Bearing Currents and Their Mitigation in Frequency Converter-driven Induction Motors

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Summary

This thesis aims to find solutions that will mitigate bearing currents in Westenergy's frequency converter-driven induction motors. The phenomenon of bearing currents, the causes of their occurrence and mitigation methods will be researched. The goal is to find methods that are feasible and economically viable. The phenomenon will be researched by reading technical publications and other thesis works written about the subject. Measurements will be made on the motors to clarify whether they suffer from bearing currents and to examine their condition.

The result will be modifications and recommendations for future modifications that will decrease the occurrence of bearing currents in the facility's motors and hence prolong the service intervals of the motors.

Language: english Key words: bearing current, frequency converter, induction motor

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Abstrakt

Detta lärdomsprov går ut på att hitta lösningar som ska minska på lagerströmmar i Westenergys frekvensomvandlarstyrda motorer. Fenomenet lagerströmmar, dess uppkomst, orsaker och minskningsmetoder undersöks. Målet är att hitta metoder som är genomförbara och ekonomiskt lönsamma. Fenomenet undersöks genom att läsa i tekniska publikationer och andra examensarbeten som har skrivits om ämnet. På motorerna utförs mätningar för att säkerställa att de påverkas av lagerströmmar och för att undersöka skicket som motorerna befinner sig i.

Resultatet blir ändringar och rekommendationer för framtida ändringar som ska minska på uppkomsten av lagerströmmar i anläggningens motorer och därmed förlänga tiden mellan underhåll för motorerna.

Språk: engelska Nyckelord: lagerström, frekvensomvandlare, induktionsmotor

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OPINNÄYTETYÖ

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Tiivistelmä

Tämän työn tavoitteena on löytää ratkaisuja, jotka lieventävät laakerivirtoja Westenergyn taajuusmuutttajaohjatuissa oikosulkumoottoreissa. Laakerivirtailmiö, sen esiintymisen syitä ja sen lieventämiskeinoja tutkitaan tässä työssä. Tavoitteena on löytää menetelmiä, jotka ovat toteutettavissa ja taloudellisesti kannattavia. Ilmiötä tutkitaan lukemalla teknisiä julkaisuja ja muita opinnäytetöitä, jotka käsittelevät samaa aihetta. Moottoreille tehdään mittauksia joilla varmistetaan, että moottorit kärsivät laakerivirroista ja tutkitaan moottoreiden kunto.

Tuloksena on muutoksia ja suosituksia tuleville muutoksille, jotka vähentävät laakerivirtojen esiintymistä laitoksen moottoreissa ja siten pidentää moottoreiden huoltoväliä.

Kieli: englanti

Avainsanat: laakerivirta, taajuusmuuttaja, oikosulkumoottori

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Contents

1 Introduction

This thesis was commissioned by Westenergy Oy Ab. My supervisor at the company was Kai Alavillamo, the Electrical and Automation Maintenance Manager. Lars Enström supervised my thesis work at Novia. I have been asked to research the phenomenon of bearing currents and to find solutions to mitigate the problem in the frequency converter driven motors in the power plant.

Considering the age of the power plant, there is an exceptional amount of bearing problems. The severity of the problems varies, it seems that only motors that are controlled by a frequency converter, suffer from bearing problems of higher levels. This thesis will only focus on the frequency converter driven motors, a total of 29 motors manufactured mainly by ABB, Siemens and SEW-EURODRIVE. All the frequency converters are provided by Vacon. Fourteen of the motors are under warranty by Hitachi Zosen Inova AG, responsible for the boiler and auxiliary systems like waste preparation and thermal treatment. Fourteen of the motors are under warranty by LAB S.A., responsible for the flue gas treatment in the plant. The warranty period is two years and will end in approximately one year. It is of high priority to solve these issues before the warranty period ends. Doing so will save the company a lot of money in maintenance costs in the long term.

The work will involve a lot of research in the subject and collaboration with companies involved. A few theses and some technical publications have been written about this subject. However, there is no simple solution. My task is to find the best solutions to be implemented in Westenergy. Some solutions will be implemented directly and others during the next service stop of the power plant. I will compile a list of all the motors and give my recommendations for future actions to be taken.

Measurements will be made on all the relevant motors in collaboration with CMT Solutions. The theory and relevance of the measurements will be discussed. The measurement results will help in deciding which action to take.

1.1 Vision

The vision is to find solutions that are economical and feasible and that will reduce the problems with bearing currents in Westenergy. This will significantly reduce maintenance costs of electric motors in the plant. The aim is to find solutions that both the manufacturers and the component suppliers agree on. I hope this thesis work can be of help to others who are also experiencing the same kinds of problems.

The ideal solution would be to eliminate the problem at the source, the variable frequency drive. Possible solutions that can reduce the harmful effects at the motor end will also be researched.

1.2 Employer

Westenergy Oy Ab is a waste-to-energy power plant situated in Koivulahti, Mustasaari. The plant was finished in 2012 and began commercial production in January, 2013. Westenergy Oy Ab is owned by five municipal waste management companies (Lakeuden Etappi Oy, Ab Stormossen Oy, Vestia Oy, Botniarosk Oy Ab ja Millespakka Oy).

The plant burns combustible waste to produce electricity and district heating to Vaasan Sähkö Oy. The produced energy covers one third of the district heating in the Vasa region and electricity for about 7000 households.

Table 1. Technical data.

Total efficiency ratio	85 %
Waste consumption	20 000 kg/h
Burning temperature	1000 °C
Electric output power	13 MW
District heating power	40 MW
Operation time	8000 hours in a year

The flue gas emissions from the plant are carefully cleaned in a multi-phase process. Ammonia is used in the burning process to neutralize nitrogen oxides (NOx). Lime and activated carbon are used in fabric filters to absorb harmful substances. The composition of the flue gases is constantly monitored, the waste-to energy power plant has reduced the amount of harmful emissions produced by Vaasa's energy production. Vaasan Sähkö, Vaskiluodon Voima and Westenergy were selected as the winners in the Climate Act 2012 competition.

2 The electric motor

The purpose of this chapter is to learn about the theory of electric motors. Electric motors are very important parts of Westenergy; they are for example used to power fans, pumps and screws. This knowledge is important when trying to understand bearing currents and mitigation methods to reduce the phenomenon.

2.1 Functional principle

The basic principle of an electric motor is to convert electric energy to mechanical energy. The electric motor consists of two main parts, the stator and the rotor. By creating a rotating magnetic field in the stator the constant magnetic properties of the rotor will make it rotate with the stator's magnetic field. This rotating motion can be used in various applications.

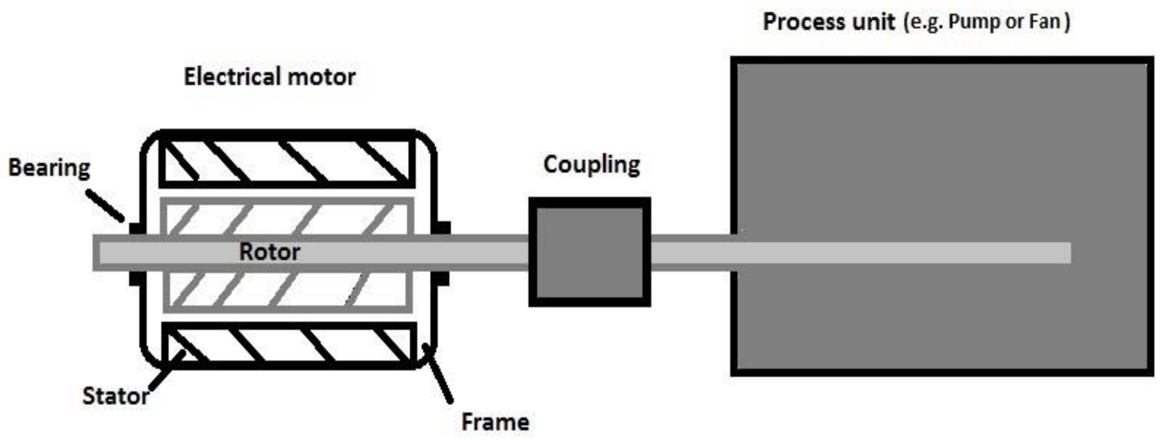

Figure 1. Basic drawing of electric motor attached to a process unit.

The stator is made up of several thin laminations of steel. (Cronqvist 2003, 161) They are punched and clamped together to form a hollow cylinder with slots for the stator windings. Each grouping of windings or coils, together with the core it surrounds, forms an electromagnet (a pair of poles) when an alternating current is supplied. The number of poles of an AC induction motor depends on the internal connection of the stator windings. (Parkeh 2003, 1)

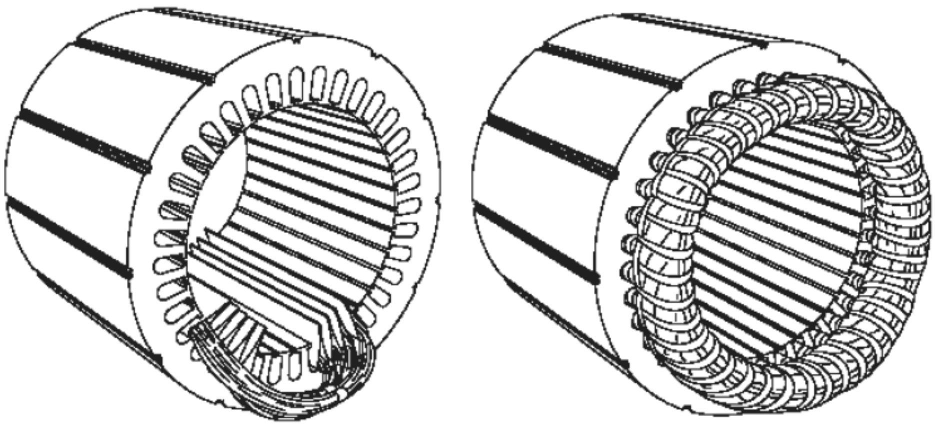

Figure 2. Stator windings. (Parkeh 2003, 1)

The stator windings are connected directly to the power supply. Internally they are connected in such a way that, on applying AC supply, a rotating magnetic field is created. The rotating magnetic field is accomplished by connecting the three phase-power supply to the stator windings in the desired rotating order. (Parkeh 2003, 1)

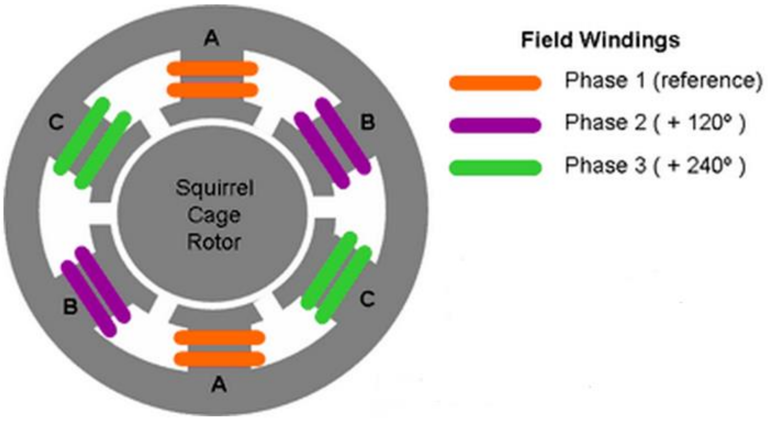

Figure 3. Clockwise rotating magnetic field. (The Electropedia n.d.)

The rotor is made up of several thin steel laminations with evenly spaced bars, which are made up of aluminum or copper, along the axis of the motor. The most popular kind of rotor is the squirrel cage rotor where the bars are connected by a ring at the ends creating a constant short-circuit connection. Almost 90 % of induction motors have squirrel cage rotors. This is because the squirrel cage rotor has a simple and rugged construction. The rotor consists of a cylindrical laminated core with axially placed parallel slots for carrying the conductors. Each slot carries a copper, aluminum, or alloy bar. This total assembly resembles the look of a squirrel cage, which gives the rotor its name. The rotor slots are slightly rotated to reduce magnetic hum, decrease slot harmonic and reduce the locking tendency of the rotor. (Parkeh 2003, 1)

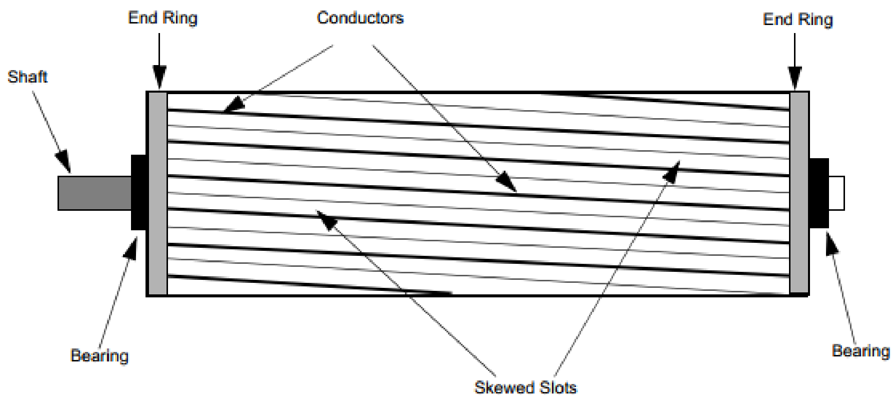

Figure 4. Squirrel cage rotor. (Parkeh 2003, 2)

The other kind of rotor is the wound rotor where the rotor has the same number of poles as the stator. The magnetized windings are placed on the stator. The windings are connected to the shaft with slip rings, which are connected to the network or a controller such as a variable resistor. (Cronqvist 2003, 138)

2.2 Speed control

The speed of the stator's rotating field is called the synchronous speed and is determined by the frequency of the power supply and the number of poles of the machine.

The synchronous speed can be calculated with the equation:

$N_s = \frac{120*f}{P}$ where $N_s =$ synchronous speed, f = frequency and P = number of poles. (Cronqvist 2003, 139)

A motor that rotates with synchronous speed is called a synchronous motor. The number of magnetic poles in the stator and rotor is the same. An asynchronous motor has no permanent magnetic poles in the rotor. In normal running conditions the stator will rotate at a slower speed than the magnetic field induced by the winding, this is called asynchronous speed. The difference between these two speeds is called “slip” and is usually given as a percentage of the synchronous speed.

The slip can be calculated with the equation:

$S = \frac{N_s*N}{N_s}$ where S = slip, N_s= synchronous speed (speed of stator) and N = speed of rotor. (Cronqvist 2003, 140)

Both the synchronous and the asynchronous motor can be used as a motor or generator. The synchronous motor is most commonly used in power plants as a generator or as a high power motor. The asynchronous motor is mostly used as a motor.

There are three main methods for speed control of electric motors: Pole changing, amending of the slip and varying the frequency.

Pole changing is common in older motors where the speed of the motor is controlled by switching between different numbers of poles. The stator is fitted with different windings for different numbers of poles. The pole change is done by switching the connection in the stator. Usually there are only two different connections. (Cronqvist 2003, 180)

Amending of the slip can be done in three different ways: by varying the input voltage to the motor, changing the rotor resistance or by feeding back rotor power to the grid. These methods can significantly reduce the efficiency of the motor or reduce the torque output to a degree that makes them non ideal for modern systems. (Cronqvist 2003, 177-180)

Varying the frequency is the most modern method of varying the speed of electric motors. This is done by using a variable frequency drive (VFD). The torque of the motor can be held constant by changing the frequency and voltage respectively in the same proportion. However, the voltage is most commonly capped at the network frequency level (400V at 50 Hz in Westenergy), after which the torque of the motor will be lowered when the frequency is raised. Using a VFD is the most energy efficient and flexible method for speed control of electrical motors. (Cronqvist 2003, 176)

VFDs are the most common cause of bearing currents in modern systems due to the fast switching frequency of the transistors used to modify the output signal. This technique will be researched more in detail in chapter 3 “Variable frequency drive (VFD)”.

2.3 Bearings

The basic principle of a bearing is to connect a spinning object to a stationary object. In the electric motor the shaft is connected to the case at the Drive End (D.E.) and the Non Drive End (N.D.E.). The bearings used in Westenergy’s motors are of the ball bearing type.

In a ball bearing, the load is transferred from the outer race to the ball and from the ball to the inner race. Only a small part of the ball contacts the races at a time, making it a very low friction connection and efficient solution.

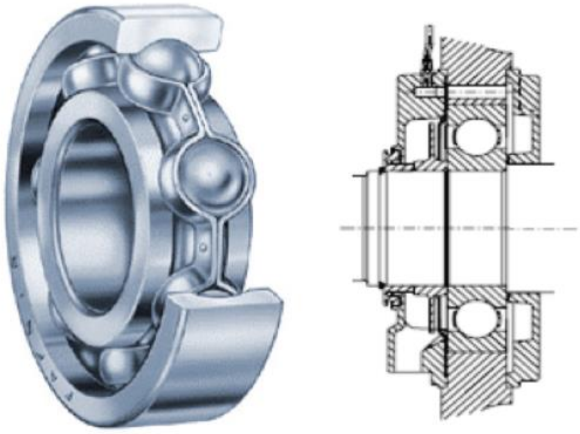

Figure 5. Ball bearing (Hoppler & Errath 2007, 2)

Usually bearings have a lifetime of many years, but many of the motors studied in this thesis work have bearings that failed in less than a year. The suspected cause of this is bearing currents caused by variable frequency drives.

When two conductive objects are close to each other with an insulating medium between them, they create a capacitive connection. In this case the metallic ball is capacitively coupled with the races of the bearing and the grease acts as an insulator. According to Muetze (2003, 11) the electrically loaded lubrication between the balls of the bearing and the running surface breaks down when the threshold voltage of the film is surpassed (5-30 V at a bearing temperature of 20 °C, 5-15 V at 70-90 °C). These kinds of voltages can occur when using VFDs to control motors and will wear out the bearings over time. This phenomenon will be discussed in detail in chapter 4 “What is bearing current?”.

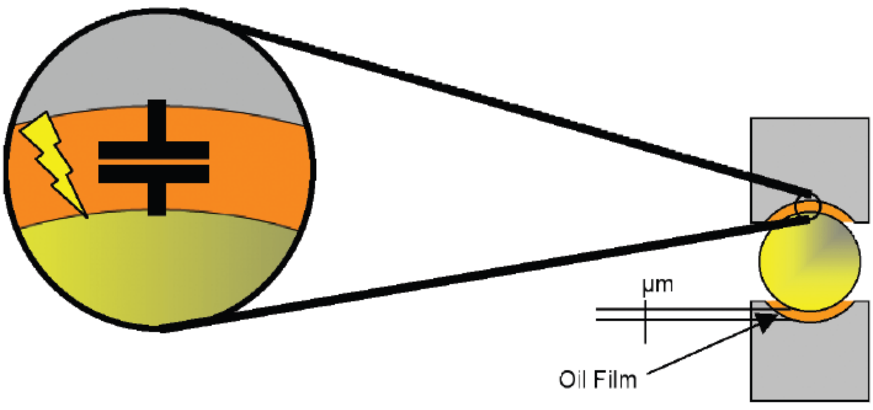

Figure 6. Capacitive connection between ball and outer race of the bearing. (Hoppler & Errath 2007, 7)

3 Variable frequency drive (VFD)

The purpose of this chapter is to learn about the theory of frequency converters. All motors investigated in this thesis are controlled by VFDs. This theoretical knowledge is important to have when deciding the best possible method to mitigate bearing currents.

3.1 Functional principle

A variable frequency drive is used to control the speed and torque of an alternating current electric motor by varying the frequency and voltage fed to the motor. Other names for a VFD are adjustable speed drive, adjustable frequency drive, AC drive, microdrive and inverter.

A VFD is used to control the motor speed in various load situations. The speed of the motor is in proportion to the frequency of the input to the motor. Being able to vary the speed of the motor can reduce wear, noise and power consumption of the motor and the controlled system.

The main function of a VDF is to convert a constant AC signal to a variable AC signal. The most common type of VFD rectifies the constant AC signal to a DC signal. This DC signal is then converted with a diode bridge to a pulsating output signal with variable amplitude or width. In modern drives the diodes are replaced with Insulated Gate Bipolar Transistors (IGBT) with fast switching frequency. (Cronqvist A. 2003, 326)

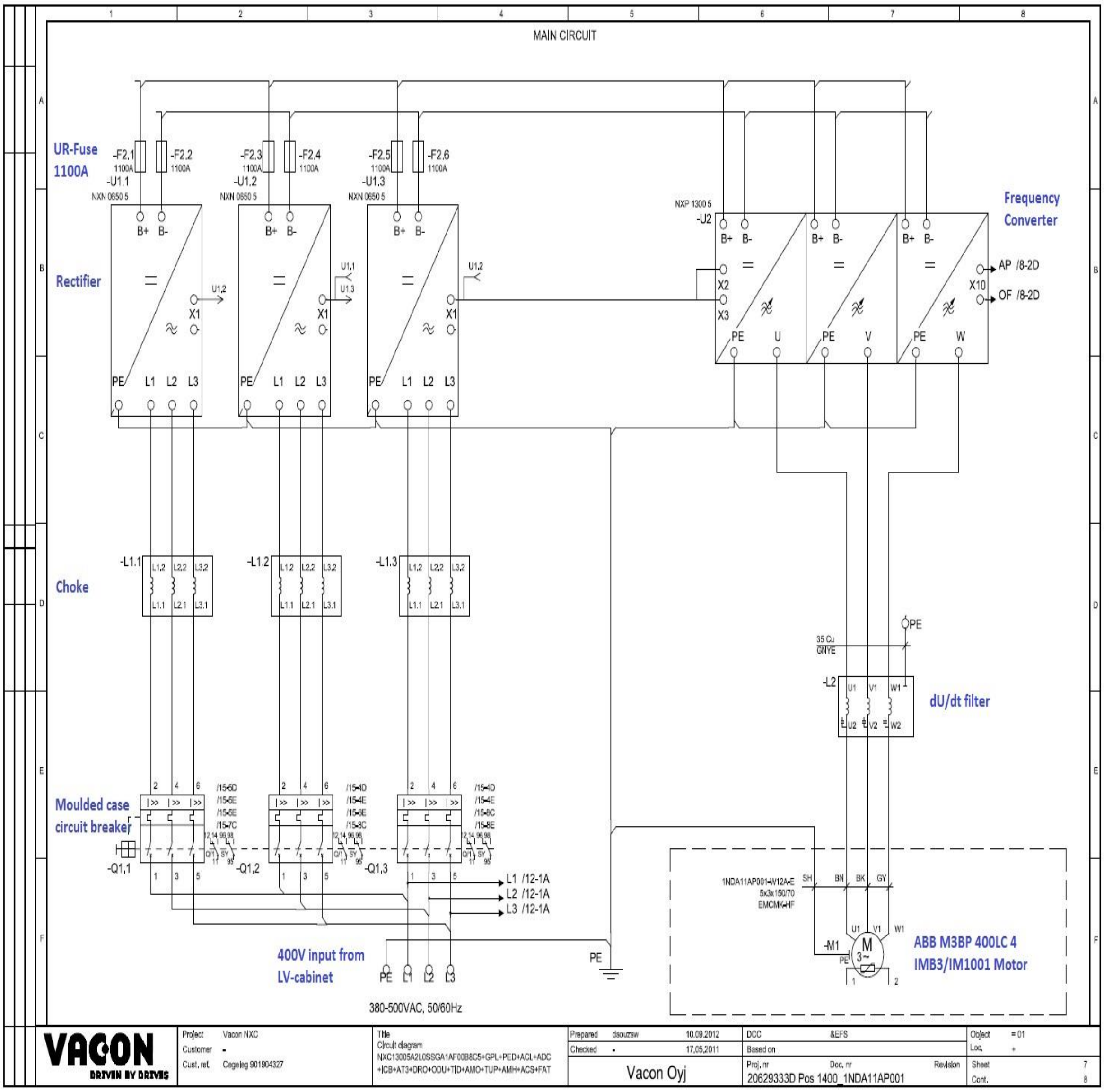

Figure 7. Circuit diagram of three Vacon VFDs connected to an ABB M3BP-series motor. This motor has an output power of 710 kW and is used to control a district heating pump. Internal documentation.

3.2 Pulse width modulation

The variable frequency drives used in Westenergy are manufactured by Vacon and use Pulse Width Modulation (PWM) to control the output signal. This technique varies the width of the output pulses to create a simulated sinusoidal load over the motor. The switching frequency of a VFD is how many pulses it produces per second. A higher switching frequency creates a smoother sinus curve but also introduces more high frequency disturbances in the system.

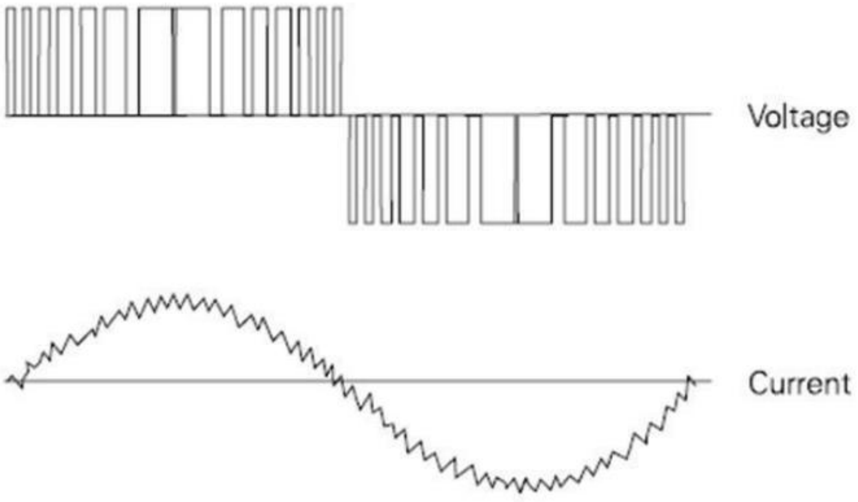

Figure 8. PWM voltage signal to the motor and the sinusoidal load over the motor (Jönsson H. & Larsson A. 2001, 4)

According to the Technical Account Manager Yrjö Karvonen at Vacon (personal communication 22.11.2013), the advantages of using IGBTs to control the voltage are their reliability and the low switching losses. The dis-advantage is the fast change in voltage over time (du/dt) which creates high frequency harmonic distortion in the currents flowing in the controlled system. These currents can cause damage to the insulation in the motor and increase the noise output of the motor. These high-frequency currents can introduce bearing currents and reduce the lifetime significantly for bearings in the motor.

Harmonic distortion is a form of electric pollution that can cause problems if the sum of the harmonic currents increases above certain limits. A harmonic current is a multiple of the fundamental frequency, for instance a 250 Hz current is the 5th harmonic of the 50 Hz fundamental current in the Finnish power system.

When a three-phase electric motor is driven directly by the network, the sum of the phases is always zero. When using a VFD the sum is not zero and, because of this, a voltage occurs between neutral and ground. This voltage is called common-mode voltage (CMV). (Jönsson H. & Larsson A. 2001, 4)

4 What is bearing current?

The purpose of this chapter is to investigate the phenomenon of bearing currents, the theory behind the problem and the different kinds of bearing currents. Bearing current is a term for unwanted currents flowing through the bearing causing damage over time. This leads to short lifetimes of bearings and high maintenance costs. My employer has asked me to come up with solutions to reduce the effect of bearing currents in electric motors driven by variable frequency drives in the power plant. The different kinds of solutions to reduce bearing currents will be discussed in chapter 5 “Common solutions to mitigate bearing currents”.

Bearing currents have been a problem since the electrical motor was invented, yet the damage they cause has increased during the last few years. This is because modern variable speed drives use fast rising voltage pulses and high switching frequencies to control the speed of the motor. These high-frequency voltage pulses can cause current pulses through the bearings, whose repeated discharging can gradually erode the bearing races. (Bearing currents 2011, 7)

A capacitance is created any time two conductive components are separated by an insulator. In the electric motor we get many so-called parasite capacitances. These unwanted capacitances get saturated by the high frequency currents from the VFD. When these capacitances are charged to the saturation point, they allow a current to flow through, causing damage to bearings in its path.

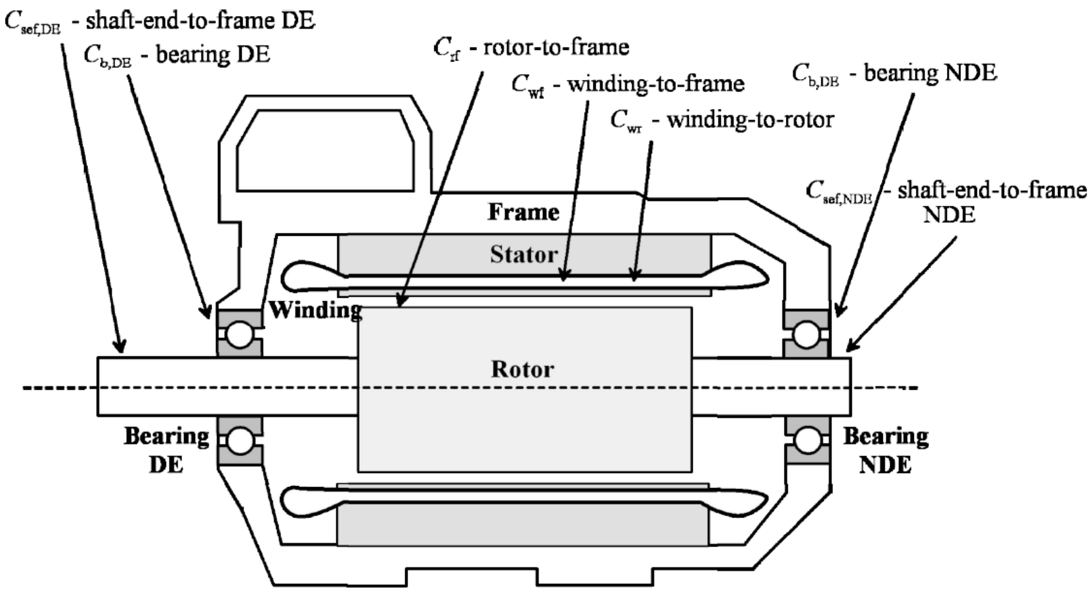

Figure 9. The most significant parasite capacitances in the electric motor. (Ahola J. 2011, 13)

When an electric current flows through a bearing it jumps from one ring to the other damaging the contact surface on the balls and the rings of the bearing. The metal is heated to the melting point and small craters and discoloration will appear on the surface of the material. Eventually, the deterioration will lead to complete bearing failure. This could be noticed in bearings already replaced by ABB.

Figure 10. Damaged inner ring of bearing. Noticeable fluting pattern caused by bearing currents. (Ahola J. 2011, 6)

Bearing currents are mainly caused by high frequency currents from variable frequency drives (VFD) and can be divided into four subcategories: Capacitive bearing currents, electrostatic discharge currents, circulating bearing currents and rotor ground currents. (Muetze A. 2003, 10)

4.1 Capacitive bearing currents

Due to the nonsymmetrical voltage of the three-phase output of the VFD, we get a common-mode voltage over the bearing. The common-mode voltage that occur, due to the sum of the three phases not being zero, will cause a voltage drop between the inner and outer race of the bearing. This will make a high-frequency current flow through the capacitive coupling of the inner and outer race of the bearing. The capacitive bearing currents dominate in smaller engines with a shoulder height smaller than 280 mm (under 100 kW). Capacitive bearing currents will only occur if the shaft is not grounded. (Jönsson H. & Larsson A. 2001, 24)

Since 19 of 29 researched motors have a lower power output than 100 kW, this will probably be the most common cause of the problems in Westenergy.

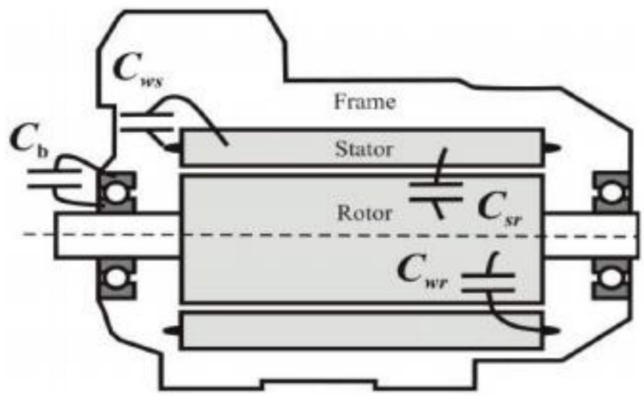

Figure 11. Parasite connections in the motor caused by the common-mode voltage. C_b = Capacitance over the bearing, C_{ws}= Winding-stator capacitance, C_{wr} = Winding-rotor capacitance and C_{sr} = Stator-rotor capacitance. (Jönsson H. & Larsson A. 2001, 25)

4.2 Electrostatic discharge currents (EDM bearing currents)

Caused by the common-mode voltage, the lubrication in the bearing becomes electrically charged at a certain speed. When the bearing balls roll fast enough, they roll on top of the lubrication and parasite capacitance is created. The electrically loaded lubrication between the balls of the bearing and the running surface breaks down when the threshold voltage of the film is surpassed (5-30 V at a bearing temperature of 20 °C, 5-15 V at 70-90 °C). The high du/dt of the input signal to the motor can cause these kinds of voltage build-ups. The lubrication film repeatedly builds up voltage and discharges causing damage to the bearing. The breakdown in the lubrication is caused by small metal particles due to wear in the grease. These kinds of bearing currents are especially harmful to small motors. (Muetze 2003, 11)

Lowering the du/dt levels of the input voltage should help to reduce this phenomenon. Eight of the motors researched in this thesis have du/dt filters installed, which should dampen this phenomenon. These eight motors still suffer from bearing currents, so this type of current may not be the main cause of the problem in the facility.

4.3 Circulating bearing currents

The circulating bearing currents are also called inductive bearing currents, and are produced by the fast changes in voltage (du/dt) at the motor terminals, which will excite the capacitive connection between windings and the frame of the motor. This causes a varying magnetic field inducing a potential difference between the ends of the shaft. When the difference in potential reaches the breakdown voltage of the lubrication in the bearing, a current will flow through the bearing damaging it in the process. The inductive bearing currents dominate in larger engines with a shoulder height larger than 280 mm (Over 100 kW). (Jönsson H. & Larsson A. 2001, 22)

The circulating bearing currents are the probable cause of the bearing damage in the larger motors in the power plant. Ten of the motors being researched have a higher output power than 100 kW. These motors have a more noticeable amount of bearing damage, hence solving this problematic phenomenon is of critical importance. The circulating current will always flow in the direction shown below, from the Non Drive End (N.D.E.) to the Drive End (D.E.) on the shaft and back through the case.

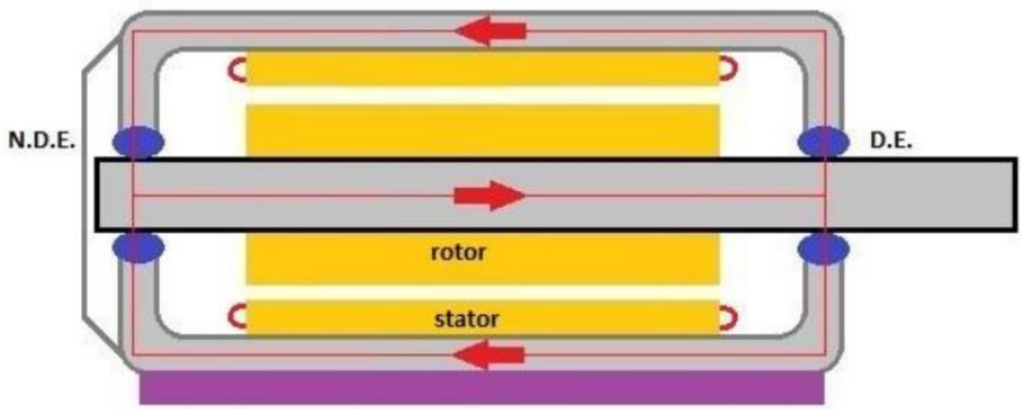

Figure 12. Direction of the circulating bearing currents. (Jönsson H. & Larsson A. 2001, 22)

4.4 Rotor ground currents

The common-mode voltage from the VFD will saturate the winding-stator capacitance, which will discharge through the grounding. Ideally this happens through the shielded cable coming from the variable frequency drive. But if the impedance path to the load is low, part of the current will go through the load to the ground. This current will go through the bearings in the motor and the load damaging both in the process. Proper grounding and shielded cables reduce this phenomenon.

This kind of bearing current only exists if the coupling to the load is conductive. This is the case in most of the researched motors. This phenomenon can appear in all sizes of motors.

(Jönsson H. & Larsson A. 2001, 25)

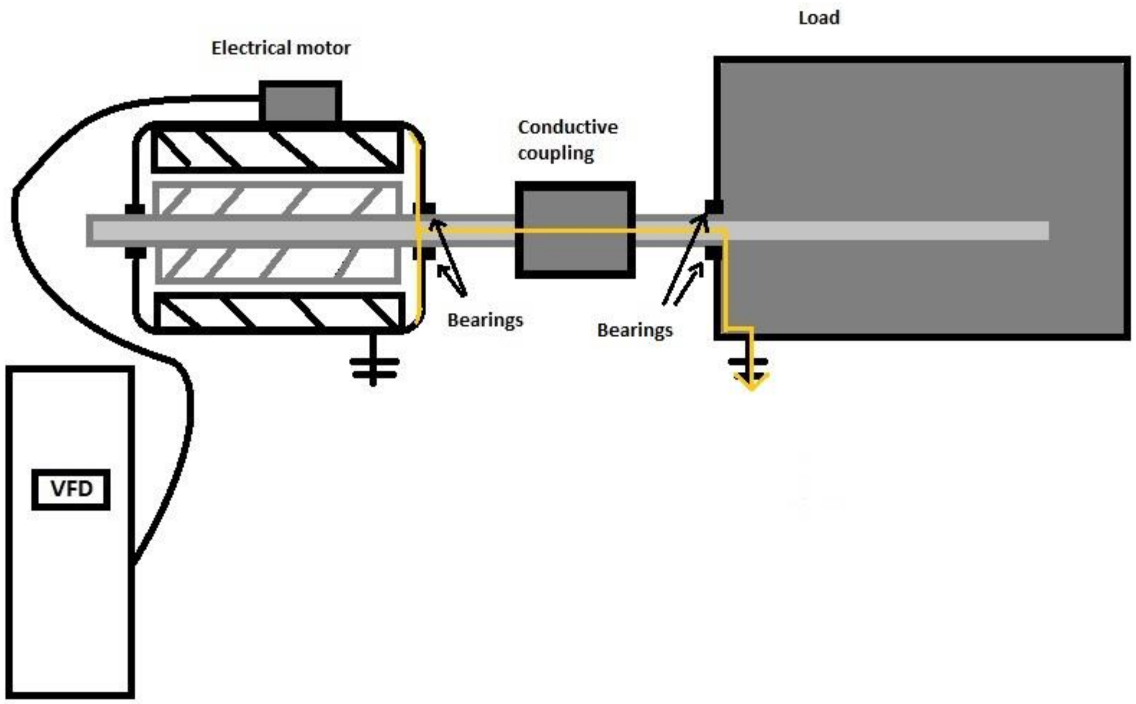

Figure 13. *The path of rotor ground bearing currents*.

5 Common solutions to mitigate bearing currents

This chapter will focus on known solutions for how to mitigate bearing currents. These methods will be explained and the implementation possibilities will be discussed. The purpose is to find an effective and suitable solution for Westenergy. The cost, ease of installation and effectiveness of these methods are important factors.

5.1 Filters

Different kinds of filters can be installed at the output of the VFD. There are three common filter types.

5.1.1 Common-mode filters

The common-mode filter is used to reduce common-mode currents caused by the VFD. It is a good solution to reduce inductive bearing currents. Common-mode filters are ferrite rings that act as an inductance, restricting high frequency current components from the VFD. This filter is the cheapest and easiest to install. (Jönsson H. & Larsson A. 2001, 26)

According to the Technical Account Manager Yrjö Karvonen at Vacon (personal communication 22.11.2013), ferrite rings can be added as many as you want, but the effect per ring will be reduced the more there are of them. A minimum of 20-30 µH of inductance is required to get the desired effect, but it is recommended to use an inductance of 50 µH or more. Ideally, every phase should go through each ring which is not always possible.

The relative cost (Motor = 100 %) of these kinds of filters are 5-10 %, depending on the size of the motor. (Variable Speed Drives & Motors 2006, 25)

5.1.2 Du/dt filters

The du/dt filter is used to dampen voltage transients to reduce the voltage derivative. This filter is more effective at dampening harmonic disturbances than the common-mode filter but causes losses due to heat. (Jönsson H. & Larsson A. 2001, 26)

According to Yrjö Karvonen (personal communication 22.11.2013), this kind of filter are more commonly used in 690 V motors to reduce the stress on the insulation caused by the voltage transients. They can also be used in 400 V motors to reduce the stress on the motor. The filter consists of inductive and capacitive components that act as a low-pass filter.

Du/dt filters were already installed in eight of the motors under warranty by Hitachi, ranging from 200-710 kW. Some of these motors are also having problems with bearing currents. These filters do not seem to be effective to reduce bearing currents in the facility.

The relative cost of these kinds of filters are 20-35 %. (Variable Speed Drives & Motors 2006, 25)

5.1.3 Sinus filters

Sinus filters convert the PWM output voltage to a sinusoidal shape by reducing the rise time of the voltage. The filter has to be configured according to the switching frequency of the VFD. The filter eliminates bearing currents but it is very expensive and causes losses in efficiency. This filter is seldom used because of its high price. (Jönsson H. & Larsson A. 2001, 26)

The relative cost of these kinds of filters are 25-65 %.(Variable Speed Drives & Motors 2006, 25)

5.2 Improvements to grounding and cabling

A proper grounding system is important in high frequency systems. A low-impedance grounding path will make the high-frequency currents to discharge through the grounding back to the VFD. If the grounding is done improperly, the currents will discharge through the bearings and the shaft. (Jönsson H. & Larsson A. 2001, 27)

Using proper grounding connections at the motor and the VFD end is essential. The case of the motor has to be grounded and the shield of the cable needs to be connected to the ground using a cable gland. The right type of cables is also extremely important. ABB advices to use only symmetrical multicore motor cables. Observations will be made to see if these requirements are met, and improvements made will be reported in Chapter 7 “Solutions”.

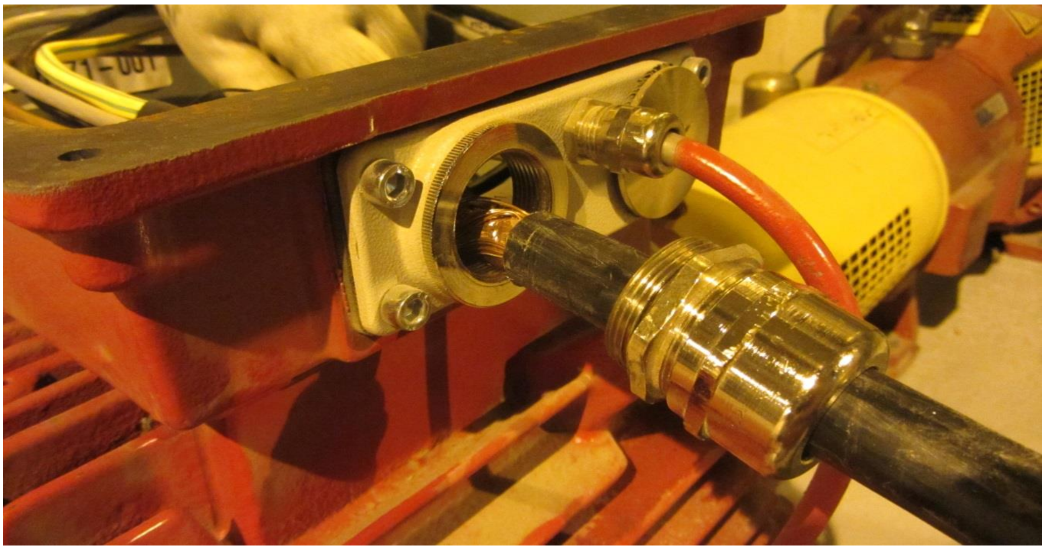

Figure 14. Example of a properly made connection to a motor in the facility. The symmetrical multicore motor cable is connected to the cable terminal box with an EMC gland. The cable shield is grounded through the case of the motor.

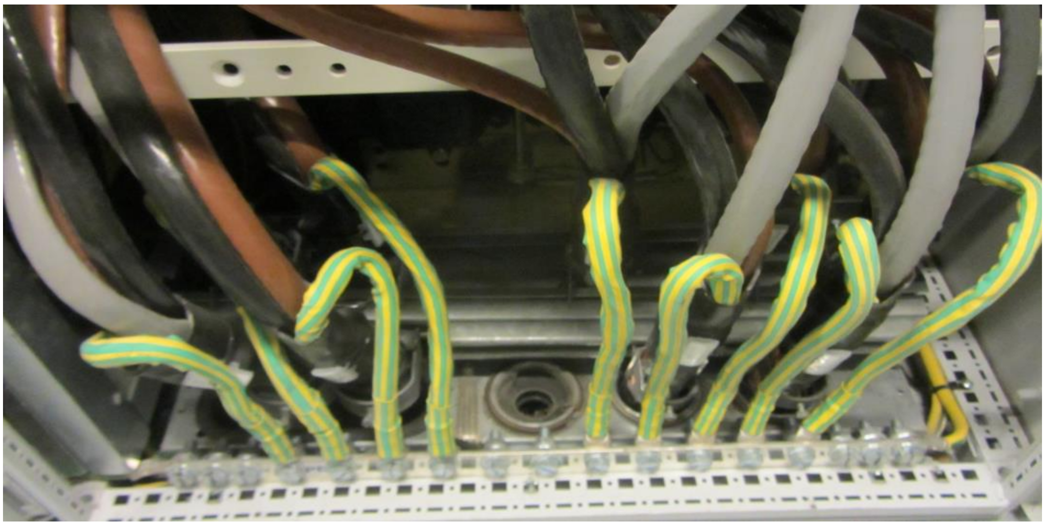

Figure 15. Example of properly made connection at the VFD end of motor cables. The ground cables and the cable shields are connected to the ground points in the VFD cabinet.

5.3 Grounding brushes

A grounding brush can be installed on the shaft to reduce bearing currents. The brush will mitigate the potential difference between the shaft and the case of the motor. This is an effective method to reduce capacitive bearing currents. (Jönsson H. & Larsson A. 2001, 26)

This method will only protect one of the bearings in large motors, because the circulating bearing currents will flow in the same direction as before, still damaging the bearing in the N.D.E. It can in fact shorten the lifetime of the N.D.E. bearing by increasing the voltage load over the bearing. This will shorten the time between service stops and increase the service costs of the motor.

Grounding brushes are relatively cheap and easy to retrofit afterwards. This could be a good solution for motors suffering from capacitive bearing currents.

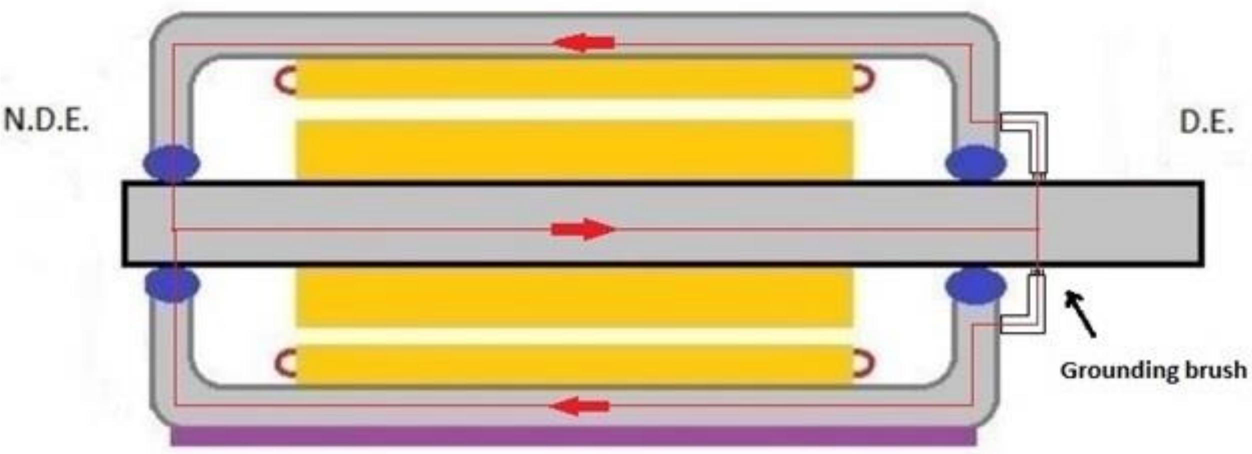

Figure 16. Installing a grounding brush at the D.E. in large motors will not protect the bearing at the N.D.E. (Jönsson H. & Larsson A. 2001, 22)

5.4 Reduction of switching frequency

The switching frequency of a VFD is how many pulses it produces per second. The advantage of a higher switching frequency is reduction of additional losses, of additional noise and torque ripples. Reduction of switching frequency does not significantly affect the amplitude of the harmonic overtones, but the occurrence rate decreases about linearly with a reduction of switching frequentency. (Muetze A. 2003, 1 & 176)

The motors in the plant use two switching frequencies. The large motors use a switching frequency of 3.6 kHz, and the small motors use 10 kHz. This mitigation method is free and easy to do at the VFD control panel. Any changes to these values will be mentioned in Chapter 7 “Solutions”.

5.5 Hybrid bearings

The bearings used in the plant are electrically insulated bearings. These bearings only insulate to a certain degree. When a breakdown voltage is reached over the bearing, they will allow currents to pass through.

Hybrid bearings use insulating ceramic balls ($Si_3\,N_4$) instead of regular conductive metal balls. The gap between the inner and outer race will now be completely insulated. Hybrid bearings are the most effective way to eliminate bearing currents.

The problem with hybrid bearings is the price, they cost about ten times as much as normal bearings. They might be a viable choice for the most critical motors, like the district heating pump motors and the plant's exhaust fan motors.

6 Measurements

Measurements were made on the relevant motors to determine where bearing currents occur. The severity of the problems in the motors will help determine which actions to take to mitigate the problems. The measurement techniques and the results will be discussed in this chapter. The measurements were made in collaboration with Mika Myllykoski from CMT Solutions.

6.1 Theory for measurements

Vibration measurements and bearing current measurements were made on about half of the motors, as all motors could not be measured due to technical impossibilities. The theory, techniques and relevance of the measurements will be discussed.

6.1.1 Vibration measurements

Vibration measurements will help to determine the condition of the motor and bearings. Analysis of velocity and acceleration of the vibrations will show in what condition the bearings are. Analysis of the frequency spectrum will help to pinpoint what part of the bearing is damaged.

Measurement devices used in vibration measurements:

- Microlog CMX 80-F-K-SL analyzer

- Acceleration sensor Wilcoxon 787AM8-1: 100mV / G

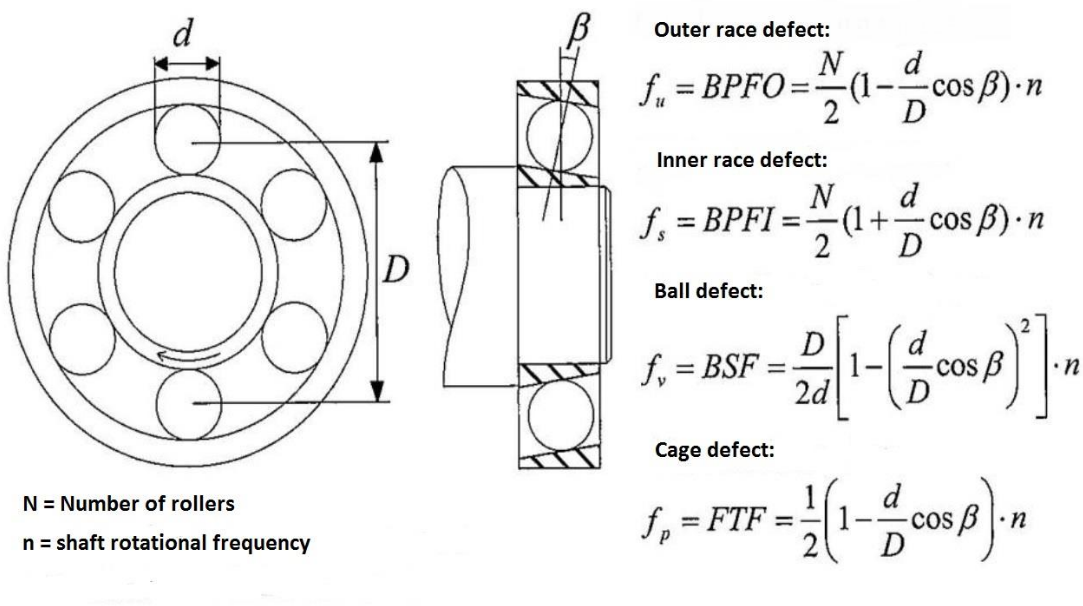

Figure 17. Calculation of defect frequencies. Internal documentation from CMT Solutions.

If there is damage in any of these parts, the defect frequencies and its harmonics can be observed in a graph showing the amplitude of vibrations at the measured frequency range.

The measurement results of the 1NDA11AP001 (District heating pump 1) motor will be more closely analyzed as an example. It is the largest motor in the plant and it is of critical importance for the process. There are clear signs of damage caused by bearing current in this motor.

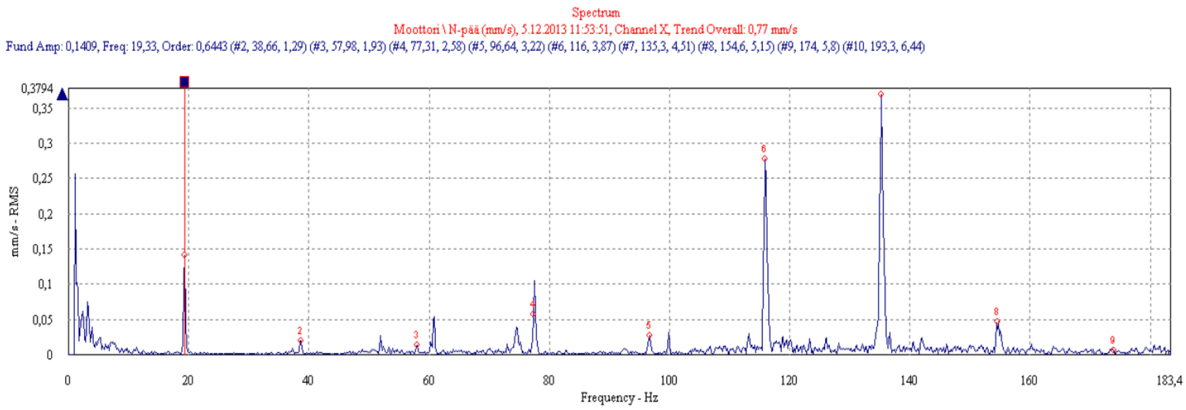

Figure 18. Vibration velocity measurement from the 1NDA11AP001 (District heating pump 1) motor. Amplitude spikes occuring with constant intervals are marked with red.

The vibration velocity measurement is measured in mm/s, and it is used to analyse the low end of the frequency spectrum. Bearing damage can be observed in this end of the spectrum if there are serious amounts of damage. In this motor the damage is minor and hence the damage can only be seen in higher frequencies. In the vibration velocity measurement we can observe spikes occurring with 19 Hz intervalls. This is the rotational speed of the motor and is considered normal.

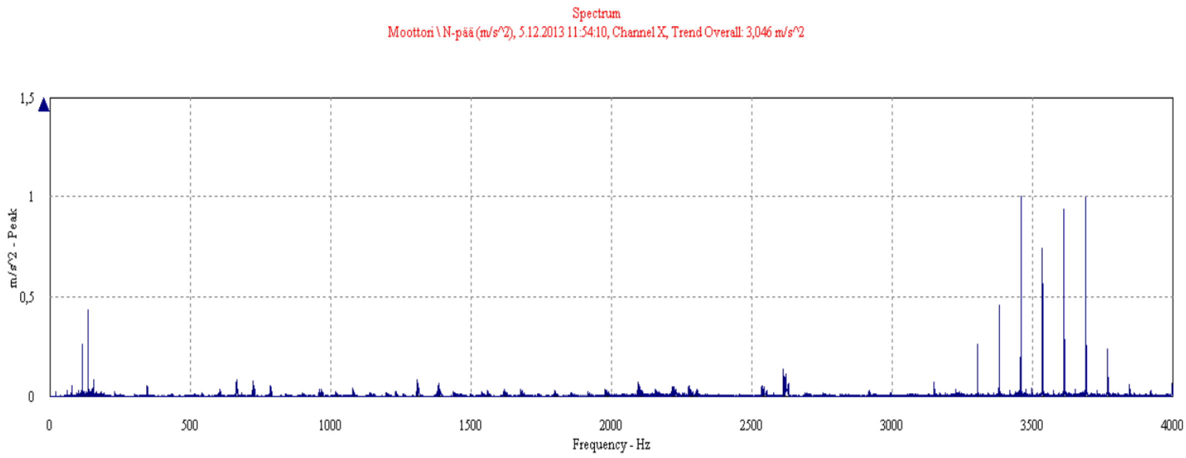

Figure 19. Vibration acceleration measurements from the 1NDA11AP001 (District heating pump 1) motor.

The vibration *acceleration* measurement is measured in m/s^2, and it is used to analyse the high end of the frequency spectrum. The switching frequency of the VFD used to control the motor is 3.6 kHz. This can be seen as amplitude spikes around that frequency and is considered normal. To determine if there is any fault in the bearing we can analyse more closely the amplitudes at lower frequencies. If there are spikes occurring at constant intervals, there might be a fault in the bearing. Spikes occurring with 19.26 Hz intervals are normal because of the rotational speed of the motor during the measurements.

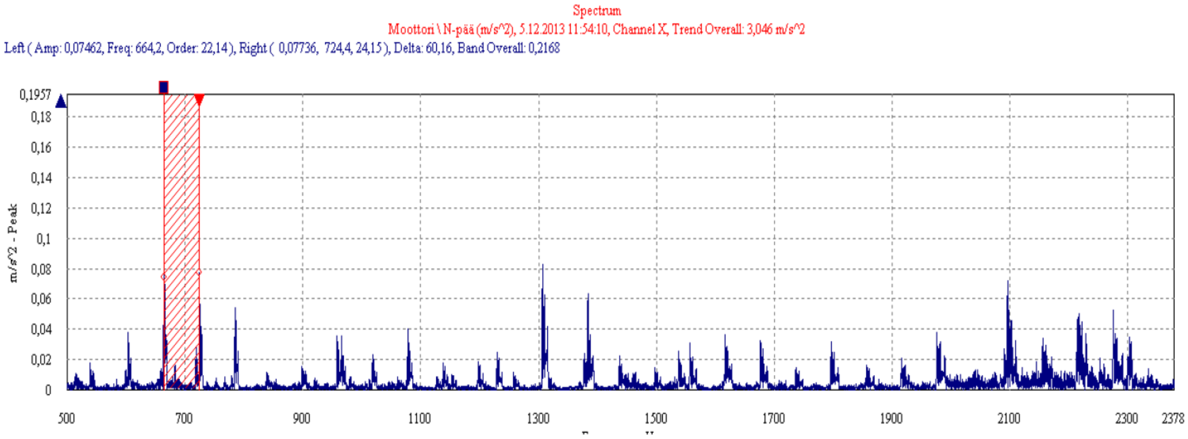

Figure 20. Zoomed in picture of figure 19. Interval of the harmonic overtones marked with red.

These harmonic overtones are occurring with ~60 Hz intervals. The bearing used in the motor is an SKF 6319. A data sheet from SKF reveals that the bearing has a plain race, 8 rolling elements, a ball diameter of 38.5 mm and a distance between the balls of 147.5 mm. Calculation of the defect frequencies as mentioned previously gives us:

Outer race defect: $\frac{8}{2}\left(1-\frac{0.0385}{0.1475}\cos 0°\right) * 19.26 = 56{,}9\ Hz$

Inner race defect: $\frac{8}{2}\left(1+\frac{0.0385}{0.1475}\cos 0°\right) * 19.26 = 77.0\ Hz$

Ball defect: $\frac{0.1475}{2*0.0385}\left(1-(\frac{0.0385}{0.1475}cos\ 0°)^2\right) * 19.26 = \ 34.4\ Hz$

Cage defect: $\frac{1}{2}\left(1-\frac{0.0385}{0.1475}\cos 0°\right) * 19.26 = 9.0\ Hz$

60 Hz is close enough to 56.9 Hz that we can safely assume that there is outer race damage in the bearing. This bearing has only been in operation for a couple of months, as the bearing has already been replaced once. The damage is very minor and doesn't need any maintenance at the moment. These results clearly indicate the presence of bearing currents in the motor because it's not normal for a bearing to show damage this soon.

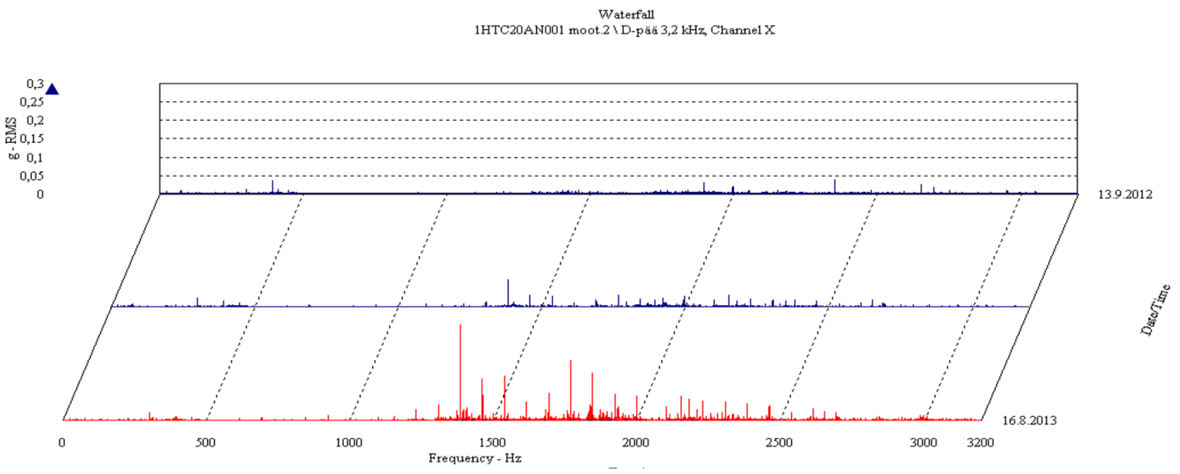

Figure 21. Acceleration spectrums from 1HTC20AN001 (Bag filter preheating fan) motor. Bearings had to be changed after about one year in operation. First measurement was made at the start of the plant and the last measurement just before the bearings were changed.

6.1.2 Bearing current measurements

The main reason for these measurements is to prove the existence of bearing currents. The frequency converters' fast switching frequency can cause voltage spikes over the bearings, which can be damaged if the spikes have high enough amplitude. Two types of measurements were made to determine the amount of bearing currents: circulating current and rotor ground current measurements. These measurement techniques are not perfect, but will show an approximate value of the currents flowing through the bearings in normal operation.

The measurement techniques are specified in technical guide number 5 from ABB "Bearing currents in modern AC drive system".

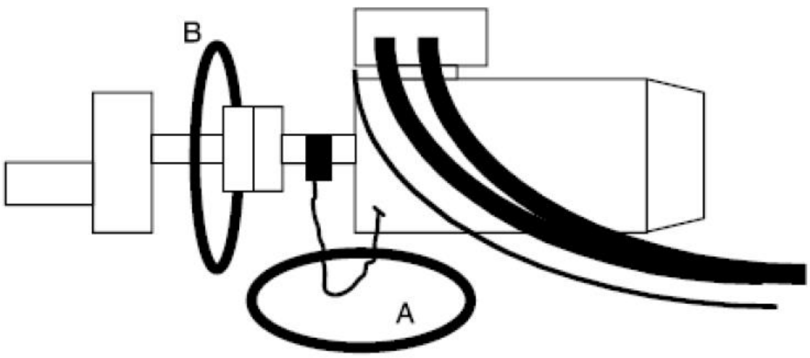

Figure 22. A=measurement of circulating current, B=measurement of the axis' shaft grounding current. (Bearing currents 2011, 20)

The circulating current measurement estimates the level of bearing currents caused by capacitive and circulating bearing currents. The shaft is connected with a ground carbon to a cable, which is connected to the case as figure 22 shows. This creates a short circuit connection between the shaft and the case. The current flowing in the cable is measured with a Rogowski probe. This simulates the current flowing through the bearing in a normal running condition. The actual current running through the bearing in operation is impossible to measure.

The shaft grounding current measurement will determine the amount of current flowing through the shaft. The Rogowski probe is placed around the axis. This current can also cause damage to the driven load.

The relevance and accuracy of these measurements can be discussed, but the main reason for these measurements is to get assurance as to what causes the bearings to die so fast. The physical patterns and burn mark seem to indicate unwanted currents flowing through the bearing.

Measurement devices used in the bearing current inspection:

- Oscilloscope Rigol DS1052E 2 Channel 50 MHz, 1 Gsa/s

- CWT015B/2.5/1000 Rogowski probe: 200mV /1 A

- Ground carbon and its rack

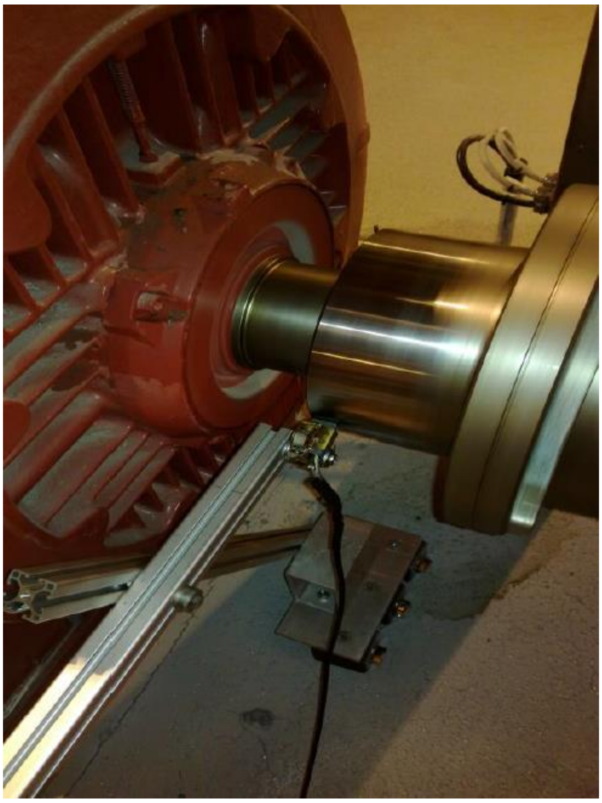

Figure 23. Measuring the circulating current. Ground carbon connects the shaft to a cable leading to the case of the motor.

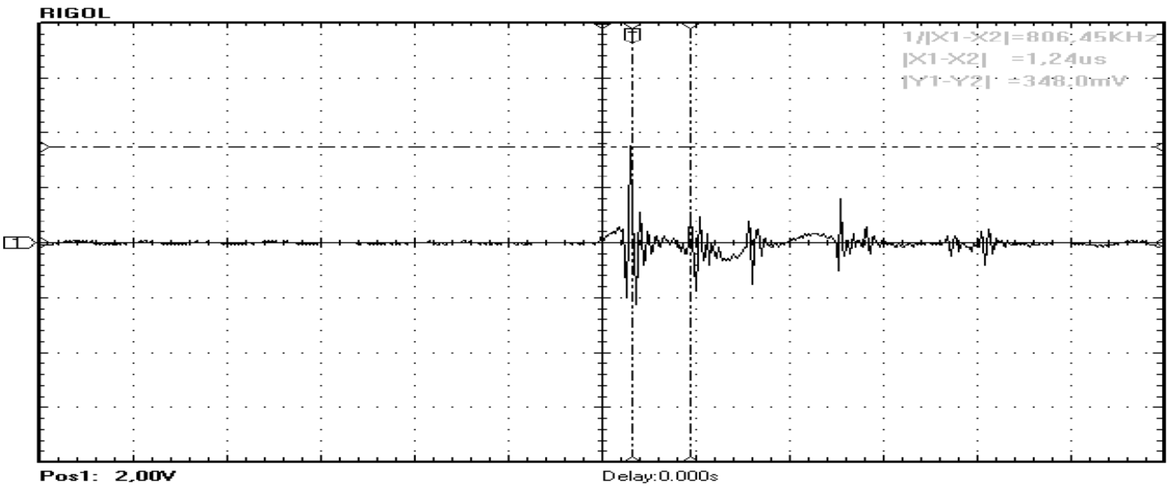

Figure 24. Circulating bearing current measurement from the 1NDA11AP001 (District heating pump 1, 710 kW) motor. The peak value is 348 mV, which corresponds to 1.74 A. (200 mV = 1 A).

Figure 25. Measuring the shaft grounding current from the axis. A Rogowski probe is held around the rotating axis.

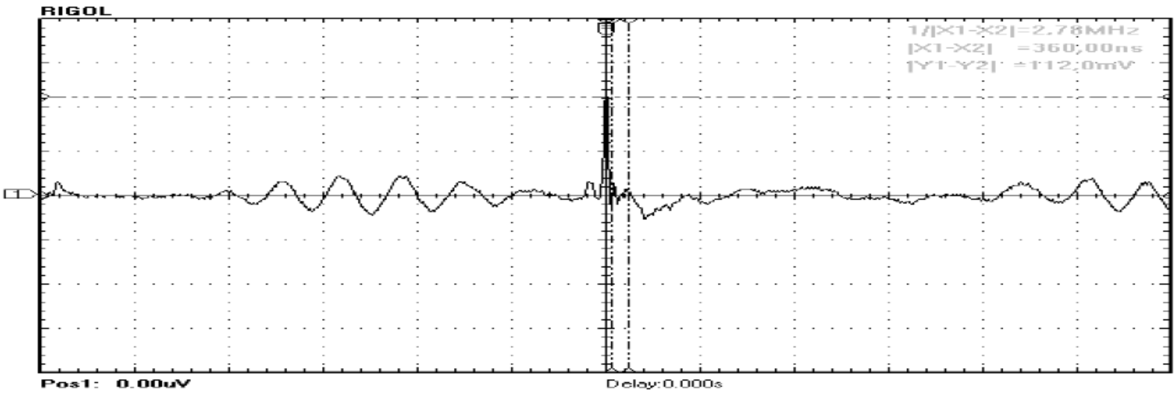

Figure 26. Measurement of the shaft grounding current from the 1NDA11AP001 (District heating pump 1, 710 kW) motor. The peak value is 112 mV, which corresponds to 0.56 A. (200 mV = 1 A).

The PSK 7708 standard classifies the severity of the bearing current problems when these measurement techniques are used. It is impossible to measure the actual current flowing through the bearing and therefore these values are only estimates.

Peak value for bearing current.	Harmfulness classification.
< 1 A	No remarkable effect on bearing life.
1 A … 2 A	Might have an effect on bearing life.
> 2 A	Remarkable effect on bearing life.

(Kokko V. et al. 2009, 53)

6.2 Results

There are 29 motors researched in this thesis, ranging from 0.55 – 710 kW. The first fourteen motors are under warranty by Hitachi Zosen Inova AG and the following 15 are under warranty by LAB S.A.

6.2.1 Motor specifications

Table 2. Motor specifications.

KKS identification number (description)	Motor	P(kW)	U(V)	Vacon VFD
1NDA11AP001 (District heating pump 1)	ABB M3BP 400LC 4 IMB3/IM1001	710	400	NXC13005A2L0SSGA1AF00B8C5
1NDA12AP001 (District heating pump 2)	ABB M3BP 400LC 4 IMB3/IM1001	710	400	NXC13005A2L0SSGA1AF00B8C5
1PAB11AP001 (District heating glycol pump 1)	M3BP 355 MLB 4	450	400	NXC08205A2L0SSGA1A300B8C5
1PAB12AP001 (District heating glycol pump 2)	M3BP 355 MLB 4	450	400	NXC08205A2L0SSGA1A300B8C5
1LAC21AP001 (Feed Water Pump 1)	ABB M3BP 355 MLA 2	400	400	NXC08205A2L0SSGA1AF00B8C5
1LAC22AP001 (Feed Water Pump 2)	ABB M3BP 355 MLA 2	400	400	NXC08205A2L0SSGA1AF00B8C5
1HLB10AN001 (Primary Air System Fan)	Siemens 1LG4 317-4AA60 B3	200	400	NXC03855A2L0SSGA1AF00B8C5
1HLB20AN001 (Secondary Air System Fan)	Siemens 1LG4 317-4AA60 B3	200	400	NXC03855A2L0SSGA1AF00B8C5
1ETA10AF001 (Mot 1 OsciConv BotAshHdlg)	M3BP 180MLA 6	22	400	NXS00315A2H1SSSA1A30000C5
1ETA20AF001 (Mot 2 OsciConv BotAshHdlg)	M3BP 180MLA 6	22	400	NXS00315A2H1SSSA1A30000C5
1LCN41AP001 (Cond Pp 1 AuxCondSys)	ABB M3BP 160 MLB 2	15	400	NXS00455A2H1SSSA1A30000C5
1LCN42AP001 (Cond Pp 2 AuxCondSys)	ABB M3BP 160 MLB 2	15	400	NXS00225A2H1SSSA1A30000C5
1ETA30AF001 (BitConv BotAshHdlg)	SEW-EURODRIVE KA67 BDRS132S4	5,5	400	NXS00045A2H1SSSA1A30000C5
1GHA10AP001 (Jockey pump)	Wonder Motor WEA80M2-2	1,1	400	NXS00315A2H1SSSA1A30000C5
KKS identification number (description)	Motor	P(kW)	U(V)	Vacon VFD
1HNC10AN 001-M01 (ID-FAN)	ABB M3BP 400LB 4 IM3/IM1001	630	400	NXC09205A5L0RSGA1AFB8D2C3
1HNC10AN 001-M02 (ID-FAN)	ABB M3BP 400LB 4 IM3/IM1001	630	400	NXC09205A5L0RSGA1AFB8D2C3
1HTC20AN 001 (Bag filter preheating fan)	ABB M3BP 200 MLA 4	30	400	NXS00725A2H0SSSA1A30000C5
1HTK12AN001 (Reagent transport fan 1)	ABB M3BP 160 MLC 2	18,5	400	NXS00455A2H1SSSA1A30000C5
1HTK22AN001 (Reagent transport fan 2)	ABB M3BP 160 MLC 2	18,5	400	NXS00455A2H1SSSA1A30000C5
1HTK32AN001 (Stand by reagent transport fan)	ABB M3BP 160 MLC 2	18,5	400	NXS00455A2H1SSSA1A30000C5
1HTP20AF001 (Residue screw conveyer 2)	SEW-EURODRIVE KA97 AM100 DRE100LC4/FF	3	400	NXS00075A2H1SSSA1A30000C5
1HTP20AF011 (Residue screw conveyer 2)	SEW-EURODRIVE KA97 AM100 DRE100LC4/FF	3	400	NXS00075A2H1SSSA1A30000C5
1HTP20AF021 (Residue screw conveyer 2)	SEW-EURODRIVE KA97 AM100 DRE100LC4/FF	3	400	NXS00075A2H1SSSA1A30000C5
1HTP30AF001 (Residue rotary valve)	SEW-EURODRIVE R67 AM90 DRE90L4/FF	1,5	400	NXS00045A2H1SSSA1A30000C5
1HTK10AF001 (Lime dosing screw 1)	SEW-EURODRIVE RF67 DRS71M4/RS	0,55	400	NXS00035A2H1SSSA1A30000C5
1HTK20AF001 (Lime dosing screw 2)	SEW-EURODRIVE RF67 DRS71M4/RS	0,55	400	NXS00035A2H1SSSA1A30000C5
1HTK30AF001 (Lime dosing screw 3)	SEW-EURODRIVE RF67 DRS71M4/RS	0,55	400	NXS00035A2H1SSSA1A30000C5
1HTK50AF001 (Activated carbon dosing screw 1)	SEW-USOCOME RF37/A/II2GD	0,55	400	NXS00035A2H1SSSA1A30000C5
1HTK60AF001 (Activated carbon dosing screw 2)	SEW-USOCOME RF37/A/II2GD	0,55	400	NXS00035A2H1SSSA1A30000C5

6.2.2 Vibration measurements

The results from the vibration measurements were analyzed in the same way as in the example in chapter 6.1.1 “Vibration measurements”. The measurement results will be summarized here with classifications for the condition of the bearings and the location of possible faults. Thirteen of the researched motors could not be measured because of their location or disturbances from surrounding machinery, causing incorrect results.

Table 3. Vibration measurements.

KKS identification number (description)	Fault location	Severity of fault	Need of maintenance
1NDA11AP001 (District heating pump 1)	N.D.E Bearing outer race	Minor	No *
1NDA12AP001 (District heating pump 2)	N.D.E Bearing outer race	Minor	No
1PAB11AP001 (District heating glycol pump 1)	N.D.E Bearing ball and cage	Minor	No
1PAB12AP001 (District heating glycol pump 2)	N.D.E Bearing outer race and bearing of pum	Minor on motor, critical on pum	Yes, replacement of pump bearing
1LAC21AP001 (Feed Water Pump 1)	Pump bearing	Minor	No
1LAC22AP001 (Feed Water Pump 2)	Pump bearing	Minor	No
1HLB10AN001 (Primary Air System Fan)	No fault		No
1HLB20AN001 (Secondary Air System Fan)	D.E Bearing outer race	Minor	No
1ETA10AF001 (Mot 1 OsciConv BotAshHdlg)	No value		
1ETA20AF001 (Mot 2 OsciConv BotAshHdlg)	No value		
1LCN41AP001 (Cond Pp 1 AuxCondSys)	No fault		No *
1LCN42AP001 (Cond Pp 2 AuxCondSys)	Bearing cage,ball and outer race	Minor	No *
1ETA30AF001 (BitConv BotAshHdlg)	No value		
1GHA10AP001 (Jockey pump)	No value		
KKS identification number (description)			
1HNC10AN 001-M01 (ID-FAN)	N.D.E Bearing outer race	Minor	No
1HNC10AN 001-M02 (ID-FAN)	N.D.E Bearing outer race and bearing of fan	Minor on motor, critical on fan	Yes, replacement of fan bearing **
1HTC20AN 001 (Bag filter preheating fan)	No fault		No *
1HTK12AN001 (Reagent transport fan 1)	No value		
1HTK22AN001 (Reagent transport fan 2)	No value		
1HTK32AN001 (Stand by reagent transport fan)	No value		
1HTP20AF001 (Residue screw conveyer 2)	Gears of the gear motor	Mediocre	No
1HTP20AF011 (Residue screw conveyer 2)	Gears of the gear motor	Mediocre	No
1HTP20AF021 (Residue screw conveyer 2)	Gears of the gear motor	Critical	Yes, motor service
1HTP30AF001 (Residue rotary valve)	No fault		No
1HTK10AF001 (Lime dosing screw 1)	No value		
1HTK20AF001 (Lime dosing screw 2)	No value		
1HTK30AF001 (Lime dosing screw 3)	No value		
1HTK50AF001 (Activated carbon dosing screw 1	No value		
1HTK60AF001 (Activated carbon dosing screw 2	No value		
* = Bearings replaced October 2013, ** = Bearings replaced March 2013			

None of the motors need immediate maintenance at this point, but some of the motors have already had their bearings replaced after under one year in operation. Three of the motor’s driven loads need service. This damage to the load is probably caused by rotor ground currents.

6.2.3 Bearing current measurements

The results of the current measurements will be summarized here with peak values for the two different kinds of measurements. All of the researched motors could not be measured because of their location or because of protective casing preventing installation of the measurement devices.

The higher the peak value of the current, the higher the possible damage is to the bearings. These measurements only tell us the peak value, not the occurrence rate of the pulses. The occurrence rate should be directly related to the switching frequency of the VFD.

Table 4. Current measurements.

KKS identification number (description)	Peak shaft grounding current (A)	Peak circulating current (A)
1NDA11AP001 (District heating pump 1)	0,56	1,74
1NDA12AP001 (District heating pump 2)	< 0,2	1,42
1PAB11AP001 (District heating glycol pump 1)	< 0,2	0,62
1PAB12AP001 (District heating glycol pump 2)	< 0,2	0,44
1LAC21AP001 (Feed Water Pump 1)	0,62	< 0,2
1LAC22AP001 (Feed Water Pump 2)	0,84	< 0,2
1HLB10AN001 (Primary Air System Fan)	< 0,2	< 0,2
1HLB20AN001 (Secondary Air System Fan)	0,44	0,53
1ETA10AF001 (Mot 1 OsciConv BotAshHdlg)	No value	No value
1ETA20AF001 (Mot 2 OsciConv BotAshHdlg)	No value	No value
1LCN41AP001 (Cond Pp 1 AuxCondSys)	< 0,2	< 0,2
1LCN42AP001 (Cond Pp 2 AuxCondSys)	< 0,2	< 0,2
1ETA30AF001 (BitConv BotAshHdlg)	No value	No value
1GHA10AP001 (Jockey pump)	No value	No value
KKS identification number (description)		
1HNC10AN 001-M01 (ID-FAN)	0,44	0,35
1HNC10AN 001-M02 (ID-FAN)	1,42	1,28
1HTC20AN 001 (Bag filter preheating fan)	No value	No value
1HTK12AN001 (Reagent transport fan 1)	No value	No value
1HTK22AN001 (Reagent transport fan 2)	No value	No value
1HTK32AN001 (Stand by reagent transport fan)	No value	No value
1HTP20AF001 (Residue screw conveyer 2)	0,82	No value
1HTP20AF011 (Residue screw conveyer 2)	0,72	No value
1HTP20AF021 (Residue screw conveyer 2)	1,26	No value
1HTP30AF001 (Residue rotary valve)	No value	No value
1HTK10AF001 (Lime dosing screw 1)	No value	No value
1HTK20AF001 (Lime dosing screw 2)	No value	No value
1HTK30AF001 (Lime dosing screw 3)	No value	No value
1HTK50AF001 (Activated carbon dosing screw 1)	No value	No value
1HTK60AF001 (Activated carbon dosing screw 2)	No value	No value

We can see from the results that only four of the measured motors have peak current levels higher than 1 A, which might have an effect on bearing life according to the PSK 7708 standard. Bearing changes and vibration measurements confirm that these four motors are among the most problematic in the facility.

The goal of these measurements was to prove the existence of bearing currents and compare the severity of the problem in the researched motors. These goals were achieved and these results will be helpful in making a decision on how to solve the problem. Unfortunately all motors could not be measured.

7 Solutions

This chapter will focus on the different kinds of solutions that will be implemented in the facility to reduce bearing currents. Some will be implemented right away and some at the next service stop of the plant. I will also give my recommendations for how things could be improved even further if the problem does not go away.

7.1 Actions taken

When I first started to research the problem I was convinced that grounding brushes were the ideal solution to the problem. This solution is effective against capacitive bearing currents and rotor ground currents. Discussions with experts from ABB revealed that grounding brushes can make things worse when circulating bearing currents are present. This solution could solve the problem in smaller motors where circulating currents should not occur.

We wanted to find a solution that would solve the problem at the source, the VFD. Eliminating the problem at the source would be a universal solution for all motor sizes. There are three methods that seemed feasible and effective: Improvements to grounding systems, installation of common-mode filters and reduction of switching frequency. The other methods were either too expensive or impossible to implement at this point.

Ensuring a good grounding system is important. Good grounding at the motor end will make leak currents return back to the VFD. If the grounding is not done properly, the currents can go through the bearings and the driven load's ground. Inspections were made of the most problematic motors and small improvements were made to a few motors. There are two examples below.

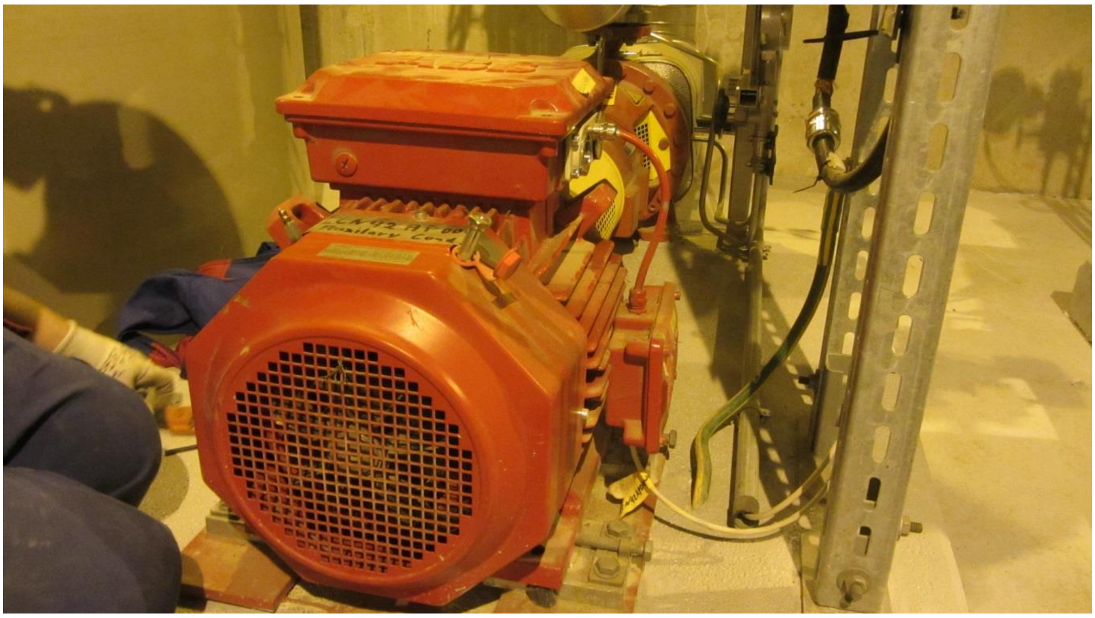

Figure 27. Some of the motors were only grounded through the incoming supply cable at the cable terminal box, like the 1LCN41AP001 (Cond Pp 1 AuxCondSys) motor in the picture. An additional grounding cable was connected to the case.

Figure 28. An EMC cable gland is used for connecting the supply cable to the cable terminal box. Many of the connection pins to the cable screen were broken at the 1HTC20AN001 (Bag filter preheating fan) motor. This gland was replaced.

A common-mode filter is a relatively cheap and easy-to-install component. Before deciding to use these filters on a majority of the motors, we decided to try them on two of the motors. These ferrite ring packages were installed on the 1LAC22AP001 (Feed Water Pump 2, 400 kW) and 1HTP20AF001 (Residue screw conveyer 2, 3 kW) motor. We consulted Vacon regarding the installation procedure of these filters. The costs of these filters were 400 € for the 400 kW motor and 60 € for the 3 kW motor.

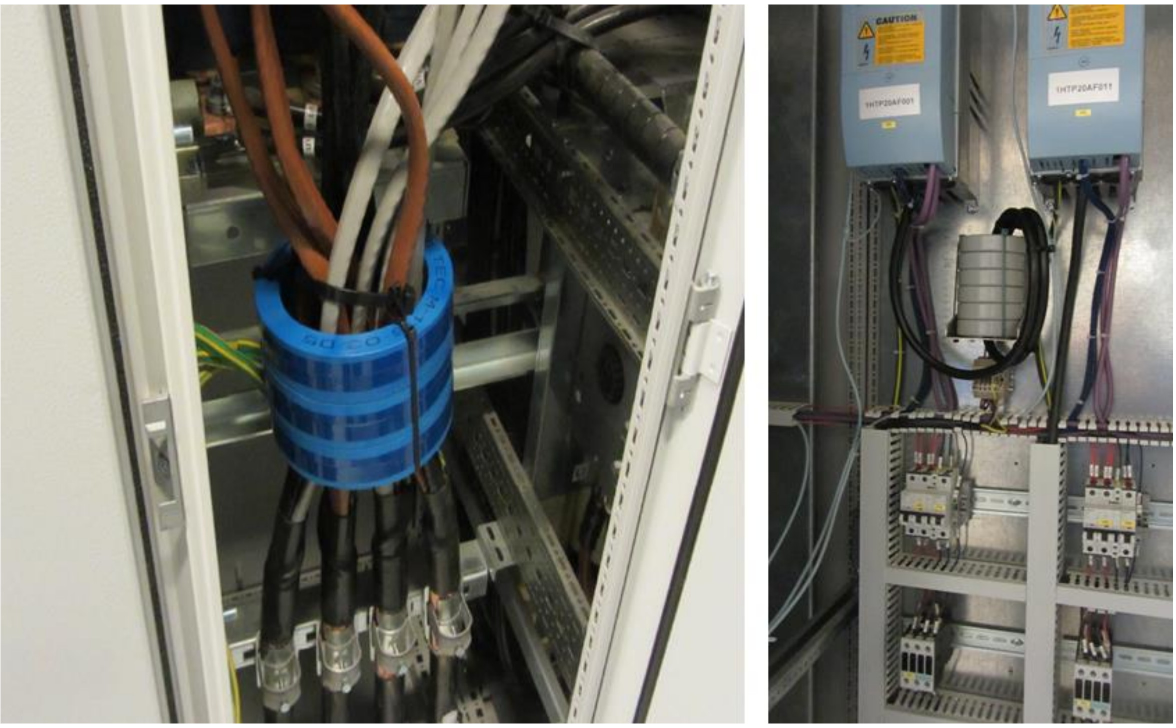

Figure 29. Installed ferrite ring packages on the 400 kW and 3 kW motor.

The same shaft ground current measurements as before were made to these two motors after the installation of the ferrite rings had been made. We wanted to get concrete results that proved that these filters work in the desired way.

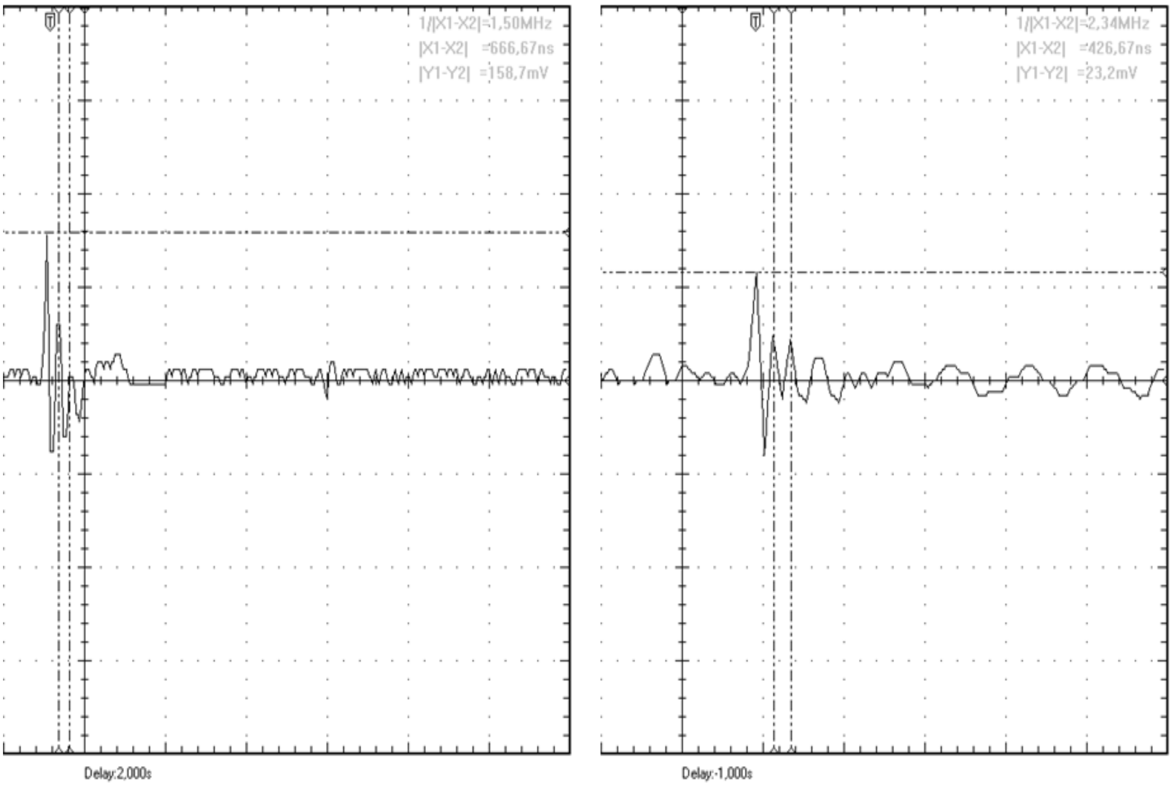

Figure 30. Before and after measurement of the shaft ground current on the 400 kW motor. Graphs are of different scales, the peak value can be seen in the top right corners (Y1-Y2).

We can see from the graph that the peak value dropped from 158.7 mV (0.79 A) to 23.2 mV (0.12 A). This is a reduction of approximately 85 %. In the 3 kW motor we saw a similar result, a drop from 132.0 mV (0.66 A) to 41.3 mV (0.21 A), a reduction of 68 %. These results are very promising, as they prove that these filters are an effective solution to the problem. The lowered peak values of the current pulses should decrease the stress on the bearings and increase their lifetime. We decided to use these filters on all motors over 1.5 kW. The smallest motors had no clear signs of bearing current damage.

Reduction of switching frequency will affect the occurrence rate of the current spikes. Reduction of this setting in the VFD’s control panel should increase the lifetime of the bearings proportionally to the reduction of the frequency. Vacon was consulted to find the minimum safe setting for the frequency. The setting can be found in the control panel of the Vacon frequency converters in section P2.6.9. The following changes were applied:

Large motors 3.6 kHz → 1.8 kHz (Reduction of 50 %)

Small motors 10 kHz → 3.6 kHz (Reduction of 64 %)

These changes should in theory double the lifetime of bearings in large motors and almost triple the lifetime in smaller motors. The negative effect of reducing the switching frequency is marginally higher losses in the motor and an increased noise output at the motor. The total efficiency of the system should remain about the same because of the lowered losses in the VFD, fewer switches by the insulated-gate bipolar transistors in the VFD result in lower losses. These motors are located in environments where noise output is not of critical importance.

7.2 My recommendations

The changes mentioned in the previous chapter should significantly reduce wear on the bearings. If bearing currents are still a problem in the future, I will mention a couple of additional improvements that could be applied to reduce bearing currents even further.

Hybrid bearings would be a viable choice for system critical motors; they are the most effective way of reducing bearing currents. They are very expensive but might be a reasonable upgrade if the problem persists. It is an expensive, difficult and time-consuming process to ship a motor to service for bearing change. These bearings would increase the time between failures.

Installing grounding brushes on smaller motors would be a good option if the problem persists. This method is a relatively inexpensive and effective way to reduce current spikes caused by shaft grounding currents and capacitive bearing currents. Installing the brushes afterwards means that they have to be retrofitted to the shafts. This is time-consuming and will require service work in a stand-by scenario. This would also increase the time between failures.

8 Conclusion

The purpose of this thesis work was to find solutions for how to reduce bearing currents in motors driven by frequency converters in a power plant. A large amount of my time was spent researching the phenomenon and the known solutions to the problem. I was able to come to a conclusion after having done my research and after some discussions with experts from ABB and Vacon. The measurements before and after installing the common-mode filters confirmed what I had learned from my research.

It is difficult to know how effective the solutions in this thesis are in practice, only time will tell. The reduction of the switching frequency alone should in theory double or triple the lifetime of the bearings. The installation of common-mode filters should increase the life even further, exactly how much is hard to estimate, but the voltage amplitudes were reduced by up to 85 % in the before and after measurements. This reduction in amplitude will reduce the damage on the bearings. The improvements to the grounding system in some of the motors could also have an effect on bearing life.

The improvements made on the basis of this thesis should multiply the lifetime of most bearings in the researched motors. These changes have the potential to save the company a lot of money in the future. I would consider this thesis work to be very successful.

9 Discussion

This thesis work has been a very interesting project. I have got a lot of new theoretical knowledge of electrical motors and related components. I have also learned about maintenance work that goes on in a facility like Westenergy and how communication is handled between different companies.

I hope that this thesis work can be of help to others who are experiencing the same kind of problems. I believe that many are not aware of bearing current problems. Deciding to get common-mode filters in the first place could potentially save a company a lot of trouble and money.

A suggestion for another thesis work at Westenergy could be a follow-up inspection of the researched motors in this thesis. This could be done after a few years; it could involve researching possibilities to improve things further.

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