



FACULTY OF ENGINEERING AND SUSTAINABLE DEVELOPMENT
Department of Electrical Engineering, Mathematics and Science

Implementation and standardization of vibration measurements in strip production processes

Eddie Ahlin

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Supervisor: Niclas Björsell
Examiner: José Chilo

Preface

I would like to give thanks to all the people involved with this thesis work.

To Niclas Björsell, my supervisor from the University of Gävle, for his help with the reports disposition and consultation regarding vibrations measurements. To Simon Blixt and Torbjörn Petterson, my colleagues at Alleima Strip, for their support and patience in answering all my questions regarding strip manufacturing processes and PLC-programming. To my friends Michael Lukkarinen and Mikael Lindorf, for taking their time reading this report and providing helpful feedback on my writing.

Thank you all!

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Eddie Ahlin

Abstract

Within the era of the fourth industrial revolution the steel production industry is faced with demands of lower environmental impact and more cost-effective production are some of the challenges faced. To achieve more sustainable and efficient manufacturing processes companies try to digitalize and automate their production to a greater extent. Creating more robust, energy-efficient and adaptable solutions to increase the competitiveness of their company.

This master thesis is about reverse engineering an existing solution for vibration measurements used at Alleima Strip. The goal was to create a new in-house solution for vibration measurements according to local programming standards using an ABB AC500v2 CPU paired with a FM502-CMS module. Using vibration measurements as a health indicator Alleima Strip hopes to progress their way of working with maintenance towards being more condition based.

The result is a solution for vibration measurements customized for Alleima Strip. The report contains suggestions for improvements of the developed solution as well as ideas for future work.

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1 Introduction

Within the steel production industry great demands are set upon manufacturing processes and finished products. Demands of lessened environmental impact and more cost-efficient production are some of the challenges faced[1]. To achieve more sustainable and efficient manufacturing processes companies try to digitalize and automate their production to a greater extent. Creating more robust, energy-effective and adaptable solutions to increase the competitiveness of their company. Described by industry 4.0 are predictive maintenance which is one way of working for a more sustainable manufacturing process[2], [3].

1.1 Background

In Alleima Strips machine park there are about 60 different machines which all contain rolling element bearings and some kind of rotating machinery. In the machines where rotating machinery is in contact with the strip, for example in cold rolling mills and grinding or polishing machines, it is of great importance for the quality of the strip that a bearing doesn't break down in the middle of a strip. This could lead to parts of, or the whole strip being scrapped in addition to potentially costly damage to machinery. Therefore, it is of great interest to work proactively with maintenance to avoid unnecessary scrapping of material in these machines. Measuring vibrations in rolling element bearings is an alternative to this way of working Alleima Strip wants to explore further.

Today three different methods are used at Alleima Strip for evaluating a rolling element bearings health condition. The first method is based on experienced personnel inspecting the bearings using a portable device for measuring vibrations. The personnel are then classifying the bearings health based on the measured vibration values. This method is time consuming and yields varying results depending on the personnel performing the measurement and the local premises.

The second method used is to buy vibration monitoring as a service from an external supplier. This is a standalone solution that can be integrated with existing equipment with minimal changes to the machine. This method has the upside of being easy to use for Alleima and doesn't require any specific competences. The downside is that data is collected and used by the third-party supplier and therefore the data can't be used for applications other than what the supplier offers.

The third method used at Alleima Strip is a solution developed for Strip on demand by ABB (Asea Brown Boveri). The solution is a program written for an ABB AC500v2 PLC (Programmable Logic Controller) that can be integrated without changes to existing equipment. The upsides to this method are that Alleima owns their own data and have easy access to the data. The source code is available to Alleima, and they can change the code to their liking. The downside to having the code designed by external personnel is that Alleima lack the competence needed for editing the solution.

During procurement of new equipment for the hardening process, the machine supplier demanded that vibrations were to be monitored by Alleima for the machinery to have a valid guarantee period. The supplier then suggested a fourth method for vibration measurements consisting of a complete solution with smart sensors for vibration measurements which delivers a calculated RMS (Root Mean Square) value through IO-link (Input/Output). Since vibration measurement is an area of interest for other machines as well, Alleima decided to implement their own solution for vibration measurement.

1.2 Problem description

The different solutions to vibration measurements installed have made Alleima Strip dependent on third-party suppliers and have made knowledge about the systems limited within the organization. As an alternative to procuring different solutions for vibration measurements Alleima Strip wants to develop a standardized methodology. One approach is to review and choose one or two suppliers that can provide Alleima Strip with a desired overall solution. Another is to develop an in-house solution.

As a step in developing their own solution Alleima Strip has decided to install necessary hardware for measuring vibrations in their newly procured equipment. The equipment will be delivered with pre-mounted accelerometers for measuring vibrations. These signals need to be monitored by a system and evaluated. Since the most used PLC-system at Alleima Strip is the ABB AC500 the accelerometers will be plugged in to a FM502-CMS (Condition Monitoring System) function module coupled with a AC500v2 CPU (Central Processing Unit).

1.3 Objectives

This thesis will focus on the development of the in-house vibration measurement solution used for Alleima Strips new equipment. The objectives are as follows:

- Develop code for vibration measurements using ABB AC500v2 CPU coupled with a FM502-CMS function module.
- Write the code in a standardized way so that the code can be implemented in existing machines as well as new machines.
- Set up a solution for real time monitoring as well as prepare for storing of historical data.
- Investigate how to initiate vibration measurements in an efficient way.
- Propose suitable health indicators for classifying state of wear of bearings.

A well-functioning solution for vibration measurements would be a step in the direction of working more predictive with maintenance and reduce the unnecessary exchange of potentially healthy equipment. This is in line with working for a more sustainable industry supported by the Global Goals goal 9 industry, innovation and infrastructure as well as industry 4.0 sustainable manufacturing[2], [4].

1.4 Disposition

- Introduction
The introduction intends to give a short description of the background resulting in this thesis work. It will also include information about the problem to be solved as well as the objectives.
- Theory
This chapter describes theory used in the thesis work including vibration theory, vibration measurements and signal processing.
- System
The system chapter will give a short description of the machinery and measurement hardware installed for this thesis as well as describe the software used.
- Process and results
This chapter will describe the implementation and development of the in-house solution for Alleima Strip, how the result was achieved, choices made and reasoning behind them.
- Discussion
In the discussion the results will be analyzed and compared to the presented objectives.

- Conclusion

In this chapter the major conclusions made from the thesis work will be presented as well as suggestions for future work.

2 Theory

This chapter aims to provide the reader with necessary theory for the thesis. Subjects described are maintenance, vibrations, vibration measurements and signal processing.

2.1 Maintenance

Maintenance is something important for companies. All companies have some kind of strategy working around maintenance whether it is working reactively, waiting until the machines break down, or proactively performing maintenance before the machines break down. Reactive maintenance has the upside of optimizing the value of wearing parts with the downside of having unplanned stops in the production. Proactive maintenance has the upside of minimizing the number of unplanned stops in a machine, with the downside of scrapping fully functional wearing parts with a lot of runnable hours left. Predictive maintenance is a way of proactive maintenance that attempts to optimize both the value of the wearing parts as well as the number of unplanned stops in the machine[5].

Predictive maintenance as a concept has been around for some time. The goal with predictive maintenance is to plan the maintenance stops in such a way that maximum value can be achieved from each part in the machine. This is done by basing the machines need for maintenance upon something measurable properties giving an indication of the machine's health status[6]. Such measurable units are often called health indicators. A commonly used health indicator for rotating machines are vibrations[7].

2.2 Vibrations

A vibration in a mechanical system can be described as a swinging motion around an equilibrium point[8]. In machines vibrations occur in moving parts and are a product of imperfections caused during manufacturing, from the design or from wear. One of those moving elements are rolling element bearings[9]–[11].

A rolling element bearing consist of an outer ring, an inner ring, rolling elements and some kind of cage or casing for the rolling elements. Each of these parts are a source for vibrations in machines with rolling element bearings even if no defects are present. The frequencies produced by a rolling element bearing can be calculated given pitch circle diameter, rolling element diameter, shaft rotation frequency and bearing contact angle. The frequencies can be calculated using equations (1)-(4)[7], [9], [10].

$$BPFI = \frac{n}{2} f_r \left(1 + \frac{d_e}{d_p} \cos(\theta) \right) \quad (1)$$

$$BPFO = \frac{n}{2} f_r \left(1 - \frac{d_e}{d_p} \cos(\theta) \right) \quad (2)$$

$$BSF = \frac{d_p}{2d_e} f_r \left(1 - \frac{d_e^2}{d_p^2} \cos^2(\theta) \right) \quad (3)$$

$$FTF = \frac{f_r}{2} \left(1 - \frac{d_e}{d_p} \cos(\theta) \right) \quad (4)$$

where $BPFI$ = Ball pass frequency inner
 $BPFO$ = Ball pass frequency outer
 BSF = Ball spin frequency
 FTF = Fundamental train frequency
 n = the number of rolling elements
 f_r = shaft rotation frequency
 d_e = diameter of rolling element
 d_p = pitch circle diameter
 θ = bearing contact angle

Pitch circle diameter is the distance between the centers of two directly opposite rolling elements. The contact angle is the angle between the plane perpendicular to the rolling elements bearing axis and the line drawn between the points where the rolling element makes contact with the inner and outer raceway[7]. In Fig. 1 is an explanatory image of the bearing dimensions and in Fig. 2 an explanatory image of the bearing contact angle.

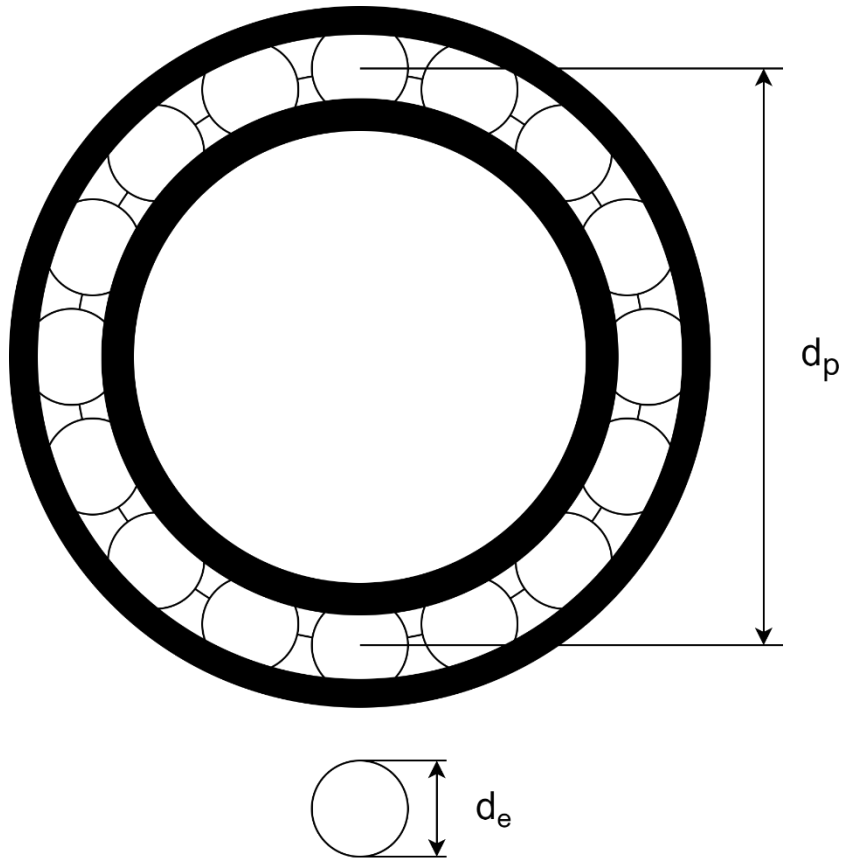


Figure 1 – An explanatory image of a rolling element bearing where d_p is the pitch circle diameter and d_e the rolling element diameter.

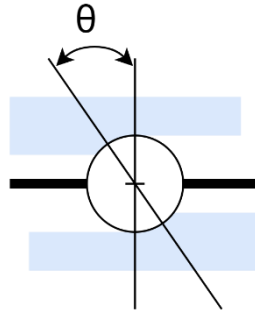


Figure 2 – An explanatory image of the contact angle where the vertical line is perpendicular to the rolling elements bearing axis and the diagonal line is the line between the rolling elements points of contact with the inner and outer raceway.

As the rolling element bearing deteriorate due to wear the levels of vibrations originating from the bearing increase. This can be caused by distributed defects and localized defects. Example of localized defects are pits and cracks. Examples of distributed defects are surface waviness or roughness and raceway defect[9], [10].

2.3 Vibration measurement

Vibrations can be measured in different ways, both with sensors needing mechanical contact with the source of the vibration as well as with optical sensors not needing mechanical contact. Vibration sensors used are displacement sensors, velocity sensors and acceleration sensors[8], [12]. A typical example of a sensor needing mechanical contact is a surface mounted accelerometer and an example of a sensor not needing mechanical contact is a laser displacement sensor[11]. Displacement, velocity and acceleration can be derived from each other. Acceleration is the differentiated function of velocity and displacement is the integrated function of velocity[8].

A machine consists of different moving parts which all generate some kind of frequency. A vibration sensor will therefore not pick up only a distinct frequency from a chosen part but rather a summarized signal generated by all the moving parts in mechanical contact with the measured point or part[13].

2.4 Signal processing

A vibration measurement is rarely enough for determining the condition of a machine or machine part. The signal needs to be processed and evaluated in some way to give useful information. Two approaches is using evaluation techniques in either time-domain or frequency-domain or a combination of both[7]–[10], [14].

2.4.1 Time-domain

In time-domain the signal of the vibration measurement itself is evaluated. To achieve more information, from the signal statistical parameters can be used for the evaluation. The approach evaluating signals using time-domain has been found useful for detecting faulty rolling element bearings but lack the precision to determine what part of the bearing is broken. Some statistical parameters that have had promising results as health indicators for rolling bearing elements are RMS, Kurtosis, Skewness and Crest factor[7], [9].

$$RMS = \sqrt{\frac{\sum_{i=1}^N (x_i)^2}{N}} \quad (5)$$

$$Kurtosis = \frac{\sum_{i=1}^N (x_i - \bar{x})^4}{(N - 1)S^4} \quad (6)$$

$$Skewness = \frac{\sum_{i=1}^N (x_i - \bar{x})^3}{(N - 1)S^3} \quad (7)$$

$$Peak\ value = \frac{\max(x_i) - \min(x_i)}{2} \quad (8)$$

$$Crest\ factor = \frac{Peak\ Value}{RMS} \quad (9)$$

Where S is standard deviation.

2.4.2 Frequency-domain

Using the frequency-domain the idea is to base the evaluation around the frequencies generated by a rolling element bearing described in (1)-(4). The amplitude in these frequencies will increase if a fault is present. Faults may also be indicated by the presence of overtones. Evaluation methods using the frequency-domain will give a good indication for which part of the bearing is broken as well as an indication of the bearing's health[7], [9].

3 System

In this section the machinery where the vibration measurement system was installed will be described in brief as well as the system for measuring the vibrations.

3.1 Machinery

The procured machinery for the hardening process is a machine which polishes the strips to achieve desired surface. The polishing is done by applying a special thick liquid, designed for this purpose, to the strip and rubbing it against the strip surface. The rubbing is done in-line using rotating brushes pushing down on the strip. A sketch of the polishing machinery can be seen in Fig. 3 where the parts labeled 1 are the brushes and the part labeled 2 a strip going through the encapsulation where the brushes are.

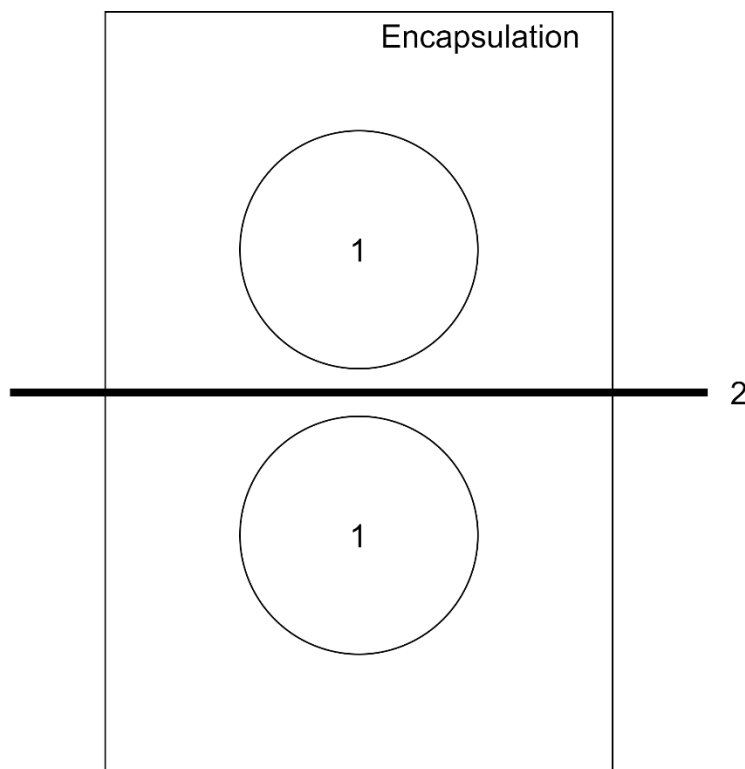


Figure 3 - A sketch of the polishing equipment where the parts labeled 1 are the rotating brushes pushed against the strip. The part labeled 2 is the strip going through the encapsulation where the brushes are.

The accelerometers are mounted in mechanical contact with the bearings on the back of the encapsulation where the shaft from the electrical motors go through to the brushes. A sketch of the back of the polishing machinery can be seen in Fig. 4 where the parts labeled 1 are the accelerometers, the parts labeled 2 are the electrical motors and the part labeled 3 is the encapsulation where the brushes are located.

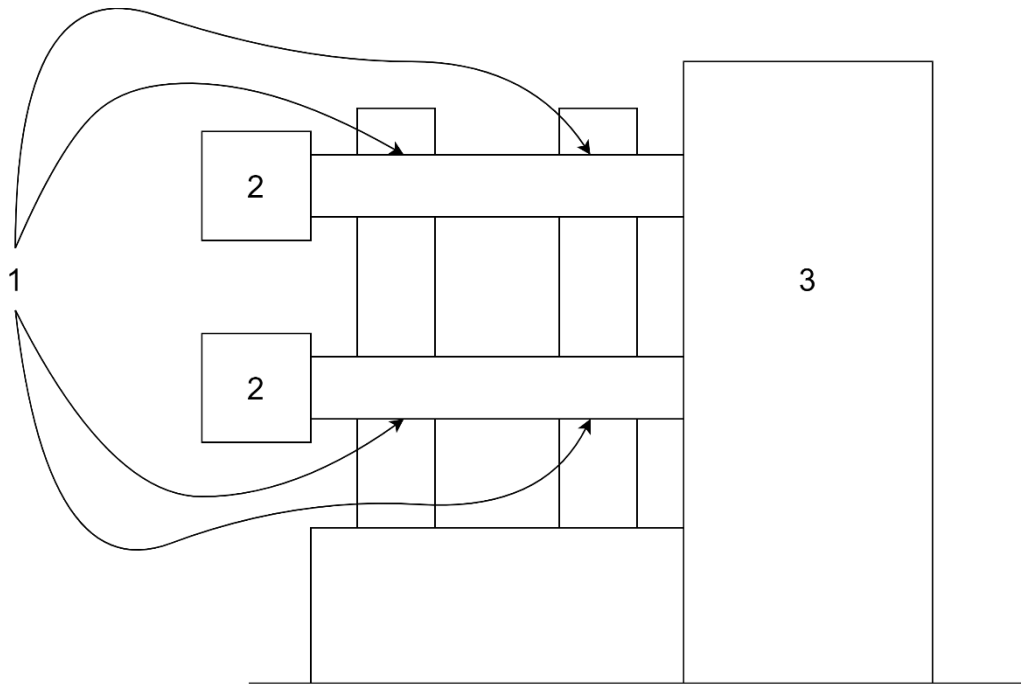


Figure 4 – A sketch of the backside of the polishing equipment where the parts labeled 1 are the accelerometers, the parts labeled 2 the electrical motors and the part labeled 3 the encapsulation where the brushes are located.

As can be seen in Fig. 4 each of the polishing machinery equipments are equipped with four accelerometers. There is a total of four identical equipments installed which gives a total of 16 accelerometers.

3.2 Measurement hardware

The hardware has been chosen and provided by Alleima Strip consisting of a PM592-ETH CPU, a FM502-CMS module, a CM589-PNIO (PROFINET Input/Output) module and 16 accelerometers.

The PM592-ETH is a CPU produced by ABB and are one of their AC500 CPUs in the version 2 line up. The CPU is equipped with a 4 GB flashdisk for data storage and paired with two extension modules[15]. CM589-PNIO module is an extension card for communication. The communication protocol used is PROFINET[16]. The FM502-CMS module is an extension card for monitoring signals with high sample rate. The module is equipped with 16 analog inputs, 2 encoder inputs and 2 digital input/outputs. Each of the analog channels can be sampled at 50000 samples per second. The module can initiate measurements of the channels parallel to the PLC cycles. The measurements are saved to WAV-files, one for each channel, and packed as a ZIP-file. After a measurement is done the ZIP-file will be sent to the CPU[17].

The accelerometers used are of the type CTC AC102 M12A. It's a sensor measuring accelerations in one axis and have a sensor factor of 100mV/g. The sensor supports IEPE (Integrated Electronics Piezo-Electric) signal mode which makes the sensor monitorable by the CPU for wire breakage and short circuits[18]. A descriptive image of the system can be seen in Fig. 5 where the AC500v3 is the CPU controlling the polishing equipment and the AC500v2 CPU is the PLC controlling the vibration measurements.

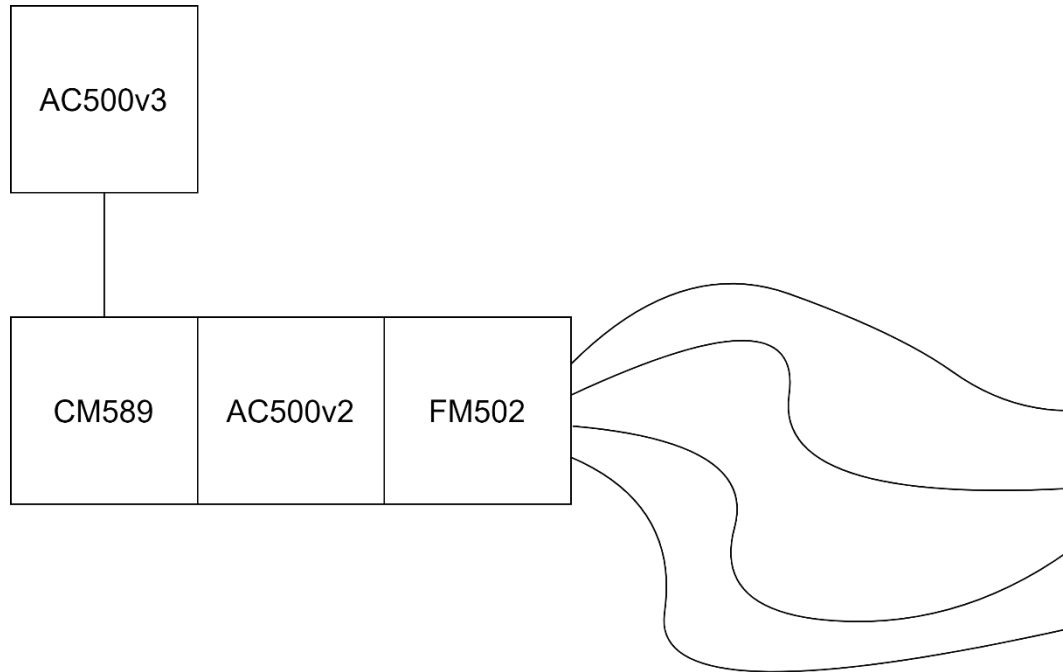


Figure 5 – Descriptive image of the system where the AC500v2 CPU is the vibration measurement system and the AC500v3 CPU the controlling CPU for the polishing equipment.

3.2.1 Software

Software that has been used is ABB Automation Builder. ABB Automation Builder is a computer program used for setting up and configure ABBs AC500 systems. Automation Builder utilizes CODESYS as a programming interface and comes attached with the installation. For signal processing the library SP_AC500_V24_App has been used.

4 Process and results

Since Alleima Strip already has a solution for vibration measurements using the specified hardware there was no need for reinventing the wheel. The new standardized solution has been reverse engineered from the already existing solution with modifications. The project has therefore consisted of two major parts. One part was to study and understand the solution developed by ABB. The second part was to develop the new standardized solution for vibration measurements. The solution developed by ABB will be broken down and explained in chapter 4.1 and the new solution will be explained in chapter 4.2.

4.1 Existing solution

The solution developed by ABB is installed in a cold rolling mill at Alleima Strip and is in use today. The solution consists of a configuration part and a program part. The configuration is set up in Automation Builder. The system consists of a PM592-ETH CPU, a FM502-CMS module, a CM589-PNIO module and 14 accelerometers. The system is also set up as an FTP-server to enable the transferring of ZIP-files. Each channel in the FM502-CMS module has the option for individual configuration. All the channels are however configured in the same way with a sample rate of 12,5kHz and a record length of 50000 samples. To be able to monitor sensor faults measurement mode is set to IEPE mode. Since the cold rolling mill is controlled from a second CPU the CM589-PNIO module is for communicating with that CPU through PROFINET.

The program is written in CODESYS using structured text and have three different modes for measuring vibrations. The measurement can be started manually, automatically on timed intervals or automatically when a peak value with high enough amplitude is measured from one of the accelerometers in real time. The options used today are measurements triggered manually and measurements triggered on timed intervals. The mode is determined in the PLC controlling the cold rolling mill and are sent to the vibration PLC through PROFINET.

4.1.1 Program sequence

The program is basically one sequence for file handling and measurement and three different functions executed each PLC cycle. The three different functions are for file name generation, sensor surveillance and PLC flashdisk monitoring. A flow chart of the PLC cycle can be seen in Fig. 6.

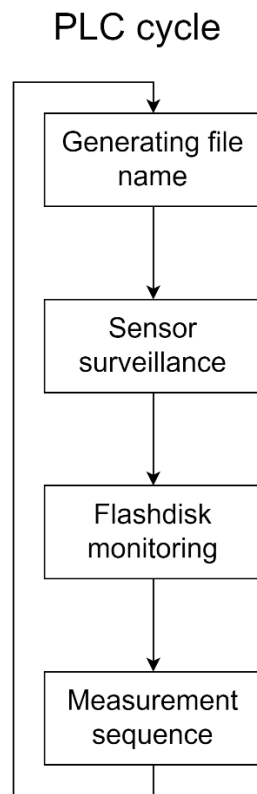


Figure 6 – Flow chart describing the PLC cycle in the solution developed by ABB.

The generated file name is based on the current date and time on the format ddhhmmss. Sensor surveillance keeps track on the PLC diagnostics and scans for alarm codes indicating a wire break or an enabled input being unplugged in the CMS module. A pseudocode describing the sensor surveillance can be seen in Fig. 7. The flashdisk monitoring is keeping track on the number of ZIP-files stored on the flashdisk. When the number of files exceeds 500 the oldest file is located and removed.

```

Read active error codes from the CPU and store in an array
For all the error codes in the array
    If error code is one of the sought error codes
        Store sensor position in output
    End if
End for
  
```

Figure 7 – Pseudocode describing the sensor surveillance function. each bit in the output represents a sensor position. Bit one sensor position one and so on.

The measurement sequence is started when the requirement for a measurement is met. These requirements are when the measurement mode is set to automatic, and the time elapsed since the last measurement exceeds 20 minutes or when a manual measurement is requested. The generated file name is then sent to the CMS module together with a start signal.

When the measurement is done the next step in the sequence is to unpack all the WAV-files in the generated ZIP-file. When the unpacking is done the flashdisk is scanned through for all the files with an ending of .WAV. Those file names are paired with each corresponding channel and stored in an array. The array is then used as an input for the signal processing which is the last step of the sequence. A flow chart of the measurement sequence can be seen in Fig. 8.

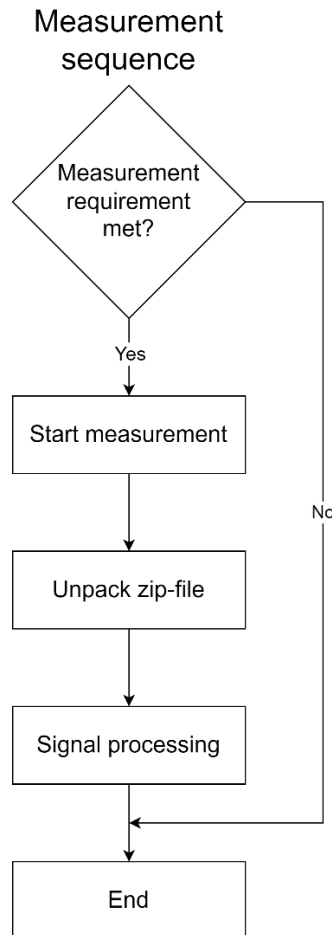


Figure 8 – Flow chart describing the measurement sequence developed by ABB.

The signal processing is different based on the type of sensor used. The types supported are acceleration sensors, velocity sensors and displacement sensors. For an acceleration sensor the signal is scaled to represent values in mm/s^2 , eventual offset is removed, the signal is integrated, eventual new offset is removed. A FFT (Fast Fourier Transform) of the signal is calculated, the FFT is filtered removing frequencies higher than 1000Hz and lower than 10Hz and lastly the RMS value is calculated from the filtered FFT signal.

For a velocity sensor the signal is scaled to represent values in mm/s and eventual offset is removed. A FFT of the signal is then calculated and filtered in the same way as for the acceleration sensor resulting in a RMS value.

For a displacement sensor the signal is scaled to represent values in mm, the signal is then differentiated and eventual offset is removed from the differentiated signal. A FFT of the signal is then calculated and filtered in the same way as for the acceleration signals and velocity signals resulting in a RMS value. A flow chart of the signal processing for the different types of supported sensors can be seen in Fig. 9. When the signal processing is done the unpacked WAV-files are removed from the flashdisk.

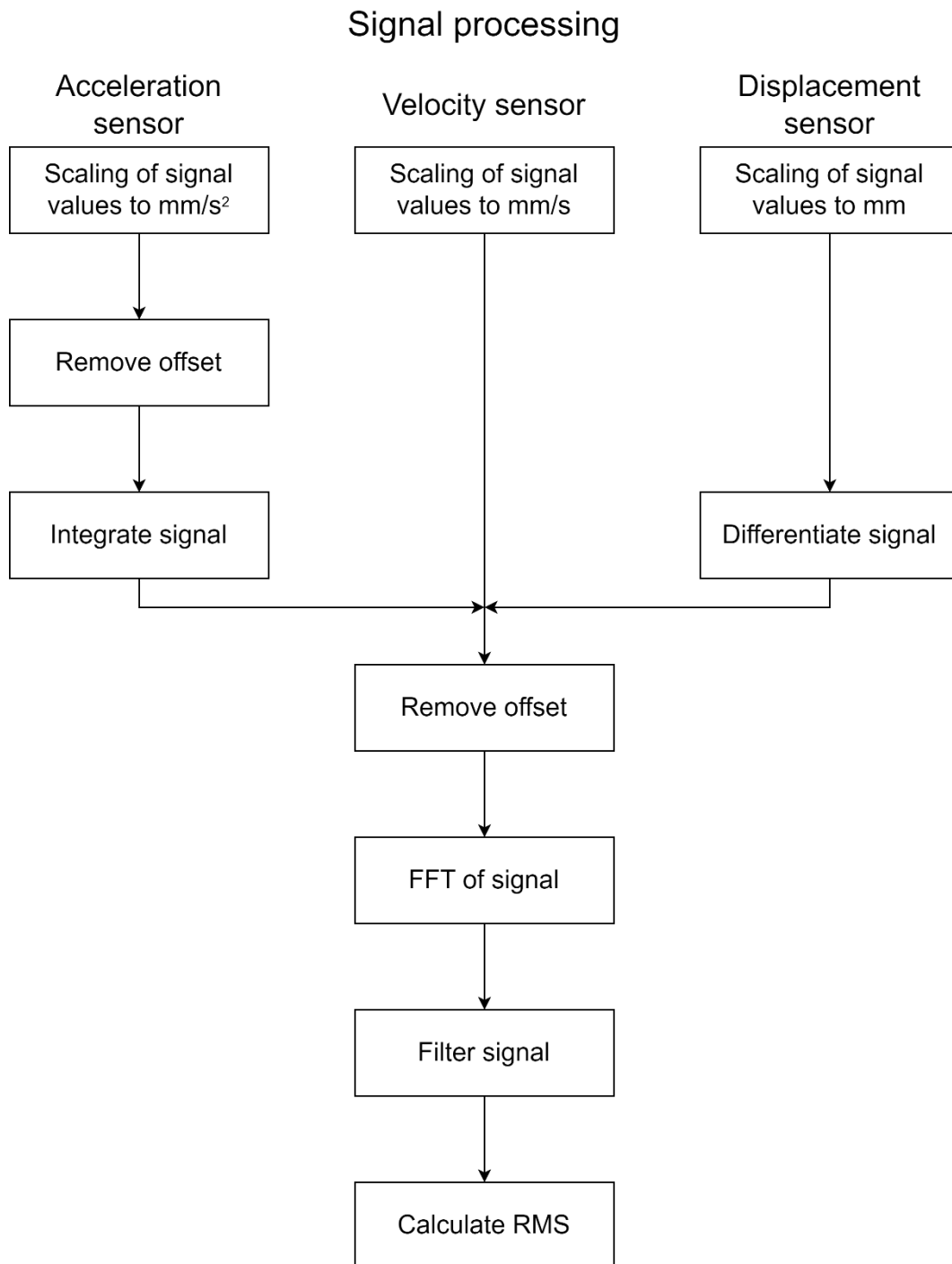


Figure 9 - Flow chart describing the signal processing step in the measurement sequence developed by ABB.

The RMS values are an output from the sequence that can be read by an HMI. The RMS values are then evaluated and analyzed. If the RMS value in a channel exceeds 2 mm/s RMS a warning is issued and if the value exceeds 3mm/s RMS an alarm is issued.

4.2 New solution

The new solution developed for Alleima Strip basically has the same configuration as the solution developed by ABB with a difference being having 16 accelerometers instead of 14. The system is also set up as an FTP-server to enable the transferring of ZIP-files. All the channels are configured in the same way with a sample rate of 12,5kHz and a record length of 50000 samples. To be able to monitor sensor faults measurement mode is set to IEPE mode. Since the polishing equipment is controlled from a second CPU the CM589-PNIO module is for communication with that CPU through PROFINET.

The program is written in CODESYS using function block diagram and have two different modes for measuring. The measurement can be started manually or automatically. The automatic choice in the new solution is a combination of the two from the old solution. When the mode is set to automatic a measurement is started on timed intervals and also if a peak value with high enough amplitude is measured in real time. The mode is prepared for being set using an HMI. All limit values have also been prepared to be set through an HMI.

The program consists of two different sequences, one for starting a measurement and one for configuring the channels of the CMS module. The solution also consists of four different functions. The different functions are sensor surveillance, flashdisk monitoring, parameterization and real time measurements. A flow chart of the PLC cycle can be seen in Fig. 10.

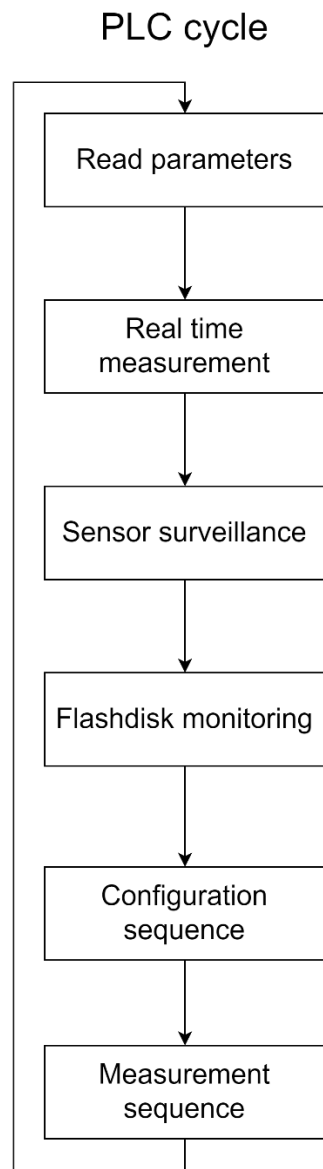


Figure 10 - Flow chart describing the PLC cycle in the in-house solution developed for Alleima Strip.

4.2.1 Configuration sequence

The configuration sequence makes it possible to change the configuration of the CMS module without using Automation Builder. This gives the option to measure separate channels directly without reprogramming the CPU. For example, there are four different polishing equipments installed where the solution is going to be used. But only three of the polishing equipments run concurrently while the fourth is being maintained. It is of no use to then measure the vibrations from the equipment that is being maintained. Which of the polishing equipments that are in use is communicated from the PLC controlling the machine over PROFINET. The configuration from the vibration PLC is built up as 2 bytes where every bit symbolizes a sensor each. The enable signal from the controlling PLC is built up in the same way, and these two signals are compared to each other each PLC cycle.

When the enable signal from the controlling PLC and the configuration variable from the vibration measurement PLC differs the configuration sequence starts. The new configuration is then sent to the CMS module. After the writing of the new configuration is done the actual configuration is read from the CMS module and stored in a local variable for comparison with the enable signal from the controlling PLC. A pseudocode of the configuration sequence can be seen in Fig. 11.

```
If enable signal not equal to the configuration variable
    Write new configuration to CMS module
    Read configuration from CMS module
    Store read configuration in the configuration variable
End if
```

Figure 11 – Pseudocode describing the configuration sequence in the in-house solution developed for Alleima Strip.

4.2.2 Measurement sequence

The measurement sequence is started when the requirement for a measurement is met. These requirements are when the measurement mode is set to automatic and the time elapsed since the last measurement exceeds a chosen time interval or when a peak at a channel is measured in real time, but not more often than a second chosen time interval. The time intervals and peak value is parameterized in the program and are prepared to be set through an HMI. The measurement sequence can also be started manually when the measurement mode is set to manual and a manual measurement is requested.

The second step in the sequence is to generate a file name. The file name is generated with the format ddhhmmss because the system doesn't support file names longer than eight characters. This file name and a start signal are then sent to the CMS module.

After the measurement is done the generated ZIP-file is unpacked in a separate folder named the same as the ZIP-file. As an example, if the ZIP-file is named 20101230.ZIP the folder is then named 20101230. In the next step all the WAV-files in the generated folder are processed with signal processing and deleted. After all the WAV-files have been processed and deleted the folder is also deleted and the measurement sequence is done. A flow chart of the measurement sequence can be seen in Fig. 12.

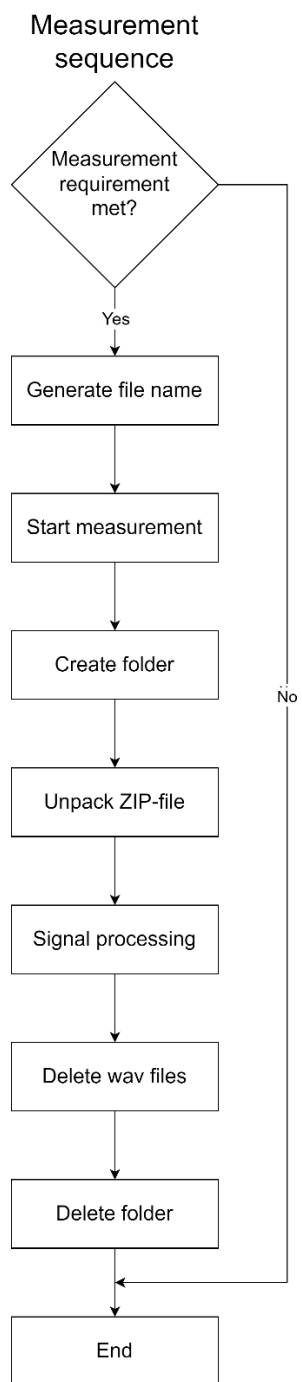


Figure 12 - Flow chart describing the configuration sequence in the in-house solution developed for Alleima Strip.

As in the old solution, the new solution also supports different types of sensors. The signal processing is different based on the type of sensor being used. The types supported are acceleration sensors, velocity sensors and displacement sensors. For an acceleration sensor the signal is scaled to represent values in mm/s^2 , eventual offset is removed, the signal is integrated and eventual new offset is removed. The signal is then filtered through a high pass filter with a chosen frequency as break point. The filtered signal is then filtered through a low pass filter with another chosen frequency as break point. Lastly statistical parameters are calculated from the filtered signal.

For a velocity sensor the signal is scaled to represent values in mm/s and eventual offset is removed. The signal is then filtered in the same way as for an acceleration signal with chosen break points for filtering and statistical parameters calculated from the filtered signal.

For a displacement sensor the signal is scaled to represent values in mm , the signal is then differentiated and eventual offset is removed from the differentiated signal. The signal is then filtered in the same way as for an acceleration signal and velocity signal with chosen break points for filtering and statistical parameters calculated. A flow chart of the signal processing for the different types of supported sensors can be seen in Fig. 13.

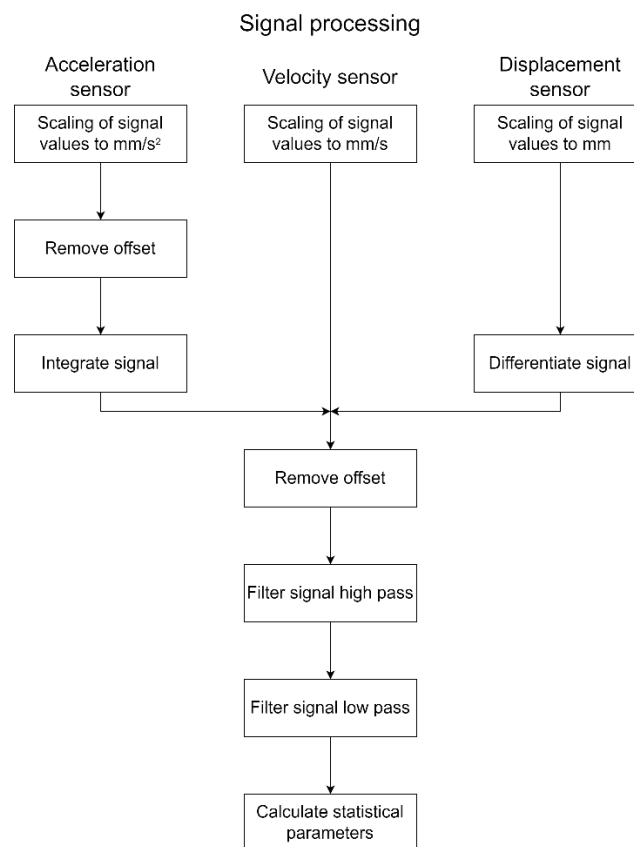


Figure 13 - Flow chart describing the signal processing step in the measurement sequence in the in-house solution developed for Alleima Strip.

The statistical parameters calculated from the filtered signals are:

- Mean value
- RMS
- Minimum
- Maximum
- Standard deviation
- Variance
- Median
- Crest factor
- Kurtosis
- Skewness

The statistical parameters are prepared to be read from an HMI where evaluation will take place.

If a bearing breaks down in a machine, Alleima Strip is not interested in evaluating what part of the bearing broke. The bearing will simply be replaced by a new one and the old bearing discarded. For this reason, no frequency-domain evaluation has been suggested. Focus will instead be on evaluating bearing health using time-domain methods.

Signals used for evaluation will be RMS value and Kurtosis after discussion with Alleima Strip. RMS value is chosen based on Alleima Strips success using it for the cold rolling mill. The limits are set to 3mm/s RMS which have yielded good results thus far in the cold rolling mill. The limits will however be evaluated after the equipment have been commissioned and eventual drive-in period elapsed. The choice of Kurtosis is based on Tandon et al. pointing out Kurtosis as the most effective statistical parameter for health indication[9]. No limit for Kurtosis has been decided but will be implemented at a later time. For this purpose, logging will be set up for the Kurtosis value so evaluation can be based on historical data. Logging will also be set up for the other statistical parameters.

4.2.3 Functions

For the functions the focus has been to extend functionality and make the solution more generalized so it can be implemented in other types of machinery as well. This has been done with the use of parameterization and generalization of function blocks.

The flashdisk monitoring is carried out in the same way as for the old solution. The number of files allowed on the flashdisk has been set to 500. This is based on the available storage on the flashdisk which is 4GB. Since each channel measurement consist of 50000 samples where each sample is 4 bytes in size, 500 files with measurements from 16 channels would then occupy 1,5GB of the 4GB flashdisk storage. This doesn't put the PLC at the maximum capacity of the storage and leaves room if the flashdisk needs to be used for other purposes.

The sensor surveillance has been generalized and extended. The sensor surveillance has been broken out and implemented as a function block. The function block has actual error codes from the PLC and an array of symbolic error addresses as inputs. The function block will search through the PLC error codes for the symbolic error codes and flag if one or more is present. The solution now has surveillance for short circuited sensors, if the sensor indicates wire break or if a sensor is enabled but no wire is present. The function block also has an output prepared for use with an HMI giving an error code packed as a WORD in which each bit indicates sensor fault on each corresponding channel.

Real time measurements have been implemented and used in the new solution. Each channel is monitored at 10ms, and the measured value is compared to a parameterized peak value. If the peak value is exceeded in any of the channels a signal for starting a measurement is issued if the measurement mode is set to automatic. To remove unnecessary starting of measurements the channels values will be set to 0 if the channel is not enabled in the configuration.

The parameterization has been split into two different segments. The first segment is related to which sensors are being used. Depending on the physical model of the sensor and its characteristics parameterization through an HMI is not suitable. The settings are therefore only possible to change through editing the code directly. These parameters are:

- Sensor factor
- Sensor type

Sensor factor is used for scaling the sensor value from the channels to the correct unit based on the sensor type. The second segment of parameters are limit values, storage path and time intervals used for evaluation and measurement which are more suitable for parameterization through an HMI. The parameters are:

- Path
- Peak value
- Warning RMS
- Limit RMS
- Measurement interval
- Minimum time interval

Break off frequency high

Break off frequency low

The storage path can be set for the entire solution from this parameter and is the location where the ZIP-files are being stored. Default value is the flashdisk. Peak value is the maximum allowed peak value of g-forces for acceleration sensors, velocity in mm/s for velocity sensors and distance moved in mm for displacement sensors. The default value is set to 2 for each corresponding sensor type and unit. This is based on historical data from the cold rolling mill. Warning RMS and Limit RMS are used for evaluation. Default values are 2 mm/s and 3mm/s respectively based on previous success with the cold rolling mill. Measurement interval is the time between measurements in automatic mode. Default value is set to 30 minutes. Minimum time interval is the amount of time that must pass from the last measurement start triggered by a peak value before a new measurement start can be initiated by a peak value. The default value for Minimum time interval is set to 5 minutes. The break off frequencies are the break points used for the filtering in the signal processing. The break off frequencies has been set to 10Hz and 1000Hz. Calculating the characteristic frequencies of the bearings used in the polishing machine using (1)-(4) places the lowest frequency around 100Hz and the highest frequency around 400Hz with varying rotation speeds. Doing the same exercise for the cold rolling mill gives the higher frequency at approximately 800Hz. The interval has then been chosen with some margin to the highest and lowest frequency trying to include the frequency components of both machines.

5 Discussion

In this chapter the achieved result will be discussed. The new in-house solution developed for Alleima will be compared with the existing. The result will be compared to the thesis objectives to see which goals are fulfilled.

5.1 Objectives

The in-house solution is completely done using function block diagrams in accordance to Alleima Strip coding standards. The code has been written in a standardized way so it is easy to parameterize for use in other machines. If an equal system is installed in an already existing machine the parameterization is the only thing that needs to be changed for the new solution to work. This has however not been tested.

The new in-house solution can monitor a machine in real time and is set up for enabling the storage of historical data. Measurements by the CMS module can be initiated using real time values from the channels and the statistical parameters from a measurement done by the CMS module can be displayed in an HMI. Historical data can be obtained using FTP-protocol. The data can then be stored in a form of storage better suitable for storing historical data, for example a database.

Initiating measurement of vibrations in an efficient way has been implemented using rules for when a measurement should start. This should not be done too often since this will flood the flashdisk storage with files. The initiating of measurements should not be set too far apart since this will yield data which do not always represent the actual state of the machine. The time intervals and the peak value are subject to change for the machine depending on the environment and the state of the machine. For example, if the machine is placed near a passage for trucks, the trucks driving by might cause a peak value to occur initiating measurements. This will result in a lot of measurements being stored when the fault isn't due to the machine. Another example is if the machine is in a bad state and a closer monitoring of the statistical parameters is wanted or if the machine is newly maintained and the monitoring does not need to be as frequent. This is possible using the parameterization of Measurement interval, Minimum time interval and Peak value from an HMI.

The statistical parameters proposed as health indicators for classifying the state of wear is RMS value and Kurtosis value. The choice behind RMS value is due to Alleima Strips usage of the RMS value in other machines. Kurtosis is however added based on the literature study. Based on this all the objectives of the thesis work have been met.

6 Conclusions

The results obtained through this thesis work is a complete program for measuring vibrations using an ABB AC500v2 CPU with a FM502-CMS module. All the objectives have been met and the code has been delivered to Alleima Strip. The machine, where the new in-house solution developed during this thesis work, will be commissioned during the fall of 2023.

6.1 Future work

The vibration measurement PLC should be connected to an HMI giving easier access to the parameters used in the in-house solution. This will make the solution more customizable since the changeable parameters could be accessed more easy through an HMI. Depending on the HMI solution used this can also be used for logging the historical data of the statistical parameters as well as being used for fetching and storing the raw data within the WAV-files. Logging of historical data of the statistical parameters can be used for evaluation of the chosen limit values after commissioning. Storing of raw data from the WAV-files can be used for evaluation of other methods. For example, analyze the WAV-files after a potential breakdown of a bearing to see if more conclusions can be drawn implementing evaluation based on the frequency-domain or other statistical parameters.

After the machine has been commissioned all the values chosen as default values are subject to evaluation. Since the environment around the polishing equipment and the cold rolling mill is not the same there are no guarantees that the chosen limit values for RMS or Peak value will yield good results for the polishing equipment. The same goes for the break points for the frequencies. The break off frequencies chosen as default values are suggested to fit the two machines where the AC500 and CMS module is used and going to be used for vibration measurements.

There might also be interesting to look into the frequency-domain to expand the functionality of the vibration measurement. The idea behind it now is using it for health indication of the bearings but could potentially be used for more.

Chandrabhanu et al. points out that vibration measurements could be used for detecting unbalance, motor fault, gear fault and cracked shafts to name some[7]. As an example the vibration measurements could potentially be used for detecting when the brushes used in the polishing equipment is unbalanced.

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