Lappeenranta University of Technology
LUT School of Energy Systems
Degree Programme in Electrical Engineering

Jaakko Reponen

THE RELIABILITY OF FREQUENCY CONVERTERS IN A PULP AND PAPER INDUSTRY COMPANY

Examiners: Professor Pertti Silventoinen
D. Sc. Tommi Kärkkäinen

Supervisor: Project Manager Ari Wallenius

ABSTRACT

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The reliability of frequency converters in a pulp and paper industry company

Master's Thesis

2019

47 pages, 21 figures and one table.

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Keywords: reliability, Weibull analysis, frequency converter, pulp and paper industry

The number of frequency converters used in industry has increased widely over the last decade. By using frequency converters, industrial processes can be controlled in a way that saves both production equipment and energy. The forest industry company Stora Enso's Imatra mills have been using frequency converters as part of their processes since the late 1980s. In 2018 at the Imatra mills in Kaukopää and Tainionkoski more than 2000 frequency converter units are used in production. Depending on the process, the failures of the frequency converters may cause long breaks in the production. Stora Enso wanted to analyse the current state of the frequency converters as well as to find potential solutions to maintain and improve the reliability of the frequency converters. In addition, suggestions on how the renewal of frequency converters should be implemented in the near future were wanted.

In this master's thesis the reliability of the frequency converters at Imatra mills was examined based on frequency converters fault history and staff interviews. The fault history statistics were compiled and the reliability of the hardware was estimated by statistical methods such as Weibull analysis. In the interviews, the views and experiences of the staff in terms of frequency converters were examined and suggestions for improving the reliability was discussed.

Based on the reliability calculations and interviews, the reliability of the equipment base of frequency converters at Imatra mills is currently at a good level. The most common fault types for frequency converters were researched and means to maintain and raise the reliability level were found. The most important of these means was to keep the device base up to date by replacing outdated models with modern models.

TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
LUT Energiajärjestelmät
Sähkötekniikan koulutusohjelma

Jaakko Reponen

Taajuusmuuttajien luotettavuus metsäteollisuusyrityksessä

Diplomityö

2019

47 sivua, 21 kuvaa ja yksi taulukko.

Tarkastajat: Professori Pertti Silventoinen
TkT Tommi Kärkkäinen

Työn ohjaaja: Projektipäällikkö Ari Wallenius

Hakusanat: luotettavuus, Weibull analyysi, taajuusmuuttaja, metsäteollisuus

Taajuusmuuttajien määrä teollisuudessa on kasvanut viime vuosikymmennen aikana paljon. Taajuusmuuttajia käyttämällä teollisuuden prosesseja voidaan ohjata tuotantolaitteistoa ja energiaa säästäen. Metsäteollisuusyritys Stora Enson Imatran tehtailla taajuusmuuttajia on käytetty osana prosesseja jo 80-luvun lopulta alkaen. Vuonna 2018 Imatran tehtaiden Kaukopään ja Tainionkosken yksiköissä taa- juusmuuttajia on käytössä yli 2000 kappaletta. Taajuusmuuttajien vikaantumiset saattavat prosessista riippuen aiheuttaa tuotantoon pitkiäkin katkoksia. Imatran tehtailla haluttiin selvittää taajuusmuuttajien nykytila sekä löytää mahdollisia parannuskeinoja taajuusmuuttajien luotettavuuden ylläpitämiseksi ja parantamiseksi. Lisäksi haluttiin ehdotuksia siitä miten taajuusmuuttajien uusintoja tulisi lähitulevaisuudessa toteuttaa.

Tässä diplomityössä tutkittiin Imatran tehtaiden taajuusmuuttajien luotettavuutta taajuusmuuttajien vikahistoriatietojen ja henkilökunnan haastatteluiden perusteella. Vikailmoitukset tilastoitiin ja laitekannan luotettavuutta tutkittiin tilastotieteen menetelmillä kuten Weibull analyysillä. Haastatteluissa selvitettiin henkilö- kunnan näkemyksiä ja kokemuksia taajuusmuuttajista sekä juteltiin keinoista, joilla parantaa laitekan- nan luotettavuutta.

Luotettavuuslaskelmien ja haastatteluiden perusteella taajuusmuuttajien laitekannan luotettavuus on Imatran tehtailla tällä hetkellä hyvällä tasolla. Taajuusmuuttajien yleisimmät vikatyypit selvitettiin ja keinoja luotettavuuden tason säilyttämiseksi ja nostamiseksi löydettiin useita. Tärkeimmäksi näistä keinoista nousi laitekannan pitäminen ajan tasalla vaihtamalla jo vanhentuneita malleja nykyaikaisiin malleihin.

PREFACE

This thesis has been made for Stora Enso Oyj's Imatra Mills regarding the reliability of frequency converters in the Mills.

I would like to thank Ari Wallenius who provided the subject and was the supervisor of this thesis. I would also like to thank other employees of Stora Enso and Efora who helped me during the work and give special thanks to people who gave me an interview to the subject.

Thanks to Asko Kavala who helped with sorting out the fault data. Thanks to Tommi Kärkkäinen and Pertti Silventoinen, the examiners of this thesis, who gave great advice and helped a lot during the work.

The biggest thanks for my mother who always believed in me and gave her 100 percent support.

Jaakko Reponen
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Mikkeli, Finland

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USED SYMBOLS AND ABBREVIATIONS

Roman letters

a	Year
f	Failure density function
F	Failure function
R	Reliability function
t	Time

Greek letters

β	Shape parameter
η	Characteristic life of an item
λ	Failure rate

Acronyms

AC	Alternating Current
CSI	Current Source Inverter
DC	Direct Current
dU/dt	Filter that protects the motor by reducing quick voltage changes
DT	Downtime
IGBT	Insulated-Gate Bipolar Transistor
MTTF	Mean Time To Failure
NPN	a type of bipolar junction transistor with P-doped base between two N-doped layers
OT	Operating Time
PID	Proportional-Integral-Derivative controller
PWM	Pulse Width Modulation
RAMS	Reliability, Availability, Maintenance and Safety
RMIO	Remote Module Input/Output, frequency converter’s control circuit
RMS	Root Mean Square
RPM	Rounds Per Minute
VAC	Alternating Current Voltage
VSI	Voltage Source Inverter

1. INTRODUCTION

1.1. The background of the thesis and the company

A Frequency converter is an electronic device that is installed between two different power grids and it can can convert the frequency and the amplitude of voltage to a certain level. One of the most common uses is to place a frequency converter between a power grid and an alternating current or AC motor. If an AC motor is plugged straight in the power grid, the motor will spin with the frequency of the grid. With a frequency converter AC motors can be driven with optimal speed for every process. This makes the processes more efficient energy vice and no other control devices are needed to control the motor.

Stora Enso has a total of 2447 frequency converters in production in Imatra mills in Kaukopää and Tainionkoski together. In Imatra mills frequency converters are mainly used to control motors, pumps and cranes. Yearly approximately 25 units fail which is around 1% of the total installed base. However, many of the frequency converters are getting old or are already out of production so new investments should be made in the near future.

Reliability defines the probability of success. The high reliability of the equipment in production is an important factor. In case of frequency converter failure, the model is replaced with a new one, or if possible, repaired on site. Longer standstills are naturally unwanted and one hour of standstill costs approximately 10 400 €/h as production losses. This has lead Stora Enso Imatra mills to monitor the reliability of their frequency converters more closely. Through reliability calculations, the average service life of a frequency converter can be evaluated. This helps the production to plan the renewal of frequency converters financially and in time.

Stora Enso Oyj itself is a multinational pulp and paper company. It has mills in 35 countries and over 26 000 employees of which 6000 are located in Finland. Stora Enso Oyj is a leading provider of renewable solutions in packing materials, biomaterials, wood products and paper. (Mäkelä, 2017) Stora Enso invests heavily in sustainable development through the increasing and innovative use of renewable materials.

Imatra Mills was founded in southern Finland in 1935 and it consists of two production units, Kaukopää and Tainionkoski that produce chemical pulp, consumer board and plastic coating. Imatra Mills is one of the largest consumer board mills in the world. Over 90% of its production is exported to Europe and Southeast Asia. Annually Mills produce 1 155 000 tons of consumer board, 825 000 tons of pulp in Kaukopää and 195 000 tons in Tainionkoski and 285 000 tons of plastic coating. Imatra Mills has 1300 employees. (Stora Enso, 2018)

1.2. Objectives of the work

In this master's thesis, the reliability of Stora Enso Oyj's frequency converters in Imatra mills is analysed. Analyse is based on a long time fault statistics of frequency converters and the interviews of the staff. Based on this information the present state of frequency converters and their reliability is evaluated and ways to improve and maintain reliability is proposed. The main goal of the thesis is to answer to question ”What to do in the near future with the frequency converters and how would it be best to renew them?”.

1.3. The structure of the thesis

Chapter two introduces frequency converters in general. Their structure, benefits, basic usage and deployment information is told. The structure of a frequency converter was important to know well to fully understand the fault reports.

Chapter three covers the basics of reliability engineering and presents the tools needed to analyse the reliability of frequency converters like the Weibull analysis. RCM and the cost effects of reliability are also discussed briefly.

Chapter four presents the information of the frequency converters in Imatra mills. Frequency converters manufacturers, maintenance schedules, operational locations, applications, life cycle statuses and criticality ratings are told.

Chapter five focuses on the estimation of reliability of the frequency converters in Imatra mills. Fault statistics are analysed with the Weibull analysis and the current state of frequency converters is analysed.

Chapter six introduces the ways to maintain and improve the reliability of frequency converters in Imatra mills. These means are based on the reliability analysis, the fault statistics and the interviews.

Chapter seven presents the conclusions and summarises the thesis.

2. FREQUENCY CONVERTER

A frequency converter is a power electronic device that is used in the industry to control and adjust the speed of an AC motor. If the AC motor is connected straight to the power grid, it will rotate at the frequency of the power grid. When a frequency converter is connected between the power grid and the motor, the frequency converter adjusts AC's voltage, current and frequency. This allows user to steplessly control the speed of the motor and produce the required torque for the start-up. In general and especially in industrial use frequency converters are three-phase. (Mäkinen et al., 2009)

The block diagram of a typical intermediate circuit frequency converter is shown in Figure 2.1. The figure shows how the different components are connected to each other. These components are discussed later in this chapter.

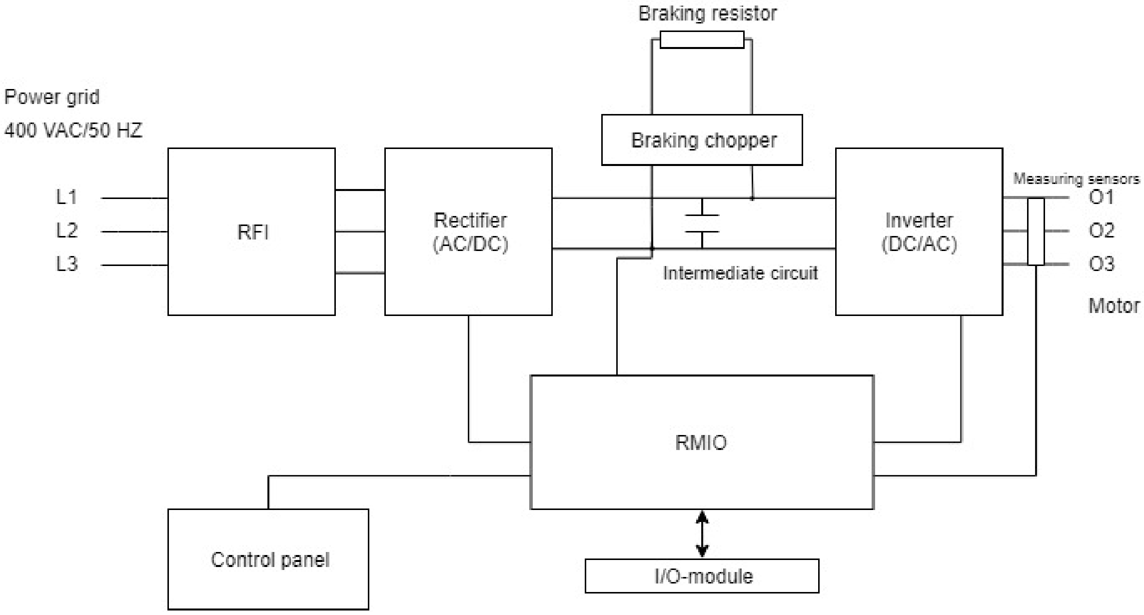


Figure 2.1: The block diagram of a frequency converter with an intermediate circuit. L1, L2 and L3 are the three input phases of the power grid and O1, O2 and O3 are the three output phases that are connected to the controlled motor.

2.1. Power, types and structure of frequency converter

The most common operating voltage for a frequency converter is 380-690 three-phase alternating current voltage (VAC) but they are also made for the higher voltages. Some low power models can be supplied from a 100-240 VAC single-phase power grid from which the converter generates 230 VAC adjustable three-phase AC. The power of frequency converters varies from a few hundreds of watts to megawatts. (Mäkinen et al., 2009)

There are two main types of frequency converters, direct and intermediate circuit frequency converters. The direct frequency converters cut the power grid's AC with semiconductor switches straight into the desired frequency and voltage. Direct frequency converters are divided into matrix converters and cycloconverters.

Intermediate circuit frequency converters turn AC into direct current, DC, and back into AC again. Most of the frequency converters used in industry have an intermediate circuit. Intermediate circuit frequency converters consist of four main parts: a rectifier, a DC voltage or a DC current intermediate circuit, an inverter and a control unit. (Niiranen, 2000)

2.1.1. Rectifier

As shown in figure 2.2 rectifier consists of six diodes but it can also be implemented with thyristors. In the top, the diode that has the highest potential in its anode will conduct and the other two are reverse biased. In the bottom, the diode that has the lowest potential in its cathode will conduct and the other two are again reverse biased. Three-phase rectifiers are used because their waveforms have lower ripple content and they can handle higher powers than single-phase rectifiers. (Mohan et al., 2002)

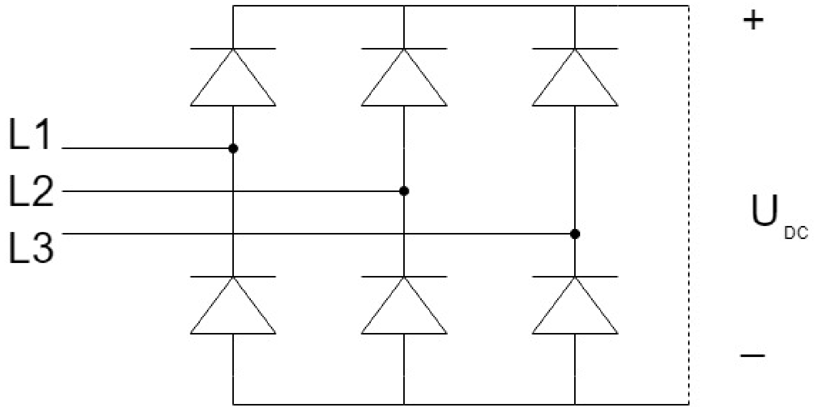


Figure 2.2: The rectifier of the frequency converter often consists of six diodes. This rectifier is called three-phase full-wave bridge rectifier.

The rectifier works as a bridge between the power network and the intermediate circuit. The diodes used in the bridge prevent the braking power from turning back to the power grid. The rectifier can also be active which means that the intermediate circuit's DC voltage can be feed back to the power grid. Active rectifiers are often implemented with insulated-gate bipolar transistor (IGBT) components. When IGBT components are used, they are coupled in parallel with diodes to prevent over voltages from occurring when the switch is opened or closed. (Hietalahti, 2011)

2.1.2. Intermediate circuit

There are two kinds of intermediate circuits: current and voltage intermediate circuits. The current intermediate circuit consists of a smoothing inductor which reduces the DC current ripple. The voltage intermediate circuit consists of a capacitor and a smoothing inductor. Capacitors used in the older intermediate circuits are often electrolytic capacitors. The inductor and the capacitor work together as energy storage to smoothen the DC voltage ripple. Frequency converters with current intermediate circuits are called current source inverters (CSI).

Frequency converters with voltage intermediate circuits are called voltage source inverters (VSI). VSI normally uses a diode bridge rectifier to produce the DC voltage for the intermediate circuit. The downside is that the diode bridge can't be controlled so VSI uses pulse width modulation (PWM) to adjust the voltage of the motor. The advantages of PWM are dynamic adjusting and almost sinusoidal phase current. The average output voltage can be changed by almost without any delay by just changing the lengths of the pulses. VSI can feed both synchronous and induction motors. (Niiranen, 2000) At this moment, VSI is the most used type of frequency converter at Imatra Mills. VSI is shown in Figure 2.4.

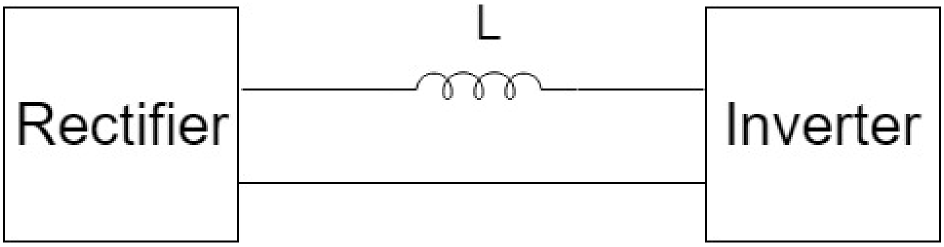


Figure 2.3: CSI. There is only an inductor in the intermediate circuit.

If the rectifier of the frequency converter is active, the energy of the motor can be fed back into the power grid. If not, a brake chopper is used. The brake chopper is an electronic switch that connects the intermediate circuit's DC into a resistor where the braking energy is converted to heat. The brake chopper works even if the input AC is turned off. The brake chopper is needed for example during a blackout or a short-term power grid failure. (Farin et al., 2009)

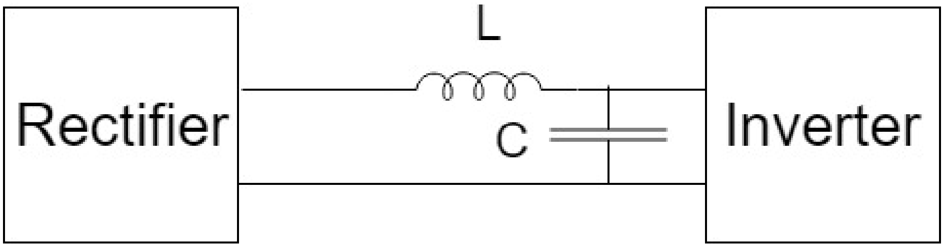


Figure 2.4: VSI. In addition to the inductor, the intermediate circuit also has a capacitor.

2.1.3. Inverter

The inverter changes the DC back into the AC. Inverter's semiconductor switches, nowadays often IGBT components as shown in Figure 2.5, are turned on and off based on the switching instructions coming from the control circuit. At a fast pace, each IGBT-pair conducts in turn to form a sinusoidal AC. The faster the IGBT-pairs switching frequency is, the better the sinusoidal form is. Very fast switching frequency can cause problems because increasing the switching frequency increases the power losses. (Mohan et al., 2002)

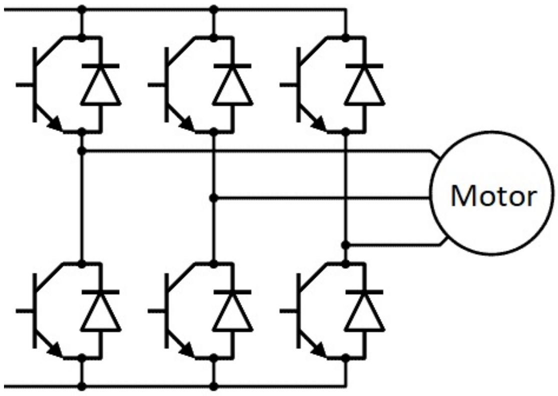


Figure 2.5: An inverter circuit that consists of IGBTs. Diode is connected anti-parallel across IGBT to eliminate sudden voltage spikes seen across the switch when supply current changes.

2.1.4. Control circuit

The control circuit, RMIO, monitors and adjusts the operations of the frequency converter. The RMIO consists of a signal processor and the logic built around it. RMIO controls the inverter's semiconductor switches and the output current, measures the intermediate circuit's voltage and manages communications with the control panel.

The state of the frequency converter can be monitored via analog or relay outputs. Digital inputs normally control start ups, rotation directions and nominal speeds. Frequency references are given via analog inputs, which are current or voltage inputs. Relay outputs can be used to get information on the fault conditions of the frequency converter. RMIO gets different measurement data from the main circuit of the frequency converter. This data helps RMIO to control the inverters' semiconductor switches as needed. (Kiiski, 2012)

2.2. Controlling and matching the motor with the frequency converter

When a frequency converter and an electrical motor are working together, the combination is called an electric drive. The frequency converter works as an energy bridge between the power network and the motor and the energy transfers into the process through the motor. The frequency converter adjusts the amount of transferred energy based on the information available from the axle of the motor. The controlled value can be either the torque or the speed. Depending on which value is controlled, the adjustment is called torque or speed control.

Starting and controlling a frequency converter driven AC motor is generally implemented in two different ways; manually via the control panel of the frequency converter or remotely via automation system. The characteristics of the power grid, the frequency converter, the motor, the machine or the processor used, and their mutual suitability, must always be checked on a case-by-case basis. When the frequency converter drives the motor at low speeds, the continuous load rating of the motor is less than the nominal load rating. In this case, the motor can warm up excessively. Situation can be improved by installing a separate constant speed cooling fan into the motor.

The current of the frequency converter isn't always exactly sinusoidal. This causes greater electrical stress to the insulations of the motor than a normal sinusoidal current from the national power grid. At the same time the noise, the temperature, vibration and losses of the motor can increase. This can be avoided by using a motor that has a strengthened insulation in the windings or dU/dt- or a sinusoidal filter in the motor input of the frequency converter. These means reduce bearing currents and voltage fluctuations in the windings.

A frequency converter can also cause high frequency bearing currents in the motor and this can shorten the life of the bearings dramatically. These problems can be avoided by using insulating bearings and a symmetric motor cable that consists of many smaller cables. Also earthing the cable properly helps. (Mäkinen et al., 2009)

The dimensioning of the frequency converter has to be done according to the intended use. In Imatra Mills frequency converters are dimensioned for heavy duty use so that they do not have to be driven with full power. (Vinni, 2018) All manufacturers have their own recommendations for heavy duty use. Manufacturer ABB for example recommends in their manual for ACS880-01 drives in general that the continuous RMS output current allows 50% overload for one minute every five minutes in an ambient temperature of 40 celsius degrees. (ABB, 2019)

To make a frequency converter and a motor match, the frequency converter has to be parameterised. The parameterisation can be done locally from the frequency converters control panel, by computer connected to the frequency converter with a parameterisation program or through the automation system if the frequency converter is fieldbus-connected. Different applications are pre-installed in the frequency converters, from which the user can choose the most suitable ones for the intended purpose. Applications properties, deployment, couplings and their parameterisation are described in detail in the manufacturer's manual. (Mäkinen et al., 2009)

Frequency converters have different control methods, scalar and vector. In scalar control only the magnitude of variable like voltage and frequency is controlled to control flux and torque. Due to the coupling effect this control method is quite slow. Controlling flux or torque affects the other variable as well because both are functions of voltage and frequency. In a vector or a field oriented control, flux and torque are both controlled independently without the drawback of the coupling effect. This is why the vector control is a much faster and more dynamic control method. Made changes in the flux and torque can be seen almost immediately in the operation of the motor. A vector or a field oriented control frequency converters are nowadays the most used because of their better performance. (Jisha and Powly Thomas, 2013)

2.3. Protection of the frequency converter and motor

The frequency converter protects the motor from the overload. No thermal relays are required for the overcurrent protection of the motor unless multiple motors are used with one frequency converter. The best motor temperature protection is achieved by the thermistors that are placed in the windings of the motor. The thermistors monitor the temperature of the motor and are wired to the thermistor connection of the frequency converter. The thermistor relay can also be a separate device in the housing of the frequency converter or the motor center.

In the protection of the frequency converter the size and the type of the feeder fuses must be taken into account. They are selected according to the manufacturer's instructions. In control messages galvanic separators are used so that analog messages between the frequency converter and the automation system can be separated. The frequency converter also protects itself against overload and overheating.

The temperature of the frequency converter's installation environment should be optimal. This varies between manufacturers but normally this means between -10 to +50 celsius degrees. Within this temperature range frequency converter works normally. If the temperature differs from the set range, the frequency converter will give a temperature alarm and stop after a set time. The loss of power and the space required for the frequency converter must always be asked from the manufacturer before the enclosure. Frequency converter's efficiency is usually over 95%. The rest of the power is converted to heat. This heat must be transferred away from the installation space by conducting, ventilating or using a separate heat exchanger. (Mäkinen et al., 2009)

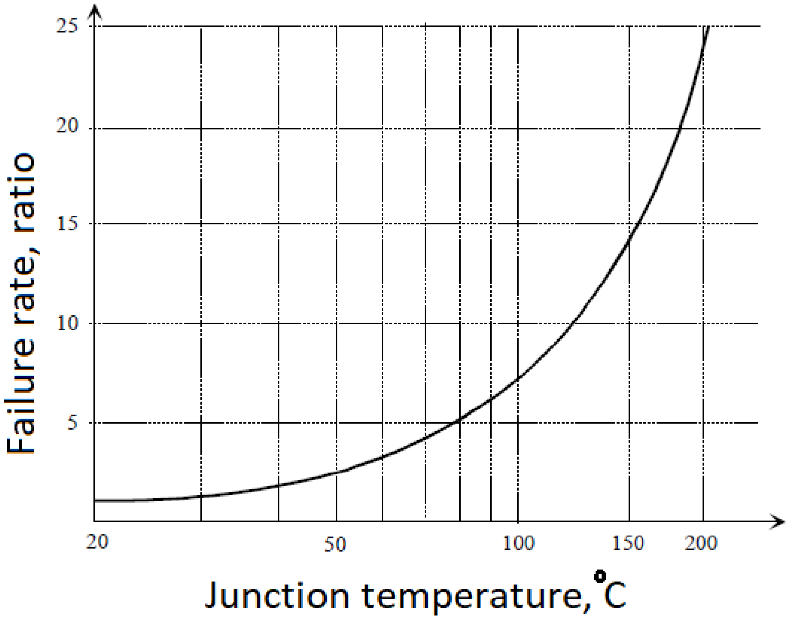


Figure 2.6: A relative failure rate ratio as a function of temperature for a certain NPN transistor. Relative failure ratio is a failure ratio at the temperature in question divided by the failure rate at 20 degrees Celsius. Even a small increase in temperature can significantly affect the failure rate of the component. (Huppunen et al., 2011)

If the extra heat is not transferred away, it will eventually affect the life time of the frequency converter. It has been found out that especially semiconductor components, like IGBT's and thyristors, lifetimes are heavily dependent on the temperature. (Huppunen et al., 2011) Figure 2.6 shows a certain NPN-transistor's failure rate as a function of temperature. It can be seen from the figure that for example at 80 degrees Celsius temperature the components failure rate is five times higher than at 20 degrees Celsius.

In addition to the temperature, the air humidity is a significant factor in the aging of electronics. During the mills stoppages, the devices are powerless and the components temperature will drop. The humidity in the air can condense on the surface of the cold frequency converter and its components. When the processes are started again, this condensed humidity can cause short circuits and other problems in the frequency converter. Humidity and temperature can together cause corrosion. The corrosion is stronger in humid and warm conditions and over 50% relative humidity will accelerate corrosion process considerably. (Kiiski, 2012) For this reason frequency converters should be installed in well ventilated spaces. Good air conditioning keeps the humidity low and steady and the temperature appropriate.

2.4. Commissioning measurements, test run and maintenance

There is no need for external electrical measurements for the frequency converter because the local control units can monitor all electrical status data related to the operation of the frequency converter. The voltage supplied by the frequency converter to the motor can be little different from the perfect sine wave, so reliable measurement results are obtained with a true RMS instrument. When insulation resistance measurement is performed for motor cables, the cable must first be disconnected from the frequency converter output terminals.

Before turning the power on and the motor test run, the following preparations must be made. The power-up and motor circuit commissioning checks are completed and the results are recorded in the inspection report. After that, the frequency converter is visually inspected, the correct fuses are installed and all covers are fastened or closed. Next the protection switch of the motor is opened. After this, the person responsible for the commissioning will give a permission to power the frequency converter on and to rotate the motor.

After turning the power on, the frequency converter is parameterised and the control messages and startup commands are checked. Before starting the motor, the user has to be sure that the test run does not cause a dangerous situation and the protection switch of the motor is closed. Now the test run can be made. The test run makes sure that the motor runs in the right direction and works as it should. If the motor rotates in the wrong direction, the phase sequence is rotated from the frequency converters output terminals or from the connection box of the motor.

The frequency converter does not have any other moving parts except the cooling fan. For this reason the maintenance of the frequency converter is mainly limited to the monitoring of the fan. The cooling fan and coolant openings are checked regularly and the air filters are replaced if necessary. The exterior of the casing is cleaned to ensure heat conductance and the tightness of the casing and condition of the cables and other parts are checked visually. (Mäkinen et al., 2009)

2.5. Benefits of using frequency converter

The following advantages can be obtained by using frequency converters:

1. A small start-up current for the motor and a low voltage drop for the power grid:

   Three-phase induction motors have a large starting current regardless of the machine the motor is attached to. With a help of the frequency converter, the frequency and the voltage are adjusted so that the motor accelerates advantageously from the process point of view. Starting current stays reasonable and power grid’s voltage drop is smaller in comparison with a direct start-up.

2. A stressless start-up and stop to working machines and materials:

   Slow acceleration removes the fluid pressure shocks in pump drives and decreases the mechanical stress and failures of gears and v-belts for a conveyor, screw and gear drives. Smooth and slow stops keep the transferable process material on a conveyor.

3. A stepless and accurate speed control that allows the production rate to grow:

   The motor speed can be adjusted steplessly. The most common frequency range is from zero to 50 hertz but the frequency can be adjusted up to 500 hertz. An accurate adjustment and control of the speed improve the properties of the process and the quality of the end product.

4. Saving electricity:

   Controlling the power and the production rate of the devices is recommended to do through the speed control of the motor. The motor rotates at speed required by the load. The biggest savings can be achieved with the machines that have a quadratic load torque curve. In this case, the load increases in the square of the rotational speed and the power consumption in the cubicle of the rotational speed. For example, pumps and fans are such devices.

5. The Possibility of remote control:

   A frequency converter can be integrated into an automation or a control system by the means of analog and binary messages or a fieldbus. The device can be controlled or programmed from control room.

6. The programmability of a frequency converter:

   The inputs and outputs of the frequency converter are usually freely programmable. The frequency converter can in itself also have an automation system, a fully programmable PID controller.

7. Low need for maintenance:

   The maintenance of the frequency converter is mostly visual inspection from time to time. A cooling fan, an air filter and a capacitor are replaced if necessary. (Mäkinen et al., 2009)

2.6. Most common reasons for frequency converter failures

The following reasons are the most common causes for the failure of the frequency converter:

1. Improper installation:

   This is often a combination of selecting inappropriate cable types, gauges or fuses and neglecting the instructions of the installation manual. Problems caused by the improper installation often become apparent early at the testing and commissioning phase.

2. Cooling fan wear:

   Internal cooling fans are in constant stress in continuous use and are often the first part to fail in frequency converters. However, the failure of the cooling fan does not always mean the failure of the whole device. The cooling fan can often be replaced with a new one but the failure always causes an unwanted downtime in the use of the drive.

3. Capacitor wear:

   Capacitors wear electro-mechanically during the use. Especially electrolytic capacitors have a limited life time and age faster than dry components. Capacitors are also temperature sensitive. High temperatures, often caused by a high current, can affect the life time of the component negatively.

4. Overuse:

   The life time of the components that are used at a rating higher than its operating limit will decrease and eventually fail. Most frequently these components are located in the inverter bridge of the frequency converter.

5. Over- and undervoltage and current:

   If either the voltage or the current is at the level that the frequency converter is not rated for, it is possible that the components will be damaged and eventually they will fail. Often the excess heat generated by the spikes in voltage or current is the reason for this damage. (Wilkins, 2014)

3. RELIABILITY ENGINEERING

When the equipment in the production starts failing, one way to search for the reason behind the failures is the statistical reliability analysis of the failure data. Word reliability often also includes terms availability, maintainability and safety. Availability tells how well the equipment keeps its functioning state in its environment. The more equipment is in use during its lifetime, the better the availability is. Maintainability tells how time consuming it is to maintain the equipment. The less time it takes, the better the maintainability. Safety stands for equipment's ability not to harm anyone or anything in its lifetime. Together reliability, availability, maintainability and safety are abbreviated as RAMS. In the reliability engineering the main purpose is to develop ways and tools for assessing RAMS of components, equipment and systems. (Birolini, 2017) In pulp and paper industry all unnecessary production breaks are minimised to keep the production both cost and time effective. Integrating reliability engineering in the process helps the production to achieve this goal.

3.1. Reliability

Reliability expresses the probability for an item that ”it will perform its required function under given conditions for a stated time interval.” Reliability is normally expressed by *R*. Qualitatively reliability can be defined as the ability of the item to remain functional and quantitatively it tells the probability that no operational interruption will happen during a stated time interval. Reliability applies to both repairable and nonrepairable items. (Birolini, 2017) Frequency converters are sometimes repairable, for example if the smoothing capacitor fails. Sometimes the damage can be so severe that the frequency converter is beyond repair and it needs to be changed to a new one. In this thesis both repairable and nonrepairable frequency converters are researched. A common factor for inspected frequency converters in this thesis is that they have failed so that repairs or replacement are needed.

For reliability to make sense, a numerical presentation of reliability, for example $R = 0.95$, must be accompanied with a definition of required function, environmental, operation and maintenance conditions, mission duration and the state of the item at the beginning of the mission. (Birolini, 2017)

3.1.1. Characteristics of reliability

The simplest way to express reliability is to compare the amount of functional items with the entire item base. Reliability *R(t)* is the number of functional items *I(t)* until the moment *t* divided by the whole item population *N* according to

$$R(t) = \frac{I(t)}{N}. \tag{1}$$

Reliability function *R(t)* tells the probability if item, component or system will work at the time *t*, or that it has not failed by the time *t*. (Kiiski, 2012)

Failure function *F(t)* is a distribution function of failure probability. It tells the probability that component or system will break in a certain time. Failure function is integral of failure density within a certain time as shown in (2).

$$F(t) = 1 - R(t) \tag{2}$$

Failure density tells the statistical probability for failure within a certain time. If we test for example ten components until every component fails, and then mark the result up every day and during day three two of the components fail, the failure density for day three would be 0,2. Failure density *f(t)* can be expressed as a failure functions *F(t)* time derivate. Failure density is defined in accordance with (3).

$$f(t) = \frac{dF(t)}{dt} \tag{3}$$

Failure rate $\lambda(t)$ tells the frequency of failures in a system or a component. Failure rate can be used to deduce when systems or components lifetime is about to end so it works as a measure of the reliability of the item. Failure rate depends on the failure density $f(t)$ and reliability function $R(t)$ according to (Mäkelä, 2017)

$$\lambda(t) = \frac{f(t)}{R(t)} = -\frac{dR(t)}{R(t)}. \tag{4}$$

3.1.2. Exponential distribution model

Exponential distribution is defined in (5).

$$R(t) = e^{-\lambda t} \tag{5}$$

Exponential distribution is very popular mainly for its simplicity and it fits well in describing the reliability of complex systems especially during their operational phase. One of the exponential distribution model's features is that item's or system's probability for failure is always the same regardless of its age. This means that in exponential distribution model the item's failure rate λ is always constant. This is often not true and this is why the exponential model is suitable for describing only a small part of failure mechanisms.

Mean time to failure or MTTF gives items average lifetime expectancy before its first failure. MTTF is defined by the average value of the reliability function $R(t)$ which can be also be expressed as the expected value of the density function $f(t)$ of time until failure. These formulas are shown in (6).

$$MTTF = \int_0^\infty R(t)dt = \int_0^\infty tf(t)dt = \int_0^\infty t\lambda e^{-\lambda t}dt = \frac{1}{\lambda} \tag{6}$$

In exponential distribution model MTTF and failure rate λ are thus reciprocal numbers of each other and the failure rate is a constant. (Mäkelä, 2017)

MTTF is used in cases where the device is unrepairable. When the parts or components of the frequency converter are damaged, they are often just replaced with new ones.

MTBF is different from MTTF in a way that it takes into account the time used for repairs so it gives the mean time between a failure and a last time the device was repaired and put back into production. (Birolini, 2017) Repair times are often unknown for frequency converters, because they are just replaced with new ones. Failured units, if repairable, are then repaired and stored for later use. MTBF can still give an indication of how often the devices fail on average. MTBF can be calculated if the time period (t) and the amount of failures are known (N_f) during the time period.

$$MTBF = \frac{t}{N_f} \tag{7}$$

3.1.3. Weibull distribution

A wider range of different systems can be described by using the Weibull distribution which is a generalised version of exponential distribution. (Birolini, 2017) It can characterize all increasing, constant and decreasing failure rates and can be very helpful when decisions involving life-cycle costs and maintenance have to be done. With the help of Weibull analysis, the point where a certain percentage of items will have failed can be calculated. This helps to estimate when to replace the items and the developing maintenance schedules and inventories of replacement units. (Mraz, 2013)

Weibull distribution has two parameters and the reliability function $R(t)$ is described

$$R(t) = e^{-(\frac{t}{\eta})^{\beta}}. \tag{8}$$

Parameter η describes the characteristic life of an item. It tells when 63.2% of the population has failed. Variable t is the time of interest for the item. When equation is solved, user can insert time into it to get the probability for the item to last that certain period of time. (Mraz, 2013)

Parameter β is called the shape parameter because it defines the slope shape of Weibull distribution line that best fits the data points. When β is smaller than one, items' failure rate decreases with time. This means that item will fail soon after commissioning. In this case Weibull resembles the gamma distribution. If β equals one the failure rate is constant as in the exponential distribution model. If β is bigger than one, the failure rate increases with time meaning the older items are more likely to break than the new ones. In cases where β is two, analysis becomes the Rayleigh distribution and if β is bigger or equals three, data resembles a normal distribution. (Mraz, 2013) Examples of how β defines the shape of Weibull reliability function are given in Figure (3.1).

One way to calculate these parameters is to linearize the Weibull distribution. This is done by taking a natural logarithm twice on both sides of (8). This is presented in (9).

$$ln(-ln(R(t))) = \beta ln(\frac{t}{\eta}) = \beta(ln(t) - ln(\eta)) \tag{9}$$

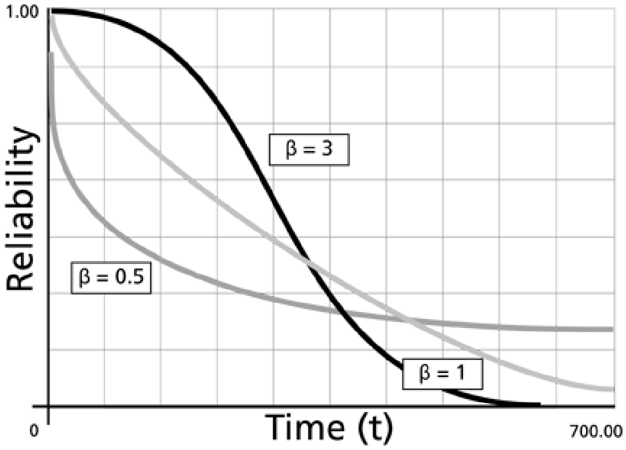


Figure 3.1: Different shapes of Weibull reliability function. The shape of the curve is defined by parameter β, the shape parameter. (Reliawiki, 2019)

Selecting new variables as $x = ln(t)$ and $y = ln(-ln(R))$ gives a linear equation (10).

$$y = \beta(x + ln(\eta)) \tag{10}$$

The Weibull model is then formed by calculating new variables x and y from failure data. By using linear regression analysis slope β and constant term $\beta ln(\eta)$ can be calculated. Characteristic life η can be solved from constant term.

The accuracy of Weibull analysis depends on the quality, quantity and type of the data and it has several requirements to do a valid analysis. First, data must include item-specific failure data and time to failure has to be known for the population. Second, you have to have the information about the items that did not fail. Third, it is highly recommended to know failure mode root causes and separate them. However, Weibull analysis can be done even if all these points are not known. In this case analysis is not as accurate as with specific failure data but it can still be very valuable in analysing the reliability of an item.

Two different categories of data are used in a Weibull analysis which are time to failure (TTF) and censored or suspension data. In TTF data tells how long an item lasts before breaking. Censored data has failure data that has been saved over the operating period of an item and it has three different categories, right censored, left censored and interval data. Right censored data includes operating times for items that did not fail. If data is left censored, the exact time of failure is unknown. It is just known that the failure happened before it was found. Interval data includes all failures within a specific time interval but exact time to failure is not known.

Two parameter Weibull analysis is done by plotting the data manually or by software on Weibull probability paper. Failure times are ranked based on the amount of items that did and did not fail at that specific time. Most popular rankings resemble the mean and median of the data. A line that best fits the data points can be used to determine how well the Weibull analysis describes the data. This line gives item's characteristic life η and the correlation coefficient of the line describes how well the line fits the data.

If the fit is not good, Weibull analysis can still give a direction to a more suitable distribution or suggest a better way to interpret the data. There are many different reasons why the fit might not be good. For example, unidentified failure modes, a change in the major cause of failures or different or changed environmental conditions all can influence the data and the fit. Plots that have the so called knees (corners) or S-shapes are the result of these problems.

When the Weibull parameters are calculated, reliability can be estimated using the reliability function $R(t)$ or reading it from Weibull reliability plot's y-axis. Reliability function can also be used for example to calculate when the population's reliability is at a certain level. When the reliability is for example 90%, the calculation is called B 10 life of an item. (Mraz, 2013)

3.2. Reliability centered maintenance or RCM

Unexpected failures may be expensive in pulp and paper industry. In Stora Enso Imatra mills it has been calculated that the loss of production costs is approximately 10400 €/h when a production line is down. (Mäkelä 2017) To prevent and minimise these unexpected standstills and failures, reliability centered maintenance (RCM) is used in many different industry areas nowadays.

RCM is a systematic procedure of maintenance that represents an ongoing process to always pick the most effective and optimal methods of maintenance for every process. The main goal of RCM is to implement the maintenance cost efficiently with right actions and times so that the reliability and safety of every process and equipment can be maximised.

RCM utilises many different maintenance strategies and aims to specify the right relations between them. Three main maintenance strategies used are the corrective, preventive and condition-based maintenance. In corrective maintenance, the device is used until it breaks and then it is fixed. Preventive maintenance tries to find faults with systematic inspections before the equipment breaks. Condition-based maintenance is used when the need arises. When one or more indicators show that the equipment is going to fail soon, the maintenance is performed.

Formerly, maintenance was carried out after the equipment failed and it was thought that the failures were directly proportional to the age of the equipment. Nowadays it is known that the connection between failures and service life is actually smaller than thought before and equipment can follow many different failure curves during their service life. It has also been found out that a large part, as large as 40%, of the preventive maintenance carried out is actually unnecessary. In preventive maintenance, equipment might be disassembled to examine their condition. This action often just increases the likelihood of equipment failure and takes also a lot of time. In addition, maintenance methods can not be targeted and planned well enough. (Kiiski, 2012)

During the last 20 years there have been huge changes in maintenance and the need for it has grown because processes and equipment have become more complex. At the same time new techniques for maintenance have been developed which have made it possible for producers to keep even better care of their systems and items. Maintenance organisations have developed and become more professional and expectations by companies towards maintenance have become more demanding. Companies want to make sure that their production and products are cost effective, safe, high quality and support sustainable development. Processes and equipment are monitored more closely to keep their reliability and maintainability on a high level and failures are inspected more thoroughly than before. Computer software offer many ways to explore these failures and their effects on production. Employees are also becoming more qualified to organise, plan and execute new and different maintenance methods in order to improve reliability and prevent failures.

For RCM to be applied properly it is important to continuously collect information about the performance of the process. The acquired data helps to make the maintenance plans better and to design better solutions to carry it out and to schedule it right. It should be considered what the function of the device is, what kind of failures occur in the device, what are the reasons behind those failures and what to do to decrease the probability of failures and their consequences. (Kiiski, 2012)

RCM is based on the next seven steps which are carried out together with operational and maintenance staff. All the steps are considered individually for every process.

1. Define the functionality and performance of the device in its current operating environment.
2. Find out the fault conditions and malfunctions.
3. Declare the ways of failures.
4. Find out how failures affect the process.
5. Find out the consequences of the faults. The hidden types of faults, the functional and the non-functional consequences as well as the safety and the environmental consequences should all be taken into account.
6. Define the most appropriate maintenance strategy for each device.
7. Define the actions according to the principles of the RCM. (Kavala, 2010)

3.3. The cost impacts of reliability in pulp and paper industry

In pulp and paper industry unexpected stoppages are expensive and undesired. The processes are ongoing and the aim is to keep the utilisation rate as high as possible to minimise losses.

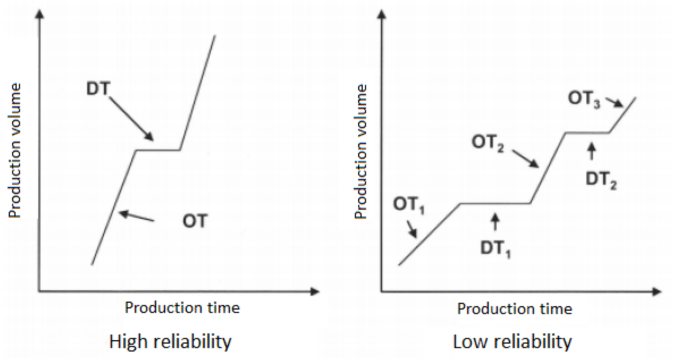


Figure 3.2: The effects of high and low reliability in production volumes. It takes more time for low reliability to achieve the same production volume with high reliability. DT means downtime and OT operating time. (Kunnossapitoyhdistys ry, 2007)

The good reliability of equipment helps to keep the utilisation rate high, which directly affects the production volume and productivity level of production. The effects of reliability on production are presented in the Figure 3.2.

If the level of reliability is low, the process will stop more often, the production volume is smaller and the productivity level will drop. When the equipment breaks down, the maintenance will repair or replace the device with a new one in order to continue production. Continuous breaks and long repair times affect productions reliability and cost efficiency negatively. At high reliability mills, the equipment will not break as often and repairs are performed quickly. Reliability therefore has a great impact on the utilisation rate and costs in pulp and paper industry.

4. FREQUENCY CONVERTERS AND THEIR MAINTENANCE IN IMATRA MILLS

Stora Enso has two mills in Imatra, one in Kaukopää and one in Tainionkoski. First frequency converters came to the Mills in the late 1980's and the amount has increased greatly since then. Nowadays Kaukopää and Tainionkoski Mills together have a total of 2447 active frequency converters in production. This chapter presents all the information about the frequency converters like their manufacturers, production lines, operational environment, different uses and maintenance procedures.

4.1. Searching for the frequency converters fault data

All the data used in this thesis was acquired from Stora Enso's database system and through staff interviews. The database system SAP was introduces in May 2003. All the production lines have their own codes in the system and all the devices are registered there with their own device numbers. With the help of these codes and numbers, all the devices are linked to their own production lines. When a production line suspects or notices a fault, a fault entry is recorded in SAP. The maintenance organisation makes a work order of the entry and directs it to the organisation responsible for the maintenance of that production line.

When searching for the fault data from SAP, the problem was that there were no straight ways to find reports that deal with the frequency converters and their problems. Fault reports are recorded in the system with code numbers 11 and 21 and there are tens of thousands of reports with these numbers. To find the reports that deal with the frequency converters, a search had to be modified so that it checks the topic and the content of the report for certain key words. After this search, all the unnecessary reports were excluded. The results consist of 228 pages and one page has from one to eight reports depending on the length of the report. The first report that was included in this study was dated the 15th of April 2009 and the last the 16th of August 2018 so the review period was 3410 days long.

To find the reports where frequency converters were actually failed, all the reports had to be read and sorted. Failed ones were considered the ones where the frequency converter stopped unexpectedly and had to be repaired somehow or completely replaced with a new one. Problems where frequency converters did not fail were calculated separately. These were the problems like overcurrents or motor's thermistor triggers that could often be bypassed quickly by resetting the frequency converter or the motor.

Fan problems were separated from other failures because they proved to be somewhat different. Fans are often treated as individual devices that are part of the frequency converters. Fans are frequency converters the most fault-prone parts because they are the only mechanical and physically moving parts. The life cycle of the fan in Imatra Mills is between two to five years. When a fan fails, it does not mean that the frequency converter will fail too. Often a frequency converter will function normally for a while after the fan fails and then stop for high temperature alarm. Often failed fans could be replaced with an external fan during the production and then changed later during the scheduled stoppages. As told earlier, fans are regularly changed in preventive maintenance. This helps to keep the fan related failures as low as possible.

To get a better understanding and more knowledge of the Mills' frequency converters and problems related to them, six interviews with the Stora Enso and Efora staff were performed. These interviews discussed the Mills frequency converters, their maintenance, storaging, problems and ways to make their reliability better in the Mills.

4.2. Installed base in Imatra Mills

Imatra Mills frequency converters are manufactured by 13 different manufacturers. The total number of devices has been calculated from SAP, which is the database for all the production lines and equipment in Imatra Mills. Every frequency converter has been given its own device number which helps to calculate the amount. Figure 4.1 shows how the installed base is divided between the different manufacturers.

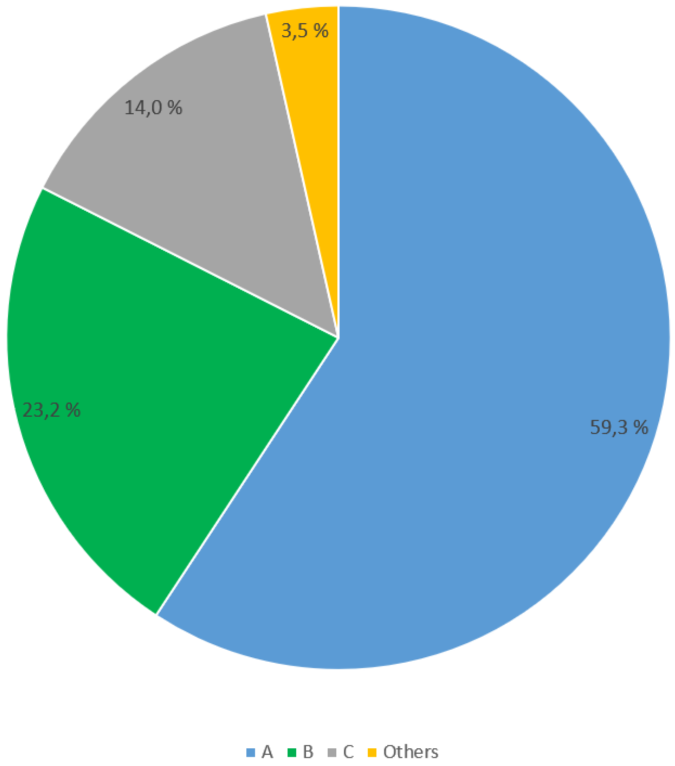


Figure 4.1: The installed base of frequency converters in Imatra Mills sorted by manufacturers. Manufacturer A has over 50% share of the installed base.

As the figure shows, there are three different manufacturers, which account for 96,5% of the total amount. Manufacturer A has a total of 1450 (59,3%) frequency converters, B 568 (23,2%) and C 343 (14%). In addition to these three largest manufacturers, there were 86 (3,5%) frequency converters manufactured by ten other manufacturers.

4.2.1. Life cycle status

All three main manufacturers have their own life cycle models but they are all very similar in practice. Figure 4.2. gives an example of how the life cycle policy works.

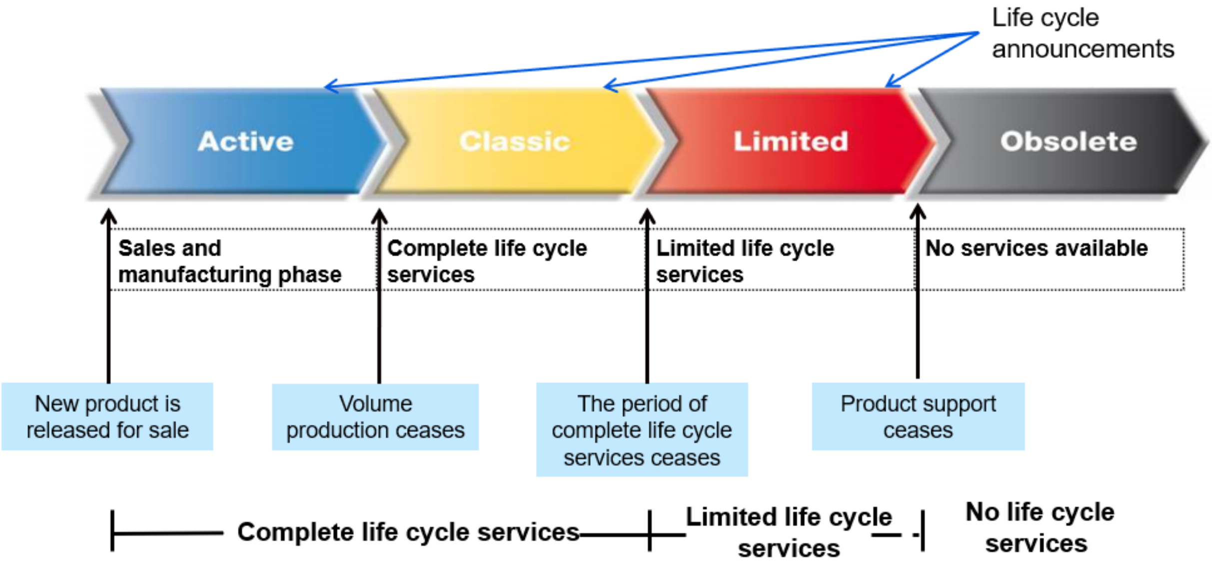


Figure 4.2: An example of a life cycle model by ABB. In this policy, the life cycle of the frequency converter has four different phases called active, classic, limited and obsolete. (ABB, 2019)

In this model, the active phase means that the product is in active sales and is still manufactured. It has a full range of life cycle services available.

In classic phase serial production has ceased but the product is often still available for spare part or extension purposes. It still has a full range of life cycle services and the product could be available for enhancement through upgrade or retrofit solutions.

The limited phase means that the product is no longer available. It has only limited range of life cycle services and spare parts' availability is limited to available stock. When the product reaches this phase, it is highly recommended to migrate to active products.

In the obsolete phase there are no services available. The product is no longer in production and it has no life cycle services available. In this phase too, it is naturally crucial to migrate to active product generation.

Manufacturers give life cycle announcements to customers in advance before product's life cycle status changes. This helps customers to prepare for needed actions like renewals and retrofits.

Most of the Mills' frequency converters are in the active or classic phase but there are a total of 687 frequency converters in the obsolete phase. Obsolete devices are found in the two biggest manufacturers and they are divided according to Figure 4.3.

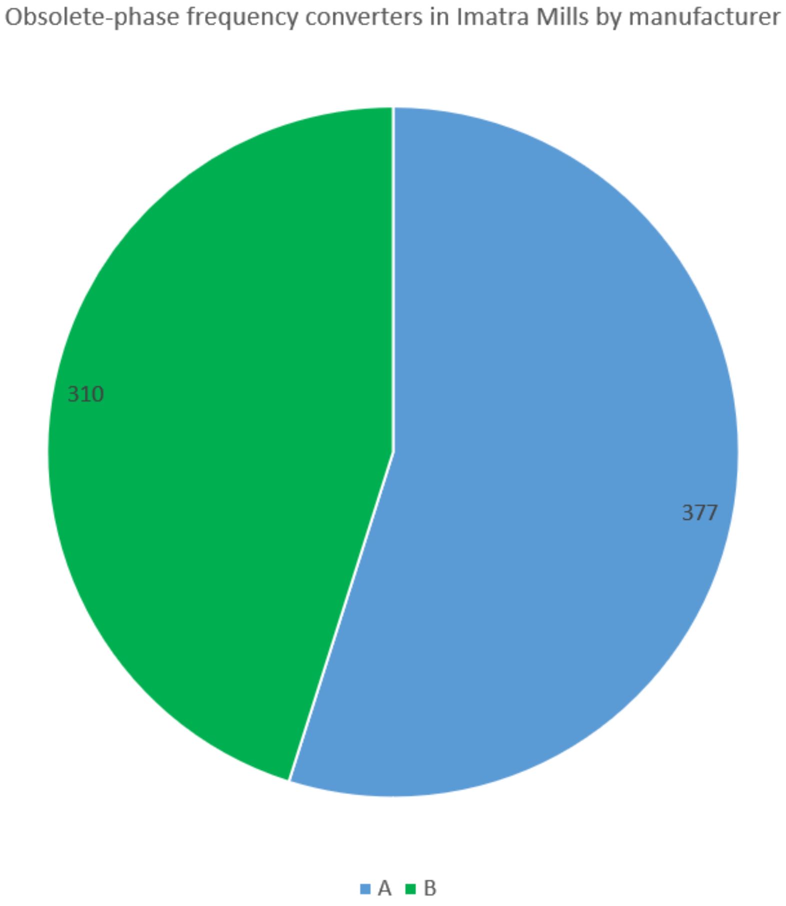


Figure 4.3: Frequency converters that are in the obsolete phase are divided by two main manufacturers. The total number of frequency converters in the obsolete phase is 687, which is 28.1 percent of the whole installed base.

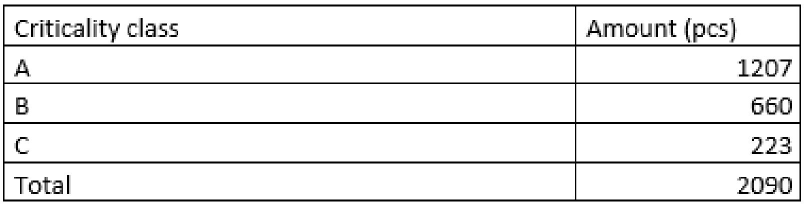
From the total number of 2447 frequency converters, 687 (28.1%) are in the obsolete phase. 377 (54.9%) of these are frequency converters of manufacturer A and 310 (45.1%) of manufacturer B.

4.2.2. Criticality classification

All the operational lines in production have their own criticality classes. The classes are based on the operational line's criticality for the production and have been evaluated together with each lines line organisations. The classification takes into account the safety, environment, quality, running time, production impacts and costs of each line. All these points are scored individually and scores are then summed up. The number obtained determines the line's criticality class. Criticality classes are A, B and C, A being the most critical. This classification applies to all devices at the operational line. The Table 4.1 shows how the frequency converters are divided into different criticality classes.

As the table shows, there are 2090 frequency converters that have been given the criticality classification. The ones excluded from this classification have not been classified yet or are not that vital for the production itself. 57.7% of the installed base with criticality classification is classified in class A. These are the frequency converters that are important for the continuation of the production and in case of failure will be immediately repaired or changed. Class A frequency converters are very

Table 4.1: Frequency converters criticality classifications in the production.



Criticality class	Amount (pcs)
A	1207
B	660
C	223
Total	2090

important or critical and failure could harm the whole process. 31.6% of the classified ones are in class B. Class B equipment are important and their impact on the process is moderate. 10.7% of the equipment are in class C. These frequency converters are not that vital for the production and are so called common equipment. Their impact on the process is negligible but they still need to be kept in good condition.

When comparing the number of obsolete equipment to criticality classifications, there are 185 class A obsolete frequency converters in production by manufacturer A and 105 by manufacturer B. This means that 290 class A frequency converters are in the obsolete phase which is 24% of the criticality class A and 11.9% of the whole installed base.

4.3. Operational places and applications

All the frequency converters of the mill are located indoors in the centres reserved for electrical devices. In the centres, small frequency converters are installed in the hubs. Due to the lack of space and partly practicality, small converters have also been installed on the walls. The bigger frequency converters have their own cabinets. Hub and cabinet installations are shown in Figure 4.4.

Figure 4.4: Small frequency converters are installed in hubs as shown on the left. Bigger ones have their own cabinets like the ones on the right.

There are several centres in the mills' area, but their conditions are quite similar. Centres have air conditioning, they are overpressurised and air conditioners have chemical filters. (Inkilä, 2018) Air-conditioning keeps the air cool and dry. Conditioning recycles the same air in and out through the heat exchanger where the air is cooled down. From the heat exchanger, the heat flows out and new cooling air for the exchanger is taken in. Overpressurisation keeps the centres dust and bug-free. When the door of the centre is opened, the air flows out of the centre instead of going in. The chemical filters filter all harmful chemicals and other impurities from the air. All in all environments are very ideal for frequency converters.

There are many different applications for frequency converters in the mills. The most common applications were pump, conveyor and fan applications. Frequency converters must be dimensioned for every application as told in Chapter 2.2. All the frequency converters in production are dimensioned mainly for the heavy duty. This is done because the cost differences between heavy and normal duties are not that big and on a large scale, it is better to leave a little more operating margin for individual devices than to drive them to the limit. All the different application types are listed below:

1. Pumps
2. Conveyors
3. Fans
4. Cutters
5. Cranes
6. Screw and fabric presses
7. Unloaders
8. Mixers and grinders
9. Rolls
10. Elevators
11. Air conditioning

The production processes in the mills are ongoing and the equipment required is constantly in use, with the exception of stoppages, so the use of frequency converters is often continuous. For frequency converters, continuous use is often better than cyclic use. In cyclic use, the device would be stopped and started frequently or the size of the load varies greatly. This would make the frequency converter's temperature rise and fall repeatedly. If there is enough humidity in the air of the centre, it could condense on the surface of the cooling device.

Stora Enso's subsidiary Efora is responsible for the maintenance planning and implementation. The maintenance is carried out in accordance with safety weighted RCM strategy. In the spring of 2014, the mills moved from the shift maintenance to user maintenance model. Nowadays Stora Enso's user maintenance performs repairs if the maintenance staff is not available. (Mäkelä, 2017)

The dependability and reliability of the production lines and frequency converters are optimised with the help of Efora's optimisation strategy for dependability. Dependability optimisation aims for continuous and uninterrupted production throughout the life cycle of the mills with cost effective maintenance.

Dependability optimisation is applied for all the maintenance activities in the Imatra mills. The operations are based on the high quality proactive maintenance and good availability of spare parts. Use and maintenance information is analysed to provide solutions for dependability management and maintenance staff. Root cause analysis is done on the possible costs of production losses and reliability engineers analyse problems in order to overcome them. The continuous practice of dependability and reliability is maintained through continuous improvement meetings and discussions. (Mäkelä, 2017)

4.3.1. Frequency converters maintenance

In Imatra Mills, every frequency converter that is in production has its own preventive maintenance scheduled in SAP. This preventive maintenance includes external inspection and checking the functioning of the fan. External inspection is done visually to check that the frequency converter is clean from dust and other dirt and that it looks normal inside and outside. The fan is checked with a vibration meter that can tell if the fan bearings are starting to wear out. Fan replacement intervals vary slightly between different manufacturers, but normally they are changed every three to five years.

Replacement units located in the storage are also maintained. The electrolytic capacitors of intermediate circuits must be periodically restored with voltage treatment to maintain their operating condition. This is done by connecting the capacitor to the charger that will slowly rise the voltage level to the operating voltage of the capacitor. This voltage treatment is scheduled in SAP and it is done every one to two years.

When a frequency converter breaks, user maintenance or maintenance staff will assess the situation. If the failed unit is a small one, installed inside the hub or mounted on the wall, it will immediately be changed to a new unit. A replacement unit is taken from the storage and the failed one is sent to the service station or scrapped depending on its condition. If the failed unit is big and it has its own cabinet, it is very hard to replace it because they are heavy and it can take several hours to replace them. That is why big frequency converters are often repaired on site if possible.

5. THE RELIABILITY OF FREQUENCY CONVERTERS IN IMATRA MILLS

5.1. Analysing the fault data

During the review period from 15.4.2009 to 16.8.2018 there were a total of 1070 frequency converter fault reports. 969 of the reported faults happened in Kaukopää and 101 in Tainionkoski. Kaukopää has 2056 frequency converters so it is natural that it has more fault reports.

153 of the reports were concerned with a failed frequency converter. Fan failures are excluded from these calculations, because of their different nature as stated earlier. Mean time between failures in all frequency converters in Imatra Mills according to the (7) was

$$MTBF = \frac{3410\ days}{153\ failures} \approx 22 \text{ days.}$$

This means that on average 16 frequency converters failed yearly during the review period.

129 of the failed frequency converters were in Kaukopää and 24 in Tainionkoski. Figure 5.1 shows the number of failed frequency converters yearly.

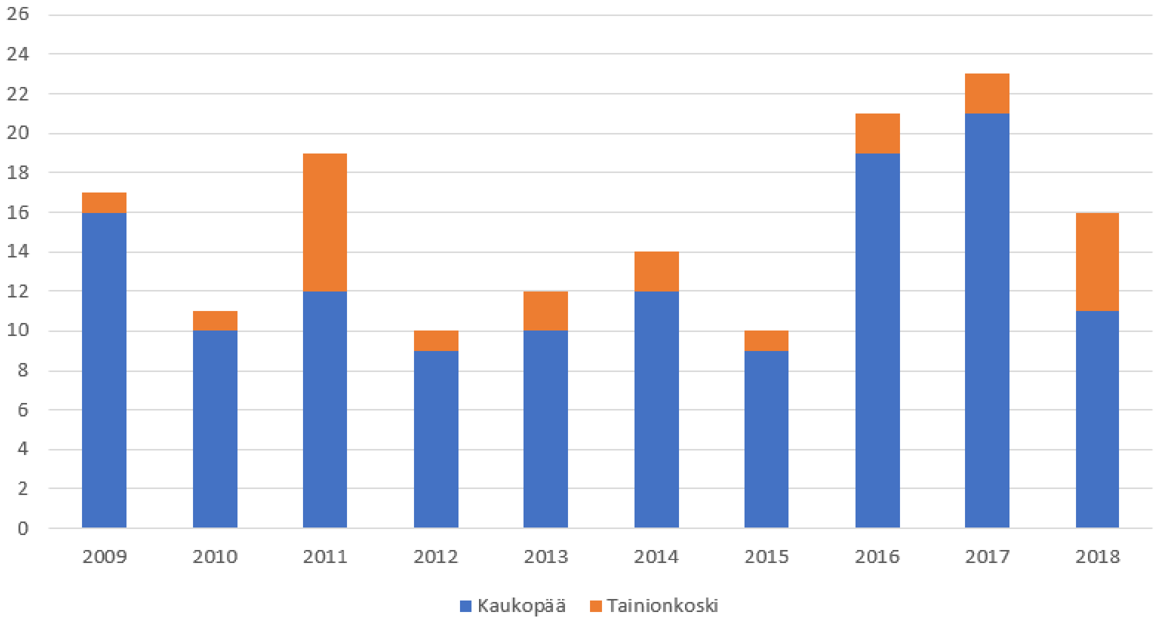


Figure 5.1: The number of failed frequency converters in Imatra Mills yearly. The failed units of Tainionkoski are shown in orange and Kaukopää in blue.

As the figure shows, in 2016 and 2017 had most failures. 23 failures in 2017 and 21 in 2016. The lowest number was in 2012 and 2015 when only ten frequency converters failed. On average every 11th frequency converter failed in Tainionkoski and Kaukopää.

The reason for varying highs and lows might be the wide age distribution of the equipment. Some of the devices are quite new, only several years old, while some have been introduced in the late 80's. Frequency converters are in the different phases of their life cycles and have been in use for different lengths of time. Different models by different manufacturers vary from each other so they endure the use differently and fail at different times.

According to the staff interviews, the number of failed units seems realistic. For the whole review period, the reliability R according to (1) was

$$R = \frac{2447-153}{2447} 100\% = 93,747...\% \approx 93,7\%$$

From this sample it can't be deduced if the failures are going to increase or decrease in the coming years, because the number of failures has changed from year to year. It is very likely that the failures will remain averagely at the same level if the number of devices stays the same. However, the reliability of the installed base in general view at the moment can be said to be on a good level. Approximately 16 failed units per year means the yearly reliability of 99,35%. This means that the annual average of failed units is less than one percent of the whole installed base.

5.2. Different fault types

All the different fault types are listed and shown in Figure 5.2.

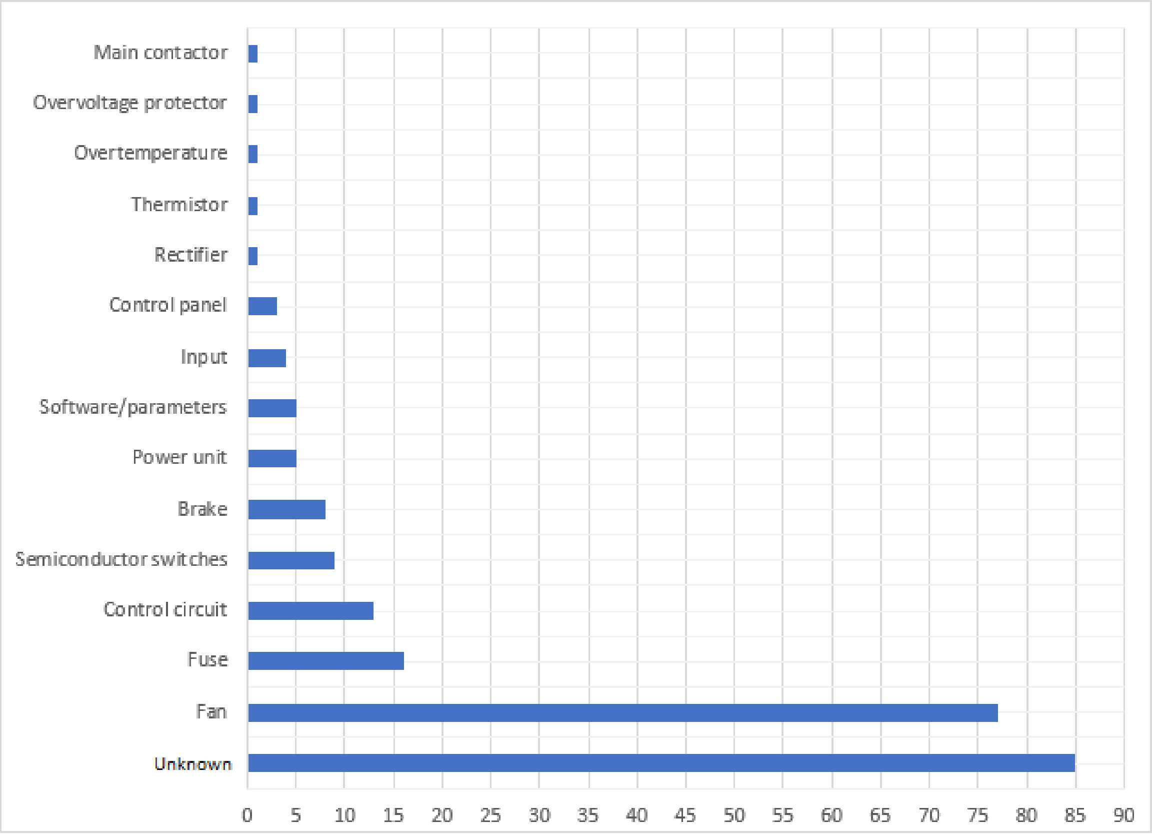


Figure 5.2: Different fault types of the frequency converters in Imatra Mills.

Unknown ones were the units that did not have a specific reason for failure in the failure report. Often the report tells that the frequency converter in question just failed. There are 85 of these units which is 37% of all failures. To be able to specify the reason for failure would be important for accurate reliability calculations and to get better understanding why frequency converters break. The reasons for not specifying the failed part are several. Sometimes the frequency converter is so badly damaged and burned that it is simply impossible to determine the exact cause of the failure. Sometimes it is not seen useful to spend time searching for the reason. If the failed unit is small and quickly replaceable, it is just removed and replaced with a new one without a closer look.

Fan problems were the biggest single problem with the frequency converters and this was also stated in all of the interviews. Even though the frequency converters have scheduled fan changes, the number of fans that failed in the middle of production is still quite high. During the review period there were 77 reported fan failures which is 33% of all failures. Based on the interviews the reason for this high amount is the poor and degraded quality of fan bearings. As a result, the fans' replace interval has decreased continuously.

Fuse related problems were the second biggest problem with the amount of 16 failures. Fuses trigger and cut the frequency converter from the power supply when the current value exceeds a certain level so they work as a protection device to prevent further damage. The sudden increase in current is often the result of other problems with the frequency converter. Fuses itself are not the cause of these problems, but in these cases reports did not give a better specification of the problem.

RMIO-circuit failures were the third biggest problem with the amount of 13 failures. Control circuit problems are often due to corrosion caused by moisture from the air. These problems can be prevented by using conformal coating like lacquer in the circuits.

Semiconductor switch failures were the fourth biggest problem with the amount of nine failures. Semiconductor switches have to withstand high powers and because of their threshold voltages, there can happen large power losses that warm up the switches. Variable temperature and variation in the quality of the switches can cause failures in the semiconductor parts of the frequency converter. There were a few reports telling that the frequency converter was failed due to a saturation fault. This means that the voltage across the semiconductor switch, like inverter's IGBT, in the conducting state has grown too big and the switch has failed.

Other listed problems are quite self-explanatory with the exception of software and parameter failures. In these cases frequency converter stopped in software failure or due to losing all the parameters. Even though the parameters were re-entered to the frequency converter, they would be lost again after a short while.

5.2.1. Other problems

During the review period there were 840 frequency converter related problems where frequency converters did not fail but had to be reset or stopped for a while to be able to continue the production. Reasons for these are many. For example, over and under voltage or current, saturation, overheating or otherwise incorrect operation. Often these problems are not caused by the frequency converter itself but by the production equipment it controls. Overheating, jamming or high RPM of the motor can as well be the reason behind the problem, frequency converter just tells the user that something is wrong with the production. The number of these problems are yearly shown in the Figure 5.3.

The amount of problems varies yearly. Lowest it was in 2009 when only 56 problems were reported. The highest amount was registered in 2014 with 117 problems. This means that 91 problems occur yearly on average. Noticeable is the gap between the years 2014 and 2015. From the year 2009

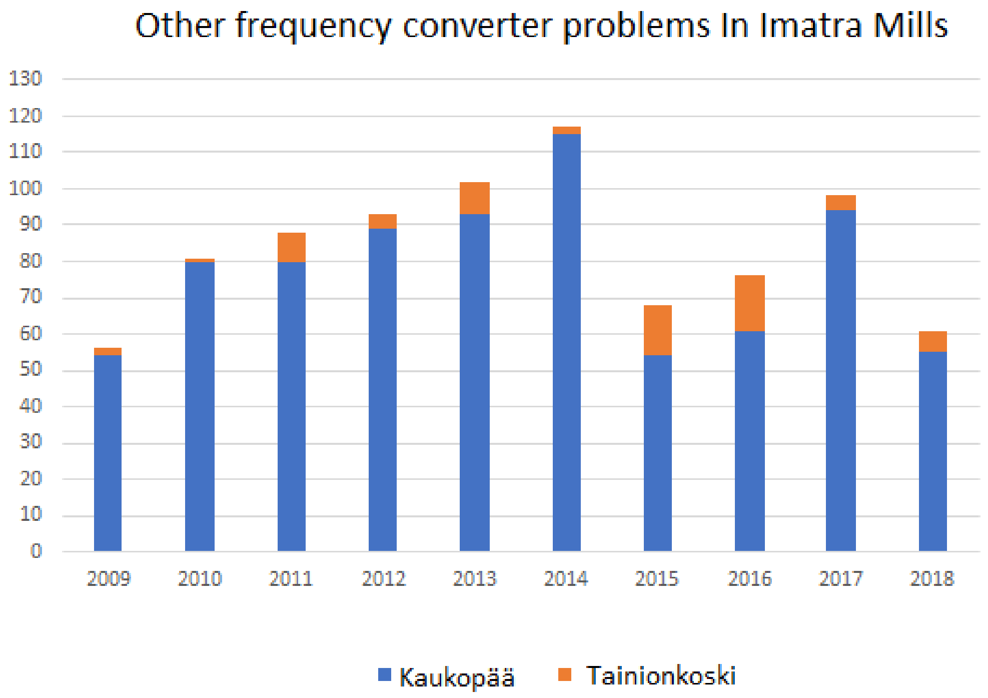


Figure 5.3: Other frequency converter related problems in Imatra Mills yearly.

the number of problems have risen steadily till the year 2014. In 2015, the number drops from 117 problems to 68 problems. After this, the number starts to rise steadily again. The reason for this drop is hard to guess. The most likely reason for this might be the changed practices in reporting. The steady rise from 2009 till 2014 can be explained by the continuous growth of frequency converters during last ten years.

The impact of these problems on reliability and availability is difficult to estimate. DT is not told on the reports and often frequency converter is not the problem in these situations as told. With the continuous maintenance of equipment and renewal of frequency converters, the number of problems could probably be reduced.

5.3. Failures by manufacturer

All the identified failed units were produced by three main manufacturers. In Figure 5.4 it is shown how the failures were distributed.

56 (36.6%) of the failed units were manufactured by manufacturer A, 55 (35.9%) by manufacturer B and 11 (7.2%) by manufacturer C. In addition, there were 31 (20.3%) failed units whose manufacturer could not be accurately specified. There were no marked target devices in the failure reports and it was often almost impossible to say afterwards which manufacturer's device was in that operational place during the failure time.

When comparing the number of failures with the installed base, it is noticed that the frequency converters by manufacturer B failed relatively more. During the review period, there were 568 frequency converters by manufacturer B and 55 units failed. This is 9.6% of manufacturer B's

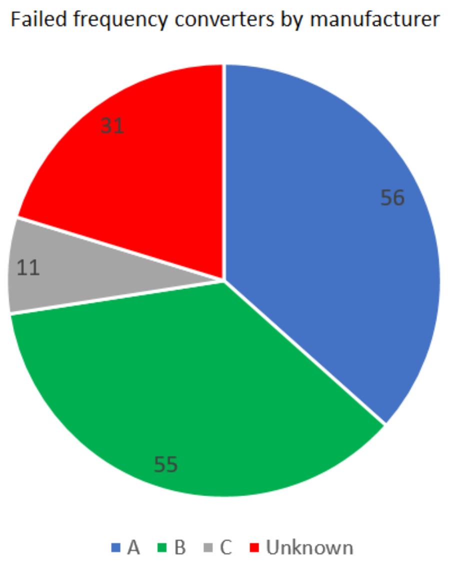


Figure 5.4: Imatra Mills frequency converter failure distribution by manufacturers.

installed base. The corresponding percentage by manufacturer A is 3.9% and by manufacturer C is 3.2%.

Fan failures by manufacturer are shown in Figure 5.5

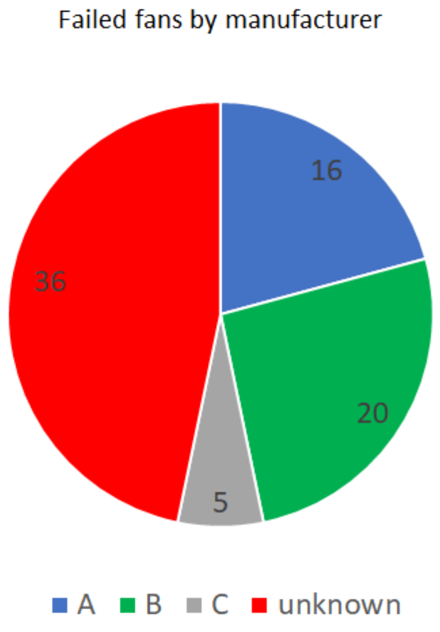


Figure 5.5: Imatra Mills frequency converters' cooling fan failures distributed by the manufacturer.

The reliability of fans by the manufacturer is hard to estimate accurately because 46.8% of the failures could not be merged with any manufacturer. Cooling fans are also replaced continuously in accordance with the maintenance program so the average lifetime of a single fan is hard to estimate. Based on the interviews cooling fan lifetime varies from 1.5 years (Inkilä et al, 2018) to four years. (Tella, 2018)

Otherwise the distribution is quite similar to frequency converter failures. Manufacturer B has the most, 20 failed fans during the review period. This is 26% of all fan failures. Second is the manufacturer A with 16 fails which is 20.7% of all failures and third manufacturer C with five failures which is 6.5%. Even though the manufacturer B has a lot less installed base than manufacturer A, it has more fan failures. Based on the interviews this result was expected because manufacturer B's fan quality was told to be less reliable. (Husu, 2018)

5.3.1. Weibull analysis

Weibull analysis was done for each manufacturer's frequency converter failure data. The failure data was ranked by time and then plotted into Weibull probability plot to see how well the data fits the Weibull distribution. With linear regression analysis, the correlation coefficient was calculated to give some numeral value for the fit. After that the data was plotted into Weibull reliability which describes how the frequency converters reliability drops over time. First analysed was manufacturer A which Weibull plots are shown in Figure 5.6.

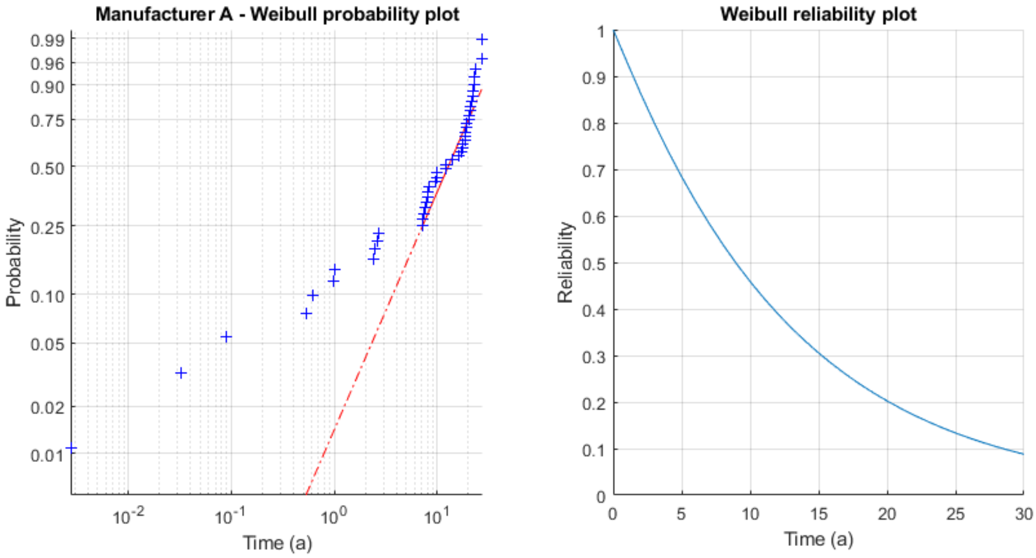


Figure 5.6: The Weibull probability and reliability plot of manufacturer A.

Probability shows that the data fits quite well into the Weibull distribution. The correlation coefficient for this data is 0,86 which is a strong positive correlation. The Weibull fit can be said to be quite good. From the probability line 0.25 to 1, the model fits well. There is a little S-shape in the points that indicates that there are different failure modes between units. Data points before the probability line 0.25 indicate that there are many units with early failures.

The reliability plot shows that the reliability of manufacturer A deteriorates quite steadily. 50% reliability rate (where 50% of units have failed) is reached in 8.9 years. Characteristic life η for manufacturer A is 12.7 years and MTTF 12.5.

When looking closer at the probability plot, interesting points can be found between points 13 and 20. There are four points presenting one certain manufacturer's A model that all have failed almost at the same age between seven and eight years and for the same reason. Three of these models have been in use in the same operational place KP-564. When looking closer to the fault reports there are many reports considering this model and this same fault reason in lines KP-564 and KP-611. Sometimes this fault could be fixed by resetting, but other times it lead to failure. This certain failure mode seems to be a type failure in this particular model.

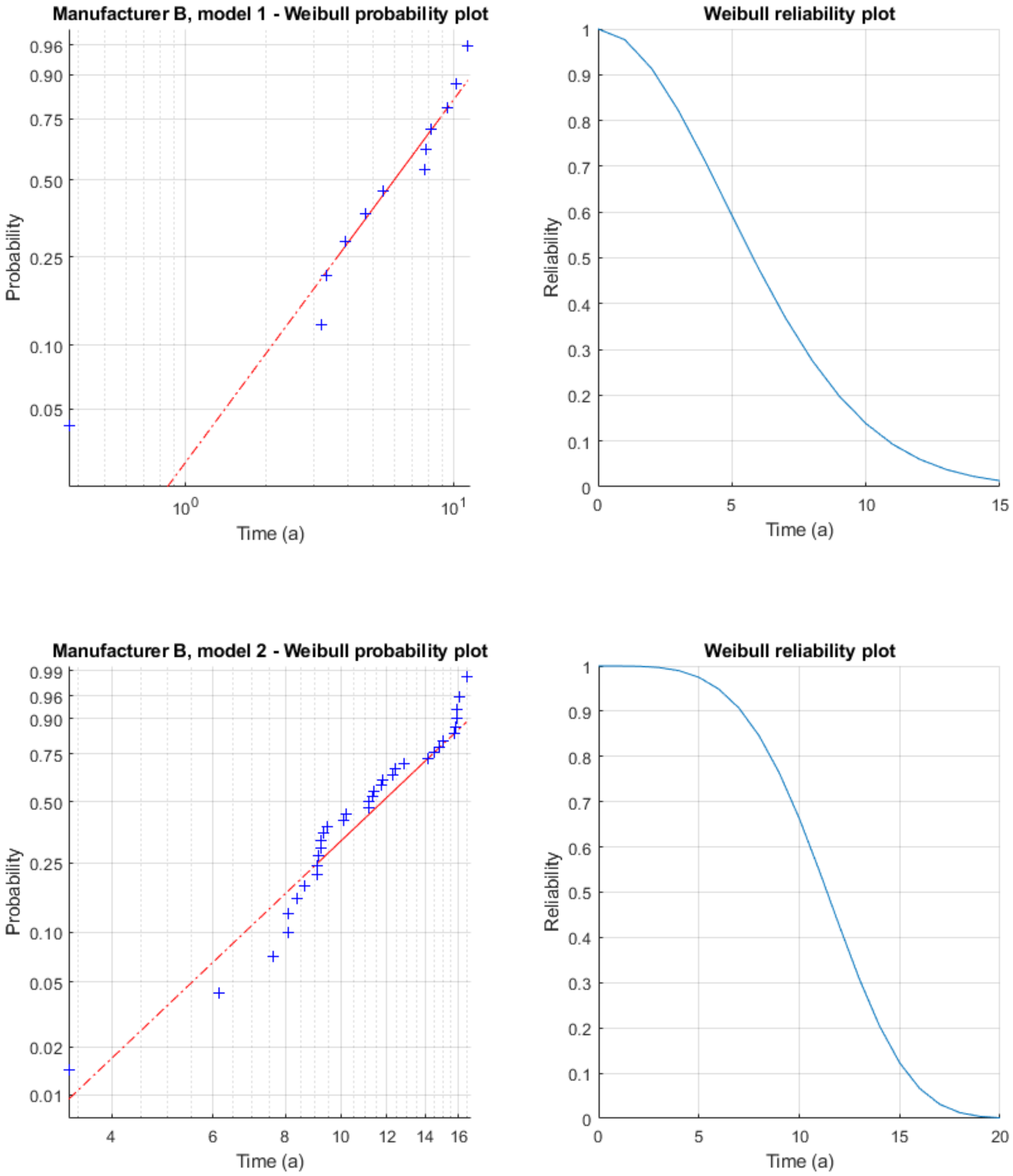


Figure 5.7: The Weibull probability and reliability plots of Manufacturer B model 1 and 2.

Figure 5.7 shows manufacturer B's model 1 and 2 Weibull probability and reliability plots. Both models have a strong positive correlation coefficient so they fit well in the Weibull distribution. Correlation is 0,85 for model 1 and 0,94 for model 2. Once again there are some S-shapes in both curves which tell that the fit is not optimal. The reliability plot shows that 50% of model 1 will fail in 5.7 years and 50% of model 2 in 11.4 years. Characteristic life η for model 1 is 7 years, MTTF 6.2 and for model 2 η is 12.5 years and MTTF 11.3.

Looking closer at points 7, 8 and 9 in model 1 probability plot it is noticed that these units are of the same type, have failed around the same age and at the same operational place KP-753-312. Fault reports have one additional unit of the same type at the same operational place. This unit is not included in the Weibull plot, because the commissioning date of the unit could not be found. Fault reports do not tell any clear reason for these failures, but it could be interesting to examine this more closely.

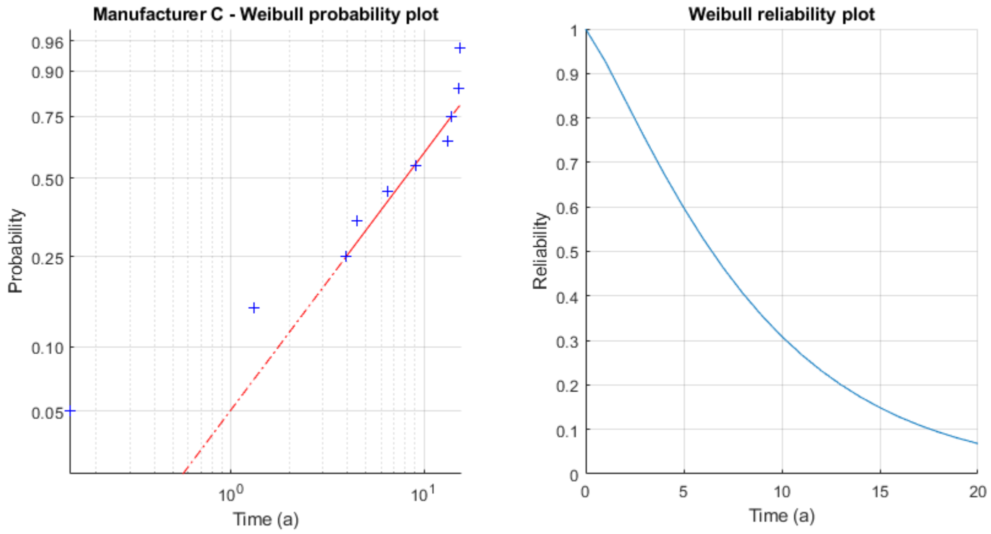


Figure 5.8: The Weibull probability and reliability plots of manufacturer C.

Figure 5.8 shows manufacturer C's Weibull probability and reliability plots. The correlation coefficient's value is 0.89 which is a strong positive correlation so this model fits also well into Weibull distribution. Like other probability plots, this plot shows some S-shapes as well. The reliability plot shows that in 6.4 years 50% units have failed. Characteristic life η for manufacturer C is 8.7 years and MTTF 8.2 years.

As the result of Weibull analysis it seems that the failure data somewhat fits the Weibull distribution. Correlations vary from 0.85 to 0.94 which means that the data has a strong positive correlation with the Weibull distribution. Manufacturer A has the longest MTTF, 12.5 years. Second comes manufacturer B's model 2 with 11.3 years. Third is the manufacturer C with 8.2 years and fourth manufacturer B's model 1 with 6.2 years. When comparing these mean lives, they seem to be realistic and in unison with failure reports and interviews. However, frequency converter's do not fail in order by age so the prediction of failure is hard. (Vinni, 2018)

This Weibull analysis is only an estimation and the fits correlation should be close to 1 to be perfect. The different fault types, differences between models and conditions create uncertainty in the analysis. Also the fact that some units have been in production from the beginning of 1990 affect these results. Some of these old models could have failed and be repaired before the introducing of SAP but we do not have the information of that. All in all it can be said that the level of reliability in Imatra mills at the moment is on a good level. Although there are a lot of frequency converters, there are relatively few failures yearly.

6. MEASURES TO PRESERVE AND IMPROVE THE RELIABILITY OF FREQUENCY CONVERTERS IN IMATRA MILLS

6.1. Renewal of the installed base

Based on the SAP data and the interviews, keeping the installed base new and up to date and ensuring that every unit has a suitable replacement unit in the storage is the best way to maintain and develop reliability in Imatra Mills. During the review period, many of the failed units were in the obsolete phase on their life cycle. Every interviewee also told that renewing the units in the obsolete phase is the main target in the already ongoing renewal of the frequency converters. This ensures the availability of replacement units, repair parts and obtaining repair assistance and product support from the manufacturer on the spot when needed.

During the renewals, the number of different device manufacturers should be kept between two and three so that the know-how of production keeps on a good level. (Vinni, 2018) New units should also have a simpler user interface, because now they are often too complicated in relation to the intended purpose. In the future, frequency converters could also become part of the already fast growing trend of Internet of things. These kind of frequency converters could produce data about themselves with self-diagnosis to help production with premaintenance. (Akkanen, 2018) Stora Enso as a customer could ask the manufacturers to invest in these things in the future.

There are also some problems in the renewal process. As shown in the figure 4.3 about 28% of the installed base are in the obsolete phase which is a great number of units. Renewals are mostly made during cases of failure and standstills. During a week long standstill there is not enough time or resources to install enough new units so the process is advancing slowly. (Huhtanen, 2018)

Sometimes older models are also seen to be more reliable than the new ones and for some models this might be true. Older models were simpler and had more space inside them to ensure proper ventilation. SAP data tells that some of the older models were installed as early as 1990's and they are still working with the help of regular maintenance. Nowadays newer models have many features that are irrelevant to the pulp and paper industry when often the speed control of the motor is the only feature of the frequency converter that is needed in the process. New models may also have some unexpected problems in the early stages of their life cycle like one of the newer models has shown in Imatra Mills.

Even though renewal has its problems, it should be continued in the coming years. Reliability level of frequency converter is now on a good level (Huhtanen, 2018) and it should be kept there. Renewals should be targeted especially in the most critical class A units. One line in Imatra Mills for example still has some obsolete units in the production that in the case of failure might be fatal. These units don't have directly suitable replacement units for them so the replacement process might be hard and time consuming and so affect the production rate negatively. (Husu, 2018) Imatra mills do not yet have a common policy for renewals or centralized life cycle management for frequency converters so these should be made. (Akkanen, 2018)

6.2. Installation centers

Even though the conditions in the centers have hugely improved and thus prolonged the lifetime of frequency converters, there is still room for improvement. There are cases where rainwater has entered the interior and caused equipment failures. (Akkanen, 2018) These cases should be investigated thoroughly and prevent from happening again.

Also the temperature of the electrical centers causes problems. Sometimes the air temperature inside a center can rise too high. There have been cases where the temperature has been as high as 50 Celsius degrees. (Tella, 2018) These kind of temperatures accelerate the wearing of the equipment and shorten their lifetime significantly. Special attention should therefore be paid to the cooling of the centers. Different methods of ventilating and cooling down centers could be considered. (Akkanen, 2018)

The installation hubs are also problematic. Dimensions vary between manufacturers and models, so it is not always certain if the replacement unit fits to replace the old one. (Akkanen, 2018) This problem could be avoided by changing hubs into open walls where frequency converters could be placed more freely. This could also make the cooling of the centers and single frequency converters easier.

6.3. Maintenance and commissioning

The current maintenance period of the frequency converters varies from three to five years in Imatra Mills and regular checks are made between three to four months. (Husu, 2018) Time between checks and maintenance varies between different lines and is based on every lines installed base and the size of the cooling fan of the model. Smaller fans tend to fail in a shorter time than bigger fans. (Tella, 2018) Every manufacturer has their own guidelines for maintenance schedules. These guidelines are followed and often the time interval between maintenance is kept even shorter than recommended to prevent failures. (Huhtanen, 2018)

Even though the maintenance schedules are often tighter than the manufacturer requires, some models have problems with the fans. The quality of the fan bearings has decreased on some manufacturers which leads to an even shorter lifetime of fans. Also some model's cooling fans are very tricky and slow to change so it slows the process even more. (Inkilä et al., 2018) This means that frequency converters maintenance and check periods should be kept even shorter. The maintenance period should be between one to three years depending on the model and check period between two and three months. This could prevent more failures.

In production there have been cases where the cabling of the frequency converter has failed over time due to being bend on commissioning. The switching frequencies of frequency converters are getting faster nowadays and this might cause high peaks in the output voltage. When cables are bend, the insulation spacing gets thinner and these voltage peaks can breakdown the cable. (Inkilä et al., 2018) In the future, more attention should be paid to the durability of the cables and not install them so that they are bend. One way to prevent these kind of failures could also be frequency converters with lower switching frequency. This would mean that it would use scalar control over vector control. The problem is that nowadays many models use vector control. (Inkilä et al., 2018) Commissioning programs and knowledge should also be integrated into production. This way the production could do the commissioning without the manufacturer's help which would make the commissioning faster. (Vinni, 2018)

Replacement units for frequency converters are kept in storage. According to manufacturers, the storage units' electrolytic capacitors need to be revived every one to two years with a voltage treatment. In reality, however, over a year old stored capacitors should not be replaced without a revival in the older models. (Inkilä et al., 2018) Voltage treatments should be implemented regularly every year for the important replacement units and accurate records of these revivals should also be kept.

6.4. SAP entries

The way to fill in the fault reports in SAP should be standardised. 85 of the 153 failure reasons were marked as unknown because the failure reports only told that the frequency converter was broken. 31 of these reports did not even specify the failed unit by id number and only 18 reports included both the exact time when the failure happened and when it was resolved. This is a clear place where the ways of the RCM are not always met. To be able to know the failure reasons, manufacturers and maintenance times would be very important to further and better analyse frequency converters' reliability, maintainability and availability.

There are many important sections on the failure report entry. The failed device should always be marked with the id number and choose the right device from the list of the operational place. The operational place itself should be marked as well. The failure has to be described fully in detail in the description section and mark the estimate times of failure start and stop time. If the reason for the failure is not known, the frequency converter will always give some kind of error code or message to give some idea what might have caused the failure. These error codes and messages should also be included in the reports. The id of the notifier and the mechanic should also be marked in their own fields. In short, the better the report is filled, the more useful it is.

In addition to fault reports, there are sometimes shortcomings in the input of the device itself. There are many sections to be filled considering the frequency converter itself but the most important ones in terms of reliability calculations are the commissioning date, manufacturing date, serial number and criticality classification. These should always be filled when new frequency converters are introduced.

7. CONCLUSIONS AND SUMMARY

Frequency converters are daily part of industrial processes nowadays. They allow the electric motors to be controlled steplessly and exactly at speed and precision required by the process. A good level of reliability of frequency converters is important for the profitability and continuity of production. Production disruptions can cause large financial losses for businesses. Equipment failures will always have to be repaired and they consume time and resources. Monitoring and improving the reliability of the production equipment reduces the cost of production loss while also improving the operational reliability and safety of the equipment.

The aim of this thesis was to examine the reliability of frequency converters at the Stora Enso Imatra Mills and to consider new solutions for the renewal process of the frequency converter base in the future. The reliability study was based on fault and problem reports from the broken frequency converters collected from the SAP database and the data was analyzed by Weibull's reliability analysis. In addition, six staff interviews were conducted to discuss the frequency converters of the Mills, their reliability and the most important problem areas. Together with SAP data and interviews, suggestions were made to maintain and improve the reliability of the frequency converters at the Mills.

The work revealed that the current state of the frequency converters at the Mills is stable and the reliability is at a good level. On average 16 frequency converters fail per year, which is less than 1% of the total installed base. The average lifetime of the converters varied by the manufacturer between 6 and 12 years. However, it must be remembered that the Weibull analysis of the reliability of the device is only an indicative estimate for the probability of failure.

The most common faults in the frequency converters were related to the failure of the fan, main fuses, control circuit or semiconductor switches. The root causes of the problems could not be identified, but the heat generated by the hardware along with normal aging is probably the biggest cause of all the failures. However, a large part of the fault types of the frequency converters remained dark due to a poorly filled fault report and SAP information. 37% of the reports did not tell what happened when the device failed, in what part of the hardware the fault might have been, or which error code the frequency converter has given.

Two interesting production places were found in the review where the frequency converters are failing systematically for the same reasons. A closer examination of these sites for failures and their conditions should be carried out.

Many solutions were found to maintain and improve the reliability of the frequency converters. The most important one of these is to keep the device base fresh and up to date with systematically changing the old and outdated models for new ones. Upgrading ensures the existence of replacement parts and the manufacturer's support in the event of a potential hardware failure. 28% of the frequency converters are currently in the obsolete state. The obsolete state is a state where the manufacturer no longer manufactures the device or its spare parts. In addition, 24% of the obsolete devices are classified in the highest critical category A. The Mills has many replacement parts in case of failures, but for some models, the replacement parts are low or have no equivalent at all. It would be advisable to quickly update such models for new models.

In addition to the renewal process, it was proposed that the conditions of the installation centers would be improved. The centers should be better ventilated and the equipment should have more free space between them. In addition, improved hardware commissioning, the better premaintenance of critical equipment, and better fulfilment of SAP data and reports were suggested. Accurately filled SAP data and failure reports containing precise information about the frequency converter itself and the fault code it provides would be important things to do. With the help of this information, the reliability could be analysed more thoroughly in the future.

No new solutions were found for the renewal of the frequency converter base. The above mentioned, keeping the equipment base fresh and new, has been going on at the Mills even before the start of this thesis and it would be good to continue the process in the future. Continuous and accurate data collection on malfunctions as well as monitoring of the equipment base during active operation would improve the ability to prepare for and prevent frequency converter failures.

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