MonitorX – Experience from a Norwegian-Swedish research project on industry 4.0 and digitalization applied to fault detection and maintenance of hydropower plants

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1 Introduction

Driven by new "digitalization opportunities" in terms of new, better and cheaper solutions for data access and analysis, Norwegian and Swedish hydropower plant operators are currently testing and implementing new solutions for condition monitoring, fault detection, data collection and storage (incl. SCADA data access), data analysis and visualization. These new solutions will play a key role in the transition from corrective and traditional scheduled maintenance to condition-based and predictive maintenance. To support the operators' digitalization initiatives in the field of fault detection and data analysis, as well as model development and testing, the Norwegian-Swedish research project MonitorX was initiated in 2015.

This paper provides an overview of the activities in the MonitorX project and summarizes the project results. The paper discusses status and trends in Norway and Sweden for data collection and data analysis in hydropower plants. In recent years, several of the plant operators that participate in the project started to use central data collection and analysis systems and platforms. This improved data access, which enables development, testing and implementation of different types of models for condition monitoring and fault detection.

Furthermore, the paper presents an overview of the cases that were conducted in the MonitorX project. To illustrate some of the main findings, three cases are briefly discussed in the paper: a case on detection of rotor faults in hydropower generators, a case on monitoring the condition of drainage pumps, and a case on monitoring the condition of the hydraulic system of Kaplan turbines. The case presentations illustrate the use of different types of models and their data requirements. The cases include both simple and more advanced models. Furthermore, the cases include both models that are built on good physical understanding of the failure mechanisms and failure consequences (physical models) and models that utilize learning and identification of trends and patterns from historical data (data-driven models).

One of the results that MonitorX provided to the project partners is knowledge and information about new concepts related to industry 4.0 and digitalization. The cases carried out in the project demonstrated how these concepts can be applied to optimization of maintenance by using new methods and models for condition monitoring and fault detection. Based on the project results and the experience from the cases, recommendations regarding model development, application and implementation are given.

2 Background

The hydropower industry in Europe is currently in a phase of *digitalization* driven by new possibilities given by cheaper solutions for data collection and storage, cheaper sensor technology and new solutions for data analysis. Concepts and methods such as cyber-physical systems (CPS), Internet of Things (IoT), big data analytics, cloud computing and machine learning are of great current interest, and their industrial use is commonly called *industry 4.0*, the fourth industrial revolution. This provides new opportunities for many of the core businesses in power generation and distribution, including maintenance and asset management of hydropower plants.

The overall aims in maintenance optimization are to increase reliability and availability, reduce the number of failures and thus minimize the costs used for operation and maintenance of the equipment. These aims can be reached by a transition from a corrective to a preventive maintenance strategy with a trend to change from traditional preventive strategies with time-/calendar-based and manual inspections to strategies with condition monitoring and predictive models. This results in a new, predictive and proactive maintenance strategy [1][1]. Digitalization is assumed to be an enabler for this transition.

The hydropower industry in Norway and Sweden has initiated several projects and activities to explore and evaluate the new opportunities that industry 4.0 and digitalization provide them. One of the ongoing and most progressed projects is the research project "MonitorX – Optimal utilization of hydropower asset lifetime by monitoring of technical condition and risk". MonitorX is a joint industry project initiated and led by Energi Norge (Energy Norway – the association for Norwegian utilities and grid companies) in cooperation with Energiforsk (the Swedish Energy Research Centre). More than 20 Norwegian and Swedish power companies participate in the project, as well as several equipment manufacturers and service providers. Furthermore, the research institutions SINTEF Energy Research (Trondheim, Norway), Comillas Pontifical University (Madrid, Spain) and the Norwegian University of Science and Technology, NTNU (Trondheim) are participants. MonitorX started in July 2015 and lasts until June 2019. The project is financially supported by the Research Council of Norway and the industry partners. This paper briefly describes the project activities and summarises the results from the MonitorX project.

2.1 Project overview

The aim of the MonitorX project is to develop models, algorithms and corresponding software prototypes for optimal lifetime utilization of hydropower components based on monitoring of technical condition and risk. Here, *optimal lifetime utilization* means to conduct maintenance and component replacements when required, i.e. not too late, but not too early either. To reach the aim of optimal lifetime utilization, methods, models and algorithms for condition monitoring and early warning of faults are necessary.

The project focus on data analysis models and algorithms was chosen, because one of the starting points of the project was the assumption that sensor and measurement data are basically available (e.g. SCADA data), but not much used for planning and optimization of maintenance and refurbishment. Thus, a project with focus on model and algorithm development is useful to motivate plant operators to accelerate and implement solutions for (online) data collection and analysis.

MonitorX mainly focuses on models for condition monitoring and fault diagnosis based on machine learning and artificial intelligence. The models are currently applied to different practical cases and have been tested together with the industry partners for selected power plants. Thus, the work in MonitorX is case-driven, which means that identification of practical cases and development of the cases with the industry partners is the main approach used in the project.

The MonitorX project started with an initial phase (see Fig. 1) where the status for collection of monitoring data and use of monitoring data in the power companies were analysed and where a list with relevant cases were developed together with the industry partners. Furthermore, an introduction to methods and models for data analysis and anomaly detection was provided. Results from the status analysis can be found in section 3.1. The initial phase was followed by the main phase where the project worked with case development. A case overview and a description of selected cases can be found in section 4. The project is finalized by a summary of the results and lessons learned from the cases, as described in section 5.

Note that MonitorX did not focus on development of systems and platforms for data handling and analysis, such as solutions for data collection and storage. A number of different systems and platforms are available on the market, and it is assumed that these solutions serve most of the current needs, even though further developments may be required, e.g. within system security and interoperability (both towards data sources and solutions for data analysis).

[1] For definitions of different types of maintenance (corrective, preventive, etc.), see EN 13306:2010 [2] and IEC 60050-192:2015 [3].

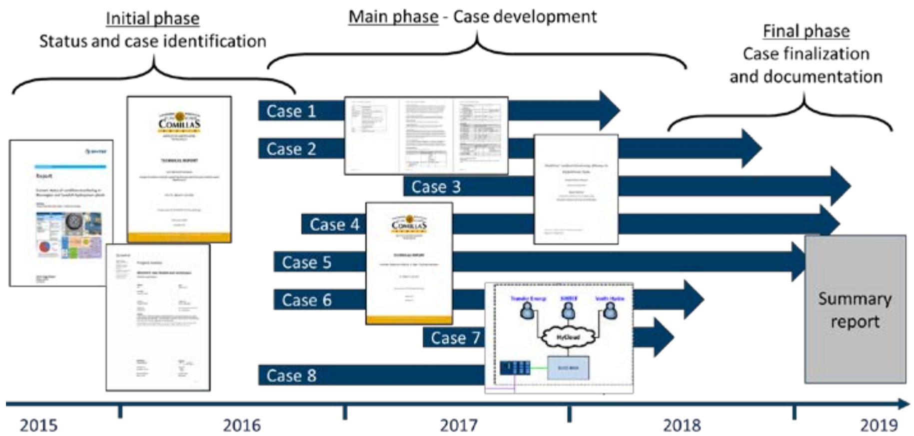

Fig. 1. MonitorX project phases.

3 Status of data collection and use

3.1 Status in the beginning of the project

One of the first activities in the beginning of the MonitorX-project (i.e. autumn 2015) was a survey of the general status for collection of monitoring data and use of monitoring data in the power companies that participate in the project. In addition to interviews with selected project participants, a survey was conducted. Six power companies replied to the survey and some of the results are presented in this section. It is planned to repeat the survey at the end of the project, i.e. in 2019, to identify areas of progress and topics for further research.

The survey was conducted as a set of statements to which the companies could express their agreement or disagreement on a scale from 0 (disagree) to 10 (fully agree). Fig. 2 shows the results where the blue bar is the average of the answers and the green error bars (± 1 standard deviation) illustrate the variation of the answers.

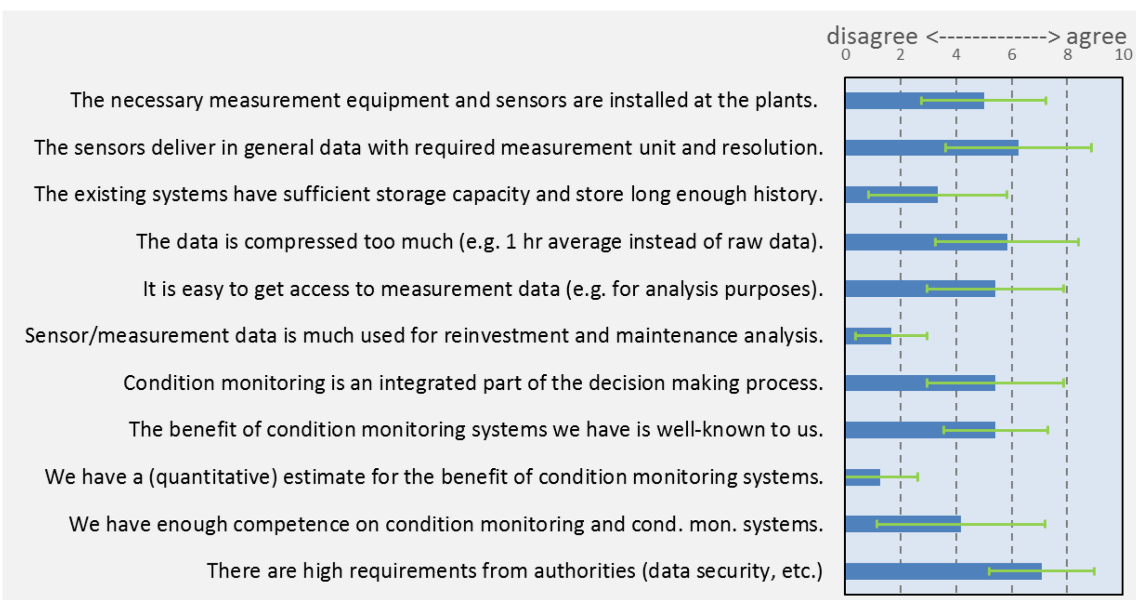

Fig. 2. Results from survey in the beginning of the MonitorX project (autumn 2015).

The companies neither agreed or disagreed completely with most of the statements. This can be because there are some solutions already in use, but that there is need for improvement. For example, most of the companies had access to some monitoring data, mostly via SCADA or via special measurement systems and sensors (e.g. vibration, dissolved gas in oil and dam leakage monitoring). The access via the SCADA system led usually to some restrictions regarding ease of data access (e.g. manual download and transfer required for analysis purposes) and available history and resolution (e.g. low resolution, such as 1 hr average values, and overwriting of data after some time due to restricted storage capacity). The survey clearly confirmed the initial hypothesis for the project that the available data is hardly used for making decisions on reinvestment (i.e. refurbishment and replacement) and maintenance, even though some of the larger companies already started to visualize and analyse data and to use different types of models for data analysis.

An interesting observation from the survey was that the companies partly agreed with the statement that the benefit of condition monitoring systems is well-known to them, whereas they do not have an estimate of this benefit. This indicates a challenge and need for further work within the area cost-benefit estimation of condition monitoring. It is important to mention here that the willingness to invest in monitoring solutions depends on the ability to prove the benefit and return of investment for such solutions. It can also be pointed out that several companies indicated that the authorities have high requirements, e.g. regarding data security.

Most hydropower companies do not have better access to monitoring/SCADA data than the access that the monitoring equipment and the SCADA system itself offers. This means that specific infrastructures or systems for data collection, permanent storage and data access are hardly in use. This also means that monitoring data for analysis must be directly extracted from the SCADA system or from the monitoring equipment, which sometimes may require some work, such as travelling to the plant to copy the data to an external storage device.

3.2 Recent development

In recent years, several of the plant operators that participate in the MonitorX project started to systematically collect monitoring data from their hydropower plants by using a central data collection and storage solution (i.e. a software system or digital platform, called *big data platform* in the following). The overall aim is to establish better access to the data that is already available in various other systems (SCADA, measurement equipment, sensors, etc.) to make the data available for analyses.

To be able to develop, test and implement data analysis models, an integration of data analysis, presentation and visualization of analysis results, and data collection/storage is desired. The automatization of the data stream from sources via storage and analysis to result presentation requires also integration. Thus, the big data platform and the solutions for data analysis and visualization must be integrated. Several plant operators have started to use big data platforms that include solutions for data analysis and result presentation and visualization. Where the analysis is not directly conducted in the big data platform, models or software code developed in data analysis software, such as MATLAB, Python and R, can be called or run from the big data platform. Result presentation and visualization includes hand-hold devices, such as tablets and smart phones, and fault alarms automatically sent by email or SMS.

4 MonitorX cases

The table below shows the MonitorX cases. Some of the cases are carried out in close collaboration with other projects, such as the Norwegian Research Centre for Hydropower Technology (HydroCen)[2] and the Norwegian Hydropower Centre (NVKS)[3]. This section provides a general overview of the cases. Furthermore, results from selected cases will be presented in more detail in the following subsections. Since the project focus was on models and algorithm for data analysis, most cases include model and algorithm development and testing. Nevertheless, one of the cases (case 7) focused on collection of data from the hydropower plant's local control system; see also section 5.1.

[2] HydroCen is a research program within the Research Council of Norway's Centre for Environment-friendly Energy Research (FME) scheme. HydroCen conducts concentrated, focused and long-term research with focus on hydropower technology. See www.ntnu.edu/web/HydroCen for more details.

[3] The Norwegian Hydropower Centre (Norsk Vannkraftsenter - NVKS) is a cooperation between universities, various research institutions, the hydropower industry as well as Norwegian authorities with the aim to ensure and develop research and education in hydropower related technology, see www.ntnu.edu/nvks.

Tab. 1. MonitorX cases.

	Case	Aim	Project partners involved	Comment
1	Rotor fault detection	Develop new methods for online fault detection of generator rotor faults	NTNU, Vattenfall, Eidsiva, Statkraft	Feasibility of new fault detection method successfully demonstrated by finite element method (FEM). Testing of method in laboratory setup planned.
2	Condition monitoring of pumps	Detecting faults and degraded condition of drainage pumps using SCADA data	NTNU, SINTEF, TrønderEnergi, Vattenfall, Voith	Pre-study finalized (2016/2017). Model for pump performance monitoring successfully tested with data from power plant (2018).
3	Condition monitoring headrace tunnel	Developing and testing of new method for headrace tunnel monitoring	NTNU, Andritz, Sira-Kvina	Monitoring method described and evaluated. Installation of equipment partly performed and start of data collection in 2018.
4	Audio surveillance	Anomaly and fault detection in power station by monitoring sound/noise from the hydropower unit	Statkraft, Andritz, SINTEF	Installation of monitoring equipment planned. Test results expected after some months testing.
5	Bearing monitoring	Algorithms for early detection of bearing faults using SCADA data	Comillas University, BKK, SINTEF	Anomaly detection models (temperature model) developed and successfully tested with data from two power plants.
6	Kaplan turbine hydraulic system monitoring	Algorithms for monitoring of Kaplan hub mechanism and hydraulic system using SCADA data	Comillas University, Glitre, Skellefteå	Anomaly detection models tested with data from a run-of-river power plant. Fault that occurred in the plant was successfully detected. Model also implemented and tested with data from another power plant.
7	Transformer monitoring	Identification of abnormal temperature behaviour	SNTEF	Anomaly detection model tested, giving reasonably accurate results.
8	SCADA data collection system	Establish good and continuous access to SCADA data	TrønderEnergi, Voith	SCADA data collection system developed by Voith. System established in power plant (March 2017) and tested for data collection since then. Data used in case 2.

4.1 Case no. 1 – Rotor fault detection

The aim of this case was to propose methods for on-line detection of rotor short-circuit faults and other faults in hydro generators. This case was carried out in close collaboration with HydroCen, and the work was carried out by NTNU postdoc Mostafa Valavi and master student Kari Gjerde Jørstad [4, 5] in close collaboration with the hydropower plant operators and MonitorX industry partners Eidsiva, Vattenfall and Statkraft. In the first stage of their work, an idea was evaluated to use available SCADA data for fault detection. However, simulation of the generator in healthy and faulty state by FEM (finite element method, electromagnetic field simulation) showed that this idea is not feasible. Thus, a new fault detection method was proposed, and its feasibility was evaluated in the second stage of the work.

The new method uses spectral analysis of stator voltage and current for fault detection. The results of the spectral analysis are illustrated for two examples in Fig. 3, where the frequency spectrum of both a generator with healthy rotor winding and a rotor winding with faults are shown. In a case of an inter-turn short-circuit, in addition to the amplitudes at 50 Hz and its odd multiples, sideband harmonics appear at each side of the main harmonics. These sideband harmonics could be used as indicator for fault detection. The method requires a much higher data resolution (voltage or current) than usually available through the SCADA-system, and a sampling frequency of at least 500 Hz is recommended. However, the data collection must not necessarily be continuous, but samples of at least 2 seconds could be collected regularly, e.g. once in a day or week.

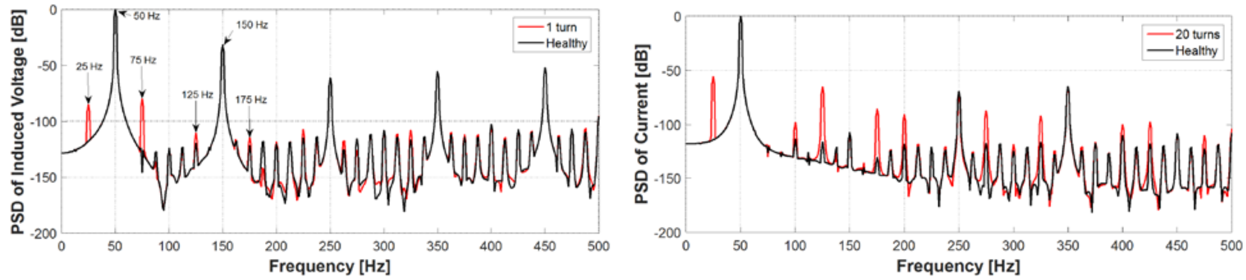

Fig. 3. Frequency spectrum of induced voltage at no-load, healthy vs. 1 turn (left), and frequency spectrum of stator current at full-load, healthy vs. 20 turns (right). Courtesy of K. G. Jørstad [4]. PSD: power spectral density.

The detection of rotor inter-turn short-circuits with the new method was primarily investigated, but also detection of other types of faults, including eccentricity and bearing faults, were included. A detailed description of the work and the results can be found in [4] and [5].

4.2 Case no. 2 – Pump condition monitoring

The aim of this case was to develop and test models for monitoring the performance and condition of drainage pumps in hydropower plants. Even though drainage pumps usually are not considered as the most critical equipment of hydropower plants, they play an important role for protecting the power station from flooding. The drainage system is designed as a redundant system with two or several pumps in parallel, and an ejector as last barrier if all pumps fail. If one of the pumps has failed, it must be quickly replaced to maintain the high reliability of the redundant system, since the reliability of a redundant (i.e. parallel) system drops significantly if one of the components fail.

The drainage system is usually not specifically equipped with sensors and monitoring systems. The information that often is available is the on and off signal for the pumps and/or the water level of the drainage pit. Some other signals, such as the motor current, may be available in some cases. The on and off cycles of the pump result in a quite regular pattern (see Fig. 4) given that the pump and the surrounding systems work faultless. The pump pattern will change when the inflow changes (e.g. due to changed operating conditions of the plant, due to seasonal effects, or due to increased leakage water inflow to the drainage pit from faulty surrounding equipment) or when the capacity of the pump changes (e.g. due to pump degradation) [6]. Thus, the analysis of the pump cycles and the inflow pattern can indicate problems with the surrounding equipment, and the analysis of the pump capacity can indicate problems with the drainage pumps and drainage system.

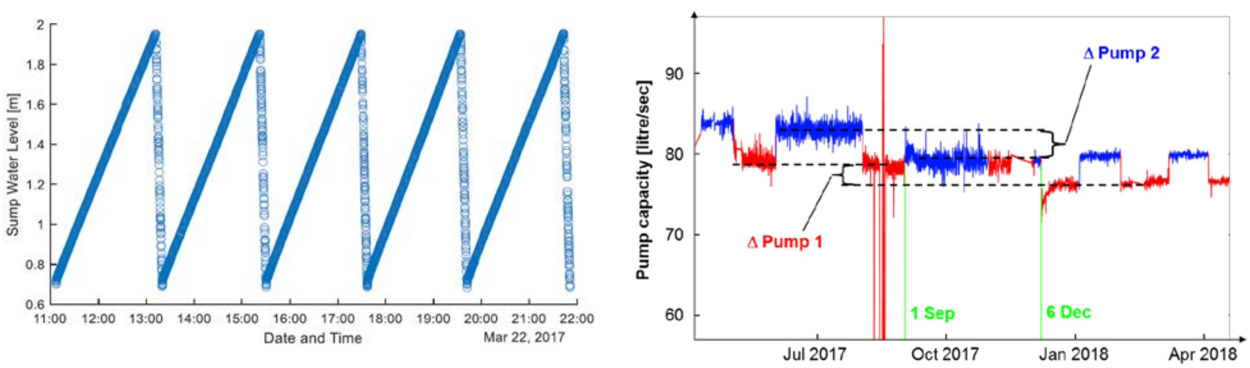

Fig. 4. Raw data, i.e. drainage sump water level (left), and pump capacity (right). Courtesy of K. Prajapati [7].

In a master student project carried out by NTNU master student Kishan Prajapati [7], a model for estimating the pump capacity was developed. This model considers changes of the inflow as a function of different operating conditions. Thus, it can – in addition to detect changes in the pump capacity – also be used for detecting abnormal changes of the inflow. The model was developed and tested with data from Brattset power plant (2 x 40 MW, Francis, head: 273 m) were two drainage pumps are installed. The two pumps are used alternately. The estimated pumped capacity is shown in Fig. 4, where both the estimates for pump 1 (red) and pump 2 (blue) are illustrated. Changes of the pump capacity can be seen at the points in time indicated in the diagram (1 September and 6 December). The pump capacity dropped significantly, by 5 to 7 %. The reason for this is not clarified yet, but maintenance carried out at the plant is a likely cause. Nevertheless, the example indicates that the same approach may be used for detecting pump capacity changes that are caused by degradation of the pumps.

4.3 Case no. 6 – Kaplan turbine hydraulic system monitoring

The aim of this case was to develop algorithms for monitoring the condition of the hydraulic regulation system for a Kaplan turbine using SCADA data. The work was carried out by professor Miguel Sanz-Bobi from Comillas Pontifical University in Madrid, Spain, in close collaboration with the hydropower plant operator and MonitorX industry partner Glitre [8]. Part of the motivation for this work is that the Kaplan propeller and hub is not accessible for inspection during production. A method for online condition monitoring without the need for unwanted production stops is therefore beneficial. The hydraulic system is of special interest as it is vital for the control of the turbine, and because oil leakage is a known issue.

A Kaplan turbine is regulated by adjusting the position of the wicket gates and the turbine runner blades. This is done by a high-pressure hydraulic system, typically consisting of an oil tank, oil pumps, valves, filters, coolers, and accumulator banks for the wicket gates and runner blades. To enable dynamical condition monitoring of this system, a normal behavior model was developed for the level in the oil tank, using artificial neural networks (ANN). Such a model predicts the normal state of a variable, in this case the oil level, from other explanatory variables. Based on a physical understanding of the system, the explanatory variables were here chosen to be the power, the oil tank temperature, and the oil level in the accumulators. Before the model can be used for anomaly detection, the model first learns the normal behavior from carefully selected historic data. Once trained, the model can be used to detect anomalies, i.e. deviations from normal behavior.

Selected results are shown in Fig. 5. The left diagram illustrates the training of the model, and the right diagram testing of the model for anomaly detection. It can be seen that the model accurately predicts the systems normal behavior for the training set (left), and that an apparent anomaly is detected in the test set (right). The increasing deviation between the model (estimated value) and real data (real value) in the test set indicates a possible oil leakage. This was confirmed by the plant operator to be a leakage in one of the accumulators.

The model was also tested by SINTEF on data from the hydropower plant operator and MonitorX industry partner Vattenfall. The test confirmed the ability of ANNs to accurately predict the normal behaviour of the hydraulic system. The ANN model must however be rebuilt and trained for the hydraulic system at hand, showing that significant work is required to deploy such models for multiple turbines, see also discussions in section 5.5.

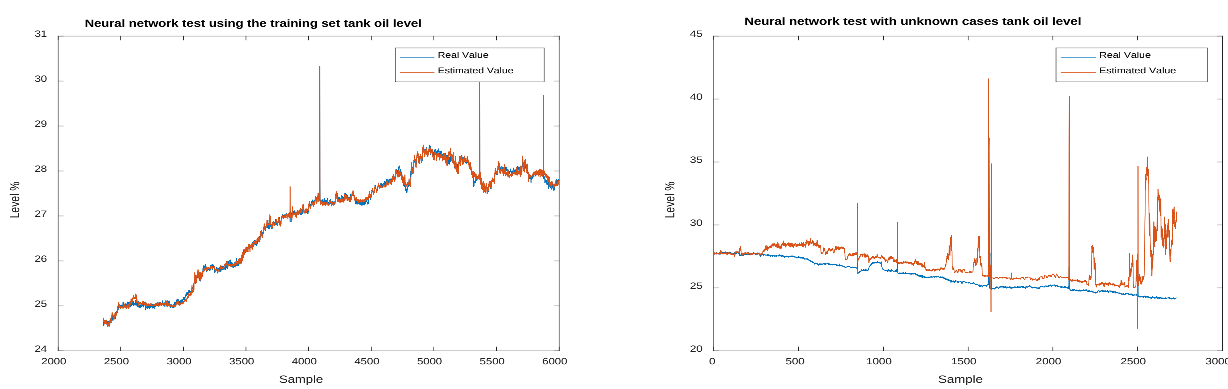

Fig. 5. Estimated value from the ANN model and real measured value for the oil tank level for the training data set (left) and the test data set (right). Courtesy of Prof. Miguel A. Sanz Bobi.

5 Lessons learned

This section summarizes some of the general lessons learned from the project.

5.1 System and platform for data collection and handling

Even though MonitorX did not focus on solutions for data collection and storage, exchange of experience with different systems and platforms was part of the project activities. A central system or platform (big data platform) is one of the requirements for providing effective and easy access to monitoring and sensor data. Thus, the big data platform is an important link between the data sources and the data users. Automatization and continuous monitoring require that solutions (i.e. algorithms, models and software) for data analysis can be integrated in the systems/platforms or can be interconnected, as already discussed in section 3.2.

One of the Monitor cases (case 8) focused on collection of data from the hydropower plant's local control system. The hydropower equipment manufacturer Voith developed a new solution for data access to supply the project with high quality data. The developed solution has been tested in the Brattset power plan, and data for case 2 (see section 4.2) was accessed with this solution.

5.2 Reference designation system

Through the MonitorX project and related activities in the participating companies, experience concerning collection, handling and utilization of data from multiple sources and systems has been gained. A review of existing reference designation systems (RDS) used in the sector found that they were not logically coherent and had not been updated to include new components. The referencing of the elements and systems of the power plants and the signals from various sensors did not follow a coherent system, and there were differences in the labelling (tags) depending on the suppliers of the system and even on the individual programmers that had been involved.

For future digitalisation projects in the hydropower sector, a coherent naming convention or an RDS is of importance. A proposal for a new RDS is therefore currently being developed by a Norwegian working group initiated by Energy Norway. The new system will be based on the principles of IEC 81346 [9] and is scheduled to be completed by February 2019.

5.3 Type of models

In the cases in the MonitorX project, different models and algorithms that are both of the simple and advanced type (as exemplified in Fig. 6) were developed and tested. The models belong both to the group of physical models, and data-driven models and machine learning. See references [10] and [11] for further discussions about types of models, their properties, and their advantages and disadvantages.

As illustrated by case 6 (section 4.3), the machine learning models applied in MonitorX are designed as normal behaviour models. Because hydropower components are often unique designs, there are few of them, and they have a high reliability and long lifetime, learning from historical faults is usually not feasible.

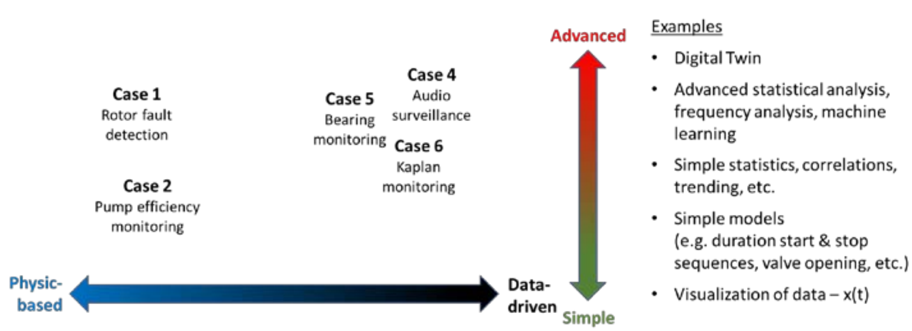

Fig. 6. Types of models and relation to MonitorX cases.

5.4 Type of data and data resolution

The different cases illustrated the requirements regarding data resolution. While case 6 (section 4.3) uses historical data available in already aggregated form as average values from the SCADA system with 1 hr resolution, and case 2 (section 4.2) uses raw data from the plant's control system with approx. 30 sec. resolution, case 1 (section 4.1) requires high resolution data with around 1 kHz sampling frequency. These examples illustrate that the required data resolution depends on the type of model that is used for data analysis. Furthermore, the physical effects and phenomena that are analysed influence the requirements regarding data resolution. Slow effects, such as temperature changes and developments in large technical components that require several hours for heating up and cooling down (e.g. case 5, see Tab. 1), can be modelled with data of low resolution, whereas high frequency phenomena, such as sideband harmonics around and beyond the grid frequency of 50 Hz (see section 4.1), require high resolution data.

5.5 Scalability

So far, the models discussed in this paper have only been developed for individual components. If such models are to be implemented on a large scale throughout an organization, the time and resources needed to do this should be considered. Typically, the scalability (or transferability) is a larger issue for the advanced models than the simple models. For example, the ANN model for Kaplan turbines (section 4.3) must be rebuilt and trained for each turbine, whereas the pump model (section 4.2) may be used as-is for drainage systems with the same sensor measurements available. Furthermore, maintenance-related changes in the plants may influence the model's predictability and accuracy and may require a re-training. Hence, approaches for automatic model training and updating would be helpful.

5.6 Competence requirements

The extended use of digital systems requires an extension of available, or new, resources and competences. More ICT competences and resources are required to carry out the implementation of a big data platform. Furthermore, new resources such as data analysts or scientist might be valuable. One important aspect in this discussion is outsourcing of competence, i.e. to which degree the power plant operator wishes and needs to have new competences inhouse, or if these are bought from external service providers, hydropower equipment manufacturers and consultancies.

6 Summary and further work

This paper presented and summarized the MonitorX project. The background for the project, as well as the project activities and cases and their results, were briefly presented. On the one hand, MonitorX supported the project partners with knowledge and information about new concepts related to industry 4.0 and digitalization. On the other hand, the project provided a set of methods and models for different monitoring purposes. The project demonstrated through practical cases how these concepts can be applied to optimization of maintenance by using these methods and models for condition monitoring and fault detection. Furthermore, the cases demonstrated the practical application of different models and their advantages and disadvantages. Based on these results, various recommendations regarding model development, application and implementation could be given.

The project can be followed-up in different areas, for example, further model development and testing (incl. upscaling, i.e. applying models to all plants and components in a company), testing of models with field data (e.g. model developed in case 1, because until now only tested with FEM), developing of methods for simulation of faults in power plants (i.e. introducing "artificial" and "virtual" faults), development of models for evaluation of cost-benefit of new monitoring and fault detection solutions, and development of standards that simplify the exchange and use of data for different purposes. The latter may include standardization of designation of components, signals, failure modes and failure consequences.

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