HydroCord Condition Monitoring System

Erik J. Wiborg (erik.jacques.wiborg@statkraft.com)
Dr. Håkon H. Francke (hakon.francke@fdb.no)
Prof. Torbjørn Nielsen (torbjorn.nielsen@ntnu.no)

June 10, 2016

Trollheim Power Plant in Norway is being equipped with an experimental condition monitoring system called HydroCord. The measurement system is complex and designed to monitor a large number of characteristics, notably and maybe most importantly, the turbine runner hydraulic efficiency. Through the use of an automated stability control, the efficiency will be continuously computed when the stability criteria in the waterway are met. Because of the size and complexity of the HydroCord system, this paper is restricted to only present the systems main ideas and concepts, it's goals and benefits, along with some results from an early correlation analysis of the newly acquired data.

1 Background

Condition monitoring is a well established tool for optimizing maintenance on industrial equipment, increasing efficiency and profitability [1]. Countless standards and guides exist on the matter. As of May 2003, there where 98 published ISO standards related only to TC108, the technical committee guiding standards for machinery vibration monitoring and analysis.

Hydropower is no exception, with numerous research papers published world wide (e.g. [2], [3] and many more). The Norwegian research institution SINTEF started a project in 2014 who's goal was to collect state of the art in hydro power condition monitoring technology and methods [4].

All the systems are aimed at establishing a good monitoring system for the mechanical equipment. Some, like the HAICMON hydro system (HAINZL, see www.hainzl.at) integrate damage detection systems (in this case a cavitation detection system). Most are however, as the name implies, systems aimed at providing data to optimize maintenance and survey only the condition of singular vital components in the production system. The HydroCord system stands out as it is designed not only to assist the maintenance process, but also the production planning through a holistic view of the power plant.

This paper aims to present the system, its benefits and presenting some early results and discussions.

2 The HydroCord monitoring system

2.1 The project - aim and scope

Trollheim power plant is a single unit 130MW Francis type power plant situated in Surnadal, Norway. The Norwegian power production company Statkraft initiated in 2010 a research and developmental (R&D) project aiming at the design, production, installation and testing of a condition monitoring system (later named HydroCord), lead by the author of this paper.

The system was designed to support both Statkraft's production and maintenance units. This would be done in several ways, listed bellow are three of the main goals of the system.
- Supplying vital information as input for Statkraft's models production planing and hydrological prediction
- Supply useful information to plan refurbishments of major components
- Warn the operators and the maintenance crew of damaging behaviour to the runner during operation.

Flow Design Bureau (FDB), greatly involved in the initiation and realisation of the main ideas and hypothesises behind the system, where selected as suppliers for the system.

A study was undertaken to list the main characteristics needed to optimize production and maintenance, a study leading to a list of desired continuous measurement. First and foremost a good monitoring of the flow (and thereby the runner hydraulic efficiency) proved to be in high demand. Most of the measurements, now part of the HydroCord system in Trollheim power plant, are listed bellow.

- Hydraulic efficiency of the runner
- Water flow through the power plant
- Headloss measurements in the tunnels and penstock
- Dynamic pressure measurements in the system waterway
- Cavitation intensity measurements
- Sand transporting indexing
- Turbine pressure pulsations
- Grid frequency
- Turbine floor sound frequency
- Water temperature through the system and downstream
- Water turbidity measurement

As is probably quite apparent, some of the measurements listed will not be vital for the operation and maintenance optimization, but where added to gather experimental data for future R&D projects. Many of the listed measurements are in fact values computed from sets of single point measurements. The list of these single point measurements is provided in the next section.

2.2 The system

2.2.1 General description

Much like the spinal cord, the HydroCord was designed to relay signals from the sensors, placed through the whole body of the hydro power plant system, through a high speed fibre network to a "main brain" for processing.

Data acquisition hubs are placed in five positions through the power plant system as

shown in figure 1. At the time of writing, most of the sensors are in place and supplying data to the system. Note that the figure is only an illustration of a generic power plant and should not be considered as a scaled visualisation of the Trollheim Power plant. All data is relayed to the control room hub containing a processor for data analysis and computation. The raw and processed secondary data is stored locally in a network-attached storage system (NAS). The distribution of the data beyond the local system is discussed in section 6.
Added to the control room hub is also a human machine interaction system (HMI). The HMI, still under development at the time of writing. It should provide navigation options through the collected data, displaying key figures and graphs with historic data for visual inspection of trends.

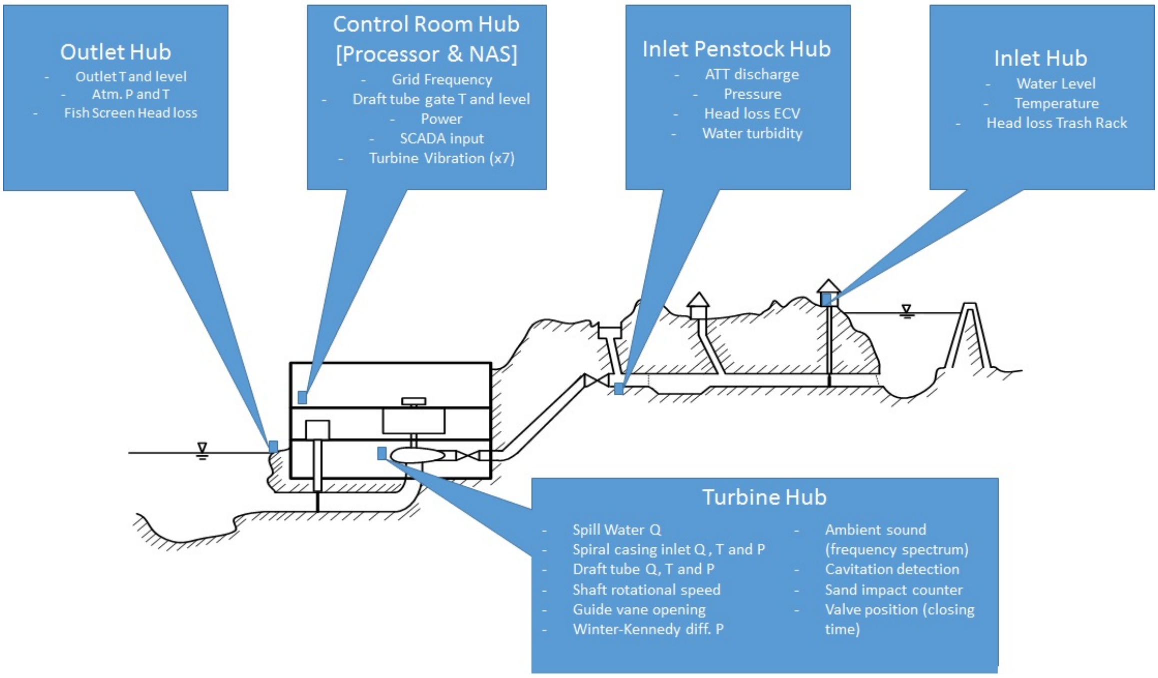

Figure 1: **HydroCord system overview**
Five data acquisition hubs are place in different geographic locations, all communicating through a fibre based network. The control room hub is also ecquiped with a processor for analysis and computation and a network-attached storage system.

The HydroCord software is entirely programmed in LabView and was designed to be scalable. Future installations on other power plants will most likely vary in terms of which characteristics need monitoring, and to easily provide a tailored solution for new installations an appropriate software architecture had to be devised. The general idea behind the programming was to design a generic base (including standardised code for data storage, communication, averaging, and so on), and connected to the base code, a set of smaller optional software modules (applications) performing more specific processing routines (ranging from computation of the hydraulic efficiency to an alarm application for high surge chamber level). This design provided a time saving ease of scalability, while at the same time made the code uniformed and easy to work with. These benefits where proven on several occasions during the Trollheim project lifetime.

2.3 Flow measurements

The discharge, vital for computing the efficiency, and a highly valued characteristic by the hydrological department, is measured in several ways listed bellow. By comparing the results, the condition monitoring system will be able to detect errors in measurements or indicate if a discrepancy exist between them, notifying the owners of the system that a measurement error exist or that some of the equipment requires recalibration.

The Winter-Kennedy measurement is a relative measurement that once calibrated should provide a solid measure of the flow through the turbine. It is described in the IEC41, section 15.2. The main benefits of the method is its ease of implementation and low cost (with only a differential pressure measurement needed). At the same time, it is placed close to the runner and therefore displays a good indication of the flow and hydraulic conditions of the turbine, compared to some of the measurements listed bellow.

The Acoustic Transit Time (ATT) measurement is placed upstream the emergency closing valve (approximately two diameters upstream). The placement is not ideal, but in view of the available placements it was the only option. This measurement was the most interesting because of its presumed high uncertainty, and because of the less than ideal placement. The benefits, should this measurement prove to be reliable, would be great. For Trollheim, as it is the only direct measurement of the discharge it would represent a good way of controlling the other methods validity over time. For future installations, since the equipment is relatively cheap, and easy to place, it would make an excellent option to the Winter-Kennedy method should the spiral casing be out of reach (embedded in concrete) for future installations. Also for a mobile version of the HydroCord system, this would be the preferred method, as it would not need calibration (as long as the internal diameter of the measurement section is known). For more information on how the method work refer to e.g. the IEC41, appendix J.

Finally, as a third option for discharge estimation, head loss measurements will be used. Once calibrated (head loss coefficient k known) the flow can be estimated by the simplified head loss equation 1 (a simplification of the Darcy Weisbach equation, see e.g. [5]).

$$\Delta H = kQ^2 \tag{1}$$

This is of course assuming the head loss coefficient is constant, which is not the case over time. A self calibrating routine will have to be set up to re-assess the k-values at a certain frequency (estimated twice a year). Because of this, the flow estimation will only be used to verify coherence in data over shorter periods of time, and will not be used for long-term evaluations.

A correlation analysis was performed to compare the three types of measurements. It is presented in section 3.

2.4 Continuous efficiency measurement

The main issue with a continuous efficiency measurement is the fact that it must be performed during normal operation. To provide a usable efficiency estimation, the uncertainty must be reduced to a minimum. This is usually done by sampling the required data over a long period. During normal operation the turbine is subjected to regulation (primary, tertiary, and for some power plants also secondary). Every load shift provokes the birth of a pressure oscillation through the system that would potentially cause false measurements.

To ensure that the efficiency is computed based on steady measurement conditions an automated validation system had to be set up. The validation would have to reject measurements during transient states, but accept and deal with the long lasting oscillations present in the datasets after a larger shift of the flow (typically after tertiary regulation). The method devised during the main authors PhD will be presented in his thesis, but some of the basic concepts where presented in an earlier conference [6].

In brief the validation system loops through three steps. The first rejects measurement series containing fluctuations or with unstable running means. If accepted, the second step checks if the data in normally distributed. If it is, the data is accepted for further computation of the efficiency. If not, the data is subjected to an FFT-based surge extraction process removing the sinusoidal component of the the data with the highest amplitude. Once the oscilatory component removed, it is resubjected to the three steps of the validation process.

The validation system has been tested thoroughly and is ready for implementation to the Trollheim HydroCord system.

Both the Winter-Kennedy differential pressure, the ATT flow measurement, and all other pressure measurements relevant for the computation of the efficiency of the runner will be subjected to the validation method. This means that the continuous efficiency measurement will not have a static frequency, but will provide data only during steady condition, ensuring good quality measurements at all time.

Once the quality of the measured data ensured, the data will be plotted continuously in the turbine Hill-Chart. It is expected that after a years worth of measurements, the Hill-Chart will be fully updated. It will then be saved, such as it is, and be used for visualisation in other application (see section 4.2). The newest Hill-Chart will at any time be the one displayed and used by the system. The outdated charts will be stored for R&D purposes (see section 6).

3 Testing the system

To fully test and calibrate the HydroCord system a thermodynamic field efficiency measurement is planned to be performed on site. It will provide the means to verify the measured results and to evaluate static and semi-static characteristics needed for the Winter-Kennedy efficiency measurement and head-loss measurements.

At the time of writing the calibration test has yet to be performed, and as such only the results of a correlation analysis of the three flow measurement methods presented in section 2.3 can be presented. It is important to note that we therefore only can test the signal variations and not their actual value. Discrepancies are to be expected between the different datasets, but the correlation analysis will show that that the samples have a linear relationship with each other.

The correlation coefficient between two datasets is defined as in equation 2.

$$corr[X,Y] = \frac{cov[X,Y]}{\sqrt{var[X]var[Y]}} \tag{2}$$

With the covariance estimated as in equation 3.

$$cov[X,Y] = \frac{1}{n}\sum_{i=1}^{n}(x_i - \bar{x})(y_i - \bar{y}) \tag{3}$$

Where n is the dataset size, and x_i and y_i the index i value of datasets X and Y.

The correlation coefficient, ranging from -1 to 1 quantifies how much two samples change together, i.e. if two datasets have a covariance of 1 they are perfectly synced and experience the same variances. If two datasets have a covariance of -1 they are 180 degree out of phase and vary equally in the opposite direction from one another.

The graphs presented in figure 2 are normalized values (displayed in percentage of the datasets highest recorded value during the measurement period) to help visualize the correlation between them. The values are the recorded flow from the ATT (red), the square root of the differential pressure from the Winter-Kennedy measurement (green) and the square root of the head loss measurement (red - differential pressure over the emergency closing valve).

The correlation matrix is displayed in table 3. There is an excellent correlation between the head-loss measurement and the ATT method. This is not surprising as they are geographically very close. The correlation coefficient between the Winter-Kennedy method and the two others is 0.8, which would indicate that other factors influence the measurement.

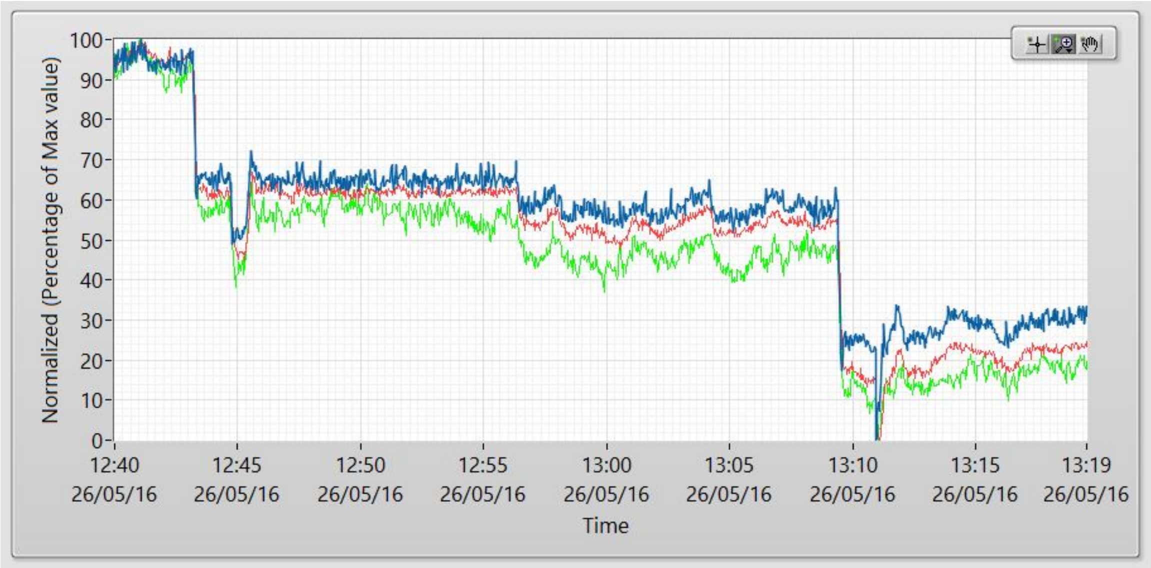

Figure 2: **Normalized raw values for correlation analysis**
Data subjected to a correlation analysis used in the determination of the flow, using three separate methods. Red: ATT, Blue: Head-Loss, Green: Winter-Kennedy

	Winter Kennedy	ATT	Head-loss
Winter Kennedy	1	0.79	0.79
ATT	0.79	1	0.99
Head-loss	0.79	0.99	1

Table 1: **Correlation analysis results**
The correlation analysis results corresponding to the values displayed in figure 2

Adding the guide vane opening to the correlation analysis, the coefficient of these values with the square rooted Winter-Kennedy measurements was 0.99, while the correlation with the two measurement near the emergency closing valve was 0.80. Again, these results are not surprising because of the geographic situation, and correspond well with the results of the first analysis.

Another interesting analysis was the influence of the grid frequency on the flow, i.e. the effect primary regulation has on the flow in the power plant. Figure 3 displays the data

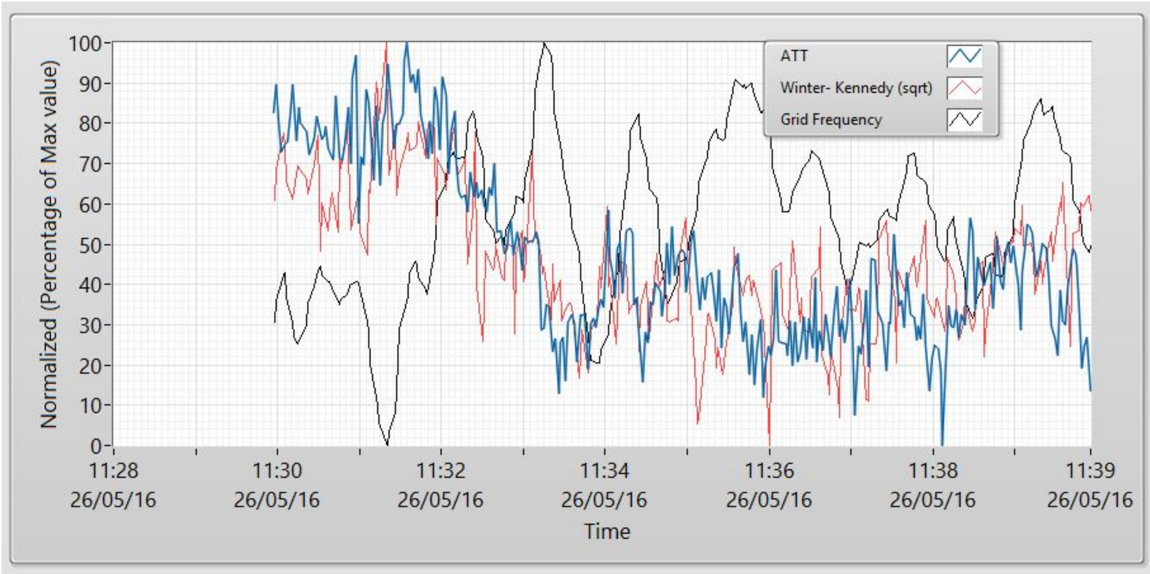

Figure 3: **Normalized raw values for correlation analysis - Grid influence** Similar data as those presented in figure 2, but aiming at evaluating the influence of the grid on the flow. Black: Grid frequency, Blue: ATT, Red: Winter-Kennedy

selected. The correlation coefficients of the frequency with the squared Winter-Kennedy differential pressure and the ATT discharge measurement where, in order, -0.32 and -0.27. Both coefficients indicate a significant influence. This indicates that primary regulation (or frequency variations in the grid) do influence the guide vane, and in turn the flow in the power plant waterways. This is a confirmation that a validation system is required for continuous efficiency measurements. Large fluctuations in the grid will most likely cause fluctuations in the flow, disturbing the efficiency measurements.

It could seem that the ATT measurements are less influenced by primary regulation than the Winter-Kennedy measurements. Repeating the correlation test with other datasets revealed the same pattern, with a varying degree of correlation to the grid frequency, but always higher with the Winter-Kennedy than with the ATT.

4 Benefits of the HydroCord system

4.1 Benefits for maintenance

Condition monitoring system are, as mentioned in the introduction section 2.1 usually installed to support the maintenance of the equipment in question. This is of course the case for the HydroCord as well. However the focus has not been on components usually monitored like the shaft, bearings, generator or transformer. Commercially available systems already exist for that. The focus has been on providing specific hydro power related data, such as cavitation intensity, head-loss coefficients and of course the runner efficiency. Monitoring the runner efficiency is not novel in its self, but the low uncertainty through the use of the validation process, and the vast amount of parallel measurements performed, makes the system quite unique.

Stakraft is in the process of upgrading its maintenance scheme. Up until now the maintenance has usually been either frequency based or based on low frequency condition assessments (e.g. efficiency measurement are done every tenth year or more). Prediction based maintenance is a more efficient and economically sound scheme, however the prediction models will need to be fed data describing the condition of the system. Most of all, the HydroCord system aims at providing information to optimize refurbishment timing for some of the larger components of the system (i.e. the runner, the penstock or the tunnels). Weeks of down time for a power plant are very costly, and ensuring that the project is initiated at the right time will have large financial benefits. As an example, the gain from delaying the refurbishment of one of Statkrafts largest runners with one year could be in the order of two million Euro. High uncertainty to the condition and the evolution of it gives poor basis for the refurbishment planing.

As previously mentioned, new installations of the HydroCord system are to be tailored to the power plant in question. This means that through input from the local staff, all measurement of interest to the maintenance team will be added. As an example, the next implementation of the system is in one of Statkrafts power plants where the part load draft tube vortex heavily damaged the draft tube walls. To notify the dispatch centre of damaging conditions, vibration measurements of the draft tube will be added. Some power plants may have a history of problems with a certain bearing, if that was the case a temperature measurement of the oil, and a differential pressure measurement on the filter would be added.

4.2 Benefits for production planning

Statkraft production planing staff relies on models to help optimize the production of the machine portfolio. The model is based on a number of characteristics, one of them is the efficiency of the turbines. After field efficiency measurements are performed the models are updated. But as mentioned in section 2.4, they are performed every tenth year or more. The models base their calculations on outdated values most of the time. Also, when performing a field efficiency measurement the resulting efficiency curve is only valid for a certain head range. A yearly updated Hill-Chart provided by the HydroCord system would ensure valid efficiency curves for the models to base their calculations on.

To prevent damaging the runner technical restrictions are applied to the production. Overload and part-load, for francis turbines in particular, have a heavy life time reducing effect (see e.g. [7]). The two major damaging mechanisms are cavitation, usually occuring at high loads, and heavy draft tube pressure pulsations, usually at part load. Setting technical restrictions has up until now mostly been done through rules of thumb and subjective human interpretation of sound and vibration in the power plant. Another factor to take into account is that because of head variations, the mechanisms may very well appear at a certain power production level in some cases, and be non-existing when the head is significantly different (and visa-versa).

Providing a yearly updated Hill-Chart would in itself be extremely useful to update production models. If the chart also mapped actual damaging Head/flow areas, new technical restrictions based on actual cavitation (for the detection system, see [8]) and pressure pulsation measurements would ensure valid technical restriction and enabling the full use of the runners flexibility.

4.3 Benefits for research and development

To the authors knowledge, no hydro power plant is monitored to the extent that Trollheim power plant is today. The amounts of data collected will be vast, not necessarily compared to other industries, but for Hydro Power these data files should represent a great potential for future and ongoing use in R&D projects.

Naturally the data collected will be used by Statkrafts own analysis group, but to help the global community, some of the data will be publicly released. All data generated during a weeks production, along with datasets from special events (grid failure, emergency shut-downs, and so on) will be available from Statkrafts home page. The release date is expected to be end 2016 - beginning 2017. A collaboration project with the Norwegian University of Science and Technology (NTNU) and the Norwegian Hydro Power Centre NVKS will be started by the end of 2016 to help coordinate R&D projects related to condition monitoring or heavily based on the collected data from the HydroCord system.

5 Discussion

The results displayed in this paper are still inconclusive to the well functioning of the HydroCord system when it comes to efficiency measurements, however the correlation study shows promise, and may have revealed some interesting facts about the different methods strong and weak points for studies on Hydro Power plants.

As we have seen good correlation exist between the Winter-Kennedy approach and the guide vane opening. An equally good correlation exist between the head-loss based estimation of the flow and the ATT measurements. The correlation between these two sets of measurements is acceptable, but it seems that the Winter-Kennedy and guide vane opening are influenced by other factors, as it displays more erratic behaviour than the ATT measurements (see 2). The difference in water velocity and regulator hysteresis may explain some of the differences.

Considering these results, an important question still remains unanswered. Should the ATT values or the Winter-Kennedy flow measurements be used in the efficiency computation? This is of course a subject for discussion, as the Winter-Kennedy measurement shows a more accurate picture of the flow through the turbine (because of its geographical position). On the other hand, the more steady measurement conditions of the ATT could ensure lower uncertainty to the end result (less influence visible from primary regulation for example, see section 3). The uncertainty evaluation of the measured results will be critical in the assessment of which method should be used.

6 Future Work

6.1 Field efficiency measurement

A thermodynamic field efficiency measurement (FEM) will be undertaken on Trollheim power plant. The results of the test will serve multiple purposes, i.e. calibrate the Winter-Kennedy measurement. Calibrate the flow estimation based on head-loss, and control/calibrate the flow measurement through the ATT measurement.

The measurement uncertainty will be a major contributor to the uncertainty of the continuous measurement methods for flow, it is imperative that the FEM is done under good conditions.

The results of the FEM and the comparison test are expected to be published as soon as possible.

6.2 Data distribution

Condition monitoring has well documented merits. The HydroCord system will collect data and process it into useful and meaningful values to be used in maintenance, production and research. However, the efforts put into the development of the system are in vain as long as the data can not be communicated in a good way to the stakeholders. Creating translators of the data, to fit the various uses for Statkraft will be key to the success of the project. Although not particularly sensitive, the data must reach the users, and as it is collected at site, security measures must be taken to provide a safe communication out of the local network.

6.3 HMI

The focus of the HMI will have to be user friendliness, as a way to ensure that system actually get used to its full potential. This includes work to make the system intuitive, and pleasing to work with. It includes an ease of access, and tools to provide relevant information in an easy to understand manner. Finally it includes applications to mould the data in a matter that is usefull for all relevant application frequently used by the stakeholders.

The HMI should provide the local maintenance staff with information helpful when performing tasks at cite through a hand-held device.

6.4 R&D projects

Statkraft has already initiated the construction of another experimental system at Trollheim power plant. Its main goal is damping of pressure pulsations at part load (see [9] and [7]). The extensive instrumentation at Trollheim makes the power plant ideal for impact asessements, and to control the effects of the experimental system on the power plant components and waterways.

A future project that the authors hopes will be realised, is a study of the development of the turbine characteristics over time. This could be done by using the collecting yearly updated Hill-Charts, along with the rest of the data gather by the HydroCord.

References

[1] B. Rao, *Handbook of condition monitoring.* Elsevier, 1996.

[2] Z. Lihua, Z. Shuyun, L. Zhong, and Z. Rujun, “Labview-based turbine condition monitoring and fault diagnosis system,” *Water Power*, vol. 3, p. 029, 2010.

[3] Y. Power, G. Neil, E. S. Fouad, and S. Crisafulli, “Advanced condition monitoring of a hydroelectric power generation facility.” [Online]. Available: http://www.rockymug.org/Meridian%20PAM%20Paper%20-%20Asset%20Health%20Monitoring.pdf

[4] SINTEF, “Handbooks on condition monitoring of hydropower plants,” 2014. [Online]. Available: https://www.sintef.no/en/projects/handboker-for-tilstandskontroll-av-vannkraftverk/

[5] A. R. Rao and B. Kumar, “Friction factor for turbulent pipe flow,” *Journal of Indian Water Works Association*, pp. 29–36, 2006.

[6] E. Wiborg, H. Hulaas, H. Francke, and T. Nielsen, “Applied statistical quality control on field measurement data,” International Group for Hydraulic Efficiency Measurement, Tech. Rep., 2014. [Online]. Available: http://www.ighem.org/Papers_IGHEM/392.pdf

[7] H. Francke”, “Increasing hydro turbine operation range and efficiencies using water injection in draft tubes,” Ph.D. dissertation, NTNU, 2010.

[8] J. Ekanger”, “Investigation of the relationship between water quality variations and cavitation occurence in power plants,” Ph.D. dissertation, NTNU, 2016.

[9] E. J. Wiborg and M. Kjeldsen, “Francis at part-load with water injection,” 2012.