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Technical guide No. 5

Bearing currents in modern AC drive systems

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Bearing currents in modern AC drive systems

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Chapter 1 - Introduction

General

Some new drive installations can have their bearings fail only a few months after startup. Failure can be caused by high frequency currents, which flow through the motor bearings.

While bearing currents have been around since the advent of electric motors, the incidence of damage they cause has increased during the last few years. This is because modern variable speed drives with their fast rising voltage pulses and high switching frequencies can cause current pulses through the bearings whose repeated discharging can gradually erode the bearing races.

Avoiding bearing currents

To avoid damage occurring, it is essential to provide proper earthing paths and allow stray currents to return to the inverter frame without passing through the bearings. The magnitude of the currents can be reduced by using symmetrical motor cables or inverter output filtering. Proper insulation of the motor bearing construction breaks the bearing current paths.

Chapter 2 - Generating bearing currents

High frequency current pulses

Bearing currents come in several different guises. However, while modern motor design and manufacturing practices have nearly eliminated the low frequency bearing currents induced by the asymmetry of the motor, the rapid switching in modern AC drive systems may generate high frequency (HF) current pulses through the bearings. If the energy of these pulses is sufficiently high, metal transfers from the ball and the races to the lubricant. This is known as electrical discharge machining or EDM. The effect of a single pulse is insignificant, but a tiny EDM pit is an incontinuity that will collect more pulses and expand into a typical EDM crater. The switching frequency of modern AC drives is very high and the vast number of pulses causes the erosion to quickly accumulate. As a result, the bearing may need replacing after only a short time in service.

High frequency bearing currents have been investigated by ABB since 1987. The importance of system design has been highlighted in the last few years. Each individual item involved, such as the motor, the gearbox or the drive controller, is the product of sophisticated manufacturing techniques and normally carries a favourable mean time between failure (MTBF) rate. It is when these components are combined and the installed system is looked upon as a whole, that it becomes clear that certain installation practices are required.

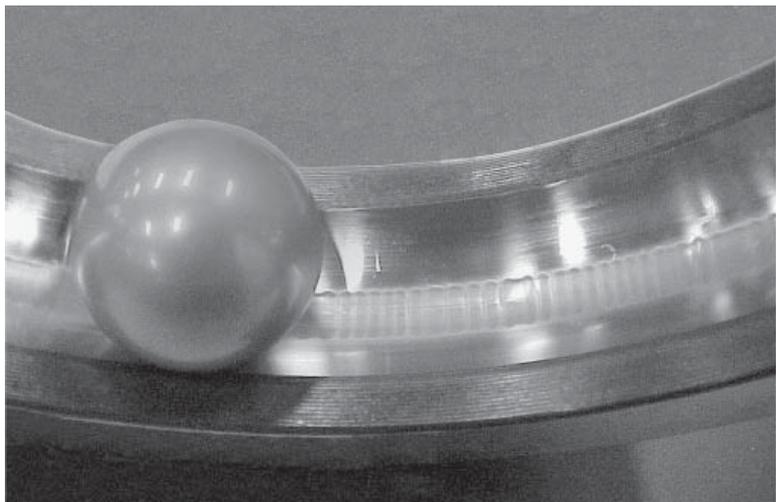


Figure 1: Bearing currents can cause “bearing fluting”, a rhythmic pattern on the bearing’s races.

Faster switching

Current AC drive technology, incorporating insulated gate bipolar transistors (IGBT), creates switching events 20 times faster than those considered typical ten years ago. Recent years have seen a rising number of EDM-type bearing failures in AC drive systems relatively soon after startup, within one to six months. The extent to which this occurs depends on the AC drive system architecture and the installation techniques used.

How are HF bearing currents generated?

The source of bearing currents is the voltage that is induced over the bearing. In the case of high frequency bearing currents, this voltage can be generated in three different ways. The most important factors that define which mechanism is prominent, are the size of the motor and how the motor frame and shaft are grounded. The electrical installation, meaning a suitable cable type and proper bonding of the protective conductors and the electrical shield, plays an important role. du/dt of the AC drive power stage components and the DC-link voltage level affect the level of bearing currents.

Circulating current

In large motors, high frequency voltage is induced between the ends of the motor shaft by the high frequency flux circulating around the stator. This flux is caused by a net asymmetry of capacitive current leaking from the winding into the stator frame along the stator circumference. The voltage between the shaft ends affects the bearings. If it is high enough to overcome the impedance of the bearings' oil film, a current that tries to compensate the net flux in the stator starts to flow in the loop formed by the shaft, the bearings and the stator frame. This current is a circulating type of high frequency bearing current.

Shaft grounding current

The current leaking into the stator frame needs to flow back to the inverter, which is the source of this current. Any route back contains impedance, and therefore the voltage of the motor frame increases in comparison to the source ground level. If the motor shaft is earthed via the driven machinery, the increase of the motor frame voltage is seen over the bearings. If the voltage rises high enough to overcome the impedance of the drive-end bearing oil film, part of the current may flow via the drive-end bearing, the shaft and the driven machine back to the inverter. This current is a shaft grounding type of high frequency bearing current.

Capacitive discharge current

In small motors, the internal voltage division of the common mode voltage over the internal stray capacitances of the motor may cause shaft voltages high enough to create high frequency bearing current pulses. This can happen if the shaft is not earthed via the driven machinery while the motor frame is earthed in the standard way for protection.

Common mode circuit

High frequency bearing currents are a consequence of the current flow in the common mode circuit of the AC drive system.

A typical three-phase sinusoidal power supply is balanced and symmetrical under normal conditions. That is, the vector sum of the three phases always equals zero. Thus, it is normal that the neutral is at zero volts. However, this is not the case with a PWM switched three-phase power supply, where a dc voltage is converted into three phase voltages. Even though the fundamental frequency components of the output voltages are symmetrical and balanced, it is impossible to make the sum of three output voltages instantaneously equal to zero with two possible output levels available. The resulting neutral point voltage is not zero. This voltage may be defined as a common mode voltage source. It is measurable at the zero point of any load, eg. the star point of the motor winding.

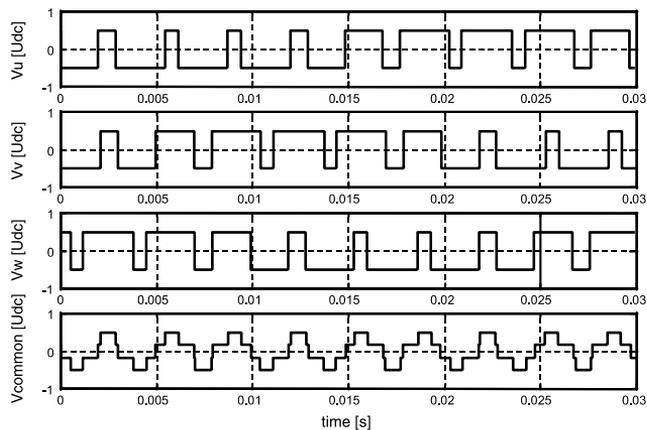


Figure 2: This schematic shows the phase voltages of a typical three phase PWM power supply and the average of the three, or neutral point voltage, in a modern AC drive system. The neutral voltage is clearly not zero and its presence can be defined as a common mode voltage source. The voltage is proportional to the DC bus voltage, and has a frequency equal to the inverter switching frequency.

Any time one of the three inverter outputs is changed from one of the possible potentials to another, a current proportional to this voltage change is forced to flow to earth via the earth capacitances of all the components of the output circuit. The current flows back to the source via the earth conductor and stray capacitances of the inverter, which are external to the three phase system. This type of current, which flows through the system in a loop that is closed externally to the system, is called common mode current.

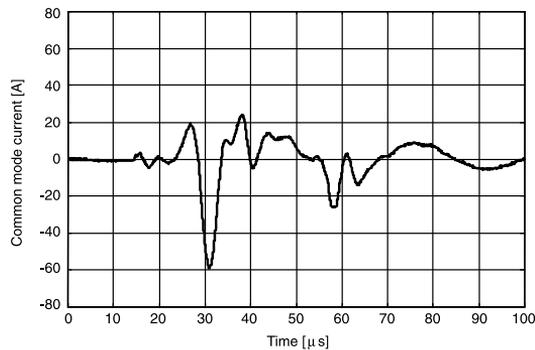


Figure 3: An example of the common mode current at the inverter output. The pulse is a superposition of several frequencies due to the different natural frequencies of the parallel routes of common mode current.

Stray capacitances

A capacitance is created any time two conductive components are separated by an insulator. For instance, the cable phase wire has capacitance to the PE-wire separated by PVC insulation, for example, and the motor winding turn is insulated from the frame by enamel coating and slot insulation, and so has a value of capacitance to the motor frame. The capacitances within a cable and especially inside the motor are very small. A small capacitance means high impedance for low frequencies, thus blocking the low frequency stray currents. However, fast rising pulses produced by modern power supplies contain frequencies so high that even small capacitances inside the motor provide a low impedance path for current to flow.

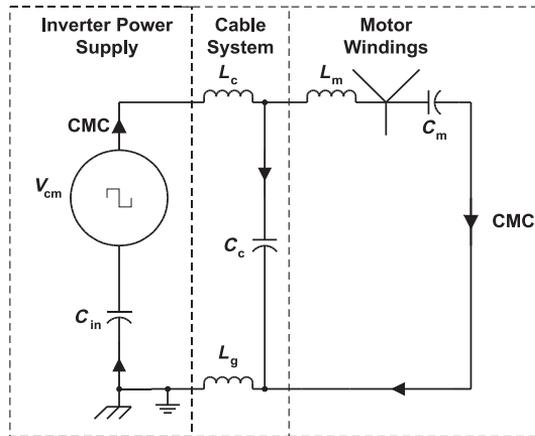


Figure 4: Simplified loop of the common mode current of a PWM inverter and induction motor. The inverter power supply acts as a common mode voltage source (V_{cm}). Common mode current (CMC) flows through the common mode cable and motor inductances, L_c , L_m and through the stray capacitances between the motor windings and motor frame, combined to be C_m . From the motor frame, the current proceeds through the factory earth circuit which has the inductance L_g . L_g is also fed common mode current from the stray cable capacitance C_c . The inverter frame is connected to the factory earth and couples the common mode current/earth currents through stray inverter to frame capacitances, combined as C_{in} , back to the common mode voltage source.

How does the current flow through the system?

The return path of the leakage current from the motor frame back to the inverter frame consists of the motor frame, cable shielding or PE-conductors and possibly steel or aluminium parts of the factory building structure. All these elements contain inductance. The flow of common mode current through such inductance will cause a voltage drop that raises the motor frame potential above the source ground potential at the inverter frame. This motor frame voltage is a portion of the inverter's common mode voltage. The common mode current will seek the path of least impedance. If a high amount of impedance is present in the intended paths, like the PE-connection of the motor frame, the motor frame voltage will cause some of the common mode current to be diverted into an unintended path, through the building. In practical installations a number of parallel paths exist. Most have a minor effect on the value of common mode current or bearing currents, but may be significant in coping with EMC-requirements.

Voltage drops

If the value of this inductance is high enough, the reactance at the upper range of typical common mode current frequencies, 50 kHz to 1 MHz, can support voltage drops of over 100 volts between the motor frame and the inverter frame. If, in such a case, the motor shaft is connected through a metallic coupling to a gearbox or other driven machinery that is solidly earthed and near the same earth potential as the inverter frame, then it is possible, that part of the inverter common mode current flows via the motor bearings, the shaft and the driven machinery back to the inverter.

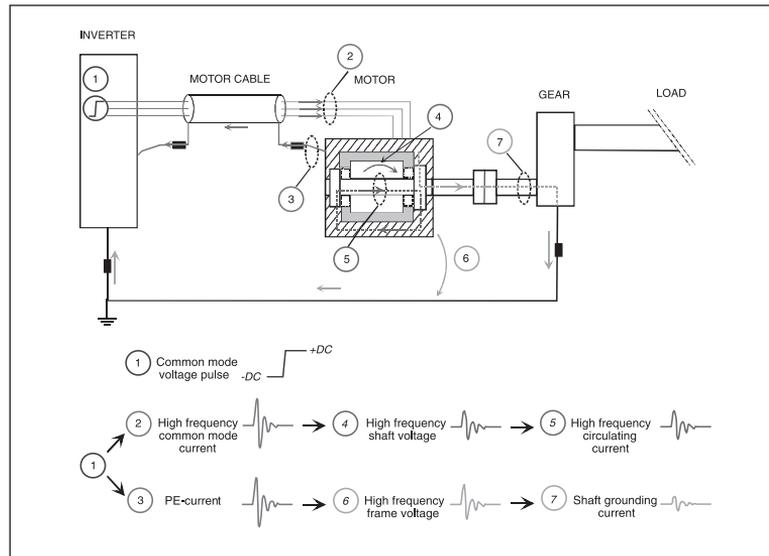


Figure 5: A schematic presentation showing the circulating current and shaft grounding current, the latter resulting from high motor frame voltage with superior machine earthing.

If the shaft of the machinery has no direct contact to the ground level, current may flow via the gearbox or machine bearings. These bearings may be damaged before the motor bearings.

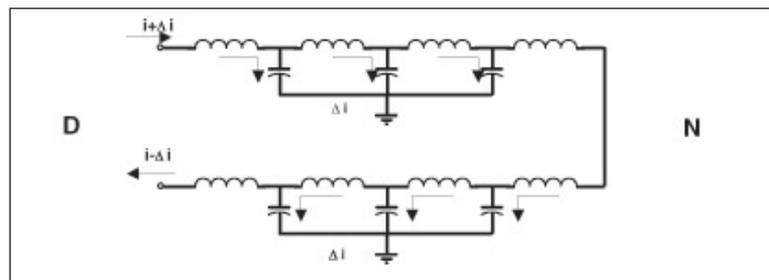


Figure 6: Source of circulating high frequency bearing current. Current leakage through distributed stator capacitances gives a non-zero current sum over the stator circumference. This leads to a net magnetising effect and flux around the motor shaft.

Common mode transformer

The largest share of the motor's stray capacitance, is formed between the stator windings and the motor frame. This capacitance is distributed around the circumference and length of the stator. As the current leaks into the stator along the coil, the high frequency content of the current entering the stator coil is greater than the current leaving.

This net current produces a high frequency magnetic flux that will circulate in the stator laminations, inducing an axial voltage in the shaft ends. If the voltage becomes large enough, a high frequency circulating current can flow, internal to the motor, through the shaft and both bearings. The motor can, in this case, be thought of as a transformer, where the common mode current flowing in the stator frame acts as a primary and induces the circulating current into the rotor circuit or secondary. This bearing current is considered to be the most damaging with typical peak values of 3 to 20 amps depending on the rated power of the motor, du/dt of the AC drive power stage components and DC-link voltage level.

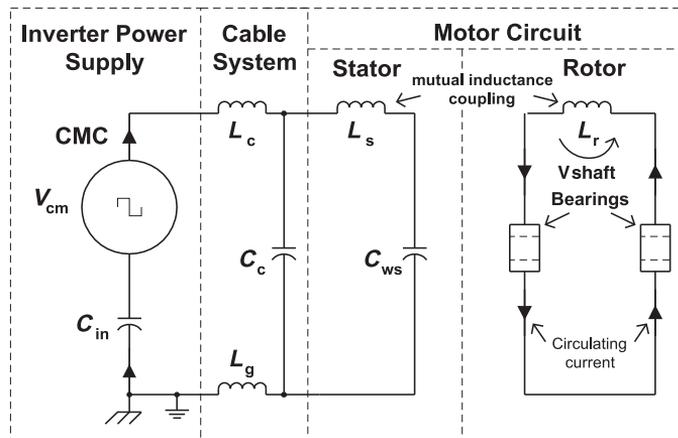


Figure 7: The high frequency axial shaft voltage can be thought of as the resultant of a transformer effect, in which the common mode current flowing in the stator frame acts as a primary, and induces the circulating current into the rotor circuit or secondary.

Another version of circulating bearing current occurs when, the current, instead of circulating completely inside the motor, flows via the shaft and the bearings of the gearbox or driven machinery and in a structural element that is both external and common to the motor and the driven machine. The origin of the current is the same as in the current circulating inside the motor. An example of this “vagabond” circulating bearing current is shown in figure 8.

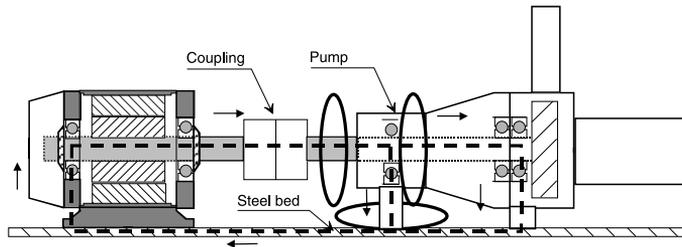


Figure 8: “Vagabond” circulating bearing current, where the current loop is external to the motor.

Capacitive voltage divider

Other stray capacitances are also present in the motor, such as the capacitance between the stator windings and the rotor, or that existing in the motor’s airgap between the stator iron and the rotor. The bearings themselves may even have stray capacitance.

The existence of capacitance between the stator windings and the rotor effectively couples the stator windings to the rotor iron, which is also connected to the shaft and the bearing’s inner races. Fast changes in the common mode current from the inverter can not only result in currents in the capacitance around the circumference and length of the motor, but also between the stator windings and the rotor into the bearings.

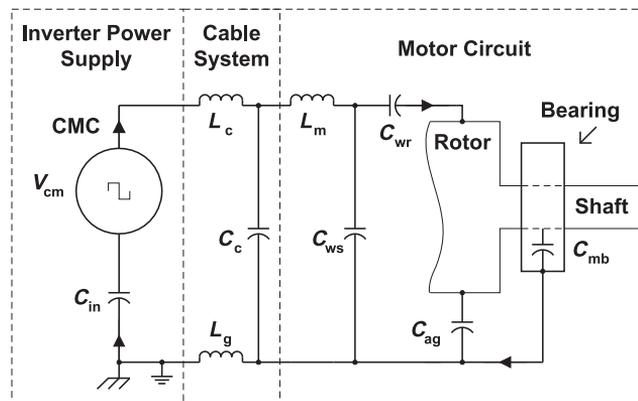


Figure 9: Common mode loop of variable speed drive, showing stator, rotor and bearing stray capacitances.

The current flow into the bearings can change rapidly, as this depends on the physical state of the bearing at any one time. For instance, the presence of stray capacitance in the bearings is only sustained for as long as the balls of the bearings are covered in oil or grease and are non-conducting. This capacitance, where

the induced shaft voltage builds up, can be short-circuited if the bearing voltage exceeds the threshold of its breakover value or if a “high spot” on a ball breaks through the oil film and makes contact with both bearing races. At very low speed, the bearings have metallic contact since the balls have not risen on an oil film.

Generally, the bearing impedance governs the voltage level at which the bearings start to conduct. This impedance is a non-linear function of bearing load, temperature, speed of rotation and lubricant used, and the impedance varies from case to case.

Chapter 3 - Preventing high frequency bearing current damage

Three approaches

There are three approaches used to affect high frequency bearing currents: a proper cabling and earthing system; breaking the bearing current loops; and damping the high frequency common mode current. All these aim to decrease the bearing voltage to values that do not induce high frequency bearing current pulses at all, or damp the value of the pulses to a level that has no effect on bearing life. For different types of high frequency bearing currents, different measures need to be taken.

The basis of all high frequency current mastering is the proper earthing system. Standard equipment earthing practices are mainly designed to provide a sufficiently low impedance connection to protect people and equipment against system frequency faults. A variable speed drive can be effectively earthed at the high common mode current frequencies, if the installation follows three practices:

Multicore motor cables

Use only symmetrical multicore motor cables. The earth (protective earth, PE) connector arrangement in the motor cable must be symmetrical to avoid bearing currents at fundamental frequency. The symmetry of the PE-conductor is achieved by a conductor surrounding all the phase leads or a cable that contains a symmetrical arrangement of three phase leads and three earth conductors.

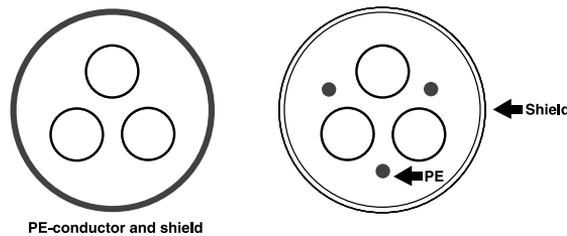


Figure 10: Recommended motor cable with symmetrical core configuration.

Short impedance path

Define a short, low impedance path for common mode current to return to the inverter. The best and easiest way to do this is to use shielded motor cables. The shield must be continuous and of good conducting material, ie, copper or aluminium and the connections at both ends need to be made with 360° termination.

Figures 11a and 11b show 360° terminations for European and American cabling practices.

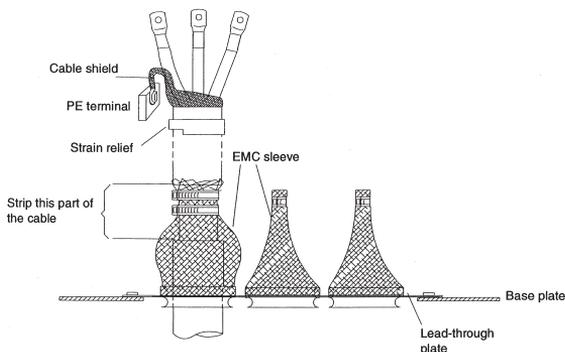


Figure 11 a: Proper 360° termination with European cabling practice. The shield is connected with as short a pigtail as possible to the PE terminal. To make a 360° high frequency connection between the EMC sleeve and the cable shield, the outer insulation of the cable is stripped away.

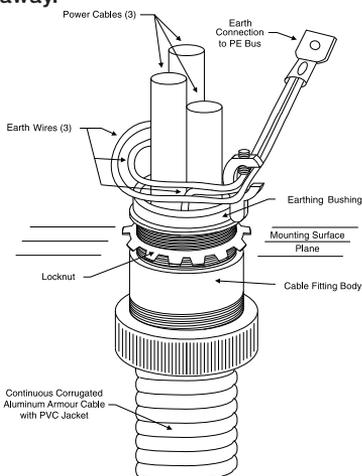


Figure 11 b: Proper 360° termination with American cabling practice. An earthing bushing should be used on both ends of the motor cable to effectively connect the earth wires to the armour or conduit.

High frequency bonding connections

Add high frequency bonding connections between the installation and known earth reference points to equalise the potential of affected items, using braided straps of copper 50 - 100 mm wide; flat conductors will provide a lower inductance path than round wires. This must be made at the points where discontinuity between the earth level of the inverter and that of the motor is suspected. Additionally it may be necessary to equalise the potential between the frames of the motor and the driven machinery to short the current path through the motor and the driven machine bearings.

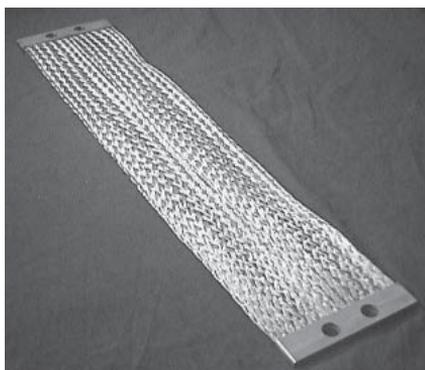


Figure 12: HF bonding strap

Follow product specific instructions

Although the basic principles of installations are the same, for different products suitable installation practices may differ. Therefore, it is essential to carefully follow the installation instructions given in product specific manuals.

Additional solutions

Breaking the bearing current loops is achieved by insulating the bearing construction. The high frequency common mode current can be damped by using dedicated filters. As a manufacturer of both inverters and motors, ABB can offer the most appropriate solution in each case as well as detailed instructions on proper earthing and cabling practices.

Measuring high frequency bearing currents

Monitoring the bearing condition must be conducted with established vibration measurements.

It is impossible to measure bearing currents directly from a standard motor. But if high frequency bearing currents are suspected, field measurements can be taken to verify the existence of suspected current loops. Measuring equipment needs to have wide bandwidth (minimum 10 kHz to 2 MHz) capable of detecting peak values of at least 150 to 200 A and RMS values at least down to 10 mA. The crest factor of measured signals is seldom less than 20. The current may flow in unusual places, such as rotating shafts. Thus, special equipment and experienced personnel are needed.

ABB uses a specially designed, flexible, air-cored, Rogowski-type current sensor with dedicated accessories and has vast experience of over one thousand measured drives in different applications worldwide.

The most important measurement points are within the motor. During measurements, the motor speed needs to be at least 10% of the nominal for the bearings to rise on the oil film. As an example, basic measurements are shown in figure 13. Figure 14 shows examples of measured current waveforms. GTO (gate turn-off thyristor) inverters were used mainly in the 1980s and IGBT inverters are used today. Note the different scale in the various graphs.

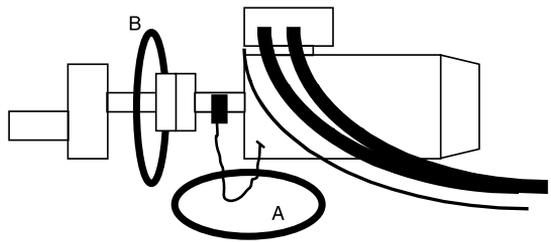
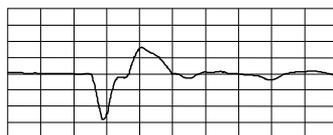
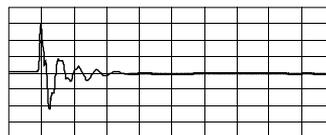


Figure 13: Basic measurements: A) circulating current measured with a jumper, B) shaft grounding current.

A) Circulating current

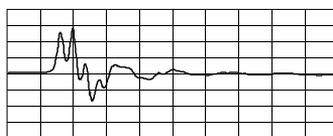


GTO-inverter, 5 μ s/div, 2 A/div

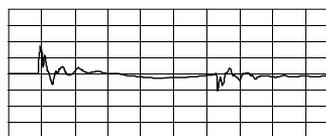


IGBT-inverter, 5 μ s/div, 2 A/div

B) Shaft grounding current



GTO-inverter, 2 μ s/div, 10 A/div



IGBT-inverter, 5 μ s/div, 500 mA/div

Figure 14: Examples of current waveforms at the measuring points shown in Figure 13.

Leave the measurements to the specialists

Since suitable commercial measurement equipment is not available on the market and specialised experience is needed to make the measurements and interpret the results, it is advisable that bearing current measurements are made by dedicated personnel only.

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See also product specific installation manuals.

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