over time. The statistical weighting represents the possibility of the diagnose to be true. Figure 4.4 shows a window from WebCon showing such a representation of different diagnoses. In the diagram

for the different diagnoses there are tree different coloured areas. If the diagnose trend moves into the red area this means that the possibility of the diagnose being true is very high and an alarm is presented. If the trend is in the pink area there is a warning situation present, and if the trend is in the white area the possibility of the diagnose being true is small. In figure 4.4 the trend for the diagnose "Vanes Propeller" is making large jumps. The probability moves directly from being very high to being very small. This is a trend that needs special attention and should be questioned. A diagnose is a combination of several key vibrations and a statistical analysis of these. Drastic changes like the ones shown in this example should therefore be investigated closer by vibration experts [23]. The vibration experts will find out why the diagnose is reacting like it does and draw a conclusion of how this problem should be handled.
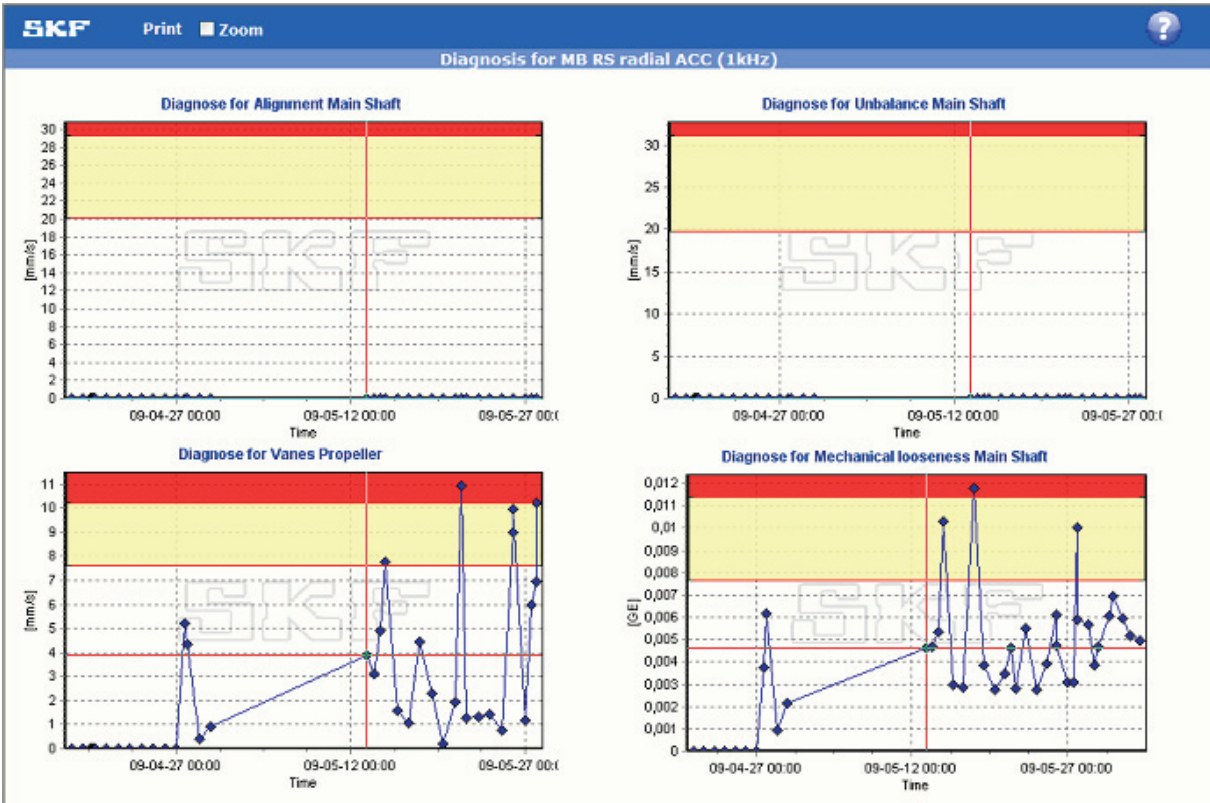
Figure 4.4: The graphical representations of diagnoses in WebCon [16]

4.8 Results from hydro power stations

The @ptitude Observer system is installed in several hydro power stations in Sweden and in this report some of the results from the monitoring of these hydro power stations will be

presented. These results give examples on how the @ptitude Observer can be used to detect faults and to give valuable information about the operating conditions of hydro power stations.

4.8.1 Loose runner blade

At the Långbjörn hydro power station a hydro power machine with a Kaplan turbine is being monitored by the @ptitude Observer system. The monitoring of this Kaplan machine showed that there were axial vibrations detected in the thrust bearing of the turbine. Also in the lower trust bearing it was detected axial vibrations. These axial vibrations proved to be generated from the runner blades. These vibrations are shown in figure 4.5 where the vibration spectrum from the lower thrust bearing is shown. The two spectrums at the top are the measurements in radial directions separated by 90 °. The bottom spectrum is the measurement in axial direction.
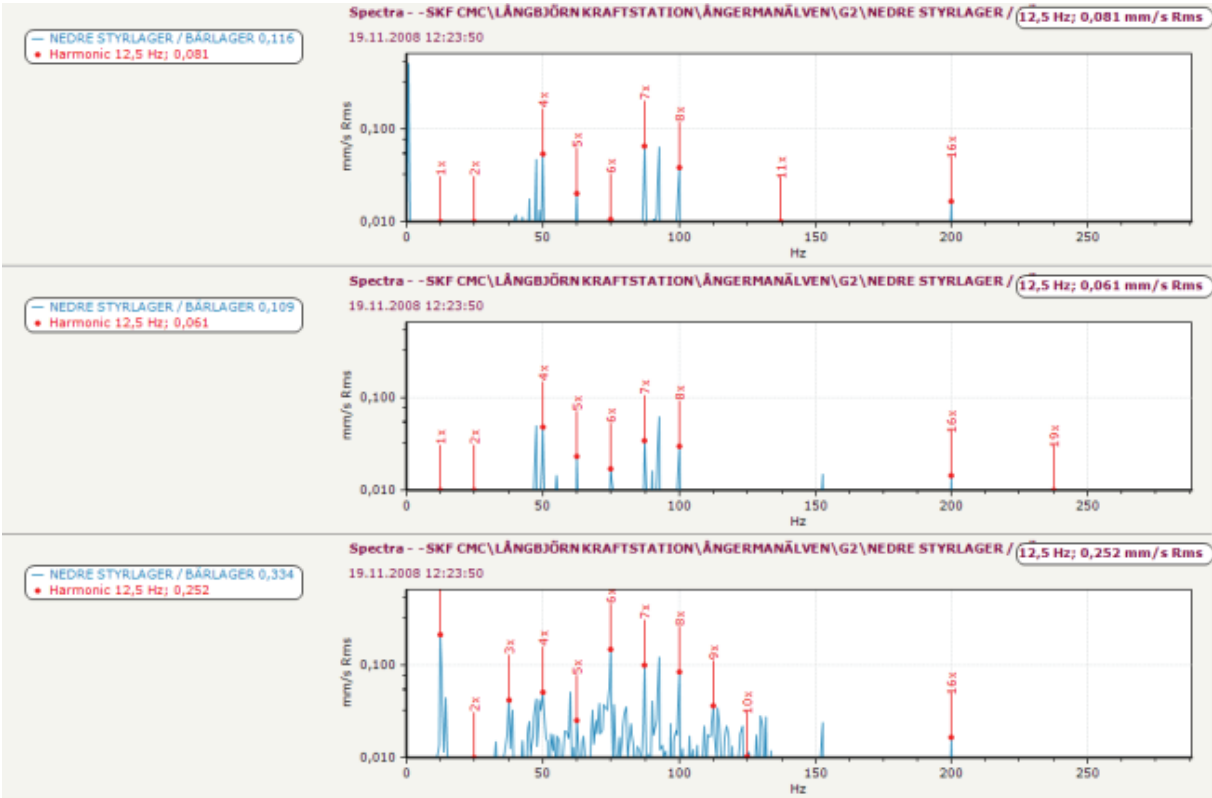
Figure 4.5: Vibration spectrum with evident vibrations from loose mechanical parts [16]

In the bottom spectrum the vibration pattern of a mechanical looseness is clearly visible. The first peak with the red marker on top is the fault frequency and the other red markers show the harmonics of this. These other peaks at the harmonics of the fault frequency are evident signs of mechanical looseness. The fault frequency points out that the fault is generated by the blades of the runner wheel. Therefore the conclusion was that there most likely was some

looseness in the runner blades of the Kaplan turbine and that this should be observed more closely. Trough a later inspection it was confirmed that the runner blades were loose and the fault was repaired.

By recognising this vibration pattern and analysing the fault frequency of the vibrations this fault is easily detected by the diagnosis system of the @ptitude Observer [16]. When the diagnosis has detected the fault the diagnosis alarm is presented to the user and the fault can be investigated closer to find the correct action to avoid the fault in developing further.

4.8.2 Incorrect Bearing Play

From the monitoring of the Kaplan machine at the Stjern hydro power station it was detected unchanged high vibrations over time. In the higher thrust bearing it was detected high vibrations clearly modulated by the number of revolutions. These vibrations are shown in figure 4.6.
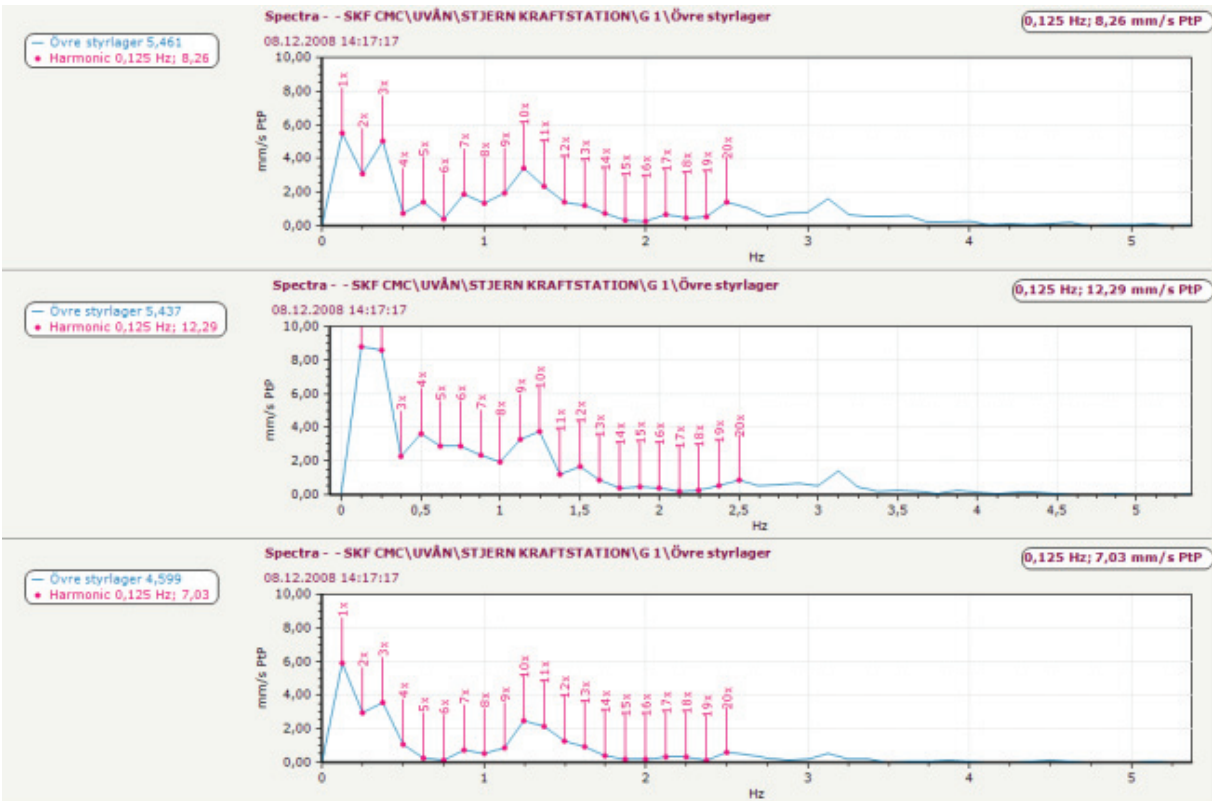
Figure 4.6: Vibration spectrum showing rotational speed modulated vibrations coming from a too large bearing play at the Stjern hydro power plant [16]

By comparison of older measurements it is evident that these vibrations have been almost unchanged over time which means that it is an old fault. The type of vibrations shown in figure 4.6 gives indications of being created by the bearing play. Therefore was an inspection of the bearing play planned. During this inspection signs of a too large bearing play were found. From these discoveries it was concluded that the bearing play was too large and a repair of the bearing play where planned.

4.8.3 Electrically generated vibrations

The hydro power machine at the Stalon hydro power station has a Kaplan turbine and a rebuilt generator. During monitoring of this hydro power machine it was found electrical generated vibrations. These vibrations are shown in the vibration spectrum in figure 4.7.
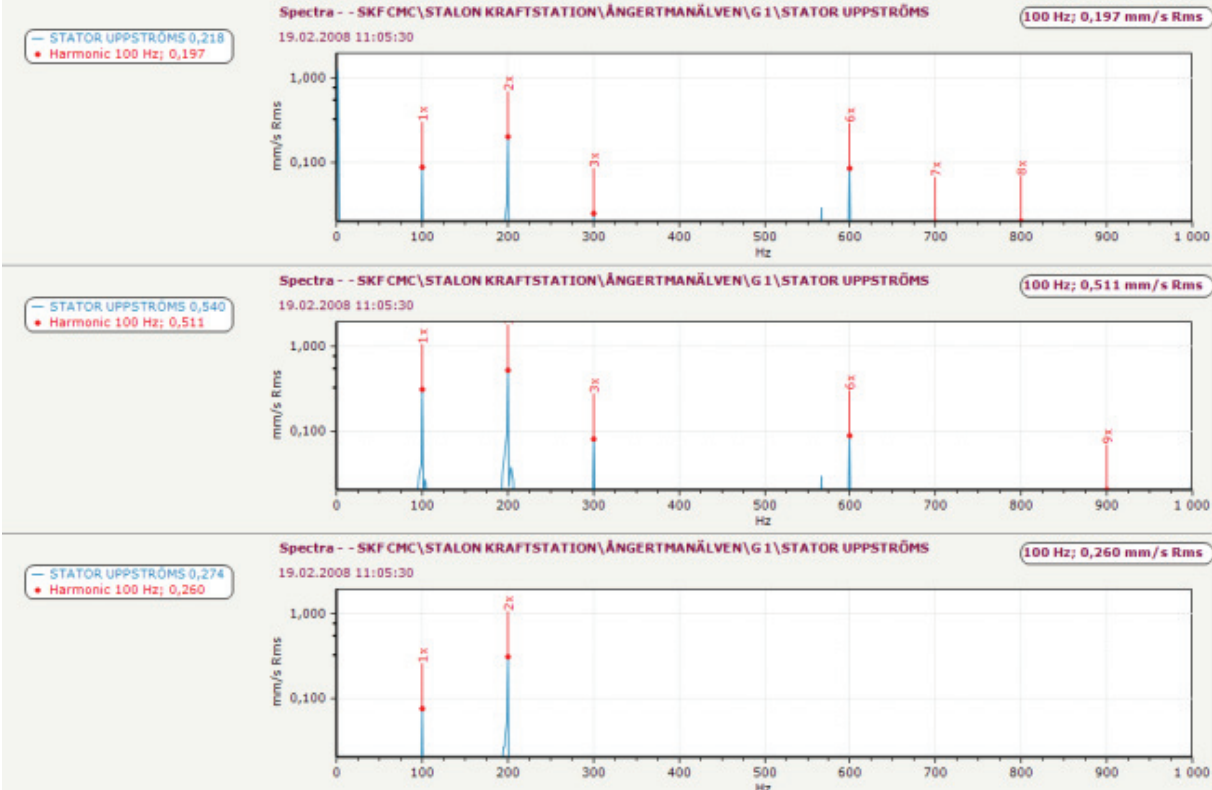
Figure 4.7: Vibration spectrum showing electrical generated vibrations in the Stalon hydro power plant [16]

In the vibration spectrum in figure 4.7 vibration peaks at 100 Hz and the multiples of this is clearly visible. These vibrations is clearly electrical generated vibrations since vibrations created by the electrical equipment of the machine often gets high levels of vibrations at two times the main grids frequency and the multiples of this. The amplitude of the vibrations is

high and this could normally be sign of faults at the generator. However the generator at this hydro power machine is rebuilt and these vibration levels can just be the new normal operating conditions of this generator. Therefore is the conclusion of these measurements that there are electrical generated vibrations present at this machine which could be signs of a fault in the generator, but the generator is rebuilt and it is difficult to give a good conclusion. Because of this the generator should be observed closely in the future to find out whether the vibrations is a sign of a fault developing or if it is just the normal operating condition of this generator.

4.9 Evaluation

In this report it has been investigated how the @ptitude Observer software can be used in monitoring of the bearing system of hydro power stations to give the user support in decision making and information about faults under development. The different features of the software and some results from monitoring of hydro power stations in Sweden have been presented. From these investigations it should be possible to give an evaluation of the different advantages and disadvantages of the system.

4.9.1 Advantages

The @ptitude Observer is a software that is already in use in monitoring of hydro power stations in Sweden. It has also been used in monitoring of bearing systems of other industries in Norway. The results from monitoring of these units show that the system is giving the user the necessary tools to find faults at an early stage and to avoid breakdowns. The experience from monitoring bearing systems of Swedish hydro power stations and of other industry equipment in Norway can be used in the planning when installing this system in Norwegian hydro power stations.

The possibilities to trend different variables are very good in the @ptitude Observer software. It is possible to trend all types of measurements from operational times of motors and equipment, temperature and vibrations to load and water flows. These trends can give important information about the development of the station and not only equipment influencing on the bearing system. For instance a drainage pump that is showing increasing operational time can be sign of a leakage developing. Or if the flow of water in a cooling

circuit is measured and trended a decreasing trend can be sign of clogging. In this way it is possible that the trending functionality of the @ptitude Observer can be used to detect faults not directly influencing the bearing system. This has not been tested and it needs to be done before any distinct conclusions can be drawn.

The WebCon makes the level of availability of the monitoring features of this software very high. It is possible to inspect all the monitored units from any computer with access to internet and a windows internet browser installed. This makes it possible to access the monitoring features of the program from anywhere in the world even tough no computer with the @ptitude Observer installed is present.

4.9.2 Disadvantages and uncertainties

@ptitude Observer is specialised to monitor bearing systems and rotating equipment of different industry processes. The diagnostics of the system builds its conclusions on vibration measurements and knowledge about rotating speeds and the construction of the monitored units. This means that the system has low flexibility and that the ability of the system to monitor other parts of the hydro power station will be limited.

Because of the low flexibility of the system new types of sensors giving new measurements can be difficult to include in the system. New sensors can measure new variables of the hydro power station that has not traditionally been measured. These new measurements can give important information that will make it possible to detect faults that it is difficult to detect today because of lack of information. However if the monitoring system is incapable of interpreting the information given by the new measurements and adding it to the diagnostics of the software the benefits of the new measurement can not be fully utilized.

The system has the ability to detect faults and unwanted operating conditions by itself from the constructed diagnoses. However when a diagnose or an alarm is presented it will often be preferable to get more information about the situation because the automatic diagnose in many situations is not precise enough. To get more information about the situation the root cause analysis tools in the @ptitude Observer is used. It is by using these tools the potential of the system can be fully utilised and give enough information to conclude with the most precise diagnoses. When using these tools it is no longer the software that analyses, concludes

and gives the user advice on its one. The system is then become more of a tool to make the user capable of analysing and drawing conclusions. To manage these tools the user will need to have some knowledge about vibration analysis.

5 Additional sensors to improve detection of faults

The information given by the measuring equipment in hydro power stations is limited. To develop the monitoring systems further so that it can give even better and more reliable results it is important to increase the information flow into the system. It is the information given to the monitoring system by measuring equipment that is the key to detect faults. To increase this information flow it is necessary to install new sensors which are not part of the monitoring equipment in hydro power stations today. These new sensors can give new information to the monitoring system that will increase the reliability of the system and the ability of the system to predict faults and unwanted operating conditions.

This report will comment upon two different types of sensors or sensing devices that are currently not in use in most hydro power plants. These sensors will contribute with important information that will increase the ability to predict and detect faults in the machinery of hydro power stations. They are already in use for monitoring of similar and comparable equipment as to what is present in a hydro power station. Therefore they will be a natural choice for further expansion of the monitoring equipment in a hydro power station.

5.1 Smoke sensors

Smoke sensors can be installed to give early signs of smoke developing. This will make it possible to detect faults that cause development of smoke. These smoke sensors will represent the sense of smell of the old machine expert who could smell the development of smoke. Today there are two main types of smoke sensor technologies that are competing, the photoelectric smoke sensors and the ionization smoke sensor. Since there are different types of fires producing different kinds of smoke it is impossible to simply tell which one is the better technology. To find the type of smoke sensor that will be the best one to choose it is important to understand how the different technologies work and what type of fire or smoke it is going to detect. In a hydro power station it is desirable that the smoke sensor are capable of detecting smoke developed from heat generation in different equipment of the power station. As an example it is possible to look at the stator of the generator in the hydro power machine. If there is a short circuiting between different turns in the stator this is a fault that is not easily detected by the existing sensor equipment today. The heat generation from a fault like this can be severe because of the large short circuit current. This heat generation will lead to

development of smoke as the winding insulation is decomposed by the heat. A smoke sensor capable of detecting this smoke will give the monitoring system of the hydro power station information about this smoke development and the fault can be detected.

5.1.1 Ionization smoke sensor

An ionization smoke sensor uses a small amount of radioactive material to ionize air in the sensing chamber. As a result, the air chamber becomes conductive permitting current to flow between two charged electrodes. When products of combustion enter the chamber the conductivity of the air in the chamber decreases. When this reduction in conductivity is reduced to a predetermined level, the alarm is set off. Most smoke detectors used in civil homes today uses this type of sensor and it is the least expensive one. The principle of this type of smoke sensor is shown in figure 5.1.
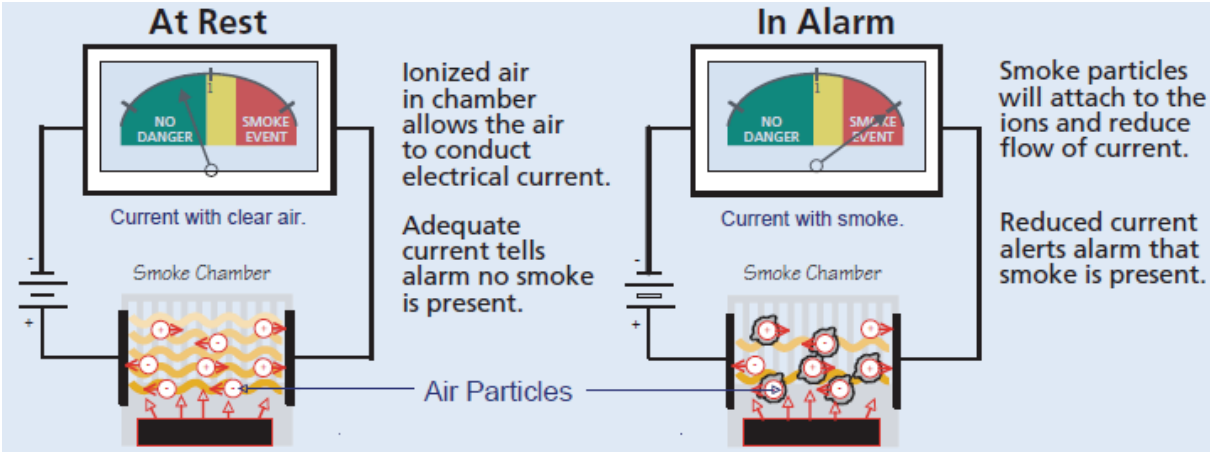
Figure 5.1: Principle drawing of an ionization smoke sensor [16]

Ionization sensors may respond slightly faster to flaming fires and fires with small and less visible smoke particles [21].

5.1.2 Photoelectric smoke sensor

A photoelectric type smoke sensor consists of a light emitting diode and a light sensitive sensor in the sensing chamber. The presence of suspended products of combustion in the chamber scatters the light beam. This scattered light is detected and sets off an alarm. The principle of this type of smoke detector is shown in figure 5.2.
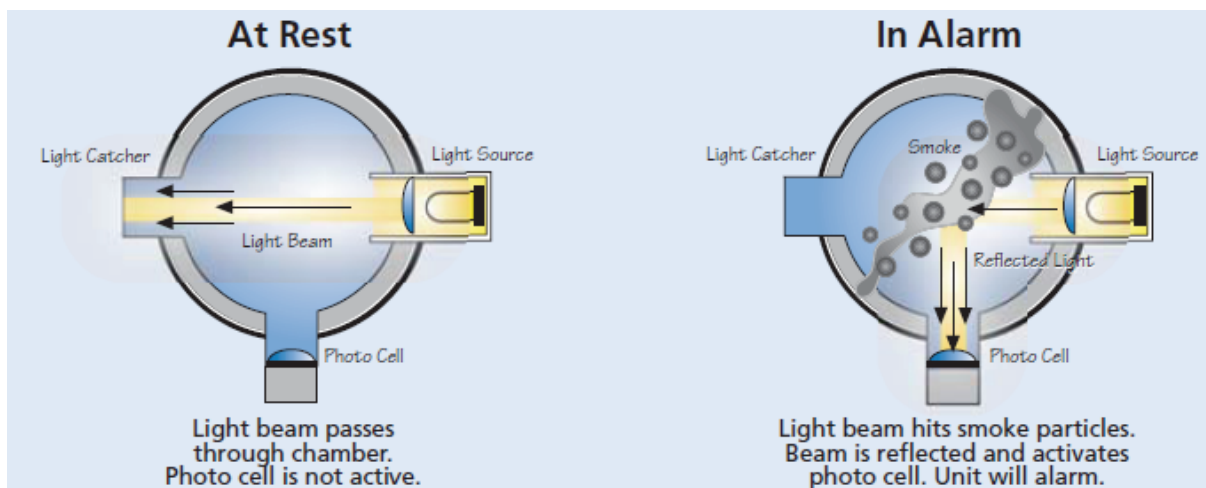
Figure 5.2: Principle drawing of a photoelectric smoke sensor [16]

In addition to this type of photoelectric smoke sensor, which is often referred to as a photoelectric light scattering smoke sensor, there is a second type of photoelectric smoke sensor. This type is often referred to as a photoelectric obscuration smoke sensor. This type sends out a light beam towards a receiver which register that the light beam hits it. When smoke particles then block the light beam less light will hit the receiver causing the alarm to go of. The receiver can be set to react at different levels of sensitivity meaning that the receiver can be set to release the alarm when different percentages of the light beam is blocked. This type is typically used to cover large areas of space. The principle of this type of smoke sensor is shown in figure 5.3.
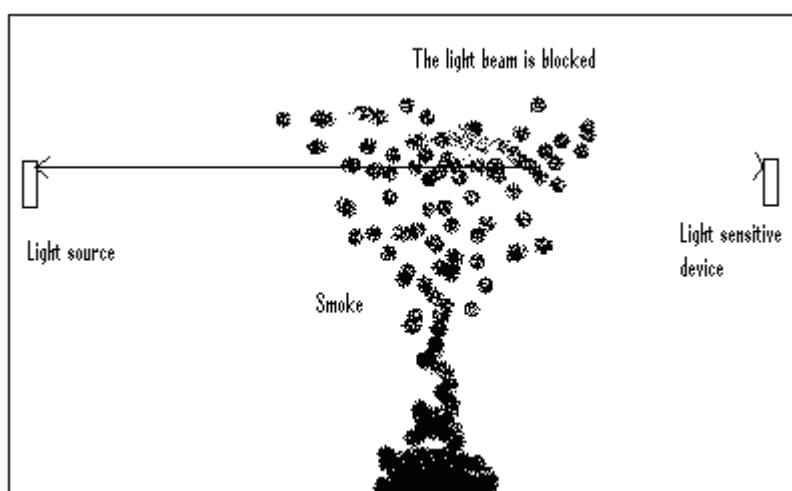
Figure 5.3: Principle drawing of photoelectric obscuration smoke detector [21]

Photoelectric smoke sensors may respond faster to smouldering fires and fires with large and more visible smoke particles [21].

5.1.3 More advanced smoke sensors

The basic principle of how the smoke particles are detected is normally the same for these more advanced smoke sensors as for normal smoke sensors. In this report they are grouped as more advanced because they have different adaptations to make them more suited for different industrial applications.

5.1.3.1 *Laser technology smoke sensors*

Laser technology smoke sensors are a type of more advanced smoke sensors [17]. Basically it uses the same technology as the photoelectric smoke sensor but instead of a light emitting diode it uses a laser beam. This makes these types of smoke sensors much more sensitive than a normal photoelectric smoke sensor. Since the sensitivity of this technology is so high the smoke detectors using this type of sensor has algorithms built in to determine whether the particle scattering the laser beam is a dust particle or a smoke particle. This insures that the smoke detector releases the alarm only when it is a smoke particle that scatters the laser beam and in this way it avoids false alarms.

5.1.3.2 *Aspirating smoke detectors*

Aspirating smoke detectors are smoke detectors that use a fan to actively drag air samples trough pipes and past a sensing device. In most cases this sensing device has the same basic principle as a photoelectric smoke sensor, and a laser is often used to make the sensitivity of the system as good as possible [21].

The intake to the pipes of aspirating smoke detectors can be placed away from the sensing device. This makes it possible to collect air samples from difficult accessible places and yet having the sensing device in an easy accessible place. This again makes maintenance on the sensing device easier. Normally one sensing device is connected to a network of pipes. In this way one sensing device covers a large area. The disadvantage with this is that the system will not be able of telling which pipe and hence from which position the smoke is coming. To avoid fouls alarms triggered by dust particles the pipes can be equipped with different types of filters. In addition the sensing device can be equipped with the same type of algorithms as the laser technology smoke detectors to distinguish smoke particles from dust particles.

5.1.3.3 *Cloud chamber principle smoke detector*

This smoke detector also uses a fan to drag air samples to a centrally stationed sensing device. In this way also this smoke detector is an aspirating smoke detector. However this smoke detector uses a very advanced sensing technology. The sample air is filtered and it then goes into a humidifier. In the humidifier distilled water is used to raise the relative humidity to about 100 %. After this the sample air is decompressed using a vacuum pump. This makes the sample air super saturated. If any smoke particles are present in this super saturated air they will work as condensation nuclei for water droplets leading to the formation of a cloud inside the chamber. The density of this cloud is measured by a photoelectric light scattering sensor which will release the alarm if a pre determined alarm limit value is exceeded [21]. This technology has the ability to detect submicron particles that are produced in abundance by the thermal decomposition during the precombustion phase of incipient fires. For example an electrical motor will release large numbers of decomposition molecules from insulation on the windings long before there is any visible smoke or flame. This gives the cloud chamber principle smoke detectors unsurpassed sensitivity and ability to provide very early warning of incipient fire. The problem with these cloud chamber smoke detectors is that they are expensive and they need more frequent servicing.

5.2 Ultrasonic sound detection

Several bearing problems can be detected trough ultrasonic sound detection and it complements the properties of vibration analysis [15]. Based on research by NASA, it was established that ultrasonic monitoring provides early warning of bearing failure [18]. There are several characteristic of ultrasonic sound that contributes in making ultrasonic sound detection valuable for surveillance purposes:

- The attenuation rate of ultrasound is high and because of this it dose not travel huge distances from its source.
- Ultrasound is more directional than normal sound.
- Since the dispersion of ultrasound is little it tends not to travel around corners and it is easily shielded. This makes it possible to locate an airborne source of ultrasound within a few mm and a source in a metal structure within cm.

- Damage processes tend to produce detectable levels of ultrasound long before audible sound.

- Because of the short wavelength it is possible to use highly directional sensing apparatus capable of determine the direction of an ultrasound source with an uncertainty of only a degree or two.

These characteristics show that ultrasonic sound detection is capable of giving an early warning of faults since the ultrasound is produced already at an early stage of the fault development. In addition it shows that ultrasonic sound in many situations can give a very precise location of a fault since the sound does not travel distances very well [19].

In addition to give important information of bearing behaviour ultrasonic detection can also give important information about faults in other equipment of industrial processes [19]. The most interesting one seen from a hydro power plant surveillance point of view is the capability of the ultrasonic sound detection system to detect electrical discharges. Electrical discharges emit ultrasonic sound at the site of emission and with an ultrasonic sound detection probe it will be possible to detect this sound.

The typical equipment that is used for ultrasonic sound detection is [19]:

- A sensitive high frequency microphone
- An adjustable amplifier
- Circuitry to "down-convert" the ultrasound to audible frequencies
- An analogue meter allowing the ultrasound amplitude to be measured

In addition it is possible to attach several different sound guiding accessories so that the instrument matches the application in the best possible way. The sound guiding accessories can be concentrators and parabolic concentrators for airborne ultrasound, and contact probes for detecting ultrasound transmitted in a solid structure. A picture of this equipment is shown in figure 5.4.

Figure 5.4: Typical ultrasonic sound detection equipment [20]

The ultrasound is "down-converted" to audible sound so that it is possible for the user to hear the ultrasound. In fact in most cases it is preferable to hear the sound and not only to measure it. The sound picture is complex and many factors are involved, this means that quantitative measurements is of limited validity [19]. When the user hears the ultrasound different faults will sound different and the human ear easily blocs out noise. This capability of the human ear to separate the noise from the sound created from the fault is very difficult to implement in computer software [16]. This makes it difficult to use the ultrasonic sound detectors in stand alone monitoring systems. However with only very little training a user should be capable of testing bearings for a series of faults [20]. This means that the user has to get directly involved in the measurements to fully take advantage of the potential in this technology. Nevertheless this technology is interesting since it can give valuable information in addition to the information given by the stand alone monitoring systems which is the scope of this project. If for example the monitoring system gives indications of a fault developing it is possible to send a technician out to the station to do some ultrasonic sound detection tests [15]. With the additional information from these tests it is possible to give an enhanced and more precise

diagnose [20]. It should be a goal to find out how these sensors can be placed permanently in the hydro power station and how the information given by them can be interpreted by the software in a remote surveillance system.

6 Discussion

The intension of this project is to investigate two different types of computer software to find out whether they are suitable to make a monitoring system capable of giving the user information about faults and unwanted operating conditions at an early stage. It has been investigated whether the software has proven the capability to detect faults and the different advantages and disadvantages has been discussed. In addition two different types of sensors that are capable of giving additional information to the monitoring system of the hydro power station have been investigated. The two sensor types perform measurements that the normal measuring equipment of today is incapable of.

6.1 Discussion of software

The software from Volve, called Volve Knowledge Tools, is software developed for the purpose of constructing expert systems for monitoring of oil well drilling. The other software, called @ptitude Observer, is produced by SKF and is specially developed to monitor bearing systems of different industry machinery.

The Volve Knowledge Tools is software developed to build expert systems that uses cased based reasoning to detect faults. When the expert system is constructed it shall be capable of detecting faults by recognising previous and similar faults that are saved in the case base of the expert system. When a case matching the current operating condition is found information about the case and information about how to handle the situation is automatically presented to the user. The expert systems developed in Volve Knowledge Tools have proven its capability to detect faults in a hydro power station trough the simulations done by Erlend Timberlid.

The @ptitude Observer is software that interprets measurements and presents them to the user in an easy understandable way. Different alarms make the user aware of faults that are under development. In addition it is possible to construct intelligent diagnoses that recognise patterns of faults in the measurements and to use tools available in the software to analyse the measurements. This makes the user of the @ptitude Observer capable of detecting faults, but information about how the fault should be handled is not presented. @ptitude Observer has proven its capability to detect faults trough the use of this software in Swedish hydro power plants.

Since the Volve Knowledge Tools is used to build an expert system from scratch the flexibility of this system is very high. As long as enough information is collected about a process to make a case that it is possible to separate from another case the system will be capable of recognising the case and fault situation. This makes the expert system capable of monitoring all equipment in the hydro power station as long as enough information is given. However it has not been proved that an expert system developed by the Volve Knowledge Tools will get enough information to separate one case from another when several cases is saved in the database. This is a great uncertainty with the Volve system and has to be tested. The @ptitude Observer is specially made to monitor bearing systems by analysing vibration measurements. This makes the flexibility of the @ptitude Observer low. However it is possible to make trends of measured variables of the other processes and machinery in the hydro power station. These trends can give important information to the user that is not available today. Because of the low flexibility it can also be a problem to include the additional information given from new sensors in the monitoring process with @ptitude Observer.

The @ptitude Observer detects faults under development and makes the user aware of it by presenting an alarm. However in many situations it is then preferable to get more information about the fault. To get more information the different tools for analysing the results is then used. By doing this the root cause of the fault can be found and the correct action planned. This demands a person to operate the tools and this person will need some knowledge about vibration analysis and some knowledge about faults in a hydro power station. The expert system developed by the Volve Knowledge tools is performing all the analysis by its own and presents only the results and information to the user. This means that no involvement is needed from the user to find the fault. The user is also presented with information about how this fault was solved the last time it was present. This is an advantage of the Volve system since it saves time the user would have used in analysing. This is of course implied that the system is capable of detecting faults down to the same level as the human analysis in the @ptitude Observer. Because the test results from the Volve system is so limited it is difficult to conclude on which level of faults the system will be able of detecting.

6.2 Discussion of additional sensors

The additional sensors investigated in this report are smoke sensors and sensor equipment for ultrasonic sound. These sensors are investigated since they are in use in machinery of similar industries and they are thought to be a natural choice in expanding the measuring equipment in the hydro power stations.

Smoke sensors will be capable of giving information to the monitoring system of the hydro power station about all types of faults that will develop smoke. This is typically faults that generate high temperatures in a constricted area. Temperature sensors installed to measure temperature levels in different equipment will not necessary detect any temperature raise from these very constrict areas. But the smoke developed when for example insulation is combusted because of the high temperature released by a short circuit in a stator winding will be detected by a correct mounted smoke sensor. In this way the smoke sensors will contribute with important information to the monitoring system of the hydro power plant. This report tries to give an overview over the different smoke sensor technologies that are available. This is important in deciding which type of smoke sensor that should be installed in a hydro power station to detect smoke. To draw a final conclusion on which type of smoke sensor that should be installed in a hydro power station an investigation of the smoke developed by different faults in a hydro power station should be performed. This is because different smoke sensor technologies are better at detecting different types of smoke. While photoelectric sensor technologies are better at detecting larger smoke particles ionization sensor technologies are better at detecting small smoke particles.

Ultrasonic detection equipment is today used in different industries to give additional information to vibration analysis in monitoring of bearing systems. This is because bearings with faults developing seem to produce ultrasonic sound before audible sound. In addition the ultrasonic sound does not travel distances very well because of the short wavelength. This makes it possible to give a very precise location of a fault by using ultrasonic detection. Ultrasonic sound sensors are also used to detect electric discharges because electric discharges send out ultrasonic sound at emission. The disadvantage with ultrasonic detection is that the "sound picture" is very complex and it is difficult for computer software to interpret the signal. Because of this ultrasonic detection is today most usually done manually by hearing the signal after it is been "down-converted" to audible sound. This means that this technology is used to get extensional information by inspecting the equipment when there is

suspected that there is a fault developing. By other means it is difficult to include this technology in a continuous monitoring system today, but if interpreted correctly this technology can give very important information to the user.

7 Conclusions

In this report two different software products for monitoring of a hydro power station is been investigated. The two software products are quite different. The software from Volve is software meant to construct an expert system capable of recognising faults from previous cases of faults. The software from SKF is software that gives intelligent machine diagnostics from analysis of vibration measurements in addition to measuring and trending of other variables. It also gives the user tools for analysing the root cause of faults influencing the bearing system of different industry machinery.

Tests showing that the Volve system is capable of separating cases when many different cases is saved in the database and tests showing which level of faults the Volve system will be capable of detecting has to be performed before distinct conclusions about the software can be drawn. The software from SKF has proved the ability to make the user capable of detecting faults influencing the bearing system trough the experience from use in Swedish hydro power stations. It is not possible to conclude which of the two software products is better since they are so different.

New sensors measuring variables that is not measured today is needed to expand the ability of the monitoring systems to detect faults. By introducing smoke detectors in the measuring equipment it will be possible to detect faults that produce smoke. To decide which type of smoke sensor to install the smoke developed from faults in hydro power stations need to be investigated.

Ultrasonic detection equipment is not available for continuous monitoring today since the signal has to be interpreted by the human ear to give trustworthy results. However this technology can give a lot of information about faults in bearing systems and it makes it possible to detect electric discharges because electric discharges emit ultrasonic sound at emission.

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Appendix I

Measurement points available in @ptitude Observer

Vibration

The vibration measurement point is a measurement of a dynamic signal such as vibration sensors, AC current, or any other dynamic signal that could change at a frequency faster than 0.1 Hz.

Envelope

This is a measurement of repetitive frequencies. It is used to detect and monitor repetitive frequencies, which is important in bearing failure detection and monitoring.

Harmonic

This is a measurement of a dynamic signal with vibration sensors or eddy current probes.

Process Fast Fourier Form

This is a measurement point similar to the vibration measurement point, but instead of a dynamic signal, it uses an analogue sensor for the measurement. For example it can be used for motor current analysis.

Process

This is a measurement of a static/process signal such as load sensors, temperature sensors, pressure, flow or any other static signal.

Speed

This measurement point is used to measure rotational speed of the shaft. It uses a speed pickup sensor for the measurement.

Digital

This is a measurement of an input that reacts like a digital signal. This means that the input signal basically has only two states: a digital 1 or a digital 0. This measurement point can be used to control when to take trend vibration data and when to take spectrum data.

Shaft centreline

This is a measurement that uses information from two radial displacement sensors located in the same axial position 60-120 degrees from each other to determine the radial movement of the shaft.

Counts

This is a measurement that counts digital pulse changes which produces a value with the total amount of digital value changes. It can be reset and the value will start from zero again.

Counts rate

This measurement point creates a new channel that counts pulses per hour on a digital channel. This measurement point can also be used to measure a particle counter.

Derived point

This is a measurement point that uses measurements from other measurement points to calculate the result to trend.

Torsion

This is a measurement point that uses two digital channels to measure the torsion of a shaft.

Time difference

This is a measurement point where the time difference between two digital channels is measured.

OPC

This is a measurement point that is used when the system requires data from an external system with help of an OPC server.

SW (softwear) speed

This is a manual speed point with static value.

SW (softwear) derived

This is a general measurement point. A derived measurement is a calculation point that uses other measurement points to calculate what to trend. For example, you can trend the sum of all vibrations of a machine or the average efficiency of four different turbines. This derived measurement point can take data from measurement points with sensors and from an OPC measurement point. The measurement value is calculated in the @ptitude Observer Monitor every 10 seconds.